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Rainfall-runoff modeling: A modification of the EBA4SUB framework for ungauged and highly impervious urban catchments

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ABSTRACT

There are no doubts that prediction of runoff is one of the crucial hydrological research topics when dealing with catchments. It is noteworthy that the rapid land use change in catchments due to urbanization strongly modifies runoff formation, and the use of many common rainfall-runoff models often is not appropriate in such situations. Moreover, in small catchments with a high percentage of impervious areas, highly detailed hydrometeorological data are needed to calibrate the parameters of advanced rainfall-runoff models. Facing the new challenges of urban catchment runoff, this work presents a modification of the EBA4SUB (Event-Based Approach for Small and Ungauged Basins) rainfall-runoff model to improve its applicability in urban areas. The proposed approach is a combination of the original model with a newly formulated excess rainfall calculation (named P4URB) that considers pervious and impervious areas. Indeed the original EBA4SUB model does not consider impervious areas as a separate form of land use. Based on results, we can conclude that EBA4SUNURB (Event-Based Approach for Small and UNgauged Urban Basins) is better suited for urban catchments because it includes a more rational depiction of how impervious areas influence runoff formation. The shape of the design hydrograph and related peak flow are significantly different from those generated from the commonly used Nash model. The main advantage of EBA4SUNURB model is that it can be used in ungauged catchments because all parameters are calculated based on catchment characteristics as opposed to being estimated through a calibration process.

1. Introduction

It is recognized in literature that the world's urban population is increasing, with projections indicating that two-thirds of the world's total inhabitants by the year 2050 will be concentrated in cities, giving rise to environmental impacts at a global scale (United Nations, 2012). Consequently, understanding and predicting the causes and consequences of the urbanization process has become a major challenge to environmental risk assessment. The urbanization process involves an unsustainable use of natural systems and creates numerous problems both within and outside the city (Hamdi et al., 2011). Hydrologically, this includes the increase of peak flows, runoff volumes, frequency of extreme events as well as reduction of water retention. The increase of hydrological extremes in urban areas is mainly caused by a reduction of infiltration and, as a consequence, by an higher excess rainfall (Kibii et al., 2021). The loss of pervious surfaces reduces infiltration in soils, while the construction of artificial drainage networks (open and closed channels) alters natural pathways (Lizárraga-Mendiola et al., 2017; Wałęga et al., 2019). This combined physical alteration has a considerable effect on the catchment's hydrological response to rainfall, leading to a faster response (Huang et al., 2015), a greater magnitude of river discharge (Miller et al., 2014) and an higher recurrence of small floods (Braud et al., 2013).

The increasing imperviousness of urban catchments seems to be a main problem for changes of runoff. The study described by Xu et al. (2020) showed that, compared with low-density settlements, high-density settlement areas tend to generate more surface runoff because they have considerably less vegetative surfaces and more land cover characterized by built up areas. That way the main measure of the catchment imperviousness appears to be the total area where water does

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not infiltrate into the soil, including roads, rooftops, sidewalks, patios, and to some degree compacted soil. Imperviousness is an integrative indicator, and it can be used to estimate or predict cumulative impacts on water resources. Research in various regions of the world has been consistently showing a strong influence of imperviousness areas on the flood formation phenomenon (Klein, 1979; Schueler, 1994; May 1996), and literature reveals that this is still an open topic. For instance, Recanatesi et al. (2017) and Recanatesi and Petroselli (2020) investigated the relationship between floods and urbanization in two *peri*-urban areas of the city of Rome and found that the hydraulic risk was more pronounced in the part of the selected areas that was more extensively urbanized.

Similar results were achieved by Umukiza et al. (2021), that demonstrated how the configuration and composition of land use can affect peak discharge and flow volume in selected catchments of Narok Town, Kenya. Therefore, impervious surface percentage has been recognized and widely adopted as a key indicator in urban environmental assessment (Ansari et al., 2016; Qiao et al., 2018; Li et al., 2019) and should be one of the major parameters in hydrological models in urban areas (Ren et al., 2020). Another issue is that the hydrological link between impervious and pervious areas has not well been considered in runoff simulations due to the complexity of flow routing (Deng et al., 2020; Epps and Hathaway, 2018).

Despite this knowledge regarding the strong influence of impervious surface on surface flow formation, in areas where runoff processes are based on Hortonian law, simple rainfall-runoff models are still used (Blair et al., 2012). These models are not able to accurately describe the complexity of runoff as response to rainfall, especially for catchments with an heterogeneous distribution of impervious and pervious areas. This is a complex problem because, even in urbanized catchments, natural areas can alter the response to rainfall. On the other hand, in suburban areas where lawns and other permeable landscapes may be common, rainfall can saturate thin soils and produce overland flow, which runs off quickly (Konrad and Booth, 2002). The dense network of ditches and culverts in cities then allows quick transport to nearby streams and rivers.

Unfortunately, the effect of impervious areas on rainfall-runoff modeling for small and urbanized catchments has not been fully determined (Lei et al., 2016). Hydrological modeling of these catchments is an important tool for analyzing and managing the flood hazard, but it requires an understanding of the areas contributing to runoff from the urban parts of the catchment (Birkinshaw et al., 2021). In practice, hydrological models may include soil moisture to correctly asses the direct runoff (Fidal and Kjeldsen, 2020), or consider high-rise buildings to improve runoff predictions (Yoo et al., 2021). For more complex, physically based models, Cea et al. (2010) showed that the dynamic wave model is able to predict the peak discharge and its arrival time, as well as the shape of the outlet hydrograph, while the diffusive wave model gives less accurate results. In another example of a complex model, Perrin and Bouvier (2004) used a distributed modeling approach that develops and generalizes the concept of the unit hydrograph to a grid-cell structure in a mountainous urban catchment with physiographic heterogeneity and high variability of the rainfall.

One of the key considerations for modeling the hydrological phenomena, not only in urban areas but also in rural catchments, is the sensitivity of models to various parameters and methodological approaches. Sangati and Borga (2009) examined the role of river network geometry on the averaging of space–time rainfall and on simulated peak discharges after rescaling the rainfall fields to preserve rainfall volumes in small catchments. They showed that increasing the resolution length may lead to a distorted geometry of the rainfall field with respect to the river network. Ballinas-González et al. (2020) studied the Storm Water Model Management (SWMM) and showed that the sensitivity of the parameters depends on the basin under study and on the effects of secondary interactions between the model parameters. It was also shown that the most sensitive parameters in a simulation vary according to the storm and the accumulated precipitation. Saadi et al. (2020) showed that GR4H and IHACRES, two conceptual and continuous models, agreed less in reproducing the internal fluxes over the urbanized catchments than over the rural ones.

As it can be seen, knowledge regarding rainfall-runoff modeling in catchments characterized by a high percentage of urban cover is still lacking. In particular, although they can be valuable for representing complex urban hydrology, sophisticated physically based models are not preferable in all cases. Firstly, there is often a lack of data in urban catchments for the calibration of advanced models' parameters (Gumindoga et al., 2017). Indeed, the ungauged basin perspective, in particular in urbanized catchments, poses a challenge in the provision of accurate flood predictions (Fava et al., 2020). Secondly, climate changes can influence the measured discharges that are used during the calibration process, increasing the uncertainty of models. One way to address the above issue is to develop a rainfall-runoff model that does not present free parameters, i.e., an inherently calibration-free rainfall-runoff model. In reality, very little research has been devoted towards developing calibration-free hydrological models as it is generally believed that no hydrological model can perform reasonably well without calibration (Nag and Biswal, 2019). In their study, Nag and Biswal (2019) argued that a calibration-free rainfall-runoff model could be used to predict flow duration curves in regions where observed discharge data are inadequate both quantitatively and qualitatively. Therefore, it is very important to find solutions for modeling hydrological phenomena that can avoid the calibration process when the challenges noted above are present. Specifically, approaches are needed to find balance between complex models that have many parameters and thus can generate high uncertainty in simulation and simple conceptual models, that can easily describe crucial hydrological processes. If simple rainfall-runoff theories are to be preferred, models including spatial heterogeneity of catchments parameters could be adopted, like the hydrological models referred to as variable source area models (Blazkova and Beven, 1997; Gioia et al., 2014; Szymczak and Krężałek, 2018; Krężałek, 2018), Such models may balance the need for accurately representing the effects of urbanization while alleviating the need for extensive calibration.

One example of a simple rainfall-runoff model that does not require a calibration process to estimate its parameters is EBA4SUB (Event-Based Approach for Small and Ungauged Basins) (Piscopia et al., 2015; Petroselli and Grimaldi, 2018; Petroselli et al., 2020c). EBA4SUB estimates the hydrograph shape and the related peak flow by employing the same input parameters of the well-known rational formula. The model has been fully adapted in uncontrolled catchments where agricultural and forest land cover dominate, and is based on geographic information systems, in doing so optimizing the topographic information contained in the digital elevation model (DEM). Indeed, EBA4SUB is a simple kinematic model where the generic pixel velocity value can be calculated with specific equations (developed mainly for natural areas) that are based on local slope and land use. The model was successfully employed in agricultural and forestry catchments in Poland (Młyński et al., 2018, 2020a,b), Slovakia (Petroselli et al., 2019a; Vojtek et al., 2019), Bosnia and Herzegovina (Petroselli et al., 2019b) and Iran (Petroselli et al., 2020a), but its use in catchments with high percentage of impervious areas still has not been assessed.

Considering all the aforementioned, the overall novelty and objective of this study is to present a conceptual modification of the EBA4SUB rainfall-runoff model to calculate peak discharges and hydrograph shape from catchments with high percentage of impervious area. The name of the modified model is EBA4SUNURB (Event-Based Approach for Small and UNgauged Urban Basins). In EBA4SUNURB model, two categories of areas are considered: natural (or pervious) areas, and impervious areas. For each category of area, different approaches for calculating excess rainfall are used. It should be emphasized that so far there has been no research regarding the possibility of using the EBA4SUB model to determine design hydrographs in catchments with a high percentage of impervious areas. In the present work, EBA4SUB and EBA4SUNURB approaches are used to model runoff hydrographs and compare to those obtained using the Nash model, as a reference.

2. Study area

The selected case study is the Serafa river catchment, located in the upper Vistula basin, Poland (Fig. 1). The main reason to choose the Serafa river catchment is its significant percentage of impervious area such that the basin is characterized by a fast response to rainfall events (flash floods are often observed). As a consequence, a large part of the Krakow agglomeration, downslope of the Serafa river catchment, has a high risk of floods. The case study catchment area is 72.4 km^2 and the length of the main watercourse is 12.7 km. The average catchment slope is 3.1%, the average river slope is 0.3%, and the density of the river network is 0.6 $km \cdot km^{-1}$. This information was derived using a Digital Elevation Model (DEM) provided by USGS — United States Geological Survey, with a grid resolution of about 25 m.

Based on the Hydrographic Division Map of Poland (2010) and on the Corine Land Cover (2018) database, the following forms of land uses (shown in Fig. 2) were identified together with the percentage of the catchment area respectively occupied. Discontinuous urban fabric (43.3%), industrial or commercial unit (9.4%), road and rail networks and associated land (2.8%), dump sites (0.7%), green urban areas (3.9%), sport and leisure facilities (0.8%), non-irrigated arable land (8.7%), pastures (8.1%), complex cultivation patterns (5.1%, land principally occupied by agriculture), significant areas of natural vegetation (11.4%), broad-leaved forest (1.1%), mixed forest (2.2%), transitional woodland-shrub (1.1%), and water bodies (2.5%).

3. Methods

In this work, the new approach (EBA4SUNURB) for rainfall-runoff modeling in urban catchments was developed by modifying the original EBA4SUB model. The calculations were performed for a 100-year return period as this was the flood management design storm for the local River Basin Authority. The proposed approach is the combination of the original EBA4SUB with a newly conceived estimate (named P4URB)for excess rainfall that considers pervious and impervious areas. The analysis was carried out in the following stages: calculation of design rainfall, calculation of excess rainfall, determination of design hydrograph by EBA4SUB and EBA4SUNURB. Unfortunately, the Serafa river is ungauged so the calibration of the model's parameters and the classical verification of performance is not possible. Further, all nearby catchments with similar characteristics to the Serafa are ungauged, so it is not possible to use observed discharges from other catchments. Thus, the results from EBA4SUB and EBA4SUNURB were compared to the commonly used Nash model based on cascade of linear reservoirs. The Nash model is recommended in Poland for flood analysis in small and urban catchments (Banasik et al., 2007). For instance, design discharges from Nash model were used to generate flood hazard zones in Krakow area (Koncepcja, 2011).

3.1. Calculation of design rainfall

In this study, it was assumed that the maximum flow with a specific frequency (Q_T) is caused by the occurrence of a rainfall with the same frequency (Viglione and Blöschl, 2008). The analysis was performed for the 100-year return period as noted above. Calculation of the design rainfall (P_T) was performed by applying the log-normal distribution. The parameters were established by the maximum likelihood method based on an annual maximum daily rainfall time-series from period 1971–2018. The log-normal distribution is described as in the following (Hogg and Craig, 1978):

$$f(x) = \frac{1}{(x-\varepsilon)\alpha\sqrt{2\pi}} \exp[-0.5\hat{A}\cdot(\frac{\ln(x-\varepsilon)-\mu}{\alpha})^2$$

$$x_p = \exp\left[\mu + \frac{\alpha\sqrt{2}}{\mathrm{erf}(2(1-p)-1)}\right] + \varepsilon \quad (2)$$

where:
x_p - quantile of the theoretical log-normal distribution,
ε - lower string limit,
erf(2(1 − p) − 1) - Gauss error function.

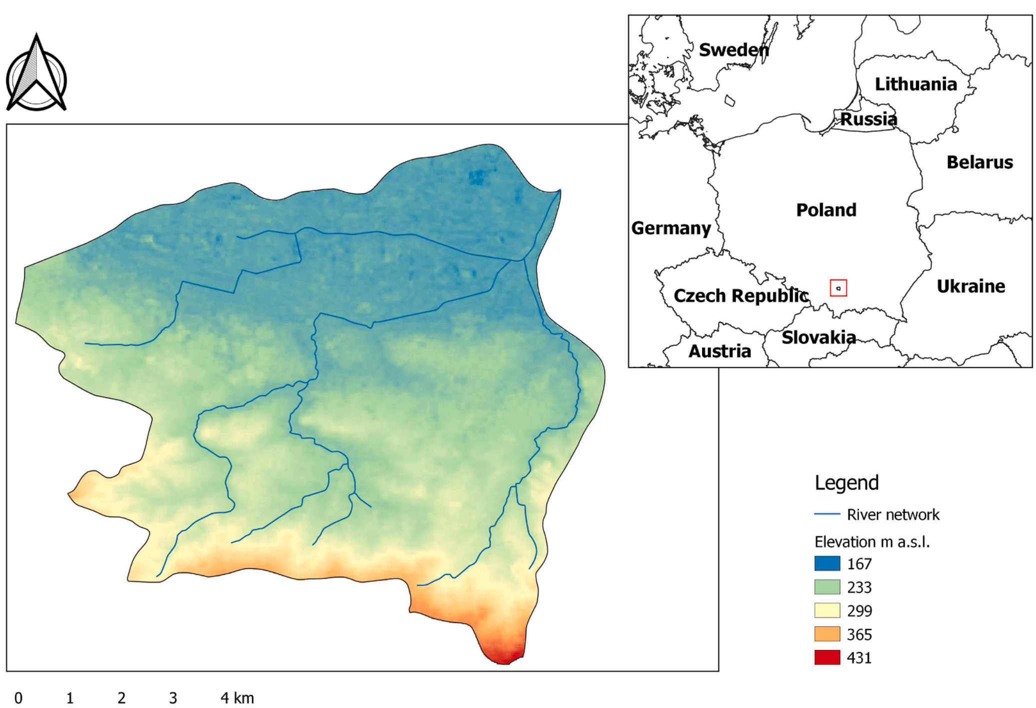

Fig. 1. Topography of the Serafa catchment.

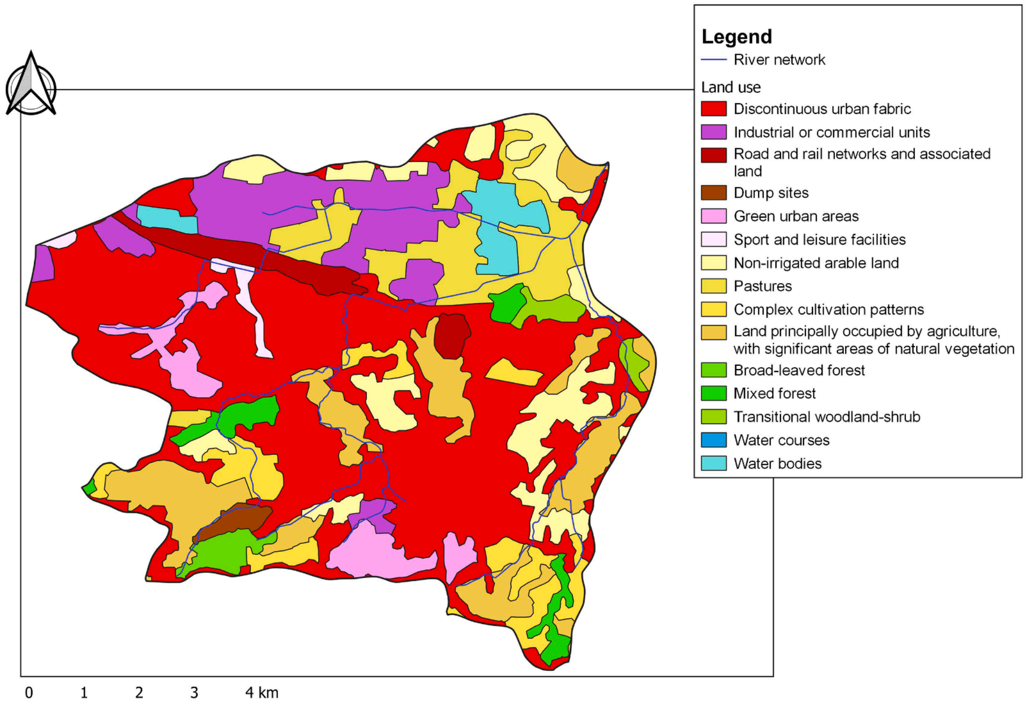

Fig. 2. Land use in the Serafa catchment.

After determining the design rainfall, the critical time was established. It was assumed this corresponded to the duration of rainfall which causes the maximum peak in design hydrograph. The depth of rainfall for the critical time was determined based on Lambor's curvers (Młyński et al., 2020b), that allow to link rainfall daily values to rainfall values for different durations. The same rainfall was assumed for each rainfall-runoff model to allow comparison.

3.2. Nash model

For the Nash model, the excess rainfall was calculated with the SCS-CN method (USDA, 2004). In the SCS-CN method, the excess rainfall depends on the category of soils, land use, and antecedent soil moisture. All these factors were considered in the CN parameter estimation. The amount of excess rainfall was calculated from the relationship (Xiao et al., 2011; Soulis and Valiantzas, 2012; Młyński and Wałęga 2020; USDA, 2004):

$$P_e = \begin{cases} \frac{(P - 0,2S)^2}{P + 0,8S}, when\ P \geqslant 0.2S \\ 0, when\ P < 0.2S \end{cases}$$

where:
P_e – excess rainfall [mm],
P – total rainfall [mm],
S – maximum potential catchment retention [mm].

The maximum potential retention of the catchment is directly related to the CN parameter, ranging from 0 (all rainfall becomes infiltration) to 100 (all rainfall becomes runoff) and described by the equation:

$$S = 25.4\left(\frac{1000}{CN} - 10\right)$$

The CN parameter was determined for the second moisture level (AMC II). Firstly, the CN was assessed for each type of land use and soil type, without impervious area, according to USDA (2004). Next the weighted value of CN was calculated taking the sum of each CN value multiplied by its fraction of the total sub-catchment area (Wałęga and Salata 2019).

In the Nash model, the catchment is described as a cascade of *N* linear reservoirs with the retention *k* parameter of each reservoir. The Nash model is based on the instantaneous unit hydrograph (IUH), which is the catchment reaction for a unitary and instantaneous excess rainfall. The IUH is described by the following two-parameters gamma function (Nash, 1957):

$$u(t) = \frac{1}{k\hat{A}\cdot\Gamma(N)}\left(\frac{t}{k}\right)^{N-1}\exp\left(-\frac{t}{k}\right)$$

where:
u(t) - ordinates of IUH [h^{-1}],
t - time from the beginning of coordinate system [h],
N – number of linear reservoirs [–],
k – retention parameter of each reservoir [h],
Γ(N) – gamma function [-].

The characteristic values of IUH hydrograph are peak (u_p), time to peak (t_p) and lag-time (LAG), that are connected with the model parameters *N* and *k* as:

$$t_p = (N-1)\cdot k(6)$$

$$LAG = (N-1)\cdot k(7)$$

$$up = \frac{1}{k\hat{A}\cdot\Gamma(N)}\frac{(N-1)}{\exp(N-1)}^{N-1}$$

where:
N – number of linear reservoirs [–],
k – retention parameter of each reservoir [h].

3.3. EBA4SUB model

EBA4SUB model determines the runoff hydrograph using the Digital Elevation Model (DEM) of the catchment and the value of the CN parameter. The excess rainfall was calculated based on the CN4GA procedure (Grimaldi et al., 2013). This method consists of two stages. In the first stage, the cumulative excess rainfall is determined based on the

SCS-CN method (Eq. 3). In the second stage, the temporal distribution of the excess rainfall within the event is determined using the Green-Ampt equation:

$$q0(t) = \begin{cases} i(t), fort < t_p \\ K_s\left(1 + \frac{\Delta\theta\Delta H}{I(t)}\right), fort > t_p \end{cases}$$

where:
q_0 – infiltration indicator [mm h^{-1}],
t_p – ponding time [h],
K_s – saturated hydraulic conductivity [mm h^{-1}],
I – cumulative infiltration [mm],
Δθ – change in soil–water content between the initial value and the field saturated soil–water content [-],
ΔH – difference between the pressure head at the soil surface and the matric pressure head at the moving wetting front [mm].

The solution of the equation (9) requires the calibration of the K_s parameter. The final (calibrated) value of K_s is determined so that the for the CN4GA, net rainfall is equal to the cumulative value provided from the SCS-CN method (that is well known in literature to be correct only at event scale and not at sub daily scale). Moreover, the CN4GA procedure is designed to preserve the ponding time information provided by the SCS-CN method. In doing so, K_s loses its physical meaning and it becomes essentially a calibration parameter linked to CN. The reason behind this methodology is that usually is much easier to assess CN based on land use and land cover information than to measure K_s in the field for use in calculations. After having estimated the amount of excess rainfall and its distribution, the width function instantaneous unit hydrograph (WFIUH) is determined based on the following relationship (Grimaldi et al., 2012):

$$WFIUH(t) = \frac{L_c(x)}{V_c(x)} + \frac{L_h(x)}{V_h(x)}$$

where:
L_c, L_h – hillslope and channel flow paths, functions of DEM cell ×, respectively [m],
V_c, V_h – runoff velocity for hillslope cells and flow channel cells [$m \cdot s^{-1}$].

After defining WFIUH, the final flood hydrograph Q(t) [m^3 s^{-1}] is determined, described by the following relationship:

$$Q(t) = A\int_0^t WFIUH(t - \tau)P_n(\tau)d\tau$$

where:
A – catchment area [m^2],
t – duration of rainfall [s],
$P_n(t)$ – excess rainfall determined by the CN4GA method [$m \cdot s^{-1}$].

3.4. Concept of the EBA4SUNURB model

In the presented concept, it was assumed that for impervious areas (parking lots, roads, roofs and so on), the net rainfall should be calculated independent from pervious areas. In impervious areas, identified via land cover data, infiltration is not possible and lost rainfall is caused by depression storage. In the Serafa catchment we assumed that the impervious areas (i.e. industrial or commercial units, road and rail networks, and/or sport and leisure facilities) are located throughout the catchment area and are separated by pervious area (i.e. meadows, pastures, forests and arable area). It was assumed that rainfall falls on impervious area, where infiltration and depression retention are negligible, and subsequently overflows on pervious area. Assumed that runoff will be calculated from the whole catchment, the following procedure (P4URB) for modeling the runoff is proposed. A catchment is divided into two categories: pervious area, P1, and impervious area, P2, where rainfall outflows to area P1. It is a simplification of real situations where some impervious areas drain into one another and are routed directly to nearby streams. These detailed analyses of connections between areas with different permeability are possible oi a small scale to prepare local projects for stormwater management. In case where larger catchments are analyzed, this approach can lead to too complicated models and the advantage with using these models is not too high in comparison to cost and time needed to perform calculations.

In the impervious areas, the excess rainfall is not correctly calculated using the original SCS-CN method because the original value of the initial abstraction ratio, equal to 0.20 (USDA, 2004), is too high and thus runoff can be underestimated, circumstance that may have serious consequences in terms of the underestimation of flood risk in these areas (Krajewski et al., 2020). Therefore, in this concept, impervious areas have a *d2* depression storage that can occur after rainfall fills such depression storage. So, *d2* is added to the total rainfall occurring on pervious areas. Depression storage of impervious areas can be calculated based on the following equation (Krzanowski and Wałęga, 2007):**

$$d2 = 0.77 \cdot J_{ave}^{-0,49} \text{ [mm] (12)}$$

where:
J_{ave} – average slope of impervious areas [$m \cdot m^{-1}$].

The total excess rainfall in EBA4SUNURB is calculated based on CN4GA method. In the proposed EBA4SUB modification, the input rainfall for CN4GA is assumed as total equivalent rainfall P*, calculated based on the following formula:

$$P^*(i) = P1(i) + Aca \bullet P2(i) \quad (13)$$

where:
P1(i) is the sum of rainfall impulse for each Δt [mm],
P2(i) is the sum of rainfall impulse for each Δt minus *d2* from eq. (12) [mm].

$$Aca = \frac{AP2}{AP1} \quad (14)$$

where:
AP1 - catchment area of category P1 [km^2],
AP2 - catchment area of category P2 [km^2].

Using this methodology, the total equivalent rainfall is the sum of the total rainfall falling on pervious area plus the overland runoff from an impervious area that cannot be stored in depression storage.

In summary, the following procedure (EBA4SUNURB) is proposed for hydrograph calculation in urban catchment:

1) identification of AP1 and AP2 area, based on land cover data;
2) calculation of the precipitation P*(i), based on P4URB procedure;
3) calculation of the excess rainfall as combination of CN4GA and P4URB procedure; CN in CN4GA is calculated only for pervious areas;
4) determination of Q(t), based on the WFIUH.

The CN4GA from P*(i) was used to assess the excess precipitation and perform the convolution integral with WFIUH, obtaining Q(t). The critical rainfall duration was determined using a simulation procedure where different durations of rainfall events were assumed, and the rainfall duration that caused the maximum peak discharge was selected. The same critical time of rainfall was assumed for EBA4SUB and EBA4SUNURB models.

3.5. Sensitivity analysis

The sensitivity analysis for EBA4SUNURB was conducted using the coefficient of flexibility *e*, which is expressed as (Wałęga et al., 2014):

$$e = \frac{\%\Delta_{output}}{\%\Delta_{input}}$$

where:
Δ_{output} – changes in peak flows [%],
Δ_{input} – changes in degree of surface sealing [%].

The analysis was performed by changing the degree of surface sealing by increments of 1%. If $e \geq 1$, then the parameter is flexible. Otherwise, if $e < 1$ then the parameter is inflexible.

4. Results and discussion

4.1. The critical rainfall duration

In the first stage of analysis the design rainfall for 100 years return period was determined, using log-normal function (theoretical distribution). The results were presented in Fig. 3.

Based on these calculations, the design rainfall for the return period of 100 years was 86.7 mm. The use of a log-normal distribution for calculating the design rainfall was supported by research conducted by Młyński et al. (2019) and it has been shown to be best suited to the empirical rainfall distribution P_T.

The crucial parameter related to design rainfall is the critical duration, which is defined as the time that yields the maximum peak flow of the runoff hydrograph. For small and urban catchments, the critical rainfall duration usually is assumed as the time of concentration (Meynink and Cordery, 1976; Wałęga et al., 2019). The relationship between rainfall duration and peak flows for the Serafa catchment is presented in Fig. 4.

The critical rainfall duration for the Serafa catchment was 12.5 h, a value that is not distant from the theoretic value (10.1 h) estimated thanks to Kirpich formula. The rainfall depth for the critical rainfall duration was found to be 74.1 mm. The amount of total rainfall P_{tot} for return period 100 years was determined by reducing the daily amount calculated by log-normal distribution to the amount corresponding to a critical rainfall duration equal to 12.5 h. The relatively long critical rainfall duration is caused mostly by the relatively high catchment area (72.4 km^2) and by the spatial distribution of land use, where, despite the fact that main land uses in the catchment are impermeable and semi-impermeable areas, large areas are also covered by agricultural lands. Furthermore, the upper parts of catchment are forested areas, a configuration that may lead to a longer response to rainfall events (Rogger et al., 2017). It should be emphasized that determining the critical rainfall duration plays a crucial role in determining the design hydrograph as shown by the study conducted by Krvavica and Rubinić (2020). This study showed that the method utilized for determining the design rainfall and critical rainfall duration has a significant impact on the flood modeling results and thus can lead to an over or underestimation of peak flow, confirming the results obtained by Gericke and Smithers (2014). The assumption that critical rainfall duration is equal to time of concentration is of course a simplification. For instance, for the flood hazard assessment, the critical rainfall duration is related to both maximum peak flow and maximum volume (Nguyen et al., 2010). Moreover, in complex and urbanized catchments, the rainfall-runoff processes are highly non-linear and strongly depend on antecedent moisture conditions, a circumstance that complicates the prediction of critical rainfall duration (Schmid, 1997).

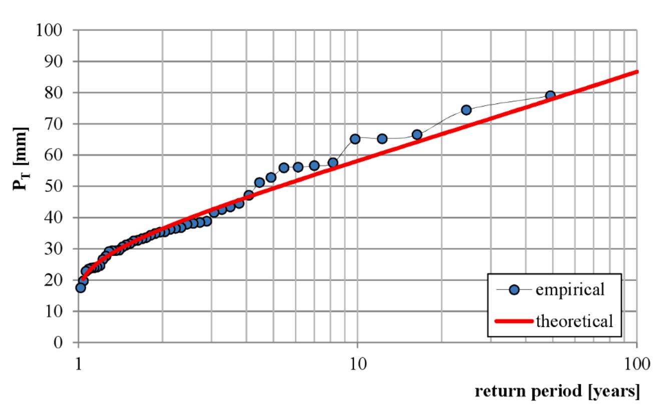

Fig. 3. Probability distribution curve for annual maximum daily precipitation.

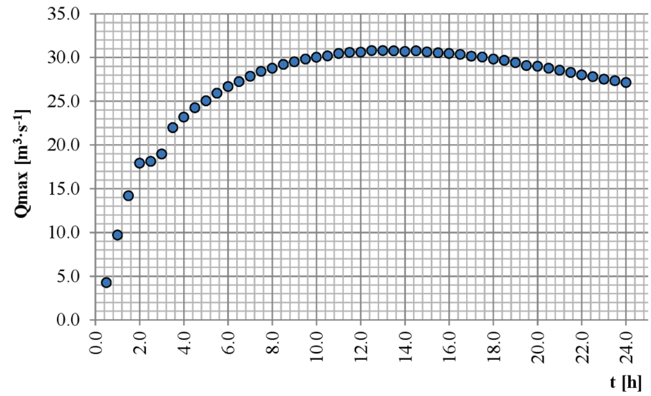

Fig. 4. Relationship between rainfall duration and peak flow.

4.2. Excess rainfall

In order to apply the investigated rainfall-runoff models, the excess rainfall depth was determined using methods SCS-CN, CN4GA, and the CN4GA-P4URB combination. The results of these calculations are summarized in Table 1, while Fig. 5 shows the excess rainfall and the design rainfall hyetographs, and finally Fig. 6 shows the spatial distribution of direct runoff calculated using SCS-CN, CN4GA and CN4GA-P4URB.

The higher value of CN calculated for the SCS-CN and CN4GA methods was caused by including all types of land cover in the calculation (pervious and impervious areas). In case of CN4GA-P4URB, CN was only calculated for pervious areas, where the infiltration process occurs (Chen and Young, 2006). The results show that time of excess rainfall calculated by the SCS-CN method was almost 3.5 times longer than for CN4GA and CN4GA-P4URB. In Fig. 5 it can be seen that, for the SCS-CN method, the excess rainfall is distributed in a longer time in comparison to CN4GA and CN4GA-P4URB. As shown in Grimaldi et al. (2013) this behavior can be explained by different assumptions in the distribution of excess rainfall between the SCS-CN and CN4GA methods. In case of SCS-CN, due the employed empirical formula, a long sequence of excess rainfall in the final part of the event is generated. The CN4GA procedure, which incorporates the Green-Ampt infiltration equation, better presents time distribution of excess rainfall depending on change of rainfall rate during the event. The shape of design hyetograph may affect the culmination of design hydrograph. Młyński et al. (2018) and Petroselli et al. (2020b) have identified that the EBA4SUB model is sensitive to changes in the design hyetograph shape. Usually the highest peak flows have been determined using DVWK method (Młyński et al., 2018). Because the Serafa river is ungauged, the same design rainfall hyetograph was used in calculations.

The calculated direct runoff values ranged from 3.8 mm to 74.1 mm

Table 1
Excess rainfall amounts determined by the SCS-CN, CN4GA and CN4GA-P4URB methods.

Method	P_{tot} [mm]	CN [-]	t_{net} [h]	P_{net} [mm]
SCS-CN	74.1	71.6*	8.5	19
CN4GA		71.6*	2.5	19
CN4GA-P4URB		70.2**	2.5	23.2

*CN was calculated for all types of land cover including pervious and impervious areas
** CN was calculated only for land cover including pervious areas

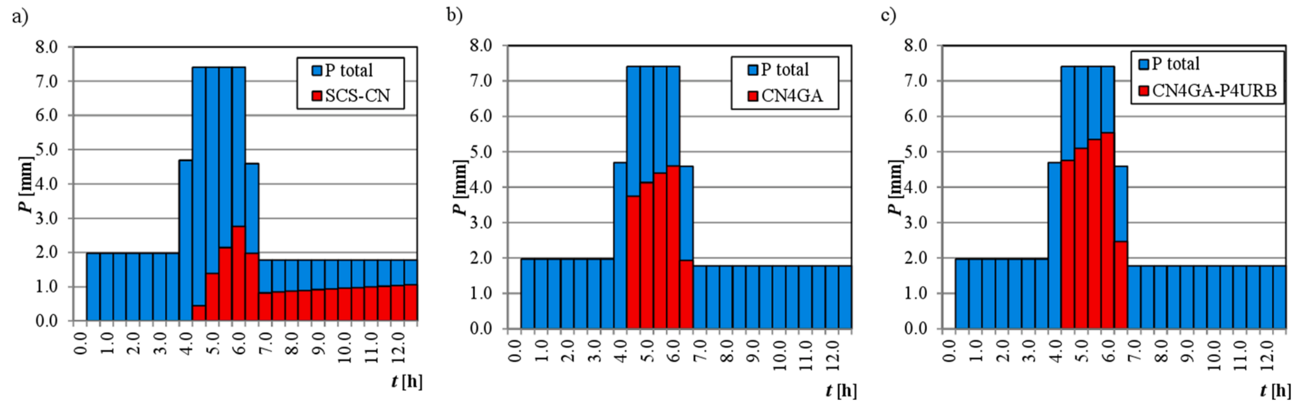

Fig. 5. Excess rainfall and total rainfall hyetographs, determined by following methods: a) SCS-CN; b) CN4GA; c) CN4GA-P4URB.

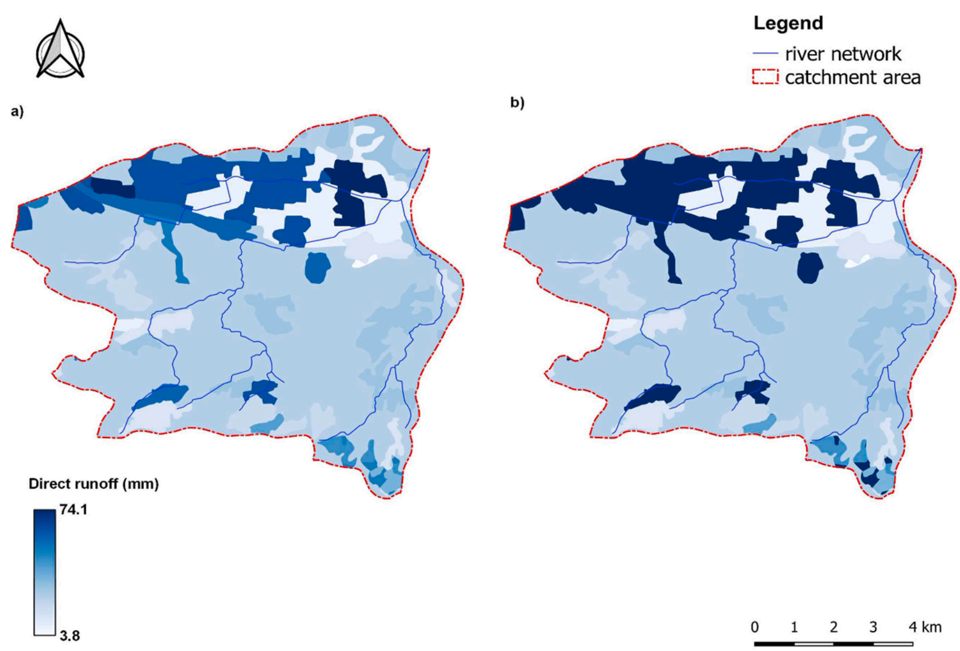

Fig. 6. Direct runoff for the Serafa catchment calculated using: a) SCS-CN and CN4GA; b) CN4GA-P4URB.

with the smaller values corresponding to areas with a small CN and vice versa. The direct runoff equal to 3.8 mm is related to the portions of the catchment consisting of discontinuous urban fabric, where are located soils having low runoff potential and high infiltration rates even when thoroughly wetted. The highest value of direct runoff was found for water courses. Generally, the highest direct runoff was observed in northern part of catchment where impervious areas are located. For the SCS-CN and CN4GA methods, the direct runoff from impermeable areas ranged from 38.6 mm to 48.5 mm. The different values of direct runoff in these areas are caused by variable values of the CN parameter for land uses that are primarily impermeable (from 85 to 90). In the CN4GA-P4URB method it was assumed that for impermeable areas the rainfall first filled the depression storage. The remaining part of the rainfall is then transformed into overland runoff. The depression storage calculated based on eq. (12) was equal only to 2.54 mm, slightly higher than the value reported by Skotnicki and Sowiński (2015) in an urban catchment in Poznań, Poland. The Authors calculated a 1.5 mm depression storage value in an urban area, that was estimated after calibration using a SWMM model. As noted above, the impervious areas are not included in CN under the CN4GA-P4URB approach, leading to a lower CN than that calculated for CN4GA or SCS-CN. Thus, excess rainfall in CN4GA-P4URB is higher than in other models (Table 1). For the CN4GA-P4URB method, the direct runoff calculated for impermeable areas (71.5 mm) was almost 40% higher than average values from SCS-CN and CN4GA approaches. A similar methodology for modeling overland flow formation in impervious areas is utilized in SWMM (Behrouz et al., 2020; Rossman and Huber, 2016).

4.3. Peak discharge and outflow hydrograph

In the next stage of this study, the design hydrographs were determined using the Nash model, the EBA4SUB model, and the proposed approach (EBA4SUNURB). Table 2 summarizes the characteristics of design hydrographs, while Fig. 7 presents their shapes. Substantial

Table 2
The characteristics of design hydrographs determined by analyzed models. Q_{max} – peak flow; V – hydrograph volume; t – duration time; α - slenderness coefficients.

Model	Characteristics Q_{max} [$m^3 s^{-1}$]	V [mln m^3]	t [h]	α [-]
Nash	30.78	1.449	46	2.88
EBA4SUB	51.76	1.362	15	0.63
EBA4SUNURB	63.95	1.680	15	0.63

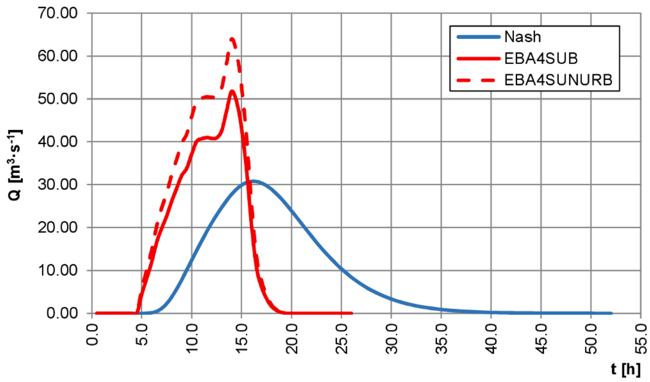

Fig. 7. Design hydrographs determined using the investigated models.

differences were noted between the methodologies as described below.

Because the catchment is relatively flat, it is assumed that DEM with grid resolution 25 m is sufficient for use in the EBA4SUB and EBA4-SUNRB calculations. In cases where more fine scale DEM resolution is available, the slope of watercourse and travel time could be more precisely determined and thus velocity of runoff could change the obtained values. Specifically, a smaller pixel dimension, like 1 m or 5 m, should be used in catchments with higher slopes. However, higher resolution DEMs also introduce errors. For example, Grimaldi et al. (2007) reported that the number of depressions is inversely proportional to the DEM resolution. Pits/depressions can be generated while interpolating DEMs as part of the process for changing grid spacing. Resampling a DEM to increase the resolution (downscaling) leads to more pits while decreasing the resolution (upscaling) reduces the total number of pits but the total percentage area covered by pits increases. Also the resolution of DEM has not shown a strong influence on peak discharges for return periods greater than 5 years (Petroselli et al. 2019a). Based on the results, EBA4SUB and EBA4SUNURB provided higher peak flows than Nash model, with the highest value generated by EBA4SUNURB. The peak discharge from EBA4SUNURB were 52% higher than from Nash model and 20% higher than from EBA4SUB. Higher peak flows, determined by EBA4SUB and EBA4SUNURB in comparison to the Nash model, are due to the fact that both the models take into account the surface runoff velocity via the WFIUH formulation. The analyzed catchment is strongly urbanized, circumstance that increases the surface flow velocity. Therefore, the catchment response to rainfall, described by EBA4SUB and EBA4SUNURB models, is faster than for the Nash model. Additionally, EBA4SUB and EBA4SUNURB discriminate river and hillslope DEM pixels to calculate velocity of outflow and thus the catchment response time. Hillslope velocities are defined using a spatially-distributed empirical formula based on the specific pixel information provided by DEM and CORINE data (specifically slope and land use). Conversely, in the river network, the runoff velocity is assumed constant following the Leopold and Maddock's findings (1953) that for small basins the increase in the downstream channel velocity is balanced by changes in channel width, depth, roughness and slope. The river network velocity was estimated considering the basin lag time. Specifically, we impose that the projection on the time axis of the median point of the WFIUH (that represents the travel time distribution) is equal to the basin lag time that is estimated as 60% of the concentration time (Tc). The proposed approach has the ability to consider that in different parts of the catchment, the hillslope velocity has different values from pixel to pixel. As reported by Grimaldi et al. (2010), higher velocities usually characterize low contributing area cells (upslope areas) and the lower velocities are distributed in high contributing areas (downslope areas). As a result, valley bottoms are found to play a major role for the travel time estimation impacting the receding limb of the hydrologic response. In the upper part of catchments, the DEM resolution should be higher to more precisely determine the flow velocity. In valleys, DEM resolution could be smaller. Indeed the presence of the drainage network can determine a faster time response of catchments (Jung et al., 2017). Conversely, the Nash model does not discriminate river network and hillslopes. The disadvantage of such a model structure is that the representation of physical processes is often too crude and the scales of measurements for many hydrologic parameters are incompatible with the scales used in models (Yu, 2015). For this reason, the Nash model cannot reflect the spatial heterogeneity of catchment topography. For EBA4SUB and EBA4SUNURB models, the surface flow velocity is calculated for each pixel of the DEM, allowing the characterization of the runoff dynamics for the whole catchment. Conversely, the Nash model describes the catchment as a cascade of linear reservoirs, whereby parameters are determined from empirical formulas (Sikorska et al., 2012; Karabová et al., 2012). Similar results were reported by Młyński et al. (2020a), where hydrographs determined by the EBA4SUB, SCS-UH, and Snyder models were compared. Młyński et al. (2020a) also showed higher peak discharge values for EBA4SUB. The differences were 46% and 40% compared to the SCS-UH and Snyder models respectively. It should be emphasized that SCS-UH and Snyder are lumped models, where the topography information is generalized. Despite the large differences between peak flows, the volume of runoff for the Nash model and EBA4SUB is similar, while for EBA4SUNURB the volume is larger. This is due to how the excess rainfall is calculated in CN4GA-P4URB approach as described above.

The flow duration, as determined by the Nash model, is three times longer than the corresponding estimated by EBA4SUB and EBA4SUNURB. The flow duration is 46 h for Nash model and 12 for the other two models. The shorter flow duration is the result of the distribution of excess rainfall determined by CN4GA and CN4GA-P4URB (2.5 h). In the Nash model, the SCS-CN method was used to determine excess rainfall, and the duration is 8.5 h. Therefore, the excess rainfall determined by CN4GA and CN4GA-P4URB is concentrated in a shorter time. This is reflected in the design hydrograph. Analyzing the slenderness coefficients it was concluded that for the hydrograph determined by the Nash model the value is greater than 1.0, conversely in EBA4SUB and EBA4SUNURB a value smaller than 1.0 is obtained. This indicates that for the Nash model the flood volume increases until the peak flow and then decreases slowly. In EBA4SUB and EBA4SUNURB the flood volume in the rising limb of the hydrograph is larger than in the falling limb.

Based on obtained results, we can conclude that the proposed approach combining the EBA4SUB model with a new method for calculating the excess rainfall in urban areas may be an alternative to the Nash model for determining the design hydrograph in urban catchments. In particular, the proposed model is better equipped to represent the flash floods of urban watersheds than the Nash model. It should also be emphasized that EBA4SUB model is a parsimonious model in terms of input parameters and reduces the user's subjectivity. The model simplicity means that the proposed approach can be fully used by practitioners, e.g. for determining flood zones or designing hydrotechnical infrastructures. Furthermore, the Nash model commonly used in urban catchments has some limitations. For instance, the model's parameters can by determined by various methods (Sikorska and Banasik, 2010), and the choice of method affects the obtained results. Nonetheless, the Nash model is still commonly applied in urban catchments (Banasik et al., 2007; Kołodziejczyk, 2017). Conversely, the parameters of the EBA4SUB model are determined directly on the basis of physiographic catchment characteristics and, in doing so, preclude the subjectivity of their determination. This plays a crucial role, especially in situations where different users aim to determine the design hydrograph for the same catchment and with the same input data. In short, EBA4SUB provides similar results when it is used by different practitioners. It should also be emphasized that data availability may limit the model selection. For that reason, simple models are commonly used because for smaller catchments the characteristics are unknown or too expensive to determine (Sitterson et al., 2017).

Summarizing, the proposed approach is based on a lumped procedure. Different land categories are used to calculate net rainfall. From pervious areas the CN4GA procedure is used whereby land uses without impervious areas are used to calculate CN parameter, and subsequently net rainfall. For impervious areas like roofs, roads, and parking lots where infiltration does not occur, the lost rainfall is assumed as depression storage. We identified impervious areas and pervious areas based on land use data from CORINE Land Cover information. The runoff from impervious areas is added to net runoff from pervious area and input to the kinematic component of model (Width Function based Instantaneous Unit Hydrograph, that is a lumped approach).

4.4. Sensitivity analysis

To further test the proposed approach, a sensitivity analysis was conducted. The sensitivity analysis consisted of calculating the coefficient of flexibility *e* output values (peak flows) by varying input values (degree of surface sealing). The results are presented in Figs. 8 and 9.

The degree of soil sealing is important considering the current trend of land planning in Krakow area, and throughout the world, where permeable areas like arable land and grassland will likely be replaced by impervious areas. The results presented in Fig. 8 indicate that 1% change of degree of surface sealing (*U*) produces a change of peak flows of about 2%, and similar changes for hydrograph's volume. The peak flows increase linearly as the degree of surface sealing was varied from 5% to 25%. The results are similar to the ones achieved by Wałęga et al. (2019) that indicated a similar rise in peak discharges with an increase of impervious areas in Sudoł Dominkanski – another second highly urbanized catchment inside the Krakow agglomeration. For the Serafa river, the lowest peak flow was 51.85 $m^3 s^{-1}$ and the highest was 77.65 $m^3 s^{-1}$. It should be emphasized that the lowest peak flow from EBA4-SUNURB, for *U* equal 5%, was similar to the peak flow determined by EBA4SUB. Such results indicate that EBA4SUB may be used in catchments where impervious area percentage is up to 5%. When the catchment has a greater impervious area percentage, the EBA4SUNURB is likely a better choice. The results presented in Fig. 9 show that the calculated coefficient of flexibility *e* is ranging from 0.08 to 0.63 in the sensitivity analysis. Because the obtained values were smaller than 1.0, it means that EBA4SUNURB is inflexible to the change of *U* value.

5. Conclusions

Urban catchments, where the majority of people live, are very sensitive areas where any change of runoff might influence dramatically water balance, retention and flood risk. Because of that the aim of this study was to develop a new approach for design hydrograph formulation in urban catchments. The proposed approach is a combination of the already existing EBA4SUB model and a new method for calculating excess rainfall. The model estimates by default some important parameters used for its application. This information can be changed by user if more specific data are available, leaving the model flexible to be used in either ungauged and gauged basins. The first parameter is related to the net rainfall estimation, and the second is related to the runoff propagation and is determined using the WFIUH framework. In this framework, the surface runoff velocity estimation is crucial. As a result, the new model, named EBA4SUNURB, for urban catchment is proposed. Considering the obtained results it was concluded that EBA4SUNURB can be a very good alternative to the commonly used Nash model in urban catchments because it more reasonably represents the influence of impervious areas on runoff formation and thus provides significantly different peak discharge and flood volume estimates. Moreover, the shape of the design hydrograph in the proposed method is more typical for urban catchments in comparison to the Nash model.

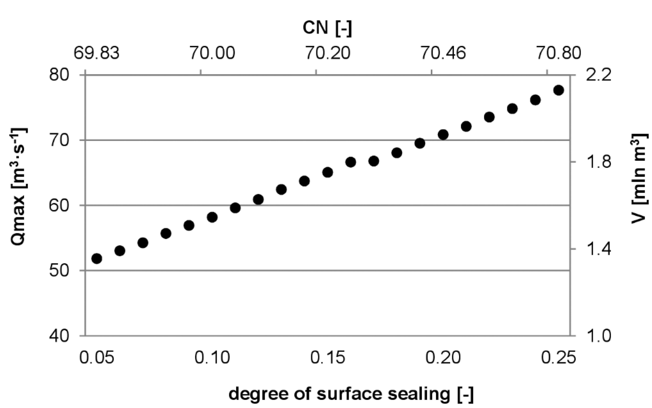

Fig. 8. Impact of change of degree of surface sealing for peak flows and hydrographs volume.

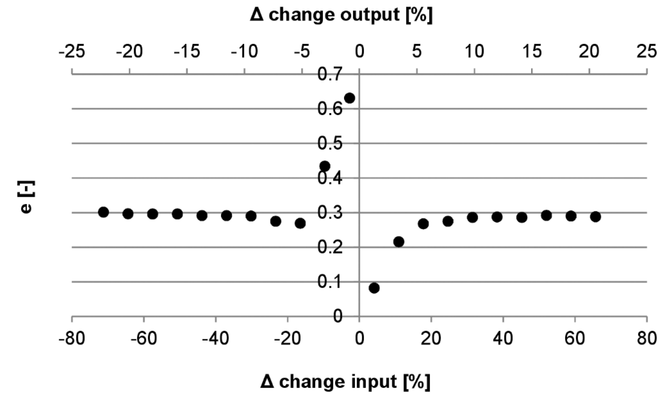

Fig. 9. The coefficient of flexibility for the peak flows.

An important benefit of the EBA4SUNURB model is that it is particularly useful in ungauged catchments because all its input parameters are calculated by default by the model based on more readily available catchment characteristics such as topography, land use and soil data, and thus does not explicitly require a calibration process. Of course, the input parameters of the model can be more precisely calculated or taken into account when a gauged catchment is investigated. Finally, a sensitivity analysis showed that EBA4SUNURB is inflexible in terms of degree of impervious of surface.

The main limitation of EBA4SUNURB is its inability to consider the role of storm sewer systems during the flood generation. Thus, at the moment, the model can be promoted for use by hydrologists aiming to perform preliminary studies for flood protection or design hydraulics structures. In case of more detailed and specific analysis, process-based models should be recommended. The future research for developing EBA4SUNURB model would be aim to: 1) test the proposed approach in gauged catchments with high impervious cover percentages, 2) include a synthetic time series of rainfall to generate continuous runoff, and 3) update the model by including the sewer systems contribution.

CRediT authorship contribution statement

Andrea Petroselli: Methodology, Software, Validation, Formal analysis, Writing – review & editing, Supervision. **Andrzej Wałęga:** Conceptualization, Methodology, Investigation, Writing – original draft, Supervision, Project administration. **Dariusz Młyński:** Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Visualization. **Artur Radecki-Pawlik:** Writing – review & editing, Supervision, Project administration. **Agnieszka Cupak:** Writing – review & editing. **Jon Hathaway:** Writing – review & editing, Supervision, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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