ANALYZING CHANGES AND FREQUENCY DISTRIBUTION IN MAXIMUM RUNOFF VOLUMES WITH DIFFERENT DURATION OF THE DANUBE RIVER AT BRATISLAVA

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The volume of the flood waves and its importance is evaluated rarely. But, without these data, it would not be possible to imagine the extreme nature of the distribution system. Several hypotheses claim that more extremes in climatic and hydrologic phenomena are anticipated. In the present study, the annual maximum runoff volumes with t-day durations were calculated for a 144-year series of mean daily discharge of the Danube River at Bratislava gauge (Slovakia). The statistical methods were used to estimate T-year annual maximum runoff volumes and clarify how the annual maximum runoff volumes of the Danube River at Bratislava changed over period 1876–2019 and over dry and wet periods. The conclusion is that the runoff volume regime during floods has not changed significantly during the last 144 years. The annual maximum runoff volumes of the wet period have a greater impact on changes in LPIII exceedance curves at volumes with a time duration more than 20-days.

KEY WORDS: The Danube River, wave volume, Log-Pearson III probability distribution, T-year volume

Introduction

In studying the flood wave parameters, the attention is often focused on the culmination or maximum water level. However, these basic data on extreme floods are not enough for modern water management needs. Apart from the peak runoff another very important streamflow characteristic of a river is its runoff volume. Some issues in water management and engineering hydrology require that peak discharge (Q_{max}) and the shape of a flood wave or a flood runoff volume (V_{max}) are known. In applied hydrology, it is often difficult to assign exact values of a flood wave volume to a particular probability of exceedance and hence to its corresponding T-year discharges. Such relationships are very irregular in nature, so a flood wave hydrograph of a given exceedance probability must be a priory known. Pekárová and Miklánek (2019) described statistical processing of the maximum discharges and flood volumes based on a set of distribution function. The team of authors Hladný et al. (1970) dealt with the processing of volumes of flood waves from stations throughout the territory of the Czechoslovakia. To define the volumes of individual waves, the authors introduced the parameter t – the duration of the flood wave in days. In this way, they determined maximum runoff volumes lasting 2, 5, 10 and 30 days. Čermak (1956) studied the flood wave volumes of flood events with peaking

above the long-term annual mean discharge Q_a, on the regional scale. The determination of maximum volumes was, for example, addressed by Beard (1956). Beard (1956) also used theoretical exceedance probability curves and the parameter t – for flood wave duration, to determine the annual extreme runoff volumes. The values of t – parameter depend on the catchment characteristics of the river being studied. However, the author selected only one value for the extreme runoff volumes in every year of the data sets. Knowledge of flood-wave volumes – as an important hydrological characteristic – was apparent during a flood on the Danube in 1965 (Zatkalik, 1970; Hladný et al., 1970). During this flood event, the river dikes broke under the pressure exerted by the long duration of high water stages, but not because of the extremely high water stages themselves. Recently in Slovakia a few studies, analyses and estimations of flood wave volumes corresponding to the maximum design discharge with a return period of T-year on the River Danube at Bratislava have been carried out by e.g. Mitková et al. (2002) and Halmova et al. (2008), but more studies have focused on the joint probability of total volume and peak discharges, e.g. Bačová Mitková and Halmová (2014), Gaal et al. (2010), Szolgay et al. (2012), Szolgay et al. (2016), and Pekárová et al. (2018). The influence of human activity occurs in the Danube River to change the transformation properties of the channel, to change

the travel time of the waves as well as to a different outflow behaviour at the passage of the flow wave through the riverbed compared to the past. Case study of large flood events and hydrological simulation of flood transformations in the upper Danube River were investigated in Bačová Mitková et al. (2016). Authors concluded that the travel times of high floods have not significantly changed at the Kienstock–Devín section. On the other hand, the peak water levels for recent river conditions are higher at the same discharges.

In assessment of the climate change impacts on the river discharge regime (extremes, flood hydrographs and drought periods), it is expected that an increase in air temperature may cause (or already has caused) an increase in extreme discharges and flood volumes (Blöschl et al., 2017; 2019).

Since a 143-year series of the mean daily discharge of the Danube at Bratislava gauging station is available. Therefore, we could calculate the 144-year series of the highest (annually) 2-, 5-, 10-, 20-, 30- and 60-consecutive days' wave volumes. Than their probability distribution functions and trends were analysed. These series were subsequently divided into dry and wet periods and changes in their probability distribution functions and trends were analysed.

The aim of this study is:
- assess the maximum annual runoff volumes V_{tmax} lasting 2-, 5-, 10-, 20-, 30- and 60-days of the wave belongs to annual maximum discharges of the Danube River at Bratislava (1876–2019);
- determine the theoretical exceedance probability curves;
- estimate the T-year annual maximum runoff volumes with t-day durations belongs to annual maximum discharges;
- analyze changes in the maximum annual runoff volumes V_{tmax} of the Danube River at Bratislava during the period (1876–2019);
- analyze the changes in the maximum annual runoff volumes V_{tmax} in wet and dry periods during the period 1876–2019.

Methodology

In Czechoslovakia, Bratránek (1937) was the first who investigated the issue of runoff volumes. He used direct and indirect methods of peak vs. flood volume assessment.

The direct method was based on compiling runoff volumes higher than a chosen discharge threshold with assistance of the probability of exceedance (related to the T-year return period). The T-year discharges were then determined by extrapolating probability curves to the domain of low exceedance probability. In the latter method the author used generalized results of empirical relationships among several flood hydrograph characteristics.

In order to determine the runoff volume $W_{20,Q1}$ (Equation 1), the author used not only the highest discharge Q reduced to ($Q_{20} - Q_1$), but also values of the flood wave duration t_{20}, related to the catchment area.

$$W_{20,Q_1} = \frac{3600 \cdot t_{20} \cdot Q}{2.10^6} = \frac{t_{20} \cdot Q}{556} \tag{1}$$

where:
$W_{20,Q1}$ – runoff wave volume with the extreme discharge Q_{20} above the selected threshold Q_1 [mil m³];
Q – reduced extreme cumulative discharge ($Q_{20}-Q_1$) [m³ s⁻¹];
Q_{20} – extreme 20-year discharge;
Q_1 – extreme 1-year discharge;
t_{20} – the average flood wave duration of the reduced discharge ($Q_{20}-Q_1$) [hrs].

The main disadvantage of this method is that it is not applicable for flood-wave volumes with smaller exceedance probabilities than once in 20 years.

The treatment of the calculation of the maximum volumes of the Danube was dealt with by Zatkalík (1970). When calculating the maximum volumes of flood waves, he chose as a basis a procedure taking into account the duration of the flood wave in days – t.

The introduction of this parameter allows:
- a clear assessment of the probability of exceeding the volume of a given flood wave,
- creation of a basis for solving the problem of design flood, which would consist in allocating such a flood wave volume that would be maximum for a given T-year peak flow.

Log-Pearson III distribution

For the estimation of the maximum annual runoff volume V_{tmax} series distribution function we used Log-Pearson type III distribution. The Log-Pearson distribution type III. is used to estimate extremes in many natural processes and it is one of the most commonly used probability distribution in hydrology (Bobee, 1975; Pilon and Adamowski, 1993; Griffis and Stedinger, 2007; Pawar and Hire, 2018). In some previous works (Pekárová et al., 2018; Pekárová and Miklánek, 2019) we compared LPIII distribution with theoretical probability distributions, which were and still are also among the most used in Slovak hydrological practice. The Log-Pearson Type III distribution is a three-parameter gamma distribution with a logarithmic transformation of the variable. The cumulative distribution function and probability distribution function according Hosking and Wallis (1997) are defined as:

If $\gamma \neq 0$ let $\alpha = 4/\gamma^2$ and $\xi = \mu - 2\sigma/\gamma$
If $\gamma > 0$ then:

$$F(x) = G(\alpha, \frac{x-\xi}{\beta})/\Gamma(\alpha) \tag{2}$$

$$f(x) = \frac{(x-\xi)^{\alpha-1}e^{-(x-\xi)/\beta}}{\beta^\alpha \Gamma(\alpha)}, \tag{3}$$

where:
ξ – location parameter;
α – shape parameter;

β – scale parameter

Γ – Gamma function.

If $\gamma < 0$ then

$$F(x) = 1 - \frac{G\left(\alpha, \frac{x-\xi}{\beta}\right)}{\Gamma(\alpha)}, \qquad (4)$$

$$f(x) = \frac{(\xi - x)^{\alpha-1} e^{-(\xi-x)/\beta}}{\beta^{\alpha} \Gamma(\alpha)}. \qquad (5)$$

The Kolmogorov-Smirnov test was performed to test the assumption that the discharge magnitudes follow the theoretical distributions. The *p*-value ($p \geq 0.05$) was used as a criterion for rejection of the proposed distribution hypothesis.

Mann-Kendal nonparametric test

The Mann-Kendall nonparametric test (M-K test) was used for determining the significant trends detection in time series. The nonparametric tests are more suitable for the detection of trends in hydrological time series, which are usually irregular, with many extremes (Hamed, 2008; Yue, et al. 2002; Gilbert, 1987). By M-K test, we want to test the null hypothesis H0 of no trend, i.e. the observations x_i is randomly ordered in time, against the alternative hypothesis *H1*, where there is an increasing or decreasing monotonic trend.

For *n* (number of tested values) ≥ 10, the statistic *S* is approximately normally distributed with the mean and variance as follows

$$E(S) = 0 \qquad (6)$$

$$VAR(S) = \frac{1}{18}\left[n(n-1)(n-2) - \sum_{p=1}^{q} t_p(t_p - 1)(2t_p + 5) \right] \qquad (7)$$

where:

q – is the number of tied groups,

t_p – the number of data values in the *p* group.

The standard test statistic *Z* is computed as follows

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{VAR(S)}} & if \quad S \rangle 0 \\ 0 & if \quad S = 0 \\ \dfrac{S+1}{\sqrt{VAR(S)}} & if \quad S \langle 0 \end{cases} \qquad (8)$$

The presence of a statistically significant trend is evaluated using *Z* value. A positive (negative) value of *Z* indicates an upward (downward) trend. The statistic *Z* has a normal distribution. To test for either an upward or downward monotone trend (a two-tailed test) at α level of significance, hypothesis *H0* (no trend) is rejected if the absolute value of |*Z*| is greater than $Z_{1-\alpha/2}$, where $Z_{1-\alpha/2}$ is obtained from the standard normal cumulative distribution tables. The M-K test detects trends at four levels of significance: $\alpha=0.001$, 0.01, 0.05 and $\alpha=0.1$.

Significance level of 0.001 means that there is a 0.1% probability that the value of x_i is from a random distribution and are likely to make a mistake if we reject the hypothesis *H0*; Significance level of 0.1 means that there is a 10% probability that we make a mistake if we reject the hypothesis *H0*. If the absolute value of *Z* is less than the level of significance, there is no trend.

For the four tested significance levels the following symbols are used in the template:

***   if trend at $\alpha=0.001$ level of significance – *H0* seems to be impossible,

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

*   if trend at $\alpha=0.05$ level of significance – 5%, mistake if we reject the *H0,*

+   if trend at $\alpha=0.1$ level of significance.

Blank: the significance level is greater than 0.1, cannot be excluded that the *H0* is true.

The most significant trend is assigned three stars (***), with a gradual decrease in importance, the number of stars also decreases.

Case study area

The Danube River and Input data

The Danube River is the second greatest river in Europe, after the Volga. The basin covers an area of $817\,000$ km². The river originates from the Black Forest in Germany at the confluence of the Briga and the Breg streams. The Danube then discharges southeast for 2 872 km (1 785 mi), passing through four Central European capitals before emptying into the Black Sea via the Danube Delta in Romania and Ukraine. The Danube River Basin landscape geomorphology is characterized by a diversity of morphological patterns. The territory of the Danube River Basin is also one of the most flood-endangered regions in Europe.

The mean daily discharges (Fig. 1) and maximum annual discharges of the Danube River at Bratislava from the period 1876–2019 were used as input data. The course of annual peak discharges, long-term linear trend and 5-year moving trend are illustrated on the Fig. 2a. The annual peak discharges of the Danube River at Bratislava show increasing long-term linear trend during the selected period of 1876–2019. There were also occurred some extreme floods in 1899, 1954, 2002 or 2013 (Fig. 2a). The Fig. 2b shows the alternation of dry and wet years at intervals of approximately every three to four years. The minimum annual discharge was occurred in 1934 (3000 m³ s⁻¹). Since year 2014 to year 2019 we also record dry years.

The maximum number of the events with annual maximum flows occurs in month of July it can be cause by summer rainfall especially in upper part of the Danube basin. The second peak of the number in occurrence of the annual maximum flows is in month of March when snow melts in higher parts of the basin and rainfall occur in lower part of the basin. The Fig. 3a illustrates the distribution of the annual maximum flows occurrence in individual months during the period of 1876–2019 and in dry and wet years. The Fig. 3a shows, that distribution

of the annual maximum occurrence during the period 1876–2019 has maximum in the month of July. The dry and wet years has annual maximum flows occurrence in July. The annual maximum flows occurrence during the last nineteen years (2001–2019) was in January (Fig. 3b).
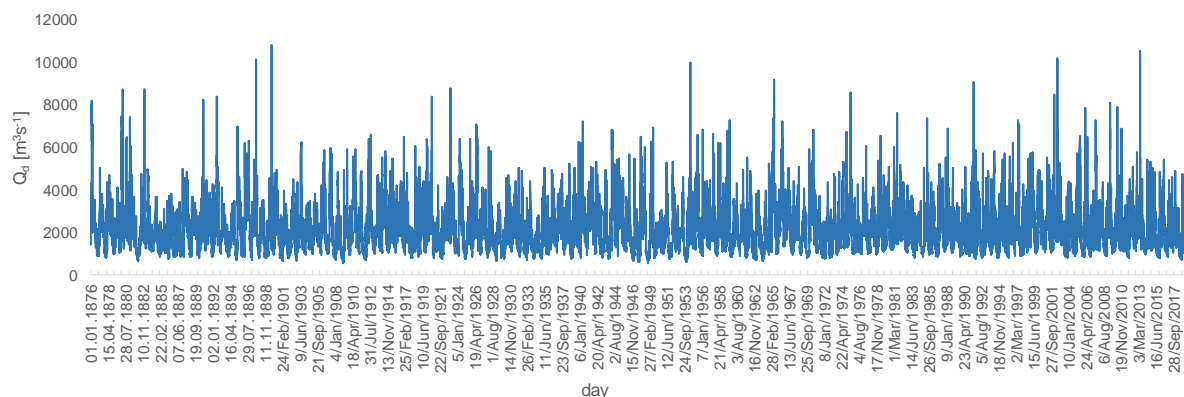

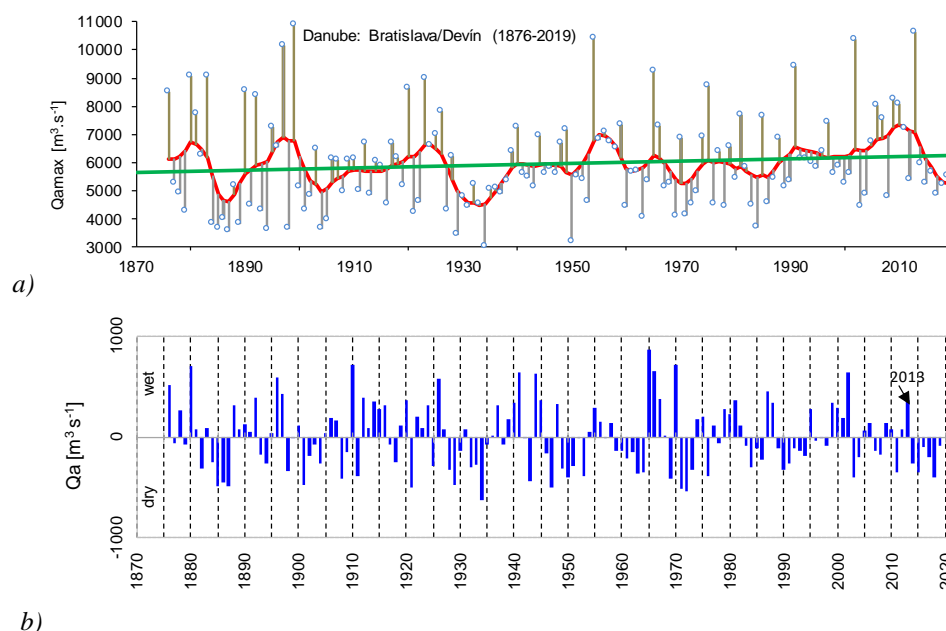*Fig. 1.   The mean daily discharges of the Danube river at Bratislava (1876–2019).*

a)

b)

Fig. 2.   a) the maximum annual discharges of the Danube River at Bratislava (1876–2019), their linear trend and 5-year moving trend, b) the deviation from long-term annual discharge during the period of 1876–2019.

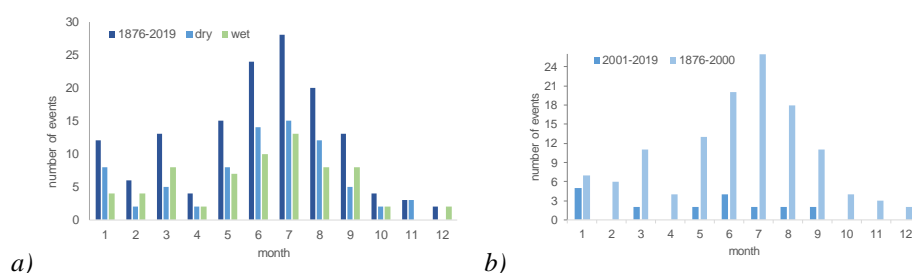
a)   *b)*

Fig. 3.   Monthly distribution of the annual maximum flows of the Danube river at Bratislava a) for period 1876–2019 and in dry and in wet years and b) for periods of 1876–2000 and 2001–2019.

Results

Determination of maximum volumes of Danube flow waves for the period 1876–2019

In the present paper for determining the maximum annual runoff volumes V_{tmax}, we used the procedure published in Zatkalík (1970). The mean daily discharges and maximum annual discharges of the Danube River at Bratislava from the period 1876–2019 were used as input data. We introduced the parameter t – runoff duration in days to define the t-days maximum volumes of individual waves. In this way, we determined the maximum runoff volumes of t=2-, 5-, 10-, 20-, 30- and 60-days. The series of mean daily discharges were used to determine

the annual maximum runoff volume V_{tmax} lasting 2-, 5-, 10-, 20-, 30- and 60-days. In each year separately, a flood event with an annual maximum flow was selected for the set of volumes. Than the 2-, 5-, 10-, 20-, 30- and 60-days moving averages of the volume around the peak flow were calculated and the maximum volume for each t-days were selected. Fig. 4 presents an example of the determination of maximum volumes with a given runoff duration.

The runoff volume series are shown in Fig. 5. Considering the 2-day and 5-day maximum runoff volumes, the flood of 1899 was the highest one and the lowest one was in 1934, within the period 1876–2019. But considering the 10- to 60-day runoff volumes, the highest flood was that of 1965.
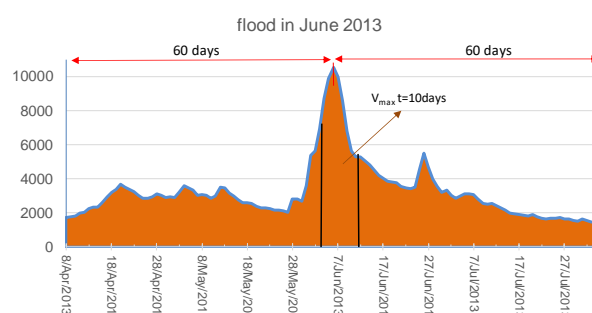

Fig. 4.   Example of the determination of the maximum volume with a given runoff duration t=10 days on The Danube River at Bratislava (flood occurred in 2013).
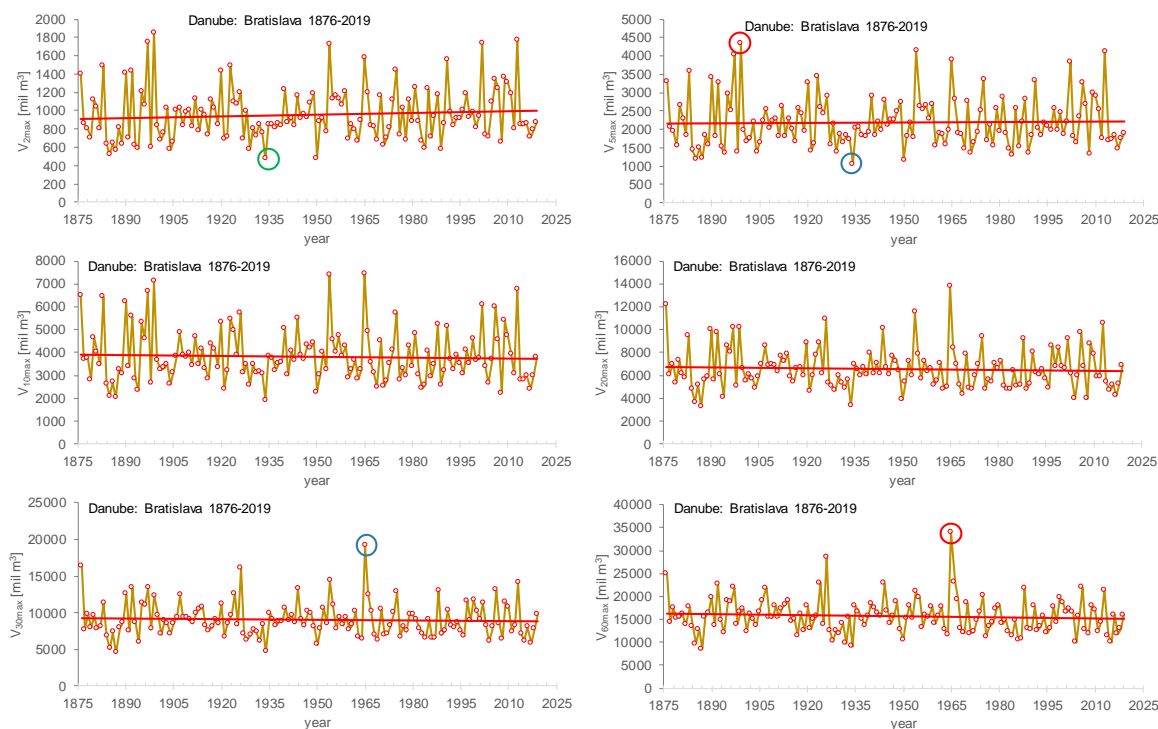

Fig. 5.   Flood wave volume series of the Danube for various flood durations t (e.g. V$_{20}$max means maximal annual runoff volume in 20 days).

Calculation of the theoretical probability curves of the maximum annual runoff volumes V_{tmax} for various flood durations t

A Log-Pearson III distribution was selected to calculate the T-year maximum runoff volume with the given runoff time duration (t). The examples of the theoretical (LPIII)

exceedance probability curves of the maximum annual runoff volumes with durations t equal to 2-, 5-, 10-, and 60- days are demonstrated in Fig. 6. The results suggest (Table 1) that the 100-year maximum of 2-day runoff volume (V_{2max}) is 1896 mil m^3, 4398 mil. m^3 for 5-day (V_{5max}), and 7470 mil. m^3 for 10-day (V_{10max}) runoff volumes.
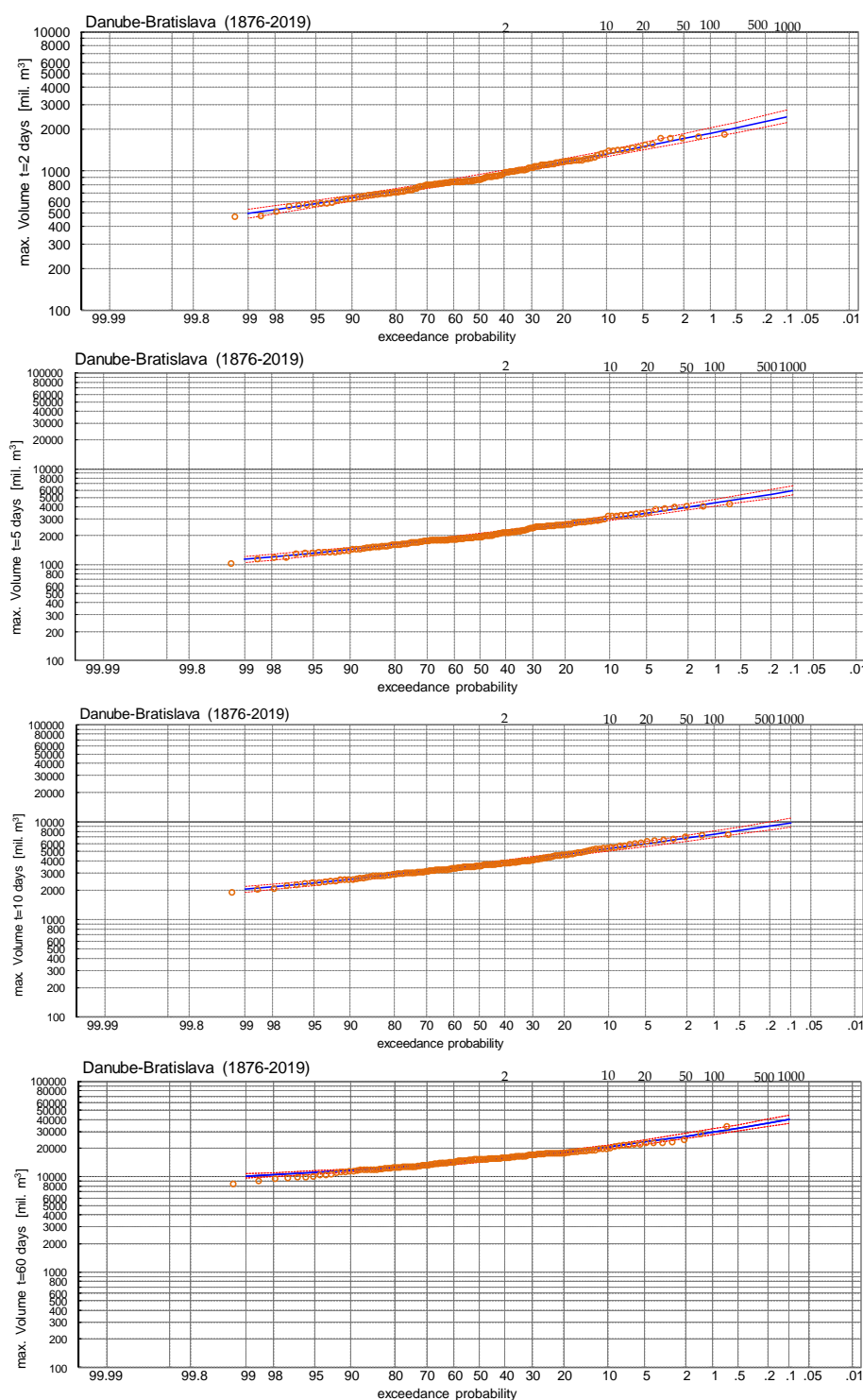

Fig. 6.   *Examples of the theoretical LPIII exceedance probability curves of the Danube maximum annual runoff volumes V_{2max}, V_{5max}, V_{10max} and V_{60max} for Danube: Bratislava (1876–2019).*

Trend analysis of annual maximum runoff volumes V_{tmax} on the Danube River at Bratislava (1876–2019)

The Mann-Kendall nonparametric test (M-K test) was used for detection of the significance in long-term trends of annual maximum runoff belong to annual maximum flows of the Danube River at Bratislava for period 1876–2019. The M-K trend test did not show significant long-term trends in annual maximum runoff volumes with duration *t* belong to annual maximum flows of the Danube River at Bratislava for selected period.

After dividing the whole time series1876–2019 into shorter periods, about 40 years the M-K trend analysis indicates an increasing long-term trends in annual maximum runoff volumes V_{tmax} with *t*=2 days and *t*=5 days and we can reject the hypothesis *H0* at significance level *α*=0.05 and *α*=0.1, for period 1921–1960 (Table 3). The long-term trend of the M-K test for annual maximum runoff volumes with duration *t*=2 days and *t*=5 day of the Danube River at Bratislava (1921–1960) are illustrated in Fig. 7.

Analysis of annual maximum runoff volumes V_{tmax} on the Danube River at Bratislava (1876–2019) in dry and wet periods

In this part of the work, we divided the sets of volumes with *t*-day into two sub-sets based on dry and wet multiannual periods. The dry and wet periods we determined on the basis of double 5-year moving averages of the Danube River flows at Bratislava for the period 1876–2019 (Fig. 8a).

The wetness of individual years is different and more or less independent of each other. It is to be understood that the various physical causes also distort the action of the decisive factors to such an extent that we can speak of randomness. According to this, but also from experience, we can say that years of a similar nature usually group together, (Dub, 1957). The limit value for determining the dry and wet periods was the value of the long-term average annual flow Q_a=2049 m³ s⁻¹. Due to the fact that we took the period as a result of the moving average, dry and wet years can also occur in it.

Table 1. *T-year maximum discharges Q_{max} and T-year annual maximum runoff volumes V_{tmax} of the Danube River at Bratislava (1876–2019) (Log-Pearson III) ($P=p*100\%$, $p=1-e^{-1/T}$)*

River: Gauging station	P	Q_T [m³s⁻¹]	*t*=2 days	*t*=5 days	*t*=10 days	*t*=20 days	*t*=30 days	*t*=60 days
Danube: Bratislava	2	Q_{50}		V_{50tmax} [mil. m³]				
		10159	1706	3985	6814	11292	15777	26666
	1	Q_{100}		$V_{100tmax}$ [mil. m³]				
		11060	1869	4398	7470	12329	17513	29464
	0.2	Q_{500}		$V_{500tmax}$ [mil. m³]				
		13193	2262	5410	9056	14830	21989	36654
	0.1	Q_{1000}		$V_{1000tmax}$ [mil. m³]				
		14140	2439	5875	9773	15961	24141	40100

Table 2. **Conclusions of Mann-Kendall trend test for annual maximum runoff volumes V_{tmax} with time duration *t* for waves belong to annual maximum flows of the Danube River at Bratislava (1876–2019)**

V_{tmax} [mil m³]	First year	Last Year	*n*	Mann-Kendall trend Test Z	Signific.)	Sen's slope estimate A	B
V_{2max}	1876	2019	144	0.91	No	0.84	864
V_{5max}	1876	2019	144	0.02	No	0.06	1975
V_{10max}	1876	2019	144	-0.43	No	-1.76	3682
V_{20max}	1876	2019	144	-0.77	No	-4.67	6450
V_{30max}	1876	2019	144	-1.10	No	-8.83	8791
V_{60max}	1876	2019	144	-1.53	No	-23.40	15935

The number of 71 years were included in the dry period and number of 73 years in the wet period (Fig. 8b). Fig. 8b also shows that since 2005 to 2019 the dry period is recorded. The M-K trend analysis indicates an increasing long-term trend in annual maximum runoff volumes V_{tmax} with t=2-days and we can reject the hypothesis $H0$ at significance level α=0.05 for dry period (Fig. 9). A Log-Pearson III distribution was used to calculate the T-year maximum runoff volume with the given runoff time duration (t) for dry and wet periods. The T-year maximum annual runoff volumes of duration t=2-days,

5-days and 10-days has no significant changes in estimation. In the wet period (except for volumes with t=2- and 5-days), with the same probabilities of exceeding, higher values of maximum volumes may occur compared to the dry period. Dividing of the period 1876–2019 into dry and wet periods had a greater impact on changes in LPIII exceedance curves of the maximum runoff at higher values of volumes with time duration t=20-, 30-, and 60-days. The examples of differences between estimated T-year maximum annual runoff volumes for dry and wet period are illustrated in Fig. 10.
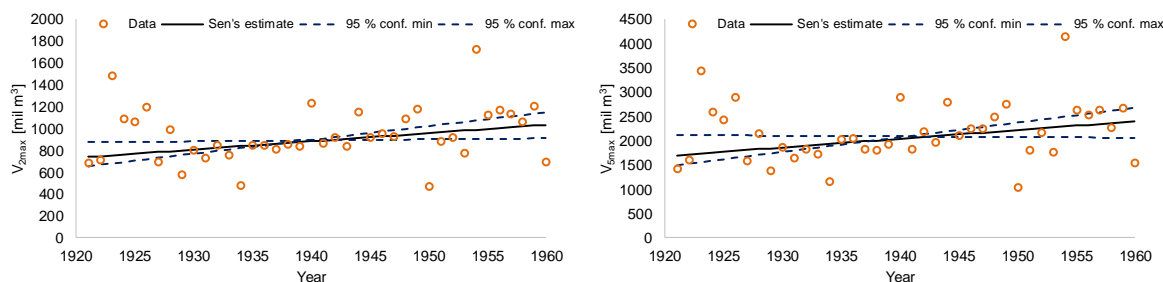

Fig. 7. *The Mann-Kendall trend test for annual maximum runoff volumes V_{tmax} with time durations t=2 days and t=5 days for waves belong to annual maximum flows of the Danube River at Bratislava (1921–1960).*

Table 3. **Conclusions of Mann-Kendall trend test for annual maximum runoff volumes V_{tmax} with time durations t=2 days and t=5 days for waves belong to annual maximum flows of the Danube River at Bratislava (1921–1960)**

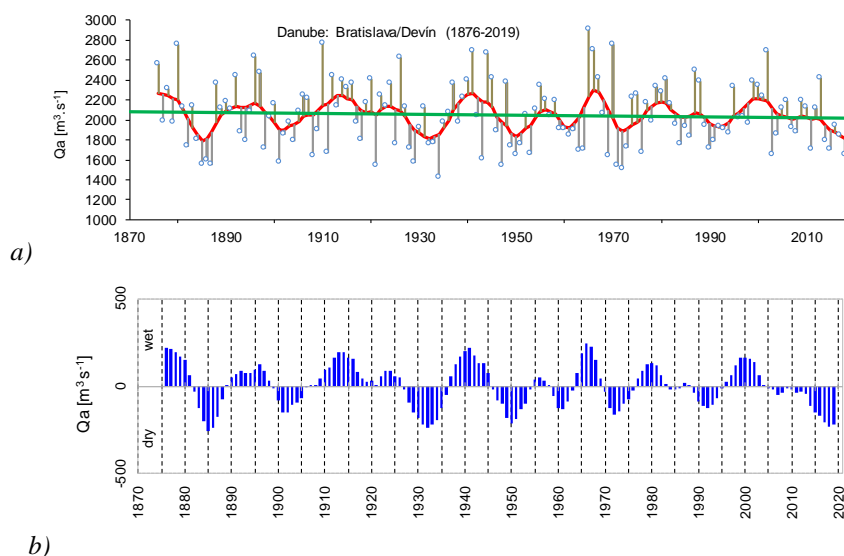| V_{tmax} [mil m³]	First year	Last Year	n	Mann-Kendall trend		Sen's slope estimate	
				Test Z	Signific.	A	B
V_{2max}	1921	1960	40	2.20	*	7.572	735.74
V_{5max}	1921	1960	40	1.83	+	17.970	1690.04

a)

b)

Fig. 8. *Course of the a) mean discharges, their linear trend and b) dry and wet periods based on double 5-year moving averages of Danube flows of the Danube River at Bratislava for the period 1876–2019.*
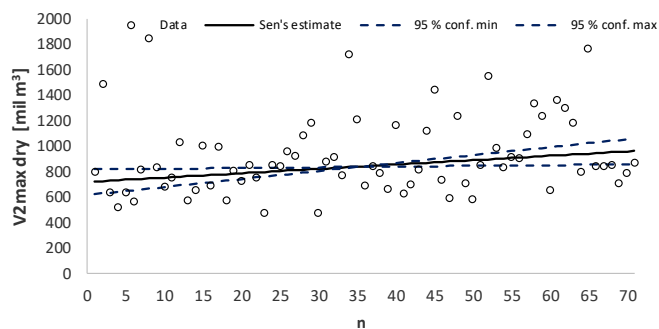
Fig. 9.   The Mann-Kendall trend test for annual maximum runoff volumes V_{tmax} with time durations t=2-days for waves belong to annual maximum flows of the Danube River at Bratislava (dry period).

Fig. 10.   Example of the differences in estimated T-year maximum annual runoff volumes with time duration t=2-, 5-, 30- and 60 - days for dry and wet periods of the Danube River at Bratislava (1876–2019).

Conclusion

In the present paper we analyzed, the occurrence of annual maximum runoff volumes with t-day durations for a 144-year series of mean daily discharge of the Danube River at Bratislava gauge (Slovakia). The statistical methods were used to clarify how the maximum runoff volumes of the Danube River at Bratislava changed over period 1876–2019 and over dry and wet periods. On the Danube River is usually the maximum annual flow occur simultaneously with the annual maximum runoff volume of waves with a given time duration t. However, the corresponding values in terms of significance are not equivalent. Based on the exceeding probability curves of the annual maximum runoff volumes, it is possible to determine to the selected volume V for different t the probability of its exceeding and return period.

The M-K tests showed increasing trend of the annual maximum runoff volume at significance level $\alpha=0.05$ and $\alpha=0.1$, for period 1921–1960. Based on M-K test we can conclude that the runoff volume regime during floods has not changed substantially during the last 144 years, which is of importance to water management. This conclusion pertains not only to the short-term flood runoff episodes (V_{2max}), but also the long-term ones (V_{60max}).

Based on the division of the given interest period 1876–2019 into dry and wet ones, we also plotted and compared the probabilities of exceedance the annual maximum runoff volumes on the Danube at Bratislava for selected runoff durations $t = 2, 5, 10, 30, 60$ days in given periods. The M-K trend analysis indicates an increasing long-term trend in annual maximum runoff volumes V_{tmax} with $t=2$ days and we can reject the hypothesis $H0$ at significance level $\alpha=0.05$ for dry period. The results suggest that the T-year maximum annual runoff volumes of duration $t=2$- days, 5-days and 10-days has no significant changes in estimation. In the wet period (except for volumes with $t=2$- and 5-days), with the same probabilities of exceeding, higher values of maximum volumes may occur compared to the dry period. Dividing the period 1876–2019 into dry and wet periods had a greater impact on changes in LPIII exceedance curves of the maximum runoff at higher values of volumes with time duration $t=20$-, 30-, and 60-days.

The results are useful in the water planning and flood protection and can help mapping flood risk areas and developing river management plans in Danube River basin. In the future, it would be desirable to confirm the conclusions also on other rivers in Slovakia with satisfactory long runoff data series, or on the basis of reconstructed discharge values by indirect methods (analogy, mathematical runoff modeling etc.).

Acknowledges

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