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Effective Impervious Area Mapping in Modeling Runoff from Urban Catchment

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1. Introduction

The effective impervious area (EIA) is a part of the total impervious area (TIA), from which the runoff goes directly to the storm water sewer system. Determination of the effective impervious area (EIA) is one of the main stages of building the storm water sewer systems simulation models for urban areas (Lee & Heaney 2003, Seo et al. 2013, Yao et al. 2016, Ebrahimian et al. 2018). TIA for a specific catchment can be estimated according to the information about land use, such as maps, aerial and satellite images, data from laser scanning (Mostrales et al. 2018). The EIA can be calculated on basis of a model calibration or with the use of empirical formulas based on TIA (Sahoo & Sreeja 2013, Gulliver et al. 2015, Ebrahimian et al. 2016, Zhuk et al. 2018).

Regardless of the method of determining the EIA, the value of EIA as an input data to the simulation model is necessary. This issue is connected with the method of reduction of impervious area and is particularly important when using one-dimensional (1D) runoff models. Despite the increasing popularity of two-dimensional (2D) models, the calculation of surface runoff using them is limited, mainly by data availability and long calculation time (Pina et al. 2016, Bermúdez et al. 2018). The most common use of 2D runoff models is the analysis of the flooded areas when storm water sewers are overloaded (Son et al. 2016). In this case, the surface runoff is determined using the 1D runoff model and the 2D model is used only to calculate the flow which occurs above ground level as a result of the storm water system overload. It means that the simulation result depends on the parameters of the one-dimensional surface runoff model.

In one-dimensional surface runoff models, such as SWMM5 (Rossman 2015, Nowogoński 2018), the catchment area is represented by impervious and pervious areas. The contribution of impervious area in the total catchment area determines the imperviousness degree of a catchment area. The easiest way to put information about the EIA into the model is to use the imperviousness degree as a parameter used during the model calibration (Niazi et al. 2017). The reduction in the value of impervious area with the use of imperviousness degree eliminates the impervious area that is the difference between TIA and EIA from the model. It is replaced by a pervious area. Another option to include information about the EIA in the model is also available, e.g. in SWMM5 there is a possibility to redirect a part of the runoff from the impervious area to the pervious area. This is a situation that is definitely more relevant to real conditions. In case of reducing the imperviousness degree, a part of impervious area is removed from the catchment. In fact, this part of area does not disappear – the runoff from this surface is not discharged directly into the storm water sewer system. In other words, reduction of the imperviousness degree results in replacing an impervious area by a pervious area. Then the runoff is indirect – through the permeable surface.

Surface runoff from pervious areas is generated by heavy rainfalls and largely depends on the parameters characterizing soil infiltration capabilities. In that case in sewers the outflow generated by a runoff from pervious area takes place under hydraulic overload conditions and may be accompanied by a flooding. Such runoff conditions are the basis for flood risk assessment (PN-EN 752). If the storm water sewer system works under hydraulic overload conditions when flooding occurs, it is practically impossible to determine model parameters (especially infiltration) while model calibration based on the volume balance of registered and calculated outflow. Infiltration parameters can be determined mainly on the basis of analysis of soil conditions and land cover. In that case the infiltration parameters can be taken from the literature. However it may cause that the reliability of the simulation results of the runoff from pervious areas is lower than for the runoff from impervious areas, as the values selected from literature might not represent real conditions.

From a practical point of view, it is therefore important to know the influence of parameters characterizing the pervious part of the catchment area, including the EIA mapping in the model, on the simulation results. This gives rise to a rational selection of the values of these parameters, ensuring the reliability of the simulation results as high as possible. The easiest way to determine the influence of the model parameters on calculation results is sensitivity analysis (James 2003, Barco et al. 2008). It is based on assessing the impact of changes in values of model parameters on calculated values.

The publication presents the results of the sensitivity analysis used to assess the impact of the method of mapping the EIA in the model on the calculated runoff volume in case of runoff from the previous areas.

2. Catchment

2.1. Catchment characteristic

Presented analysis was performed for existing urban catchment located in Bydgoszcz (Fig. 1). The total area of the catchment was 78.3 ha. The predominant types of land use were single-family housing and multi-family buildings. The value of TIA for chosen catchment, which includes the surfaces of roofs and roads, was determined by Miejskie Wodociągi i Kanalizacja company (MWiK) in Bydgoszcz (the operator of storm water sewer system in the city) on the basis of the digital maps and aerial photographs. The size of the TIA for the catchment area was assessed as 35.4 ha.

The simulation model was performed with the use of SWMM program, widely used in urban catchments analysis (Zawilski & Dziedziela 2018, Nowogoński 2020). The model consist of 156 subcatchments and 171 conduits. Only sewers with diameter above 300 mm were considered. The areas of subcatchments (except two cases) were below 2 ha. The accuracy of storm water sewer system structure represented in a model is sufficient according to the requirements from the literature (Zawilski 2010, Krebs et al. 2014, UDG 2017). The model was provided and made available by MWiK company in Bydgoszcz.

Fig. 1. Catchment area (a) and its model (b)

2.2. Assessment of EIA

Due to the lack of measurement data to determine the EIA on basis of the balance of rainfall-runoff volume for analyzed catchment, the EIA value was calculated according to the empirical formula (Alley & Veenhuis 1983, Sutherland 1995) represented by the equation:

$$EIA = a \cdot TIA^{b} \text{ [ha]} \quad (1)$$

The values of coefficients (a) and (b) depend on the catchment characteristic, interpreted as a part of impervious area that can be connected to the storm water sewer system. As the impervious area connected to the sewer system decreases, the values of coefficient (a) decrease and the values of coefficient (b) increase (Table 1).

Equation 1.1 concerns conditions for which the most of impervious area of the catchment is connected to a drainage system, a rainwater is not harvested and the roofs of single-family houses are connected to a storm water sewer system. Average conditions described by equation 1.2 are similar to the previously described - the difference is that the most of roofs of single-family houses are not directly connected to a drainage system. The catchment characteristics described by equations 1.3 and 1.4 represent the situation where only part of the catchment is connected to a drainage system and a rainwater is locally harvested. For equation 1.5 no specific conditions were given. The only information was that the values of coefficients (a) and (b) were determined for typical urban buildings (Alley & Veenhuis 1983).

Table 1. EIA values calculated by equation (1) for different coefficients a and b

Eq. number	a	b	EIA [ha]	RC [%]	Catchment characteristic (*)
1.1	0.4	1.2	28.85	18.4	highly connected
1.2	0.1	1.5	21.02	40.5	Average
1.3	0.04	1.7	17.15	51.5	somewhat disconnected
1.4	0.01	2.0	12.50	64.7	extremely disconnected
1.5	0.15	1.41	22.87	35.3	lack of data//information

(*) explanation in text

The change of an impervious area was expressed by a reduction coefficient RC (Table 1):

$$RC = \left(1 - \frac{EIA}{TIA}\right) \cdot 100 \ [\%] \tag{2}$$

The basic value RC = 40% which corresponds to the average characteristic of the catchment (equation 1.2) was assumed. Taking into account the characteristics of given catchment, this value was the most probable. Nevertheless, the possibility that the real value of EIA might be greater as described in equations 1.1 or 1.5 cannot be excluded. Due to the lack of information about local rainwater harvesting systems for analyzed catchment areas, the values of EIA calculated by equations 1.3 and 1.4 were rejected as not very probable.

3. Scope of analysis

3.1. Determining the EIA – variants

Two variants of the EIA mapping in a simulation model were considered. In variant A a decrease of imperviousness degree by a reduction coefficient RC (equation 2) was assumed. For each subcatchment the reduction in the impervious area causes an increase of the pervious area in order to remain the constant value of the total catchment area. In other words, the part of impervious area from which the runoff is not directed into the storm sewer system is converted into the pervious area in the model.

In variant B the SWMM option which allows to direct a part of runoff from the impervious area to the pervious area was used. The value for a part of the impervious area, from which the runoff was directed to the pervious area was considered similar to variant A – as a reduction coefficient RC. For the purpose of the analysis, an equal change in the impervious area for all subcatchments in both variants was assumed.

When the runoff occurs only from the impervious area, what can takes place for rainfalls with low intensity or in the case of very high infiltration capacity of pervious areas, both simulation variants generate the same runoff volumes. The impact of the EIA mapping method is significant during the runoff from pervious areas. In presented analysis this runoff was generated by a synthetic rainfall of high intensity and chosen parameters describing infiltration.

In the analysis four values of the reduction coefficient RC (equal to 10%, 20%, 30% and 40%) were taken into account. The values of assumed reduction coefficient RC corresponds to the values of the impervious area calculated according to the empirical formulas for the analyzed catchment (Table 1).

3.2. Rainfall

The Chicago hyetograph (Keifer & Chu 1957, Yao et al. 2016) with a peak intensity located at the centre was used to describe the variability of the rainfall intensity over time. In the analysis the synthetic rainfall with a frequency of occurrence c = 20 years was used. Rainfalls of such frequency of occurrence are considered to cause a significant runoff from pervious areas (Stall & Terstriep 1972). The duration of assumed rainfall T_D was equal to 60 min. The time that corresponds to the peak location (30 min) is longer than the longest flow time through the analyzed sewer system, which was calculated as equal to 27 min. Such rainfall should generate the largest instantaneous outflow in sewers (Mazurkiewicz & Skotnicki 2018), what is important while determining the flood volume V_F as a result of sewers overloading. The greatest outflow should also generate a maximum flood volume.

The rainfall depth was calculated with the use of Bogdanowicz and Stachy formula, which is the form of DDF curve for Polish conditions (Bogdanowicz & Stachý 1998). The value of rainfall depth for assumed rainfall was calculated as 39.7 mm.

3.3. Infiltration

The infiltration for pervious areas in the simulation model was computed according to the Horton equation (Rossman & Huber 2016). It was assumed that the soil in analyzed catchment had a good permeability. The values of initial infiltration rate F_{MAX} varied from 100 mm/h to 200 mm/h, while final infiltration rate F_{MIN} changed from 20 mm/h to 35 mm/h. The decay constant k for the Horton infiltration curve ranged from 2 h^{-1} to 8 h^{-1}.

Parameter	Values
F_{MAX} [mm/h]	100; 125; 150; 175; 200
F_{MIN} [mm/h]	20; 25; 30; 35
k [h^{-1}]	2; 4; 6; 8

Table 2. Assumed ranges of infiltration parameters for the Horton equation

In further analysis a cumulative effect of infiltration parameters on the volume of infiltrating rainwater was considered. The infiltration was expressed in a unit form with regard to the total pervious area of the catchment and described as UI [m^3/ha].

The UI values were calculated with the use of SWMM5 for assumed rainfall with total depth equal to 39.7 mm. In SWMM5 the infiltration process is connected with surface retention on the pervious area. For analyzed sets of the parameters of Horton equation and assumed rainfall (Table 2), the unit infiltration varied from 305 to 397 m^3/ha. The maximum value of calculated unit infiltration of 397 m^3/ha means that the entire rainfall infiltrated into the ground. Therefore, selected infiltration parameters of the Horton equation (Table 2) allowed to analyze the runoff from pervious areas from a threshold value equal to zero. It should be noted that the determined unit infiltration values do not represent the maximum soil infiltration capabilities. In case of an increase of a rainfall intensity, the volume of infiltrated rainwater may increase.

4. Results and discussion

The influence of mapping the EIA in simulation model on two basic characteristics – total runoff volume V and flood volume V_F was analyzed. The total runoff volume is the basic value that shows the impact of EIA mapping. The results represented by a runoff volume V are more universal as they depend only on the parameters of the catchment. The value of V is not influenced by the individual properties of the storm water sewer system, as it is calculated as the sum of the volume of runoff from individual subcatchments. The flood volume of V_F is influenced by the sewer parameters (e.g. diameters, slopes, lengths, roughness, etc.), therefore the results obtained for V_F are largely dependent on the specific storm water sewer system characteristics. However, according to the flood risk for storm water sewer system, the volume of V_F is of greater importance for maintenance these kinds of systems and, therefore, was also chosen with the runoff volume for the further analysis.

For all analyzed values of infiltration parameters (F_{MAX}, F_{MIN}, k) and reduction coefficient RC, the runoff volume V and the flood volume V_F were greater for variant B, which assumed the directing the runoff from the impervious area to the pervious one, than for variant A, which assumed the decrease of reduction coefficient RC (Fig. 2). It suggests that using the imperviousness degree as a parameter for EIA mapping can lead to underestimation of runoff simulation results.

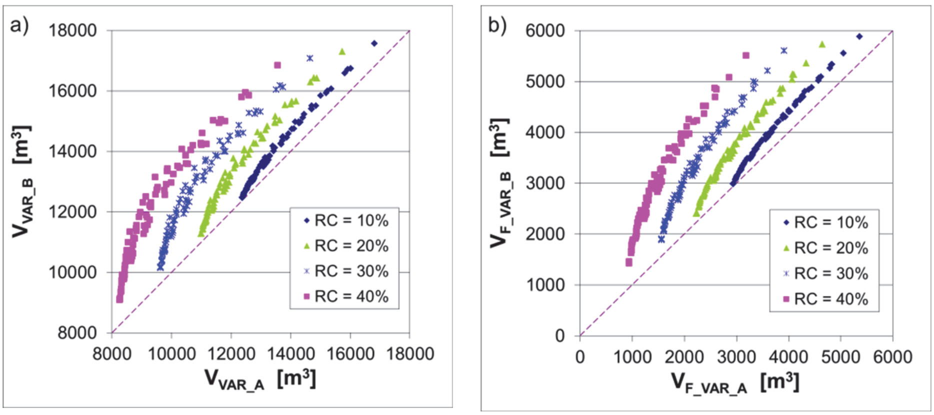

Fig. 2. The comparison of runoff volume V (a) and flood volume V_F (b) calculated for variants A and B

The volume increments ΔV and ΔV_F were used to compare the differences between variants A and B. These increments were calculated for each analyzed value of the reduction coefficient and were described by the equations:

$$\Delta V = V_{VAR\_B} - V_{VAR\_A} \; [m^3] \tag{3.1}$$
$$\Delta V_F = V_{F\_VAR\_B} - V_{F\_VAR\_A} \; [m^3] \tag{3.2}$$

where:
V_{VAR} – the runoff volume for variant A or B of EIA mapping $[m^3]$
V_{F_VAR} – the flood volume for variant A or B of EIA mapping $[m^3]$

Such defined volume increments ΔV and ΔV_F can be interpreted as a vertical difference in the location of the points regarding to the line with slope 45° presented in charts shown in Figure 2.

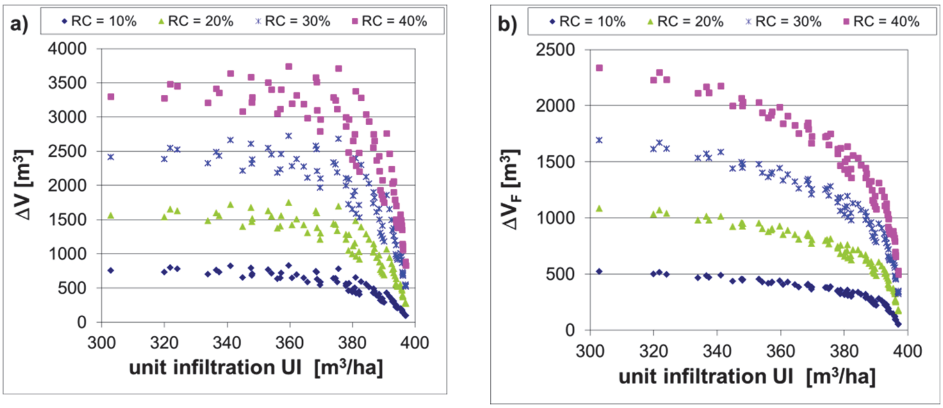

Fig. 3. The comparison of runoff volume increments ΔV (a) and flood volume increments ΔV_F (b) as a function of unit infiltration UI

The runoff volume increments ΔV had the lowest values for maximum values of a unit infiltration (Fig. 3a). With the decrease of unit infiltration, the runoff volume increments initially increased. The maximum value of ΔV was calculated for unit infiltration of approximately 360 m^3/ha. Further decrease of unit infiltration caused the decrease of the ΔV increments. This trend occurs for all analyzed values of reduction coefficient RC. With the increase of reduction coefficient RC, the range of variability in increments ΔV also increases.

For the flood volume increments the decrease of values ΔV_F with the increase of a unit infiltration was noticed (Fig. 3b). Similar to runoff volume increments ΔV, the range of ΔV_F variability was greater for higher values of reduction coefficient RC. The relation between the variability of increments ΔV and $ΔV_F$ and unit infiltration had met the expectations. The higher the infiltration values, the smaller the runoff from the pervious areas and thus the less impact of the EIA mapping in the model.

In order to find the average values of increments ΔV and $ΔV_F$, a probability distribution describing the variability of those increments was determined. The best fitting was achieved for the Beta distribution. For known probability distribution parameters the mean and standard deviation (Table 3) were specified.

Table 3. Mean values and standard deviations of increments ΔV i $ΔV_F$

Value	Reduction coefficient RC [%]			
	10	20	30	40
mean ΔV [m^3]	473	1073	1764	2521
std. deviation ΔV [m^3]	219	436	644	843
mean $ΔV_F$ [m^3]	305	654	1033	1422
std. deviation $ΔV_F$ [m^3]	126	243	359	484

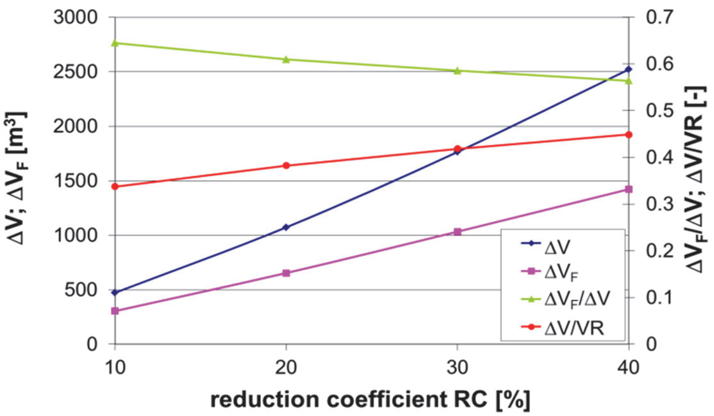

Fig. 4. Mean values of increments ΔV and $ΔV_F$ and ratios $ΔV/ΔV_F$ and ΔV/VR as the function of reduction coefficient RC

Functions that describe the relations between mean values of increments ΔV and $ΔV_F$ and reduction coefficient RC were close to linear (Fig. 4). The differences in the runoff volume or flood volume calculated for different EIA mapping variants increased directly proportional to the difference between EIA and TIA.

The mean values of increments ΔV were compared with the volume of runoff from the impervious area VR, which is directed to the pervious area in variant B. For the rainfall depth equal to 39.7 mm and TIA equal to 35.4 ha, the total volume of runoff from impervious area was approximately 14000 m^3. Therefore, each 10% of reduction coefficient corresponds to the volume approximately 1400 m^3 of runoff from impervious area that was directed to the pervious area. The runoff volume increments varied from 34% to 45% of this value (Fig. 4).

According to the European Requirements 752 in order to assess the operating conditions of the storm water sewer system, in particular with regard to flood risk, the relation between increments ΔV_F and ΔV was consider as important. With the increase of the reduction coefficient RC from 10% to 40%, the value of runoff increment ΔV that was converted into the flood volume ΔV_F decreased from 64% to 56% (Fig. 4). Therefore, the method of the EIA mapping can have significant impact on the flood risk assessment results.

5. Conclusions and summary

On basis of results of analysis presented in the publication, the following conclusions were formulated:

1. Directing a part of runoff from impervious area to pervious area instead of reduction in imperviousness degree results in greater calculated value of runoff volume and flood volume.
2. Increments of runoff volume and flood volume between two analyzed variants of EIA mapping decrease as infiltration increases.
3. The mean values of increments of runoff volume and flood volume increase almost linearly with the increase of reduction coefficient.
4. The value of increment of the runoff volume is approximately 40% of the volume of the runoff from impervious area that was directed to the pervious area.
5. The increment of the runoff volume is in approximately 60% converted into flood volume.

It should be made clear that at this stage of the analysis there are no grounds for generalization the relations presented in the paper. Obtained relations between the reduction of the impervious area and the increments of runoff volume ΔV can be expected to be similar for other catchments. For presented calculations only surface runoff was considered, so the results are not dependent on the storm water sewer system characteristic.

The relations between the increments of flood volume ΔV_F and the reduction of the impervious area or the increments of runoff volume ΔV may be characteristic only of the analyzed catchment. The flood volume is a function of the sewers parameters that are individual of each urban catchment. In addition, the results may depend on assumed infiltration parameters and used method for calculating the infiltration in SWMM5.

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Abstract

The publication presents the results of an analysis concerning the impact of the method of an effective impervious area (EIA) mapping in the simulation model on the runoff from urban catchment. The runoff volumes and flood volumes generated by heavy rainfall, causing the runoff from pervious area, were compared. Two EIA mapping variants were taken into account – first one, concerning reduction in imperviousness degree and, second one, directing the runoff from impervious to pervious area. The runoff calculations were made on basis of simulation results in SWMM5. For building the catchment model data of existing catchment with the area of nearly 80 hectares in Bydgoszcz was used. The value of the EIA was estimated on the basis of empirical formulas. The reduction in impervious area connected directly to the storm water sewer system from 40% to 10% of the total impervious area were considered. It has been shown that using the reduction in imperviousness degree for EIA mapping can lead to underestimation of runoff volume. The difference in runoff calculated for analyzed EIA mapping variants increases with the decrease in infiltration capacity of pervious area and is in large part transformed into a flood volume.

Keywords:
effective impervious area, hydrodynamic modeling, SWMM5, urban catchment

Odwzorowanie efektywnej powierzchni szczelnej w modelowaniu odpływu ze zlewni miejskiej

Streszczenie

W publikacji przedstawiono wyniki analizy wpływu sposobu wprowadzenia danych o efektywnej powierzchni szczelnej (EIA) do modelu symulacyjnego zlewni miejskiej na odpływ. Porównywano objętości odpływu oraz objętości wypływu na powierzchnię terenu generowane przez opad o znacznym natężeniu, skutkujący formowaniem spływu z powierzchni przepuszczalnych. Uwzględniono dwa warianty odwzorowania EIA – redukcję stopnia uszczelnienia i skierowanie spływu z powierzchni szczelnej na przepuszczalną.

Obliczenia odpływu wykonano przy użyciu modelu symulacyjnego wykonanego w programie SWMM5. Wykorzystano dane rzeczywistej zlewni miejskiej o powierzchni blisko 80 ha znajdującej się w Bydgoszczy. Wielkość EIA oszacowano na podstawie formuł empirycznych. Rozpatrywano zmniejszenie powierzchni szczelnej podłączonej bezpośrednio do systemu kanalizacyjnego w zakresie od 10% do 40% łącznej powierzchni szczelnej (TIA). Wykazano, że wykorzystanie do odwzorowania EIA redukcji stopnia uszczelnienia może powadzić do zaniżenia objętości obliczonego odpływu. Różnica odpływu obliczonego dla analizowanych wariantów odwzorowania EIA rośnie wraz ze spadkiem zdolności infiltracyjnych powierzchni przepuszczalnych i w znacznej części jest transformowana w wypływ na powierzchnię terenu.

Słowa kluczowe:
efektywna powierzchnia szczelna, modelowanie hydrodynamiczne, SWMM5,
zlewnia miejska