Analysis of Maximum Runoff Volumes with Different Time Durations of Flood Waves: A Case Study on Topľa River in Slovakia

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Abstract. In applied hydrology, it is problematic to assign the flood wave volume values with a certain probability of exceedance to given corresponding T-year discharges. This dependence is highly irregular, and requires knowledge the flood wave course of the given probability. For this reason, this work deals with the determination of the annual maximum discharge volumes on the Topľa River for the time duration of 2-, 5-, 10-, and 15-days ($V_{t_{\text{max}}}$). The series of 84 years (1931–2015) mean daily discharges of the Topľa River at Hanušovce above Topľa station was used as input data to calculate the maximum annual volumes of runoff of the Topľa River. Subsequently, the theoretical curves of exceedance of the maximal discharge volumes $V_{t_{\text{max}}}$ were determined by the Log-Pearson distribution of the Type III. This type of probability distribution is used to estimate maximum (extreme) values across a range of natural processes. The results showed relatively small differences in estimated T-year volumes when compared to other types of theoretical distribution functions used in hydrological extreme analyses in Slovakia (Gamma, Log-normal, etc.). The second part of our work was focused on the bivariate analysis of the relationship between T-year maximum volumes with different duration and peak discharges by the three Archimedean copula functions (Clayton, Gumbel-Hougaard and Frank). The LPIII distribution was used as marginal probability distribution function. Subsequently joint and conditional return periods of the T-year maximum annual flows and T-year maximum volumes with different time duration were calculated. The first one defines joint return periods as the return periods using one random variable equalling or exceeding a certain magnitude and/or using another random variable equalling or exceeding another certain magnitude. The second one is conditional return periods for one random variable, given that another random variable equals or exceeds a specific magnitude.

1. Introduction

In the study of the flood wave parameters the attention is usually given to the culmination or maximum water level. Solution of some water management tasks requires not only knowing maximum discharge but also the shape of the flood wave or at least its volume. The volume of the flood waves and its importance is evaluated rarely. The analysis and estimation of the flood wave volumes corresponding to the maximum design discharge with a return period of T-years in Slovakia was reported e.g. in [1]; [2]; [3].

The mathematical expressions for probability distribution of runoff volume and the maximum discharge from the selected basin were derived by [4]. The probability method SCHADEX for extreme flood estimation presented [5]. The modelling of flood flows and flood wave volumes using special statistical methods has also been addressed by [6].
The flood wave is a multidimensional hydrological event depends on many factors. Therefore, there is a need to know interdependence, and model two hydrological components, that are somewhat dependent on themselves. In the case of modelling without evaluating this mutual dependence of the flood wave characteristics, they may be overestimated (in the case of negative dependence) or underestimated (in case of positive dependence). Many hydrologists analysed mutual dependence between components of the hydrological cycle to identify flood-generating processes using copula function ([7]; [8]; [9]; [10]; etc.). The hydrological mutual dependences in the field of natural processes— in particular the relationship of maximum discharge, volume, or the duration of flood waves on selected Slovak basins – are modelled and presented in [11] or [12].

This paper is focused on determination of maximum volumes of given duration (2, 5, 10 and 15 days) on the Topľa River in Hanušovce nad Topľou during period of 1931–2015. Subsequently, the theoretical curves of exceedance of the maximum discharge volumes \( V_{\text{max}} \) will be determined by the selected probability distributions and the \( T \)-year maximum annual volumes will be estimated. At the end of the article an analysis and statistical evaluation of the mutual dependence and occurrence of maximum discharges and volumes with different time duration using the copula functions will be done. Results of the analysis will be discussed and presented in figures and tables.

2. Topľa River basin and data

The Topľa is upland/lowland type river in eastern Slovakia. The catchment drainage area is 1 506 km² with length of 129.8 km (figure 1). The long-term mean daily discharge amounts in Hanušovce a. Topľa was 8.1 m³s⁻¹ during period 1931–2015 (runoff height was 244.2 mm). The maximum discharge during the analysed period was 449 m³s⁻¹ (06.04.1932) in the station Hanušovce a. Topľa. Figure 1 also shows the exceeding probabilities of the maximum annual discharges according to Log-Pearson Type III. probability distribution (LPIII). The course of the maximum annual discharges and their long-term trend are shown in figure 2. In the analysed period, two dry periods of 1954–1964 and 1990–1999 were occurred. While wet periods can be described only as years with extreme flood events (e.g. 1932, 1948, 1952, or 1980), a relatively prolonged wet period was in 2004–2010. Annual maximum discharges show a decreasing trend for the period of 1931–2015.

![Figure 1](image1.png)

**Figure 1.** A scheme of the Topľa River basin (left) and exceedance probabilities of the annual peak discharges of the Topľa River: Hanušovec above Topľa within 1931–2015 period (right).
3. Preparing of the data - determination of annual maximum volumes of a given duration

The series of mean daily discharges (1931–2015) of the Topľa River at Hanušovce a. Topľa station was used as input data. Maximum volumes with time durations \( t \) (2, 5, 10 and 15 days) of the wave was determined. If the wave duration was less than 15 days, the steady discharges were included into the data series. Figure 3 presents example of the determination of maximum volumes with given durations. In case of the flood in 1932 and \( t=5 \) days, the fifth 5-daily move averages were calculated around the culmination. Consequently, only one maximum value was included into the statistical data set for analysis (figure 3a). The maximum time durations of the flood waves for maximum annual discharges during the period of 1931–2015 are presented in figure 3b. The time course of the maximum runoff volumes on the Topľa River for the selected runoff duration is shown in figure 4 a-b.

![Figure 2](image)

**Figure 2.** Peak annual discharges (points), linear trend (red line), and 4-years moving averages for the Topľa River at Hanušovce a. Topľa during the period 1931–2015.

![Figure 3](image)

**Figure 3.** a) A scheme for determining of the maximum flood wave volume on Topľa River for flood in 1932 for \( t=5 \) days and b) maximum flood durations of the flood waves corresponding to maximal annual discharges during the period 1931–2015.

![Figure 4](image)

**Figure 4.** Flood wave annual maximum volumes for various flood duration of the Topľa: Hanušovce a. Topľa during the period 1931–2015.
4. Results

4.1. Estimation of the T-year maximum annual volumes for different durations of the flood waves on the Topľa River (1931–2015)

In our analysis we use one type of the theoretical probability distribution – the Log-Pearson distribution type III (LPIII). The advantage of this particular technique is that extrapolation can be made of the values for events with return periods well beyond the observed flood events. This theoretical distribution belongs to the family of Pearson distributions, so called three parametric Gamma distributions, with logarithmic transformation of the data. Its parameters are median $\mu$, variation $\sigma^2$ and asymmetry $\gamma$. In many countries is LPIII distribution used as a first chose for flood design values. Parameters can be determined by several methods e.g.: LGMO – method of logarithmic moments, RLMO – method of real moments or MXM – method of mixed moments. The cumulative distribution function and probability distribution function according [13] are defined as:

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

If $\gamma > 0$ then:

$$F(x) = G(a, x-\xi/\beta) / \Gamma(\alpha), \quad (1)$$

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

If $\gamma < 0$ then

$$F(x) = 1 - G(a, \frac{\xi-x}{\beta}) / \Gamma(\alpha) \quad (3)$$

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

Where: $\mu$ - location parameter; $\sigma$ - scale parameter; $\gamma$ - shape parameter; $\Gamma$ – Gamma function.

In the world literature, there are a number of scientific papers dealing with the selection and testing of the suitability of theoretical probability distributions in estimating the maximum values of hydrological characteristics. Therefore, we compared the LPIII distribution with the theoretical probability distributions that were (and still are) most widely used hydrological practice in Slovakia: Gamma distribution and Log-normal distribution. To verify the accuracy of theoretical distributions, we used a non-parametric Kolmogorov-Smirnov goodness of fit test for the significance level $\alpha = 0.05$. Figure 5 shows the exceeding probabilities of the maximum annual volumes for different values of the flood wave duration $t = 2$ and 15- days on the Topľa River at Hanušovce a. Topľa. Estimated values of $T$-year maximum annual runoff volumes for given duration according selected LPIII, Gamma and Log-normal distributions are listed in table 1. Kolmogorov-Smirnov test showed, that we cannot reject hypothesis that selected theoretical probability distributions fit well the observed data at 5% significance. Results shoved relatively small differences between estimated values of $T$-year maximum volumes when comparing the individual types of theoretical probability distributions used in hydrological analyses of extremes. The Gamma theoretical probability distribution reached the lowest values of estimated $T$-year $V_{\text{max}}$, especially for volumes with high return periods (table 1).
Figure 5. Exceedance probabilities of maximum flow volume of Topľa: Hanušovce a. Topľa for two values of $t = 2$ and $t = 15$ days.

Table 1. T-year maximum discharges $Q_{\text{max}}$ [m$^3$s$^{-1}$] and T-year runoff volumes $V_{\text{max}}$ [mil. m$^3$], Topľa River: Hanušovce a Topľa, period 1931–2015.

| $T$ [years] | 2   | 5   | 10  | 50  | 100 | 200 | 500 | 1000 |
|------------|-----|-----|-----|-----|-----|-----|-----|------|
| $P$ [%]    | 39  | 18  | 9.5 | 2   | 1   | 0.5 | 0.2 | 0.1  |
| $Q_{\text{max}}$ [m$^3$s$^{-1}$] | 139 | 193 | 249 | 398 | 473 | 556 | 679 | 783  |

| $V_{\text{max}=2}$ d [mil. m$^3$] | 14.3 | 19.8 | 25.3 | 39.0 | 45.5 | 52.3 | 62.0 | 69.8  |
| $V_{\text{max}=5}$ d [mil. m$^3$] | 24.7 | 34.6 | 44.9 | 72.3 | 85.9 | 100.9 | 123.0 | 141.6 |
| $V_{\text{max}=10}$ d [mil. m$^3$] | 36.0 | 50.1 | 64.4 | 101.2 | 119.0 | 138.2 | 166.0 | 189.1 |
| $V_{\text{max}=15}$ d [mil. m$^3$] | 45.1 | 61.9 | 78.8 | 121.8 | 142.4 | 164.7 | 196.7 | 223.0 |

| $V_{\text{max}=2}$ d [mil. m$^3$] | 14.4 | 19.2 | 24.8 | 37  | 42.6 | 48.5 | 56.6 | 63.1 |
| $V_{\text{max}=5}$ d [mil. m$^3$] | 24.8 | 34.7 | 44.6 | 69.9 | 82.0 | 94.9 | 113.4 | 128.5 |
| $V_{\text{max}=10}$ d [mil. m$^3$] | 36.1 | 50.2 | 64.4 | 100.1 | 117.1 | 135.2 | 161 | 182.0 |
| $V_{\text{max}=15}$ d [mil. m$^3$] | 44.9 | 61.9 | 79.2 | 122.7 | 143.5 | 165.6 | 196.9 | 222.7 |

4.2. Analysis of the dependence between maximum annual volumes with different duration and maximum annual discharges on Topľa River by copula functions

A copula function is a mathematical technique which offers a flexible way of describing nonlinear dependence among multivariate data and serves as a powerful tool for modelling of such data system. The word “copula” was first used in mathematical or statistical sense by [14]. Using copulas – that combine one-dimensional marginal distributions of random variables with their associated distribution – we tried to process and analyse the interdependence structure of the variables $Q_{\text{max}}$ and $V_{\text{max}}$. The dependence between variables $Q_{\text{max}}$ and $V_{\text{max}}$ for $t = 2$ and 15 days is presented in figure 6. Calculated values of the Spearman $\rho$ and Kendall’s $\tau$ correlation coefficients are listed in table 2. The LP III distribution was used as marginal distribution. Archimedean copula functions (Clayton, Gumbel-Hougaard and Frank) were used in our analysis. Probability functions, parameter space, generating function and relationship of non-parametric dependence measure with association parameter for selected copulas are listed in table 3. Copula parameters for selected combination of the variables and results of the Kolmogorov-Smirnov goodness-of fit test are listed in table 4.
Figure 6. Relationships between annual peak discharges $Q_{\text{max}}$ and maximum wave volumes $V_{\text{max}}$ of Topľa: Hanušove a. Topľa for different values of $t=2$ and 15 days.

The results of the relationship between the maximum annual discharges $Q_{\text{max}}$ and the volumes with different duration $V_{\text{max}}$ showed the best fit for the Gumbel-Hougaard copula (figure 7). Figure 8 shows simulation of 1000 pairs of variables $Q_{\text{max}}$ and $V_{\text{max}}$ using by Gumbel-Hougaard copula function.

**Table 2.** Values of the Spearman $\rho$ and Kendall’s $\tau$ of the selected combination of $Q_{\text{max}}$ and $V_{\text{max}}$.

| $Q_{\text{max}}$ | $V_{\text{max}}$ | Spearman $\rho$ | Kendall’s $\tau$ |
|------------------|------------------|-----------------|-----------------|
| $V_{\text{max}}=2d$ | $Q_{\text{max}}$ | 0.88            | 0.61            |
| $V_{\text{max}}=5d$ | $Q_{\text{max}}$ | 0.80            | 0.71            |
| $V_{\text{max}}=10d$ | $Q_{\text{max}}$ | 0.76            | 0.56            |
| $V_{\text{max}}=15d$ | $Q_{\text{max}}$ | 0.73            | 0.53            |

**Table 3.** Probability functions, parameter space, generating function and relationship of non-parametric dependence measure with association parameter Archimedean copulas.

| Copula function | $C(u, v, \theta)$ | parameter $\theta$ | Kendall’s $\tau$ | Generator $\phi(t)$ |
|-----------------|------------------|-------------------|-----------------|-------------------|
| Clayton         | $(u^{-\theta} + v^{-\theta} - 1)^{-\theta}$ | $[-1, \infty)/\{0\}$ | $\frac{\theta}{\theta + 2}$ | $\frac{1}{\theta}(t^{\theta} - 1)$ |
| Gumbel-Hougaard | $\exp[-((-\ln u)\theta + (-\ln v)^\theta)]$ | $[1, \infty)$ | $\frac{\theta - 1}{\theta}$ | $(-\ln t)^\theta$ |
| Frank           | $\frac{1}{\theta} \ln[1 + (e^{-\theta t} - 1)(e^{-\theta t} - 1)]$ | $(-\infty, \theta)/\{0\}$ | $1 + \frac{1}{\theta} [D_{\phi}(\theta) - 1]$ | $-\ln \frac{e^{-\theta t} - 1}{e^{-\theta t} - 1}$ |

Debye function $D_{\phi} = \int_{\theta_{-1}}^{\theta_{-1}} \frac{dt}{t^{\phi} - 1}$. $\phi = -\log(\theta)$

**Table 4.** Copula parameters (C - Clayton, G-H - Gumbel-Hougaard, F - Frank) for selected combination of the variables and results of the K-S test.

|        | $Q_{\text{max}}$ | $V_{\text{max}}=2d$ | $Q_{\text{max}}$ | $V_{\text{max}}=5d$ | $Q_{\text{max}}$ | $V_{\text{max}}=10d$ | $Q_{\text{max}}$ | $V_{\text{max}}=15d$ |
|--------|------------------|---------------------|------------------|---------------------|------------------|---------------------|------------------|---------------------|
| C      | 4.99             | 3.06                | 2.51             | 2.29                |
| G-H    | 3.5              | 2.53                | 2.26             | 2.15                |
| F      | 12.1             | 8.2                 | 7.2              | 6.4                 |
| $p_{\text{value}}$ KS (C) | 0.028            | 0.032               | 0.098            | 0.140               |
| $p_{\text{value}}$ KS (G-H) | 0.067            | 0.071               | 0.274            | 0.274               |
| $p_{\text{value}}$ KS (F) | 0.058            | 0.061               | 0.199            | 0.265               |
Figure 7. The comparison of the empirical copula with the corresponding values derived by the selected parametrical copulas (Clayton, Gumbel-Hougaard Frank) for $Q_{\text{max}}$ and $V_{\text{max}}$ with $t=2, 15$ days.

Figure 8. Simulations of 1000 pairs of the $Q_{\text{max}}$ and $V_{\text{max}}$ with $t=2$ and $t=15$ days using the Gumbel-Hougaard copula.

4.2.1. Joint and conditional return period.

In hydrological frequency analysis the return period of the hydrological variable that occurs once in a year, we can define as:

$$T = \frac{1}{1-F(x)} \quad (5)$$

Where, $T$ is return period in years and $F(x)$ is univariate cumulative distribution function.

In multivariate statistical analysis, we can determine the return period of the phenomenon in two ways. The first is a joint return period and second, is a conditional return period.

Joint return period for two variables defined more authors ([15]; [16]) and it can be written in the form:

$$T^{\text{and}}_{x,y} = \frac{1}{\frac{1}{1-F(x)-F(y)+H(x,y)}} \quad (6)$$
or

\[ T_{x,y}^{or} = \frac{1}{1 - H(x,y)} \]  \hspace{1cm} (7)

Equation (6) represents joint return period of \( X \geq x \) and \( Y \geq y \). Equation (7) represents joint return period of \( X \geq x \) or \( Y \geq y \). These relationships indicate that different combinations of the numbers \( x \) and \( y \), can take same return period (equation 8). \( H(x, y) \) is the joint cumulative distribution function (can be expressed as copula function).

\[ T_{x,y}^{or} \leq \min[T_x, T_y] \leq \max[T_x, T_y] \leq T_{x,y}^{and} \]  \hspace{1cm} (8)

Conditional return period for \( X \) given \( Y \geq y \) may be expressed as:

\[ T(x|Y \geq y) = \frac{1}{1 - F(x) + (1 - F(x) - F(y)) + H(x,y)} \]  \hspace{1cm} (9)

Where \( x \) and \( y \) are random variables and \( H(x, y) \) is the joint cumulative distribution function.

An equivalent formula for conditional return period of \( Y \) given \( X \geq x \) can be obtained. The example of joint and conditional return period (T = 2, 5, 10, 50 and 100 years) of the \( Q_{max} \) and \( V_{tmax} \) with \( t=15 \) days on the Topľa River is presented in table 5.

| \( T \) [year] | \( P \) [%] | \( Q_{max} \) [m³ s⁻¹] | \( V_{tmax} = 15 \) d [mil. m³] | \( F_{Q_{max}} \) | \( F_{V_{tmax} = 15 \) d} | \( C_{G@H} \) | \( T_{v}^{or} \) [year] | \( T_{v}^{nd} \) [year] | \( T_{V/Q} \) [year] |
|---|---|---|---|---|---|---|---|---|---|
| 2 | 39 | 139 | 45.1 | 0.610 | 0.505 | 2 | 4 | 9 |
| 5 | 18 | 193 | 61.9 | 0.820 | 0.610 | 0.760 | 4 | 8 | 46 |
| 10 | 9.5 | 249 | 78.8 | 0.905 | 0.905 | 0.871 | 8 | 16 | 172 |
| 50 | 2 | 398 | 121.8 | 0.980 | 0.980 | 0.972 | 36 | 80 | 4006 |
| 100 | 1 | 473 | 142.4 | 0.990 | 0.990 | 0.986 | 73 | 161 | 16094 |

5. Conclusions and discussions

The first part of the paper deals with the determination of the annual maximum discharge volumes on the Topľa River for the duration of 2-, 5-, 10- and 15-days \( (V_{max}) \). The series of 84 years \( (1931–2015) \) mean daily discharges were analysed. The empirical probability distribution of the data was compared with the theoretical Log-Pearson probability distribution. Subsequently, the maximum volumes with different duration were estimated by Log-Pearson distribution type III (LPIII). The results of comparison with two other theoretical distribution types used in Slovakia: Log-normal and Gamma probability distribution showed:

- The high sensitivity of the LPIII distribution to extremes of the dataset. We can say that this probability distribution is appropriate for design hydrological values with higher values of the return period.
- Relatively small differences in the values of estimated T-year maximum volumes in compared types of theoretical probability distributions used in hydrological analyses of extremes in the Slovakia.
- The lowest values of estimated T-year volumes of a given duration, achieved Gamma theoretical probability distribution, especially for volumes with high repeat times.
In interpreting the results, it should be kept in mind that $T$-year maximum discharges related to the length of the analysed data set, and therefore estimated values with very high return periods are extrapolated values. An each statistical method includes some uncertainty that may be caused by the method but also the data may be affected by certain measurement error.

The second part of our paper was focused on bivariate analysis of the relationship between $T$-year maximum volumes with different duration and annual maximum discharges by the three Archimedean copula functions (Clayton, Gumbel-Hougaard and Frank). The LPIII distribution was used as marginal probability distribution function. The results of this analysis showed:

- From a visual comparison of the empirical and parametric copula functions, was evident that if correlation between variables is lower, than the match between the theoretical and the empirical copulas was better.

- The difference between selected theoretical copulas was not significant, but Gumbel-Hougaard copula was the most suitable for maintaining and monitoring the interdependence of the variables.

- Subsequently joint and conditional return periods of the $T$-year maximum annual flows and $T$-year volumes with different time duration on the Topľa River, were calculated. The first one defines joint return periods as: the return periods using one random variable equalling or exceeding a certain magnitude and/or using another random variable equalling or exceeding another certain magnitude. The second one is conditional return periods for one random variable, given that another random variable equals or exceeds a specific magnitude.

The results obtained from the bivariate as well as multidimensional analysis of the variables, which characterize the hydrological waves (flow, volume, time) can contribute to more reliable assessment of flood risks. Hence, they give an overview of the flood event as a whole and might be practically used in water management and in the design of flood protective systems.

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