ГОДИШНИК НА УНИВЕРСИТЕТА ПО АРХИТЕКТУРА, СТРОИТЕЛСТВО И ГЕОДЕЗИЯ
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DESIGN FLOOD HYDROGRAPH FOR FLOOD PROTECTION SYSTEMS

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ABSTRACT

Design hydrograph determination for flood protection system plays a key role in terms of economy and risk of flooding. The first part of the paper describes the procedure for defining theoretical hydrograph using the "limited runoff intensity" (LRI) method for different probabilities of occurence and the bivariate probability distribution function for determining coincidence of various hydrograph parameters – PROIL model (i.e. maximum anual flow and flood wave volume in the same calendar year). In the second part the criteria for adopting the optimal combination of parameters for defining the (design) theoretical hydrograph depending on the type and purpose of the hydraulic structure, is presented.

The results, theoretical hydrographs for different probabilities occurrence: 0,1, 1,0, 2,0, 5,0 and 10,0%, are presented for the Oršava Hydrological Station at the Danube River in Romania.

1. Introduction

The flood hydrograph is a flow function of time at particular profile of the river. The hydrograph shape depends on the physical and geographical factors, then the topographic characteristics of the basin (drainage area shape and cathment slope), as well as the climatic factors of the catchment area. Above all, the shape of such a hydrograph is affected by the duration and the intensity distribution of the precipitation [2].

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The Design Flood Hydrograph (DFH) represents the key parameter for hydrotechnical structures design and reaching economic and safety benefits. It is necessary in flood protection system design. That is why it has the key role in hydrological analysis.

The basic parameters of flood hydrograph which should be taken in consideration in practice are maximum hydrograph ordinate, flood wave volume, shape and duration. For structures design, or their capacity estimation, authoritative is the maximum flow, then the duration and the flood volume.

The fact is that most of the methods in the hydrological practice used in both hydrological gauged and ungauged basins define theoretical hydrographs through its two basic parameters, maximum ordinate and volume of the flood wave, and for the same, predefined probability of occurrence – *p* (%), and/or return period – *T* (year). This means that it is assumed that there is a very strong (one hundred percent) coincidence, with a correlation coefficient of R = 1,0 in the basic hydrograph parameters, maximum ordinate and the volume of the flood, which is not realistic in practice.

2. Materials and Methods

To define the basic parameters of the theoretical flood hydrographs as well as their shapes, the “limited runoff intensity” method (LRI) is used. The selection of a combination of characteristic parameters, which define the theoretical hydrographs, is obtained from a pre-defined two-dimensional probability distribution of occurrence of basic parameters – peak and volume. Hydrograph shape parameters are determined based on observed flood waves on the considered hydrological station. In this paper, methods described below are applied on the Oršava Gauging Station at the Danube River in Romania, with catchment area of 576,232 km^2 and gauging period from 1901 to 2007.

2.1. Limited Runoff Intensity Method

The LRI method is based on rational method and described in more detail in literature [3].

The maximum flow of probability of occurence $p(Q_{max,p})$ is computed from the formula:

$$Q_{max,p} = 16,67 \cdot \bar{i}_{max,p}(\tau) \cdot \phi \cdot F \tag{1}$$

where: $Q_{max,p}$ – maximum hydrograph ordinate of probability p in m^3/s,

$\bar{i}_{max,p}(\tau)$ – maximum average rainfall intensity of design rainfall duration τ,

φ – total runoff coefficient,

F – catchment area in km^2,

τ – time of concentration, in minutes.

The time of concentration τ_p, is obtained from the relationship with the maximum hydrograph ordinate $Q_{max,p}$ in the form of:

$$\tau_p = \frac{16.67 \cdot K \cdot L}{a \cdot I_a^{1/3} \cdot Q_{max,p}^{1/4}} \tag{2}$$

where: τ_p– time of concentration in minutes,

K – rising to falling limb time ratio,
α – coefficient dependent on riverbed roughness and weighted channel slope,
L – main stream length in km,
I – weighted channel slope in ‰.

The flood wave volume is computed from the formula:

$$W_p = 1000 \cdot h_p \cdot F \tag{3}$$

where: h_p – runoff layer (mm).

The flood hydrograph ordinates $Q_{p,i}$ (i = 1, 2, 3, ..., T_B, T_B – hydrograph time base) are calculated according to the Goodrich law of distribution:

$$Q_{p,i} = Q_{\max,p} \cdot 10^{-a\frac{1-X_i}{X_i}} \tag{3}$$

$$T_p = B_p \cdot \frac{0,278 \cdot \lambda^* \cdot h_p}{q_{\max,p}} \tag{4}$$

where: $X_i = \frac{t_i}{T_p}$ – relative abscissa of the hydrograph,

T_p – conditional hydrograph rising limb time of probability p,

$q_{\max,p} = \frac{Q_{\max,p}}{F}$ – maximum runoff modulus ($m^3/s/km^2$),

a – parameter that depends on the skewness coefficient of the hydrograph $K_s = \frac{1}{1+K}$, or the coefficient of the hydrograph shape $\lambda^* = \frac{Q_{\max,p} \cdot T_P}{W_{por}}$,

B_p – coefficient to be calibrated,
W_{por} – volume under rising hydrograph limb.

The correlations among a, λ^* and K_s are discussed in the literature [7]. The main parameters, K, α i B_p are calibrated applying LRIM.

2.2. Flood Hydrograph Parameters Coincedence

Using corresponding values ($Q_{\max,i}$;$W_{\max,i}$), where i – the number of the year in a series of N members, dependency graphs of above mentioned parameters are formed, which was the basis for defining a two-dimensional distribution function (coincidence) of the basic parameters flood waves (the maximum annual volume and flood flow) at all considered gauging station profiles [1, 4, 5]. For this purpose, model PROIL is used which defines following [3, 6]:

- Density functions (lines of equal bivariate probabilities of occurrence)

$$F(Q_{max};W_{max}) = p \tag{5}$$

for probabilities p = 0,1, 1,0, 5,0 i 50%.

- Distribution functions (lines of bivariate exceedance probabilities)

$$P\ \{(Q_{max} \geq q_{max,P}) \cap (W_{max} \geq w_{max,\,P})\ \} = P \tag{6}$$

for exceedance probabilities P = 0,1%, 1,0%, 2,0% i 5,0%.

Quantitative strength indicators defined by the correlation depending on the considered flood waves parameters, the Pearson correlation coefficient $R(Q,\ W)$ and the standard error of correlation coefficient assessment σ_R, indicate that established the two-dimensional correlation or the coincidence of the basic flood waves parameters is statistically significant, if inequality (7) is satisfied [8]:

$$|R| \geq\ 3\sigma_R \tag{7}$$

where: $\sigma_R = \dfrac{1-R(Q,W)}{\sqrt{N}}$,

N – total number of members in series (Q_{max} ;W_{max}).

3. Results and Discussion

Test results of adjustment of theoretical and empirical probability distribution of maximum annual flows, as well as the maximum annual volume of flood waves, at all considered gauging station profiles showed that the time series of maximum annual flow best follow Log Pearson III distribution function, and the series of maximum flood waves volume Pearson III distribution.

To illustrate, the first theoretical flood waves by the LRI method was made for the “maximum possible” combination of basic parameters of flood waves – maximum annual volume and maximum flood flow. For these assumptions, the parameters of the LRIM method are calibrated to the empirical distribution functions of the maximum annual flood wave flows and volumes, as shown in Figs. 1 and 2. The results of the calculation of the basic elements of flood waves at all hydrologic profiles along the Danube, according to LRIM are shown numerically in the Tab. 1 and graphically in Figs. 1 and 2.

Table1. Maximum annual flood waves flows and volumes at the Oršava hydrological station at the Danube

p(%)	LRIM		Theoretical values	
	$Q_{\max,p}$	$W_{\max,p}$	$Q_{\max,p(\text{LP III})}$	$W_{\max,p(\text{P III})}$
0,1	17457	89466	17550	89343
1,0	16095	83636	16126	83514
2,0	15532	80684	15463	80556
5,0	14805	77360	14759	77224

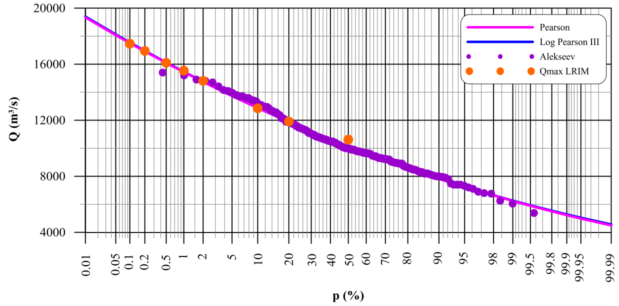

Figure 1. Theoretical maximum annual flows of the Danube River at the Oršava hydrological station profile according to Log Pearson III and Pearson III distribution functions and LRIM

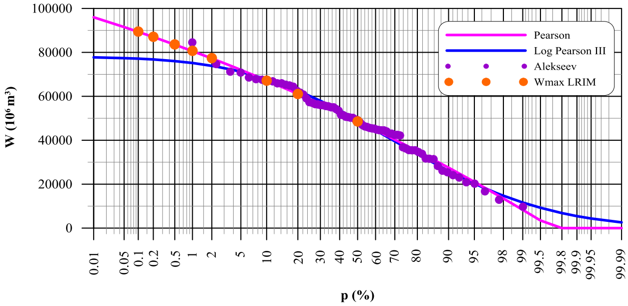

Figure 2. Theoretical maximum annual volumes of the Danube River at the Oršava hydrological station profile according to Log Pearson III and Pearson III distribution functions and LRIM

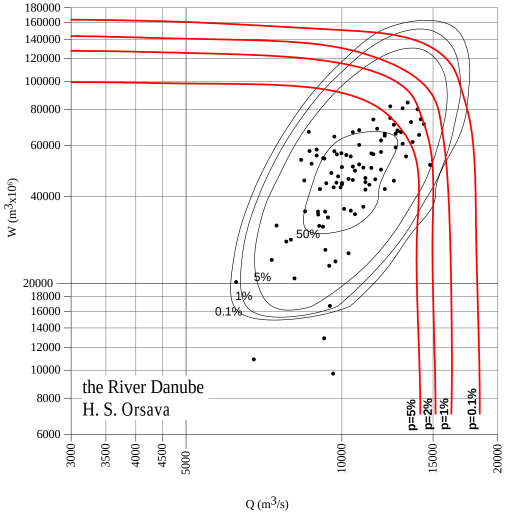

Figure 3. Bivariate distribution (coincidence) of basic parameters of the flood hydrograph (maximal ordinate – Q_{max} and maximum volume – W_{max}) at the Oršava hydrological stations profile at the Danube River

Graphical presentation of results of two-dimensional distribution function of the basic parameters of the flood hydrograph at the Oršava hydrological station profile is shown in Fig. 3. The diagram shows the empirical values of the fixed points of corresponding hydrograph parameters, the maximum annual flow and the maximum annual volume of flood waves, then the two-dimensional density functions and the lines of their exceedance probability (distribution function).

Defined bivariate distribution functions of the main flood hydrograph parameters at the Oršava hydrologic station profile indicate that for a certain exceeding probability $P\{(Q_{max} \geq q_{max,\,P}) \cap (W_{max} \geq w_{max,\,P})\} > P$ exists a wide range of possible combinations of maximum annual flows and maximum flood wave volumes. This practically means that there are many combinations (constellations) of the main flood hydrograph parameters that correspond to the same exceedance probability P. Therefore, it is necessary to find a procedure that, from the viewpoint of the users of the results, will define the most optimal combinations.

The authors of this paper suggest that in the field of flood protection, for the predefined exceedance probability P, it is best for users to work with the following combinations of parameters of the same marginal probabilities:

1. Maximum annual flow – maximum flood wave volume of the same marginal probabilities – $P(Q_{max,\,P}, W_{max,\,P})$.
2. Maximum annual flow of the same marginal probability – the corresponding flood wave volume for the selected exceedance probability – $P(Q_{max,\,P}, W_{cor,\,P})$.
3. The corresponding maximum annual flow for the selected exceedance probability – the maximum flood wave volume of the same marginal probability – $P(Q_{cor,\,P}, W_{max,\,P})$.
4. The most probable combination (Mod) of the maximum annual flow and maximum flood wave volume for the selected exceedance probability – $P(Q_{Mod,\,P}, W_{Mod,\,P})$.

The numerical values of the selected constellations of the flood hydrograph parameters of the Danube River at Oršava profile are given in Tab. 2.

Table 2. Selected combinations of the main flood hydrograph parameters of the Danube River at Oršava for different exceedance probabilities *P*

No	Combinations of variables	Exceedance probability – $P\{(Q_{max} \geq q_{max,P}) \cap (W_{max} \geq w_{max,\,P})\}=P$							
		0,1%		1%		2%		5%	
		Q_{max} (m^3/s)	W_{max} ($10^6 m^3$)	Q_{max} (m^3/s)	W_{max} ($10^6 m^3$)	Q_{max} (m^3/s)	W_{max} ($10^6 m^3$)	Q_{max} (m^3/s)	W_{max} ($10^6 m^3$)
1	$Q_{max,P}$- $W_{max,P}$	17550	99506	15463	89004	14759	85100	13742	79086
2	$Q_{max,P}$- $W_{cor,P}$	17550	78000	15463	65000	14759	62000	13742	58000
3	$Q_{cor,P}$- $W_{max,P}$	16500	99506	15000	89004	13900	85100	12000	79086
4	$Q_{Mod,P}$- $W_{Mod,P}$	17000	95000	15200	85000	14100	80000	12700	72000

The selected combinations of variables (main flood hydrograph parameters – maximum ordinate and flood wave volume) for an exceedance probability of:

$P\{(Q_{max} \geq q_{max,P}) \cap (W_{max} \geq w_{max,P})\}$=1,0%, are shown in Fig. 4 along with the bivariate coincidence function. The combinations are numbered as in Tab. 2.

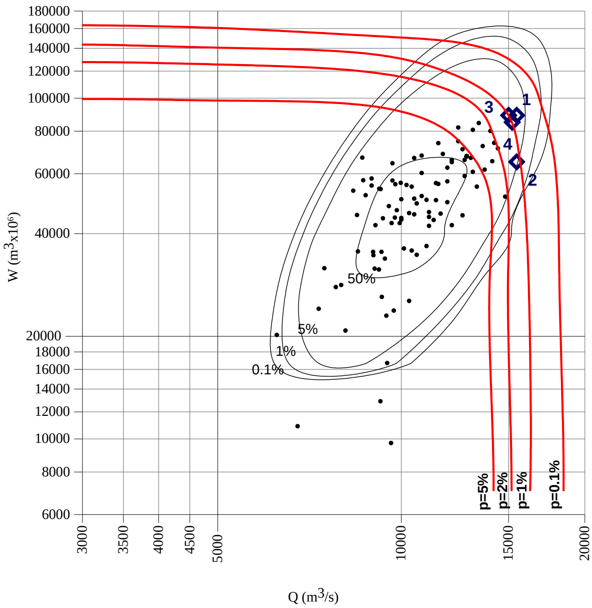

Figure 4. Bivariate distribution (coincidence) of basic parameters of the flood hydrograph (maximal ordinate – Q_{max} and maximum volume – W_{max}) at the Orsava hydrological station profile at the Danube River with selected combinations for the exceedance probability P = 1%

For all four selected combinations of variables, for an exceedance probability of P = 1,0%, theoretical flood hydrographs were assessed at Oršava profile according to LRIM. The results are graphically represented in Fig. 5.

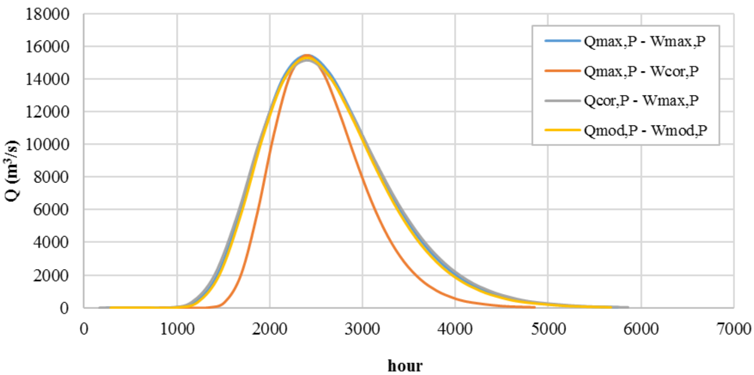

Figure 5. Flood wave hydrographs with return period 100yr at the Orsava hydrologic station profile for selected combinations of basic parameters (maximal ordinate – Q_{max} and maximum volume – W_{max})

As it is shown in Fig. 5, there are four different hydrographs, composed of marginal probabilities – $P(Q_{max,P}, W_{max,P})$, which is the "maximum possible" hydrograph, is a "quasi-100-year" hydrograph by both parameters (maximum ordinate and maximum volume), and it basically exceeds probability p (i.e. $p > P$). This is corroborated by the position of characteristic point 1 in Fig. 4, which cannot represent a 100-year theoretical hydrograph (p = 1,0%) because its actual position evidently corresponds to the line of exceedance probability:

$P\{(Q_{max} \geq q_{max,P}) \cap (W_{max} \geq w_{max,P})\} = P < p = 1{,}0\%$.

Its real exceedance probability is (Fig. 4): $P\{(Q_{max} \geq q_{max,P}) \cap (W_{max} \geq w_{max,P})\} = P = 0{,}8\% < p = 1{,}0\%$.

This means that flood hydrograph 1 corresponds to **125** –year return period.

The practical value of theoretical flood hydrographs, determined on the basis of the four characteristics points (Fig. 4), for the same exceedance probability $P\{(Q_{max} \geq q_{max,P}) \cap (W_{max} \geq w_{max,P})\} = P \cong p$, lies in the following:

1. A theoretical hydrograph, composed of marginal probabilities – $P(Q_{max,P}, W_{max,P})$, represents the "maximum possible" hydrograph by both parameters (maximum ordinate and maximum volume), and in effect exceeds probability p (i.e. $p > P$), the position of characteristic point 1 in Fig. 4. Its actual exceedance probability corresponds to a 125-year return period.
2. A 100-year theoretical hydrograph composed of marginal probabilities – $P(Q_{max,P}, W_{cor,P})$ is a 100-year hydrograph (p = 1,0%) only with regard to the maximum ordinate. It can only be used to design spillways, levees, bridges, culverts and cannot be used to design reservoirs and retentions.
3. A 100-year theoretical hydrograph composed of marginal probabilities $P(Q_{cor,P}, W_{max,P})$ is a 100-year hydrograph (p = 1,0%) only with regard to the maximum volume parameter. It can be used to design reservoirs and retention areas, but not for spillways, levees, bridges, culverts, etc.
4. A theoretical hydrograph composed of marginal probabilities – $P(Q_{Mod,P}, W_{Mod,P})$ is the "most probable" hydrograph, whose exceedance probability P and probability of occurrence p are identical, i.e. $\mathbf{P\{(Q_{max} \geq q_{max,P}) \cap (W_{max} \geq w_{max,P})\} = P = p}$.

4. Conclusion

The main idea of the authors of this paper was to propose a **novel approach for defining theoretical flood hydrographs at river gauging stations**, such as official stations with long time-series of river stages and flows.

From the stand point of various water-management activities all flood waves parameters does not have the same importance. The most frequent practical use has the maximum ordinate of hydrograph (wave peak) and it plays a dominant role. Flood volume is very important for the purpose of optimal design of dams and retentions, as well as for the successful implementation of flood control, flood spatial distribution analysis, flood risk assessment and flood control. The duration of floods is important for optimal embankments design and successful flood protection, etc.

The initial assumption is that each of the main flood hydrograph parameters is a random variable that follows a univariate, bivariate or multivariate distribution. The bivariate probability analyses show that there is a broad range of possible combinations of hydrograph parameters, which can be used to define a theoretical hydrograph of a certain probability of occurrence. For example, for an exceedance probability of $P\{(Q_{max} \geq q_{max,P}) \cap (W_{max} \geq w_{max,P})\} = P$, there are four characteristic points whose coordinates determine the theoretical hydrograph of the same probability of occurrence $P \cong p$.

The authors of this paper suggest that “most probable” hydrograph for any probability ($P\{(Q_{max} \geq q_{max,P}) \cap (W_{max} \geq w_{max,P})\} = P = p$) **should be used as a control in all above mentioned cases of hydrotechnical projects design.**

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