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The influence of synthetic hyetograph parameters on simulation results of runoff from urban catchment

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Abstract. The paper presents the results of analysis of the influence of the maximum intensity (peak) location in the synthetic hyetograph and rainfall duration on the maximum outflow from urban catchment. For the calculation Chicago hyetographs with a duration from 15 minutes to 180 minutes and peak location between 20% and 50% of the total rainfall duration were design. Runoff simulation was performed using the SWMM5 program for three models of urban catchment with area from 0.9 km^2 to 6.7 km^2. It was found that the increase in the rainfall peak location causes the increase in the maximum outflow up to 17%. For a given catchment the greatest maximum outflow is generated by the rainfall, which time to peak corresponds to the flow time through the catchment. Presented results may be useful for choosing the rainfall parameters for storm sewer systems modeling.

1 Introduction

Rainfall input data for modeling the outflow from urban catchment can be represent by the historical recorded rainfalls, synthetic hyetographs or hyetographs developed with stochastic models [1, 2]. Synthetic hyetographs are mainly used in the design of new sewerage systems, including determining the level of flood protection. They are useful especially where there is no access to historical rainfall data. Synthetic rainfalls can be developed on the basis of direct analysis of recorded rainfall data or IDF (or DDF) curves. This form of data is very often the only source of information about the characteristics of rainfall in the area. IDF curve allows to specify the average rainfall intensity as a function of the rainfall duration and the frequency of occurrence. DDF curve shows a similar relationship in relation to the cumulative rainfall depth. With the use of IDF or DDF curves block rainfalls can be determined, i.e. the rainfalls with constant intensity for considered rainfall duration. This kind of data is insufficient for the rainfall - runoff transformations in the simulation model [3]. It's because they do not take into account the one of the main rainfall characteristics - the variability of intensity over time.

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Basic rainfall characteristics obtained from the IDF or DDF curves are transformed into synthetic rainfall with variable intensity or depth in time. One of the most popular synthetic rainfall in Germany and Poland is Euler (type II) rainfall [1], characterized by the location of the maximum intensity (intensity peak) in the 30% of the total rainfall duration. The popularity of this hyetographs is a result in large part of simple design. Location of the rainfall intensity peak for real rainfalls is not constant [4, 5, 6]. Synthetic rainfall should represent the characteristics of real rains, so the construction of the synthetic hyetograph should enable the change of rainfall intensity peak location. This possibility is given by Chicago hyetographs [7]. The development of synthetic rainfall by this method, however, is relatively complex, especially when compared with Euler rainfalls.

The use of synthetic rainfall is sometimes criticized [8]. The primary complaint is the lack of linearity of the rainfall - runoff transformation which causes that rainfall and runoff frequency of occurrence are not equal [9]. The rainfall frequency of occurrence considered in the IDF or DDF curves concerns only one rainfall characteristic, which is the average intensity or cumulative depth. The outflow is much more complex, characterized for example by volume and intensity peak. The rainfall frequency of occurrence can be assigned to one of the outflow characteristics. In the simulation analysis of sewerage systems both the free surface flows and pressure flows are taken into account. If there is no flooding, runoff is generated from impervious area. Runoff from pervious area does not occur or is negligibly small [10, 11]. In this situation, if the parameters of the catchment are constant for concerned task, rainfall with given depth will generate the same runoff volume, regardless of the form of synthetic hyetograph. This outflow characteristics can be compared with the frequency of rainfall occurrence. In formulating the assumption that for a given depth of rainfall and it's duration synthetic hyetograph generates the greatest outflow peak, it can be assumed that the frequency of rainfall occurrence can be identified with the frequency of occurrence of maximum outflow. This justifies the use of synthetic rainfalls, especially in the case of a limited access to other rainfall data.

The value of the frequency of rainfall occurrence for a given task are specified in regulations, for example European Standards [12]. The rainfall duration is usually determined according to individual decisions. In the literature recommended rainfall durations are mostly related to the flow time through the catchment and are equal to multiply of this value [13]. The flow time by the catchment, identified with the time of concentration, is derived from the traditional methods of sewerage systems design based on The Rational Formula [14]. For constant rainfall intensity maximum outflow will occur at a time when the whole catchment will be involved in generating the outflow. To meet this condition the rainfall must last so long that storm water from the farthest point of the catchment will reach the considered cross section. In the case of rainfalls with parameters variable at the time, the greatest outflow appears after the pulse of rainfall with a maximum intensity or depth. Therefore, it should be expected that the peak location is related to the area of the catchment, represented by the flow time. Mentioned issue is raised in very small number of publications [1,13], so it was consider worth investigating.

The aim of the analysis presented in the paper is the assessment of the impact of the synthetic hyetograph parameters (rainfall duration and peak location) on the maximum outflow. Obtained results can be used to unify the determination of the synthetic hyetograph parameters for the verification of sewerage systems requirements according to the EN 752 standards.

2 Materials and methods

In presented analysis the synthetic hyetographs, whose design is based on the assumptions of the Chicago method [7], are used. The location of the maximum intensity (the peak) is specified by the ratio *r* - the dimensionless time to peak related to the rainfall duration. A detailed description of the construction of this hyetograph can be found in the literature [15, 16]

The rainfall intensities were calculated with the use of Bogdanowicz-Stachý Formula, which is a form of DDF curve for Polish conditions [17]. To achieve the purpose of this analysis the hyetographs for frequency of occurrence of 2 years were developed. This value is recommended for storm sewer design according to the standards EN-752. Outflows caused by these rainfalls should be the free surface flows and the outflow hydrographs should not be distorted as a result of the pressure flow. The synthetic rainfalls with a durations T_D from 15 min to 180 min were analyzed (the durations increased of 5 min). The ratio *r* was established on the basis of the literature review and analysis of rainfall data registered in the city of Poznań [15]. The values of ratio *r* varied from 0.2 to 0.5 (the increment was 0.1). In total, 136 synthetic rainfalls were used for storm sewer system simulations. The examples of hyetographs developed for T_D = 90 min are shown in the figure 1.

The decrease in the maximum rainfall intensity with the increase in the value of the ratio *r*, can be assign to properties of used hyetographs. The functions describing the variation of the rainfall intensity before the peak and after the peak are dependent on the value of the ratio *r* [7]. The higher the *r* value, the smaller increases of rainfall intensity in the following time steps. For values of *r* = 0.5, functions describing the rainfall intensities before and after the peak are equal and the hyetograph is symmetric.

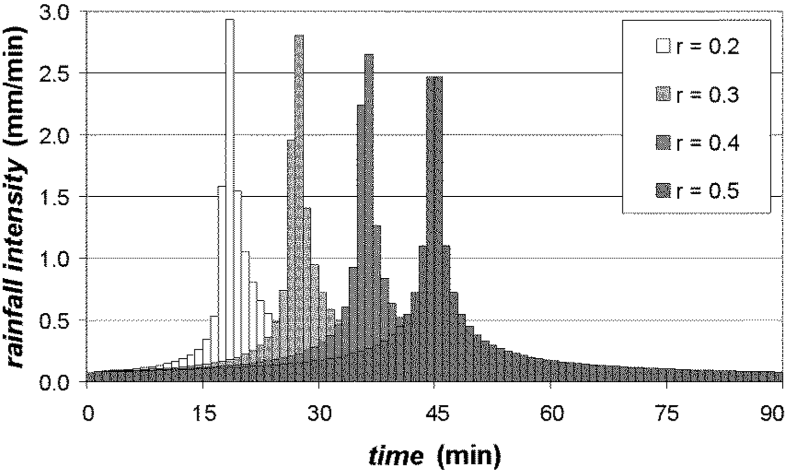

Fig. 1. The examples of synthetic hyetographs for rainfall duration T_D = 90 min and different values of the ratio *r*

Determined synthetic hyetographs were used to perform outflow simulations from three real catchments. Their basic characteristics are shown in table 1. Catchments described by A and B are located in the city of Bydgoszcz, the catchment described by C is located in the city of Poznań. Catchment models have been developed in SWMM5 [18].

The storm water from all catchments is collected into drainage system of circular cross-sections (fig. 2). In concerned drainage systems there are no special objects e.g. retentions reservoirs or pumping station, which could affect the hydrographs. The rainfall - runoff transformation is a result only of the surface runoff and flow in the channels.

Table 1. The basic characteristics of the catchments used in the analysis

Catchment description	**Total area F(ha)**	**Percent of impervious area ψ (%)**	**Longest flow time T_F (min)**
A	89	26	21
B	172	26	30
C	670	29	50

To determine the relationship between the catchment characteristics and the parameters of synthetic rainfalls generating the maximum outflow for each catchment, the longest time flow T_F through the channels for each catchment was calculated (table 1). The values of T_F were calculated using the Chezý formula with the Manning coefficient for cross-sections and slopes of sewers the same as in the catchment models, assuming full flow conditions.

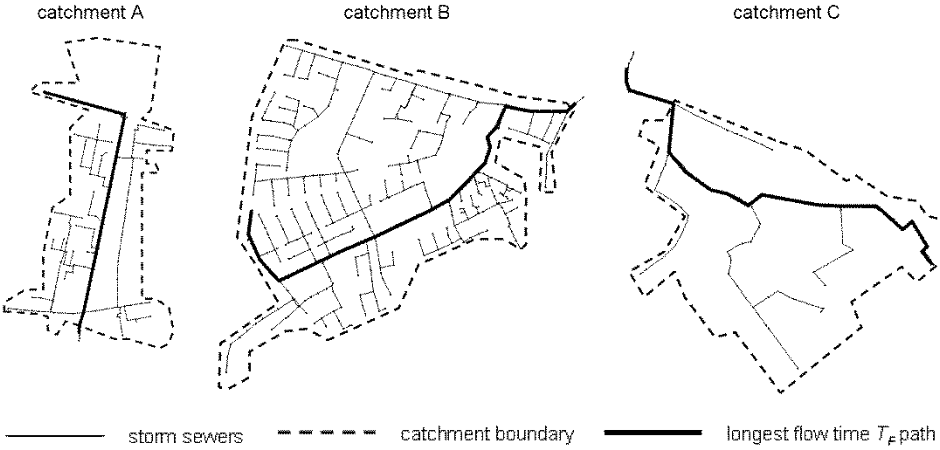

Fig. 2. The schemes of analyzed catchments (figures without proportions between catchments)

Concerned catchments have a monitoring system of rainfalls and outflows. On the catchments A and B rain gauges and flow meters are operated by MWiK in Bydgoszcz. Measurements on the catchment C are performed by Poznań University of Technology. Data provided by MWiK in Bydgoszcz shows that for the real rainfalls catchment models represent the maximum outflow with an accuracy of ±15% and the differences of the times to peak do not exceed 5 min. A similar accuracy were obtained for the catchment C [19]. Thus the accuracy of simulation results should be considered as acceptable.

The influence of rainfall duration T_D and rainfall peak location (represented by the ratio r) on maximum outflow Q_P were examined. The maximum outflow is the greatest outflow computed for specific rainfall parameters: T_D and r. Outflow hydrographs were determined for the cross – sections located at the end of the longest flow time path (fig. 2). Due to the different areas of the individual catchments, the calculated values of the maximum outflow vary significantly. To allow the comparison of values Q_P computed for each catchment, a dimensionless relative maximum outflow δQ was used:

$$\delta Q = \frac{Q_P}{Q_B} (-) \tag{1}$$

where:
Q_P –maximum outflow computed for a specified rainfall duration T_D and ratio r (dm^3/s)
Q_B - base maximum outflow computed for the duration T_D = 180 minutes and r = 0.3 (dm^3/s)

The value of ratio r for rainfall generating base maximum outflow was taken according to the Euler hyetograph type II, where the peak is located at 30% of the total rainfall duration. In presented analysis the longest rainfall duration was chosen, as for long rainfall durations maximum outflows take the greatest values. The base maximum outflow is therefore the greatest maximum outflow generated by the rain with ratio r equal to 0.3, and this value is constant for the catchment area.

3 Results and discussion

For a specific rainfall duration T_D, the increase in ratio r causes an increase in maximum outflow (fig. 3a, c, e). These changes are similar for all catchments - the increments of the relative maximum outflow δQ vary from 0.02 to 0.17. The average value of the increment δQ changes from 0.09 for catchment C to 0.14 for the catchment B and is not related to the catchment area. Changes of Q_P may be partly related to the changes of the maximum rainfall intensity, which are a result of changes in the ratio r.

It should be noticed that the increase in the maximum outflow occurs in spite of decrease in the maximum rainfall intensity (fig. 1). This is the result of the catchment capacity to buffer short rainfalls with high intensities. Assumed time step of discretization equal to 1 minute allows to accurate describe the rainfall variability within rainfall duration. However, high temporary rainfall intensities do not generate sufficiently great outflows. Buffering maximum rainfall intensities is not related to the total area of the catchment area. It takes place at the stage of transformation the rainfall into the surface runoff in the subcatchments.

For large catchment areas (catchments B and C), maximum outflows for rains of short durations (less than 30 min) are clearly smaller than the value Q_P calculated for the longer rains. This is the result of surface retention of the catchment. In case of short rains, the rainfall depth before the peak is used to fill the surface retention. The less rainfall depth is transformed into the outflow, what in turn reduces the outflow peak.

For constant ratio r, the increase in rainfall duration T_D causes the increase in maximum outflow (fig. 3b, d, f). Change of relative maximum outflow δQ vary from 0.07 to 0.21. The average increase of value δQ ranges from 0.09 to 0.19, respectively for the catchment A and C. For considered rainfall durations and values of ratio r, the influence of the rainfall duration T_D on the maximum outflow is slightly greater than the influence of the ratio r. Average change of the maximum outflow increases with an increase in the catchment area.

When a certain value of rainfall duration, called threshold time T_{DT}, is reached, the maximum outflow remains almost constant (fig. 3b, d, f). Values of T_{DT} evaluated for each catchment were compared with the longest flow time T_F through a network (tab. 2). In addition, for a given rainfall time to peak T_P for hyetograph was specified. Time to peak T_P was obtained by multiplication rainfall duration T_D and ratio r. On the basis of a comparison of an average values of time to peak for hyetograph T_P and flow time T_F for a considered catchments, it can be concluded that these values are similar.

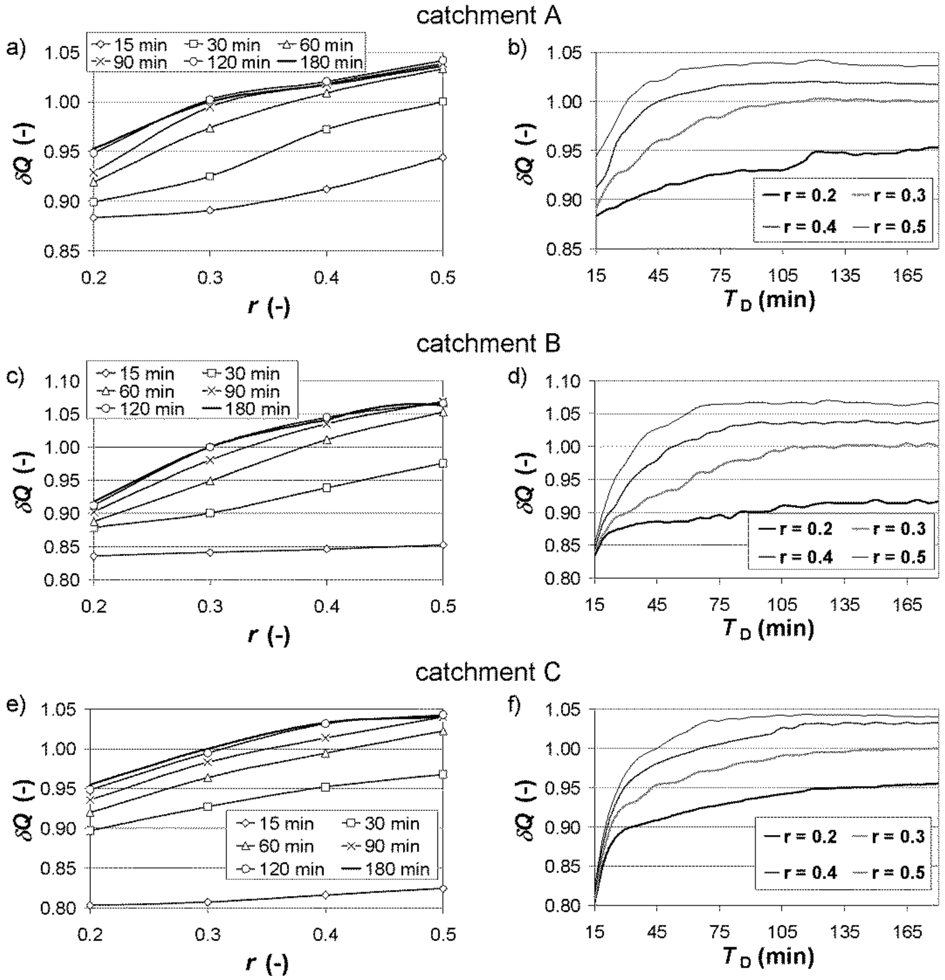

Fig. 3. The relative maximum outflow δQ as a function of the ratio r (a)(c)(e) and as a function of the rainfall duration T_D (b)(d)(f)

In order to complete the analysis the outflow hydrographs were compared. The hydrographs calculated for catchment A and rainfalls with equal time to peak T_P were taken into account (fig. 4).

All considered rainfalls generate maximum outflows of comparable value and in the same time (for the same time to peak of maximum outflow). The maximum difference Q_P does not exceed 8% and times to peak of maximum outflows do not differ by more than 2 min.

Presented results indicate that the maximum outflow from the catchment is a function not only of the total rainfall duration and the corresponding average rainfall intensity or depth (according to the IDF or DDF curve), but also of the location of the peak in the hyetograph. The increase in rainfall depth as a result of increase in rainfall duration changes the shape of outflow hydrograph after the peak (fig.4).

According to recommendations presented in the literature, the maximum outflow from the catchment is generated by the rainfall with a duration of at least four times larger than the flow time [13]. Cited analysis was performed with the use of Euler hyetograph type II, whose peak is at 30% of the total rainfall duration (time to peak T_P is therefore 0.3 T_D).

After extending the rainfall duration T_D to the value of the 4 T_F, time to peak T_P of 1.2 T_F is obtained. This value corresponds to the results presented in the paper. Increase in the time to peak T_P can be obtained not only by extending the total rainfall duration but also by changing the rainfall peak location. In case Chicago hyetographs increase in the value of ratio r leads to the slightly increase in the maximum outflow.

Table 2. Threshold times T_{DT} of rainfalls for analyzed catchments

Ratio r (-)	**Catchment A (T_F = 21 min)**		**Catchment B (T_F = 30 min)**		**Catchment C (T_F = 50 min)**	
	T_{DT} (min)	**T_P (min)**	**T_{DT} (min)**	**T_P (min)**	**T_{DT} (min)**	**T_P (min)**
0.2	120	24.0	125	25.0	175	35.0
0.3	100	30.0	110	33.0	165	49.5
0.4	70	28.0	95	38.0	135	54.0
0.5	55	27.5	70	35.0	90	45.0
	Average	27.4	Average	32.8	Average	45.9

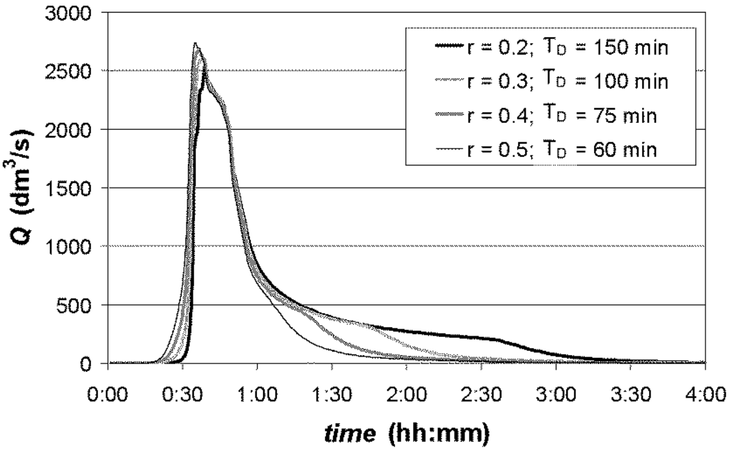

Fig. 4. Examples of outflow hydrographs for catchment A and rainfalls of T_P = 30 min

4 Conclusions

Results of the presented analyses allow to formulate the following conclusions:

1. The increase in the ratio r causes the increase in the maximum outflow.
2. For a specific value of ratio r maximum outflow increases with an increase in rainfall duration until the threshold time is reached. After exceeding the threshold time maximum outflow does not change its value.
3. The threshold time decreases with an increase in ratio r.
4. The comparable maximum outflows can be generated by synthetic rainfalls with a specific time to rainfall peak, regardless of the value of the total rainfall duration and ratio r.

5. The greatest maximum outflow is caused by the hyetograph with the location of the rainfall peak similar to the longest flow time through the drainage network.

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