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Application of dynamic and conceptual models for simulating flow hydrographs in an urbanized catchment under conditions of controlled outflow from stormwater tanks

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ABSTRACT

The main aim of the research presented in the work was to assess the usefulness of the dynamic SWMM (stormwater management model) and the conceptual SBUH (Santa Barbara Urban Hydrograph) model for simulating and predicting flow hydrographs in a small urbanized catchment under conditions of controlled (using valves) outflow from stormwater retention tanks in response to rainfall events. Most of the analyzed catchment of the Służewiecki Stream consists of the area beneath F. Chopin International Airport in Warsaw. A further aim of the study was the development of method for indicating the concentration time for a given rainfall–runoff event, where the influence of delaying the outflow of stormwater from the catchment as a result of its retention in tanks on the value of this parameter will be accounted for. The values of the median of absolute errors, obtained in a simulation using the SWMM in relation to peak flows and hydrograph volumes for the analyzed events, were 15.4 and 18.4%, respectively. The adequate values of simulation errors, obtained in the SBUH model using concentration times determined according to the developed method, were 11.4 and 15.4%. Satisfactory results of simulations were received using both models.

Key words: rainfall–runoff process, rainwater management, retention tank, SBUH model, SWMM, urban catchment

HIGHLIGHTS

- Development of a method for indicating the concentration time for a given rainfall–runoff event in an urbanized catchment.
- Application of the dynamic SWMM and conceptual Santa Barbara Urban Hydrograph model for simulating flow hydrographs in a catchment under conditions of controlled (using valves) outflow from stormwater retention tanks.
- Assessment of the usefulness of models belonging to different classes for simulating flow hydrographs.

INTRODUCTION

Models of varying degrees of complexity (WMO 1994; Singh 1995) are classified as different types (classes) of mathematical models due to their divergent properties, such as the structure of the model, the availability of information on the inside structure of the modeled object, cognitive values of the model or the properties of the function of the operator. The Muskingum model (McCarthy 1938) is commonly applied in hydrological practice to predict hydrographs of flows in rivers and the transformation of flows through retention tanks (Chow *et al.* 1988; Perumal *et al.* 2017). The calculation of the outflow hydrograph is made possible by a conceptual model (symptomatic), the structure of which and the form of operators result from the assumed concept on the functioning of the modeled catchment. Examples of conceptual models are cascades of linear tanks (Nash's model) or models of an individual linear tank (SBUH – Santa Barbara Urban Hydrograph model). The SBUH model (Stubchaer 1975) is one of few conceptual models which are intended for carrying out calculations in urbanized catchments. The only variable of this model is the routing constant, K_r, which is dependent on the concentration time in the catchment. The SBUH model is one of two which have been applied in this work for simulating the flow hydrograph in the Służewiecki Stream subcatchment, the majority of which comprises land under Frederick Chopin International Airport. The results of analyses using the SBUH model in a small catchment located in Warsaw can be found in the work of Barszcz

(2014), in which values of relative errors of hydrograph peak flow simulations ranged from −28.3 to 87.6% with an average of 8.9%.

The second model, which was applied to simulate the flow hydrograph in the analyzed catchment, was the SWMM – stormwater management model (Rossman 2015; USEPA 2020). This is a dynamic model (modeling the processes taking place in the catchment in the function of time) with a known inner structure. An advantage of this type of model is the fact that its parameters are mostly physically measurable characteristics of the catchment and hydrometeorological conditions.

Significantly, more articles can be found in scientific literature containing the results of analyses carried out with the use of SWMM than those applying the SBUH model. One of them is the article by Peng *et al.* (2020), which presents results of peak flow and hydrograph volume simulations in a small catchment at Beijing Airport in China. The results showed that the SWMM can serve as a simulation tool for implementing a real-time rainwater drainage control system in the studied catchment. The work of Yazdi *et al.* (2019) compiled the results of flow simulations using the SWMM obtained by various authors (Guan *et al.* 2015; Palla & Gnecco 2015; Rosa *et al.* 2015; Alamdari *et al.* 2017; Moore *et al.* 2017) in urbanized catchments which varied in terms of surface area (catchments ranging in size from 2 ha to 150 km^2, though it primarily took into account smaller urban catchments). An assessment of the agreement of observed and simulated flows in these catchments was carried out by applying various statistical measures, including *PBIAS* (percent bias), the values of which ranged from −38.7 to 12.1%. Moreover, the work of Yazdi *et al.* (2019) presenting the ability of the SWMM and the HSPF (Hydrologic Simulation Program-Fortran) model to simulate streamflows from a small urban catchment located in Virginia was compared. HSPF is a comprehensive process-based catchment model that simulates catchment hydrology (Aqua Terra 2001). The analysis revealed that, although both models simulated streamflows adequately, SWMM simulated peak flow better than HSPF. In another analysis (Lee *et al.* 2010), it was indicated that the SWMM and the HSPE model provide similar results. The papers by Sañudo *et al.* (2020) and Yang *et al.* (2020) present the results of hydrological analyses in which models combining SWMM with the Iber and MIKE21 models were used, respectively. The results of analyses regarding flow simulations in urbanized catchments using the SWMM can be found in many other articles (Warwick & Tadepalli 1991; Barco *et al.* 2008; Krebs *et al.* 2013; Wu *et al.* 2013; Li *et al.* 2016; Barszcz 2018; Szeląg *et al.* 2019).

The time of concentration t_c is an important description of a catchment, seeing as how it holds a vital role in defining the shape of a runoff hydrograph. This parameter is defined in different ways, but most often as the longest travel time taken by a particle of water to reach a discharge point in a catchment (Wanielista *et al.* 1997). As had already been mentioned, the time of concentration is also a very important element in the SBUH model procedure, since it determines the value of the sole parameter of this model. The shape of the unit hydrograph (time to peak, time base, and peak) is also determined by the catchment time of concentration in the Soil Conservation Service (SCS) method (USDA-SCS 1975).

Several methods for estimating the time of concentration are available (Hall 1984). In the procedure presented by Stubchaer (1975), the time of concentration in the SBUH model is calculated in a conventional manner by summing the initial time, street travel time, and storm sewer travel time. The Manning equation (Chow 1959) is most commonly used to estimate the velocity of flow in the sewer pipes and open channels, which makes it possible to calculate the travel time of rainwater in a catchment.

Urbanization generally tends to decrease the time of concentration, thereby increasing the peak discharge. In urbanized catchments, technical solutions aiding the natural retention of rainwater in the catchment, which includes the construction of retention tanks, are carried out relatively frequently. This leads to the lengthening of the retention time of rainwater in the catchment and, thus, the time of concentration. Moreover, in an urban catchment, the concentration time can be increased by the ponding of rainwater in too small or inadequate drainage systems, including storm drain inlets and road culverts (USDA-SCS 1986).

The main aim of the research presented in the work was to assess the usefulness of the dynamic SWMM and the conceptual SBUH model for simulating flow hydrographs in an urbanized catchment under conditions of controlled (using valves) outflow from retention tanks in response to rainfall events. The above-mentioned models were adapted for the analyzed catchment of the Służewiecki Stream in Warsaw and verified on the basis of observed and simulated values of peak flow and hydrograph volume for analyzed events. There are few scientific articles that report the results of flow hydrograph simulations performed simultaneously with the use of models belonging to different types (classes) due to their different properties, as is the case in this work. The application of the conceptual SBUH model for simulating flow hydrographs in the analyzed catchment with retention tanks required the development of an original method for indicating the concentration time for individual rainfall–runoff events. The SWMM and the SBUH model, which were verified for the analyzed catchment, were also applied to predict flow hydrographs in the cross-section at the outlet of the catchment, in response to the design (control) rainfall.

MATERIALS AND METHODS

Description of the analyzed catchment and stormwater retention system

The Służewiecki Stream catchment is located in the south-western part of Warsaw. Its surface area up to its estuary in Wilanowskie Lake is 55.2 km^2. The entire length of the Służewiecki Stream (referred to in this model as the main collector) is approximately 15 km. The catchment area has a temperate climate. The annual mean temperature is approximately 9 °C, and the mean annual maximum and minimum temperatures are around 25 °C and −5 °C, respectively. The annual mean rainfall is 500–550 mm. The given characteristics apply to the period 1981–2010.

The analyses presented in the work cover the upper part of this catchment up to the 'P1' measuring and calculating cross-section (latitude: 52°9′31.43″N; longitude: 20°59′27.2″E), comprising the outlet with a surface area of 17.6 km^2 (Figure 1). The minimum and maximum altitudes in the analyzed catchment are 96.3 and 113.3 m above sea level, respectively. The length of Służewiecki Stream up to this section is 7.5 km. Two main areas can be distinguished in the area of the analyzed catchment, i.e. the area of F. Chopin International Airport (in the lower and middle part of the catchment) and the higher situated urban area, which functions, above all, as an area of residential development and an industrial zone.

The segment of Służewiecki Stream from the source to the 'P1' cross-section is made up of a circular concrete collector almost along its entire length. The diameter of the collector, which Służewiecki Stream runs through in the area of the airport,

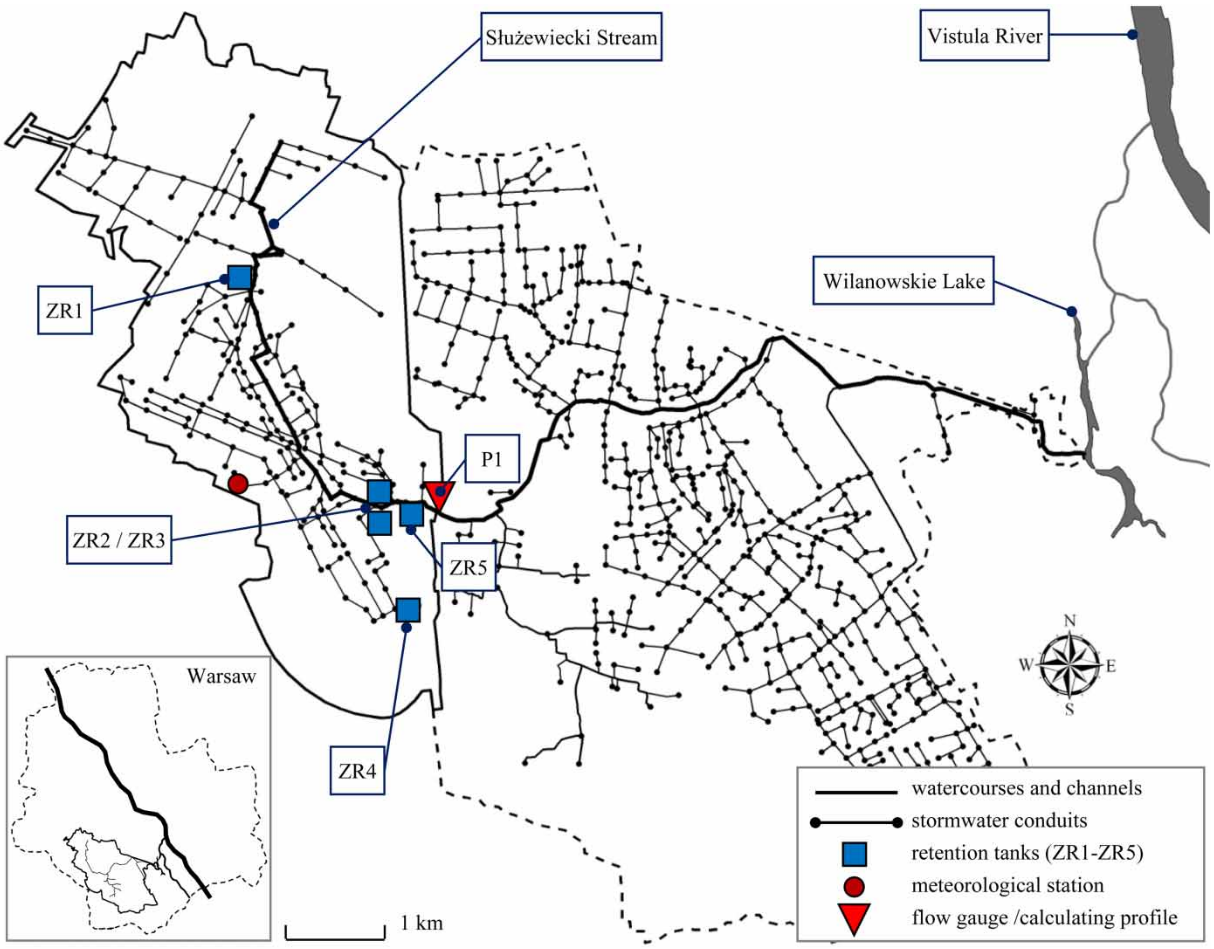

Figure 1 | Stormwater sewer system and rainwater retention system in the Służewiecki Stream catchment.

is 2.5 m for the majority of its length (1.8 m in the upper part of the airport). The total length of all stormwater conduits within the area of the airport amounts to approximately 30 km.

Five underground retention tanks for rainwater are found in the area of Frederick Chopin International Airport (Figure 1), which have a combined storage capacity of 42,490 m^3. Their construction was completed in June 2005. The tank indicated by the abbreviation ZR1 (side tank) has a capacity of approximately 8,000 m^3 and is located at the beginning of the airport. It captures rainwater which flows to the airport through the main collector, from the upper part of the catchment. Tanks ZR2 and ZR3, the retention capacities of which are 11,130 and 15,620 m^3, respectively, are found in the lower part of the airport, on both sides of the main collector (Służewiecki Stream). Their task is, above all, to store rainwater draining out of the area of the airport. The ZR4 tank, with a capacity of 1,900 m^3, is located near the building of the airport freight service. The ZR5 tank, with a capacity of 5,840 m^3, is the lowest-lying in the airport drainage network and is included in the technological sewage treatment system. The described retention tanks have regulation chambers where the height of raising and lowering of valves is controlled (usually, control is done automatically) in order to ensure flow below each tank smaller than 1.53 $m^3 \cdot s^{-1}$.

Adaptation of the SWMM for the analyzed catchment

The SWMM in its 5.0.022 version, developed by the U.S. Environmental Protection Agency – EPA in cooperation with the CDM Inc. engineering company, was adapted for the analyzed Służewiecki Stream catchment to the 'P1' cross-section (Figure 2). SWMM is a dynamic model with spatially distributed parameters (accounting for the spatial variability of

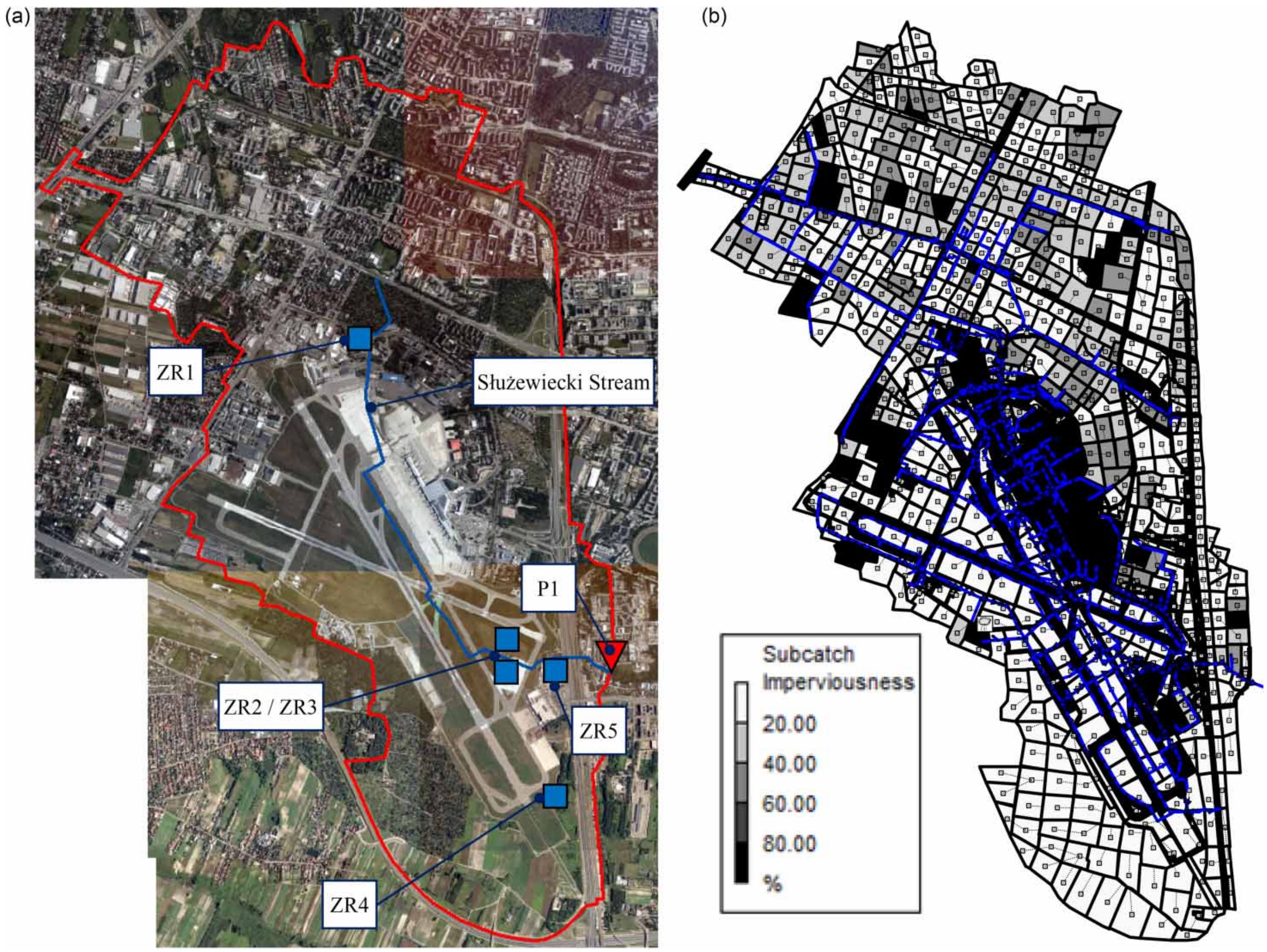

Figure 2 | An aerial photograph of the Służewiecki Stream catchment (a); the division of the analyzed catchment into subcatchments in the SWMM (b). Designations: channels and stormwater sewer system – blue lines; ZR1–ZR5 – stormwater retention tanks; P1 – calculating profile. Please refer to the online version of this paper to see this figure in colour: doi:10.2166/wcc.2021.211.

parameters of the actual catchment system), intended for simulating the runoff of stormwater (also the quality of water) in response to single and long-term events, principally in urbanized catchments. Two main modules for realizing calculation procedures of processes taking place in the hydrological and hydraulic system of the catchment can be distinguished within the structure of the discussed model. The procedure of stormwater runoff is based on a set of subcatchments with specified parameters which transform the rainfall falling onto their surface into runoff. The calculated runoff from individual subcatchments is then transported in the model to the outlet through sewer network pipelines, open channels, tanks, culverts, pumps, and various types of flow regulators (weirs, orifices, etc.).

The curve number method (USDA-SCS 1975, 1986) was used to calculate the infiltration rate for pervious areas in the analyses presented in this work. The effective rainfall rate for impervious areas was calculated as the difference between the total rainfall depth and the depression storage depth (Barszcz 2018). The dynamic wave model (uses the Saint-Venant flow equations) was used in order to calculate the transformation of flows in the investigated catchment. A full description of the SWMM can be found in the manual (Rossman 2015).

The adaptation of the SWMM for the analyzed Służewiecki Stream subcatchment relied on creating objects (in the window of the computer program), which represent the physical components of the actual hydrometeorological and hydraulic systems of the catchment in the model, and then determining the value of their parameters. The values of parameters for the objects accounted for in the model were assumed based on data determined for physically measurable characteristics of the object or values recommended in the model manual and other literature (Peterson & Wick 2006; Park *et al.* 2008). The characteristics and dimensions of the structures located in the area of the airport (such as stormwater conduits, and tanks) were assumed in accordance with technical data obtained from design and as-built documentation of the airport drainage system.

In the model of the analyzed catchment, the following objects were accounted for:

- Rain gauge: one object, situated at the existing 'Okęcie' meteorological station (Figure 1), which belongs to the Institute of Meteorology and Water Management of the National Research Institute, was created.

Rainfall values registered for a few dozen events at the 'Okęcie' meteorological station, in time intervals of $\Delta t = 10$ min, as well as designed rainfall depths with a $C = 5$-year frequency of occurrence and duration time of $t = 15$ min in time intervals of $\Delta t = 5$ min, were adopted in the model for simulations.

- Subcatchments: 1,509 objects.

The main criteria of dividing a catchment into subcatchments (Figure 2(b)) was the type of land use and the percentage share of impervious surfaces connected with it, which, in reference to the identified types of terrain, was determined on the basis of analyses using the ArcGIS program. For each subcatchment, the values of a few dozen parameters, e.g. width of the overland flow path, Manning's n coefficient for overland flow, (hydraulically connected) impervious portion of the catchment, and the depth of depression storage, were determined. The division of the catchment into subcatchments was carried out on the basis of a so-called orthophoto map (aerial photograph).

- Open channels, stormwater sewer network conduits, and nodes (corresponding to the location of junctions in the stormwater sewer system or determining the change in stormwater conduit characteristics): 1,001 segments of channels/conduits and 984 node points were created.

The parameters of the sewer network were accounted for in the model on the basis of data obtained from a so-called master map and/or information contained in the available technical studies. For each channel/conduit and node point, the values of a few parameters were established in the SWMM.

- Rainwater storage tanks (underground and concrete) in the area of the Frederic Chopin airport: five objects (ZR1–ZR5).
- Flow regulation chambers which are situated next to four retention tanks (ZR1–ZR3, ZR5) in which the height of raising and lowering of the valves is controlled: three objects, as well as sideflow/transverse weirs.

SBUH model procedure

The SBUH model was developed by Stubchaer (1975) of the Santa Barbara County (California) Flood Control and Water Conservation District. The conceptualization of the SBUH model is based on a linear tank, whose parameter K_r (Equation (1)), described as the routing constant, is calculated based on the concentration time of the catchment t_c (h) and the assumed time interval of calculations Δt (h).

$$K_r = \frac{\Delta t}{(2t_c + \Delta t)} \tag{1}$$

The $I(\Delta t)$ ($m^3 \cdot s^{-1}$) function of the instantaneous hydrograph is dependent on the size of the surface of the catchment A (km^2), the time interval of calculations Δt (h), as well as the effective rainfall depth in subsequent time intervals $R(\Delta t)$ (mm). It is calculated on the basis of a relationship by Equation (2) – the form of the function adapted by the author of this work to SI system units.

$$I(\Delta t) = 0.275 \frac{R(\Delta t)A}{\Delta t} \tag{2}$$

Flow hydrograph coordinates – flow rate $Q(t)$ ($m^3 \cdot s^{-1}$) – are then obtained by routing the instantaneous hydrograph $I(\Delta t)$ through an imaginary reservoir, with the time delay calculated using the time of concentration t_c. This flood routing is done by the use of Equation (3) to estimate routed flow Q (Wanielista *et al.* 1997).

$$Q(t) = Q(t - \Delta t) + K_r[I(t - \Delta t) + I(t) - 2Q(t - \Delta t)] \tag{3}$$

The total effective rainfall depth in subsequent time intervals $R(\Delta t)$ was assumed in the Służewiecki Stream catchment as a weighted average for effective rainfall depths calculated in relation to the pervious and impervious surfaces (the weights were the percentage amounts of these surfaces in the analyzed catchment). To indicate the effective rainfall depth for pervious surfaces, the method developed by the SCS was applied, assuming the value of parameter $CN = 74.0$ (USDA-SCS 1975). The effective rainfall depth for impervious areas was calculated as the difference between the total rainfall $P(\Delta t)$ at the time interval Δt and the rainwater depth retained on their surface $D(\Delta t)$. According to ASCE (1992), the surface retention depth $D(\Delta t)$ for impervious surfaces falls within the range of 1.27–2.54 mm. For purposes of simulations presented in this work, varied surface retention depths were assumed, analyzing their influence on the effective rainfall depth.

RESULTS AND DISCUSSION

Characteristics of rainfall–runoff events

For analyses in accordance with the scope of this work, 16 rainfall–runoff events were assumed, for which measurement data of both rainfall events as well as flows were available (flows were registered in the analyzed catchment during the period from 2006 to 2009 under Grant No. COST/210/2006). Their basic characteristics are contained in Table 1.

The total rainfall depths for the analyzed events were registered at the 'Okęcie' meteorological station (Figure 1) using an electronic tipping bucket rain gauge by SEBA Hydrometrie. The flow hydrographs, on the other hand (for which the peak flow values and volumes were determined), were observed in the measuring cross-section of Służewiecki Stream belonging to the Warsaw University of Life Sciences – SGGW, the location of which corresponds to the location of the 'P1' calculating cross-section (Figure 1). The water levels, which were then recalculated into flow values using the determined water level – flow relation (rating curve), were registered in 10-min time intervals with the use of a Diver-type hydrostatic sensor (manufactured by Eijkelkamp).

The events assumed in this work for analyses were characterized by diverse values of rainfall and flow hydrograph characteristics (Table 1). The total rainfall sums for 16 events ranged from 3.6 to 24.2 mm, with a median value of 9.6 mm. The rainfall event on 15 August 2008 was characterized by the highest total of those measured at the 'Okęcie' station. The durations of rainfall fell within the range from 30 to 910 min. The peak flow and volume values for the observed hydrographs were from 0.504 to 1.622 $m^3 \cdot s^{-1}$ (the value of the median was 0.931 $m^3 \cdot s^{-1}$) and 8.9×10^3 to 95.7×10^3 m^3 (the value of the median was 28.6×10^3 m^3), respectively. The sums of effective rainfall, which were calculated on the basis of values of direct flows for the observed hydrographs, were from 0.50 to 5.44 mm (value of median was 1.65 mm).

Calibration of SWMM

The adaptation of the SWMM for the analyzed catchment (described in the section 'Adaptation of the SWMM for the analyzed catchment') relied on creating the objects of the hydrometeorological and hydraulic systems of the catchment in the

Table 1 | Characteristics of the observed rainfall–runoff events

Date of the event	Rainfall totals (mm)	Effective rainfall totals (mm)	Rainfall duration (min)	Peak flow ($m^3 \cdot s^{-1}$)	Volume (10^3 m^3)
19.09.2006	11.2	1.62	50	1.275	25.7
15.05.2007	12.2	2.79	910	0.785	49.1
02.06.2007	9.4	1.82	530	0.729	32.0
13.06.2007	16.4	2.78	50	1.298	49.0
19.06.2007	14.0	1.74	110	0.922	30.6
21.06.2007	9.8	1.69	230	1.079	29.7
02.07.2007	8.6	1.38	90	0.804	24.3
20.07.2007	5.6	0.99	30	0.940	17.5
22.07.2007	9.4	1.56	30	1.005	27.5
27.07.2007[a]	11.2	1.70	50	0.940	29.8
05.09.2007	14.6	2.70	620	1.079	47.5
28.09.2007[a]	3.6	0.50	180	0.504	8.9
02.08.2008	8.8	0.81	60	0.729	14.2
09.08.2008	6.8	0.98	60	0.659	17.2
15.08.2008[a]	24.2	5.44	180	1.622	95.7
16.08.2008	5.6	1.12	50	0.813	17.8
Median value	9.6	1.65	75	0.931	28.6
Average value	10.7	1.85	202	0.949	32.3

[a]Events assumed for calibrating the SWMM and optimizing the parameters applied in the SBUH model procedure.

model, and next on determining their characteristics and parameters. Some of the initially assumed parameters were later corrected in the model calibration process, which was carried out on the basis of peak flows and hydrograph volumes for three selected rainfall–runoff events observed in the analyzed catchment on 27 July 2007, 28 September 2007, and 15 August 2008 (characterized by diverse values of rainfall total and the hydrograph parameters induced by them; Table 1), as well as water levels in the specified objects of the hydraulic system of the catchment located in the area of Frederic Chopin airport. Water levels were registered in five stormwater retention tanks (ZR1–ZR5), as well as in the main channel above/below the flow regulation chambers situated near four of these tanks (ZR1–ZR3 and ZR5). The given parameters of the objects were corrected in the model, up to the moment of obtaining optimal compatibility between the measured and simulated data for individual events.

In the calibration process, parameters of subcatchments (1,509 objects) created in the model were corrected, among others: the width of the overland flow path, the depth of depression storage, and Manning's n coefficient for overland flow. Manning's roughness coefficient for conduits was assumed to be 0.011 $s \cdot m^{-1/3}$. The average surface slopes were ranging from 0.1 to 0.5%.

Values of the model parameters were determined based on the calibration:

- The values of the width of the overland flow path were determined for individual subcatchments in the model, ranging from 7 to 200 m (most often 100–150 m).
- The values of Manning's coefficient for impervious and pervious surfaces were found to be, in most cases, equal to 0.013 and 0.13 $s \cdot m^{-1/3}$, respectively (in relation to areas used as forest and arable land, they were 0.25 and 0.15, respectively);
- The values of the depression storage depth for impervious and pervious areas were equal to 1.3 and 2.5 mm (only for forest areas, arable land, and green areas on the airport, the surface retention depth was 5.0 mm).
- The parameter defined as the percent of impervious area with no depression storage assumed the value of 25%.

The optimization of the scheme of how the valves in the flow regulation chambers operate (as well as those built-in to the side wall of the ZR5 tank), which rise and fall depending on the level of water and/or value of flows in specific rainwater sewer pipes and/or stormwater retention tanks. The result of these optimizing measures was the determination of the relationship between values of flows or the levels of water in specific objects and the levels of raising and lowering of the valves. Moreover, the model accounted for the conditions of activating individual valves (also pumps), by applying functions made available in the 'Control Rules' editor.

Compatibility assessment of the two selected parameters of the flow hydrograph (i.e. peak flow and volume) for the analyzed events obtained on the basis of observed and simulated data in the 'P1' cross-section was carried out with the use of values of relative error – *RE* (Equation (4)), recommended by ASCE (1993) for a single event. Based on the classification given by Moriasi *et al.* (2007) for a similarly calculated statistical measure – *PBIAS*, the model performance can be evaluated as 'satisfactory' if $RE < \pm 25\%$, 'good' if $RE < \pm 15\%$, and 'very good' if $RE < \pm 10\%$.

$$RE = \frac{X - X_o}{X_o} 100\% \quad (4)$$

where *RE* is the relative error, *X* is the calculated value, and X_o is the observed (measured) value.

The values of the relative error for the analyzed hydrograph parameters, which were obtained as a result of calibrating the SWMM for three rainfall–runoff events, have been compiled in Table 2. In relation to the peak flow and volume of the outflow hydrograph, the values of the relative error amounted to −6.1 and 7.7% as well as −14.6 and 3.5%, respectively. In each case, simulation errors were lower than the value of 25%, which had been assumed as the cut-off limit for accepting the model. The SWMM for the analyzed catchment was assumed for further analyses in accordance with the scope of the work.

Establishing the time of concentration for rainfall–runoff events

Applying the conceptual SBUH model for the calculation of flow hydrographs in the analyzed Służewiecki Stream catchment required the time of concentration t_c to be established, which determines the values of the sole parameter of this model – the routing constant K_r. Parameter t_c was defined in the Introduction section. According to the SBUH procedures (Stubchaer 1975), the time of concentration is calculated in a conventional manner by summing up all the travel times for consecutive components of the drainage conveyance system. The travel time in various flow components (overland flow, storm sewer flow, and flow in open channel) depends on the length of travel and the flow velocity. In the analyzed catchment, the storm sewer travel time in the stormwater collector, the length of which to the 'P1' calculating cross-section is 7.5 km, had a decisive influence on the value of t_c.

The Manning equation has been used to estimate flow velocity in the main collector, which is circular in shape. Along its entire length, 103 pipe sections with diverse characteristics (lengths, slopes, and diameters) were separated, for which the mean flow velocities were calculated. The estimated total flow time through the collector, which corresponds to the concentration time t_c, was 208 min (Table 3).

The flow time in the main collector was also indicated on the basis of maximum velocities, which were determined for 103 conduit segments using simulations in the SWMM for a sample rainfall–runoff event on 27 July 2007. The concentration time, which was calculated based on maximum velocities in conduits, was 163 min.

The value of parameter t_c was also estimated using two selected empirical equations, which were assumed to be appropriate for calculations in the analyzed catchment due to the validity ranges specified for them. Kreps's (as quoted in Ciepielowski & Dąbkowski 2006) and Kirpich's (1940) formulas, in which the concentration time is, respectively, dependent on the surface area of the catchment and the length of the stormwater collector, as well as the differences in its elevations along its length, were chosen for this analysis. The t_c values estimated using these formulas were 159 and 244 min, respectively. The first of the mentioned values was very close to the value of the concentration time calculated based on maximum flow velocities (163 min).

Table 2 | Results of SWMM test calibration

Date of the event	Simulated values: Peak flow ($m^3 \cdot s^{-1}$)	Simulated values: Volume (10^3 m^3)	Relative error (%): Peak flow	Relative error (%): Volume
27.07.2007	0.979	30.9	4.1	3.5
28.09.2007	0.543	8.6	7.7	−3.1
15.08.2008	1.523	81.8	−6.1	−14.6

Table 3 | Results of calculations of the concentration time and peak flow of the hydrograph

Method of indicating the concentration time	t_c^a (min)	Date of the event	Peak flow[b] ($m^3 \cdot s^{-1}$)	Peak flow[c] ($m^3 \cdot s^{-1}$)	Relative error[d] (%)
The Manning equation	208	27.07.2007	0.923	2.059	119.0
Max. flow velocity – in the SWMM	163			2.554	171.7
Empirical equation of Kreps	159			2.610	177.6
Empirical equation of Kirpich	244			1.782	89.6
Equation of Rao for lag time	194			2.191	133.1
Equation (6)	539	27.07.2007	0.923	0.862	−8.3
	291	28.09.2007	0.509	0.398	−21.1
	975	15.08.2008	1.637	1.468	−9.5

[a]The concentration time calculated using different methods.
[b]Values calculated using Equation (5).
[c]Values simulated using the SBUH model.
[d]Values calculated for peak flow simulated using the SBUH model.

The concentration time was indicated for a selected event (on 27 July 2007) based on an equation intended for calculating the catchment lag time, developed by Rao *et al.* (1972), increasing its value by the coefficient of 1.67 – in accordance with the methodology given by the SCS (USDA-SCS 1975). This equation accounts not only for the characteristics of the catchment (surface area and percentage share of impervious catchment), but also for the characteristics of effective rainfall (depth and duration). The obtained t_c was 194 min.

The concentration time estimated based on a few of the above-described methods was assumed for calculating pertinent values of the K_r retention coefficient of the tank, which was then applied for simulating flow hydrographs in the SBUH model in reaction to rainfall for an exemplary event on 27 July 2007. The value of the simulated hydrograph parameters (peak flow and volume) in the SBUH model, obtained in reference to concentration times estimated using various methods, was compared to corresponding values of observed parameters of the hydrograph for an exemplary rainfall–runoff event. In reference to each method of indicating the concentration time, very high values of relative error with a positive sign were obtained (Table 3), falling into the range from 89.6 to 177.6%.

The retention tanks present in the analyzed catchment in the area of Chopin Airport, from which outflow is controlled with the use of valves (located in the main collector), lead to an extension of the retention time of stormwater in the catchment, and thus extending the flow time in Służewiecki Stream and concentration time. The peak flow simulation errors obtained in the above analyses revealed the necessity to develop an original methodology for indicating the concentration time, which will be adapted to the conditions of the outflow in the analyzed catchment. The first stage was indicating equation (Equation (5)), which describes the relationship between the effective rainfall depth R (mm) for a given event (calculated based on the volumes for the observed hydrograph and surface area of the catchment) and the peak flow values of the hydrograph Q_p ($l \cdot s^{-1}$) caused by this effective rainfall. Events observed in the analyzed catchment on 27 July 2007, 28 September 2007, and 15 August 2008, characterized by diverse total, and effective rainfall depths and peak flow values (Table 1), were assumed for indicating this equation. Values of the peak flow of the hydrograph, which were calculated using Equation (5) for the analyzed events (Table 3), were nearly equal to corresponding peak flow values of the observed hydrographs.

$$Q_p = 712.14R^{0.4915} \tag{5}$$

Effective rainfall volumes V_r (m^3), which correspond to values of direct outflow volume for hydrographs observed in the 'P1' cross-section, were determined for the three events assumed for the analysis. In the presented methodology, for indication of the concentration time, the assumption was made that the time necessary to empty the retention tanks and stormwater conduits in the area of catchment t (min) corresponds to the value of the travel time in Służewiecki Stream (main collector) to the 'P1' cross-section and, at the same time, the value of concentration time t_c for the given rainfall–runoff event (Equation (6)).

$$t_c = t = \frac{V_r}{3.6Q_p}60 \tag{6}$$

where t_c is the concentration time (min), V_r is the effective rainfall volumes (m^3), and Q_p is the peak flow of the hydrograph calculated from Equation (5), expressed in $m^3 \cdot s^{-1}$.

The values of the concentration time, which were estimated for three selected events using Equation (6), were compiled in Table 3. The t_c values, which were indicated according to the above-described methodology, were significantly higher than those calculated when applying conventional methods. The estimated concentration times were assumed for simulating outflow hydrographs in the SBUH model in response to observed rainfall depths for the analyzed events. The values of the relative errors, which were calculated for the simulated values of peak flow, fell into the range from −21.1 to −8.3% (Table 3). They were lower than the value of 25%, which was set as the limit for acceptance of the model, in every case. The values of relative error for the hydrograph volume obtained in these simulations (not shown in the table) were −1.0% for each of the analyzed events.

In all analyses presented in this section, the effective rainfall depths were calculated in particular time intervals of the duration of the rainfall according to the methodology described in the section 'SBUH model procedure'. To indicate the effective rainfall depth for pervious surfaces, the method developed by the SCS was applied, assuming the value so the parameter $CN = 74.0$. The method applied for indicating the effective rainfall for impervious surfaces assumed depths of the rainwater retained on their surface D, which were indicated as a result of the optimization for each of the three analyzed events on days 27 July 2007, 28 September 2007, and 15 August 2008. The values of D were 5.34, 1.86, and 6.42 mm, respectively, and were positively correlated with the total rainfall sums for these events. The effective rainfall sums for the analyzed events, which were indicated according to the methodology assumed in this work, corresponded to those calculated based on volumes for hydrographs observed in Służewiecki Stream.

Based on the depth of depression storage on impervious areas D (mm), which were optimized for three analyzed events, as well as total rainfall sums P (mm) corresponding to these events, Equation (7) was indicated, with a correlation coefficient equal to 0.98.

$$D = 2.4455 \ln P - 1.0735 \tag{7}$$

Flow hydrograph simulations in the analyzed catchment

The total rainfall depths measured at the 'Okęcie' meteorological station for 13 events (Table 1) were applied for simulating the flow hydrographs in the 'P1' calculating cross-section on Służewiecki Stream applying the SWMM dynamic model and the SBUH conceptual model. The values of the hydrograph parameters (peak flow and volume) as well as corresponding values of the relative error for the analyzed events, which were obtained in simulations using these models, are given in Tables 4 and 6. The observed and simulated flow hydrographs for the example event on 22 July 2007 are shown in Figure 3. The assessment of the agreement between observed and simulated values of parameters of the hydrograph was carried out using relative error (Equation (4)). The results of simulations were further assessed using the coefficient of determination – R^2 and the Nash–Sutcliffe efficiency coefficient – NSE (Nash & Sutcliffe 1970). Typically, values of R^2 greater than 0.5 are considered acceptable. Model performance can be evaluated as satisfactory if $NSE > 0.50$, good if $NSE > 0.65$, and very good if $NSE > 0.75$ (with $NSE = 1$ being the optimal value) (Moriasi *et al.* 2007).

The values of the water balance components of the analyzed catchment are also given in Table 4 (depths of water in the processes of infiltration, surface runoff, and storage), which are obtained in simulations using the SWMM for individual rainfall–runoff events. The total rainfall depths are given in Table 1. The values of the water balance components of the individual retention tanks ZR1–ZR5 are given in Table 5 (volumes of rainwater flowing into and out of the tank, as well as stored in the tank), the locations of which are shown in Figure 1.

The values of peak flow and hydrograph volume, which were obtained for analyzed events in a simulation using the SWMM, fell into the respective ranges of 0.822–1.138 $m^3 \cdot s^{-1}$ (the value of the median was 0.905 $m^3 \cdot s^{-1}$) and from 10.7×10^3 to $51.0 \times 10^3\,m^3$ (the value of the median was $24.7 \times 10^3\,m^3$). Relative errors of the simulation were from −23.5 to 24.7% for peak flows and from −39.8 to 58.6% for hydrograph volumes. The value of the median of simulation errors, calculated for the analyzed events based on the values of absolute errors (minus signs were ignored) were 15.4 and 18.4%, respectively. This was lower than the 25% value which was assumed as the stipulated limit for model acceptance. In this study, both underestimation (negative values of the relative errors) and overestimation of the simulated parameters of hydrographs were observed. The estimation accuracy of simulated parameters for the analyzed events, as assessed by the NSE

Table 4 | Results of simulations obtained using the SWMM

Date of the event	Simulated values		Relative error (%)		Components of the catchment water balance – depths (mm)		
	Peak flow ($m^3 \cdot s^{-1}$)	Volume (10^3 m^3)	Peak flow	Volume	Infiltration	Runoff	Storage
19.09.2006	0.976	30.2	−23.5	17.4	8.110	1.841	1.251
15.05.2007	0.848	37.3	8.0	−24.0	8.723	2.277	1.201
02.06.2007	0.872	24.7	19.6	−22.8	6.833	1.518	1.050
13.06.2007	1.138	51.0	−12.3	4.2	12.108	3.020	1.274
19.06.2007	1.082	48.6	17.3	58.6	9.439	3.035	1.528
21.06.2007	0.905	25.9	−16.1	−12.9	7.199	1.547	1.055
02.07.2007	0.928	21.3	15.4	−12.4	6.354	1.297	0.949
20.07.2007	0.842	10.7	−10.4	−39.1	4.462	0.686	0.453
22.07.2007	0.945	24.2	−6.0	−12.1	6.888	1.460	1.054
05.09.2007	0.963	46.8	−10.8	−1.5	10.572	2.831	1.197
02.08.2008	0.863	19.7	18.4	38.7	6.614	1.216	0.972
09.08.2008	0.822	14.0	24.7	−18.4	5.401	0.881	0.520
16.08.2008	0.870	10.7	7.0	−39.8	4.252	0.732	0.617
Median value	0.905	24.7	15.4	18.4	6.888	1.518	1.054
Average value	0.927	28.1	14.6	23.2	7.458	1.719	1.009

Table 5 | Components of the water balance of the individual tanks (ZR1–ZR5) obtained using the SWMM

Date of the event	ZR1			ZR2			ZR3			ZR4			ZR5		
	I[a]	S[b]	O[c]	I	S	O	I	S	O	I	S	O	I	S	O
19.09.2006	3.12	0.10	3.02	9.03	0.15	8.88	11.77	0.27	11.50	0.69	0.16	0.53	0.00	0.00	0.00
15.05.2007	0.00	0.00	0.00	2.67	0.10	2.57	2.67	0.20	2.46	0.85	0.16	0.69	0.00	0.00	0.00
02.06.2007	0.13	0.10	0.03	3.97	0.10	3.88	3.97	0.14	3.83	0.51	0.16	0.35	0.00	0.00	0.00
13.06.2007	7.86	0.10	7.75	12.99	0.10	12.89	16.45	0.20	16.24	1.19	0.16	1.03	0.85	0.26	0.59
19.06.2007	4.29	0.10	4.19	11.68	0.10	11.59	14.63	0.14	14.50	1.28	0.16	1.12	0.00	0.00	0.00
21.06.2007	0.75	0.10	0.65	7.56	0.15	7.42	9.23	0.27	8.96	0.57	0.16	0.41	0.00	0.00	0.00
02.07.2007	1.26	0.10	1.16	6.52	0.05	6.48	8.12	0.14	7.99	0.44	0.16	0.28	0.00	0.00	0.00
20.07.2007	0.19	0.10	0.09	2.80	0.05	2.75	2.80	0.14	2.66	0.18	0.16	0.02	0.00	0.00	0.00
22.07.2007	2.10	0.10	2.00	7.17	0.10	7.07	9.28	0.14	9.15	0.53	0.16	0.37	0.00	0.00	0.00
05.09.2007	0.00	0.00	0.00	10.39	0.05	10.34	12.12	0.14	11.99	1.18	0.16	1.02	0.00	0.00	0.00
02.08.2008	1.78	0.10	1.68	6.73	0.10	6.64	8.55	0.20	8.35	0.46	0.16	0.30	0.00	0.00	0.00
09.08.2008	0.65	0.10	0.55	4.60	0.05	4.55	4.91	0.14	4.77	0.33	0.16	0.17	0.00	0.00	0.00
16.08.2008	0.13	0.10	0.03	2.66	0.15	2.51	2.65	0.27	2.38	0.16	0.16	0.00	0.00	0.00	0.00
Median value	0.75	0.10	0.65	6.73	0.10	6.64	8.55	0.14	8.35	0.53	0.16	0.37	0.00	0.00	0.00
Average value	1.71	0.09	1.63	6.83	0.09	6.74	8.24	0.18	8.06	0.64	0.16	0.48	0.07	0.02	0.05

[a,b,c]Volumes of inflow, storage, and outflow (10^3 m^3), respectively.

values, were 0.57 and 0.89, respectively, for values of peak flow and hydrograph volume. These values indicate a satisfactory and a very good level of performance, respectively. The coefficients of determination were 0.50 and 0.71.

The values of peak flow and hydrograph volume, which were obtained for the analyzed events in simulations using the SBUH model (Table 6), fell into the respective ranges from 0.543 to 1.186 $m^3 \cdot s^{-1}$ (at the value of the median 0.730 $m^3 \cdot s^{-1}$)

Table 6 | Results of simulation obtained with the use of the SBUH model

Date of the event	Effective rainfall totals (mm) $D^{a}_{1.5\,mm}$	D^{b}	Relative error (%) $D_{1.5\,mm}$	D	Peak flow Q^{c}_{p} ($m^3 \cdot s^{-1}$)	Relative error for Q_p (%)	t^{d}_{c} (min)	Simulated values[e] Peak flow ($m^3 \cdot s^{-1}$)	Volume (10^3 m^3)	Relative error (%) Peak flow	Volume
19.09.2006	2.87	1.88	77.7	16.6	0.972	−23,8	514	0.919	29.7	−27.9	15.4
15.05.2007	3.09	2.07	10.9	−25.8	1.018	29,7	596	0.695	36.0	−11.4	−26.6
02.06.2007	2.28	1.44	25.4	−20.7	0.853	17,0	496	0.730	25.2	0.1	−21.5
13.06.2007	4.31	3.07	54.7	10.4	1.237	−4,7	729	1.186	53.6	−8.6	9.3
19.06.2007	3.61	2.49	107.6	43.2	1.115	20,9	655	1.015	43.4	10.0	41.7
21.06.2007	2.40	1.53	42.3	−9.3	0.878	−18,7	511	0.726	26.7	−32.7	−10.2
02.07.2007	2.05	1.28	48.6	−7.7	0.803	−0,2	466	0.727	22.2	−9.6	−8.6
20.07.2007	1.19	0.71	19.2	−28.4	0.602	−35,9	346	0.557	12.4	−40.7	−29.2
22.07.2007	2.28	1.44	46.2	−7.6	0.853	−15,1	496	0.812	25.2	−19.2	−8.5
05.09.2007	3.79	2.64	40.2	−2.4	1.147	6,3	674	0.880	45.9	−18.4	−3.4
02.08.2008	2.11	1.32	161.5	63.2	0.815	11,8	474	0.749	22.9	2.7	61.5
09.08.2008	1.53	0.92	56.9	−5.7	0.684	3,8	395	0.651	16.1	−1.2	−6.5
16.08.2008	1.21	0.73	8.5	−34.9	0.609	−25,1	317	0.543	11.5	−33.2	−35.5
Median value	2.28	1.44	46.2	16.6	0.853	17.0	496	0.730	25.2	11.4	15.4
Average value	2.52	1.66	53.8	21.2	0.891	16.4	513	0.784	28.5	16.6	21.4

[a,b]Effective rainfall totals estimated accounting for the value of surface retention depths: D=1.5 mm and calculated using Equation (7), respectively.
[c]Values calculated using Equation (5).
[d]The time of concentration calculated using Equation (6).
[e]Values simulated using the SBUH model for concentration times tc given in the table.

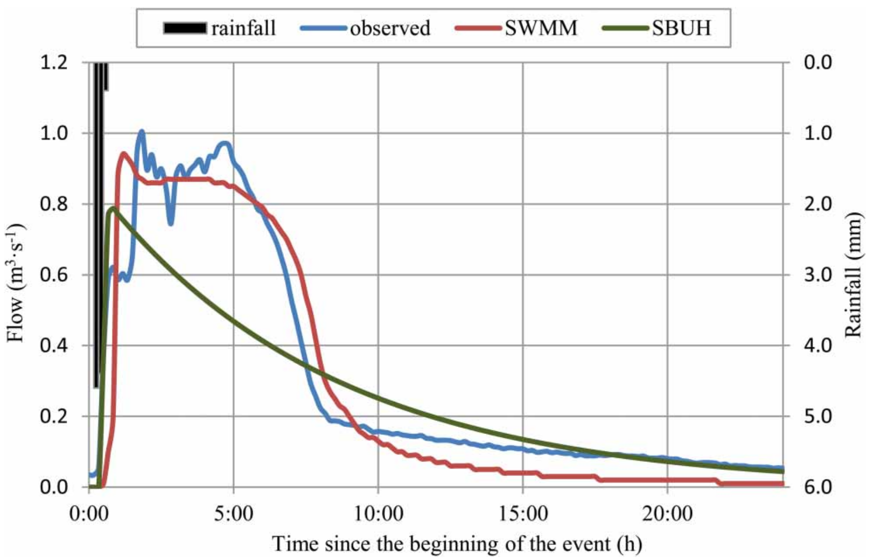

Figure 3 | Flow hydrograph simulation results for the SWMM and the SBUH model and observations during storm event on 22 July 2007.

and from 11.5×10^3 to 53.6×10^3 m^3 (at the median value of 25.2×10^3 m^3). The relative errors of simulations were between −40.7 and 10.0% for peak flows and from −35.5 to 61.5% for hydrograph volumes. The simulated hydrograph parameters were underestimated in the majority of cases. The values of the median of simulation errors, calculated for the analyzed events based on the values of absolute errors, were 11.4 and 15.4%, respectively. Moreover, these values of the simulation error median were slightly lower for both parameters than those obtained in parallel analyses applying the SWMM. The coefficients of determination were 0.46 and 0.72, respectively, for values of peak flow and hydrograph volume. The value of $R^2 = 0.46$ is slightly below a typical value considered satisfactory ($R^2 = 0.5$). The obtained values of NSE, i.e. 0.58 and 0.81, indicate a satisfactory and a very good level of performance, respectively.

The values of concentration time t_c (Table 6), which were assumed for flow hydrograph simulations, were from 317 to 729 min for particular rainfall–runoff events (with the value of the median equal to 496 min); they were calculated according to the methodology described in the present work using Equation (6), in which Q_p flows were calculated from Equation (5) and the volumes of the effective rainfall V_r based on the values of effective rainfall sums indicated for a given event accounting for the optimization of surface storage depths D (Equation (7)). The value of the median of absolute errors (17.0%), which was calculated for flows Q_p, was higher than the corresponding values for simulated flows in the SBUH model (11.4%).

Table 6 also contains the values of the effective rainfall totals, which were determined for the analyzed events according to the methodology described in the section 'SBUH model procedure'. These are the values obtained in analyses carried out accounting for two different approaches to determining the depth of the rainwater stored on the surface of impervious surfaces D (mm). In the first of them, the assumption was made that the value D is constant for each of the analyzed events and amounts to 1.5 mm. In the second approach, the surface retention depth D was calculated for each of the analyzed events from Equation (7) specified in this work based on a measured total rainfall depth for a given event at the 'Okęcie' meteorological station. The effective rainfall totals, which were indicated for the analyzed events, fell into the ranges of 1.19–4.31 mm and 0.71–3.07 mm, respectively, in regard to the analyses carried out accounting for the first and second approach with respect to parameter D. The estimated effective rainfall totals for individual events were compared with appropriate values of effective rainfall totals, which were calculated based on volumes for hydrographs observed in the 'P1' cross-section (given in Table 1). The value of the median of absolute errors, obtained in relation to the effective rainfall totals indicated for the value of $D = 1.5$ mm, was very high (46.2%). Conversely, that obtained in relation to the effective rainfall totals indicated for the D value, which was calculated from Equation (7), was 16.6%.

Prediction of the flow hydrograph for design rainfall

The SWMM and the SBUH model, which were adapted and verified for the analyzed Służewiecki Stream subcatchment, were applied to predict flow hydrographs in the 'P1' cross-section, in response to the design (control) rainfall with a frequency of occurrence equal to $C = 5$ years (1 in 5 years) and duration time of $t = 15$ min. The design rainfall depth, which was calculated applying the formula developed by Bogdanowicz & Stachý (1997) – recommended for calculations in the area of Poland, is 18.7 mm. In these analyses, the assumption that the entire area of the catchment is covered by a rainfall characterized by this depth was made. The value of the time of concentration $t_c = 796$ min, which was assumed for predicting the flow hydrograph in the SBUH model, was indicated using Equation (6). The Q_p flow found in this equation was calculated from Equation (5), whereas the effective rainfall volume was based on the effective rainfall total determined accounting for the optimized surface retention depth D (Equation (7)).

The values of peak flow and hydrograph volume, which were calculated applying the SWMM and the SBUH model, were 1.195 and 1. 307 $m^3 \cdot s^{-1}$, and 60.3×10^3 and 63.6×10^3 m^3, respectively. Despite the fact that the mentioned models belong to various types (classes) due to their diverse properties, the values obtained with their application were similar to each other for corresponding hydrograph parameters. The differences between the corresponding peak flow and volume values were 9.4 and 5.5%, respectively.

Calculations carried out in the SWMM for design rainfall were used to create a profile of the maximum level of stormwater in the collector (in the Służewiecki Stream) in the section located in the lower part of the catchment (Figure 4). The results of this analysis showed that there is no risk of stormwater overflowing from the collector onto the surface of the terrain; the only thing that may happen is short-term operation under pressure in some conduits.

CONCLUSIONS

1. Applying concentration times t_c in the procedure of the SBUH model, which were assessed for individual rainfall–runoff events using conventional methods (based on empirical formulas or solely on the travel time of rainwater through the stormwater collector), leads to large simulation errors for the peak flow of the hydrograph in an urbanized catchment, where a delay in the outflow of stormwater occurs as a result of its retention in tanks. The values of the relative error, obtained on the basis of observed and simulated peak flows, ranged from 89.6 to 177.6%.

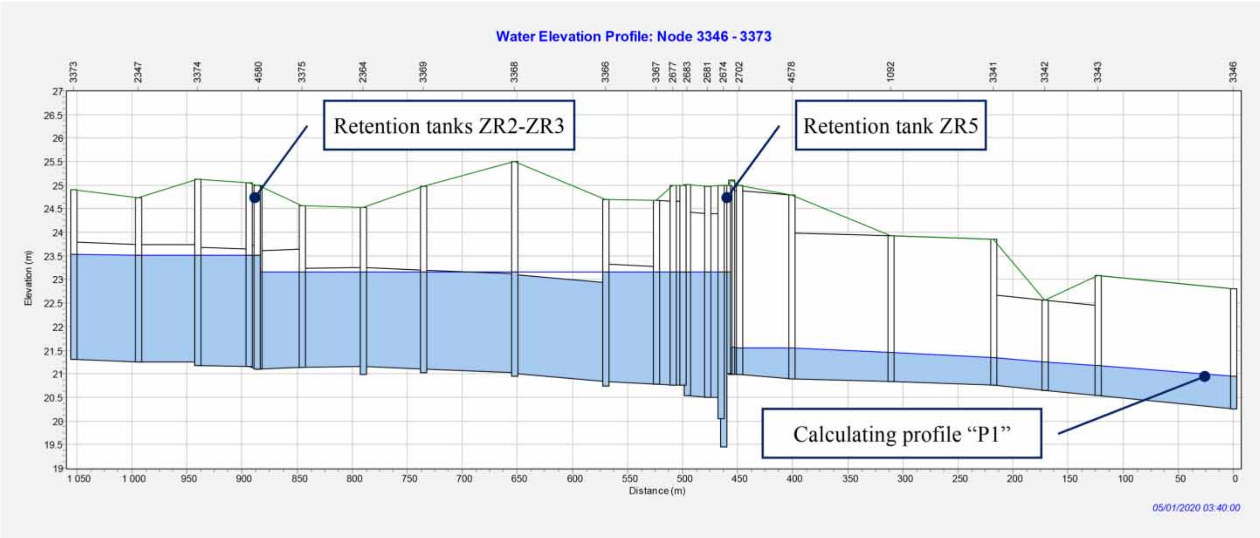

Figure 4 | Profile of maximum stormwater levels in the main collector in the section located in the lower part of the catchment, obtained using the SWMM for design rainfall.

2. As a result of applying the developed method for indicating the concentration time (presented in the work) for 13 individual rainfall–runoff events, which accounts for, among others, the time necessary to empty retention tanks and stormwater conduits in the area of the catchment, satisfactory results of the simulation of flow hydrograph parameters were obtained using the SBUH model. The relative errors of simulations were between −40.7 and 10.0% for peak flows and from −35.5 to 61.5% for hydrograph volumes. The values of the median of absolute simulation errors were 11.4 and 15.4%, respectively. The obtained values of NSE, i.e. 0.58 and 0.81, indicate a satisfactory and a very good level of performance. The determined values of concentration time for individual events were within a large range of variability, from 317 to 729 min.
3. The results of flow hydrograph parameter simulations and forecasts in response to analyzed rainfall events, which were obtained using the conceptual SBUH model (with the concentration times determined according to the developed method), were similar to corresponding results obtained using the dynamic SWMM. Relative errors, obtained in simulations using the SWMM, were from −23.5 to 24.7% for peak flows and from −39.8 to 58.6% for hydrograph volumes. The values of the median of absolute simulation errors were 15.4 and 18.4%, respectively. The obtained values of NSE for the analyzed events, i.e. 0.57 and 0.89, indicate a satisfactory and a very good level of performance.
4. Satisfactory results were obtained as a result of using the above-mentioned models, despite the fact that they belong to different types (classes) due to their diverse properties. This indicates that the conceptual SBUH model can be applied as an alternative to more complicated models, such as the SWMM, in hydrological analyses carried out for an urbanized catchment with stormwater retention tanks. An advantage of this conceptual model is, above others, the fact that its adaptation to a particular catchment is, relatively speaking, not very time-consuming.
5. The method of determining the concentration time presented in the work enables the calculation of this parameter for individual rainfall–runoff events in small urbanized catchments, taking into account the influence of delaying in the outflow of stormwater from a catchment as a result of its retention in tanks (with controlled outflow) on the value of this parameter. The concentration times determined according to this method can be used for simulating flow hydrograph parameters using the SBUH model and other hydrological models in the analyzed catchment and other catchments with similar properties.
6. The developed method of indicating the concentration time for individual events in the catchment with retention tanks is limited to the catchment where measurement data of rainfall and flows are available for at least several events with different characteristics. Further works should include a modification of this method to enable the determination of concentration times for individual events only on the basis of rainfall measurement data and parameters of a catchment drainage system. Future work should also be focused on the verification of the developed method of determining the concentration time in another urbanized catchment using more events of rainfall–runoff.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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