

## INFLUENCE OF TIME OF CONCENTRATION ON VARIATION OF RUNOFF FROM A SMALL URBANIZED WATERSHED

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### Summary

The main objective of the paper is to estimate the influence of time of concentration (TC) on maximum flow in an urbanized watershed. The calculations of maximum flow have been carried out using the Rational method, Technical Release 55 (TR55) procedure based on NRCS (National Resources Conservation Services) guidelines, and NRCS-UH rainfall-runoff model. Similarly, three methods were used to calculate the overland flow component of the TC: the Kerby method, the Morgali and Linsley method and the NRCS travel time method.

The TC was calculated in a watershed located in Krakow city in Poland, małopolskie voivodeship. Total area of the watershed has about 180 ha. It's a highly urbanized watershed with a significant land cover (29.6% of total area) influencing the runoff, in the form of an impervious industrial area.

The highest value of time of concentration was achieved for Morgali and Lindley method in case of the subwatershed with dominant pervious areas, as opposed to the NRCS method for the subwatershed with dominant impervious areas. The highest value of TC was obtained for NRCS method. With reference to the whole watershed, the highest values of the time of concentration were obtained for the Morgali and Lindley method and the lowest for the Kerby formula. Based on this study, authors recommended the Kerby method for estimating TC for overland surface dominated areas because this method requires only a small number of input parameters, that are straightforward to estimate.

### Keywords

urban areas • travel time • NRCS method • Kerby method

### 1. Introduction

Characterization of hydrologic processes of a watershed in the context of drainage design requires estimation of time-response characteristics, which was used in hydrologic models and influence model response to rainfall from real or design storms [Roussel et al. 2005]. Generally, the time-response characteristics of a watershed hydrograph frequently is represented by time of concentration (TC). The time of concentration is the most widely used time parameter for hydrologic analysis.

The time of concentration is an idealized concept and is defined as the time taken by a water parcel of runoff to travel from the hydraulically most remote part of a watershed to its outlet, where remoteness relates to time of travel rather than distance [Maidment 1993]. The author states that probably a better definition is that it is the time after commencement of rainfall excess when all portions of the drainage basin are contributing simultaneously to flow at the outlet. It is one of the most important parameters for determining timing of direct runoff response of a watershed to precipitation. The time of concentration is correlated to different watershed parameters such as watershed area, main channel length, basin slope, soil type, and vegetation (roughness) [McCuen 1989]. Generally, the time of concentration is required for estimating peak discharge by the Rational method or the rainfall-runoff models [Fang et al. 2007, McCuen 1989]. In the context of the Rational method, TC represents the time at which all areas of the watershed will contribute to runoff at the watershed outlet. So, at the time equal to TC the watershed is fully contributing. When TC has been determined, storm duration is made equal to time of concentration [Ponce 1989]. On the other hand Banasik [2009], found that the higher peak flow caused by critical storm duration is higher than time of concentration. In turn, German Association of Water Management and Reclamation [DVWK 1984] suggests that the critical value of precipitation occurs in a time between the time of concentration (TC) and twice the TC. Weinerowska-Borys [2010] suggests that among many methods defining the time of concentration in urbanized watersheds, generally in Polish circumstances, values based on multipurpose guidelines are accepted. Often it leads to accept values of too short TC without considering actual conditions of runoff hydrograph shape, consequently leading to overestimation of maximum flows.

The aim of the paper is to evaluate influence of time of concentration estimated by different methods on maximum flow rate in an urbanized watershed in Poland. The calculations of maximum flow rate have been carried out using Rational method and a method based on NRCS (National Resources Conservation Service) guidelines using Technical Release 55 (TR55) procedure and NRCS-UH rainfall-runoff model.

## 2. Site description

The study watershed is located in within Krakow city in Poland, Małopolskie Voivodeship. Total area of the watershed is about 180 ha. It is a highly urbanized watershed in which a significant land cover from the runoff perspective is composed of an impervious industrial area (29.6% of total area). The general watershed characteristics is presented in Table 1. There are no open channels, streams, and storm sewage system in the watershed, resulting in only surface runoff. The study watershed is an uncontrolled one, with medium porous soils. The Drwinka Długa stream – a left tributary of Serafa, receives discharge from the study site. The watershed has often submergence caused by heavy storms; the last such event occurred in May 2010. For the purpose of the calculations the watershed was divided into two sub-watersheds A1 and A2, which have a different type of land cover; the permeable areas (meadows) are dominant in A1 watershed, while the urbanized areas are dominant in A2.

**Table 1.** Characteristics of study watershed

Parameters	Sub-watershed		Total watershed
	A1	A2	
Area [km <sup>2</sup> ]	0.81	0.99	1.80
Type of cover:			
Industrial areas [km <sup>2</sup> ]	0.00	0.53	0.53 (29.6%)
Streets [km <sup>2</sup> ]	0.015	0.017	0.032 (1.81%)
Meadows [km <sup>2</sup> ]	0.78	0.44	1.22 (67.37%)
Commercial areas [km <sup>2</sup> ]	0.022	0.00	0.022 (1.22%)
Flow length [km]	0.745	1.03	1.775
Weighted land slope [m · m <sup>-1</sup> ]	0.0083	0.00304	0.00541
Watercourse slope [m · m <sup>-1</sup> ]	0.00402	0.00304	0.00353

### 3. Materials and methods

The surface runoff value from the watershed was calculated using Rational method, graphical method featured in TR55 procedure, and NRCS-UH rainfall-runoff model. In case of the Rational method, the flow culmination was evaluated for every sub-watershed and for the whole watershed. The Rational method was tested here although the one subwatershed A2 and the whole watershed drainage area somewhat exceed the limit of 200 acres (80 ha) commonly suggested, although not any hard rule [Thompson et al. 2007]. In the TR55 procedure and rainfall-runoff model, calculations were carried out individually for both sub-watersheds, and calculated hydrographs for direct runoff were summed up at the outlet to obtain the runoff hydrographs for whole watershed.

The Rational method is based on a simple formula that relates runoff-producing potential of the watershed, the average intensity of rainfall for a particular length of time (the time of concentration), and the watershed drainage area. The rational formula is described by the following equation [Trommer et al. 1996]:

$$Q_p = C \cdot q \cdot A \cdot 10^{-3} \quad (1)$$

where:

- $Q_p$  – peak discharge [m<sup>3</sup> · s<sup>-1</sup>],
- $C$  – runoff coefficient [-],
- $q$  – rainfall intensity [dm<sup>3</sup> · s<sup>-1</sup> · ha<sup>-1</sup>],
- $A$  – watershed drainage area [ha].

The runoff coefficient, is a dimensionless ratio intended to indicate the amount of runoff generated by a watershed given an average intensity of precipitation for a storm. The coefficient represents the fraction of rainfall converted to runoff. The values of this coefficient have been established according to watershed land cover using published data [Ponce 1989]. For the settled  $C$  values the weighted-averages as a function of each land cover area were calculated.

Because of absence of precipitation station at or the nearby the study watershed, the intensity of rainfall was evaluated using an empirical method – a regional equation elaborated by Bogdanowicz and Stachy [1998] for Poland, with the exception of mountainous area. The magnitude of maximum rainfall with known time of duration and frequency of occurrence ( $P_{\max(t,p)}$ ) is described by the following equation [Bogdanowicz and Stachy 1998]:

$$P_{\max(t,p)} = 1.42 t_d^{0.33} + \alpha(-\ln p)^{0.548} \quad (2)$$

where:

- $t_d$  – storm duration [min],
- $p$  – probability [-],
- $\alpha$  – parameter of scale and position [mm].

At first the intensity in  $\text{mm} \cdot \text{min}^{-1}$  was evaluated to convert the magnitude of maximum rainfall, which is expressed in  $\text{mm per dm}^3 \cdot \text{s}^{-1} \cdot \text{ha}^{-1}$ . Later it was multiplied by a constant value of 166.7 as a unit conversion factor. For the purpose of this paper, the intensity of rainfall for 1, 10 and 50% exceeding probability was evaluated. In the calculations of rainfall intensity, the time duration of rain was the same as the time of concentration (TC).

However, there are many methods available for estimating TC [McCuen 1989, Thompson et al. 2007]. Three methods were used to calculate the overland flow component of the TC: the Kerby method, the Morgali and Linsley method and the NRCS travel time method. In hydrological practice in Poland, the Kerby method is usually used.

Kerby [Roussel et al. 2005] provides a method to estimate using the following equation:

$$t_c = \frac{0.606 \cdot (L \cdot n)^{0.467}}{S^{0.234}} \quad (3)$$

in which,  $t_c$  is the time of concentration in hours,  $L$  is length of the principal watercourse from outlet to divide in km,  $n$  is the roughness factor and  $S$  is slope between maximum and minimum elevation in meters per meter. The values of  $n$  coefficient were defined based on characteristic of watershed land cover [Ponce 1989]. This method is generally used for areas dominated by surface overland runoff [McCuen 1989, Thompson et al. 2007].

The TC, according to Morgali and Linsley [Aron and Erborge 1973] is described by the following equation:

$$t_c = \frac{0.94 \cdot (L \cdot n)^{0.6}}{i^{0.4} \cdot S^{0.3}} \quad (4)$$

in which,  $t_c$  time of concentration in min.,  $L$  is length of the principal watercourse from outlet to divide in feet,  $n$  is Manning's roughness coefficient,  $S$  is slope between maximum and minimum elevation in feet per feet and  $i$  is rainfall intensity in inches per hour. This method was tested here although it was recommended for urban areas less than 5–10 ha [Thompson et al. 2007].

Rainfall intensity for the watershed, in this method, is estimated using the 2-year recurrence interval. Rainfall duration, which is watershed specific, is computed by an iterative process.

According to the NRCS guideline, it is necessary to add many different times of travel resulting from different field conditions that runoff flows through to reach the point of investigation for the TC estimate. Water moves through a watershed as sheet flow, shallow concentrated flow, swales, open channels, street gutters, storm sewers, or some combination of these. The total time of concentration, TC, is the sum of all runoff travel times. As there is only surface runoff in the watershed, both the sheet flow and shallow concentrated flow were included in calculation of the time of concentration using the NRCS method.

*Sheet flow* is the flow over plane surfaces (parking lots, farm fields, lawns, etc.). It usually occurs in the headwater of streams. With sheet flow, the friction value (Manning's  $n$ ) is an effective roughness coefficient that includes the effect of rain drop impact; drag over the plane surface; obstacles such as litter, vegetation, crop ridges, and rocks; and erosion and transportation of sediment. Travel time ( $t_T$ ), in hours, for sheet flow is computed using NRCS [1986]:

$$t_T = \frac{0.007 \cdot (L \cdot n)^{0.8}}{(I_2)^{0.5} \cdot S^{0.4}} \quad (5)$$

in which,  $L$  is length of the principal watercourse from outlet to divide in feet,  $n$  is Manning's roughness coefficient,  $S$  is slope between maximum and minimum elevation in feet per feet and  $I_2$  is 2-year, 24 hour rainfall intensity in inches.

*Shallow concentrated flow.* After a maximum of 300 feet, sheet flow usually becomes shallow concentrated flow. The average velocity for this flow can be determined from nomogram.

With an objective to conduct a comparison of the results of flow as impacted by the time of concentration, calculations were conducted for the urbanized study watershed according to the Rational method, the TR55 procedure, and the NRCS-UH model in HEC-HMS 3.4. The TR55 procedure details are found elsewhere [NRCS 1986]. TR-55 procedure includes four regional rainfall time distributions. All four distributions are for a 24-hour period. In our calculations the Ia rainfall distribution curve was considered, because according to Banasik [2009], it matches most closely to the time distribution of rainfall found in Poland. The size of surface runoff is defined in accordance with the method elaborated by NRCS (previously SCS) with the use of a curve number (CN) parameter. Determination of CN depends on the watershed's soil and land cover conditions, which the model represents as a hydrologic soil group, cover type, treatment, and hydrologic condition. The very critical parameter in the method described above is the time of concentration. The peak discharge is determined by a graphical method but the runoff hydrograph is calculated using the dimensional unit hydrograph from a Tabular Hydrograph. The unit peak discharge used in the graphical method is similar in concept to the runoff coefficient of the Rational method.

The basis of the study of NRCS-UH model was to test it with numerous unit hydrographs obtained for watersheds with different characteristics and locations. The dimensionless unit hydrograph could be expressed by means of a triangular unit hydrograph. The flow rate in culmination of the unit hydrograph is described by the relationship [Belete 2009]:

$$q_p = \frac{c \cdot A \cdot PE}{t_p} \quad (6)$$

$$t_p = \frac{D}{2} + t_{lag} \quad (7)$$

where:

- $c$  – conversion coefficient,
- $A$  – watershed area [km<sup>2</sup>],
- $t_p$  – time to peak [h],
- $D$  – time of duration of effective precipitation [h],
- $PE$  – unit effective precipitation with 1 mm height,
- $t_{lag}$  – lag time [h].

The lag time,  $t_{lag}$ , has been described as a function of time of concentration in the following relationship:

$$t_{lag} = 0.6 \cdot t_c \quad (8)$$

where, the time of concentration was established according to the NRCS method. The calculations were made using the HEC-HMS 3.4 program [US ACE 2009] and all assumptions for distribution of precipitation and its weight, CN parameter, and watershed structure were made following the TR55 procedure. Some of the discussions on these three methods of estimating the time of concentration are provided by [Thompson et al. 2007].

#### 4. Results and discussion

In table 2, the calculated results of runoff coefficient and times of concentration according to the above described methods are shown. Because of dominance of pervious areas, the weighted-average runoff coefficient of the A1 watershed is much lower than that of the impervious A2 watershed. In case of A2 watershed, where the impervious areas cover almost 54% of its total area, the value of this coefficient is about 71% higher than in case of the A1 watershed. This difference in the C coefficient value is a result of quick response of rainfall on A2 watershed from the watershed. The value of the runoff coefficient for the whole watershed equal 0.295 was because of the considerable proportion of pervious areas in the watershed (over 67% of total area – Table 1). Those proportions of impervious areas in the watershed have repercussions on the values of the time of concentration. It is noticed in the example of TC calculated by Kerby and Morgali and Linsley methods. In case of the A1 watershed, for both methods, the time of concentration is greater than that of the much more impervious A2 watershed. For

Kerby and Morgali and Linsley methods, the TC evaluated for A1 watershed is about 53% higher than for the A2 watershed. It is worthy noting the large differences in evaluated values of time of concentration for both the described methods. The values of TC obtained from Morgali and Linsley method is about 53% higher from those received from Kerby method. Roussel et al. [2005] have observed the similar tendency in their study. These differences have resulted from different approach of TC evaluation used in both the methods, but mostly from different values of coefficient of flow resistance, which is found in described methods. For example, in case of the A1 watershed the value of the coefficient  $n$  in Kerby method was 0.2 and in Morgali and Linsley only 0.05. In the second method the  $n$  values are identical to those given by Manning-Strickler. In case of the A2 watershed, the differences in values of coefficient of flow resistance are lower. The second reason of these differences is the presence of the rain factor as a rainfall with two years of return period in Morgali and Linsley formula. In Kerby method, the time of concentration is only a function of watershed characteristic. The times of concentrations estimated here in Table 2 are well within the range of 10 to 300 min recommended by U.S. Texas Department of Transportation when using the Rational method [Thompson et al. 2007].

**Table 2.** Calculated runoff coefficients and time of concentration for the study watershed

Characteristic	Sub-watershed		All watershed
	A1	A2	
Weighted runoff coeff. [-]	0.124	0.436	0.295
Time of concentration [min], according to:			
Kerby	54.34	25.68	80.02
Morgali and Linsley	117.68	54.65	172.33
NRCS	40.68	61.92	102.6

A very important parameter in Morgali and Linsley and NRCS methods is intensity of precipitation. To evaluate the intensity of precipitation, the empirical formula elaborated by Bogdanowicz-Stachy was used in case of the study watershed. The precipitation curves with 1, 10 and 50% probability of exceedance and time of duration from 1 to 1440 min are shown in Figure 1. The method used to calculate the value of the precipitation properly describes the real progress of precipitation in the Krakow area. According to Cebulak et al. [2000], the precipitation with 24 hour duration and 1% exceedance probability equals to 100–110 mm, 10%–70 mm and 50%–40 mm, respectively. The values of these precipitations had been developed based on distribution of Fishera-Tippeta III max and the data from years 1951–1997. The values of 24-hour duration precipitation obtained from Bogdanowicz-Stachy method for 1%, 10%, and 50% exceedance probability were 94 mm, 67.5 mm, and 41.4 mm, respectively.

To evaluate the time of concentration as per the TR55 procedure, a sheet flow was assumed in the first parts of the A1 watershed with flat and pervious surfaces (roads), and the formula (5) was adopted for calculating the travel time. In the remaining part

of the A1 watershed and for the whole length of runoff path in the A2 watershed, a shallow concentrated flow was assumed. The calculated time of concentration value for the A1 watershed was the lowest based on the described methods. However, its value is higher relative to those evaluated for the much more pervious A2 watershed. This has resulted from the fact that the velocity of runoff, in case of shallow concentrated flow, was based for the roughness coefficient  $n$  equal to 0.025 [SHA 2005], which is much higher in comparison with the one (0.011) obtained from Morgali and Linsley method. In general, the NRCS method based values of time of concentration for the whole watershed are higher by about 22% in comparison with the Kerby method and lower by about 40% in comparison with the Morgali and Linsley method. According to Fang et al. [2007],  $TC$  estimated using the velocity method is subject to large variation, dependent on the approach and parameters selected by the analyst responsible for estimating the flow velocity. Precise estimation of some of the input parameters for the NRCS travel-time method is difficult. In particular, repeatable application of Manning's equation using generalized measures of geometry and roughness that are representative of the hydraulic and hydrologic processes influencing the watershed is

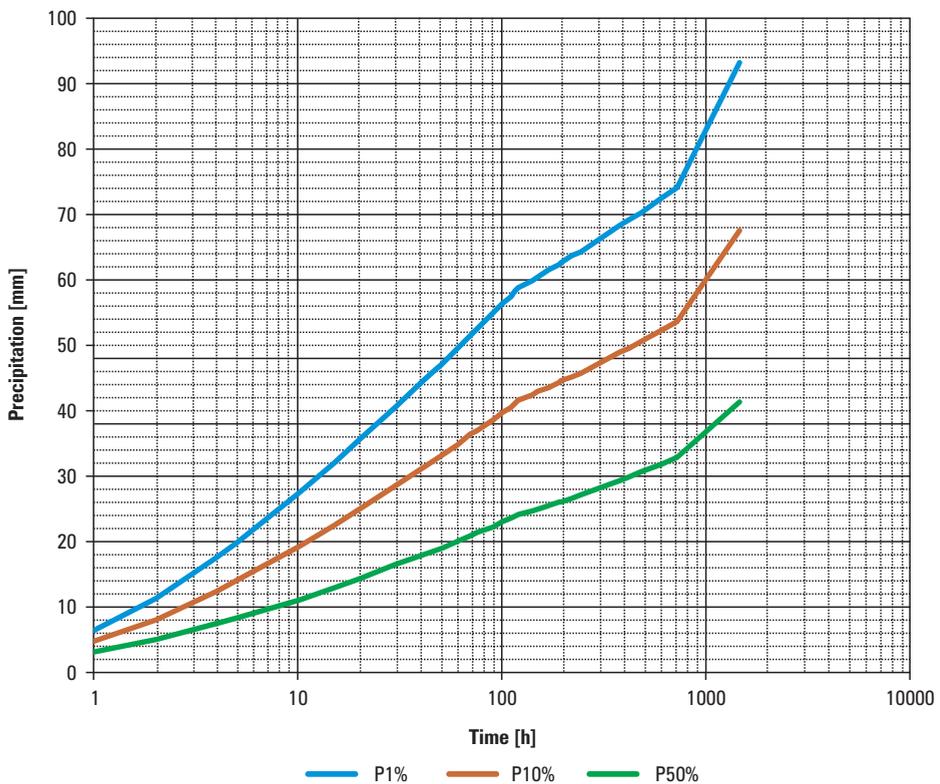


Fig. 1. Relationship between precipitation depth and duration for different probabilities of exceedance

difficult. Overall, the time of concentration developed by Kerby method has a greater recurrence of the results in comparison with the NRCS method, and therefore, this method is much more preferred to the NRCS method by the hydrologists [Roussel et al. 2005]. A considerable simplification of estimation of parameters and a big effectiveness of the NRCS method can be obtained for the assessment of runoff by GIS techniques [Green and Nelson 2002].

The values of time of concentration have effects on the maximum flow values – Table 3. In case of the Rational method in A1 watershed, the biggest maximum flow with 1% exceedance probability has been observed for TC calculated by the NRCS method, and the lowest for the TC obtained by the Morgali and Linsley formula. As it was stated before, the values of time of concentration have influenced on the results of flow calculations. Its high values on A1 watershed was almost 118 min, which was the reason for the very small value of flow –  $0.59 \text{ m}^3 \cdot \text{s}^{-1}$ . An opposite situation was obtained in case of the impervious A2 watershed. The lowest value of TC of 26 min was obtained by Kerby formula resulted in the highest value of runoff ( $7.59 \text{ m}^3 \cdot \text{s}^{-1}$ ) of all the comparable methods. The lowest values of flow were obtained for the TC calculated by the NRCS method. Comparing the results of  $Q_{1\%}$  for the three methods of estimating TC with reference to the whole watershed, it can be ascertained that the highest value of  $4.15 \text{ m}^3 \cdot \text{s}^{-1}$  was obtained for the TC defined by the Kerby method and the lowest for the TC defined by the Morgali and Linsley formula. The  $Q_{1\%}$  flow calculated by Kerby formula was higher than those from the other two methods by about 17 and 44%. For comparison, the maximum flow using the Rational method for rainfall event recorded at Jagiellonian University precipitation station has been calculated as  $99 \text{ m}^3 \cdot \text{s}^{-1}$  in 120 min. In addition, the highest rainfall event was noted from the beginning of precipitation observed in Krakow [Niedźwiedz 1988], which is about 1 km away from the study watershed. For calculating the time of concentration, it was assumed equal to the time of rainfall event duration, e.g. 120 min. It was the same time of rainfall duration for each of the sub-watersheds. In terms of the extreme duration of rainfall, the values of maximum flow exceeded those obtained from the other described methods, except for the A2 watershed. The smallest differences were observed in case of the A1 watershed that is characterized by considerable parts of pervious areas, in which a big part of rainfall is lost by interception and infiltration. In watersheds where the impervious areas are dominant, the differences were much bigger. However, in case of the A2 watershed the highest flow noted was for the TC calculated using the Kerby formula. Maximum flow with 1% exceedance probability, calculated for the whole watershed based on the observed rainfall was the highest one in comparison to the two other methods. In summary, the highest values of flow by the Rational method were obtained when the time of concentration was calculated using the Kerby method. In case of the watershed where pervious areas are dominant, the differences between the NRCS and Kerby methods were found insignificant. However, the value of the flow calculated using the Morgali and Linsley method in calculation of the time of concentration was considerably different. It seems that this method, in this case, is of no use in calculation of runoff. In case of the impervious watershed, differences between flows are clearly

insignificant between the NRCS and Morgali and Linsley methods, but the values obtained by the Kerby method were markedly different.

In Table 3, the values of  $Q_{1\%}$  calculated using the TR55 procedure and rainfall-runoff model based on the NRCS unit hydrograph are presented. In case of both the methods the value of CN parameter was assumed equal to 80 for the A1 watershed and 84 for A2. There was only a small difference of 4% in  $Q_{1\%}$  values between these methods, in case of A1 watershed, Since these values increase with the increase of degree of imperviousness, it reached almost 30% for the A2 watershed. In general, the values of  $Q_{1\%}$  flows obtained from the NRCS-UH model were higher by about 21.4% compared to these calculated by TR55. The differences in results could be due to other values of initial abstraction or differences in calculations of flow in culmination of unit hydrograph. It is very interesting to note that the values of  $Q_{1\%}$  for the whole watershed calculated by the Rational method with TC value evaluated by Kerby formula and by the TR55 are almost similar.

**Table 3.** Comparison of  $Q_{1\%}$  in  $m^3 \cdot s^{-1}$  calculated from rational method, TR55 procedure and for different times of concentration

Method	Sub-watershed		All watershed
	A1	A2	
Rational method: TC from:			
Kerby	1.04	7.59	4.15
MorgaliandLinsley	0.59	4.46	2.32
NRCS	1.29	4.06	3.43
Observed precipitation	1.39	5.91	7.30
NRCS method from TR55 model	1.83	2.41	4.12
NRCS – UH model	1.902	3.43	5.243

The comparison of hydrographs of surface runoff obtained from the TR55 and NRCS methods using the HEC-HMS 3.4 program are presented in Figures 2 and 3, respectively. The progress of the hydrographs is similar in both the cases, the largest differences are noticed at the beginning of the rise; the NRCS-UH method gets the better image of the watershed response from the beginning of the runoff. In case of both the methods, a rapid A2 watershed response of the rain has been observed, with higher runoff from much more impervious watershed. The volume of the runoff from A2 watershed equaled 38500  $m^3$  and from A2 – 74500  $m^3$  for NRCS method. The total value of runoff from the study watershed equaled 113000  $m^3$ , which was on the response of the 1% exceedance storm.

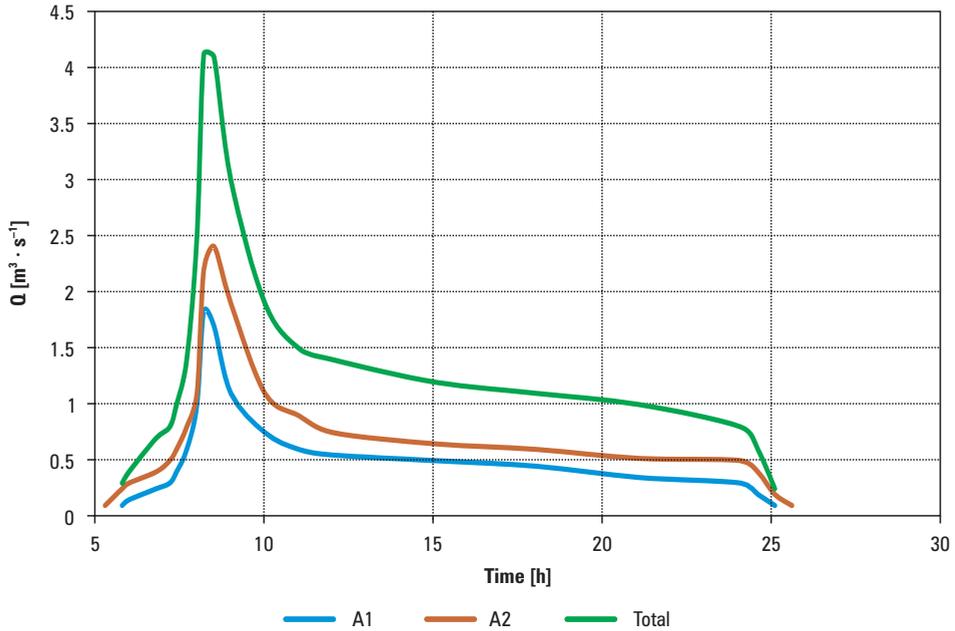


Fig. 2. Comparison of hydrographs for 1% storm from TR55 model for analyzed watershed

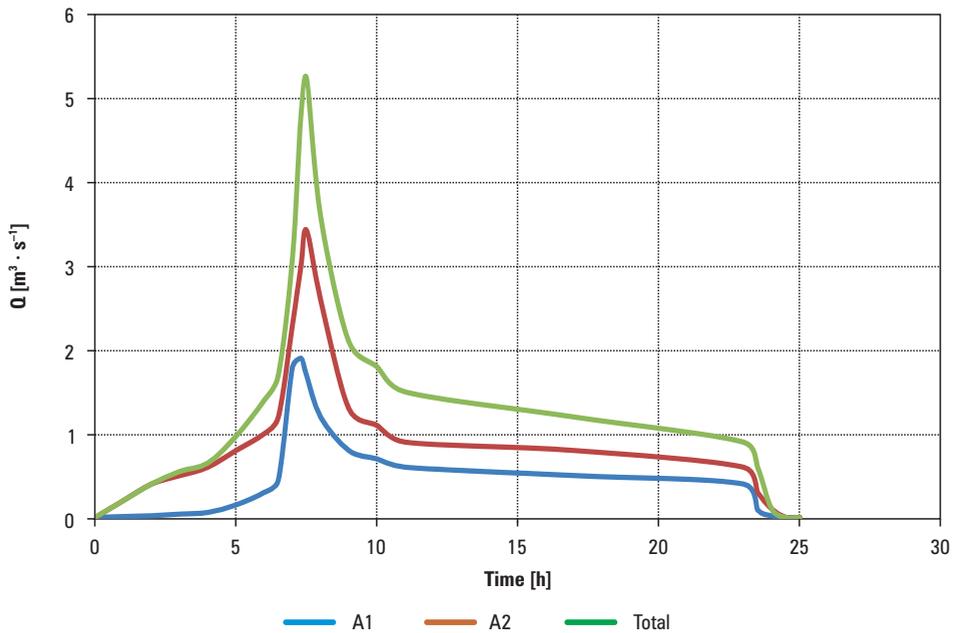


Fig. 3. Comparison of hydrographs for 1% storm from NRCS-UH model for analyzed watershed

## 5. Conclusions

Based on the calculations following results and conclusions are summarized:

1. The increase in impervious degree of watershed influenced on the faster response of the storm. It resulted in decrease of time of concentration and increase in the value of runoff.
2. In case of the watershed with dominant pervious areas, the highest value of time of concentration was achieved for Morgali and Lindley method. On the other hand, in watershed with dominant impervious areas, the highest value of TC was obtained for the NRCS method. With reference to the whole watershed, the highest values of time of concentration were obtained for the Morgali and Lindley method and the lowest for the Kerby formula.
3. Based on the results for the study, the Morgali and Lindley method is not recommended for TC evaluation for pervious area dominated watersheds, because the values of this parameter were substantially higher in comparison to the other methods, which, in consequence, leads to get the insignificant values of runoff.
4. The values of runoff obtained from TR55 procedure is higher in comparison with those calculated using the Rational method, and also that using the TC value according to Morgali and Lindley or NRCS method, but in case of Kerby method they were similar.
5. In consideration of ease of calculations and only a small number of parameters in TC calculation, the Kerby method is recommended, more so for the areas with more overland surface runoff [McCuen 1989]. The alternate option could also be the NRCS method, but only with precise calculations of all parameters including those especially important in this method, like a roughness coefficient or a runoff road characteristic.
6. The hydrographs of surface runoff obtained from both the TR55 and the NRCS-UH based rainfall-runoff model have a similar shape and demonstrate the watershed response of the storm.
7. The TR55 procedure can be used in case of a necessity of knowledge of flow in culmination and the shape of surface runoff hydrograph on impervious watersheds with small areas.

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