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Trend changes and frequency analysis of the annual maximum volumes for various runoff duration on the Morava River at Moravský Svätý Ján

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In the present paper we analyzed, the occurrence of annual maximum runoff volumes with t-day durations for a 99-year series (1920–2020) of mean daily discharge of the Morava River at Moravský Svätý Ján gauge (Slovakia). The runoff volume is, apart from the peak runoff, another very important hydrological characteristic of a river for flood hazard assessment. The maximum runoff volumes with *t*-day duration were determined. Subsequently, trends of the annual maximum runoff volumes with *t*-day durations were identified. We analyzed how the annual maximum runoff volumes of the Morava River have changed over the period 1922–2020 and how they have changed over dry and wet periods. The results indicate that the trends of the annual maximum runoff volumes with *t*-day durations decrease, especially in wet periods. On the Morava River usually the maximum annual discharges occur simultaneously with the annual maximum runoff volume of waves with a given 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_{tmax} for different t-days the probability of its exceeding and return period. The Log-Pearson distribution type III was used to determine the T-year values of the maximum runoff volumes with t-day duration.

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

Introduction

In the scientific and public spaces, there are ongoing discussions about the impact of climate change on the hydrological river regime and the frequency of extreme hydrological events (floods and drought). The confirmation or refutation of this information is only possible through statistical processing of long-term data series of the hydrological and meteorological cycle. Assessment of the impact of the notified climate change on the river regime and runoff of rivers from the basins has been a frequently discussed subject in many scientific studies (Bronstert et al., 2007; Szépszó et al., 2014; Pekárová et. al., 2016; Gaume et. al., 2016; Blöschl et al., 2017 and 2019; Didovetz, et al., 2019; Szolgay, et al., 2020). Some issues in water management and engineering hydrology require that peak discharge and the shape of a flood wave or a flood runoff volume are known. Not only high water level or peak discharge can cause damage to a protective dam, but also, the long-term high volumes – wetting, or overspill, e.g. two flood waves joining at the confluence. Such a situation was seen in the spring of 1941 on the River Morava when the flood lasted more than 2.5 months and the volume was almost twice as large as the volume of the flood wave in 1997 with an almost identical culmination. 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. The work of the collective Hladný et al., (1970) dealt with the processing of volumes of flood waves from stations throughout the territory of Czechoslovakia. To define the volumes of individual waves, the authors introduced the parameter *t*. The parameter defines the duration of the flood wave in days. In this way, they determined maximum runoff volumes lasting 2-, 5-, 10- and 30-days. The statistical data series were compiled from the maximum annual volumes of the given duration. For the extrapolation of the T-year volumes, they used theoretical lognormal probability distribution.

Zatkalík (1970) dealt with similar processing of the calculation of the maximum volumes of the Danube. The author calculated maximum runoff volumes based on the maximum runoff duration *t*.

The introduction of the *t* parameter allows:

1) a clear assessment of the probability of exceedance of the volume of a selected flood wave,
2) to create a serious basis for solving the well-known design flood problem, which would be appropriate in assigning a volume that would be maximum for the given *T*-year culmination discharge.

Since a 99-year series of the mean daily discharge of the Morava River at Moravský Svätý Ján (Moravský Sv. Ján) gauging station is available from SHMI archives and yearbooks. Therefore, we could calculate the 99-year series of the highest (annually) 5-, 10-, 15-, and 30-consecutive days' wave volumes. Then their trends and probability distribution were analysed. The whole time data series was subsequently divided into dry and wet periods and changes in their trends were analysed.

The aim of this study is:

- assess the maximum annual runoff volumes V_{tmax} lasting 5-, 10-, 15-, and 30-days of the waves which belong to annual maximum discharges of the Morava River at Moravský Sv. Ján (1922–2020);
- analyze changes in the maximum annual runoff volumes V_{tmax} of the Morava River at Moravský Sv. Ján during the period (1922–2020);
- analyze the changes in the maximum annual runoff volumes V_{tmax} in wet and dry periods during the period 1922–2020;
- determine the theoretical exceedance probability curves;
- estimate the *T*-year annual maximum runoff volumes with *t*-day durations belonging to annual maximum discharges.

Methods and material

Determination of the maximum runoff volumes with t-day duration

In the present paper for determining the maximum annual runoff volumes (V_{tmax}) we used the procedure published in Zatkalík (1970). The hydrological events belonging to annual maximum discharges were selected for the set of volumes. To determine the volume of the wave belonging to annual maximum discharge, it is necessary to identify the beginning and end of the wave. It is quite difficult to identify the beginning and end of the discharge wave, in some cases. For such events, their beginning and their end approximately at the level of the long-term average daily discharge were determined. The series of mean daily discharges were used as input data to calculate volumes of the selected waves for given *t*-days durations. Next, the moving averages of the volume around the peak discharge for given *t*-days durations were calculated and the maximum volumes were selected. For example, in the case of *t*=10 days duration, ten daily move averages were calculated around the culmination. Consequently, only one maximum value was included into the statistical data set for analysis of maximum runoff volumes with *t*=10 days runoff duration. The detailed descriptions of the method are published in Mitková, et al. (2002) or Bačová Mitková and Halmová (2021). Fig. 1. illustrates an example of the determination of maximum volumes with a given runoff duration of *t*=10-days.

Trend detection in selected hydrological data series

The Mann-Kendall nonparametric test (M-K test) we used for the detection of trends in hydrological time series. The purpose of the Mann-Kendall (MK) test (Mann, 1945; Kendall, 1975; Gilbert, 1987) is statistically assessed if there is a monotonic upward or downward trend of the variable of interest over time. A monotonic upward (downward) trend means that the variable consistently increases (decreases) through time, but the trend may or may not be linear. The presence of a statistically significant trend is evaluated using the *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 a 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 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 hypothesis *H0*. The sig significance level of 0.1 means that there is a 10% probability that we make a mistake if we reject 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:

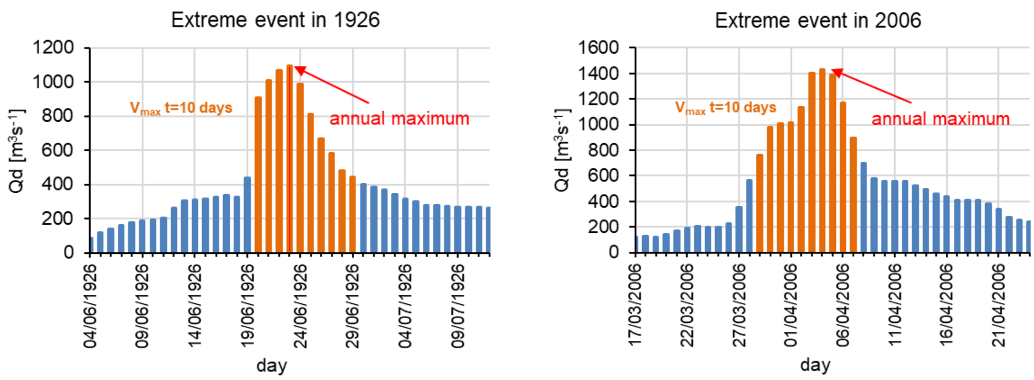


Fig. 1. Illustration of the determination of the maximum volume with a given runoff duration t=10 days on the Morava River at Moravský Sv. Ján (floods occurred in July 1926 and March–April 2006).

*** if trend at α = 0.001 level of significance – *H0* seems to be impossible
** if trend at α = 0.01 level of significance
* if trend at α = 0.05 level of significance – 5% mistake if we reject the *H0*
+ if trend at α = 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.
For *n* (number of tested values) ≥ 10, the statistic *S* is approximately normally distributed with the mean and variance as follow

$$E(S) = 0 \tag{1}$$

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

where:
q – is the number of tied groups,
t_p – the number of data values in the p group.

Estimation of the T-year annual maximum runoff volumes

The maximum annual runoff volume V_{tmax} series were fitted with Log-Pearson type III distribution. The Log-Pearson distribution type III. is used to estimate the extrema in many natural processes and it is one of the most commonly used probability distributions in hydrology (Bobee, 1975; Pilon and Adamowski, 1993; Griffis and Stedinger, 2007; Pawar and Hire, 2018). For example, in the United States, since 1967, experts often choose this distribution as "The distribution of choice for floods" (Koutsoyiannis, 2005). 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 to Hosking and Wallis (1997) are defined as:

If $\gamma \neq 0$ let α=4/ γ2 and ξ=μ-2σ/ γ

If γ >0 then:

$$F(x) = G(\alpha, \frac{x-\xi}{\beta})/\Gamma(\alpha) \tag{3}$$

$$f(x) = \frac{(x-\xi)^{\alpha-1}e^{-(x-\xi)/\beta}}{\beta^{\alpha}\Gamma(\alpha)}, \tag{4}$$

where:
ξ – location parameter,
α – shape parameter,
β – scale parameter,
Γ – Gamma function.

If γ <0 then

$$F(x) = 1 - \frac{G\left(\alpha, \frac{x-\xi}{\beta}\right)}{\Gamma(\alpha)}, \tag{5}$$

$$f(x) = \frac{(\xi-x)^{\alpha-1}e^{-(\xi-x)/\beta}}{\beta^{\alpha}\Gamma(\alpha)}. \tag{6}$$

To estimate the distribution parameters, the method described in Bulletin17B (IACWD, 1982) was used. Bulletin 17B provided revised procedures for weighting station skew values with results from a generalized skew study, detecting and treating outliers, making two station comparisons, and computing confidence limits of the frequency curve.
The Kolmogorov-Smirnov test was performed to test the assumption that the discharge magnitudes follow the theoretical distributions. The *p*-value (*p*≥0.05) was used as a criterion for the rejection of the proposed distribution hypothesis. The second criterion was the comparison between the theoretical distribution and the empirical distribution of the data series. Probability estimates are calculated for chosen plotting positions. A basic plotting position formula for symmetrical distributions is given by (7):

$$Pi = \frac{m-\alpha}{N+1-2\alpha}. \tag{7}$$

where:
p_i – is the exceedance probability of the variable (V_{tmax}),
α – is a plotting position parameter ($0 \leq \alpha \geq 0.5$),
m – is the order number of the variable (descending rank),
N – is number of variables.

The relationship between the probability of exceedance of a given value in any year and its average return period *T* is (Szolgay et al., 1994):

$$p = 1 - e\text{-}1/T. \tag{8}$$

If $T \geq 10$ we can use simplified form of equation (8):

$$P = \frac{m}{T}. \tag{9}$$

where:
m –variable order number- descending order to the statistical series,
n – number of variables.

The Morava River and Input data

The Morava River originates on the Králický Sněžník mountain in the north-eastern corner of Pardubice Region an elevation 1 380 m n. m. (Czechia). It is the main river of Czech region Moravia, which derives its name from it The Morava River is a left tributary of the Danube River. The basin covers an area of 26 658 km^2 and a length is 352 km. Morava River has a vaguely southward trajectory. The lower part of the river's course forms the border between the Czech Republic and Slovakia and then between Austria and Slovakia (Fig. 2).

The mean daily discharges (Fig. 3) and maximum annual discharges (Fig. 4a) of the Morava River at Moravský Sv. Ján from the period 1922–2020 were used as input data for analysis. The mean long-term daily discharges reached the value of 104.41 $m^3 s^{-1}$ (1922–2020) at Moravsky Ján gauge station.

The course of annual maximum discharges, long-term

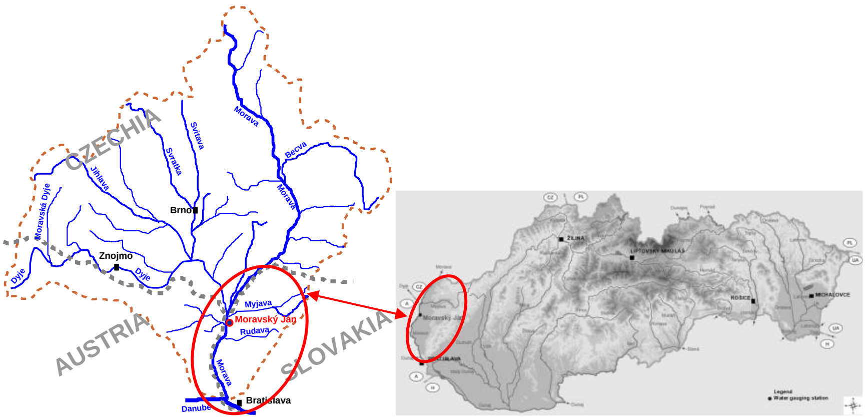


Fig. 2. Scheme of the Morava river basin and the location of the Slovak part of the Morava River basin.

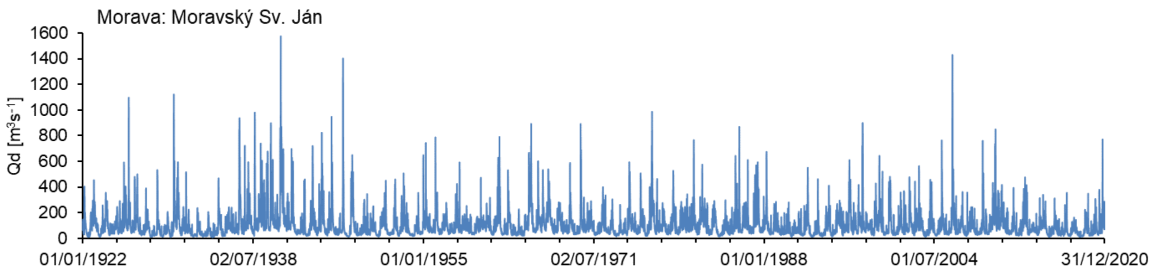
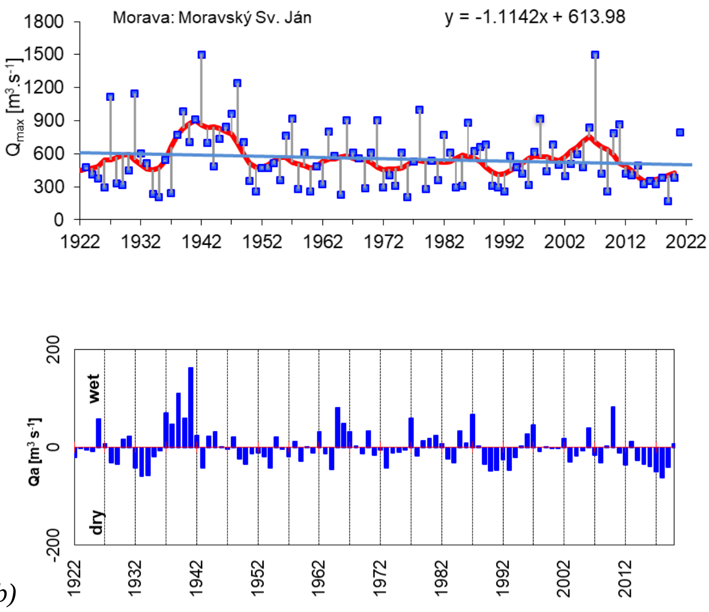


Fig. 3. The mean daily discharges of the Morava River at Moravský Sv. Ján (1922–2020).



a)

b)

Fig. 4. a) the maximum annual discharges of the Morava River at Moravský Sv. Ján (1922–2020), their linear trend and 5-year moving trend b) the deviation annual discharges from long-term annual discharge during the period of 1922–2020.

linear trend and 5-year moving trend are illustrated in Fig. 4a. The annual peak discharges of the Morava River at Moravský Sv. Ján show a slightly decreasing long-term linear trend during the selected period of 1922–2020. There also occurred some extreme floods above 1000 m^3s^{-1} (in 1926, 1930, 1941 or 2006 (Figure 4a). The largest one was in 2006 with a maximum discharge value of 1502 m^3s^{-1}. Fig. 4b shows several consecutive dry and wet years at intervals lasting approximately five or six years. The minimum annual discharge occurred in 2018 (43.82 m^3s^{-1}). From year 2011 to the year 2020 were recorded especially dry years (except 2013 and 2020). Fig. 5 illustrates the distribution of the annual maximum discharges occurrence in individual months during the period of 1922–2020 and in dry and wet years. The maximum number of the events with annual maximum discharges occurs in the month of March. It can be caused by spring rainfall in the middle and southern part of the basin and snowmelt, especially in the northern part of the basin (Fig. 5).

In the second part of the work, the sets of data were divided into two sub-sets based on dry and wet multiannual periods. The dry and wet periods we determined based on double 5-year moving averages of the Morava River discharges at Moravský Sv. Ján for the analyzed period 1922–2020 (Fig. 6). 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 discharge Q_a=104.41 m^3s^{-1}. Because we took the period as a result of the moving average, dry and wet years can also occur in it. The number of 42 years was included in the dry period and the number of 57 years in the wet period (Fig. 6). Fig. 6 also shows that from 2011 to 2019 the dry period is recorded.

Results and discussion

Based on the mentioned method, the waves that belong to the maximum annual discharge were selected. The mean daily discharges and the maximum annual discharges of the Morava River at Moravský Sv. Ján from the period 1922–2020 were used as input data for analysis. Subsequently, maximum annual runoff volume series for various duration of the discharge were calculated (Fig. 7). The maximum annual runoff volume was calculated for runoff

durations 5-, 10-, 15- and 30-days. Considering all the analysed t-days runoff durations the annual maximum runoff volume of the flood in 1941 was the highest one. Considering the runoff durations of about 10-days and 15-days the lowest annual maximum runoff volumes reached the event belong to annual maximum discharge in 2018, within the period of 1922–2020. On the Morava River usually the maximum

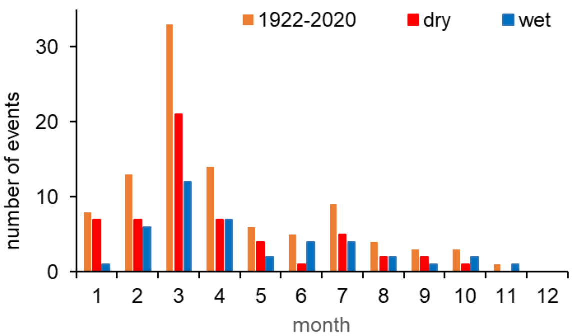


Fig. 5. Monthly distribution of the annual maximum discharges of the Morava River at Moravský Sv. Ján during the period of 1922–2020, for the dry and the wet years.

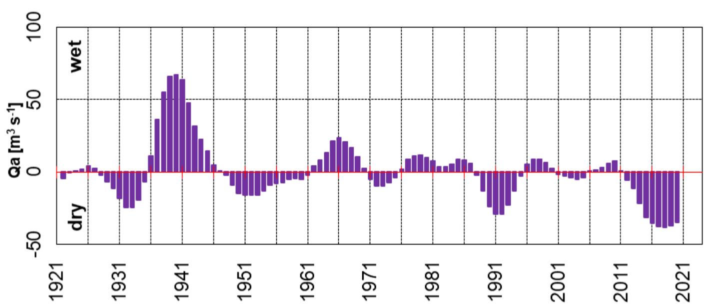


Fig. 6. Course of the dry and wet periods based on double 5-year moving averages of Morava discharges at Moravský Sv. Ján for the period 1922–2020.

annual discharge occurs simultaneously with the annual maximum runoff volume of waves with a given time duration *t*. The correlation of the annual maximum discharge and maximum annual runoff volume for selected runoff durations range between 0.90 (V_{30max}) and 0.97 (V_{5max}).

For example, correlations between Q_{max} and V_{tmax} range in similar values like the Danube River (Bratislava). On the other, hand the correlation between Q_{max} and V_{tmax} ranges from 0.76 to 0.59 for the Hron River (Banská Bystrica) and from 0.89 to 0.56 for the Váh River (Liptovský Mikuláš) (Pekárová et al. 2018).

The analyses of the long-term trends of V_{tmax} on some selected rivers in Slovakia (Topľa: Hanušovce, Váh: Liptovský Mikuláš Hron: Banská Bystrica and Hron: Brehy and Dunaj: Bratislava) showed that the annual maximum discharges and the annual maximum runoff volumes V_{tmax} with various duration of the runoff have decreasing trends for Topľa: Hanušovce and Hron: Banská Bystrica. (Bačová and Pekárová, 2020; Bačová Mitková, 2022). The trend analysis of the annual maximum runoff volumes V_{tmax} for Danube: Bratislava showed that the runoff volume regime during floods has not changed substantially during the last 134-years (Halmova et al., 2008) resp. 144 years (Bačová Mitková and Halmová, 2021).

Trend analysis of annual maximum runoff volumes V_{tmax} on the Morava River at Moravský Sv. Ján (1922–2020)

The M-K trend test shows significant long-term trends in annual maximum runoff volumes for the runoff duration of above 5 days. We can reject the hypothesis *H0* at significance levels α=0.1 (V_{5max}) and α=0.05 (V_{10max}, V_{15max} and V_{30max}), for the data period 1922–2020 (Table 1). The long-term trends of the M-K test for annual maximum runoff volumes with analysed durations *t*=10 days and *t*=30 days of the Morava River at Moravský Sv. Ján (1922–2020) are illustrated in Fig. 8. The trend analysis of the dry and the wet periods shows significant decreasing long-term trends in annual maximum runoff volumes in the wet period. We can reject the hypothesis *H0* at significance levels α=0.01 (V_{5max}, V_{10max}, V_{15max} and V_{30max}), for the data period of 1922–2020 (Table 2). The trend analysis of the dry period did not show any significant trends. Similar results were achieved for trend analysis of the dry and the wet years.

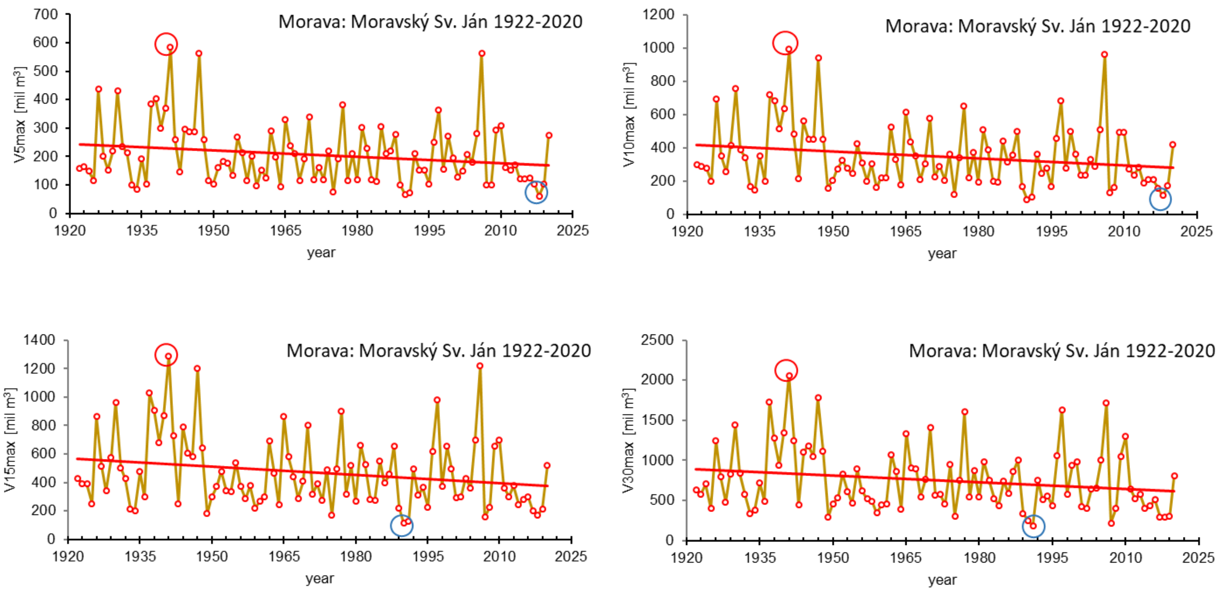


Fig. 7. Maximum annual volume series V_{tmax} of the Morava for various flood duration t (e.g. V_{20max} means maximal annual runoff volume in 20 days).

Table 1. Conclusions of Mann-Kendall trend test for annual maximum runoff volumes V_{tmax} with time duration *t* for waves belong to annual maximum discharges of the Morava River at Moravský Sv. Ján (1922–2020)

				Mann-Kendall trend		Sen's slope estimate	
V_{tmax} [mil m^3]	First year	Last Year	*n*	Test Z	Signific.	A	B
V_{5max}	1922	2020	99	-1.89	+	-0.59	213.5
V_{10max}	1922	2020	99	-2.20	*	-1.16	360.2
V_{15max}	1922	2020	99	-2.26	*	-1.66	496.7
V_{30max}	1922	2020	99	-2.13	*	-2.34	746.5

*(A, B are parameters of the linear trend line y = A*x+B, A is slope of the trend line)*

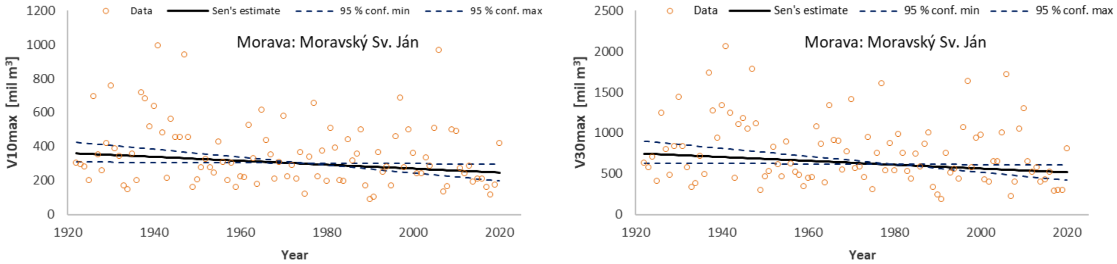


Fig. 8. Graphical results of Mann-Kendall trend test for annual maximum runoff volumes V_{tmax} with time durations t=10 days and t=30 days for waves belong to annual maximum discharges of the Morava River at Moravský Sv. Ján (1922–2020)

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 discharges in wet periods of the Morava River at Moravský Sv. Ján (1922–2020)

				Mann-Kendall trend	Sen's slope estimate
V_{tmax} [mil m^3]	n	Test Z	Signific.	A	B
V_{5max}	57	-2.64	**	-2.72	293.8
V_{10max}	57	-3.13	**	-5.03	520.3
V_{15max}	57	-3.15	**	-6.99	695.4
V_{30max}	57	-3.20	**	-10.99	1120.5

*(A, B are parameters of the linear trend line y = A*x+B, A is slope of the trend line)*

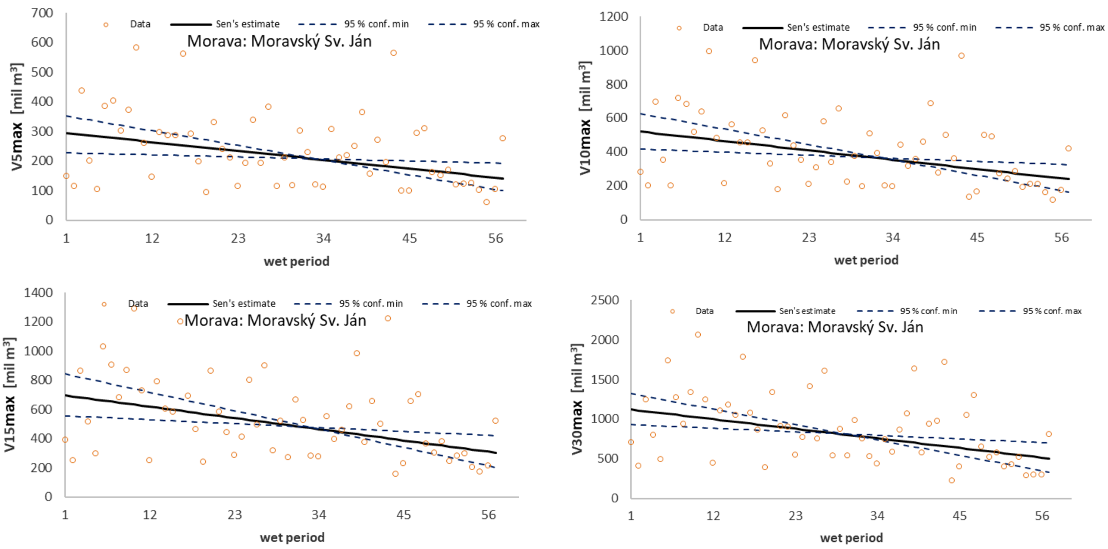


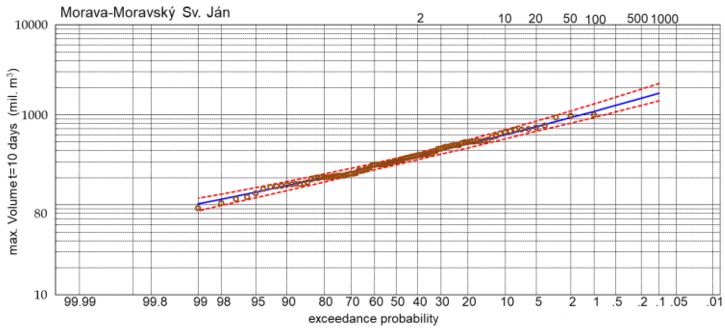
Fig. 9. The Mann-Kendall trend test for annual maximum runoff volumes V_{tmax} with runoff durations t=5-, 10-, 15-, and 30-days for waves belonging to annual maximum discharges of the Morava River at Moravský Sv. Ján (wet period).

Estimation of the T-year annual maximum runoff volumes V_{tmax} on the Morava River at Moravský Sv. Ján (1922–2020)

The estimation of the *T*-year annual maximum runoff volumes V_{tmax} with various duration of the runoff values by Log-Pearson III type probability distribution are presented in this part of the contribution. The frequency curve spreadsheet version 3.06 of IACWD, (1982) and bulletin of Flynn and al. (2006) were used to estimate the parameters of distribution function.

The calculated volumes were plotted on a log-probability scale. Fig. 9 illustrates theoretical exceedance curves of annual maximum runoff volumes with selected runoff durations on the Morava River at Moravský Sv. Ján during the period of 1922–2020.

The results suggest that for Q_{max} with T=100 years the annual maximum runoff volumes for analysed runoff duration with return period $T=100$ years are estimated at value 278 mil m^3 (V_{10max}), 238 mil. m^3 (V_{5max}), and 1098 mil. m^3 (V_{10max}) and at value 1708 mil m^3 (V_{15max}) (Table 3).



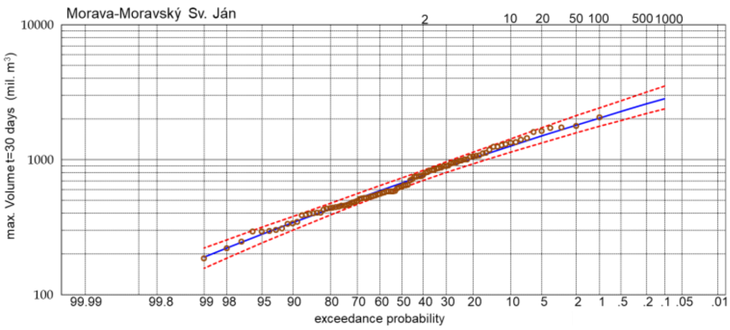


Fig. 10. Examples of the theoretical LPIII exceedance probability curves of the Morava maximum annual runoff volumes V_{10max}, and V_{13max} for Morava: Moravský Sv. Ján (1922–2020).

Table 3. ***T-year maximum discharges Q_{max} and T-year annual maximum runoff volumes V_{tmax} of the Morava River at Moravský Sv. Ján (1922–2020) (Log-Pearson III) (P=p*100%; $p=1-e^{-1/T}$)***

River: Gauging station	Q_T [m^3 s^{-1}]	P [-]	t=5 days	t=10 days	t=15 days	t=30 days
Morava: Moravský Sv. Ján	Q_{50}	0.02	V_{50tmax} [mil. m^3]			
	1403.0		542.75	935.21	1254.45	1808.44
	Q_{100}	0.01	$V_{100tmax}$ [mil. m^3]			
	1631.0		638.21	1098.19	1472.03	2042.57
	Q_{500}	0.002	$V_{500tmax}$ [mil. m^3]			
	2232.0		895.28	1533.35	2049.81	2596.88
	Q_{1000}	0.001	$V_{1000tmax}$ [mil. m^3]			
	2524.0		1023.51	1748.61	2334.08	2841.53

Conclusion

In the present paper we analyzed, the occurrence of annual maximum runoff volumes with t-day durations for a 99-year series of mean daily discharges of the Morava River at Moravský Sv. Ján (Slovakia). The statistical methods were used to clarify how the maximum runoff volumes of the Morava River at Moravský Sv. Ján changed over the period 1922–2020 and over dry and wet periods. The M-K tests showed no significant trend in annual maximum discharges. The trend analysis of the annual maximum runoff volumes shows significant long-term trends in annual maximum runoff volumes for the runoff duration above 5 days. We can reject the hypothesis *H0* at significance levels α=0.1 (V_{5max}) and α=0.05 (V_{10max} and V_{15max}), for the data period 1922–2020. Based on the M-K test we can conclude that the runoff volume regime during floods has changed during the last 99 years, which is of importance to water management. This conclusion pertains not only to the short-term flood runoff episodes (V_{2max}), but also to the long-term ones (V_{30max}). Trend analysis of the dry and wet periods (also years) showed significant decreasing long-term trends in annual maximum runoff volumes in the wet period at significance levels α=0.01. It means, that there is a 5% resp. 1% portability that we make a mistake if we reject hypothesis *H0*. The result showed that the maximum annual discharges usually occur 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 the selected volume V for different t the probability of its exceeding and return period.

The second part of the paper dealt with estimating the T-year annual maximum runoff volumes V_{tmax} on the Morava River at Moravský Sv. Ján for the period 1922–2020. For the estimation of T-year annual maximum runoff volumes V_{tmax} we used the Log-Pearson Type III distribution function. The results showed the high sensitivity of the LP3 distribution to extremes of the dataset. The Log-Pearson III distribution fits well with the observed data and it is an appropriate mathematical tool for estimating the design values with long return periods.

The results are useful in water planning and flood protection and can help mapping flood risk areas and develop river management plans in the Morava River basin. In frequency analyses, it is important to note, that the process is never-ending and, if anything, will change according to catchment; thus, it is necessary to recalculate distribution curves and define new design discharges for recent periods for particular stations.

Acknowledges

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