Estimation, trend detection and temporal changes in maximum annual flow volume series of the Hron River in Slovakia

Veronika BAČOVÁ MITKOVÁ*

The floods characterized by the volume exceedance probabilities and return periods with specific T-year flows may assist in enhancing the accuracy of local flood frequency estimates, and support the detection and interpretation of any changes in flood occurrence and their magnitudes. Therefore, the present paper deals with the trend detection and with temporal changes in the maximum flows volume series of the Hron River at Banská Bystrica and at Brehy gauging stations in Slovakia during the 90 years. The period 1931–2020 mean daily flows of the waves belong to the maximum annual flows and the series of maximum annual flows of the Hron River at Banská Bystrica and at Brehy gauging stations were used as input data. Subsequently the annual maximum runoff volumes with t-day duration were calculated. The Log-Pearson distribution type III were used to determine the T-year values of the maximum runoff volumes with t-day duration. The results indicated that there are decreasing linear trends in maximum annual runoff volumes with some duration of the flow.

KEY WORDS: the Hron River, trend detection, Log-Pearson III distribution, annual maximum runoff volumes, wave duration

Introduction

One of the basic tasks of hydrology is to correctly estimate the patterns occurrence, circulation, temporal and spatial distribution of water on Earth. With the surface water, it is mainly determining of the hydrological characteristics such as discharge, water stages or wave volume. The basic need for the dimensioning of flood protection structures are designed values of hydrological characteristics which can had disaster effect. 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). It is necessary to regularly to check the validity of the assumptions in order to have correct statistical results (IACWD, 1982). Significant changes to the river basins may have an influence on the hydrological extremes and can affect the frequency analysis. It is well known that in some small streams there have been floods with an atypical ratio of extreme flood wave volume to its culmination, which are among the phenomena no one expected. Therefore, for engineering praxis it is necessary to study the flood wave volume in time. Flood peak and volume have been shown to be interdependent (Szolgay et al., 2015), and this dependence should be taken into account when estimating design floods (Mediero et al., 2010). The design methods of the flood estimation must consider both flood volume and peak discharge. Determination of design values for extreme floods with a very low probability of exceedance, meaning with a long return period (once every 100-, 500- or 1000-years), is a very difficult and complex process, coupled with great uncertainty. There exist many studies for estimating the designed extreme hydrological characteristics; most of them are focused on the study of such extremes as discharges, water stages, discharge volume from basin area or joint probability distributions of the hydrological characteristics (e. g. Bačová Mitková and Halmová 2014; Papaioannou et al., 2016; Balistrocchi et al., 2017 or Huang and Fan 2021). In applied hydrology, the problem is the assignment values of the of flood wave volume with a certain probability of exceedance to the corresponding T-year discharges. Guo and Adams (1998) derived analytical expressions for the probability density function (PDF) of runoff event volume. The probability method SCHADEX for extreme flood estimation presented Paquet et al. (2013). Gądek and Bodziony (2015) presented the hypothetical flood wave volume in non-gauged basins for the area of the Upper Vistula River. Mediero et al. (2010) have also addressed the modelling of flood flows and flood wave volumes using special statistical methods. Based on our own experience in the field of frequency analysis of hydrological extremes (Mitková et al. 2004; Bačová
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Mitková at al. 2016; Pekárová and Miklánek eds. 2019) and the knowledge of other already mentioned studies, we decided to use a very flexible Log-Pearson type III distribution as a statistical method. The floods characterized by the volume exceedance probabilities and by the return periods with specific $T$-year discharges may assist in enhancing the accuracy of local and regional flood frequency estimates and support the detection and interpretation of any changes in flood occurrence and magnitudes. The present paper deals with the estimation, trend detection and temporal changes in annual maximum volumes of the flow waves belong to annual maximum flows at the Hron River. A 90-year series of the mean daily flows and annual maximum flows for Banská Bystrica and Brehy gauging stations were available. Therefore, it is possible to compile a 90-year volume series of the highest (annual) 2-, 5-, 10-, and 15-consecutive days wave volumes. Then their probability distribution functions and trends may be analysed.

The aim of the present paper is:

- assess the maximum annual runoff volumes $V_{t_{\text{max}}}$ lasting 2-, 5-, 10-, and 15-days of the waves belong to annual maximum discharges of the Hron River at Banská Bystrica and at Brehy gauging stations (1931–2020);
- determine their the theoretical exceedance probability curves;
- estimate the $T$-year annual maximum runoff volumes with $t$-day duration of the waves belong to annual maximum discharges;
- analyse changes in the maximum annual runoff volumes $V_{t_{\text{max}}}^t$ of the Hron River at Banská Bystrica and at Brehy gauging stations during the period of 1931–2020;
- analyse the changes in the maximum annual runoff volumes $V_{t_{\text{max}}}$ in wet and dry periods within the period 1931–2020.

Material and methods

The series of 90-years (1931–2020) mean daily flows and annual maximum flows of the Hron River at Banská Bystrica and Brehy gauging stations were used as input data. The location of the selected river in Slovak territory illustrates Figure 1. The Hron River is the second longest river in Slovakia. It is 298 km long and flows only through the territory of Slovakia and feeds into the Danube near Štúrovo. The Hron springs in the Horehronie valley, connected to the Low Tatras and the Spiš-Gemer Karst and can be characterized as a nivo-pluvial river. Scenarios of changes to selected components of the hydrosphere and biosphere in the Hron River basin are described, for example, in the monograph of Pekárová and Szolgay (2005).

The Hron River at Banská Bystrica

The Hron River at Banská Bystrica drains into a basin of 1 766.48 km². The long-term average daily flow reached 25.73 m³s⁻¹ at Banská Bystrica for the period 1931–2020. The course of mean daily flows is illustrated in Figure 2. The course of annual maximum flows, long-term linear trend and 5-year moving trend are illustrated in the Figure 3a. The annual maximum flows of the Hron at Banská Bystrica show a decreasing long-term trend in period of 1930–2020 and we can reject the hypothesis $H_0$ at significance level $\alpha=0.1$ (Mann-Kendall nonparametric test). The maximum annual flow during the period 1931–2020 at the station Banská Bystrica station was 560 m³s⁻¹ (in 1974) (Fig. 3a). The negative deviations of annual flows from the long-term annual flow have been shown more frequently since 1981, what indicate a predominance of dry years (Fig. 3b).
The Hron River at Brehy

The Hron River at Brehy drains into a basin of 3821.35 km². The long-term average daily flow reached 46.57 m³ s⁻¹ at Brehy for the period 1931–2020. The course of mean daily flows is illustrated in Figure 4. The course of annual maximum flows, long-term linear trend and 5-year moving trend are illustrated in Figure 5a. The annual maximum flows of the Hron at Brehy show a decreasing long-term trend in the period of 1930–2020 and we can reject the hypothesis H0 at significance level α=0.1 (Mann-Kendall nonparametric test). The maximum annual flow during the period 1931–2020 at the Brehy station was 1050 m³ s⁻¹ (in 1974) and the second highest maximum occurred in 1960 at value of 1000 m³ s⁻¹ (Fig. 5a). The negative deviations of annual flows from the long-term annual flow have been shown more frequently since 1981, what indicate a predominance of dry years (Fig. 5b). However, the highest positive deviation was in 2010, which ranks this year among the wettest.

Figure 6a illustrates the distribution of the annual maximum flows occurrence in individual months during the period of 1931–2020 and in dry and wet years (Hron: Banská Bystrica). The maximum number of events with annual maximum flow occurs in March. The maximum number of events with annual maximum flow in wet years occurs in April.

**Determination of the maximum runoff volumes with t-day duration**

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 flow threshold with assistance of the probability of exceedance (related to the T-year return period). The T-year flows were then determined by extrapolating probability curves to the domain of low exceedance probability. The calculation of the maximum runoff volumes with t-day duration of the Hron River was done according to 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 and 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. To determine the volume of the wave belonging to annual maximum flow, it is necessary to identify the beginning and end of the wave. It is quite difficult to identify the beginning and end of the flow wave, in some cases. In our analysis, the beginning and end of the wave were determined...
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Fig. 4. The mean daily flows of the Hron River at Brehy.

Fig. 5. a) the maximum annual flows of the Hron River at Brehy (1931–2020), their linear trend and 5-year moving trend and b) the deviation of the annual flows from long-term annual flow during the period of 1931–2020.

Fig. 6. Monthly distribution of the annual maximum flows for whole period 1931–2020 and for dry and wet years of the Hron River a) at Banská Bystrica and b) at Brehy gauging stations.

approximately at the level of the long-term average daily flow. To define the volumes of individual waves, we introduced the parameter t - flow duration in days. In this way, we determined the maximum runoff volumes with t-day duration of 2-, 5-, 10- and 15- days based on mean daily flows. If the wave duration was less than 15 days, the steady flows were included into the analysis. In the case of an example t=5 days, the fifth 5-daily move averages were calculated around the culmination maximum flow. Consequently, only one maximum value was included into the statistical data set for analysis. A more detailed description of the methodology can be found in previous works e.g. Halmova et. al., (2008), Bačová and Halmová (2021) or Pekarová et al., (2018).

Log-Pearson III distribution

For the estimation of the maximum annual runoff volume $V_{\text{max}}$ 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 Míklánek, 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 to Hosking and Wallis (1997) are defined as:

$$
\text{If } \gamma \neq 0 \text{ let } a = 4/\gamma 2 \text{ and } \zeta = \mu - 2\alpha / \gamma
$$
If $\gamma > 0$ then:

$$F(x) = G(\alpha, x^{-\xi})/\Gamma(\alpha)$$  
(1)

$$f(x) = \frac{(x^{-\xi})^{\frac{\alpha-1}{\beta}}(x^{-\xi})^{-\alpha}}{\beta^{\alpha} \Gamma(\alpha)}$$  
(2)

where:

- $\xi$ – location parameter;
- $\alpha$ – shape parameter;
- $\beta$ – scale parameter;
- $\Gamma$ – Gamma function.

If $\gamma < 0$ then:

$$F(x) = 1 - G(\alpha, x^{-\xi})/\Gamma(\alpha)$$  
(3)

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

The Kolmogorov-Smirnov test was performed to test the assumption that the flow magnitudes follow the theoretical distributions. The $p$-value ($p<0.05$) 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; Gilbert, 1987). By M-K test, we want to test the null hypothesis $H_0$ of no trend, i.e. the observations $x_i$ is randomly ordered in time, against the alternative hypothesis $H_1$, where there is an increasing or decreasing monotonic trend. For $n$ (number of tested values) $\geq 10$, the statistic $S$ is approximately normally distributed with the mean and variance as follows:

$$E(S) = 0$$  
(5)

$$\text{VAR}(S) = \frac{1}{18} \left[ n(n-1)(n-2) - \sum_{p=1}^{q} t_p (t_p - 1)(2t_p + 5) \right]$$  
(6)

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:

$$Z = \begin{cases} 
  \frac{S - 1}{\sqrt{\text{VAR}(S)}} & \text{if } S > 0 \\
  0 & \text{if } S = 0 \\
  \frac{S + 1}{\sqrt{\text{VAR}(S)}} & \text{if } S < 0 
\end{cases}$$  
(7)

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 downward monotone trend (a two-tailed test) at the $\alpha$ level of significance, hypothesis $H_0$ (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 $\alpha = 0.1$. A 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 $H_0$. A significance level of 0.01 means that there is a 1% probability that we make a mistake if we reject hypothesis $H_0$. 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 – $H_0$ 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 $H_0$
- + if trend at $\alpha = 0.1$ level of significance.

Blank: the significance level is greater than 0.1, cannot be excluded that the $H_0$ is true.

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

**Results and discussion**

**Analysis of annual maximum runoff volumes $V_{\text{max}}$ on the Hron River (1931–2020)**

Based on the mentioned methodologies, the waves that belong to the maximum annual flow were selected. Subsequently, the maximum runoff volumes with $t$-day duration were calculated. The runoff time duration was determined as $t = 2, 5, 10$ and 15 days. The calculated maximum runoff volumes with $t$-day runoff duration for the Hron River at Banská Bystrica and Brehy are illustrated in Figure 7. Considering the 2-days to 15-days maximum runoff volumes, the flood of 1974 was the highest one within the period of 1931–2020 for both analyzed Hron River stations. The lowest one was in 1973 for Hron River at Banská Bystrica. Considering the 2-days and 5-days maximum runoff volumes, the flood of 2012 was the lowest one within the period 1931–2020 for Hron River at Brehy. Considering the 10- and 15-day runoff volumes, the lowest flood was in 1943.

A Log-Pearson III theoretical distribution was selected to calculate the T-year maximum runoff volume with the given runoff time duration $t$. The calculated volumes were plotted on a log-probability scale. Figure 8a-b shows an example of the exceedance probabilities of the maximum runoff volume for a given flow time duration of 2 days and 15 days on the Hron River at Banská Bystrica and at Brehy for the period 1931–2020. From Figure 8, we can see how the slope of the maximum annual runoff volume probability curves changes from positive to negative as the runoff duration increases. The Kolmogorov-Smirnov test showed that we could not
reject the hypothesis that the selected theoretical probability distribution fit well the observed data at 5% significance. The estimated T-year maximum flows and T-year maximum runoff volumes $V_{\text{max}}$ for the Hron River at Banska Bystrica and at Brehy the period 1931–2020 are listed in Table 1.

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 Hron River at Banska Bystrica and Brehy gauging stations for period 1931–2020. The M-K trend test indicates a decreasing long-term trends in annual maximum runoff volumes with $t=5$, 10-, 15-days of the waves belong to annual maximum flows of the Hron River at Banska Bystrica for selected period 1931–2020 and we can reject the hypothesis $H_0$ at significance level $\alpha=0.1$ (Fig. 9a–c). The M-K trend test indicates a decreasing long-term linear trends in annual maximum runoff volumes with $t=15$-days of the waves belong to annual maximum flows of the Hron River at Brehy gauging station for selected period 1931–2020 and we can reject the hypothesis $H_0$ at significance level $\alpha=0.1$ (Fig. 9d).

### Analysis of annual maximum runoff volumes $V_{\text{max}}$ on the Hron River (1931–2020) in dry and wet periods

In this part of the work, we divided the sets of annual maximum runoff volumes with $t$-days 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 Hron River annual flows at Banska Bystrica and at Brehy stations for the period 1931–2020 (Fig. 10a–b).

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 $Q_0$ of the Hron River at two selected stations. 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. An average number of 46 years were included in the dry period and a number of 44 years were included in the wet period.

![Graphs of annual maximum flow volumes for Hron River at Banska Bystrica and Brehy](images/hron_river_flows.png)

**Fig. 7.** Flood wave volume series of the Hron River at Banska Bystrica and at Brehy for flood durations $t$ (2-, 5-, 10-, 15-days) (e.g. $V_{2\text{max}}$ means maximal annual runoff volume in 2 days).
Fig. 8. Examples of the theoretical LPIII exceedance probability curves of the maximum annual runoff volumes with $t=2$ days and 15-days for the Hron River at Banská Bystrica and at Brehy (1931–2020).

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

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<th>River: Gauging station</th>
<th>$Q_T$ [m$^3$/s]</th>
<th>$t=2$ days</th>
<th>$t=5$ days</th>
<th>$t=10$ days</th>
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The Mann-Kendall trend test for annual maximum runoff volumes $V_{\text{max}}$ with various time duration of the waves belong to annual maximum flows of the Hron River at Banská Bystrica gauging station and at Brehy gauging station (1931–2020).

Course of the a) annual flows, their linear trend and b) dry and wet periods based on double 5-year moving averages of the Hron River a) at Banská Bystrica and b) Brehy gauging stations for the period 1931–2020.

in the wet period (Figure 10). Figure 10 also shows that since 1980 the dry periods prevail.

The M-K trend analysis did not indicate a significant long-term linear trend in annual maximum runoff volumes for dry and wet periods. 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 example of differences between estimated $T$-year maximum annual runoff volumes for dry and wet periods are illustrated in Figure 11. In the wet period, with the same probabilities of exceeding, higher values of maximum volumes may occur compared to the dry period. Dividing the period 1931–2020 into dry and wet periods had a greater impact on changes in LP III exceedance curves of the maximum runoff at higher values of volumes with time duration t=2 and 5-days for wet period.
Conclusion

In the present paper we analyzed the occurrence of annual maximum runoff volumes with t-day durations for a 90-year series of mean daily discharge of the Hron River at Banská Bystrica and at Brehy gauging stations (Slovakia). The statistical methods were used to clarify how the maximum annual runoff volumes of the Hron River at selected gauging stations changed over the period 1931–2020 and over dry and wet periods. The highest number of flow waves belonging to the annual maximum occurs in March and in April. On the Hron 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 always equivalent. Spring flow waves usually have a larger volume, while summer flow waves have a smaller volume but a higher flow. 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 decreasing trend of the annual maximum runoff volumes at significance level α=0.1 for the period 1931–2020 for t=5-, 10-, 15-days of the waves belong to annual maximum flows of the Hron River at Banská Bystrica. The division of the period 1931-2020 into wet and dry periods has shown that the dry periods prevail since 1980 on the Hron River in analyzed gauging stations. Next, probabilities of exceedance of the annual maximum runoff volumes on the Hron at Banská Bystrica and Berhy for selected runoff durations t=2-, 5-, 10-, and 15-days in given periods were estimated, plotted and compared. The results suggest that the maximum annual runoff volumes of duration t=2-days, 5-days and 10-days has no significant changes in estimation. In the wet period with the same probabilities of exceeding, higher values of maximum volumes may occur compared to the dry period. Dividing the period 1931–2020 into dry and wet periods had a greater impact on changes in LPIII exceedance curves of the maximum annual runoff volumes with long return period values of volumes with time duration t=2-, and 5-days. The results are useful in water planning, flood protection and can help mapping flood risk areas and developing river management plans in Hron River basin. It would also be good to analyze possible long-term changes in volumes in terms of seasonality during the year. In the future, it would be desirable to confirm the conclusions also on other rivers in Slovakia with satisfactory long runoff data series, or based on reconstructed discharge values by indirect methods (analogy, mathematical runoff modeling, etc.).

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