Chapter 1

Design Rainfall in Engineering Applications with Focus on the Design Discharge

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Additional information is available at the end of the chapter

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Abstract

Design hyetograph or design storm definition is one of the most important parts of the design discharge determination in case of ungauged catchments. Design hyetograph duration and temporal rainfall distribution can have large impact on the peak discharge values and the shape of the runoff hydrograph. The influence of these two factors on the design runoff values is presented in the case study of the Glinščica River catchment that covers 16.85 km^2 and it is located in central part of Slovenia, Europe. A combination of Huff and intensity-duration-frequency (IDF) curves is used to construct the design hyetograph for the presented case study. The duration of the design storm is determined by the catchment time of concentration. The results are compared to the Natural Resources Conservation Service (NRCS) curves and the so-called frequency storm method. The hydrological modeling result that was carried out using the hydrologic modeling system (HEC-HMS) software indicates that differences among different methods should not be neglected. For the 10-year return period, differences in the peak discharge values can be larger than 10%, while even larger differences can be expected for longer return periods. Some studies showed that these can be larger than 50%. Therefore, the guidelines on how to construct the design hyetograph are presented.

Keywords: design rainfall, design discharge, modeling, rainfall, hydrologic engineering

1. Introduction

Design peak discharge values or in some cases, even the complete design hydrographs are needed for the design, planning, and construction of different hydraulic structures such as dams, water retention reservoirs, and levees that can be used to improve the flood safety. These design values or design hydrographs (sometimes also called design floods) can be determined using various approaches. In case of gauged catchments or when plenty of discharge data are available, the most commonly used approach is to perform the flood frequency analysis (FFA). Most often univariate approach is selected where usually only peak discharge values are considered in the analysis (e.g., [1]). Alternatively, multivariate approach, where besides peak discharge, also hydrograph volume and (or) hydrograph duration are selected, can be carried out. Copula functions can be used to perform the multivariate flood frequency analysis (e.g., [2–4]). Using the FFA approach, the relationship between the design discharge and the return period is estimated (e.g., [1, 5, 6]). This relationship can then be used for the design of, for example, different engineering structures or river channels. The adequate return period is selected according to acceptable risk or estimated flood damage. On the other hand, in some cases, complete design hydrograph or design flood is needed. For example, unsteady hydraulic analysis of different engineering structures, such as bridges or culverts, requires complete design hydrograph. This can be determined with the combination of the FFA results and the analysis of past measured extreme events in order to determine the shape of the design hydrograph.

In cases when no measured discharge data are available, a procedure suitable for the ungauged catchments should be selected (e.g., [7]). Ungauged catchments are those where very little or no discharge data are available. Among a set of possible procedures with different complexity for the definition of the design discharge values in case of ungauged catchments (e.g., regional flood frequency analysis), one can also use design rainfall events (also named design hyetographs or design storms) in combination with hydrological model to determine the design peak discharges and complete design hydrographs (e.g., [8]). In most cases, a nearby rainfall gauging station can be used to determine the design rainfall events. These design hydrographs can then be used for unsteady hydraulic analysis and modeling. However, appropriate rainfall properties should be used to construct the design rainfall events because in case of ungauged catchments no discharge data are available and the uncertainty in the determined design peak discharge values and complete design hydrograph depends on the model parameters and selected design storm. In addition to the intensity-duration-frequency (IDF) curves [4], temporal rainfall distribution within rainfall event also named internal storm structure (can be described with Huff curves) is important part of this procedure (i.e., design rainfall determination) and can have significant influence on the hydrological model results [9]. For example, if most of the rainfall occurs in the second part of the rainfall event, this situation is more critical from the surface runoff point of view than the case where most of the rainfall occurs in the first part of the event due to the lower antecedent wetness in this latter situation (e.g., [9]). In case that limited discharge data (e.g., some rainfall-runoff events) are available for the investigated catchment, this information should be used for model calibration.

Different procedures are possible for the determination of the design rainfall events such as Natural Resources Conservation Service (NRCS) rainfall characteristics also named rainfall profiles known as Types I, IA, II, and III (e.g., [10]) that correspond to a specific region in the United States. Moreover, also other methodologies can be found in literature (e.g., [11–13]). Huff curves [11] connect dimensionless rainfall duration with dimensionless rainfall depth and can be derived based on the high-frequency measured rainfall data. Different Huff curves can be constructed depending on the rainfall event duration (e.g., [11]). From 1967, when the Huff curves were proposed by Huff [11], several different aspects of these curves have been

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analyzed. For example, Bonta [14] indicated that different Huff curves should be derived for different seasons and Bonta and Shahalam [15] showed that a sample of 110–140 rainfall events (storms) is large enough to derive a stable set of Huff curves.

The main aims of this chapter are as follows: (i) to make an overview of the procedures available for the definition of the design rainfall events (e.g., Huff curves, frequency storm method, NRCS curves); (ii) to describe the procedure for the definition of the Huff curves that can be used to define the temporal rainfall distribution; and (iii) to analyze the influence of the temporal rainfall distribution and rainfall duration on the design discharge values.

2. Data and methods

In order to investigate the impact of the temporal rainfall distribution and design rainfall duration on the design discharge and design hydrograph values, we used a case study from one of the experimental catchments in Slovenia [16, 17]. The Glinščica catchment is part of the Gradaščica catchment [16] and it is located in the central part of Slovenia (**Figure 1**). Part of the Glinščica catchment is also located in the urban area of the Ljubljana city; therefore, the orographic catchment boundary does not represent the actual catchment area [16, 18]. Thus,

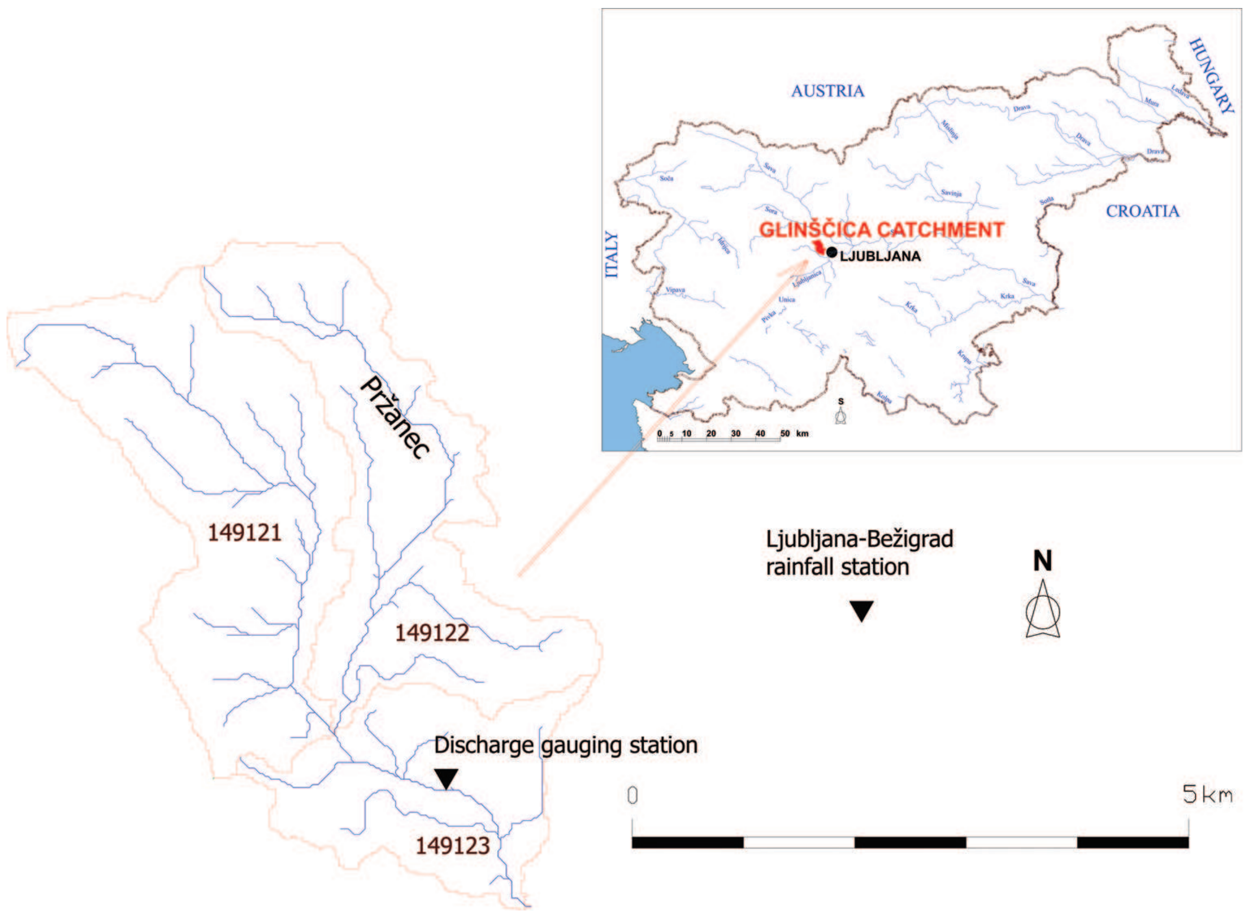

Figure 1. The Glinščica catchment with the location of the Ljubljana-Bežigrad rainfall station and the water gauging station.

the actual precipitation drainage area of the Glinščica catchment is 16.85 km^2 [18]. The elevation of this area ranges from 590 to 209 m.a.s.l. (confluence with the Gradaščica River). The Glinščica catchment was divided into three subcatchments (149121, 149122, and 149123 shown in **Figure 1**) [8]. Forest covers about 49% of the catchment, agriculture land about 23%, and urbanized areas cover 19% of the entire modeled Glinščica catchment [8]. The soil characteristics belong to C and D soil types according to the soil conservation service (SCS) classification with generally low infiltration rates [8].

The surface runoff modeling was carried out using HEC-HMS 4.2.1 model that was developed by the US Army Corps of Engineers (http://www.hec.usace.army.mil/software/hec-hms/) and it is one of the most frequently used hydrological models [19]. This model is often used for the determination of the design discharge values in case of ungauged catchments [19]. The unit hydrograph (UH) theory was used to calculate discharge based on the input rainfall in this study. The unit hydrograph was determined based on the measured discharge data and more information about this procedure can be found in Ref. [8]. Model was calibrated using the November 2003 rainfall event and validated using the January 2004 event [8]. In case of completely ungauged catchments, the unit hydrograph could be determined using the synthetic unit hydrograph methodology such as Snyder unit hydrograph (UH), SCS UH, or Clark UH. All of these methods are described in the HEC-HMS user's manual: http://www.hec.usace.army.mil/software/hec-hms/documentation/HEC-HMS_Users_Manual_4.2.pdf. In these cases, the synthetic UH is calculated based on the catchment characteristics such as slope and catchment length. These characteristics can be determined based on the digital elevation model (DEM) of the investigated area. If the detailed local DEM is not available, one can use publically available DEM such as shuttle radar topography mission (SRTM) 90 m DEM (http://www.cgiar-csi.org/data/srtm-90m-digital-elevation-database-v4-1) that is available for the entire world. The rainfall losses were estimated using the SCS curve number loss method that is one of the most frequently used methods in hydrologic engineering practice. Moreover, this method yielded the smallest RMSE values in some of the previous studies of the Glinščica River catchment where several different rainfall loss methods were compared (e.g., Horton's infiltration model, initial and constant-rate loss model, SCS curve number loss method, etc.) [8]. Based on the land-use and soil characteristics of the area, the curve number (CN) parameters for the three sub-catchments were determined as 88, 89, and 89 for the sub-catchments 149121, 149122, and 149123, respectively [8].

In order to determine the design rainfall events or design storms with a specific return period a combination of intensity-duration-frequency (IDF) and Huff curves can be used. In this study, rainfall data from the closest rainfall station were used. This is the Ljubljana-Bežigrad station that was also used in some other studies (e.g., [4, 9]). The measurements began in 1948 and 5-minutes rainfall data have been available since then [9]. The mean annual precipitation in this area is about 1370 mm [9]. For the determination of the IDF curves, rainfall data from 1948 till 2012 were used [20]. The IDF curves were derived by the Slovenian Environment Agency [20] and are shown in **Figure 2**. Dolšak [21] derived the Huff curves for several Slovenian rainfall stations including the Ljubljana-Bežigrad station. The next procedure was used for the determination of the Huff curves that were applied in this study [9, 21]:

- The inter-event time (time between two consecutive rainfall events) of 6 hours was used to define the actual rainfall events. If the time period between the two consecutive rainfall events was smaller than 6 hours, these two events were joined into one event.
- Only rainfall events with more than 12.7 mm rainfall in total were used [11].
- Based on the rainfall duration, events were divided into the following four groups: 3–6 hours, 6–12 hours, 12–24 hours, and more than 24 hours.
- All selected rainfall events in the four groups were nondimensionalized using the information about the rainfall duration and rainfall amount.
- The probability information was added to each of the four groups ($P = (100 * i)/(n + 1)$, where P is the cumulative percentage of the dimensionless-depth points, n is the total number of points, and i is the point number) [9].
- Huff curves were derived for the following probability levels: 10, 20, 30, 40, 50, 60, 70, 80, and 90%.

Additional information about this procedure for the Slovenian stations can be found in Ref. [9] and general information in Refs. [11, 14]. **Figure 3** shows the derived Huff curves for the Ljubljana-Bežigrad station for the two rainfall durations: from 3 to 6 hours and from 6 to 12 hours.

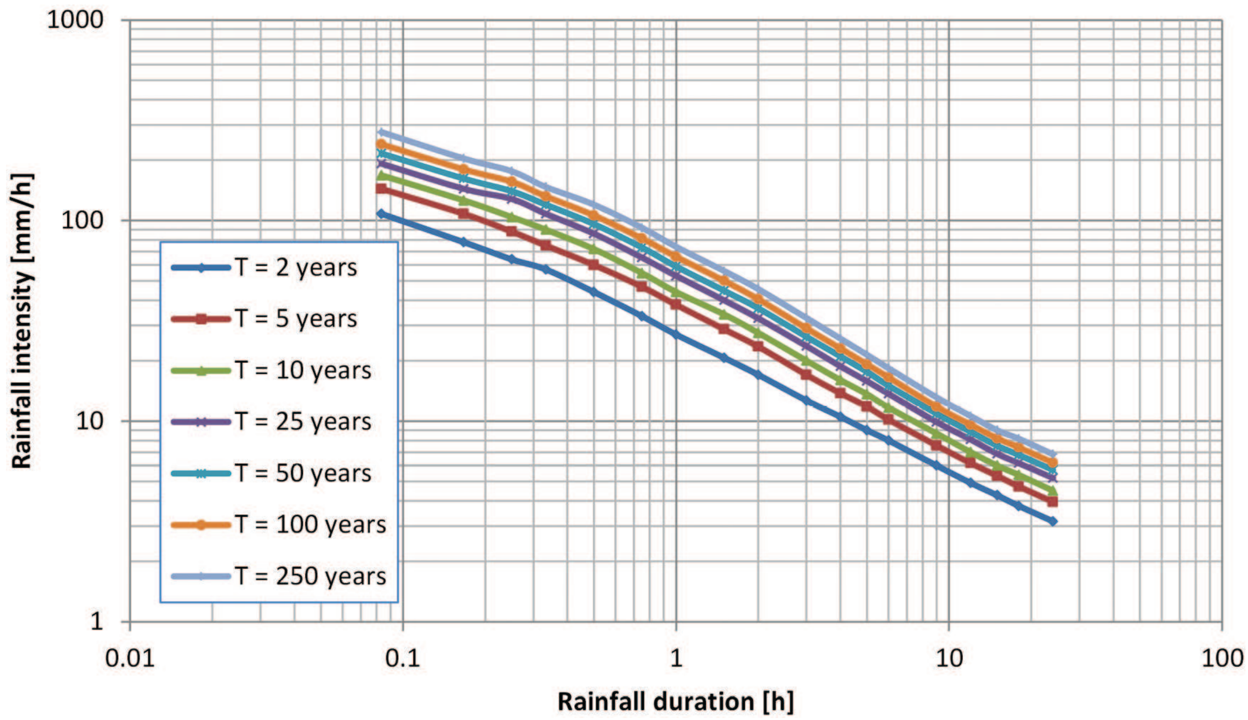

Figure 2. Intensity-duration-frequency (IDF) curves for the rainfall station Ljubljana-Bežigrad (adopted from ARSO [20]).

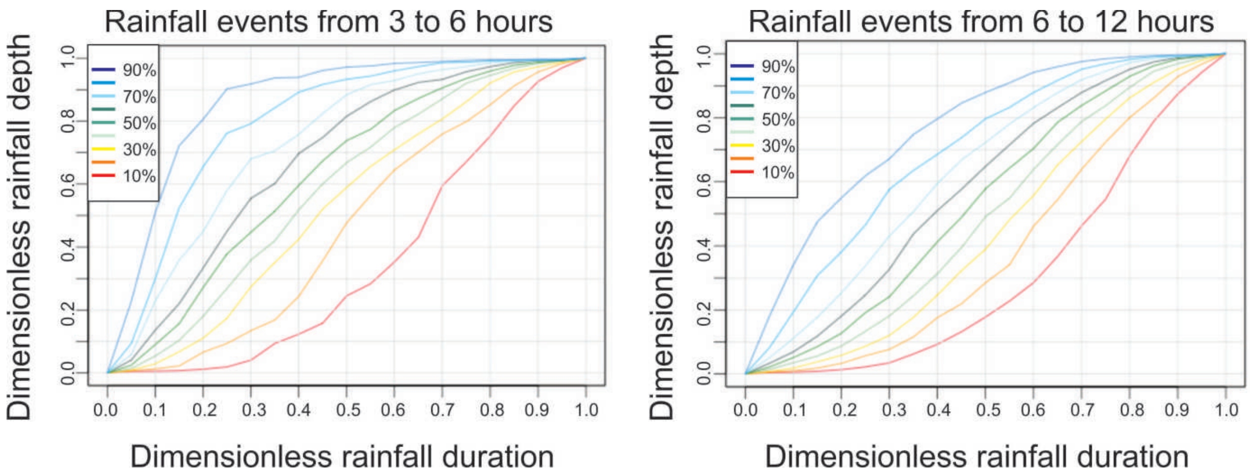

Figure 3. Huff curves for the Ljubljana-Bežigrad station for rainfall events with the duration from 3 to 6 hours and from 6 to 12 hours (adopted from Dolšak et al. [9]).

3. Results and discussion

The Glinščica experimental catchment was used for the investigation of the influence of the rainfall duration and temporal rainfall distribution on the design discharge values. All three subcatchments (149121, 149122, and 149123) were modeled as individual subcatchments (**Figure 4**). Muskingum method (K parameter was 0.5 and X parameter was 0.2) was used for the hydrograph propagation from the confluence of the subcatchments 149121 and 149122 to the subcatchment 149123 outflow (**Figure 4**) [8]. IDF and Huff curves derived for the Ljubljana-Bežigrad station were used for the design rainfall event definition.

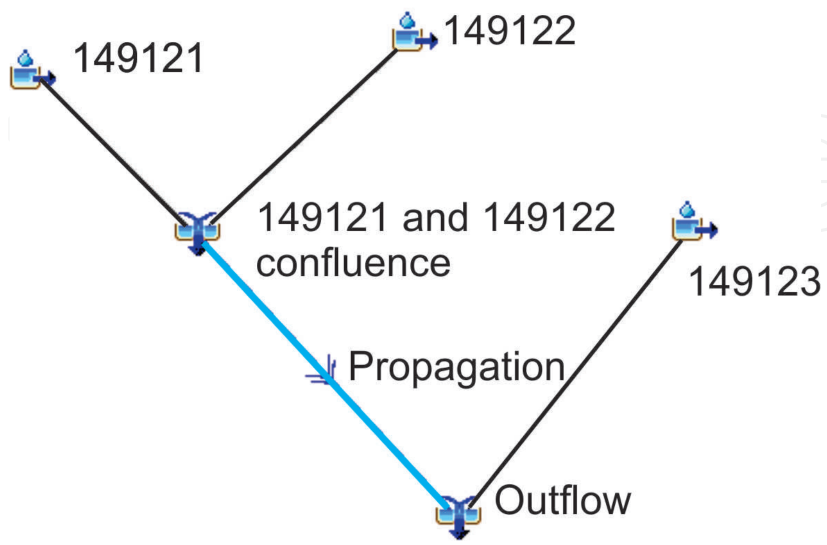

Figure 4. Modeling scheme used in the HEC-HMS model to represent the Glinščica catchment shown in **Figure 1** with three subcatchments, two junctions and one reach.

3.1. The influence of the rainfall duration on the modeled discharge values

In the first step of this study, we investigated the influence of the rainfall duration on the modeled discharge values using the (calibrated) HEC-HMS model presented in previous section of this chapter. **Figure 5** shows an example of the 50th percentile or median Huff curve for the Ljubljana-Bežigrad station (rainfall duration between 3 and 6 hours) transformation into the design rainfall event or design hyetograph using the IDF curves (**Figure 2**) with the total rainfall amount of 70 mm. In this case, the rainfall duration 6 hours and 10-year return period were selected as an example. Similarly, transformation of other Huff curves into the design hyetographs can be performed based on the selected rainfall duration and return period.

A random temporal rainfall distribution was selected for modeling and was used in case of all presented simulations. Further, design hyetographs with the 10-year return period were selected. **Table 1** shows the IDF curve properties that were used to construct the design hyetographs with duration of 2, 4, 6, 9, 12, 15, and 24 hours (**Figure 6**). Thus, using the random temporal rainfall distribution (was the same for all cases) and IDF information shown in **Table 1**, a set of design hyetographs was defined. All these hyetographs were used as an input to the hydrological model and **Figure 6** shows the surface runoff modeling results for these cases. It can be seen that differences

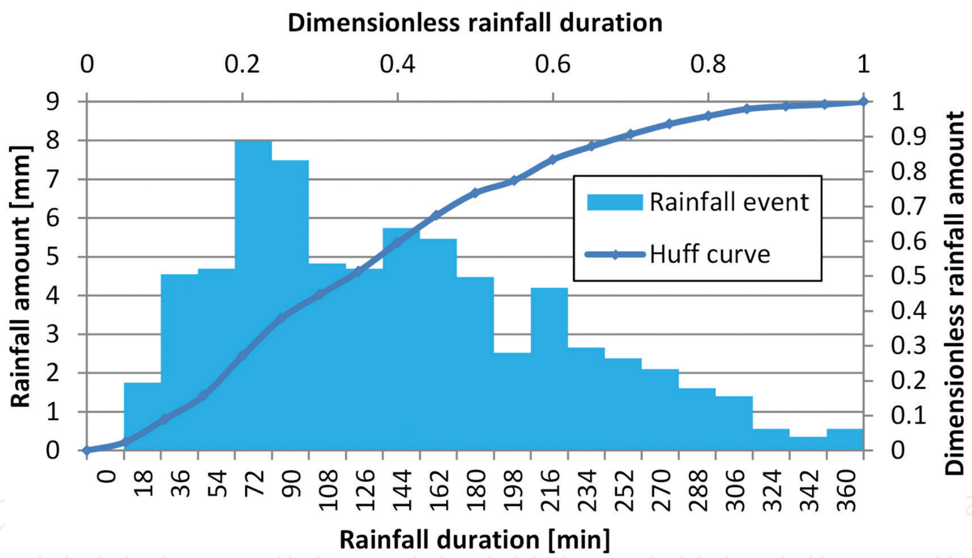

Figure 5. Example of the Huff curve transformation into the design rainfall event (rainfall duration: 6 hours and rainfall amount: 70 mm).

Rainfall duration [hours]	2	4	6	9	12	15	24
Rainfall amount [mm]	55	64	70	79	84	90	108

Table 1. Design hyetograph characteristics with the 10-year return period for the Ljubljana-Bežigrad station (**Figure 2**).

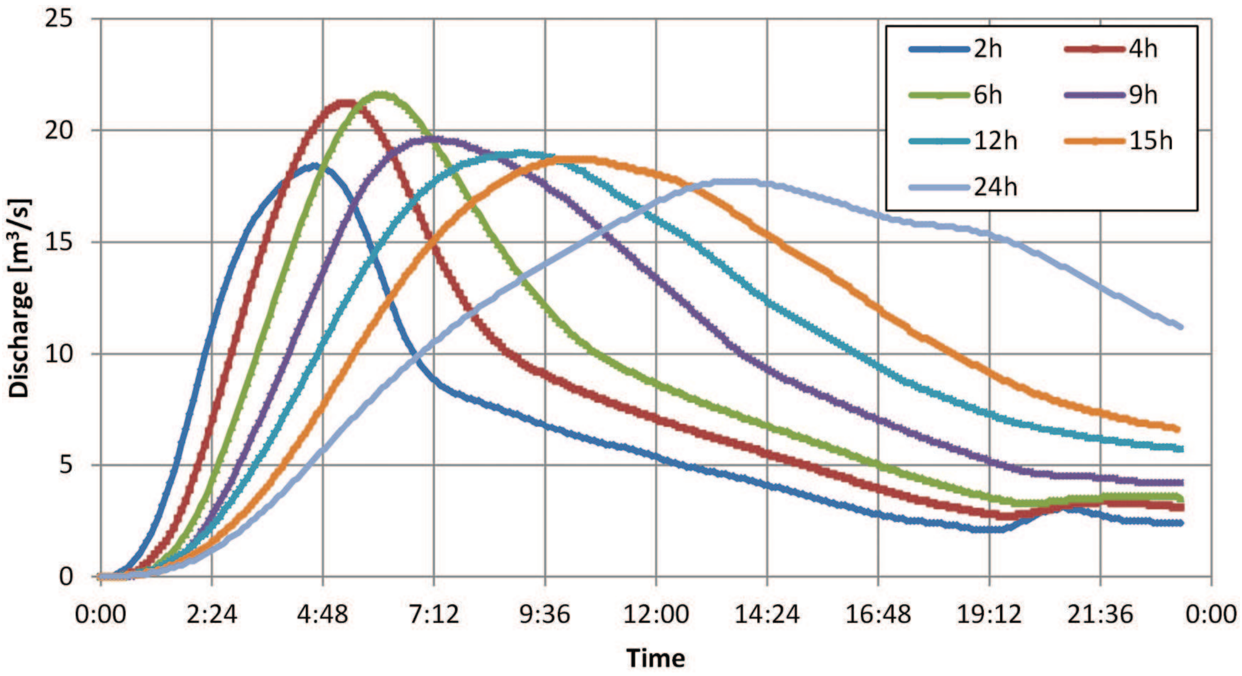

Figure 6. Influence of design rainfall duration (in hours) on the modeled discharge values. The temporal rainfall distribution is the same for all presented cases.

between some of these cases are relatively large. For example, maximum peak discharge is characteristic of the 6 hours design hyetograph (21.6 m^3/s), while the smallest peak discharge was calculated for the longest rainfall duration (24 hours) and was 17.7 m^3/s. Moreover, it is clear that the shapes of the hydrographs are also different, which leads to a different time to peak values and other hydrograph characteristics such as a duration of increasing part of the hydrograph, total hydrograph duration or a duration of falling part of the hydrograph. From **Figure 6**, it can be seen that the time of concentration of the modeled Glinščica catchment equals approximately 6 hours because the maximum peak discharge is calculated with the design hyetograph of this duration. The time of concentration is one of the most frequently used concepts in hydrology and represents the time that is needed that the entire catchment contributes to the surface runoff or in other words, the time needed that water from the most distant point of the catchment drains to the catchment outlet (e.g., [22]). Thus, design storms of durations shorter than the catchment time of concentration will result in smaller peak discharge values (**Figure 6**). Furthermore, longer durations of design hyetographs will lead to design hydrographs with longer durations and peak discharge values that are often smaller than the maximum peak discharges calculated using the design storm with duration similar to the catchment time of concentration. Moreover, these long duration events can even result in hydrograph shapes that are not representative for small size catchments such as the Glinščica catchment (**Figure 6**). Thus, in many practical cases, when modeling small catchments, the design rainfall duration is selected approximately equal to the catchment time of concentration. Also in our study, this theory was considered and the rainfall duration time of 6 hours was applied as representative for all further calculations. **Figure 7** shows the surface runoff modeling result using the design hyetograph with the rainfall duration of 6 hours and total rainfall amount of 70 mm. The results demonstrate that lag time (i.e. time between hyetograph centroid and peak discharge) of the catchment is about 4 hours, which

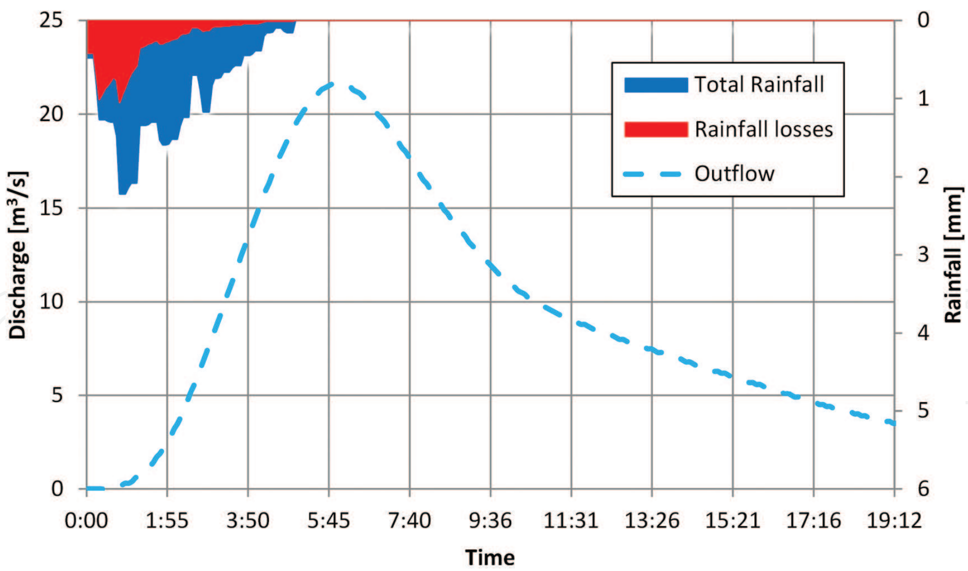

Figure 7. Design rainfall (rainfall duration 6 hours and total rainfall amount 70 mm) and modeled surface runoff for the Glinščica catchment.

means that time of concentration for this situation is really approximately 6 hours (lag time is approximately 60% of the time of concentration [10, 22]).

3.2. The influence of the temporal rainfall distribution on the modeled discharge values

When defining the design hyetograph besides rainfall duration and the return period that is usually determined for the purpose of the design process (e.g., sewage design, flood modeling), the temporal rainfall distribution within rainfall event or the internal storm structure must also be defined in order to calculate the appropriate design hydrograph. One of the most frequently used methods are the NRCS curves [10]. These curves are defined as 24-hour rainfall events with different rainfall distributions for the specific region in the United States [10]. Types 1, 1A, 2, and 3 are used for Alaska and parts of California, West Coast, most of the continental USA and Gulf of Mexico, and East Coast, respectively [10]. In the HEC-HMS model, this method is named SCS method. **Figure 8** shows a comparison between the surface runoff (design hydrograph) that was determined using the 6-hour design hyetograph shown in **Figure 7** and hydrographs that were computed using different NRCS curves. Large differences are primarily the result of the different design hyetograph durations. The results demonstrate that NRCS curves are not necessarily appropriate for the non-US catchments, especially for catchments with time of concentration significantly smaller than 24 hours.

Figure 9 shows modeled hydrographs that were calculated using different set of Huff curves. Huff curves shown in **Figure 3** were used and the rainfall amount (70 mm) was determined based on the selected return period (10 years) and rainfall duration (6 hours). The maximum peak difference was detected between the 90th percentile and median Huff curves (2.5 m^3/s). Similar difference was also detected between the median and 10th percentile Huff curves. Moreover, with decreasing the Huff curves percentile, the time to peak (i.e. time between the beginning of the event and the maximum peak discharge) also increases. For example,

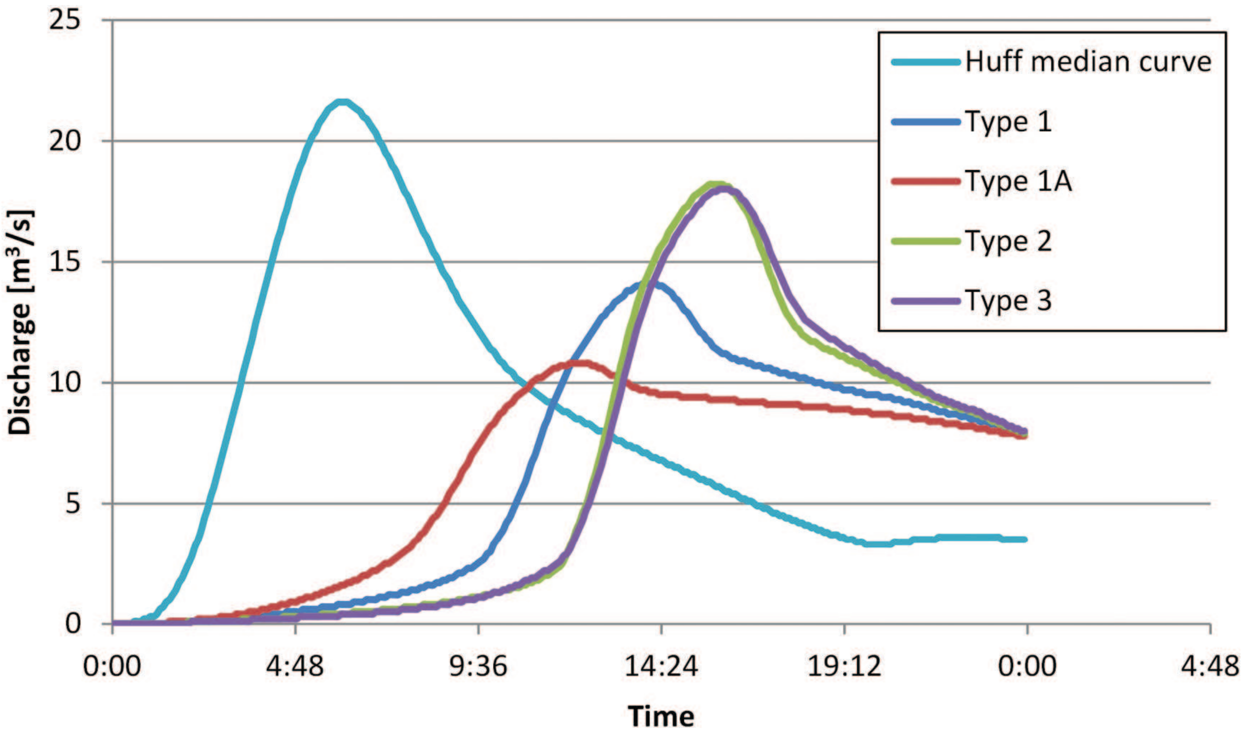

Figure 8. Comparison between modeling results using the 6-hour rainfall event where the internal storm structure was defined using the Huff curves for the Ljubljana-Bežigrad station and with the application of the different NRCS curves.

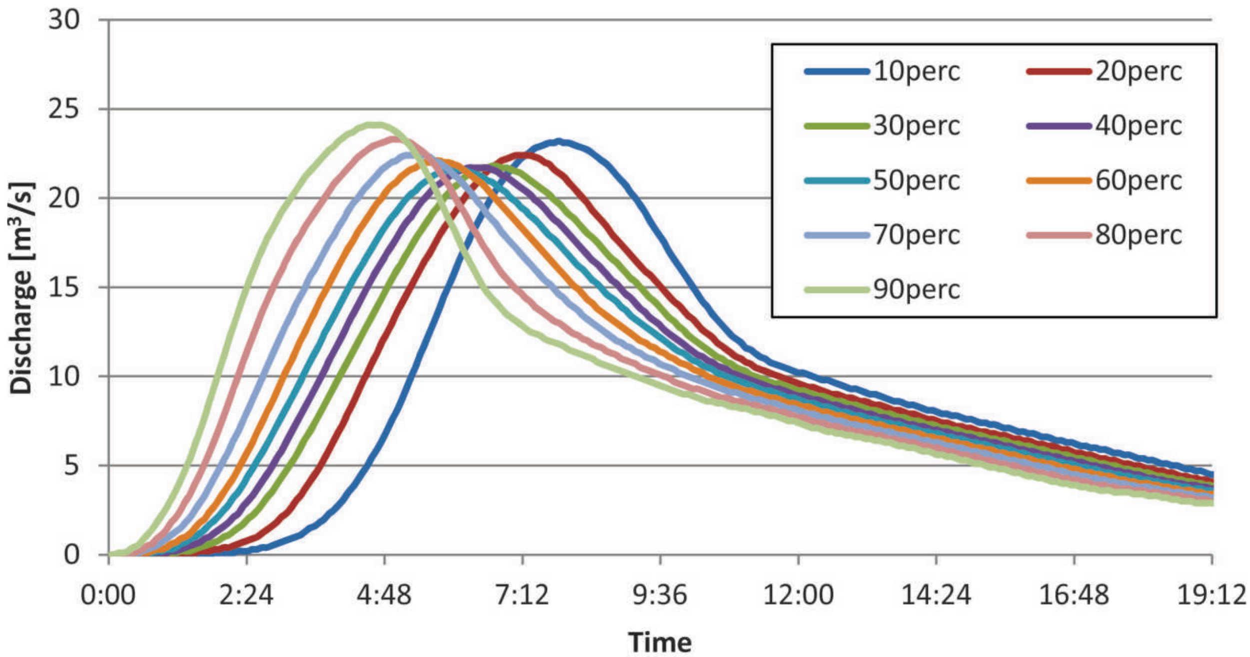

Figure 9. Modeled discharge values using different set of Huff curves (from 10th percentile curve to 90th percentile curve).

for the 10th percentile curve the peak discharge value occurred approximately 8 hours after the beginning of the rainfall event. On the other hand, for the 90th percentile Huff curve, the maximum discharge value happened less than 5 hours after the start of the rainfall event.

Figure 10 shows the comparison between the results obtained with the median Huff curve (rainfall duration 6 hours), constant rainfall intensity, and three situations using the so-called frequency storm method. The later method defines the synthetic design hyetograph using the information from the IDF curves. One can also select the location of the maximum rainfall intensity (at the 25, 50, or 75% of the total rainfall duration). Similarly, as in other studies, also **Figure 10** shows that using constant rainfall intensity instead of actual temporal rainfall distribution (e.g., Huff median curve) leads to underestimation of peak discharge values (e.g., [8, 23–25]). In some cases, these differences can be up to 50% [8]. On the other hand, using the frequency storm method to define the design hyetograph yields higher peak discharge values than the median Huff curve. The maximum peak discharge was calculated using the frequency storm method when the maximum rainfall intensity occurred after the 75% of the rainfall event. This higher peak discharge can be attributed to the higher antecedent conditions (most of the rainfall falls before the maximum intensity). Similarly, also difference in the time to peak values is relatively large (about 3 hours). Thus, it seems that selection of the method for the design hyetograph definition can have significant impact on the design peak discharge values and also on the complete design hydrographs. More precisely, it has the influence on the peak magnitude, hydrograph shape, and also on the timing of the maximum discharge (i.e., time to peak) [8]. Furthermore, these differences are even more significant for the larger return periods (e.g., 100-year return period and higher) and consequently also influence the design process.

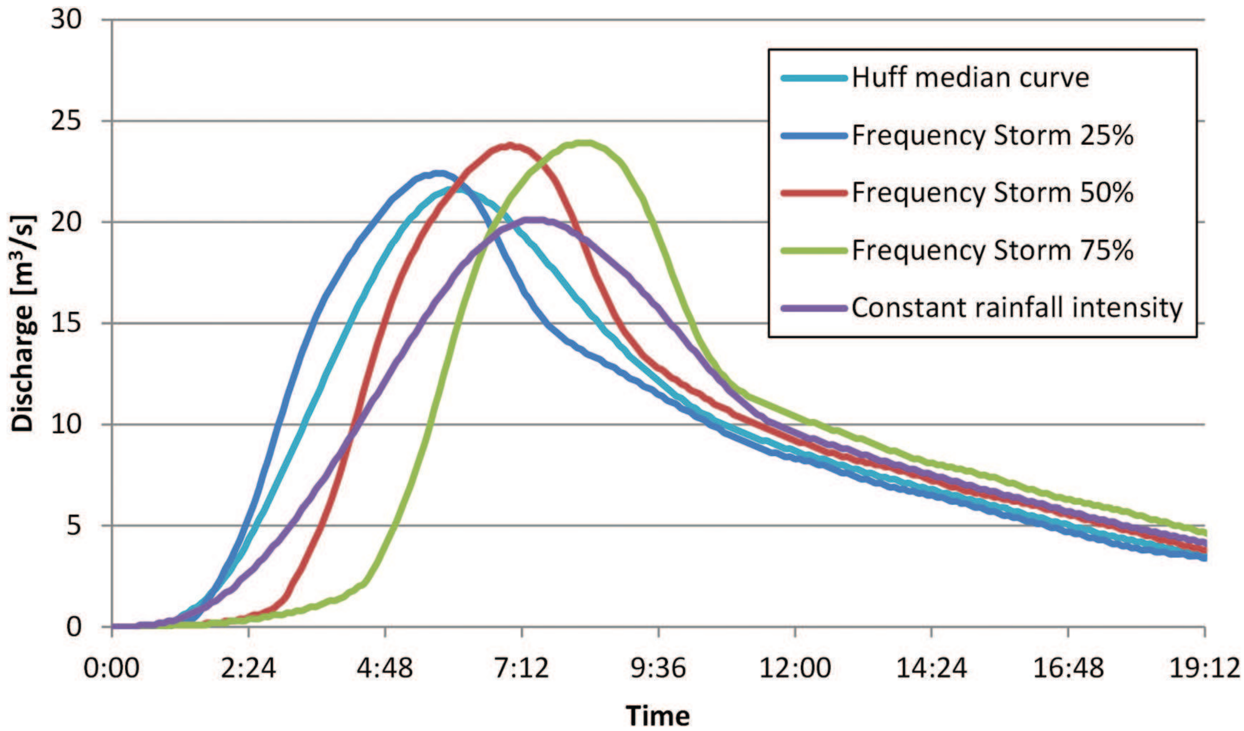

Figure 10. Influence of the temporal rainfall distribution on the modeled discharge values.

4. Conclusions

This chapter presents hydrological modeling results using various types of design hyetographs and their influence on the design discharge values. The presented methods can be used for the design peak discharge value or even complete design flood hydrograph definition in case of ungauged basins or in cases where very little discharge data are available. The HEC-HMS model and the unit hydrograph theory were used in the modeling process. This model is frequently used in the hydrologic engineering practice around the world. Surface runoff was calculated using various design hyetographs where the focus was arbitrarily set on the 10-year return period. Based on the presented results, we can propose general guidelines on how to determine the design hyetograph in case of ungauged (small size, i.e., less than 20 km^2) catchments:

i. Use at least 20 years of high-frequency data from the closest rainfall station to determine the Huff curves and the intensity-duration-frequency (IDF) curves [22].

ii. Based on the time of concentration of the investigated area (i.e., catchment), determine the design storm duration. Based on the modeling and design aim, select appropriate return period, and from the IDF curves, determine the total rainfall amount.

iii. Transform the dimensionless Huff curves into the design storm hyetograph using the appropriate total rainfall amount and duration. Select the median Huff curve as the representative one and two others (e.g., 20th and 80th percentile curves, depending on the design purpose) to calculate the confidence intervals.

Using aforementioned procedure of design hyetograph determination and selected hydrological model, one can calculate either the complete design flood hydrograph or just design peak discharge values.

Furthermore, next conclusions can be made based on the presented results:

a. Huff curves represent the actual rainfall distribution within rainfall event and should therefore be used in practical hydrologic applications.

b. Differences among available methods for the design storm definition were relatively large which was shown for the investigated Glinščica catchment and selected 10-year return period. Furthermore, even larger differences can be expected for longer return periods. Thus, one should avoid assuming and specifically using constant rainfall intensity during rainfall event in order to construct design hyetograph because this can result in the underestimation of the design discharge values and leads to the higher uncertainty in the design flood estimation because differences between constant (uniform) and temporal rainfall distribution determined by the Huff curves should not be neglected. In the case that data from nearby rainfall station are available, one should preferably use Huff curve and the procedure is described in this chapter to determine the design discharge values.

c. In case that measured discharge data are available, it is necessary to include these data in the process of the design flood hydrograph definition (either for statistical analysis or hydrological model calibration and validation).

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