Effect of Various Factors on the Estimation of T-Year Discharges for Water Management

Veronika Bačová Mitková
Institute of Hydrology SAS, Dúbravská cesta 9, 841 04 Bratislava, Slovakia
mitkova@uh.savba.sk

Abstract. The paper deals with the effect of various factors on the estimation of designed discharges. As input data, the series of daily discharges and annual peak discharges on the Topľa River at Hanušovce nad Topľou for the period of 1931-2015 were used. The first, maximum annual discharges (AM) approach was applied with the most widely used Log-Pearson III. probability distribution. The second, we analysed the effect of the time series length and the effect of seasonality (winter, summer) on the accuracy of T-year maximum discharges estimation. As an alternative to this approach (AM), the Peak Over Threshold (POT) method was used. We analysed the effect of the threshold level value selection and using of maximum daily discharges on the accuracy of T-year maximum discharges estimation. Results showed that not only the selection of the distribution function to estimate T-year discharges but also the type of used data series may affect the results of the estimation (length or selection of the period). Results also showed that the estimation of designed maximum discharges using by the POT method did not show significant differences at the selected various threshold levels, but for a relatively fast and large increase of discharges during floods, it would be necessary to have peak values for all waves included in the analysis. Determining the specific value of a 500- or 1000-year flood for engineering practice is extremely complex. Each statistical method includes some uncertainty that may be caused by the method but also the data may be affected by certain measurement error, therefore, it is also necessary to specify confidence intervals in which the flow of a given 100-, 500-, or 1000-year flood may occur with probability, for example, 90%.

1. Introduction

Flood frequency analysis plays a major role in the design of hydraulic structures and flood control management. One way of estimating the design discharges is the flood frequency analysis and solution of the relationship between peak discharges of the flood waves and the probability of their return period (T). Directive 2007/60/EC of the European Parliament of 23 October 2007 concerning the assessment and management of flood risks requires member States to draw up flood hazard maps of floods with very long return periods T (500 to 1000 years). All methods of estimating floods with a very long return period are associated with great uncertainties. Determining the specific value of a 500- or 1000-year flood for engineering practice is extremely complex. The correct estimations of potential culmination of floods require the inclusion of the longest data series of observations, as well as the inclusion of historic pre-instrumental data to statistically analysed data series [1-4] studied historic hydrological materials in order to estimate floods threat in Europe. Estimation of the uncertainty at the design discharges was investigated for example by [5]. The type of theoretical probability distribution that is used to estimate maximum (extreme) values has an impact on the estimation of T-year discharges. When the sample volume is not very large, the volume can be extended by numerical simulation of a random
variable based on the inverse method. The maximum discharges corresponding to the probability of exceedance are not unique values, but they depend on aleatory and epistemic uncertainty [6]. Aleatory uncertainty is mainly due to the time variability and the length of the maximum discharges series, while the epistemic uncertainty is the consequence of the incomplete knowledge of the hydrological system.

The paper presents the comparison of two commonly used approaches to estimate T-year extreme values in hydrology: annual maximum approach (AM) and Peak Over Threshold (POT) method. As a mathematical tool for AM approach, we used Log-Pearson type III probability distributions more frequently applied for hydrologic extremes frequency analysis. The series of daily discharges and peak discharges on the Topľa River at Hanušovce nad Topľou for the period of 1931-2015 was used as input data for our case study. The first, effect of the time series length and seasonality (winter, summer) on the accuracy of T-year maximum discharges estimation will be analysed. Next, the alternative approach, POT method, to estimate T-year maximum discharges was used. This part of the paper investigates the effect of the various threshold levels and data set series on the accuracy of the estimation.

2. Study area
The Topľa is an upland-lowland type of the river in eastern Slovakia. The catchment drainage area covers 1 506 km² with a length of 129.8 km (figure 1). The long-term mean daily discharge amounts in Hanušovce a. Topľa was 8.1 m³ s⁻¹ during period 1931–2015 (runoff height was 244.2 mm). The maximum discharge during the analysed period was 449 m³ s⁻¹ (06.04.1932) in the station Hanušovce nad Topľou. The course of the maximum annual discharges and their long-term trend are shown in figure 1. Annual maximum discharges show a decreasing trend for the period of 1931–2015.

![Figure 1. Left: scheme of the Topľa River basin, right: course of mean daily discharges and annual maximum discharges of the Topľa River: Hanušovce nad Topľou (1931–2015).](image)

3. Methodology
3.1. Annual maximum discharges method (AM)
In estimating T-year maximum discharges, the annual maximum method (AM) is generally the first and most widely used method. It aims to estimate the $Q_T$ quantiles, it means such annual maximum discharges that their probability of exceedance is $1/T$, where $T$ can be e.g. 10, 20, 50, and 100, 500 or 1000 or more years. These quantiles are determined from the distribution function of the maximum annual discharges. In our analysis, we use one type of the theoretical probability distribution the Log-Pearson distribution type III (LP III). 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. To estimate the distribution parameters, the method described in Bulletin17B was used. Bulletin 17B was issued in the USA in 1981, and re-issued with minor corrections in 1982 in the Center for Research in Water
Resources of the University of Texas at Austin [7]. 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 about a frequency curve. Bulletin 17B is based on Bulletins 15, 17, 17A (http://acwi.gov/hydrology/Frequency/minutes/index.html). The cumulative distribution function and probability distribution function according to [8] are defined as:

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

If \( \gamma > 0 \) then:

\[
\begin{align*}
F(x) &= G\left(\alpha, \frac{x - \xi}{\beta}\right)/\Gamma(\alpha) \\
f(x) &= \frac{(x - 0)^{\alpha - 1}e^{-\frac{(x - 0)}{\beta}}}{\beta^\alpha\Gamma(\alpha)}
\end{align*}
\]

If \( \gamma < 0 \) then:

\[
\begin{align*}
F(x) &= 1 - G\left(\alpha, \frac{x - \xi}{\beta}\right)/\Gamma(\alpha) \\
f(x) &= \frac{(\xi - x)^{\alpha - 1}e^{-(\xi - x)/\beta}}{\beta^\alpha\Gamma(\alpha)}
\end{align*}
\]

where: \( \mu \) - location parameter; \( \sigma \) - scale parameter; \( \gamma \) - shape parameter, \( \Gamma \) – Gamma function.

3.2. Peak Over Threshold Method (POT)

The POT (peak over threshold) method has been proposed as an alternative method to annual maximum series method in flood frequency analysis. The characteristics of this method were reviewed, for example in [9]. The basic idea is to extract from the daily discharges sequences a sample of peaks containing more than one flood peak per year, in order to increase the available information with respect to the annual maximum analysis. The POT series includes all maximum discharges over the threshold. The number of the peaks (n) in statistical series must be higher than N, where N is a number of the recorded years. To provide independence of the POT data the following criteria were used [10]:

- Time period between two peaks followed one after another must be minimally three times higher than the time of increasing of the first wave.
- Minimum discharge between two peaks must be less than 2/3 of peak discharge of the first wave.

The POT method creates two main variables: number of peaks in each year \( \nu \) and discharge exceedances over threshold \( Z_V = X - x_B \).

The occurrence of maximum flows is a random process defined with:

\[
\chi(t) = \sup_{\nu \geq 1} Z_V; Z_V = X - x_B.
\]

Distribution function of annual maximum is

\[
F(x) = P\{\chi(t) \leq x\}
\]

The probability occurrence of peak exceedance is:

\[
\begin{align*}
p'(\nu) &= \lambda(t, \nu - 1)p_{\nu-1}(t) - \lambda(t, \nu)p_{\nu}(t) \\
p'_0(t) &= -\lambda(t, 0)p_0(t)
\end{align*}
\]

3
The solution of equations (7) represents the law of the probability of peaks occurrence and depends on the shape of the intensity function $\lambda$. This function can take various forms:

$$
\lambda(t) = \lambda(t) \left(1 - \frac{y}{a}\right) \text{ Poisson}
$$

$$
\lambda(t) = \lambda(t) \left(1 + \frac{y}{b}\right) \text{ negative Binomical}
$$

(8)

Distribution function for peak discharges exceedance probability above the selected threshold level, the two parametric distributions are recommended e.g.:

- **Weibull**
  
  $$
  H(z) = 1 - \exp \left( - \left(\frac{z}{\beta}\right)^\alpha \right)
  $$

  (9)

- **Exponential**
  
  $$
  H(z) = 1 - \exp \left( - \left(\frac{z-\alpha}{\beta}\right) \right)
  $$

  (10)

- **Gamma**
  
  $$
  H(z) = \frac{\Gamma(z/\beta)}{\Gamma(\alpha)}
  $$

  (11)

where: $z$ – value of the discharge above threshold level and $\alpha$, $\beta$ – distribution parameters and $\Gamma(\alpha)$ – gamma function (also called the second Euler's integral).

Distribution function of the annual maximum discharges is a combination of the peak number distribution and distribution of the discharges above threshold level $Q_{POT}$ [11]:

$$
F(x) = p_x + \sum_{i=1}^{\infty} [H(x)]^i
$$

(12)

If the number of peaks follows Poisson distribution, then annual maximum distribution $F(x)$ is:

$$
F(x) = \exp \left( - \sum_{i=1}^{\infty} [H(x)]^i \right).
$$

(13)

If the number of peaks follows Binomalical form, then annual maximum distribution $F(x)$ is:

$$
F(x) = e^{-\Lambda} \left[ 1 + \left( e^{\frac{\Lambda}{x}} - 1 \right) H(x) \right]^{-x}
$$

(14)

If the number of peaks follows negative Binomalical form, then annual maximum distribution $F(x)$ is:

$$
F(x) = e^{-\Lambda} \left[ 1 - \left( 1 - e^{-\frac{\Lambda}{x}} \right) H(x) \right]^{-x}
$$

(15)

Chow (1964) used the definition of the annual maximum return period

$$
T_{AM} = \frac{1}{1 - F(x)}
$$

(16)

4. Results

4.1. Estimation of the T-year maximum discharges using Annual maximum approach (AM)

The exceeding probabilities of the maximum annual discharges according to Log-Pearson Type III probability distribution (LPIII) is illustrated in figure 2 and the values of some t-year maximum discharges are listed in table 1. 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.
Figure 2. The exceedance probability of the annual peak discharges of the Topľa River: Hanušovce nad Topľou within 1931–2015 period (empirical - points, blue line- LPIII distribution and redline- confidential intervals)

Table 1. T-year maximum discharges $Q_{T \text{max}}$ [m$^3$s$^{-1}$] on the Topľa River: Hanušovce nad Topľou (1931–2015) estimated from maximum annual discharges $Q_{\text{amax}}$

| T [year] | 2   | 5   | 10  | 50  | 100 | 200 | 500 | 1000 |
|---------|-----|-----|-----|-----|-----|-----|-----|------|
| P [%]   | 39  | 18  | 9.5 | 2   | 1   | 0.5 | 0.2 | 0.1  |

Log-Pearson III

| $Q_{\text{Tmax}}$ [m$^3$s$^{-1}$] | 139 | 193 | 249 | 398 | 473 | 556 | 679 | 783 |
|----------------------------------|-----|-----|-----|-----|-----|-----|-----|-----|
| K-S test p-value                 | 0.99|

4.1.1. The effect of time series length on the T-year discharge estimation. For analysing the effect of the length of the data series on the estimation of T-year discharges, the period 1931–2015 was divided into two shorter periods: 1931–1973 and 1974–2015. We had chosen this approach because for the frequency analysis is recommended the length of the observation series $5T$ [12]. If $T = 50$ years, then a 250-member observation series is required for a reliable estimate of $Q_{50}$. Such a length of data series (AM) is practically absent. Therefore, the probability of a reliable estimate of T-year maximum discharge for short-range river basins is relatively low. In the case of the 50-year observation series, the probability of $Q_{100}$ is 39% and in the case of the 100-year series is 63% [13]. The exceedance probabilities of the annual peak discharges for two shorter periods of the Topľa River at Hanušovce nad Topľou according to the LPIII distribution are presented in figure 3 and values of some $t$-year maximum discharges are listed in table 2.
Figure 3. The exceedance probabilities of the annual maximum discharges according to LP III probability distribution, left: period 1931–1973 and right: period 1974–2015 on the Topľa River: Hanušovce nad Topľou.

Table 2. Comparison of the estimated QTmax for shorter periods on the Topľa River: Hanušovce nad Topľou

| Log-Pearson III | T [year] | 2 | 5  | 10 | 50 | 100 | 200 | 500 | 1000 |
|-----------------|---------|---|----|----|----|-----|-----|-----|------|
| P [%]           | 39      | 39 | 18 | 9.5| 9.5| 9.5 | 9.5 | 9.5 | 9.5  |

1931–1973

- QTmax [m³ s⁻¹]  | 143 | 198 | 257 | 427 | 519 | 627 | 797 | 949 |

K-S test p-value | 0.813 |

1974–2015

- QTmax [m³ s⁻¹]  | 125 | 180 | 239 | 408 | 499 | 602 | 760 | 899 |

K-S test p-value | 0.74 |

4.1.2. The effect of the seasonality on the T-year discharge estimation. For dividing the year into seasons, we proceeded from the analysis of the occurrence of floods and from the evaluation of the Topľa runoff regime during the year. In terms of the type of runoff regime, Topľa belongs to the highland-lowland area with rain-snow runoff with the culmination of river runoffs in the month of March, respectively April. In terms of the Topľa runoff regime, the measured data were divided into two seasons:

- Summer season is from May to October when peak discharges occur only from heavy rainfall.
- Winter season is from November to April when peak discharges occur by combining heavy rainfall in the form of snow and rain as well as snow melting in the area.

The statistical data series were supplemented with maximum discharges in the given season so that there are still 85 measurements per season. The exceedance probabilities of the annual peak discharges for season periods of the Topľa River at Hanušovce nad Topľou according to the LP III distribution are presented in figure 4 and values of some T-year maximum discharges are listed in table 3.
Figure 4. Exceedance probabilities of the maximum discharges according to Log-Pearson Type III probability distribution (LPIII), left: summer season and right: winter season on the Topľa River: Hanušovce nad Topľou

Table 3. Comparison of the estimated $Q_{T_{\text{max}}}$ for summer and winter seasons on the Topľa River: Hanušovce nad Topľou

| Log-Pearson III | T [year] | 2 | 5 | 10 | 50 | 100 | 200 | 500 | 1000 |
|-----------------|---------|---|---|----|----|-----|-----|-----|------|
|                 | P [%]   | 39| 18| 9.5| 2  | 1   | 0.5 | 0.2 | 0.1  |
| **summer**      | $Q_{T_{\text{max}}} \ [m^3 s^{-1}]$ | 68| 124| 194| 423| 555 | 718 | 975 | 1209 |
|                 | K-S test $p$ value | | | | | | | | 0.95 |
| **winter**      | $Q_{T_{\text{max}}} \ [m^3 s^{-1}]$ | 117| 172| 228| 372| 443 | 518 | 626 | 715  |
|                 | K-S test $p$ value | | | | | | | | 0.94 |

4.2. Estimation of the T-year maximum discharges using Peak over thresholds (POT)

4.2.1. Effect of the choice threshold level. This method assumes the choice of the threshold so that the number of elements of the statistical set $n > N$, where $N$ is the number of observation years. Defining threshold QPOT is one of the main disadvantages of this method because it is a more or less subjective process. The QPOT threshold at levels of a) 0.8 percentile and b) 0.93 percentile of the long-term average daily discharge were selected. The selected waves satisfy the condition of the independence and the average number of waves per year was 3.6 and 2.8. The number of peaks had a binomial probability distribution. Estimated T-year maximum discharges did not show significant differences for the selected thresholds or selected probability distributions. In our analysis, we selected Weibull, Gamma and Pareto2 theoretical probability distributions to simulate T-year maximum discharges using the POT method. Estimated T-year maximum discharges according to selected distributions and thresholds from mean daily maximum discharges $Q_{\text{maxPOT}}$ at Topľa river in Hanušovce nad Topľou (1931–2015) are presented in table 4.
Table 4. Estimated T-year maximum discharges according to selected distributions and thresholds from mean daily maximum discharges \( Q_{\text{maxPOT}} \) at Topľa river in Hanušovce nad Topľou (1931–2015)

| \( T \) /year | 2 | 5 | 10 | 50 | 100 | 200 | 500 | 1000 |
|-------------|---|---|----|----|-----|-----|-----|------|
| \( P \) [%]  | 39| 18| 9.5| 2  | 1   | 0.5 | 0.2 | 0.1  |

| \( Q_{\text{Tpot0.8}} \) [m\(^3\)s\(^{-1}\)] | 86 | 145 | 185 | 278 | 313 | 356 | 410 | 449 |
| \( Q_{\text{Tpot0.93}} \) [m\(^3\)s\(^{-1}\)] | 87 | 146 | 186 | 275 | 309 | 350 | 402 | 433 |

| \( Q_{\text{Tpot0.8}} \) [m\(^3\)s\(^{-1}\)] | 84 | 136 | 171 | 248 | 280 | 307 | 350 | 381 |
| \( Q_{\text{Tpot0.93}} \) [m\(^3\)s\(^{-1}\)] | 86 | 137 | 171 | 246 | 278 | 308 | 349 | 378 |

| \( Q_{\text{Tpot0.8}} \) [m\(^3\)s\(^{-1}\)] | 84 | 136 | 171 | 252 | 288 | 320 | 370 | 405 |
| \( Q_{\text{Tpot0.93}} \) [m\(^3\)s\(^{-1}\)] | 84 | 137 | 172 | 251 | 278 | 308 | 361 | 394 |

There were large differences between the T-year maximum flows estimated according to the POT method from the maximum mean daily discharges and the estimated T-year discharges from the maximum annual discharges (AM). At large rivers (e.g. Danube) where there is a slower change in discharges, such a significant difference in estimates may not occur [14]. Due to the fact that only annual peak wave discharges were available and the results obtained with the POT method from the maximum average daily discharges were relatively low, we proceeded to recalculate the estimated T-year discharges. The recalculation was performed using coefficients determined from regression relations: average daily flow - peak flow based on linear and polynomial dependence (Figure 5 a) - b)). The resulting recalculated values of the T-year maximum flows by the POT method are shown in Table 5.

Table 5. Recalculated estimated T-year maximum discharges according to selected procedure of the POT method at Topľa River: in Hanušovce nad Topľou (1931–2015)

| \( T \) /year | 2 | 5 | 10 | 50 | 100 | 200 | 500 | 1000 |
|-------------|---|---|----|----|-----|-----|-----|------|
| \( P \) [%]  | 39| 18| 9.5| 2 | 1 | 0.5 | 0.2 | 0.1 |

| \( Q_{\text{Tpot0.8}} \) [m\(^3\)s\(^{-1}\)] linear | 127 | 209 | 264 | 392 | 441 | 500 | 575 | 628 |
| \( Q_{\text{Tpot0.8}} \) [m\(^3\)s\(^{-1}\)] polynom | 125 | 204 | 262 | 410 | 469 | 546 | 648 | 725 |
| \( Q_{\text{Tpot0.93}} \) [m\(^3\)s\(^{-1}\)] linear | 129 | 210 | 265 | 388 | 435 | 492 | 564 | 606 |
| \( Q_{\text{Tpot0.93}} \) [m\(^3\)s\(^{-1}\)] polynom | 126 | 206 | 264 | 405 | 463 | 535 | 633 | 693 |

| \( Q_{\text{Tpot0.8}} \) [m\(^3\)s\(^{-1}\)] linear | 125 | 196 | 245 | 351 | 395 | 432 | 492 | 535 |
| \( Q_{\text{Tpot0.8}} \) [m\(^3\)s\(^{-1}\)] polynom | 122 | 192 | 242 | 360 | 413 | 459 | 535 | 593 |
| \( Q_{\text{Tpot0.93}} \) [m\(^3\)s\(^{-1}\)] linear | 127 | 198 | 245 | 348 | 392 | 434 | 490 | 530 |
| \( Q_{\text{Tpot0.93}} \) [m\(^3\)s\(^{-1}\)] polynom | 125 | 193 | 242 | 357 | 410 | 461 | 534 | 587 |

| \( Q_{\text{Tpot0.8}} \) [m\(^3\)s\(^{-1}\)] linear | 125 | 196 | 245 | 357 | 406 | 450 | 519 | 568 |
| \( Q_{\text{Tpot0.8}} \) [m\(^3\)s\(^{-1}\)] polynom | 122 | 192 | 242 | 367 | 426 | 482 | 572 | 639 |
| \( Q_{\text{Tpot0.93}} \) [m\(^3\)s\(^{-1}\)] linear | 125 | 198 | 246 | 355 | 392 | 434 | 507 | 553 |
| \( Q_{\text{Tpot0.93}} \) [m\(^3\)s\(^{-1}\)] polynom | 122 | 193 | 243 | 365 | 410 | 461 | 556 | 617 |
Figure 5. Regression between annual peak discharges $Q_{\text{max}}$ and annual mean daily maximum discharges $Q_{\text{max_dPOT}}$ on the Topľa River: Hanušovce nad Topľou (1931–2015) (left - liner dependence and right – polynomial dependence).

5. Conclusions

The first part of the paper deals with the estimation of the $Q_T$ from annual peak discharges on the Topľa River at Hanušovce nad Topľou (1931–2015). Our analysis indicates that the LPIII distribution is a suitable distribution for T-year discharge estimation with a higher return period. Estimation of flood magnitudes to be used as a basis to design the hydraulic structures and flood control management is therefore of crucial importance. Therefore, the paper also presented an estimation of the T-year maximum discharges by the AM method and analysed the effect of the time series length and seasonality (winter, summer) on the accuracy of T-year maximum discharges estimation. Results showed that not only the selection of the distribution function to estimate T-year discharges but also the processing of the statistical series affect the results of the estimation. The shorter periods showed higher estimations of the T-year discharges. The highest estimated values according to the LPIII distribution were achieved for the summer season. The lowest estimated value according to the LPIII distribution was achieved for the winter season.

In the second part of the paper, alternative POT method to estimate T-year maximum discharges was used. This method assumes the choice of the threshold so that the number of elements of the statistical set $n > N$, where $N$ is the number of observation years. Defining threshold $Q_{\text{POT}}$ is one of the main disadvantages of this method because it is a more or less subjective process. Another potential limitation of using the POT method may be input data. The statistical series to estimate the T-year maximum discharges should be included peak discharges of selected waves. Such values may not be available for older data series. Last but not least, the suitable choice of the theoretical probability distribution affects the estimation of the T-year maximum discharge. In our analysis, we selected Weibull, Gamma and Pareto2 theoretical probability distributions to simulate T-year maximum discharges using the POT method. From the view of the mentioned limitations, we focused on analysing their impact on the estimation of T-year maximum discharge by method POT. The results showed: that the $Q_{\text{POT}}$ threshold at levels of a) 0.8 percentile and b) 0.93 percentile of the long-term average daily discharge were selected. The selected waves satisfy the condition of the independence and the average number of waves per year was 3.6 and 2.8. The number of peaks had a binomial probability distribution. Estimated T-year maximum discharges did not show significant differences for the selected thresholds or selected probability distributions. At relatively small rivers like Topľa, there is a fast and relatively large increase of the discharge during the flood. The mean difference between the maximum daily discharges and the known peak discharges (AM) of selected waves was 46 m$^3$ s$^{-1}$. The maximum difference was e.g. 210 m$^3$ s$^{-1}$ in 1948 when $Q_d = 180$ m$^3$ s$^{-1}$ and $Q_{\text{max}} = 390$ m$^3$ s$^{-1}$. The results showed (as we assumed) a large difference between the T-year maximum discharges estimated according to the POT method from the maximum daily discharges and the AM method. Subsequently, the estimated T-year maximum discharges by the POT method was recalculated according to the regression relationship between known peaks and daily maximum discharges (a) linear and b) polynomial relationships. The results showed that...
estimated T-year maximum discharges, especially with a return period of T> 50, are comparable to the AM method.

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