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IDENTIFICATION AND CLASSIFICATION OF SERBIA'S HISTORIC FLOODS

Abstract: River flooding in Serbia is a natural phenomenon which largely exceeds the scope of water management and hydraulic engineering, and has considerable impact on the development of Serbian society. Today, the importance and value of areas threatened by floods are among the key considerations of sustainable development. As a result, flood protection techniques and procedures need to be continually refined and updated, following innovations in the fields of science and technology. Knowledge of high flows is key for sizing hydraulic structures and for gauging the cost-effectiveness and safety of the component structures of flood protection systems. However, sizing of hydraulic structures based on computed high flows does not ensure absolute safety; there is a residual flood risk and a risk of structural failure, if a flood exceeds computed levels. In hydrological practice, such floods are often referred to as *historic/loads.* The goal of this paper is to present a calculation procedure for the objective identification of historic floods, using long, multiple-year series of data on high flows of natural watercourses in Serbia. At its current stage of development, the calculation procedure is based on maximum annual discharges recorded at key monitoring stations of the Hydro-Meteorological Service of Serbia (HMS Serbia). When applied, the procedure results in the identification of specific historic maximum stages/floods (if any) at all gauge sites included in the analysis. The probabilistic theory is then applied to assess the statistical significance of each identified historic flood and to classify the historic flood, as appropriate. At the end of the paper, the results of the applied methodology are shown in tabular and graphic form for various Serbian rivers. All identified historic floods are ranked based on their probability of occurrence (i.e., return period).

Key words: historic flood, reference high flow, outlier, statistical significance, probability of occurrence, return period.

Извод: Поплаве у Србији су природна појава која у великој мери превазилази обим управљања водама, и има значајан утицај на развој друштва у Србији. Данас, значај и вредност области угрожених поплавама представљају један од кључних разматрања одрживог развоја. Као резултат тога, технике и процедуре за заштиту од поплава треба да се стално усавршавају, пратећи достигнућа у области науке и технологије. Познавање високих вода је кључ за димензионирање хидротехничких објеката и за изражавање економичности и сигурности компонената структура система заштите од поплава. Међутим, уколико одређивање величине хидротехничких објеката на основу рачуна на бази високих вода не обезбеде апсолутну сигурност, постоји ризик од поплава. У хидролошкиој пракси, ове поплаве често називају историјским поплавама. Циљ овог рада је да прикаже поступак рачунања у циљу идентификације историјских поплаве, користећи дугогодишње низове података о високим водама природних водених токова у Србији. У садашњем стадијуму развоја, поступак се заснива на максималним протицајима забележеним у станицама хидрометеоролошке службе у Србији (ХМС Србија). Резултати у идентификацији специфичних историјских максималне поплаве на свим станица укључени су у анализу. Теорија вероватноће је затим примењена како би се проценила статистичка значајност сваке од идентификованих историјских поплава и као и адекватно класификовала. На крају рада, резултати примењене методологије су приказани у табеларно и графички за различите реке Србије. Све

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идентификоване историјске поплаве су рангиране на основу вероватноће појављивања (односно, повратном периоду).

Кључне речи: историјске поплаве, високе воде, статистичка значајност, вероватноћа појављивања, повратни период.

Introduction

In the water management and hydraulic engineering practice, the term „high flow" refers to a state of the water regime where the stage (or discharge) of a river rises and causes the river to overtop its main channel and flood the surrounding land. This increase in water level (or discharge) is relatively rapid but it declines gradually after it has reached its peak. The graphic representation of this occurrence is known as a flood wave hydrograph. Both terms are synonymous to „flood". Hydrologic research of floods throughout the world has so far included the study of basic quantitative flood characteristics/parameters: flood wave peak; flood wave volume; and hydrograph rise, decline (retardation), and base times; and of derived quantities such as precipitation „residence" time in the watershed, concentration times, and the like. Research and analysis rely on data recorded at select hydrologic stations.

Calculation techniques and methods are generally based on specific applications of mathematical statistics and the theory of probability, which assume that recorded flood hydrograph parameters are random variables which adhere to some theoretical law of distribution. Calculations of this nature require long time series of data. In cases where available series were not long enough for an appropriate application of mathematical statistics and the theory of probability (where the monitoring sites were not sufficiently studied from a hydrologic perspective), procedures based on establishing an „analogy" with hydrologically-studied monitoring sites were applied. For such an approach, basic postulates of physical and geographical similarities of studied watersheds need to be satisfied. If a monitoring site, or watershed, has not already been adequately studied from a hydrologic perspective, methods derived based on regional (spatial) analyses of all flood hydrograph parameters under consideration are used, or the unit hydro-graph theory is applied. Empirical methods are also used, based on simplified modeling of the genetic runoff formula, and the parameters for these methods are determined based on data obtained from hydrologically-studied monitoring sites.

The ensuing text focuses on the identification of registered events whose probability of occurrence is low (i.e., the extraction of„historic" events), and the analysis of such events which considerably exceed highest recorded levels seen during multiple-year monitoring and measurement of the flood wave hydrograph parameter under consideration. At this stage, the flood wave peak was selected as one of the most important elements which characterize a flood. The methodology can also be used for other flood hydrograph parameters, and especially for analyses of flood wave volumes and time characteristics: hydrograph rise, decline and base.

The analyzed area is the territory of the Republic of Serbia, excluding the Autonomous Province of Kosovo and Metohija. Monitoring stations which control catchment areas from 84 km^2 (Donja Šatornja MS on the Jasenica River) to 525009 km^2 (Pančevo MS on the Danube River) are included in the analysis. As such, a wide range of catchment areas have been studied, which increases the value of the analyses and the applicability of their results in practice.

Methodology for the identification of historic events

Testing of historic events

In hydrological practice, historic events are events which, in an uninterrupted declining (rising) series (time series), considerably exceed (deviate from) the subsequent, neighboring values for the event under consideration. The Pilot and Harvey test is generally used to obtain an objective identification of historic events (outliers) under extreme hydrologic conditions (floods and droughts). The assumption is that quantitative characteristics of these conditions adhere to the Log-Pearson III law of probability distribution. Under such circumstances, the upper and lower limits for the outliers are computed using the following formulas (1), (2):

• Upper limit

$$Y_H = Y_{av} + K_N S_y \tag{1}$$

• Lower limit

$$Y_L = Y_{av} - K_N S_y \tag{2}$$

(these equations apply if -0.4> C_{sy} >0.4),

where:

YH – log of the value of the upper limit of the outlier ;

YL – log of the value of the lower limit of the outlier ;

Y_{AV} - average value of the time series Y ;

Y = log X

X – basic time series ;

S_y - standard deviation of the time series Y;

C_{sy} - coefficient of asymmetry of the time series Y;

KN – frequency factor (critical value) for the risk coefficient ά = 10%

N – total number of members for the Y series for which statistical parameters will be calculated.

The frequency factor, K_N, is computed using the formula (3):

$$K_N = -3.6220 + 6.2844 N^{0.25} - 2.49835 N^{0.5} + 0.491436 N^{0.75} - 0.037911 N \tag{3}$$

The historic flood identification procedure itself involves a comparison of empirical distribution functions with defined outlier limits. If any empirical point falls outside the defined (upper or lower) limit, then such a point, whose probability is 1- a = 0.90, or 90%, is deemed to represent a historic event.

Calculations of statistical parameters and the probability of a historic event

If a historic event occurs, calculated statistical parameters do not reflect the actual characteristics of the process being analyzed. They must, therefore, be adjusted based on whether the historic even occurred during a monitoring period or not, assuming that the random variable X adheres to the Parson III, or Log Pearson III, law of distribution. In the case of a historic flood, empirical distributions are calculated separately, depending on whether the historic maximum occurred during the monitoring period or not.

If a historic maximum occurs outside an observation period, n, and if it is not exceeded during a longer period of time, N, then the empirical probabilities of an orderly (declining) total data series $\mathbf{P_i}$ (i = 1,2,3,......, n+1) are computed using the formula (4):

P1 = 1/(N+1), P2=1/(n+1), P3=2/(n+1), P4 = 3/(n+1),…..,Pn+1=n/(n+1) (4)

If two historic events have occurred, one during the monitoring period n, and the other outside that period, and neither has been exceeded during the longer period of time N, then empirical probabilities of the orderly series P_I are computed based on the formula (5):

P1=1/(N+1), P2=2/(N+1), P3=3/(n+1), P4=4/(n+1),..., Pn+1=n/(n+1) (5)

If the random variable X adheres to the **Pearson III** law of distribution, then adjusted statistical parameters for a single historic maximum outside the monitoring period are computed using the formulas (6), (7), (8):

- **Average value -** $X_{av,N}$

$$X_{av,N} = \frac{\left[X_N + (N-1)\sum_{i-1}^{n} \frac{X_i}{n}\right]}{N} \tag{6}$$

where :

X_N is the value of the historic event – random variable X, which has not been exceeded during the time period N, and

X_i are values of the members of the basic data series for the monitoring period n.

- **Coefficient of variation -** $C_{v,N}$

$$C_{v,N} = \sqrt{\frac{1}{N-1}\left[(k_N - 1)^2 + \frac{N-1}{n}\sum_{i-1}^{n}(k_i - 1)^2\right]} \tag{7}$$

where:

$k_N = \frac{X_N}{X_{av,N}}$ is the value of the modules coefficient for the historic event,

$k_i = \frac{X_i}{X_{av,N}}$ is the modules coefficient of therandom variable X during the monitoring period.

- **Coefficient of asymmetry -** $C_{s,N}$

$$C_{sN} = \frac{N}{(N-1)(N-2)C_{v,N}^3}\left[(k_N-1)^3 + \frac{N-1}{n}\sum_{i-2}^{n}(k_i-1)^3\right] \tag{8}$$

If there are two historic maximums, one during and the other outside the monitoring period, then statistical parameters are computed using the following formulas (9), (10), (11):

- **Average value -** $X_{av,N}$

$$X_{av,N} = \frac{\left[X_N + X_{N-1} + (N-2)\sum_{i-2}^{n}\frac{X_i}{n}\right]}{N} \tag{9}$$

- **Coefficient of variation -** $C_{v,N}$

$$C_{v,N} = \sqrt{\frac{1}{N-1}\left[(k_N-1)^2 + (k_{N-1}-1)^2 + \frac{N-2}{n-1}\sum_{i=2}^{n}(k_i-1)^2\right]} \tag{10}$$

- **Coefficient of asymmetry -** $C_{s,N}$

$$C_{s,N} = \frac{N}{(N-1)(N-2)C_{v,N}^3}\left[(k_N-1)^3 + (k_{N-1}-1)^3 + \frac{N-2}{n-1}\sum(k_i-1)^3\right] \tag{11}$$

If a historic maximum occurs within or outside a time series which adheres to the **Log-Pearson III** law of distribution, the following procedure is used to adjust the statistical parameters:

The **weight coefficient** - W is determined based on the number of events which fall outside the outlier limits, using the formula (12):

$$W = \frac{N-Z}{n+L} \tag{12}$$

where:

Z is the number of historic maximums,

L is the number of lower extremes, which fall outside the lower outlier limit.

The adjusted values of the statistical parameters, when there are upper and lower extremes, are determined using the log values of the basic random variable X (or using the random variable Y), as follows:

• **Average values -** Y_L^*

$$\overline{Y_L^*} = \frac{W\sum_{i=1}^{n} Y_{i,L} + \sum_{j=1}^{Z} Y_{j,L}}{N - WL} \tag{13}$$

• **Variance -** $\left(S_L^*\right)^2$

$$\left(S_L^*\right)^2 = \frac{W\sum_{i=1}^{n}\left(Y_{i,L} - \overline{Y_L^*}\right) + \sum_{j=1}^{Z}\left(Y_{j;L} - \overline{Y_L^*}\right)^2}{N - WL - 1} \tag{14}$$

• **Coefficient of asymetry -** G_L^*

$$G_L^* = \frac{N - WL}{(N - WN - 1)(N - WL - 2)}\left[\frac{W\sum_{i=1}^{n}\left(Y_{i,L} - \overline{Y_L^*}\right)^3 + \sum_{j=1}^{Z}\left(Y_{j,L} - \overline{Y_L^*}\right)^3}{\left(S_L^*\right)^3}\right] \tag{15}$$

Empirical probabilities are calculated using the expression (16):

$$P = \frac{m^*}{N+1} \tag{16}$$

with:

$m^* = m$ for $1 \le m \le Z$

$m^* = Wm - (W-1)(Z+0.5)$ for $(Z+1) \le m \le (Z+n+L)$

where:

m^* is the weighted sequential number,
m is the sequential number of the data point in the series

The adjusted values of the statistical parameters, as defined above, are used to calculate the **theoretical probabilities** (or **return periods)** of recorded historic events, based on
Pearson III – $\mathbf{P(X_N)}$ or Log-Pearson III – $\mathbf{P(X_N=10^{(YL)})}$:

$$T(X_N) = \frac{1}{P(X_N)} \quad \text{(in years).}$$

Practical application of the historic flood identification methodology within Serbia

The historic event identification methodology was developed to identify historic floods in Serbia. As shown, absolute maximum values of flood wave peaks during the year were used to represent the quantitative characteristics of the floods. The most recent data series for the maximum annual discharges of various rivers were obtained from HMS Serbia for 134 hydrologic monitoring stations which produced sufficiently long time series (in this case for the period from the time the station was commissioned through the year 2006).

The flood wave identification methodology described above was applied to these time series. The upper and lower limits for the outliers were calculated based on the original time series for the gauge sites. The results showed that only seven monitoring stations had one outlier each, on five rivers: the Luznica and the Vlasina in 1988, the West Morava in 1965, the Ibar in 1979, and the Ribnica in 1996. The absolute maximum discharges reported by all other monitoring stations in Serbia were within the outlier limits, suggesting that there is a 90% probability that these rivers had no historic floods during the multiple-year period being analyzed. Table 1 shows the rivers and respective monitoring stations which recorded historic floods, including flood characteristics and dates.

Table 1. Summary of Serbia's historic floods and their statistical significance

	River	Hydrologic monitoring station	Primary characteristics of historic flood			
			Q (W/s)	Date	T(year)	P (%)
1	Luznica	Svodje	488	26.6.1988	500	0.2
2	West Morava	Kratovska Stena	1250	14.5,1965	200	0.5
3	Vlasina	Vlasotince	1200	27.6.1988	200	0.5
4	Vlasina	Svode	580	27.6.1988	125	0.8
5	Ibar	Lopatnica Lakat	1520	19.11.1979	100	1.0
6	West Morava	Milocaj	1330	14.5.1979	100	1.0
7	Ribnica	Pastric	418	17.4.1996	77	1.3

Statistical parameters were adjusted and new probability distribution functions were calculated applying the Log-Pearson III law for all the time series for which a historic event was identified. The probability of occurrence (or the return period) of the floods was determined based on the adjusted distribution functions, as shown in Table 1. An example of the calculation of the probability of recurrence of the identified historic flood on the Luznica River at the Svodje MS is shown in Figure 1.

These results show that there were four historic floods during the analyzed time period, from 1946 to 2006. The most statistically-significant flood occurred in June 1988 on the Vlasina River and its right tributary - the Luznica. A 500-year flood wave on the Luznica, in combination with a 125-year flood wave on the Vlasina at the Svodje monitoring site, caused a 200-year flood wave along the downstream section of the Vlasnica River, at the Vlasotince MS. The second statistically-significant flood occurred on the upper West Morava in May 1965, with return periods between 200 and 100 years. A 1979 flood on the Ibar River reached the 100-year flood level. The fourth identified historic flood occurred on the Ribnica River in April 1996; its return period was 77 years.

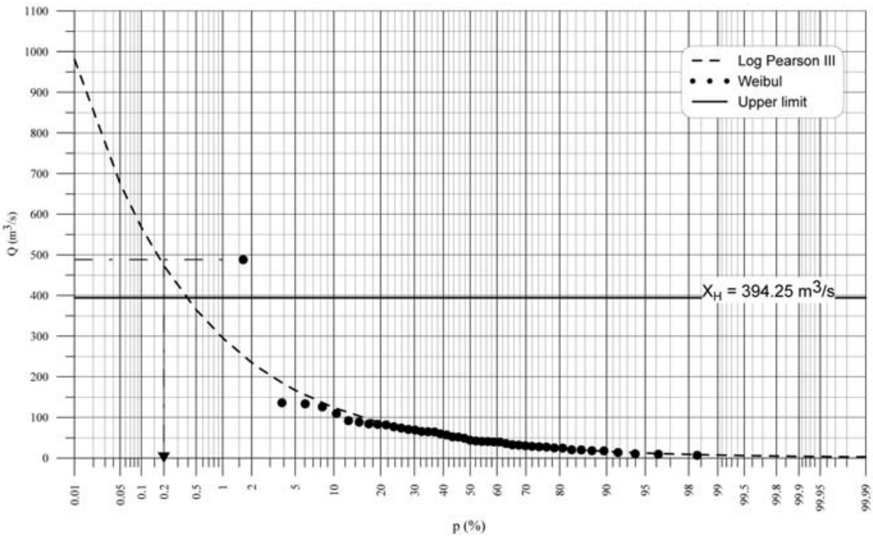

Figure 1. Distribution function of the maximum annual discharges of the Luznica River at the Svodje MS, showing outlier limits and the position of the identified historic flood.

Conclusion

The newly-developed methodology allows for an objective assessment of which floods can be deemed to have been historic events during a multiple-year period. However, the inclusion of such events in a probabilistic assessment of return periods can produce serious estimation errors, primarily with regard to statistical parameters, but also with regard to probability quintiles. For this reason statistical parameters should be adjusted if a historic event does occur, using the described procedure, and then the adjusted values should be used to calculate the probabilities of occurrence for the time series in question.

This methodology was applied for Serbia and showed that there were only four historic floods during the analyzed multiple-year period. All other floods were considered to not have been historic, which suggests that floods of this magnitude are highly probable and will, with similar levels of statistical significance, recur in the future.

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ИДЕНТИФИКАЦИЈА И КЛАСИФИКАЦИЈА ИСТОРИЈСКИХ ПОПЛАВА У СРБИЈИ

Нова методологија омогућава објективну процену поплава које се могу сматрати историјским догађајем током више година. Међутим, укључивање таквих догађаја у процену вероватноће може да произведе озбиљне грешке е, пре свега у вези са статистичким параметрима. Из тог разлога статистичке параметре треба а затим користећи описани поступак, израчунати вероватноћу појаве. Ова методологија је примењена за Србију и показано је да је било само четири историјске поплаве током анализираног периода. Све остале поплаве се сматра да нису били историјске, што сугерише да поплаве оваквих размера веома је вероватно и да ће, са сличним нивоима статистичка значајности, понављати у будућности.