MIDDLE POMERANIAN SCIENTIFIC SOCIETY OF THE ENVIRONMENT PROTECTION

Rocznik Ochrona Środowiska

Volume 22. Year 2020 ISSN 1506-218X 892-904

Duration of a Design Rainfall for Urban Drainage System Modelling

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1. Introduction

Synthetic hyetographs are one of the basic sources of rainfall data for the hydrodynamic modelling of stormwater systems (Veneziano & Villani 2009, Cazanescu & Cazanescu 2009, Ellouze et al. 2009, Lu-Hsien et al. 2011). Especially in case of the deficiency of recorded rainfall data they are an alternative input data to series of historical rainfalls and stochastic models used for generating rainfall series (Licznar et al. 2011, Knighton & Walter 2016).

The use of hyetographs with simple design is particularly justified in analyzing at the stage of designing new stormwater systems. Due to the lack of possibility of calibrating the computer model, a significant uncertainty of the simulation results, related to the unverified selection of the values of model parameters, should be expected. In that case, using complex design rainfalls is not justified.

For selection of the sewer cross sections, rainfall data in the form of IDF (Intensity-Duration-Frequency) or DDF (Depth-Duration-Frequency) curves, describing the relation between the frequency of rainfall occurrence, the rainfall duration and respectively the rainfall intensity or rainfall depth, are used. These curves give information only about average intensity at a specified time. The use of rainfalls with intensity constant in time for hydrodynamic modelling may lead to underestimating of the calculated runoff (Alfieri et al. 2008). Synthetic hyetographs should represent the basic characteristics of real rainfalls, of which the most important is the variability in time. The greatest instantaneous rainfall intensity is called a peak. The location of the rainfall peak for real rainfalls is not constant and has a significant impact on the maximum outflow (Urcikán & Horváth 1984, El-Jabi & Sarrat 1991, Mazurkiewicz 2016). Synthetic hyetographs usually represents the rainfalls with one maximum intensity (peak).

Due to the availability of IDF or DDF curves, either for local or larger areas (a region or a whole country) (Kotowski et al. 2010, Fadhel et al. 2017, Kaźmierczak et al. 2017), in hydrodynamic modelling of the stormwater systems the hyetographs based on these curves are used. For transformation rainfall data from the IDF or DDF curves to the hyetograph, widely used are Euler hyetographs (Schmitt 2000) and Chicago method (Keifer and Chu 1957, da Silveira 2016).

The use of synthetic hyetographs involves a significant limitation. The frequency of occurrence, included in the IDF or DDF curves, refers only to the rainfall depth at a specified rainfall duration, so it cannot be assigned to any of the runoff characteristics (Adams & Howard 1986, Vigilone & Blösch 2009). This is particularly important in the design of stormwater systems, where for description of the conditions of the these systems the frequency of occurrence is used (EN752 2017), for example in case of pressurized flow for a specified surcharge level in the sewer. The assessment of the conditions of pressurized flow requires the determination of maximum runoff from the catchment. Thus, the hyetograph, that for a given frequency of occurrence will generate the worst conditions, i.e. maximum outflow, is need to be found.

For a given shape of the hyetograph, change of the rainfall peak, which has an impact on the value of the outflow (Dunkerley 2012), can be caused by changing the total rainfall duration. Therefore, determining the design rainfall duration, which will generate the greatest possible outflow, is necessary. For hydraulic calculation and selection of the sewers cross sections, it is recommended that the design rainfall duration should be equal to the flow time through the catchment (ASCE 1992, Crobeddu et al. 2007). For the purpose of hydrodynamic calculations, the design rainfall duration should be at least two times longer than mentioned flow time (Kaźmierczak & Kotowski 2012). Besides these general guidelines, a more detailed information concerning the selection of a design rainfall duration were not found in the literature. Due to this fact, the need of specified recommendations for the selection of the rainfall duration, in the opinion of the authors of presented publication, justifies the topic.

Two basic aims of the analysis were formulated.

- The first was the determination of the design rainfall duration, which generates maximum instantaneous outflow from the catchment.
- The second aim was the evaluation of the relation between the design rainfall duration that generates the maximum outflow and selected catchment characteristics. The knowledge of these relations is important from a practical point of view, and can be used for estimation of the design rainfall duration for selected catchment on basis of the knowledge of its characteristics.

2. Methods

2.1. Catchments

Analyses presented in the publication were made based on eight existing urban catchments located in Bydgoszcz (Figure 1). The catchment areas varied from 35 to 280 ha. Other chosen basic parameters of the catchments are shown in Table 1 placed in the further part of the paper. The receivers of the rainwater collected in the catchments are the Brda river (for catchments C1-C5), the Brda channel (for catchments C6 and C7) and the Vistula river (for catchment C8).

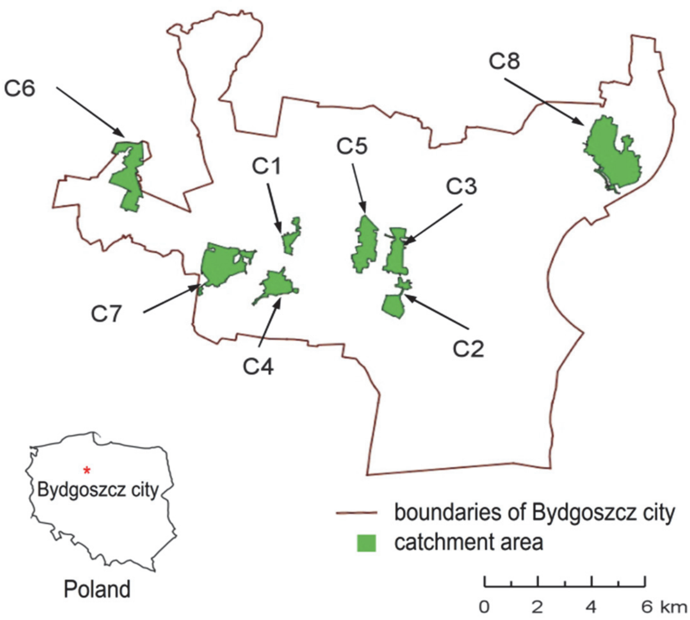

Fig. 1. The location of the catchments in Bydgoszcz

For rainfall-runoff simulations the hydrodynamic model SWMM5.1.013 was used (Rossman 2015). The catchment models have been developed and made available by MWiK in Bydgoszcz (Poland), the company that operates the described stormwater systems.

For three catchments (C3, C5 and C7) in 2016 the outflow measurements were carried out. Collected data together with data from the rainfall monitoring network in Bydgoszcz (also operated by the MWiK) allowed the calibration of models of these catchments. Values of the outflow obtained as a result of the outflow simulation and recorded outflow hydrographs were consistent.

Differences between the simulated and registered peak flows and the values of total outflow volume were compatible within the range of ±15%. These values were considered as acceptable and meeting the requirements concerning storm water system simulation models (UDG 2017). Rainfall data for catchments C3 and C5 were taken from one pluviometer located approximately 400-500 m from the catchments boundaries. In case of catchment C7 the pluviometer was located on the catchment area. All of the pluviometers registered the instantaneous rainfall intensity with the time step of 2 min. The outflow measurements were performed with the use of ultrasonic flow meters installed in the sewers close to the sewer outlets. The time step of registered outflow was also 2 min. For the models calibration the hydrographs for four rainfalls were used. These hydrographs were registered during the measurement campaign from May to July 2016.

All the catchments have very similar development and storm sewers, located on these catchments, are made of the same material, have similar age and are in similar condition. That gives grounds to assume that for all analyzed catchments the rainfall-runoff transformation will be performed under similar conditions.

For each catchment model the control cross section of main sewer, approximately 200-300 m before the sewer outlet, was chosen. For selected control cross section the outflow hydrographs were examined. For the purposes of the presented analysis, it was assumed that the outflow from the catchment would be represented by the outflow peak Q_{MAX}, that is the greatest value of the outflow calculated for a given rainfall. The use of the rainfall that generates the maximum outflow in the sewer outlet will cause the maximum outflows in other sewers, for which the flow time is shorter. That leads to assumption that the results consideration can be limited only to the outlet sewer characterized by the longest flow time.

It was assumed that analyzed catchment characteristics should have a clear interpretation and be easy to determine. It was decided, therefore, to use the four catchment characteristics: total catchment area A, the impervious area A_{IMP}, the longest flow path by the catchment L and the longest flow time through the sewers T_F (Table 1). Flow time T_F was calculated assuming steady flow and full flow conditions, described by a Manning's equation, for individual segments separately and summing the result. Taken into account during the T_F calculations, sewer characteristics (cross sections, slopes, roughnesses) were the same as in SWMM5.1.013 catchment models.

Table 1. Selected characteristics of the analyzed catchments

Catchment characteristics	Catchment description							
	C1	C2	C3	C4	C5	C6	C7	C8
A [ha]	34.8	63.9	71.3	78.3	112.6	157.3	172.1	280.2
A_{IMP} [ha]	23.9	25.3	20.2	35.4	30.4	37.6	44.5	91.1
L [m]	1520	1790	1780	1700	2250	3780	2900	3260
T_F [min]	12.4	29.3	21.7	26.9	29.4	67.6	34.8	38.2

2.2. Rainfalls

The runoff calculations were made for synthetic hyetographs of Euler type II (Schmitt 2000). The design of these hyetographs is characterized by a very simple transformation of data obtained from the DDF (or IDF) curve. The hyetograph on Figure 2a represents the rainfall intensities determined according to DDF curve as a ratio of rainfall depth increments to the duration of time step. To obtain the Euler hyetograph the maximum rainfall intensity should be set at 30% of the total rainfall duration (Figure 2b).

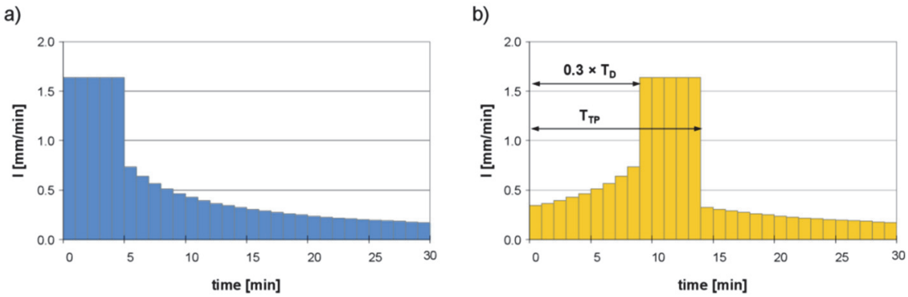

Fig. 2. Euler hyetographs design: rainfall intensities calculated directly from DDF curve (a) and Euler hyetograph with a rainfall duration T_D = 30 min (b)

As the basic DDF curve, the rainfall depth formula for Polish conditions developed by the IMGW (Bogdanowicz & Stachý 1998) was used. According to the recommendations for the Euler hyetographs, it was assumed that the beginning of the pulse with the maximum rainfall intensity was set at 30% of the total rainfall duration. In addition, a time to rainfall peak T_{TP} was concerned. The T_{TP} was represented by the part of hyetograph from the beginning of the rainfall to the end of the last pulse with maximum rainfall intensity (Figure 2b).

The design documentation of the storm sewer systems for analyzed catchments was not available. Moreover taking into account the probability of the changes in a catchment development from the time of sewerage systems realization, the simulations for design conditions were not performed. Hyetographs have been developed for the rainfall frequency of occurrence of c = 2 years. According to recommendations for sewerage systems design (EN752 2017), these rainfalls should generate outflows with the free surface, without hydraulic surcharges. Thus, the shapes of calculated hydrographs are not deformed and maximum outflows are not disrupted as a result of the flattering of the hydrographs during the pressurized flow and by backflow effects.

In the presented analysis, the hyetographs with the rainfall durations T_D from 15 min to 360 min were used. The increments of the rainfall duration were assumed as 15 minutes. The time step of reporting the calculation results and the time step of numerical calculation were set as 10 s.

The time step of hyetograph discretization was assumed as 1 min. The DDF curve (Bogdanowicz & Stachý 1998), used in calculations, allows the determination of rainfall duration of at least 5 minutes. Therefore the synthetic hyetograph peak is characterized by a constant intensity within 5 minutes (Figure 2).

3. Results and discussion

The outflow peak Q_{MAX} increases with the increase of rainfall duration T_D for all concerned values of T_D (Figure 3). After a certain value of rainfall duration, called the stabilization time in the further part of the paper, the increments of outflow peak slightly decreases.

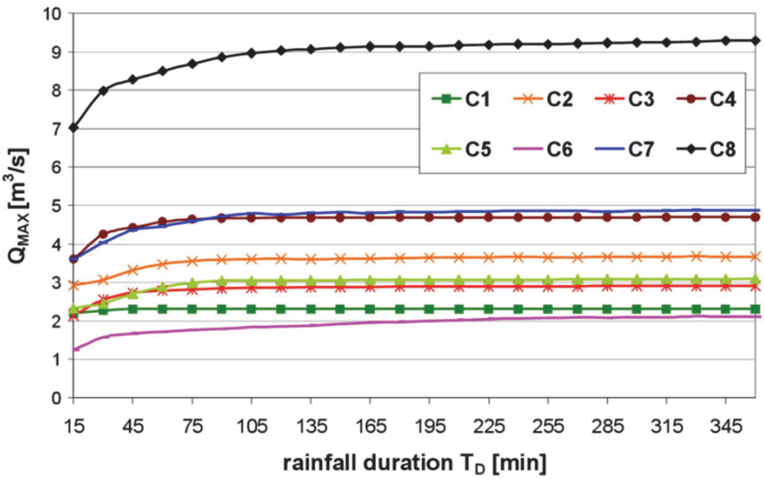

Fig. 3. The outflow peak Q_{MAX} as the function of rainfall duration T_D

In practice, determining the one value of the outflow peak may be impossible, because for longer rainfall durations a further increase of values Q_{MAX} may occur. For practical purposes it is important to specify a threshold value of rainfall duration, after which a clear decrease of outflow peak is noticed. Taking into account the graph of the function $Q_{MAX} = f(T_D)$ (Figure 4), this time was called the stabilization time T_{ST} and was identified with the design rainfall – the rainfall that generates the greatest runoff from the catchment as measured close to the sewer outlet. It was assumed that the stabilization time would be determined as the rainfall duration for which the calculated outflow peak is equal to 97% of the outflow value calculated for the longest analyzed rainfall duration (T_D = 360 minutes). The difference equal to 3% between the maximum outflow and the outflow corresponding to the stabilization time takes into account the accuracy of the outflow simulation represented as a Continuity Error in SWMM5.1.013.

The discrete form of function $Q_{MAX} = f(T_D)$ had been converted to continuous by using polynomial regression (Figure 3). The differences between the values of the outflow peak calculated during the SWMM5.1.013 simulations and based on a regression equations do not exceed 0.5%. Due to this fact, the stabilization time can be specified with an accuracy of 1 minute (Table 2) without the need of performing simulations of the outflows for all rainfall durations T_D (15-360 min).

Table 2. Determined flow times T_F, stabilization times T_{ST} and times to rainfall peak T_{TP} for analyzed catchments

Time [min]	Catchment description							
	C1	C2	C3	C4	C5	C6	C7	C8
T_F	12.4	29.3	21.7	26.9	29.4	67.6	34.8	38.2
T_{ST}	23.0	87.0	62.0	53.0	88.0	213.0	98.0	119.0
T_{TP}	11.9	31.1	23.6	20.9	31.4	68.9	34.4	40.7

In the next step, for determining the relations between the characteristics of the catchments and the stabilization time, the assessment of the correlation between these values was made (Figure 4). As a measure of the correlation, the Pearson correlation coefficient (PCC) was used (Table 3).

The correlation between the total area A or the impervious area A_{IMP} and the stabilization time was weak. For the longest flow path L the correlation was on a significant level. The highest correlation was observed for the flow time T_F.

Table 3. The values of the PCC and the coefficients α (for Equation 1) for the analyzed catchment characteristics

Catchment characteristic CC	PCC [-]	Coefficient α (Eq. 1)
A	0.582	0.670
A_{IMP}	0.346	2.051
L	0.909	0.041
T_F	0.988	2.963

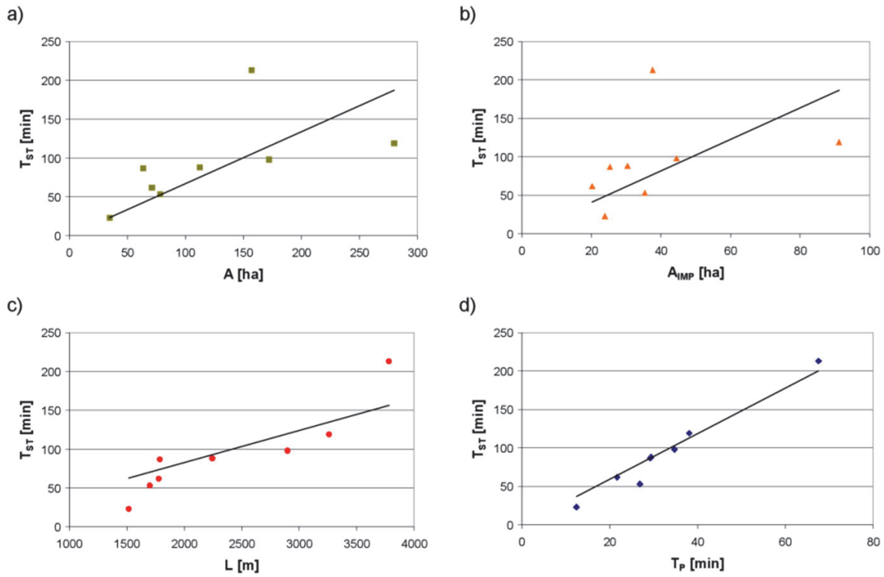

Fig. 4. The results of the analysis of the correlation between the catchment characteristics and the stabilization time T_{ST}

For rainfalls with relatively small intensities (such as included in the analysis for rainfalls with the frequency of occurrence c = 2 years) the surface runoff is only generated by the impervious area. Thus the impervious area is a characteristics of the catchment with the basic influence on the total volume of the outflow, while its impact on the outflow peak is the least significant (from among analyzed characteristics). An example might be a catchment C6, for which, despite a total area is more than four times greater (and the impervious area nearly twice greater) than for C1 (Table 1), the value of outflow peak is comparable to the outflow peak calculated for the catchment C1. It proves that in the rainfall-runoff transformation for an urban catchment, the greatest influence on the shape of the hydrograph has a flow phase in the sewer network. Between two analyzed characteristics that describe the sewer network (the flow path L and the flow time T_F) greater value of the Pearson correlation coefficient was calculated for flow time through the catchment T_F. According to the different characteristics of the sewers (cross sections, slopes, material), besides the flow path, an important issue is the flow velocity, which determines the flow time.

The proposed method of determination the flow velocity on basis of Manning's equation (for assumption of steady flow and full flow conditions) is a sufficiently accurate approximation of flow conditions in sewers in case of determining the design rainfall duration.

For the practical use of the observed relations between catchment characteristics and stabilization time T_{ST} it was assumed that this relation would take a form of a straight line:

$$T_{ST} = \alpha \cdot CC \qquad (1)$$

where:
CC – selected catchment characteristics (A; A_{IMP}; L; T_F).

The value of the coefficient α for the Equation (1) for the flow time through the catchment T_F is close to 3 (Table 3). It means that the maximum outflow is generated by the rainfall with a duration approximately three times greater than the flow time T_F.

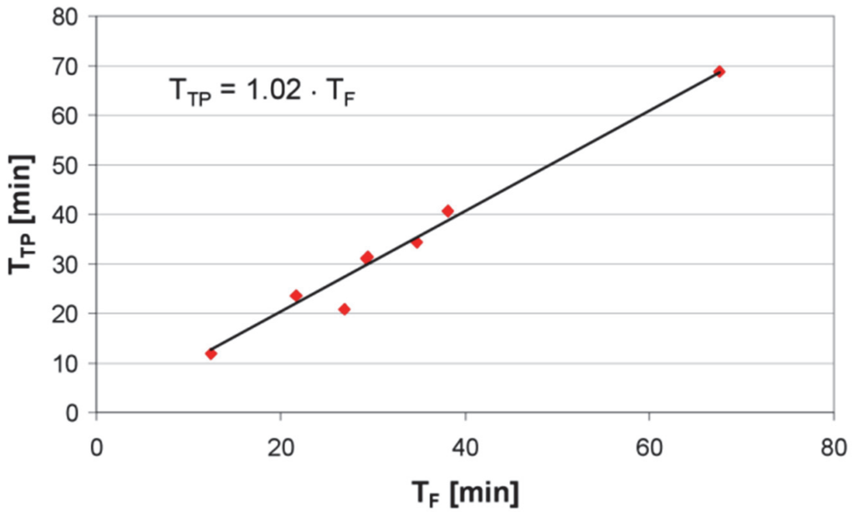

Fig. 5. Relation between the time to rainfall peak T_{TP} and the flow time through the catchment T_F

In the case of Euler hyetographs time to rainfall peak T_{TP} is approximately equal to 1/3 of the total rainfall duration. It suggests that a major role in choosing the duration of the design rainfall plays not only the total rainfall duration, but also the location of the rainfall peak. In order to confirm this observation, a linear regression between times T_{TP} and T_F was performed (Figure 5). The value of the slope of straight line is close to 1, what confirms the significant relation between the time to rainfall peak T_{TP} of rainfall generating the maximum outflow from the catchment and the flow time through the catchment T_F.

This relation is consistent with the principles of the stormwater systems design based on a Rational Formula (ASCE 1992). According to these recommendations, the design rainfall duration should correspond the flow time through the catchment. However, it should be noticed that in the case of the Rational Formula the rainfall with a constant intensity is used (so called block rainfall). The greatest outflow from the catchment will appear at the end of such a rainfall. In case of using synthetic hyetograph with the variable intensity in time, the maximum outflow will be generated at the end of the rainfall pulse with the greatest intensity. This time corresponds to the time to rainfall peak T_{TP} (Figure 2 b).

The knowledge about the relation between the design rainfall duration and the flow time through the catchment can be used in a hydrodynamic modelling of stormwater sewer systems. It can be particularly useful for stormwater sewer systems verification, when the model calibration cannot be performed due to the lack of outflow measurement data or when the historical rainfall data are not available. The relation between the design rainfall duration and the flow time through the catchment, presented in the paper, allows the easy selection the appropriate hyetograph for specified catchment. For determining the flow time through the catchment T_F any additional data are not required. The stormwater system parameters (sewer lengths, slopes, cross sections, material) are known at the stage of hydraulic calculations concerning stormwater systems.

4. Conclusions

The results of the presented analysis allow formulating the following conclusions:

1. The duration of the design rainfall, represented by the stabilization time T_{ST} is dependent on the flow time through the catchment T_F.
2. Time to rainfall peak T_{TP} for the design rainfall should corresponds to the flow time through the catchment T_F or be greater than this value.
3. The flow time through the sewers calculated for full flow conditions and the steady flow may be a measure of the flow time through the catchment.

The presented relations concern catchments with similar parameters to those used in the analyses. At the current stage of the analyses there are no grounds to extrapolation of the obtained results for other catchments with different size and sewer length. The generalization of the results requires calculations performed for larger number of catchments with different parameters. It is advisable to perform an outflow simulations for design rainfalls with a variable peak location, e.g. the Chicago design rainfall. It would allow to the clarification of relation between the hyetograph peak location and generated outflow from the catchment for specified rainfall duration.

The authors wish to thank the Miejskie Wodociągi i Kanalizacja company in Bydgoszcz for sharing their catchment models and measurement data.

This work was supported by the Poznan University of Technology under Grants (01/13/SBAD/0912 and 01/13/SBAD/0913).

No potential conflict of interest was reported by the authors.

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Abstract

In the presented paper the determination of the design rainfall duration for which the outflow from the urban catchment reaches maximum intensity and the evaluation of the relation between determined design rainfall duration and selected catchment characteristics were discussed. The analysis based on the outflow simulation results in SWMM5 obtained for eight existing urban catchment located in Bydgoszcz (Poland) with area ca. 35-280 ha. The calculations were made for the Euler hyetographs with the rainfall durations from 15 min to 360 min and the rainfall frequency of occurrence c = 2 years. For each catchment the relations between the catchment characteristics (total area, impervious area, length of the flow path and the longest flow time through the sewers) and the rainfall duration were determined. It was shown, that the design rainfall duration, represented by the Euler hyetograph, should be at least three times longer than the flow time through the catchment.

Keywords:
design rainfall, hydrodynamic modelling, SWMM5, urban catchment, Euler hyetograph

Czas trwania deszczu obliczeniowego na potrzeby modelowania odpływu ze zlewni miejskiej

Streszczenie

W publikacji zaprezentowano wyniki analizy wpływu czasu trwania deszczu projektowego na wielkość maksymalnego odpływu ze zlewni oraz relacje między tym czasem a wybranymi charakterystykami zlewni (całkowitą powierzchnią, powierzchnią nieprzepuszczalną, długością drogi przepływu przez zlewnię i najdłuższym czasem przepływu przez sieć kanalizacyjną). Analiza obejmowała symulacje odpływu w programie SWMM5 dla ośmiu istniejących zlewni miejskich lokalizowanych w Bydgoszczy o powierzchniach od ok. 35 ha do ok. 280 ha. Symulacje przeprowadzono przy wykorzystaniu hietogramu Eulera o czasie trwania deszczu od 15 min do 360 min i częstości przewyższenia deszczu c = 2 lata. Dla każdej zlewni zbadano zależność między charakterystykami zlewni i czasem trwania deszczu. Wykazano, że czas trwania deszczu projektowego, reprezentowanego przez hietogram Eulera, powinien być co najmniej trzy razy dłuższy od najdłuższego czasu przepływu przez zlewnię.

Słowa kluczowe:
deszcz obliczeniowy, modelowanie hydrodynamiczne, SWMM5, zlewnia miejska, hietogram Eulera