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ESTIMATION OF DISCHARGE WITH LONG RETURN PERIOD USING HISTORICAL FLOOD RECORDS

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Records of historical catastrophic floods provide extremely valuable knowledge about the frequency of occurrence of such events on the rivers that do not have a series of discharge observations long enough, or observations are completely absent. In this paper we present knowledge about historical floods on the Teplica River in Sobotište and its catchment. Based on statistical processing of the series of maximum annual discharge from the water gauge Sobotište-Teplica, we present the impact of the inclusion of historical floods on the estimation of the *T-year* design discharge values.

KEY WORDS: historical floods, *T-year* values, LP3 distribution, Teplica River

Introduction

One of the most important tasks of hydrology is to determine the values of a certain hydrological phenomenon (precipitation, discharge, etc.) that are exceeded with a certain preselected probability. With increasing length of observed hydrological series and with development of statistical stochastic methods it is possible to refine estimates of design values for very low probabilities of occurrence (200- to 1000-years values).

The design discharge values are generally determined for *T=1-, 2-, 5-, 10-, 20-, 50-, 100-* years according to Technical Standard 3112–1:03 (MŽP, 2003). The Technical Standard does not include methods for the determination of the *200-, 500-* and *1000-*year discharge. It is very complicated to determine discharge that occur every 200 or 1000 years.

Several methods (statistical methods, rainfall-runoff models, etc.) can be used to extrapolate the measured series over several decades for the *200-, 500-* or *1000-*year period.

It is up to the investigator's experience and knowledge, which method will be used to determine *T*-year discharge (Kohnová and Szolgay, 2003; Stănescu, 2004; Kohnová et al., 2006a, b, 2016; Šipikalová et al., 2006; Pekár et al., 2012; Pekárová et al., 2013; Gaál et al., 2010a, b; Merz and Blöschl, 2008a, b; Dysarz, 2019).

The aim of this paper is to analyze the impact of the inclusion of historical floods in the series of annual maximum discharge on the example of the Teplica River at the water gauge Sobotište. Their inclusion results in more precise *T*-year values with a long return period as determined by the statistical method. This work follows the work of Mészáros et al. (2019).

Description of the Teplica River Basin

Teplica (formerly also Vrbovčianka, or Malina) springs in the Czech Republic in the village of Kuželov in the Biele Karpaty Mountains under the pass U Tři Kamenů at an altitude of 440 m a. s. l. The length of the stream is 26.78 km and the catchment area is 152.83 km^2 (Fig. 1). The river flows through villages Vrbovce, Sobotište, Kunov and town Senica, where is the mouth to the Myjava River at an altitude 183 m a. s. l. Between the villages Sobotište and Kunov is water reservoir, but water gauge in Sobotište is uninfluenced by this water structure.

In Sobotište, the level of the river at the time of normal discharge is 237 m a. s. l. The slope of the stream bed is relatively small and therefore meanders are formed. In the Sobotiše cadastral territory the banks of the stream are natural, only partially modified.

The most part of Teplica River Basin belongs to Biele Karpaty Mountains created by flysh rocks and covered by cambisols. The southwestern part belongs to Chvojnícka pahorkatina Upland covered by loess sediments and with luvisol soli type. To the Sobotište water gauge is 20% of area covered by forest. Mean annual rainfall total is from cca 850 mm in highest locations in the northern part of the basin to cca 600 mm in the southern part of the basin.

Data

In the basin of the Teplica River, there are located four water gauges of the state hydrological network of Slovak Hydrometeorological Institute (SHMI) – namely, in Vrbovce (Fig. 2 on the left), in Sobotište (Fig. 2 on the right), under the Kunov reservoir and in Senica. We used the annual maximum discharge from the Sobotište-Teplica water gauge provided by the SHMI. This gauge has the longest observation period and there are records of the historical floods on the Teplica River in Sobotište. To calculate the regional skew coefficient, we used a series of annual maximum discharge from water gauges that are in neighbouring river basins with similar physical-geographical characteristics, are unaffected and have an observation period longer than 40 years (Table 1).

The annual maximum discharge has been measured in the Sobotište water gauge since 1974 (Fig. 3). The series was supplemented with data from records of historical floods from 1902 and 1939. Sources of data about historical floods are in the chapter 5.2.

Methods

When determining *T*-year discharge by statistical methods from the series of maximum annual discharge Q_{max}, we can proceed in two ways:

1. Either we use different types of distribution functions and determine *T*-year discharge for each compliant distribution, or
2. We choose one type of distribution, use historical observations and try to regionalize the distribution parameters for the region.

Determination of T-year discharge based on different distribution functions

We consider the observed values of the investigated hydrological series to be a realization of a random variable. The basic task in determining *T*-year discharge is to find suitable distribution functions that accurately describe the random variable. Today various software can be used to find a suitable distribution function, e.g. Easy Fit software that includes over 50 types of distribution functions. Since the discharge are bounded by zero from the bottom, it is necessary to use the bottom bounded distributions. In Fig. 4. the histogram and 15

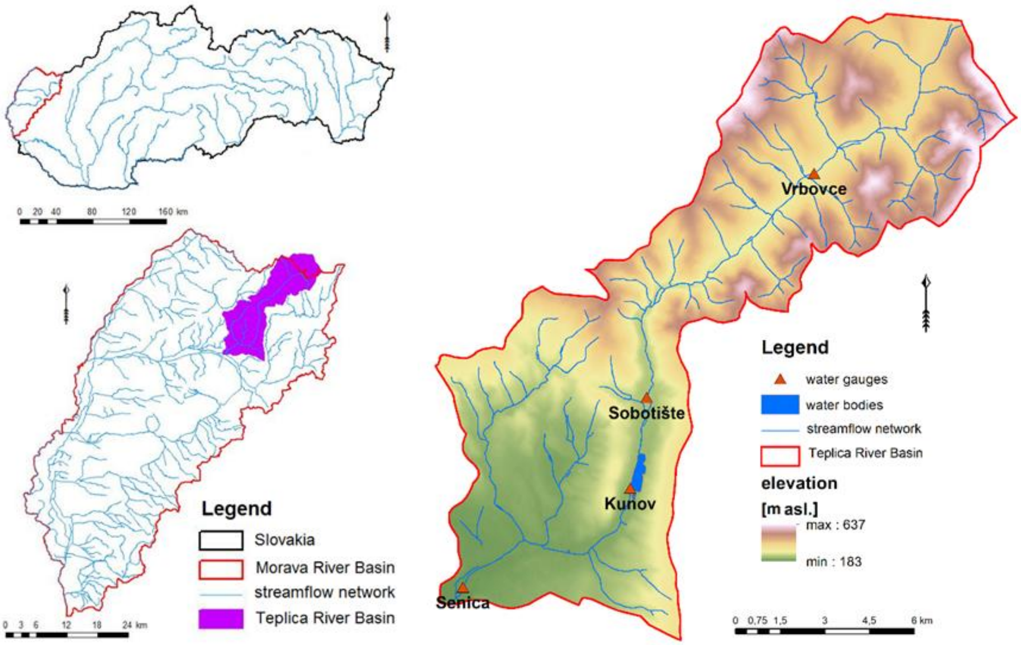

Fig. 1. Left up: Location of the Morava River Basin in Slovakia. Left down: The Teplica River Basin within the Morava River Basin and its streamflow network. Right: SHMI water gauge network and relief of the Teplica River Basin.

Table 1. Used water gauges with specified year of discharge measurement beginning and selected physical-geographical characteristics (Zítek et al., 1967; SHMI, 2017)

ID	gauge	river	discharge since	altitude [m a.s.l.]	forest cover [%]	basin shape	catchment area [km^2]	basin slope [°]
5010	Lopašov	Chvojnica	1969	272.70	40	0.25	31.13	2.27
5025	Sobotište	Teplica	1974	236.29	20	0.16	85.58	0.93
5020	Myjava	Myjava	1974	324.34	50	0.28	32.02	2.89
5030	Šaštín-Stráže	Myjava	1932	164.25	30	0.16	644.89	0.78

Fig. 2. Left: SHMI Vrbovce-Teplica water gauge in the valley of the Biele Karpaty Mountains. Source: Mészáros, January 2017. Right: SHMI Sobotište-Teplica water gauge. Source: Pekárová, February 2019.

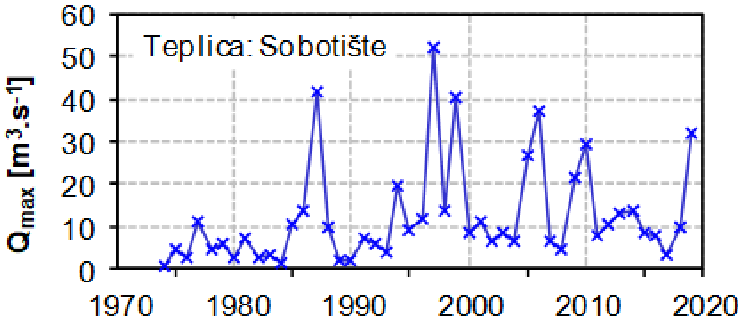

Fig. 3. Measured series of maximum annual discharge for hydrological years 1974–2018, deviations from moving averages in Sobotište-Teplica water gauge.

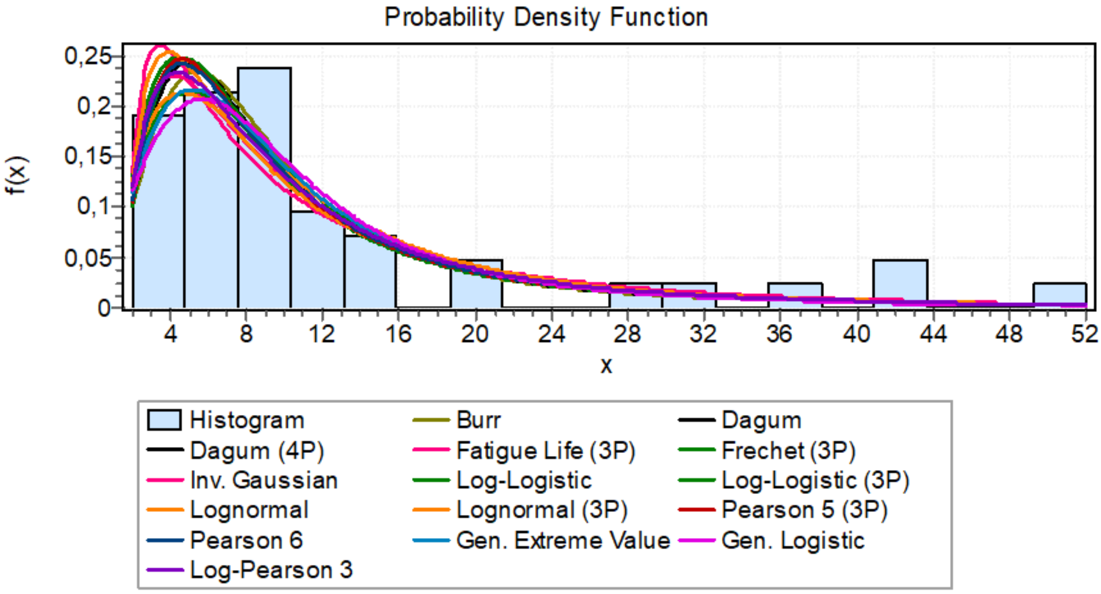

Fig. 4. Histogram and 15 probability functions of the annual maximum discharge of the Teplica River at the Sobotište water gauge.

probability functions of the maximum annual discharge Q_{max} of the Teplica River in the Sobotište water gauge for the period 1974–2018 are plotted. Using e. g. the fifteen best distribution functions calculate *T*-year discharge values. From these 15 values, the average, upper and lower estimates for each design discharge (e.g., *100-*, *200-* to *1000*-year discharge) are determined in the next step.

Determination of T-year discharge based on regionalization of parameters from one distribution function

In this work we use the methodology described in Bulletin 17B, which was published in the USA in 1981 and modified in 1982 at the Water Research Center of the University of Texas at Austin (IACWD, 1982).

According to this methodology, we test only one type of distribution, Log-Pearson III. type distribution (LP3), which is used to estimate extremes in many natural processes and is one of the most commonly used distributions in hydrology (Phien and Jivajirajah, 1984; Pilon and Adamowski, 1993; Griffis and Stendinger, 2009; Millington et al., 2011). The LP3 distribution has been used since 1976 in the USA (Koutsoyiannis, 2008). LP3 is also recommended by Stănescu (2004) to use this distribution to extrapolate regional curves in the Danube River Basin.

From the measured series of maximum annual discharge with a length about 80 years, we can afford to more accurately determine about *120*-year discharge. The author brings his own experience and estimates to the determination of *200-* or more year discharge. In any case, we must be aware that the determination of *1000*-year discharge is burdened by great uncertainty. While in determining the uncertainty of estimating design values based on the use of several types of distributions, essentially the error between estimates is determined, using one type of distribution determines the error resulting from the shortness and variance of the measured series.

The LP3 distribution is very flexible, it is a generalization of log-normal distribution and Pearson distribution. The use of one type of distribution makes it possible to estimate *T*-year discharge even in location without observation based solely on the parameters of distribution functions from neighbouring water gauge. It is possible to find the relationship of the skew coefficient on the water gauge altitude, or the catchment area, or the forest cover, or the runoff depth in the gauge. If we can find such a relationship, we can use the regional skew coefficient to refine this coefficient in gauges with short series of observations and thus improve the estimated *T*-year discharge value. We have found such a relationship along the Danube River and another in the Bela River Basin (Pekárová et al., 2018).

Historical floods

It is well known that extrapolation of data is very sensitive not only to the length of observations, but also to the inclusion of historical floods in the data series. Correct estimation of potential *T*-year discharge requires the inclusion of measured data series into the calculations, as well as the inclusion of historical data in the statistical processing of the series analyzed (Gaál et al., 2010a). Brazdil et al. (2006) studied historic hydrological materials to assess the threat of flooding in Europe. The estimation of uncertainty at the design discharge was examined for example by Merz and Thieken (2009), Merz et al. (2008a, b), or Rogger et al. (2012). Historical floods complement estimates the frequency of major floods and should therefore be included in the statistical analysis. Historical floods can also be used to assess the correctness of estimated *T*-year discharge, especially for long repetition times. If historical data are available, we can add them to the Q_{max} input set with the appropriate probability and specify the new distribution parameters.

Log-Pearson III. type distribution

The LP3 distribution is a three-parameter Gamma distribution with a logarithmic transformation of a random variable (Naghavi et al., 1990). Pearson distribution probability density function III. type is:

$$f(X|\tau,\alpha,\beta) = \frac{\left(\frac{X-\tau}{\beta}\right)^{\alpha-1}\exp\left(-\frac{X-\tau}{\beta}\right)}{|\beta|\Gamma(\alpha)} \tag{1}$$

$$\frac{X-\tau}{\beta} \geq 0,$$

where:

τ – location parameter;
α – slope parameter;
β – scaling parameter;
$\Gamma(\alpha)$ – Gamma function, given by:

$$\Gamma(\alpha) = \int_0^\infty t^{\alpha-1}\exp(-t)dt. \tag{2}$$

Random variable Q_{max} has LP3 distribution, if random variable X

$$X = \ln Q_{max}, \text{ or } X = \log Q_{max} \tag{3}$$

has Pearson III. type distribution (Decadal logarithm will be used in this paper).

Q_{max} input data requirements

The basic assumptions for the application of frequency analysis of the maximum annual Q_{max} series are as follows:

1. The series of maximum annual discharge shall be statistically independent and random;
2. Q_{max} measurements are stationary with respect to time (data series homogeneity);
3. Statistical characteristics of the measured data Q_{max} represent past, present and future.

Estimation of parameters of theoretical Log-Pearson III. type distribution

The method of moments uses the logarithms of flood flows to estimate the distribution parameters. The first three sample moments are used to estimate the LP3 parameters. These include the mean ($\hat{\mu}$), standard deviation ($\hat{\sigma}$), and skewness coefficient ($\hat{\gamma}$). If only systematic data are available, with no historical information, the mean, standard deviation and skewness coefficient of station data may be computed using the following equations:

$$\hat{\mu} = \frac{1}{n}\sum_{i=1}^{n} X_i \tag{4}$$

$$\hat{\sigma} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(X_i - \hat{\mu})^2} \tag{5}$$

$$\hat{\gamma} = \frac{n}{(n-1)(n-2)\hat{\sigma}^3}\sum_{i=1}^{n}(X_i - \hat{\mu})^3, \tag{6}$$

where:
n – number of flood observations Q_{max} series
(ˆ) – represents a sample estimate.

Regional skew coefficient Gr

There is a relatively large uncertainty when estimating the skew coefficient *G* from one water gauge. In series with short observation times, this moment is extremely sensitive to extreme events. In order to better estimate this coefficient for a given river basin, the skew coefficient *G* calculated from one gauge can be combined with the regional coefficient G_r.

If the regional skew coefficient G_r and the skew coefficient *G* from one gauge differ by more than 0.5; the input data and the physical-geographical characterristics of the river basin shall be carefully examined. Depending on the length of the observation, the greater weight can be given by the coefficient *G* calculated from the water gauge. Large deviations between regional coefficients and gauge coefficient may indicate that the characteristics at a given water gauge differ from those of the region.

On the basis of parameters of distribution functions, it is possible to estimate discharge in neighbouring river basins without observation. The estimated skew coefficient *G* of this distribution can be used for regionalization and can then be correlated with the physical-geographical characteristics of the river basin (Pekárová et al., 2018).

Results

Series of maximum annual discharge at Sobotište-Teplica water gauge.

In the first step we estimated the parameters of LP3 distribution line from the short series 2002–2018 for Sobotište-Teplica water gauge (Fig. 5 up). The skew coefficient G_s was 0.12 In the second step, we estimated the distribution curve for the series of whole observation period (Fig. 5 middle). The skew coefficient *G* was 0.07. A comparison of the graphs in Figure 5 up and in the middle shows that the extension of the range slightly increased the estimate of the *1000*-year discharge while at the same time substantially approaching the limits of 5 and 95% of the confidence limits. In Figure 5 in the middle, we can also notice two outlying values of low maximum annual discharge. In the third step we removed outliers from the series of observations as we are interested in the most accurate estimation of the upper extremes (Fig. 5 down). This step leads to *G* with value 0.27.

The regional skew coefficient G_r=0.18 was determined as the arithmetic mean of the coefficients *G* from the Lopašov-Chvojnica, Myjava-Myjava, Šaštín-Stráže-Myjava and Sobotište-Teplica water gauges. These gauges are located in the region based on similar physical-geographical characteristics *M.2 Basins of the left-sided tributaries of Moravia above Myjava* (MŽE, 2003).

Historical floods on the Teplica River

Since the historical floods in the Morava River Basin in the summer of 1997 and 1999, several extreme flood situations have occurred in the Slovak part of the Morava River Basin. These are linked to climate change. But in the history of the region, extreme floods with catastrophic consequences have also occurred in the past.

- The publication of P. Brezina (2017) lists the historical floods in Sobotište from 1630 on page 71. The three largest floods occurred in August 1672, in 1820 and in June 1902. From the flood of 5 June 1902 the house no. 310 retained the flood mark (Fig. 6).
- In the History of the Catholic Parishes of Myjava and Turá Luka, there is a mention of the catastrophic flood of 8 June 1775: "During his time in Myjava, after a storm June 8, 1775, a tragic flood came. For this reason, in December 1784 Myjava received support for the regulation of the river, thanks to which a river bed in the area of today's city was excavated".
- In the chronicle of the town Senica for the years 1936–1954 we found information about the floods on the Teplica River (there Vrbovčianka), 15 May 1939 (p. 169), 9 July 1943 (p. 202) and 30 April 1953 (p. 373).

River bed changes in the center of Sobotište village can be seen in Figure 7.

Supplementing historical floods in the skew coefficient estimation on the example on Teplica in Sobotište

Based on the field survey of the height of the flood mark from 1902 in Sobotište (the level in 1902 was 84.5 cm higher than the level of the 1997 flood), we estimated the maximum discharge from the 1902 flood on 80 $m^3 s^{-1}$ (Fig. 8).

We estimated the discharge for the flood in 1939 on the basis of historical records at 40 $m^3 s^{-1}$. We added these values to the calculation when estimating the skew coefficient G_h of theLP3 distribution including historical floods (Fig. 9).

The skew coefficient changed to 0.33. The resulting *T*-year discharge is shown in Table 2. From the values in the table, we can see that the uncertainty of the determination of 2*00*- to *1000*-year discharge values is still very high despite a thorough statistical analysis.

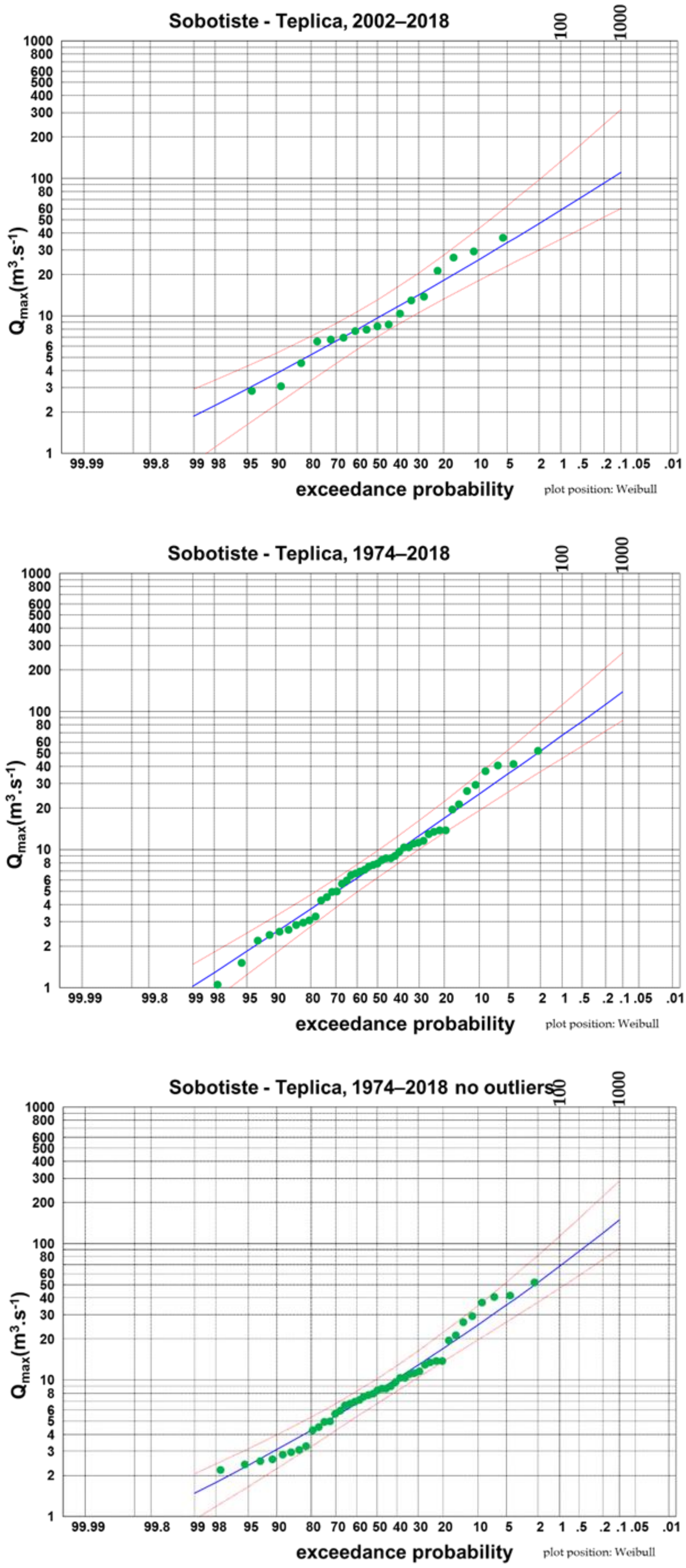

Fig. 5. *Theoretical Log-Pearson III. type distribution curve of maximum annual discharge series from the water gauge Sobotište-Teplica, 5% and 95% confidence intervals, short period 2002–2018 – up; whole period 1974–2018 – middle; period 1974–2018 without outliers – down.*

Fig. 6. Location of the flood mark from June 5, 1902 in Sobotište, level of flood in 1902 and 1997.

1938 1987

1997 2019

Fig. 7. Development of built-up area and bed of the Teplica River in the centre of the Sobotište village and historical floods. Source: Brezina (2017), author.

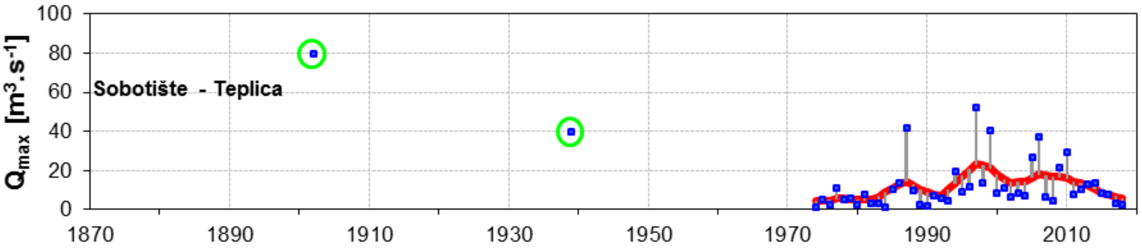

Fig. 8. Example of measured series of the maximum annual discharge (per hydrological year), deviations from moving averages, historical floods 1902 and 1939 on Teplica at Sobotište water gauge.

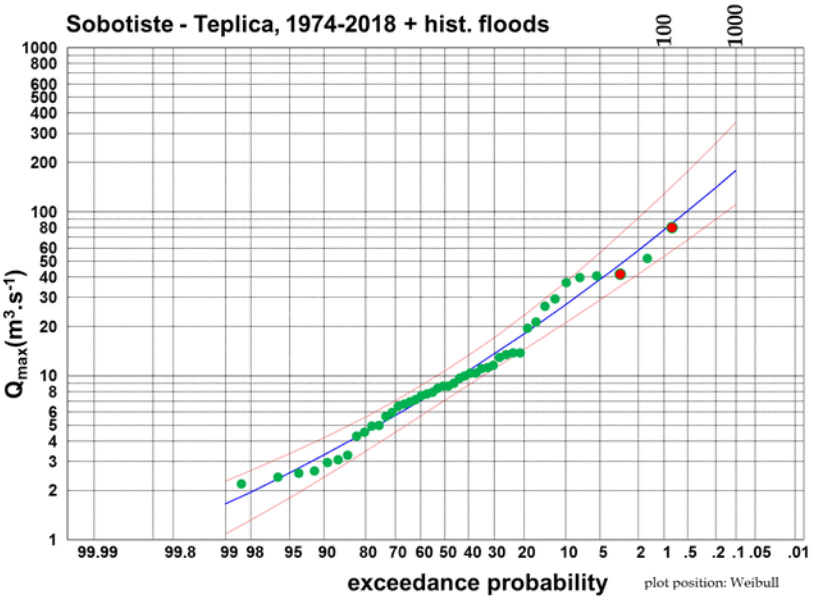

Fig. 9. Theoretical Log-Pearson III. type distribution line of maximum annual discharge series including historical floods from the water gauge Sobotište-Teplica, 5% and 95% confidence intervals.

Table 2. Estimated *T*-year discharge *Q* [m^3 s^{-1}] and specific runoff q [l s^{-1} m^2] at the water gauge Sobotište-Teplica with inclusion of historical floods, 5% and 95% confidence intervals

ID	gauge		*Q100*	*Q200*	*Q500*	*Q1000*	*q100*	*q200*	*q500*	*q1000*
5025	Sobotište	*T*-year	77	101	141	179	897	1176	1642	2085
		5%	128	176	263	350	1491	2050	3063	4077
		95%	53	67	90	111	617	780	1048	1293

Conclusion

In this paper we presented one of the methods for estimation of discharge with long return period. We used Log-Pearson III. type distribution, which contain parameter skewness coefficient. This parameter is related to physical-geographical characteristics of catchment and could be regionalised. So it is possible to use regional skewness coefficient to refine distribution and reduce uncertainty in discharge design values.

Estimation of discharge design values with long return period (*200-, 500- to 1000-year*) from short series of observations (cca 50 years) is burdened by high uncertainty. That is the reason why it is necessary to search as much information about historical floods in individual locations. An important role in reducing the uncertainty of the determination of these design values by statistical methods is played by flood marks installed directly on historical buildings near rivers. Assuming there were no significant changes in the terrain (bed regulation, new buildings near the river), it is possible to estimate the maximum discharge based on the flood mark height.

Based on the historical flood mark in the Sobotište village dated June 5, 1902, we estimated the maximum discharge of this flood on the Teplica River at 80 m^3 s^{-1}. This value and the estimated value of the 1939 flood were entered into the calculation of the design values using the theoretical LP3 distribution. After prolonging the series of observations, removing outliers, recalculating according to the regional skewness coefficient and then including historical floods, we achieved a narrowing of the design values range. On the Teplica River at water gauge Sobotište we estimated discharge with return period 1000 years in range between 111 and 350 m^3 s^{-1} with mean value 179 m^3 s^{-1}.

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