sciendo

DOI: 10.2478/ahr-2021-0008

Acta Horticulturae et Regiotecturae – Special Issue
Nitra, Slovaca Universitas Agriculturae Nitriae, 2021, pp. 37–44

LONG-TERM RUNOFF VARIABILITY ANALYSIS OF RIVERS IN THE DANUBE BASIN

Pavla PEKÁROVÁ[1]*, Jakub MÉSZÁROS[1], Pavol MIKLÁNEK[1],
Ján PEKÁR[2], Stevan PROHASKA[3], Aleksandra ILIĆ[4]

[1]Institute of Hydrology of the Slovak Academy of Sciences, Bratislava, Slovakia
[2]Comenius University in Bratislava, Slovakia
[3]Jaroslav Černi Institute for the Development of Water Resources, Beograd, Serbia
[4]University of Niš, Serbia

The long-term runoff variability is identified to consist of the selected large rivers with long-term data series in the Danube River Basin. The rivers were selected in different regions of the Danube River Basin and have a large basin area (Danube: Bratislava gauge with 131,338 km^2; Tisza: Senta with 141,715 km^2; and Sava: Sremska Mitrovica with 87,966 km^2). We worked with the station Danube: Reni in the delta as well. A spectral analysis was used to identify the long-term variability of three different types of time series: (1) Average annual discharge time series, (2) Minimum annual discharge time series and (3) Maximum annual discharge time series. The results of the study can be used in a long-term forecast of the runoff regime in the future.

Keywords: long-term discharge analysis, spectral analysis, Danube River Basin

The Danube River with a total length of 2,857 km and a long-term daily mean discharge of about 6,500 m^3.s^{-1} is listed as the second biggest river in Europe. In the terms of length, it is listed as the 21st biggest river in the world, in the terms of a drainage area, it is ranked as the 25th with a drainage area of 817,000 km^2. Nineteen countries share the Danube basin, though two thirds of the catchment lie within five countries (Romania, Hungary, Serbia, Austria and Germany). In the large international river basins – such as the Danube basin- it is necessary to synchronise the methodologies of the calculation of the hydrological characteristics and to prepare common procedures. In 1971, the hydrologists of eight Danube countries launched a regional hydrological cooperation on a voluntary basis, aiming to produce consistent hydrological information about the whole Danube basin. Since 1987, this cooperation has been carried out in the framework of the International Hydrological Programme (IHP) of UNESCO. The cooperation of the Danube countries within the framework of IHP of UNESCO is based on the project work on one hand and on the other, on the regular conferences. Several projects were finalised within the Danube collaboration. The topic of floods was observed by several of them in the last years:

- Project No. 4: Coincidence of flood flow of the Danube River and its tributaries (Prohaska et al., 1999; Prohaska, Ilić, 2010).
- Project No. 5.2: Flow regime of river Danube and its catchment (Belz et al., 2004).
- Project No. 7: Regional analysis of the annual peak discharges in the Danube catchment (Stănescu, Ungureanu, Mătreaţă, 2004).
- Project No. 9 Flood regime of rivers in the Danube River basin (Pekárová, Miklánek (eds), 2019).

Since the very inception of hydrology as a scientific discipline, hydrologists and climatologists around the world have been trying to make a science-based prediction of the future development in the hydrosphere. Generally, it is expected that the increase of temperature will increase evapotranspiration in summer and decrease the runoff.

There are two main approaches to stream the runoff prognosis in the next decades:

1. Statistical analysis of the long-term discharge series followed by a prognosis using stochastic auto-regressive models.
2. Application of the hydrological rainfall-runoff models based on the precipitation-temperature-stream runoff relations. The precipitation and temperature data are modified according to the selected climate scenarios for the future time horizons (most frequently 2050, 2075 or 2100).

In this study, the first method was used and changes in statistical characteristics of the discharge, using detailed statistical analysis of the daily, monthly and annual time series in the four selected sub-basins of the Danube River Basin were identified.

Material and method

A Danube discharge description

The Danube River originates in the Schwarzwald (Black Forest) mountains in Bavaria in Germany. It has its sources

Contact address: Pavla Pekárová, Slovak Academy of Sciences, Institute of Hydrology, Dúbravská cesta 9, 841 04 Bratislava, Slovakia; +421 232 29 35 03; e-mail: pekarova@uh.savba.sk

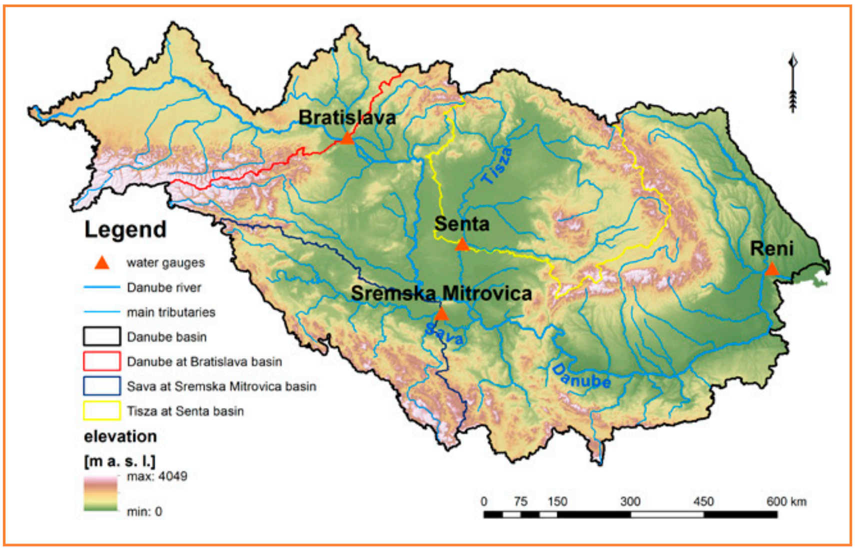

Figure 1 Scheme of the Danube River Basin. Water gauges were used

outside the Alps in an old mountainous massif. From the hydrological point of view, the Danube is an important hydrologic and hydrographic system, which is formed by several significant tributaries. Over 120 major rivers directly confluence with the Danube and a majority of them has its own significant tributaries. Approximately, in the middle of the Danube length near the end of the middle section, the Danube receives its two main tributaries Tisza and Sava in a short distance (Figure 1).

The regime of precipitation differs in different parts of the Danube basin. This variability is also reflected in a runoff regime of the individual sub-basins and it corresponds to the position of the sub-basins within the whole basin.

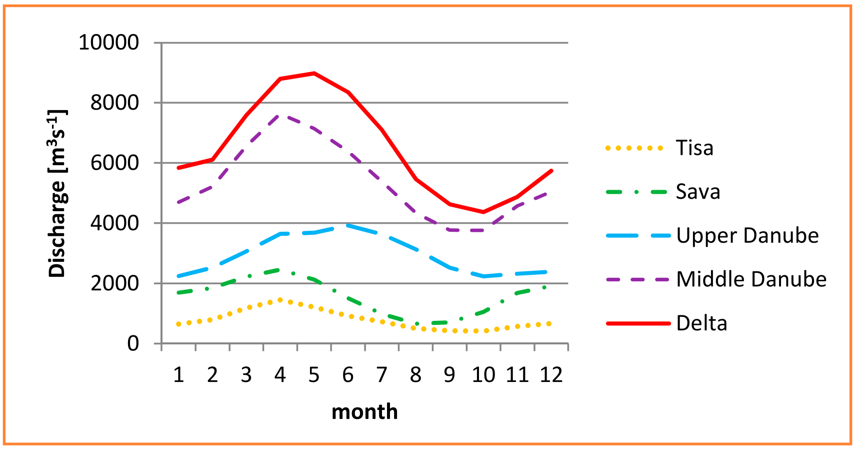

Figure 2 Mean monthly discharges of the Danube basin and its sub-basins (1931–1990)

In the period 1931–1990, the mean annual discharge of the upper Danube (upstream the confluence with Tisa), and of the Tisza and Sava River was 2,943 $m^3.s^{-1}$, 791 $m^3.s^{-1}$, and 1,572 $m^3.s^{-1}$, respectively. The mean annual discharge downstream the confluence of the three major sub-basins was 5,374 $m^3.s^{-1}$, and the mean annual runoff was 6,846 $m^3.s^{-1}$ in the Danube delta.

The maximum runoff occurs in June in the upper Danube basin, but in April in the Sava and Tisza basins (Figure 2). After the confluence of these three major sub-basins, the maximum is shifted to April at the end of the middle river section. Concerning downstream, the maximum is shifted to May in the delta region due to the tributaries in the lower Danube section. The minimum monthly runoff occurs in autumn season in the major part of the Danube basin with an exception of the Sava River with minimum flows in August and September. The increase of the monthly runoff in November and December in the Sava basin is the reason for an increase of flows at the lower section of the Danube River (Miklánek and Pekárová, 2016).

To analyse the long-term runoff variability, the daily discharge series from four water gauge stations: Danube: Bratislava gauge with 131,338 km^2 (Slovakia – SK); Tisza: Senta with 141,715 km^2 (Serbia – SR); Sava: Sremska Mitrovica with 87,966 km^2 (Serbia – SR); and Danube: Reni with 805,700 km^2 (Ukraine – UA) (Table 1, Figure 3) were used. The Tisza basin is one of the driest sub-basins in the Danube basin according to the specific yield. The daily discharge series of the Danube River were obtained from the database of the UNESCO subproject No. 4.2.1 "Water temperature simulation during summer low flow conditions in the Danube basin".

Table 1 Long-term mean annual and daily discharge characteristics of the Danube in Bratislava (SK), Tisza in Senta (SR), Sava in Sremska Mitrovica (SR), and Danube in Reni (UA)

	A (km^2)	***Q*** ($m^3.s^{-1}$)	***q*** ($l.s^{-1}.km^{-2}$)	***R*** (mm)	$Q_{d,min}$	$Q_{d,max}$	Period	
Danube: Bratislava	131,338	2,052	15.6	492.8	580	10,810	1875	2017
Tisza: Senta	141,715	782	5.5	173.9	79	3,730	1921	2017
Sava: Sr. Mitrovica	87,966	1,552	17.6	556.5	194	6,420	1926	2017
Danube: Reni	805,700	6,551	8.1	256.4	1280	15,900	1921	2015

A – a basin area; *Q*/*q*/*R* – long-term average annual discharge/specific yield/runoff depth; $Q_{d,min}$/$Q_{d,max}$ – minimal/maximal daily discharge ($m^3.s^{-1}$)

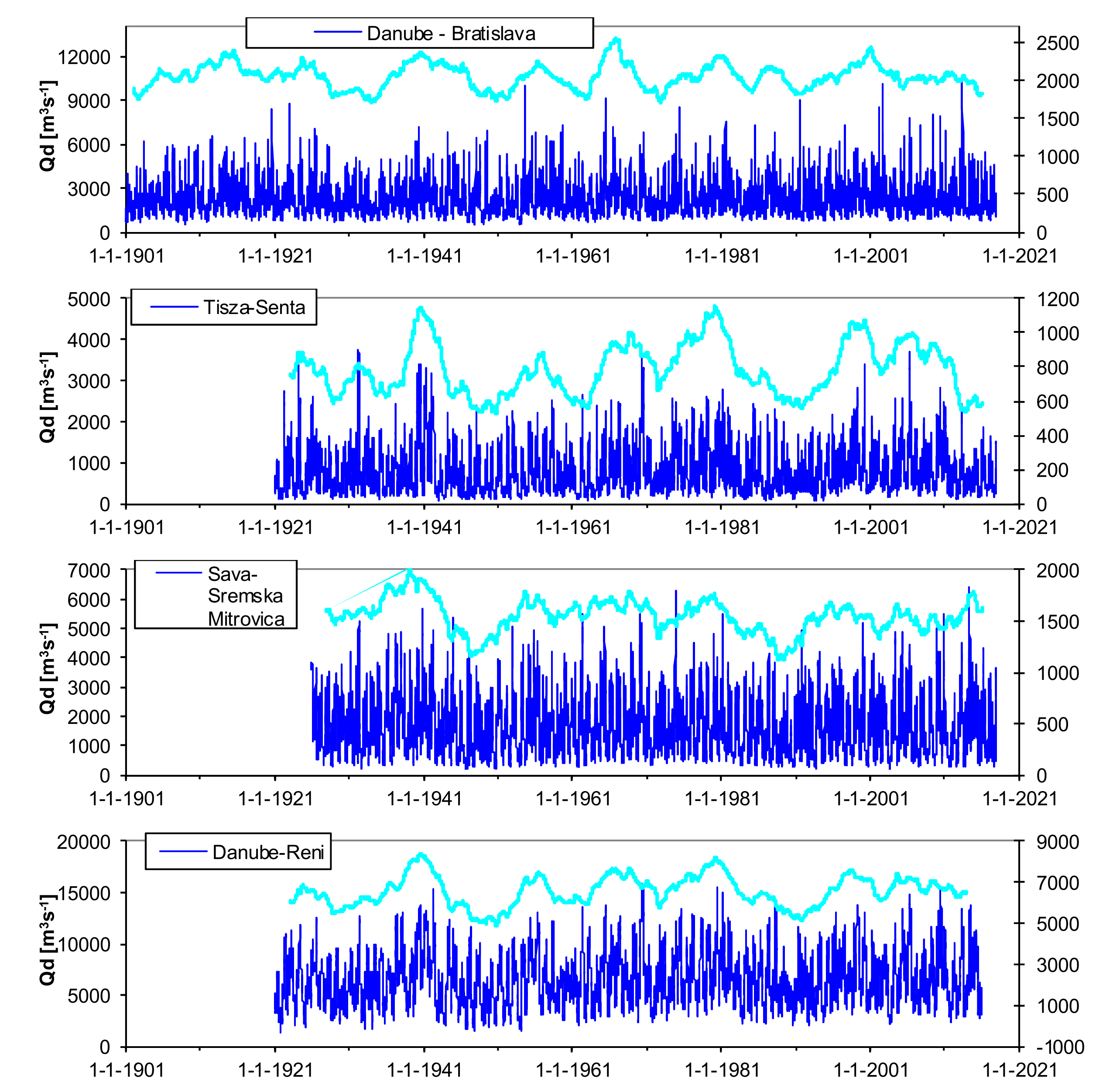

Figure 3 Daily discharge at selected stations of the Danube basin (dark blue lines) and 4-years moving averages (light blue lines) since 1901 or 1921

Identification of the long-term variability – autocorrelation, spectral and trend analysis

From Figure 3, it is evident that annual discharge series are marked by the multi-annual cycles of the dry and wet periods (data are not independent).

It is possible to identify the cyclicity in the time series by an auto-correlation and a spectral analysis. Both methods were used to look for the long-term cycles of runoff decrease and increase in the analysed runoff time series.

The estimation of both, the auto-covariance and the auto-correlation functions of given empirical series $\{x_{ij}\}_{i=1}^{n}$, is the base tool of a time series analysis.

The auto-covariance function $R(\tau)$ can be estimated by the formula:

$$R(\tau) = \frac{\sum_{i=1}^{n-\tau} (x_i - \bar{x}) \cdot (x_{i+\tau} - \bar{x}_{i+\tau})}{n - \tau} \qquad (1)$$

where:

$\bar{x}$ – mean of $\{x_{ij}\}$

The normalized auto-covariance function (with respect to the standard deviation s_x) provides an estimation of the auto-correlation function $r(\tau)$ of the form:

$$r(\tau) = \frac{R(\tau)}{s_x^2} \qquad (2)$$

where:
$\tau = 0, 1, 2...; m = n/2$
Function $r(\tau)$ reaches its values within the interval <-1, 1>.

The spectral analysis is used to examine the periodical properties of random processes $\{x\}_{i=1}^{n}$. The spectral analysis generalises a classical harmonic analysis by introducing the mean value in time of the periodogram obtained from the individual realizations. The fundamental statistical characteristic of the spectral analysis is its spectral density.

The basic tool in estimating the spectral density is a periodogram. The periodogram (a line spectrum) is a frequency plot with ordinate pairs for a specific time period. This graph breaks time series into a set of sine waves of various frequencies. It is used to construct a frequency spectrum. A periodogram can be helpful in identifying randomness and seasonality in the time series data and in recognizing the predominance of a negative or positive autocorrelation – the help you often need to identify an appropriate model for forecasting the given time series. If the periodogram contains one spike, the data may not be random. The spectral density is defined as a mean value of the set of periodogram for $n \to \infty$.
The periodogram is calculated according to the formula:

$$I(\lambda_j) = \frac{1}{2\pi n}\left|\sum_{\tau=1}^{n} x_\tau e^{-i\tau\lambda_j}\right|^2 =$$

$$= \frac{1}{2\pi n}\left\{\left(\sum_{\tau=1}^{n} x_\tau.\sin(\tau.\lambda_j)\right)^2 + \left(\sum_{\tau=1}^{n} x_\tau.\cos(\tau.\lambda_j)\right)^2\right\} \quad (3)$$

We compute the squared correlation between the series and the sine/cosine waves of frequency λ_j. By the symmetry $I(\lambda_j) = I(-\lambda_j)$ we need only to consider $I(\lambda_j)$ on $0 \le \lambda_j \le \pi$.

For real centred series, the periodogram $I(\lambda_j)$ can be estimated by an auto-covariance function as:

$$I(\lambda_j) = \frac{1}{2\pi}\left(R_0 + 2\sum_{\tau=1}^{n-1} R_\tau \cdot \cos(\tau \cdot \lambda_j)\right) \quad (4)$$

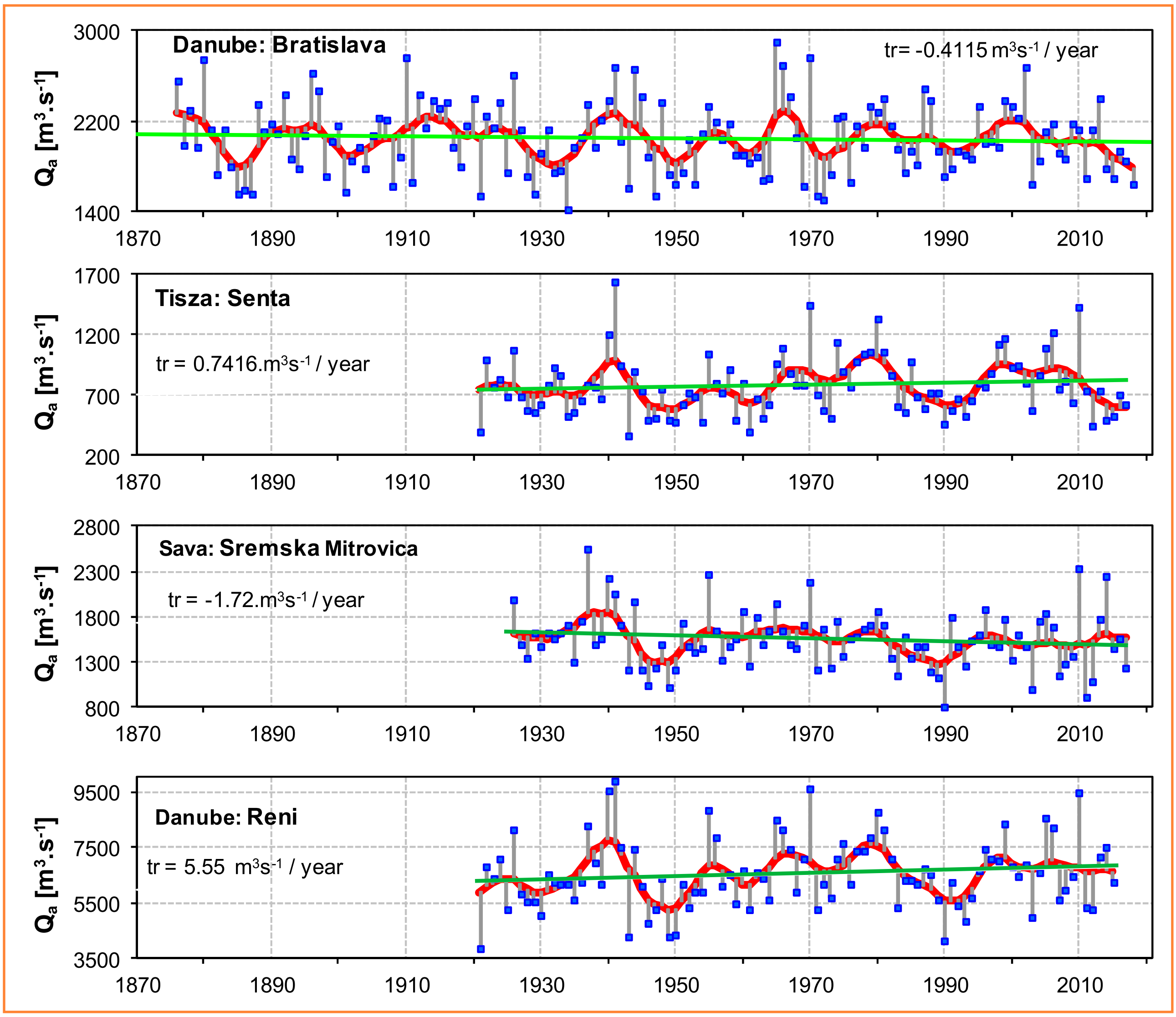

Figure 4 Average annual discharge at selected stations of the Danube basin (blue points), double 7-year moving averages (red line), long-term trend *tr* (green line)

for Fourier frequencies:

$$\lambda_{j'} = \frac{2\pi \cdot j}{n} \qquad (5)$$

where:

$j = \left\langle 1, \frac{n}{2} \right\rangle$

Due to the trend analysis of the time series, the parametric and non-parametric tests can be used. The parametric test considers the linear regression of the random variable x_i in time. The parameters of the trend line are calculated by using a standard method for an estimation of the parameters of a simple linear regression model, i.e. by using the least square method. Mann-Kendall nonparametric trend test was used to identify the long-term trends. The Mann-Kendall nonparametric test (M-K test) is one of the most widely used non-parametric tests for a significant trends detection in time series. By M-K test, the null hypothesis H_0 of no trend was tested, i.e. the observations x_i are randomly ordered in time, against the alternative hypothesis H_1, where there is an increasing or decreasing monotonic trend.

Results and discussion

Multi-annual variability identification of the runoff

More than 60 years ago, by the studies of long-term storage requirements on the Nile River, Hurst (1951) discovered special behaviour of the hydrological and other geophysical time series, which has become known as the 'Hurst phenomenon'. This behaviour is essentially the tendency of the wet years to cluster into wet periods, or of the dry years to cluster into periods of drought (Lin and Lye, 1994). In this

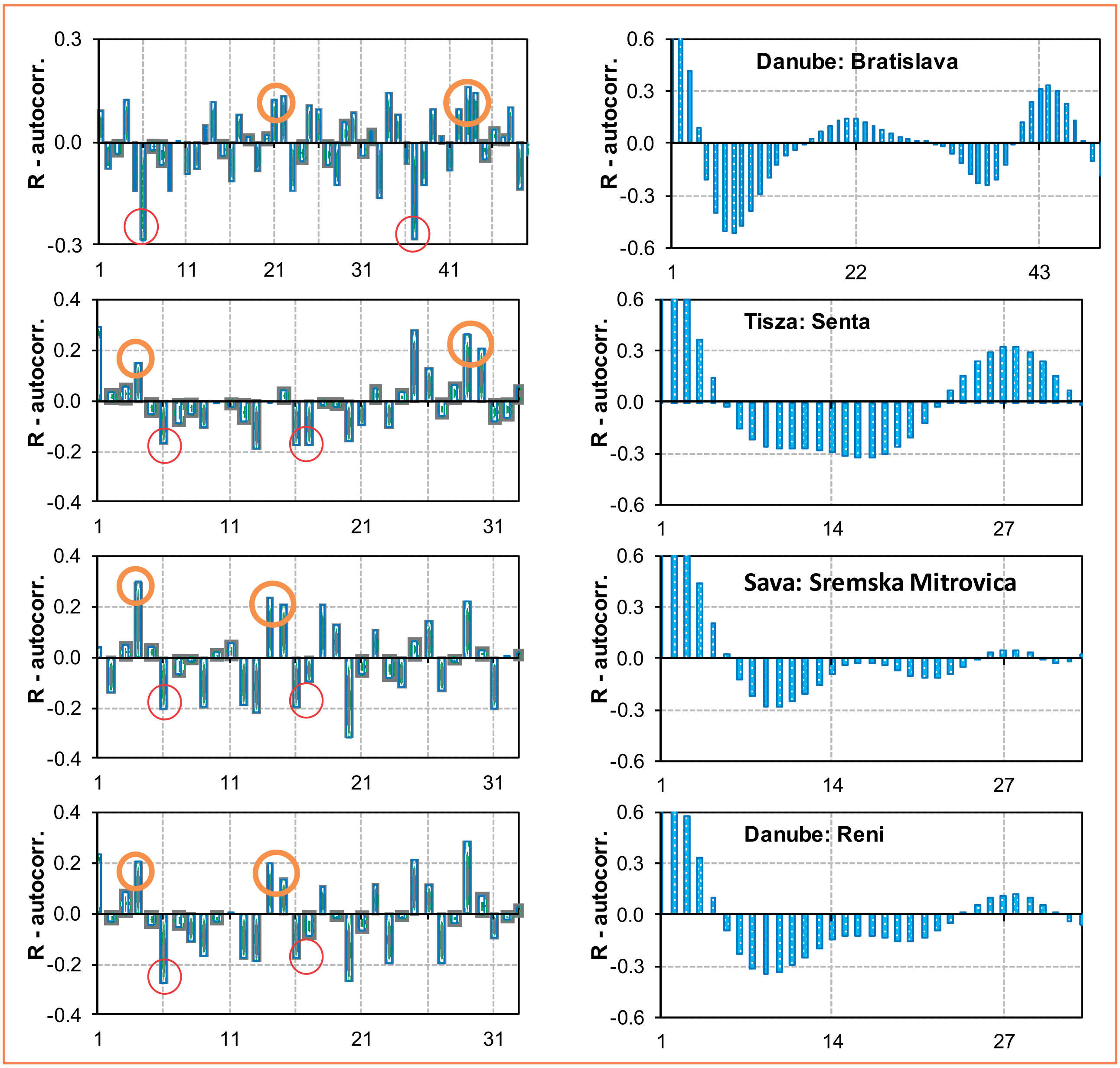

Figure 5 The auto-correlograms of the average annual discharges of the time series of the selected stations (time lag in years)

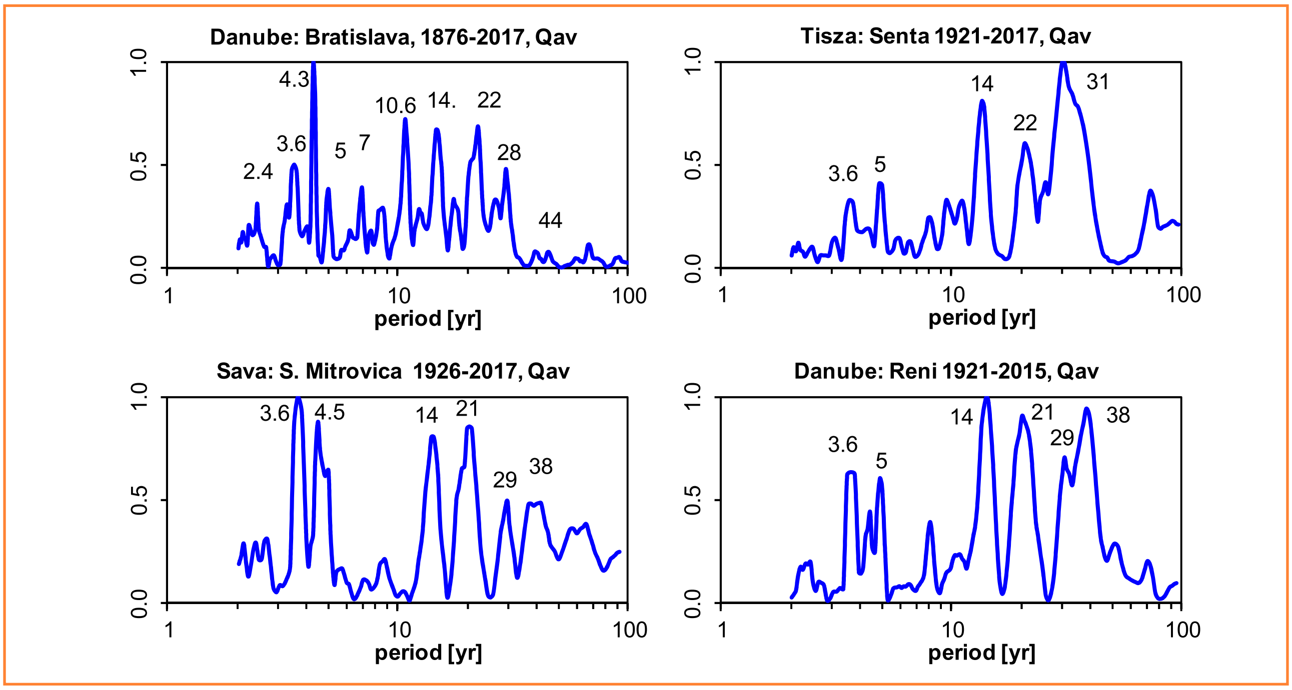

Figure 6 The combined periodograms of the average annual discharges of the selected stations

part of the study, we focused on a dry and wet multi-annual cycles identification in the annual discharge time series (Figure 4) for selected river stations.

The multi-annual cyclic component of the average annual discharges was identified by the auto-correlation analysis and also the spectral analysis. In the Figure 5, there are auto-correlograms of the average annual discharge (left), and the auto-correlograms of the 7-year moving average series of the annual discharge (right). The years of the most significant auto-correlations are marked by circles in the auto-correlogram plots. The negative dependency at minus 6 years is the most significant one. The positive dependency is at 21–22 years. It means that there exists app. 21–22 years cycle in the series.

Figure 6 depicts combined periodograms (Pekárová, Miklánek, Pekár, 2003) of average annual discharges. The spectral analysis confirmed that the occurrence of multi-annual cycles within dry and wet periods (in all basins) is of the following durations: 2.4; 3.6; 5–6; 7; 10–11; 14; 21–22; and 28–30 years.

The spectral and auto-correlation analyses show that the discharge series include cyclic components, which are to be removed from the time series before the analysis of the long-term trends is applied. The significant cycles are 3.6; 21–22 and 29 years. If we start to analyse the long-term trend during the wet period and finish during the dry period, we shall obtain a decreasing trend, of course. The long-term trend analysis has to start and finish in the same phase of the cycle.

Long-term trends identification of the runoff

In the previous part, we have shown that the annual discharge time series include cyclic components. This fact has to be included into the identification of the long-term trends.

With respect to the multiannual cycles of low and high discharges, we have to estimate the long-term trend of the Danube at Bratislava station:

1. from high discharge period to low period (e.g. since 1876 to 2018;
2. from low discharge period to low period (e.g. since 1881 to 2018; Table 2).

For cyclic functions, it is necessary to identify the trend in the whole cycles, starting at the minimum and ending at the minimum (or starting at the maximum and ending at the maximum), because data from an incomplete cycle can influence the trend.

Table 2 Results of annual discharge M-K trend tests for selected time periods, gauging station Danube: Bratislava
Equation of the lines: *f*(year) = *A*(year – first Data Year) + *B*

Time series	First year	Last year	*n*	Sen's slope estimate							
				test *Z*	signific.	*A*	*Amin 95*	*Amax 95*	*B*	*Bmin 95*	*Bmax 95*
Qa	1876	2018	143	-0.69	Non	-0.44	-1.75	0.85	2068	2145	1978
Qa	1882	2018	137	-0.10	Non	-0.06	-1.42	1.34	2033	2129	1927

** – level of significance $\alpha = 0.01$; * – level of significance $\alpha = 0.05$; +- level of significance $\alpha = 0.1$, or Non – non significant trend; *Amin 95*–95% confidence interval

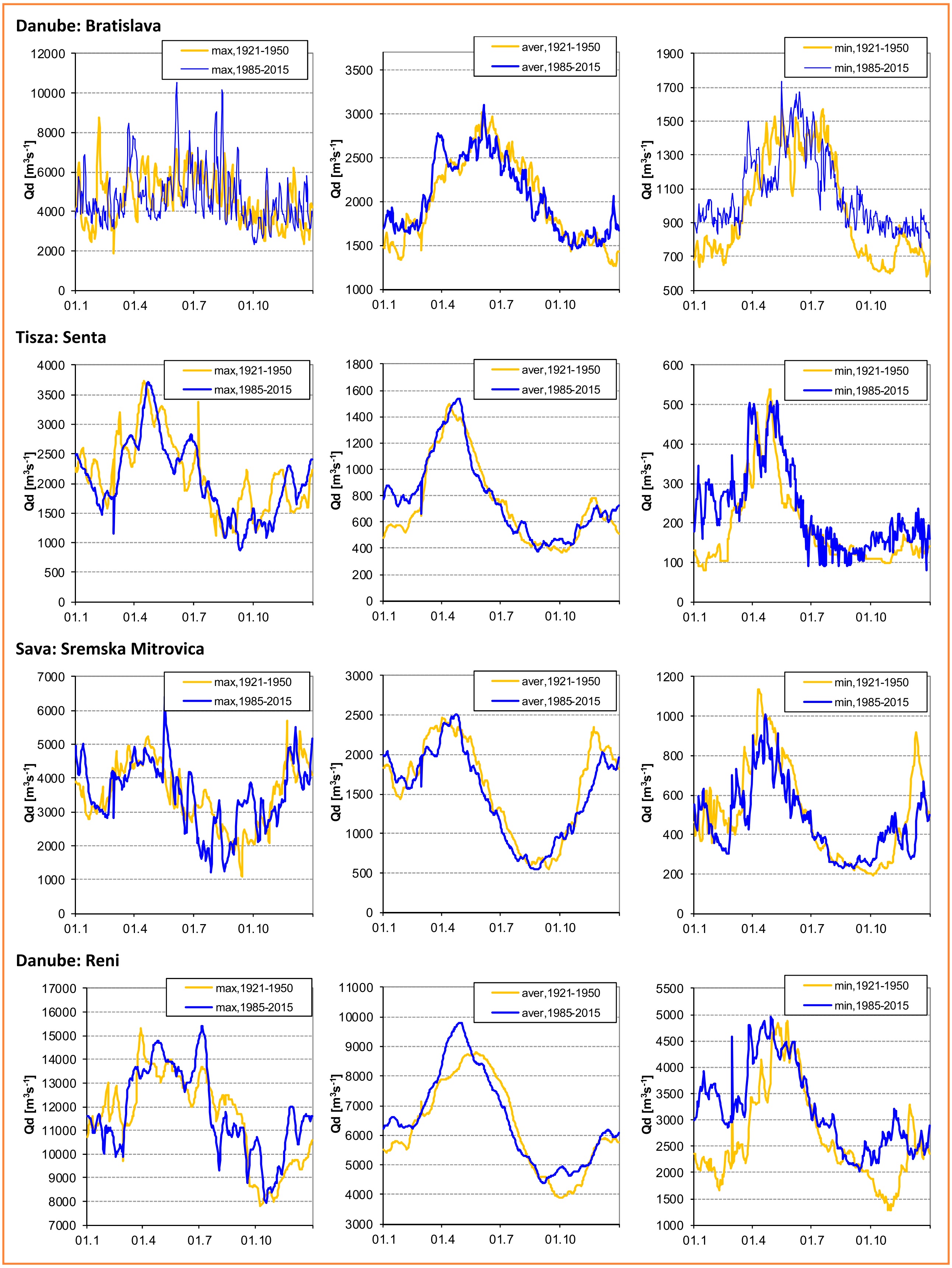

Figure 7 Comparison of the maximum (left), average (middle) and minimum (right) daily discharge regime in two different 30-year periods

Regime changes of the daily minimum, average and maximum discharge

In the last part, we focused on changes in the statistical characteristics of the minimum, average and maximum discharge of four studied rivers. In Figure 7, there are plotted the long-term daily discharges of the period 1921–1950 (yellow colour) and of the period 1985–2015 (blue colour).

We can observe an increase of discharge in the winter months in the case of the Danube in Bratislava and of the Tisza in Senta during the second period. The Danube in Reni has a higher discharge in winter-spring months, mainly in March.

Minimum long-term Danube discharges have increased, probably due to the reservoir construction and operation at the upper Danube in Germany and Austria.

Conclusions

The spectral and auto-correlation analyses show that the yearly discharge series include cyclic components, which are to be removed from the time series before the analysis of the long-term trends is applied. The significant cycles are 2.4; 3.6; 21–22 and 29 years. The length of the cycles of about 3.6 years, which was found in the flow rates, is probably related to the Southern Oscillation, expressed by the SO index. The length of cycles of about 2.47 years may be related to the QBO oscillation. The length of the cycles of about 14 years is related to the North Atlantic Oscillation, expressed by the NAO index. It follows that both the NAO and the SO phenomenon have an effect on the course of runoff fluctuations in the Danube basin.

If we start to analyse the long-term trend during the wet period and finish during the dry period, we shall obtain a decreasing trend, of course. The long-term trend analysis has to start and finish in the same phase of the cycle.

We used the statistical methods of the nonparametric Mann-Kendall test for testing the presence of the monotonic increasing or decreasing trend and the nonparametric Sen's method for estimating the slope of a linear trend.

The results show that the increasing/decreasing trends of the Danube, Sava and Tisza discharge are not significant yet. Changes can be observed in case of an increased minimum discharge at stations on the Danube River. A decrease did not occur as it could be expected due to higher air temperature and evapotranspiration.

These results have to be included into the long-term forecast of the runoff regime in the Danube River Basin.

Acknowledgements

This work was supported by the project VEGA 2/0004/19. The daily discharge series of the Danube River were obtained from the database of the UNESCO subproject No. 4.2.1 "Water temperature simulation during summer low flow conditions in the Danube basin".

References

Belz, J.-U., Goda, L., Buzás, Z., Domokos, M., Engel, H., Weber, J. (2004). *Flow regime of River Danube and its Catchment* (Follow-up volume no. VIII/2 to the Danube Monograph) (152 p.). Germany : Koblenz, Hungary: Baja.

Hurst, H.E. (1951). Long term storage capacity of reservoirs. *Trans. Am. Soc. Civ. Eng., 116*, 770–808.

Lin, Y., Lye, L. (1994). Modelling long-term dependence based on cumulative departures of annual flow series. *Journal of Hydrology*, *160*, 105–121.

Miklánek, P., Pekárová, P. (2016). *Danube River Basin*. Handbook of Applied Hydrology (2nd ed.) (5 p.). McGraw-Hill Education.

Pekárová, P., Miklánek, P., Pekár, J. (2003). Spatial and temporal runoff oscillation analysis of the main rivers of the world during the 19th–20th centuries. *Journal of Hydrology*, *274*, (1–4), 62–79.

Pekárová, P., Miklánek, P. (eds.). (2019). *Flood regime of rivers in the Danube River basin* (Follow-up volume no. IX to the Danube Monograph) (215 p. + 527 p. app.). Bratislava: IH SAS. DOI: https://doi.org/10.31577/2019.9788089139460

Prohaska, S., Isailović, D., SRNA, P., Marčetić, I. (1999). *Coincidence of flood flow of the Danube River and its tributaries* (Follow-up volume No. IV to the Danube Monograph). VÚVH, Bratislava, 187 pp. ISBN 80-968282-3-1.

Prohaska, S., Ilić, A. (2010). Coincidence of Flood Flow of the Danube River and Its Tributaries. In Mitja Brilly (Ed.). *Hydrological Processes of the Danube River Basin – Perspectives from the Danubian Countries*. Book Chapter 6. Springer (pp. 175–226). Doi: 10.1007/978-90-481-3423-6_6

Stănescu, V. A., Ungureanu, V., Mătreaţă, M. (2004). *Regional analysis of annual peak discharges in the Danube Catchment* (Follow-up volume no. VII to the Danube Monograph) (64 p.). Bucureşti: INMH.