DESIGN STORM DURATION FOR ESTIMATION OF FLOODS IN UNGAUGED BASINS

Jasna Plavšić [1]
Nikola Zlatanović [2]
Andrijana Todorović [3]

UDK: 556.532:551.501
DOI: 10.14415/konferencijaGFS2019.007

Summary: *Design flood flows in small ungauged basins are traditionally estimated by calculating flood hydrographs resulting from design storms. This paper considers traditional application of the synthetic unit hydrograph and the SCS method and the choice of the design storm duration for a case study of the Obnica River basin. By comparing the design floods obtained from design storms and the observed flood flows, recommendations for the engineering practice are given.*

Keywords: *floods, design storms, storm duration, synthetic unit hydrograph, SCS method*

1 INTRODUCTION

Hydraulic structures, such as dams or dikes, are designed according to flood flows of given probability of exceedance or return period. Design floods may be obtained by statistical analysis of the observed flows, if long and reliable series are available for the location of interest. Statistical analysis is most commonly applied to the series of annual maximum floods [1] or sometimes to the partial duration series of flood flows (peak over threshold method [2],[3]). This kind of analysis is usually referred to as the flood frequency analysis (FFA). For ungauged catchments, design floods can be estimated by using hydrologic (rainfall-runoff) models with different rainfall as the input data (*Figure 1*). This approach includes either continuous or event-based simulations. The rainfall-runoff models can be forced with the observed rainfall, while the design floods are obtained from the statistical analysis of the simulated flows series. For ungauged basins, this approach is accompanied by considerable uncertainties in basin representation by the model and in model parameters. Although continuous models can underestimate flood flows leading to biased design flood estimates [4], there are studies indicating that continuous models are useful by providing a range of flood scenarios corresponding to a wide range of possible watershed physical conditions [5]. The event-based models are generally forced with design storms to obtain design floods. This approach relies on the

[1] Jasna Plavšić, Assoc. Prof., University of Belgrade, Faculty of Civil Engineering, P.O. Box 42, 11120 Belgrade, Serbia, tel: +381 11 3370206, e-mail: jplavsic@grf.bg.ac.rs
[2] Nikola Zlatanović, M.Sc., Institute for water resources development "Jaroslav Černi", Jaroslava Černog 80, Belgrade, Serbia, e-mail: nikola.zlatanovic@jcerni.rs
[3] Andrijana Todorović, Assist. Prof., University of Belgrade, Faculty of Civil Engineering, P.O. Box 42, 11120 Belgrade, Serbia, tel: +381 11 3370206, e-mail: atodorovic@grf.bg.ac.rs

assumption that the return period of the design flood is equal to the return period of the design storm. However, this assumption has been questioned for a long time [6], [7] (more recently in [8], [9]) because estimated peak flows depend heavily on assumed initial conditions, rainfall pattern and duration. Some studies indicate that estimated design floods can exceed those resulting from FFA by an order of magnitude, depending on the initial conditions and storm duration and that the greatest discrepancies are obtained for high runoff coefficients (0.6 and above) and storm durations equal or up to three times greater than catchment time of concentration [8]. Design storm approach tendency to overestimate design floods from FFA was also demonstrated in ten mountainous catchments in Austria [9].

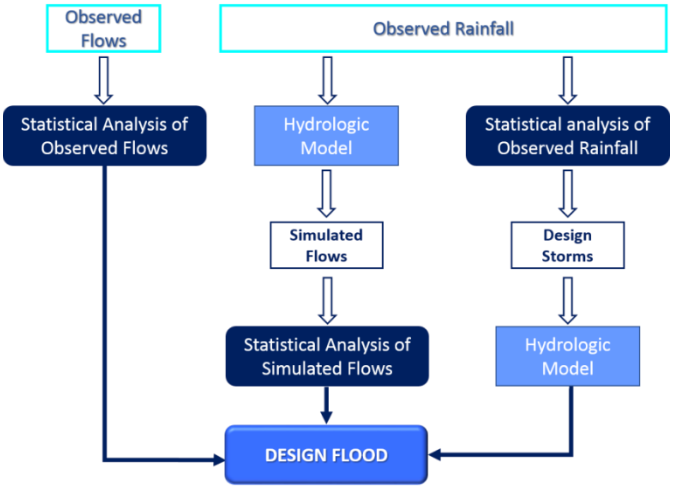

Figure 1. Approaches to design flood estimation

In this paper, performance of traditional engineering methods for design flood estimation is tested by comparing the results to design floods obtained from FFA. The emphasis was on the effects of the choice of design storm duration, temporal pattern, event-based hydrologic model (synthetic unit hydrograph) and loss method (the SCS-CN method) on the design flood estimation in the Obnica River catchment in Serbia. Based on the results, sensitivity of the design flood to the considered variables is assessed, and recommendations for design storm applications are provided.

2 METHODOLOGY AND DATA

2.1 Catchment and data

Obnica is a 25.8 km long river in western Serbia, with drainage area of 185 km^2. Together with Jablanica, Obnica makes the Kolubara River (*Figure 2*). On the southwest, the catchment is mountainous with steep hillslopes, and relatively flat in the remaining part (elevation ranges from 200 to 800 m a.s.l.). Agricultural land, forests and pastures prevail over other land use types.

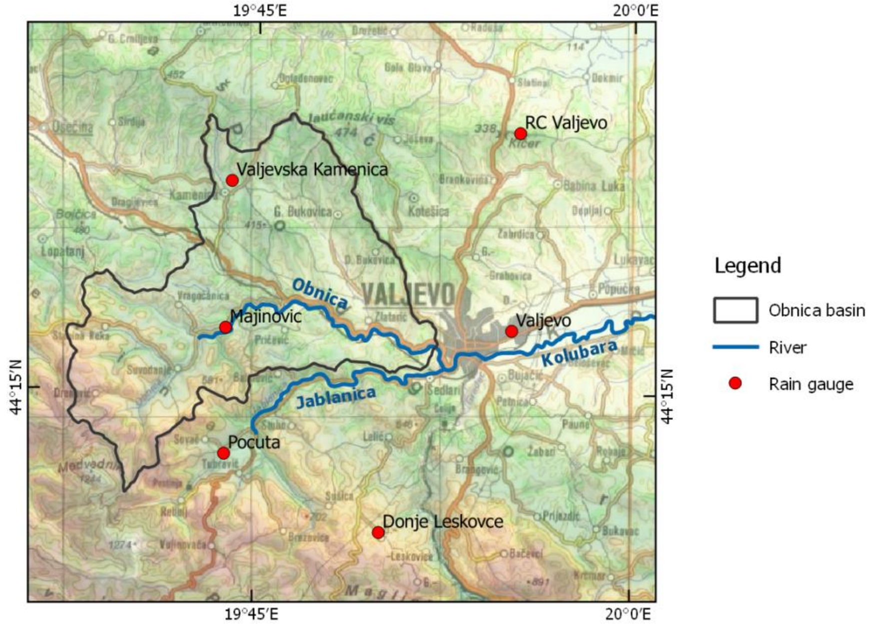

Figure 2. The Obnica River catchment location of rain gauges and Thiessen polygons.

Subdaily rainfall data is available only at Valjevo meteorological station, while daily rainfall data within the catchment and its vicinity are available at three non-recording gauges (Valjevska Kamenica, Majinović and Poćuta; see *Figure 2*). The lengths of the series of annual maximum daily rainfall depths for these four locations range from 50 to 71 years. Flow measurements are performed regularly at hydrologic station Belo Polje at the cacthment outlet since 1953, and the available series of the annual maximum floods covers a span of 64 years, from 1954 to 2017. Frequency distribution of annual maximum flows of Obnica at Belo Polje is estimated using the general extreme value distribution, which is proved to be the best fit among several candidate distributions. This distribution is shown in *Figure 3*.

2.2 Design storms

The depth-duration-frequency (DDF) relationships for the Valjevo rain gauge are taken from [10], where the distribution of daily rainfall at the same station is also given. Data used in [10] covers the period 1957-2006 and therefore does not include year 2014 with extreme precipitation record. In this study, frequency distribution of annual maximum daily rainfall at Valjevo was estimated for the period 1946-2017 and compared to the one in [10], which proved to significantly underestimate maximum daily rainfall depth quantiles. The frequency distributions of maximum daily rainfall at other three rain gauges were also computed and the basin-average quantiles of maximum daily precipitation were estimated using the Thiessen method with all four point quantiles. The DDF curves from [10] were then rescaled by multiplying the rainfall quantiles with the ratio between the annual maximum daily rainfall quantiles for the catchment and original quantiles for Valjevo from [10].

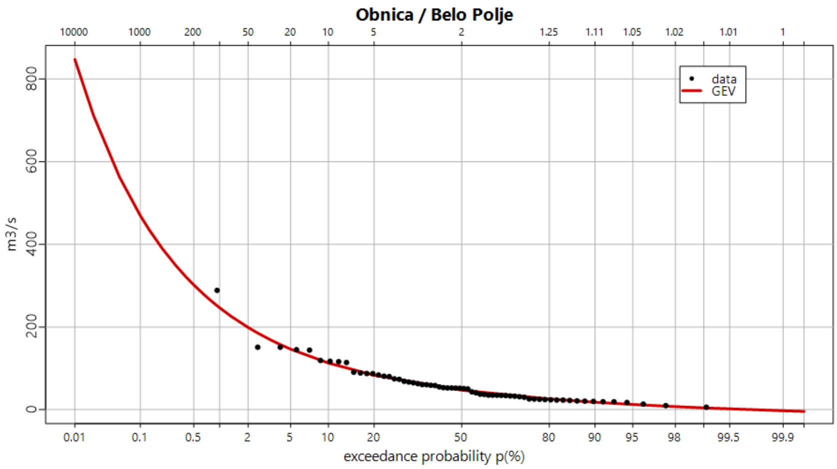

Figure 3. Frequency distribution of the observed annual maximum flows of Obnica at Belo Polje

Two types of design storms are created: (1) block storms, or storms of constant intensity, and (2) variable intensity storms formed by the alternating blocks method. Durations from 1 h to 24 h in steps of 1 h are used for the block storms, while the following durations are considered for the alternating block storms: from 1 h to 10 h in steps of 1 h, 12 h, 15 h, 18 h and 24 h. Examples of 3-hour and 24-hour design storms based on alternating blocks are shown in *Figure 4*.

2.3 SCS-CN method for losses

Runoff volume is computed by applying the SCS method [11], [12]. The SCS curve number CN is estimated on the basis of CORINE Land Cover maps [13] with ten land use types and spatial resolution of 10 m * 10 m, and assuming hydrologic soil group B [6]. Mean value of CN over the catchment is 71 for average antecedent moisture (runoff) conditions (ARC II), and 86 for wet antecedent moisture conditions (ARC III).

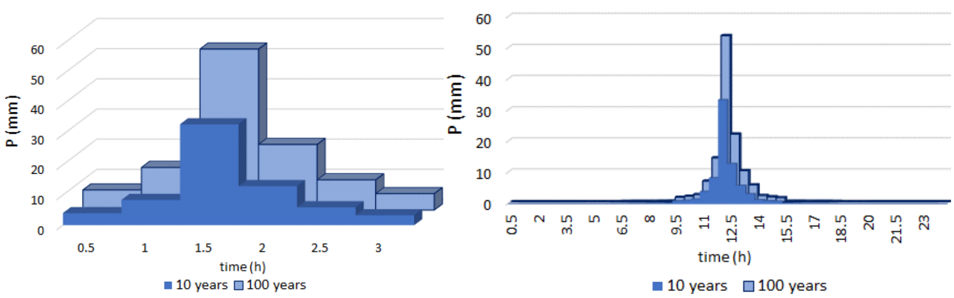

Figure 4. Design storms with duration of 3 hours (left) and 24 hours (right)

2.4 Synthetic unit hydrographs

In traditional applications, the synthetic unit hydrographs are constructed for different storm durations. Typically, a synthetic unit hydrograph (UH) has triangular shape and its time to peak T_p is defined as the sum of lag time t_p and the time from storm beginning to the centroid of the net rain hyetograph:

$$T_p = t_p + t_k / 2 \tag{1}$$

where t_k is storm duration, while the time of recession T_r is usually considered as a multiple of the time to peak:

$$T_r = rT_p \tag{2}$$

Peak flow rate, u_m, is determined from the requirement that the UH volume should be equal to the catchment area A multiplied by 1 mm of net rainfall:

$$u_m = \frac{2A}{T_p + T_r} \tag{3}$$

The basic assumption behind the theory of UH is that the storm having 1 mm of net rainfall of constant intensity produces that UH. In natural conditions this assumption may be valid only for short storm durations. Therefore, if the UHs are constructed and applied for long storm durations, the resulting design floods may be underestimated. For this reason, it is advisable to construct UH for storm duration corresponding to the desirable temporal discretisation Δt of rainfall and to assume certain temporal pattern for the design storm. The final runoff hydrograph is obtained by convolution of the elementary ones for each block of the storm with duration Δt.

In this paper, both approaches are applied: traditional approach of constructing synthetic UH for the assumed duration of a constant intensity storm, and the convolution of elementary runoff hydrographs based on the 15-minute synthetic UH for variable intensity storms. It should be noted that the first approach does not require the synthetic UH to be actually constructed for obtaining the design flood, but it only requires the peak UH ordinate u_m to be determined. In the second approach, design storms are discretised in 15-minute increments to execute convolution with the 15-minute UH.

Two different synthetic UHs are used for simulations: standard SCS UH [14], and modified SCS UH used in Serbian engineering practice [15], [16], [17]. The standard SCS UH in its triangular form is characterised by two parameters: lag time t_p, which can be estimated as 60% of the basin's time of concentration, and ratio of r = 1.67 between the time to peak T_p and time of recession T_r. Curvilinear version of the SCS UH is also available in the literature [14]. The modified SCS UH [15] has variable parameter r and lag time t_p that depends on storm duration and time t_0:

$$t_p = at_k + t_0 \tag{4}$$

where a is an empirical coefficient ranging from 0.3 to 0.7 depending on basin size, while t_0 depends on the basin physiographic characteristics [15]:

$$t_0 = 0.4L^{0.67}(L \cdot L_c / \sqrt{I_u})^{0.086} \tag{5}$$

Figure 5 compares two synthetic UHs for the Obnica basin for two setups: left plot compares UHs for different storm durations in the traditional constant storm intensity approach and right plot shows 15-minute synthetic UHs in the variable intensity storm approach.

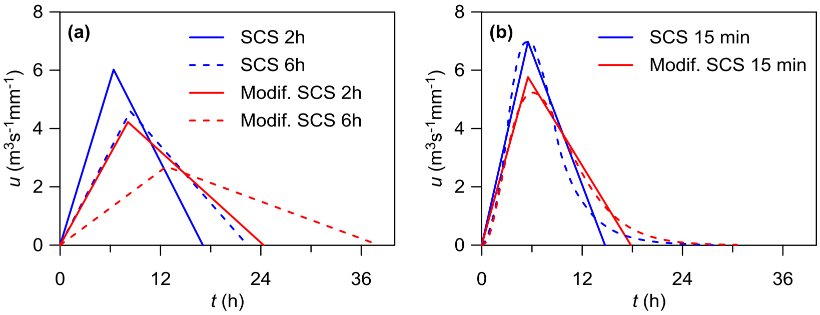

Figure 5. a) Synthetic unit hydrographs for different storm durations, (b) 15-minute synthetic unit hydrographs in triangular and curvilinear form

3 RESULTS AND DISCUSSION

Design floods for all combinations of UH, design storm duration and the CN value are compared to the corresponding design floods estimated by FFA of the observed annual maximum floods of Obnica at Belo Polje. The design floods computed from the GEV distribution fitted to the annual maximum floods are presented in*Table 1*.

Table 1. Design floods of the Obnica River at Belo Polje from frequency analysis

Return period (years)	10	20	50	100	1000
Flood flow (m^3/s)	112.7	146.3	198.8	246.2	469.5

Simulated flood flows vary widely depending on the unit hydrograph type, design storm type and duration, and assumed CN. *Figure 6* shows ratios of design floods obtained with block design storms and traditional synthetic UH approach relative to the corresponding design floods calculated from the FFA of the observed annual maximum flows. The results in *Figure 6* lead to two conclusions. First, the design storm duration leading to the greatest design flood is 4 hours for the standard SCS UH and 3 hours for the modified SCS UH. These storm durations are much shorter than estimated time of concentration of the Obnica basin (about 8 hours). Second, the traditional approach with typical CN = 71 significantly underestimates “true” design floods obtained by FFA, with an exception of standard SCS UH for high return periods. With CN = 86 for wet antecedent moisture conditions, the greatest design floods significantly overestimate true design floods, while the “best fit” to true design floods is obtained for storm durations between 12 h and 19 h for standard SCS UH and between 4 h and 7 h for modified SCS UH.
Figure 7 present the results for the second approach, and that is the use of variable intensity design storms (the alternating block method) with 15-minute curvilinear synthetic UHs. In this approach, the greatest design flood is obtained for the longest duration of 24 hours, although the differences between design floods for all durations greater than or equal to 6 hours are very small. In case of typical CN = 71, the standard SCS UH overestimates true design floods by 6% to 28% depending on the return period, while the modified SCS UH provides design floods almost equal to the true ones (design floods are slightly underestimated for shorter return periods and slightly overestimated for

longer return periods). On the other hand, with CN = 86 for wet antecedent moisture conditions, both synthetic UHs significantly overestimate design floods.

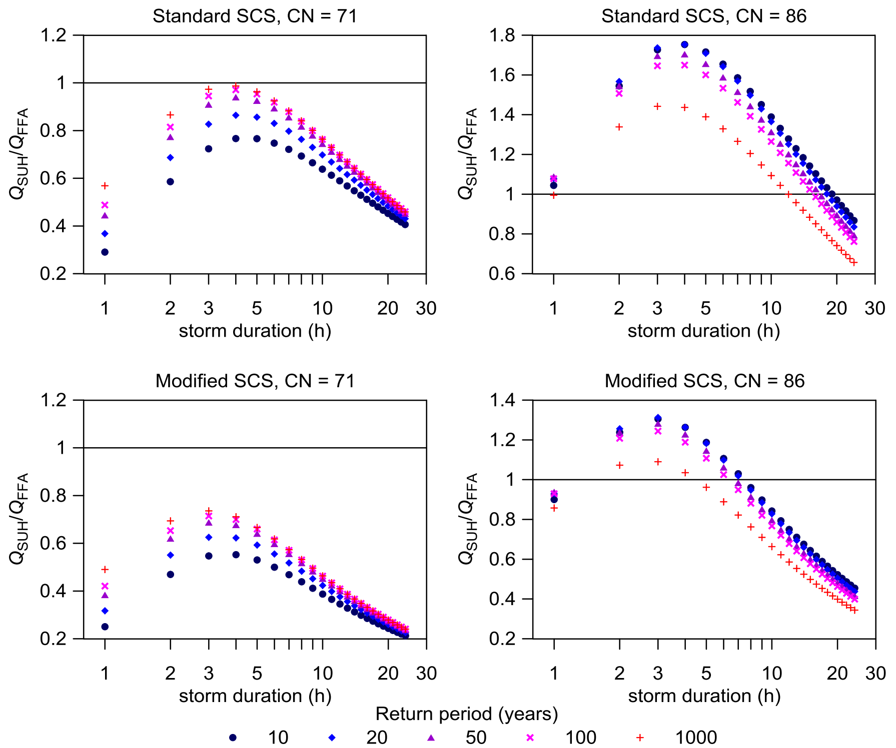

Figure 6. Ratios between design floods obtained by applying the block design storm approach with standard and modified SCS UH (QSUH) and from the flood frequency analysis (QFFA) for two curve numbers CN.

4 CONCLUSIONS

Comparison of the traditional approach for design floods estimation in ungauged basins, based on constant intensity design storms and SCS-type synthetic unit hydrographs constructed for a range of storm durations, with design storms obtained from flood frequency analysis of the observed annual maximum floods for the Obnica River basin in Serbia, has led to two important conclusions:

- The traditional approach can lead to significant under- or over-estimation of design floods and is therefore subject to great uncertainties. The underestimation results from the SCS curve number CN estimated based on basin's soil types and land use under assumption of the typical (average) antecedent moisture conditions, and the overestimation occurs when the wet antecedent moisture conditions are assumed.
- The design storm duration that leads to the greatest design flood in the traditional approach are misleading because they are much shorter than the basin's time of con-

centration. Obviously, shorter block design storms have greater mean intensity and consequently yield greater design storms.

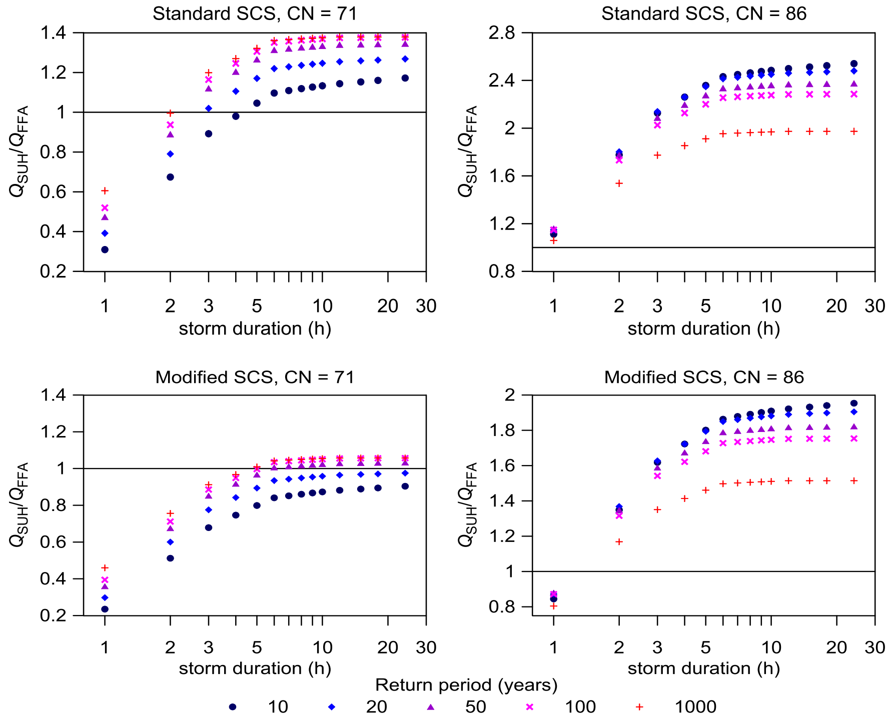

Figure 7. Ratios between design floods obtained by applying the alternating block design storm method with standard and modified SCS UH (QSUH) and from the flood frequency analysis (QFFA) for two curve numbers CN

The alternative approach for design flood estimation employed variable intensity design storms in the 1-hour blocks and the 15-minute synthetic unit hydrographs. By comparing these design floods with those obtained by flood frequency analysis, the following conclusions are reached:

- Design storm of 24-hour duration provides the most critical results in terms of design floods. This conclusion is in line with the original idea of the SCS methodology, which was developed simply to estimate the daily runoff depth [19] rather than runoff from short duration storms, as well as with previous studies [20].
- The choice of the typical SCS curve number for average antecedent moisture conditions in combination with the synthetic unit hydrograph developed and used in Serbian engineering practice provides the best agreement with the design floods obtained from flood frequency analysis.

Based on this limited study of one basin, it is recommended that the design floods in smaller ungauged basins are estimated using the modified SCS UH, variable-intensity design storms of 24-hour duration and with the SCS curve number estimated for average antecedent moisture conditions. Similar analysis should be performed for other small basins to confirm these conclusions and to identify all factors that affect the choice of methodology for design flood estimation.

Acknowledgement.

The research presented is supported by the Ministry of Science and Technological Development of the Republic of Serbia (projects TR37005 and TR37010). Data used are provided by the Republic Hydrometeorological Service of Serbia.

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MERODAVNO TRAJANJE KIŠA ZA PRORAČUN VELIKIH VODA NA NEIZUČENIM SLIVOVIMA

Rezime: *Ocena računskih velikih voda na malim neizučenim slivovima tradicionalno se zasniva na proračunu hidrograma velikih voda usled računskih kiša. Razmatra se uticaj izbora merodavnog trajanja računskih kiša na računske velike vode na primeru izučenog sliva reke Obnice za koji se računske velike vode ocenjuju klasičnim inženjerskim metodama za neizučene slivove (sintetički jedinični hidrogrami i metoda SCS). Poređenjem dobijenih računskih velikih voda sa odgovarajućim protocima dobijenim statističkom analizom podataka merenja dolazi se do preporuka za izbor merodavnog trajanja računskih kiša.*

Ključne reči: *velike vode, računske kiše, trajanje kiše, sintetički jedinični hidrogram, metoda SCS*