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APPLICATION OF RADAR DATA FOR THE ANALYSIS OF THE RAINFALL-RUNOFF PROCESS IN AN URBAN CATCHMENT

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ABSTRACT

The paper presents the results of an analysis aimed at assessing the usefulness of rainfall intensity data (maps), obtained using meteorological radar, for the estimation of the spatial distribution of rainfall amounts in the area of a small urban catchment, and their use in calculating flows using the hydrodynamic SWMM model. The analysis was carried out based on the author's own methodology. The rainfall amounts, estimated from the radar data and measured in the studied catchment of Służewiecki Stream at two rainfall stations, for three rainfall events, significantly differed in their values depending on particular time-periods of rainfall. Based on both the estimated and the measured rainfall data, the values of their ratio were calculated, which were subsequently applied to correct the radar data obtained for the 66 virtual rain gauges in the catchment under investigation. The rainfall amounts established in these analyses were incorporated into the SWMM model, and used to calculate the flows. Based on the maximum flows that were calculated and measured in two cross-sections of the Służewiecki Stream, for the three analysed rainfall-runoff events, their conformity was assessed.

Key words: urban catchment, radar data, rainfall intensity, the SWMM model, rainfall-runoff process

INTRODUCTION

In order to calculate runoff flows in response to rainfall, it is necessary to first determine the amount of rainfall. Even if rainfall measurements are carried out in the given catchment area, we are often faced with the problem of an insufficient number of rainfall stations, or the lack of continuity of the measurements. The use of data recorded at rainfall stations as an input to hydrological models requires, in a majority of cases, the spatial interpolation of rainfall data [Jatho et al. 2010]. Usually, no precipitation measurements are made in small catchments. In such instances, one way of obtaining information about rainfall is to use radar data.

One of the most important advantages of radar precipitation measurement is the spatial continuity of observations. The information obtained on the basis of meteorological radars provides the most detailed data with respect to the spatial and temporal distribution of precipitation [Mittermaier 2008]. The basic disadvantage of radar observations is the inaccuracy of the obtained rainfall data, which results from the fact that it is an indirect measurement. The classic radar measures radar reflectivity, which – on the basis of a given correlation – is converted either into the intensity or into the total amount of rainfall [Moszkowicz and Tuszyńska 2006]. The increasing use of radar data in hydrological applications, due to the rarely spaced rain gauges in most catchments, requires expanding the knowledge on the uncertainty of these data [Peleg et al. 2013]. In terms of forecasting heavy rainfall with the aid of meteorological radars and rainwater

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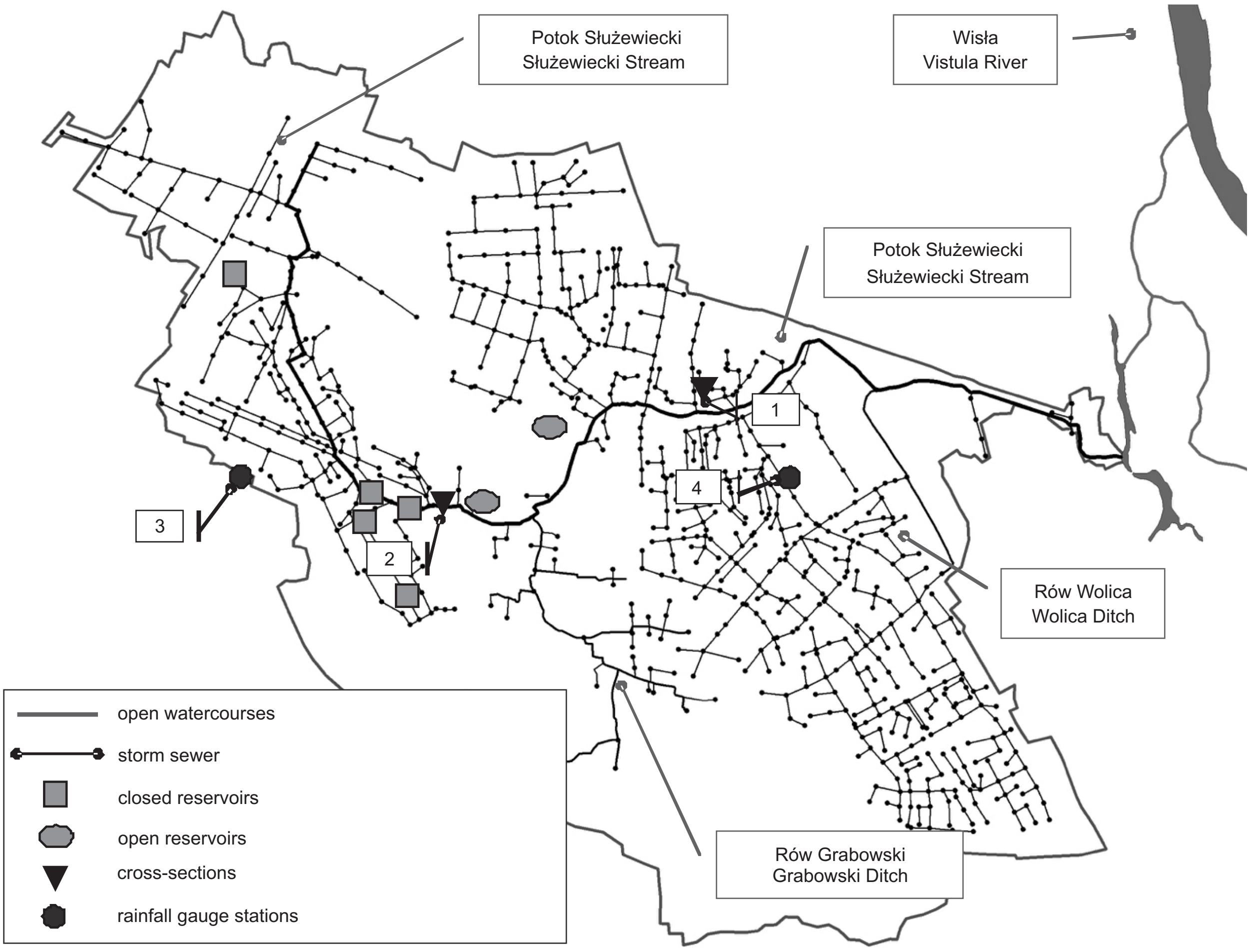
data processing systems, continuous progress is being made, but still a lot remains to be done in terms of the quality of field estimation of rainfall, and precipitation forecasts [Szturc et al. 2016].

The paper presents the results of the analysis conducted with the purpose of assessing the usefulness of data (i.e. maps) of rainfall, obtained using the meteorological radar in Legionowo, for the estimation of the spatial distribution of rainfall in the area of a small urban catchment, and their application in the calculation of flows using a hydrodynamic SWMM model. The conformity assessment was carried out of the maximum flows, which were calculated in the model and measured in the two cross-sections of the Służewiecki Stream for three rainfall-runoff events. The analysis was carried out according to the original methodology, devised by the author of the present paper.

METHODOLOGY OF THE ANALYSIS

Description of the studied area, and the measurement system

The Służewiecki Stream catchment is located in the southern part of Warsaw, and it includes either fragments or entire districts of: Okęcie, Wola, Mokotów, Kabaty, Ursynów, and Wilanów (see: Figure 1). The stream's catchment area, up to the estuary in the Wilanowskie Lake, totals 55.2 km^2. On the section from its sources to the outlet from the area of the War-



Rainfall gauge stations and computational cross-sections: 1 – "Rosoła", 2 – "Kłobucka", 3 – "Okęcie", 4 – "Ursynów"

Fig. 1. The rainwater management system in the Służewiecki Stream catchment

saw Chopin airport (up to the "Kłobucka" calculation section), the Służewiecki Stream is almost completely closed, and the section from the airport to the outlet section is an open channel. The total length of the watercourse counts approximately 15 km and its decrease is 1.6 ‰. The average drop in the catchment is approx. 3.8%. Rainwater is discharged from the catchment area to the Służewiecki Stream through an extensive rainwater sewage system.

The catchment features open reservoirs, closed reservoirs and road culverts, which have a considerable impact on the flow transformation in the watercourse. Figure 1 shows the location of two computational cross-sections in the catchment ("Rosoła" and "Kłobucka"), which double as rainfall gauge profiles. Table 1 summarizes the basic information for sub-catchments that are limited by the aforementioned profiles. The Warsaw Chopin Airport (Okęcie Airport) occupies the principal part of the catchment area to the "Kłobucka" profile. The sub-catchment of Rów Grabowski (Grabowski Ditch) is occupied mainly by agricultural land and forest. The remaining part of the catchment, limited by the "Rosoła" profile, is characterized by a large share of paved areas and sewers. This section of the catchment is used for industrial, commercial, and multi-family housing functions.

Table 1. Main characteristics of the analysed sub-catchments

Cross-section number	Closing cross-section	Kilometres	Area of sub--catchment	Hard surfaces
		km	km^2	%
1	"Rosoła"	4+910	43.0	22.8
2	"Kłobucka"	8+650	16.5	26.2

The analysis presented herein used precipitation amounts measured at two rainfall stations, i.e. "Okęcie" (controlled by the IMGW), and "Ursynów" (controlled by the Department of Meteorology and Climatology of SGGW), using electronic channel rainfall meters of Theodor Friedrichs brand. Hydrograms of flows were also used (calculated on the basis of water level measured by the "Diver" type Eijkelkamp-brand meter, and the flow curve), registered at the rainfall gauge stations of "Rosoła" and "Kłobucka", which were installed within the framework of the COST/210/2006 research project.

The procedure of the swmm model

For the analysis of runoff in response to rainfall, determined for selected events based on radar rainfall data and measured at rainfall stations, the SWMM model (Storm Water Management Model) version 5.0.022, developed by the US Environmental Protection Agency (EPA), was used. According to the classification presented in the paper by Ozga-Zielińska and Brzeziński [1997], the SWMM is a model of catchment components, which is genetic, dynamic, non-linear, as well as being classified among models with distributed parameters.

The use of the SWMM model for the analysis required its adaptation for the Służewiecki Stream catchment. The adaptation consisted in creating objects in the model that would represent the physical elements of the actual catchment system (see: Figure 4), and then in determining the relationship between them, and the values of their parameters. In order to estimate and identify the parameters of the model's objects, the characteristics of the real objects – measured in the field – were used along with parameter values recommended in the handbook tables [Rossman 2010], identified based on available studies. In the model's calibration and verification processes, flow hydrograms measured in the two water gauge profiles ("Rosoła" and "Kłobucka") by the Department of Water Engineering at SGGW and by the technical services of Chopin Airport were used in conjunction with rainfall data recorded in two rainfall gauge stations ("Okęcie" and "Ursynów"). Calibration and verification of the SWMM model, adapted for the tested catchment, exhibited high degree of conformity between the flows obtained from the model, and those obtained in the measurements. The assessment of the conformity of the maximum flows for the analysed events, which were measured and simulated in water gauge cross-sections, was made primarily with the help of a relative error. The results of the statistical analysis led to the decision on the adoption of the model. A broader description of the adaptation, as well as of the calibration and verification of the model can be found in other works [Barszcz 2015, Barszcz 2017, Waga-Bart 2015, Waga-Bart 2017].

In the SWMM model, adapted for the catchment area under consideration, the following objects were included:

- “Okęcie” and “Ursynów” rainfall stations, located in the area of the airport, and on the campus of the SGGW, respectively;
- Virtual rainfall gauges, located in the catchment area under examination, in 66 cells with the dimensions of 1 km x 1 km, which correspond to respective cells on the radar rainfall maps (66 rain gauges);
- Partial catchment areas, which were demarcated within the catchment, in order to take into account the spatial variability of the modelled hydrological processes (3392 catchments);
- Open channels and sewage system channels (2271 channel sections);
- Road culverts and other elements of the traffic infrastructure;
- Open reservoirs and closed reservoirs;
- Backflow preventers in channels, reservoir relief and overflow devices, pumps and valves cooperating with the reservoirs.

Radar data for rainfall intensity

The results of measurements carried out with the help of meteorological radars show radar reflectivity. Therefore, there is a need to process the radar reflectivity values recorded in the adopted time units, and convert them to the intensity of precipitation, or the amount of precipitation.

Currently, the Institute of Meteorology and Water Management (IMGW), which conducts radar measurements in Poland, calculates the intensity of rainfall (R) based on the recorded radar reflectivity (Z), while using the proportion derived by Marshall and Palmer (1), based on coefficients a and b determined by Marshall and Palmer, amounting to 200 and 1.6, respectively [Moszkowicz and Tuszyńska 2006]. However, there is a large variety of values proposed for these coefficients in the literature of the subject. According to the information provided in the paper by Moszkowicz and Tuszyńska [2006], the values of coefficients a and b, compiled on the basis of data from 50 reference publications, are contained within the ranges of 66–730 and 1.24–1.64, respectively.

$$Z = a \cdot R^b \qquad (1)$$

where:

R – rainfall intensity, $mm \cdot h^{-1}$,
a, b – coefficients, –.

As a result of the processing of the radar reflectivity, which had been registered by the meteorological radar, various meteorological and hydrological products are obtained. One of them is SRI (Surface Rainfall Intensity), which generates an image of the intensity of precipitation R, expressed in the units of mm/h, in a user-defined layer described by a constant height above the surface.

The SRI radar map product was used for the analyses reported in this paper, which shows the spatial distribution of rainfall in the area covered by the radar range in Legionowo, at a height of 1 km above the surface. Spatial resolution of radar rainfall data is 1 km (rainfall intensity values are related to nodal points of cells with an area of 1 km^2). Each radar map contains information for the analysed rainfall events in individual time steps within the event duration, that is every 10 minutes. Figure 2 presents one of such maps, containing information for the rainfall event on 22 July 2007, at 13.30. In this illustration, the area of the map covers the Służewiecki Stream catchment. The rainfall intensity values are described with a key containing a colour scale with assigned value ranges. For browsing the maps, we used the specialized RAPOK software (developed at the IMGW), which facilitates generation of data in the form of a file compatible with the Excel format.

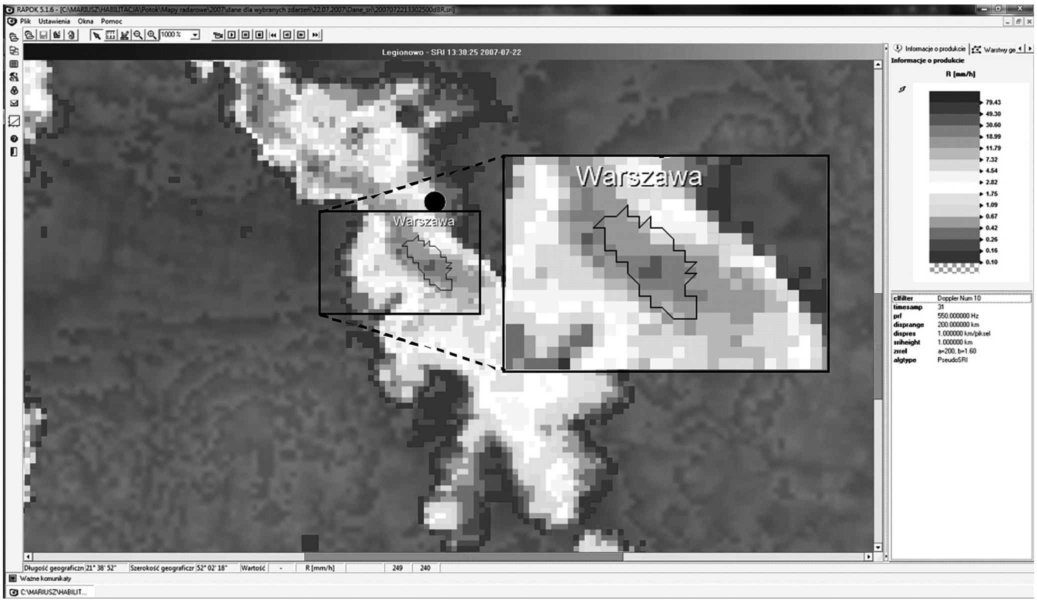


Fig. 2. Radar map showing the spatial distribution of rainfall intensity in the selected area

RESULTS OF THE ANALYSIS AND THE DISCUSSION THEREOF

The analysis of the radar data

This analysis was carried out in relation to three selected precipitation events, measured at two rainfall stations in the Służewiecki Stream catchment on 2 July 2007, 22 July 2007, and 15 August 2008 (see: Table 2). For these particular events that were selected for the analysis, rainfall intensities were recorded at the same time at "Okęcie" and "Ursynów" rainfall stations, characterized by varying precipitation volumes. These are events, for which radar data was available. The rainfall amounts for the analysed events ranged from 8.6 to 22.8 mm at the "Okęcie" rainfall station, and from 12.0 to 42.0 mm at the "Ursynów" rainfall station.

In addition to the rainfall amounts, measured for the analysed events using rain gauges, table 2 also lists the altitudes determined on the basis of the original data, read from the radar maps. These are precipitation volumes, which were calculated in the respective time intervals within rainfall duration, as average values for the original radar data specified in the 4 nodal points of the given cell in which the "Okęcie" and "Ursynów" rainfall stations are located (see: Figure 3, cells number 64 and 69). The rainfall amounts determined for individual events, based on the original radar data, were much smaller than the corresponding values measured with rain gauges. The rainfall amounts calculated on the basis of these radar data ranged from 2.2 to 11.0 mm at the "Okęcie" rainfall station, and from 3.3 to 10.0 mm at the "Ursynów" rainfall station. The rainfall amounts, which had been determined on the basis of radar data for various calculation options (discussed in the next section), were the closest to rainfall amounts measured with the rain gauges for Variant 2. Relatively good level of conformity between these rainfall amounts was also obtained for Variants 3 and 4, in respect to the "Okęcie" and "Ursynów" stations.

For the analysed rainfall events, in each time interval of rainfall duration, the value of the ratio R (according to the formula 2) of rainfall measured with rain gauges at "Okęcie" and "Ursynów" rainfall stations was determined up to the amount of precipitation determined on the basis of radar data (see: Table 3).

$$R = \frac{P_p}{P_r} \tag{2}$$

where:

P_p – rainfall amount measured using rain gauges, mm,

P_r – rainfall amount determined based on radar data, mm.

Table 2. Rainfall amount for the analysed events in relation to rainfall gauge stations

Date	Rain-gauge rainfall amount		Radar rainfall amount – original value		Rainfall amount – calculated value					
					Variant 2		Variant 3		Variant 4	
	mm									
	O	U	O	U	O	U	O	U	O	U
02.07.2007	8.6	12.0	2.2	3.3	8.6	12.1	5.2	8.0	9.2	14.1
22.07.2007	9.4	18.4	3.8	3.4	9.3	18.2	9.2	8.1	16.1	14.2
15.08.2008	22.8	42.0	11.0	10.0	25.6	42.2	26.3	24.1	46.0	42.1

Rainfall gauge stations: O – "Okęcie", U – "Ursynów"

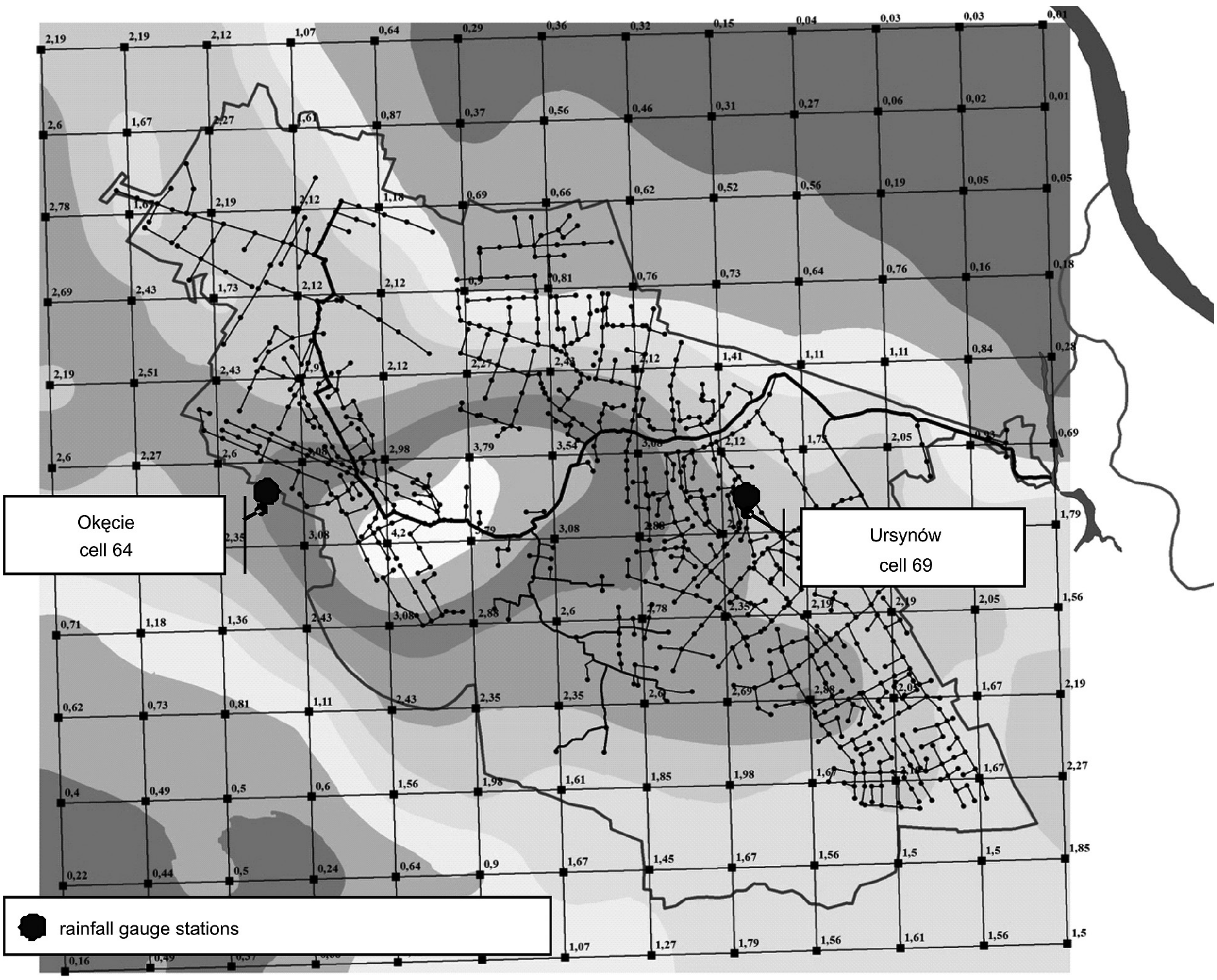


Fig. 3. Map showing the spatial distribution of rainfall amount for the event on 22 July 2007

Table 3. Results of the rainfall analysis: obtained from measurements, and based on radar data

Date	Rainfall duration	Amount of rainfall, mm				Rainfall amount ratio R, –	
		rain-gauge rainfall		radar rainfall			
		O	U	O	U	O	U
02.07.2007	21:30	0.8	0.8	0.43	0.43	1.9	1.9
	21:40	0.8	1.9	0.30	0.58	2.7	3.3
	21:50	1.4	1.9	0.36	0.65	3.9	2.9
	22:00	2.4	3.9	0.15	0.79	16.0	4.9
	22:10	0.6	0.8	0.22	0.23	2.7	3.5
	22:20	1.2	1.3	0.43	0.32	2.8	4.1
	22:30	0.8	0.9	0.17	0.19	4.7	4.7
	22:40	0.4	0.3	0.07	0.09	5.7	3.3
	22:50	0.2	0.2	0.03	0.02	6.7	10.0
	23:00	0.0	0.0	0.03	0.04	0.0	0.0
	mean	–	–	–	–	4.7	3.9
	median	–	–	–	–	3.3	3.4
22.07.2007	13:30	4.6	7.5	3.34	2.09	1.4	3.6
	14:00	4.4	3.5	0.37	0.19	11.9	18.4
	14:30	0.4	7.2	0.13	1.10	3.1	6.5
	15:00	0.0	0.2	0.00	0.00	0.0	0.0
	mean	–	–	–	–	4.1	7.1
	median	–	–	–	–	2.2	5.1
15.08.2008	18:40	2.4	0.0	0.13	0.19	18.5	0.0
	18:50	9.8	0.4	2.08	0.74	4.7	0.5
	19:00	2.4	13.6	0.73	0.72	3.3	18.9
	19:10	0.8	8.0	0.35	0.14	2.3	57.1
	19:20	1.0	0.2	0.23	0.65	4.3	0.3
	19:30	1.4	7.3	1.13	1.09	1.2	6.7
	19:40	0.6	2.5	0.23	0.74	2.6	3.4
	19:50	0.8	0.7	0.19	0.36	4.2	1.9
	20:00	0.8	0.8	0.50	0.14	1.6	5.7
	20:10	0.6	0.5	0.47	0.42	1.0	1.2
	20:20	0.8	0.7	0.50	0.45	1.6	1.6
	20:30	0.6	1.0	0.51	0.74	1.2	1.4
	20:40	0.4	0.9	0.48	0.37	0.8	2.4
	20:50	0.4	0.5	0.48	0.42	0.8	1.2
	21:00	0.0	0.5	0.13	0.13	0.0	3.8
	21:10	0.0	0.1	0.09	0.09	0.0	1.1
	21:20	0.0	0.7	0.39	0.69	0.0	1.0
	21:30	0.0	1.2	0.43	0.61	0.0	2.0
	21:40	0.0	1.0	0.91	0.40	0.0	2.5
	21:50	0.0	0.6	0.77	0.45	0.0	1.3
	22:00	0.0	0.5	0.18	0.47	0.0	1.1
	22:10	0.0	0.3	0.06	0.04	0.0	7.5
	mean	–	–	–	–	2.2	5.6
	median	–	–	–	–	1.2	1.8

Rainfall gauge stations: O – “Okęcie”, U – “Ursynów”

Based on the value of the ratio *R*, which was determined for each time period of rainfall (in 10 minute intervals), its mean and median values for individual events were calculated separately for the data for the "Okęcie" and "Ursynów" precipitation stations (see: Table 3). The values of the ratio *R*, calculated as mean and median for individual events, ranged from 2.2 to 7.1, and from 1.2 to 5.1, respectively. In most cases, their values were significantly different compared to data from rainfall stations. The values of the ratio *R*, calculated for each time interval of the rainfall event, ranged from 0.0 to 51.1. Their values changed significantly in subsequent time intervals for the given event. Mean and median values, which were calculated on the basis of all *R*-values, were 4.2 and 2.4, respectively. Their values were used in different variants of flow calculations.

Figure 3 shows a sample map, which presents a spatially continuous rainfall distribution (for the event on 22 July 2007 at 13:30) in the catchment area and in its vicinity, developed in ArcMap 10.3.1 using tools for data interpolation based on their point values. The interpolation was performed on the basis of the point precipitation intensities in individual cell nodes (in 10 minute intervals) obtained as a result of analysing the data from radar maps. The grid of cells visible in the figure (created using the ArcMap software), with the resolution of 1 km, corresponds to the adequate cell grid (in pixels) on the radar maps used in the present analysis. The figure also shows the catchment of the Służewiecki Stream along with a system of canals, and the locations of the "Okęcie" and "Ursynów" precipitation stations have been marked.

Calculation of flows in response to the rainfall

The SWMM model was used to calculate flows in response to the rainfall, which were measured in the Służewiecki Stream catchment at "Okęcie" and "Ursynów" rainfall sites, and established on the basis of radar data for the whole catchment area with respect to the 66 grid cells covering the catchment (as shown in Figure 3). Flow calculations were performed for different variants of rainfall data, which can be classified into two basic groups. The calculation using the SWMM model takes into account the spatial distribution of precipitation in the catchment basin on the basis of the data: 1) determined for the analysed rainfall stations, which were assigned to the two respective sections of the catchment; 2) set for virtual 66 rain gauges deployed throughout the catchment area, whose location is shown in Figure 4 (rain gauges located in the middle of individual cells, covering the catchment). Different variants of rainfall data were used for the analysis, in order to assess their impact on the conformity between the flows measured, and those calculated in the catchment area under consideration, and thus their suitability for the analysis of the rainfall-runoff process in the urban catchment.

Flow calculations were performed for the following variants of rainfall data, adopted in relation to the three studied events:

1. The amount of precipitation, which was measured at the "Okęcie" and "Ursynów" rainfall stations or established on the basis of radar data for the cells in which these stations are located, was assigned to the two respective sections of the catchment area under examination.
   - Variant 1: data measured at rainfall stations with rain gauges;
   - Variant 2: radar data corrected using the ratio *R* (correction factors), calculated by means of equation (2) for each time interval of rainfall duration (values given in Table 3);
   - Variant 3: radar data corrected using a median value of 2.4 (calculated on the basis of all values of the *R* ratio for each period of rainfall duration);
   - Variant 4: Radar data corrected using an average value of 4.2 (calculated on the basis of all values of the *R* ratio for each time period of rainfall).
2. Rainfall amounts, which were established on the basis of radar data (maps) for virtual 66 cells (rain gauges) deployed in the catchment area.
   - Variant 5: original radar data, obtained directly from the radar maps;
   - Variant 6: radar data corrected in the manner equivalent to Variant 2;
   - Variant 7: radar data corrected in the manner equivalent to Variant 3;
   - Variant 8: radar data corrected in the manner equivalent to Variant 4.

Tables 4–7 summarize the results of flow calculations in the two calculation sections (which are also water gauge profiles), i.e. "Rosoła" (R) and "Kłobucka" (K), which were obtained in the SWMM model for the variants of rainfall data described above, adopted with reference to the three studied rainfall events. The values of the calculated maximum flows were compared with the respective (direct) flows, measured in the same cross-sections of the Służewiecki Stream for the analysed rainfall-runoff events. The assessment of conformity of these flows was made with the application of the relative error value, which was calculated using equation (3). According to the explanation given in the paper by Ozga-Zielińska and Brzeziński [1997], a relative error rate of 25%, computed on the basis of measured and calculated flows, was assumed as the conventional limit for the acceptance of the model.

$$\delta = \frac{Q_{obl.} - Q_{obs.}}{Q_{obs.}} \cdot 100\% \tag{3}$$

where:

$Q_{obs.}$ – observed (measured) maximum flow, $m^3 \cdot s^{-1}$,
$Q_{obl.}$ – calculated maximum flow, $m^3 \cdot s^{-1}$.

Fig. 4. Sub-catchments, channels and virtual rain-gauges in the investigated catchment, shown in the SWMM model

Table 4. Results of the calculations for Variants 1 and 2

Date	Measured flow		Calculated flow				Relative error			
			Variant 1		Variant 2		Variant 1		Variant 2	
	$m^3 \cdot s^{-1}$						%			
	R	K	R	K	R	K	R	K	R	K
02.07.2007	5.935	0.733	6.195	0.822	6.209	0.827	4.4	12.1	4.6	12.8
22.07.2007	13.528	0.925	11.499	0.822	11.318	0.827	–15.0	–11.1	–16.3	–10.6
15.08.2008	21.166	1.310	18.889	1.428	18.938	1.422	–10.8	9.0	–10.5	8.5

Computational cross-sections: R – “Rosoła”, K – “Kłobucka” (also in Tables 5–7)

Table 5. Results of the calculations for Variants 3 and 4

Date	Measured flow		Calculated flow				Relative error			
			Variant 3		Variant 4		Variant 3		Variant 4	
	$m^3 \cdot s^{-1}$						%			
	R	K	R	K	R	K	R	K	R	K
02.07.2007	5.935	0.733	3.512	0.827	7.407	0.825	–40.8	12.8	24.8	12.6
22.07.2007	13.528	0.925	4.265	0.823	9.168	1.044	–68.5	–11.0	–32.2	12.9
15.08.2008	21.166	1.310	9.306	1.272	19.143	1.983	–56.0	–2.9	–9.6	51.4

Table 6. Results of the calculations for Variants 5 and 6

Date	Measured flow		Calculated flow				Relative error			
			Variant 5		Variant 6		Variant 5		Variant 6	
	$m^3 \cdot s^{-1}$						%			
	R	K	R	K	R	K	R	K	R	K
02.07.2007	5.935	0.733	0.953	0.288	6.202	0.829	–83.9	–60.7	4.5	13.1
22.07.2007	13.528	0.925	1.059	0.412	10.080	0.827	–92.2	–55.5	–25.5	–10.6
15.08.2008	21.166	1.310	4.427	0.872	24.973	1.532	–79.1	–33.4	18.0	16.9

Table 7. Results of the calculations for Variants 7 and 8

Date	Measured flow		Calculated flow				Relative error			
			Variant 7		Variant 8		Variant 7		Variant 8	
	$m^3 \cdot s^{-1}$						%			
	R	K	R	K	R	K	R	K	R	K
02.07.2007	5.935	0.733	3.780	0.841	7.097	0.829	–36.6	14.7	19.6	13.1
22.07.2007	13.528	0.925	4.096	0.825	7.882	1.085	–69.7	–10.8	–41.7	17.3
15.08.2008	21.166	1.310	10.815	1.440	24.048	2.190	–48.9	9.9	13.6	67.2

The values of relative error, determined by means of equation (3) on the basis of both the measured and the calculated flows in the two computational sections for Variant 1 (assuming the measured rainfall for rainfall calculations, and assigning it to the relevant section of the catchment), for the studied rainfall events ranged between 4.4 and –15.0% (see: Table 4). The highest value of the relative error was therefore lower than the value assumed as the conventional limit of model acceptance (25%).

The values of flows calculated in the SWMM model for Variant 2, assuming (for the purpose of the calculation) the radar data corrected using the value of the *R* ratio computed for each rainfall period, were similar to the flows measured in the rainfall gauges of "Rosoła" and "Kłobucka". The values of relative error ranged from 4.6 to –16.3% in relation to the three studied rainfall events, and were therefore slightly higher than those calculated for Variant 1.

In the calculations carried out for Variant 3 (see: Table 5), on the basis of radar data corrected using one value of the *R* ratio (median), relative error values were obtained in the range between –40.8 and –68.5% for flows related to the "Rosoła" cross-section. Error values were much higher than those obtained in the calculations for Variants 1 and 2. Furthermore, they exceeded the value of the admissible error. Lesser values of relative error were obtained in equivalent calculations for Variant 4, carried out on the basis of radar data, and corrected using one value of the *R* ratio (arithmetic mean). With respect to the "Rosoła" section, the error values ranged from –9.6 to –3.2%. In the case of one event, the relative error was greater than the value assumed as the model acceptance limit. The same situation occurred in the calculations carried out for the "Kłobucka" section.

Analyses carried out on the basis of radar data, that have been established for cells in which rainwater stations are located, and assigned to relevant parts of the catchment area (for Variants 2–4) showed that the best correspondence between the measured and the calculated flows was obtained for Variant 2. For all the analysed events, the values of relative error were less than 25%. Fairly good conformity between these flows was also obtained in the calculations for Variant 4. The values of relative error, estimated for this variant, were smaller than the accepted limit value for the predominant number of events.

The values of relative error, determined on the basis of the original radar data for the virtual 66 rain gauges located throughout the catchment area, for Variant 5, ranged from –33.4 to –92.2% (the calculated flows were much smaller than the measured ones) in relation to the cross-sections of "Rosoła" and "Kłobucka" (see: Table 6). For all of the analysed events, values of relative error significantly exceeded the value determining the model's acceptance limit.

Relatively low values of relative error were obtained in the calculations for Variant 6, carried out on the basis of radar data for 66 virtual rain gauges corrected using the *R* ratio (as presented in Table 3), calculated for each time interval of rainfall duration in relation to the events measured at rainfall stations of "Okęcie" and "Ursynów". The relative error values estimated for the computational sections of "Rosoła" and "Kłobucka", respectively, ranged from 4.5 to –25.5% and from –10.6 to 16.9%. Only in the case of one event, analysed in the "Rosoła" section for rainfall data on 22 July 2007, the relative error was slightly larger than the value determining the model acceptance limit. The values of relative errors obtained in the corresponding calculations for Variant 2 were usually smaller than the corresponding values for Variant 6. In the calculations for Variant 2, rainfall amounts determined based on the radar data were taken only for the two cells, in which the rainfall stations were located, and assigned to the appropriate sections of the catchment. In contrast, for Variant 6, data for 66 virtual rain gauges was adopted.

In the computations for Variant 7 (see: Table 7), based on the radar data corrected using the median value (in the manner equivalent to Variant 3), relative error values were obtained in the range from –36.6 to –69.7%, and from 9.9 to 14.7%, respectively, for flows in the sections of "Rosoła" and "Kłobucka". The values of error, determined in relation to the "Rosoła" section, were higher than the accepted limit value for all events. At the same time, they were close to the values of errors obtained in the equivalent calculations for Variant 3, despite the fact that in this variant, radar data for 66 cells in the catchment area were taken into account (for Variant 3, it was only for two cells).

The values of relative error, determined on the basis of radar data corrected using the average value, for Variant 8, ranged from 13.6 to –41.7% and from 13.1 to 67.2%, respectively for flows in the cross-sections of "Rosoła" and "Kłobucka". In the case of two events, the relative error was greater than the value assumed as the model acceptance limit.

Analyses carried out on the basis of radar data established for 66 virtual cells located in the catchment area (for Variants 5–8) showed that the best correspondence between the measured and the calculated flows was obtained in the case of Variant 6. For the predominant number of events, values of relative error were lower than 25%. Only in the case of one event, the error was slightly greater than this threshold value. The values of error were similar to the values obtained in the calculations for Variant 1 and 2, which were carried out for rainfall computed only for the cells where rainfall stations are located (assuming precipitation measured with rain gauges, and determined on the basis of radar data, respectively). Relatively good consistency between the flows was also obtained in the computations for Variant 8, in relation to the predominant number of events.

In addition to the relative error, three other statistical measures of model quality were applied in order to assess the consistency between the simulated and the actual measured flows. These are the correlation coefficient (R), the Nash-Sutcliffe factor (NSE), and the RSR index, which is the ratio of the RMSE error to the standard deviation of the observed results [Moriasi et al. 2007, Kilwshywe Onema et al. 2012, Ozga-Zielińska and Brzeziński 1997].

The values of these measures, determined on the basis of the maximum flows analysed in the "Rosoła" section for all calculation options, remained within the following ranges: R = 0.88÷1.00; NSE = –2.97÷0.92; and RSR = 0.28÷1.99. By applying contractual limits for acceptance of the above-mentioned indicators, given in [Moriasi et al. 2007, Ozga-Zielińska and Brzeziński 1997], it was determined that they were not exceeded in relation to the flows calculated for the Variants: 1÷2, 4, 6, and 8. Statistical analysis carried out using the maximum flows measured and simulated in the "Kłobucka" section, showed that the values of the applied measures remained within the following ranges: R = 0.94÷0.99; NSE = 0.99÷1.00; and RSR = 0.01÷0.07. Considering all the aforementioned measures jointly, the conventional limits of their acceptance were not exceeded for any of the variants. The values of these measures can be described as very good. Taking into account the results of this statistical analysis jointly for events studied in the "Rosoła" and "Kłobucka" sections, it was found that the simulation of flows using the SWMM model was satisfactory with respect to the Variants: 1÷2, 4, 6 and 8.

CONCLUSIONS

1. The rainfall amounts determined for the three analysed events on the basis of the original radar data (obtained directly from the radar maps) were much lower than the corresponding amounts measured with the aid of rain gauges at the "Okęcie" and "Ursynów" rainfall stations. The lack of precision of the rainfall data obtained by means of meteorological radar results from the fact that it is an indirect measurement.
2. The values of the *R* ratio of the rainfall amount measured with rain gauges, and the amount determined on the basis of the radar data, changed to a high degree for individual precipitation time intervals for the three events, and it ranged between 0.0 and 51.1. Furthermore, the values of the *R* ratio varied in relation to the data for the two rainfall stations in the analysed catchment. Their high temporal and spatial variability leads us to the conclusion that the characteristic value of this parameter should be used to correct the original radar data in the catchments without the precipitation stations.
3. On the basis of the value of the *R* ratio for all rainfall data, mean and median values were determined, which were 4.2 and 2.4, respectively. These values were adopted to correct the original radar data, in order to approximate the rainfall amounts for these data to the values measured using rain gauges.
4. The SWMM hydrodynamic model was used in order to calculate flows in response to rainfall amounts, which were determined on the basis of the radar data for different variants of these data (original and corrected). In the calculations carried out for Variant 5, assuming the rainfall amounts established on the basis of the original radar data for the virtual 66 rain gauges in the catchment, the values of relative error for the analysed events ranged from –33.4 to –92.2%. The values of the calculated flows were much lower than the values of the actually measured flows.

5. Taking into account, for the computation purposes, the radar data corrected using the value of the *R* ratio calculated for each time interval of the rainfall duration (Variants 2 and 6), a good level of correspondence was obtained between the measured flows, and the calculated flows in the cross-sections of "Rosoła" and "Kłobucka". With respect to both computational sections, for almost all analysed events, the values of relative error were lower than the value of 25%, which was assumed as the conventional acceptance threshold of the model. Some values of the calculated flows were larger, and some were smaller than the values of the measured flows. In the computations for Variant 2, the resultant values of error were very similar to the values for Variant 1, in which rainfall measured at the precipitation stations was taken into account. Relatively good consistency between these flows was also obtained in the computations for Variants 4 and 8, which were made on the basis of radar data, corrected using one (mean) value of the *R* ratio.
6. The SWMM model was used to calculate the runoff in response to rainfall, established on the basis of the radar data for only two cells in which rain gauges are located and assigned to the relevant part of the catchment (Variants 2–4) and for 66 cells of the network covering the catchment (Variants 5–8). For the predominant number of events, slightly greater consistency between the calculated flows and the measured flows was obtained for Variants 2–4.
7. Future analyses will be directed at improving the radar data processing methodology in order to achieve greater compliance with the rainfall data recorded using the rainfall gauges, as well as the applications of these data for hydrological computations in urban catchments that are not equipped with rainfall stations.

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NOTE ON THE RADAR DATA

The source of the data is the Institute of Meteorology and Water Management – National Research Institute (Instytut Meteorologii i Gospodarki Wodnej – Państwowy Instytut Badawczy).

The data from the Institute have been processed by the author.

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ZASTOSOWANIE DANYCH RADAROWYCH DO ANALIZY PROCESU OPAD-ODPŁYW W ZLEWNI MIEJSKIEJ

ABSTRAKT

W pracy przedstawiono wyniki analizy, której celem była ocena przydatności danych (map) natężenia opadów uzyskanych przy zastosowaniu radaru meteorologicznego do oszacowania przestrzennego rozkładu wysokości opadów na obszarze małej zlewni miejskiej i ich zastosowanie do obliczania przepływów za pomocą hydrodynamicznego modelu SWMM. Analizę przeprowadzono według autorskiej metodyki. Wysokości opadów, oszacowane na podstawie danych radarowych i pomierzone w badanej zlewni Potoku Służewieckiego na 2 posterunkach opadowych dla 3 zdarzeń opadowych, znacznie różniły się wartościami w poszczególnych przedziałach czasowych trwania opadu. Na podstawie tych oszacowanych i pomierzonych danych opadowych obliczono wartości ich stosunku, które zastosowano do korekty danych radarowych uzyskanych dla 66 wirtualnych deszczomierzy na obszarze badanej zlewni. Ustalone w tych analizach wysokości opadów wprowadzono do modelu SWMM i zastosowano do obliczania przepływów. Przeprowadzono ocenę zgodności pomiędzy przepływami maksymalnymi, które obliczono i pomierzono w dwóch przekrojach Potoku Służewieckiego dla 3 analizowanych zdarzeń opad-odpływ.

Słowa kluczowe: zlewnia miejska, dane radarowe, natężenie opadu, model SWMM, proces opad-odpływ