*Article*

# Radar Data Analyses for a Single Rainfall Event and their Application for Flow Simulation in an Urban Catchment Using the SWMM model

**Mariusz Barszcz**

Department of Hydraulic Engineering, Warsaw University of Life Sciences – SGGW, 02-776 Warsaw, Poland; mariusz_barszcz@sggw.pl; Tel.: +48-22-593-5284

**Abstract:** In this study, regression analyses were used to find a relationship between the rain gauge rainfall rate *R* and radar reflectivity *Z* for the urban catchment of the Służewiecki Stream in Warsaw, Poland. Rainfall totals for 18 events which were measured at two rainfall stations were used for these analyses. Various methods for determining calculational values of radar reflectivity in reference to specific rainfall cells with 1-km resolution within an event duration were applied. The influence of each of these methods on the *Z*-*R* relationship was analyzed. The correction coefficient for data from the SRI (Surface Rainfall Intensity) product was established, in which the values of rainfall rate are calculated based on parameters *a* and *b* determined by Marshall and Palmer. Relatively good agreement between measured and estimated rainfall totals for the analyzed events was obtained using the *Z*-*R* relationships as well as the correction coefficient determined in this study. Rainfall depths estimated from radar data for two selected events were used to simulate flow hydrographs in the catchment using the SWMM (Storm Water Management Model) hydrodynamic model. Different scenarios were applied to investigate the stream response to changes in rainfall depths, in which the data both for 2 existing as well as 64 virtual rain gauges assigned to appropriate rainfall cells in the catchment were included.

**Keywords:** urban catchment; radar reflectivity; rainfall rate; *Z*-*R* relationship; SWMM model; flow simulation

---

## 1. Introduction

Monitoring and prediction of rainfall events and their consequences are of primary importance to hydrology [1-3]. In many small urban catchments, there is a problem with obtaining rainfall data necessary for hydrological applications. In the case of taking measurements using rain gauges, there is often a problem resulting from their low density in the catchment or as a result of them temporarily turning off due to failure. Applying data registered at rainfall stations as input data for hydrological models requires, in the majority of cases, the spatial interpolation of rainfall data [4]. One of the means of measuring rainfall depth is to make use of weather radar technology. Information obtained on the basis of weather data provides the most detailed information in regards to the spatial and temporal distribution of rainfalls [5]. These features potentially improve the simulation and forecasting of stream flows [6-10].

The demand for a better understanding of hydrological processes at different spatial scales requires the application of more integrated and advanced techniques of rainfall detection and estimation rather than applying only data from conventional networks of ground based rain gauges [11]. Due to their ability to capture the spatial characteristics of rainfall fields well and their evolution in time, radar rainfall estimates are playing an increasingly important role in urban hydrological applications [12-16]. The use of more detailed and distributed models increased the demand for good quality, high resolution inputs, which promotes the use of radar rainfall data in urban hydrology [17].

The use of radar data in hydrological applications requires expanding on knowledge on the topic of the uncertainty of radar data [18]. The main flaw of radar observations is the imprecision of the obtained rainfall data [19-21], which results from the fact that it is an indirect measurement. Weather radar do not measure rainfall directly but rather the back scattered energy from precipitation particles from elevated volumes, and an algorithm should be developed and calibrated against the rain gauge network [22].

This research uses regression analyses to compare the relationship between the rain gauge rainfall rate $R$ and radar reflectivity $Z$ to find a proper $Z$-$R$ relationship for the investigated catchment area of the Służewiecki Stream in Warsaw, Poland. The analysis was carried out on the basis of rainfall data which were registered at 2 rainfall stations in the analyzed catchment for a few single rainfall events as well as obtained as a result of processing radar data. On the basis of the established $Z$-$R$ relationship, the rainfall depth for the analysed events was calculated and compared with respective data measured using rain gauges. Such a comparison was also carried out on the basis of data established directly from the SRI (Surface Rainfall Intensity) as well as data calculated upon applying an established value of the correction coefficient.

Rainfall depth for two selected events which were obtained on the basis of radar data using various methods and registered using rain gauges were applied to simulate flows in the analysed catchment with the use of the hydrodynamic SWMM model. The values of peak flow and outflow volume, which were calculated for the analysed rainfall-runoff events were compared with respective parameters of the hydrograph measured in two cross-sections of the Służewiecki Stream (located at two subcatchment outlet profiles).

As described in the paper [23], it appears that the uncertainty on the simulated peak flow is significant, reaching for some conduits in the small urban catchment of Cranbrook (London) 25% and 40% respectively for frontal and convective events. For some events, radar data input resulted in better flow simulations whereas for other events, the rain gauge data input resulted in better flow simulations [24].

## 2. Materials and Methods

### *2.1. Description of the studied area*

In quantitative rainfall analysis, data registered at the Okęcie and Ursynów rainfall stations, located in the area of the analysed Służewiecki Stream catchment in Warsaw, were applied. In the quantitative analysis regarding the flows, hydrographs measured in the Kłobucka and Rosoła cross-sections were used (see Figure 1).

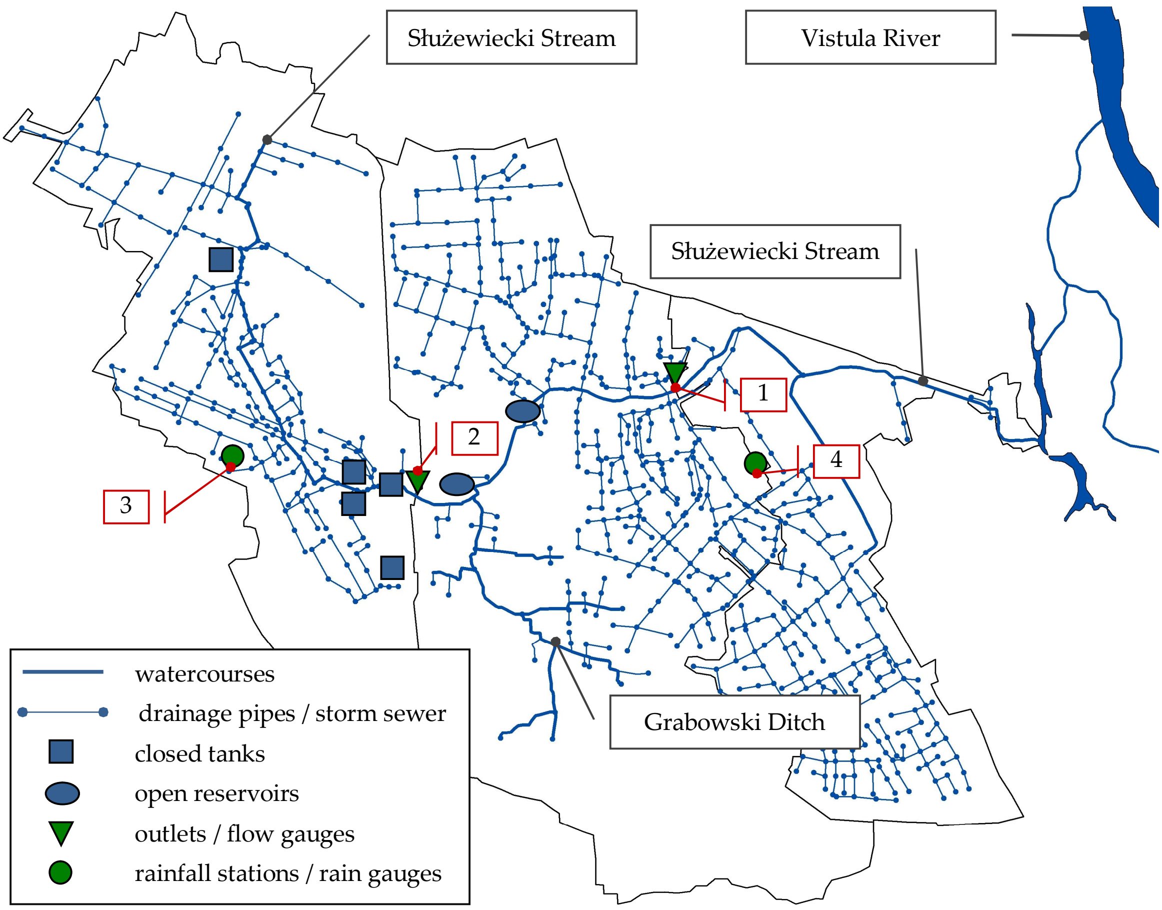


**Figure 1.** Drainage and measuring system of the Służewiecki Stream catchment in Warsaw; cross-sections (outlet-profiles) and rainfall stations: 1 - Rosoła, 2 - Kłobucka, 3 – Okęcie, 4 – Ursynów.

The area of the subcatchment for the Kłobucka cross-section is 16.5 km$^2$, with a share of effective impermeable surfaces (hydraulically connected with storm sewers) equal to approx. 23%. Warsaw Chopin Airport, from which rainwaters are directed to the Służewiecki Stream by a storm water drainage system, occupies the vast majority of the area of this catchment. The Służewiecki Stream, in the segment from its source to the Kłobucka cross-section (6.5 km in length), is closed along almost the entire length. In the area of the airport, retention tanks with a total capacity of 42,490 m$^3$, which have a large influence on the transformation of flows in the watercourse, are found.

The area of the subcatchment to the Rosoła cross-section is 43.0 km$^2$. The share of effective impermeable surfaces is approx. 26.0%. A part of this catchment, which is drained by the Grabowski Drainage Ditch, is mainly agricultural and forest-type land. The remaining part of the catchment, drained by a drainage system, is used for industrial, commercial, transportation and multi-family residential development purposes. It is characterized by a large share of impermeable surfaces. The average slope of the Służewiecki Stream is approx. 1.5‰, and slopes of the areas in the catchment are usually less than 1%.

Rainfall depths at the Okęcie and Ursynów rainfall stations were registered using electronic tipping bucket rain gauges. The first of them is controlled by the Institute of Meteorology and Water Management – National Research Institute (Polish: IMGW-PIB), while the second – by the Division of River Engineering in Warsaw University of Life Sciences – SGGW. Water levels on the basis of which flows were calculated were registered using a hydrostatic sensor of the "Diver" type.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 1 June 2018 doi:10.20944/preprints201806.0006.v1

Peer-reviewed version available at Water 2018, 10, 1007; doi:10.3390/w10081007



### 2.2. The SWMM model for the studied area

To stimulate flow in the analysed catchment in response to single rainfall events, version 5.0.022 of the SWMM (Storm Water Management Model) was applied. SWMM is a fully dynamic rainfall-runoff model, as well as being a fully distributed deterministic model. The model is characterized by a large number of parameters, which are mainly physically measurable characteristics of the catchment and hydrometeorological conditions. An extensive description of the model can be found in the manual [25]. Numerous examples of its application for simulating flow in urbanized catchments can be found in the scientific publications of various authors [26-30].

The adaptation of the SWMM model for the analysed catchment relied on creating objects in the model which represent the physical elements of the actual hydrological and hydraulic system of the catchment, and next - on determining the values of their parameters and calibration. In order to assess and identify the parameters of the objects in the model, the authors used characteristics of real objects measured in field and identified based on the available studies, as well as values of parameters recommended in the tables of the manual [25].

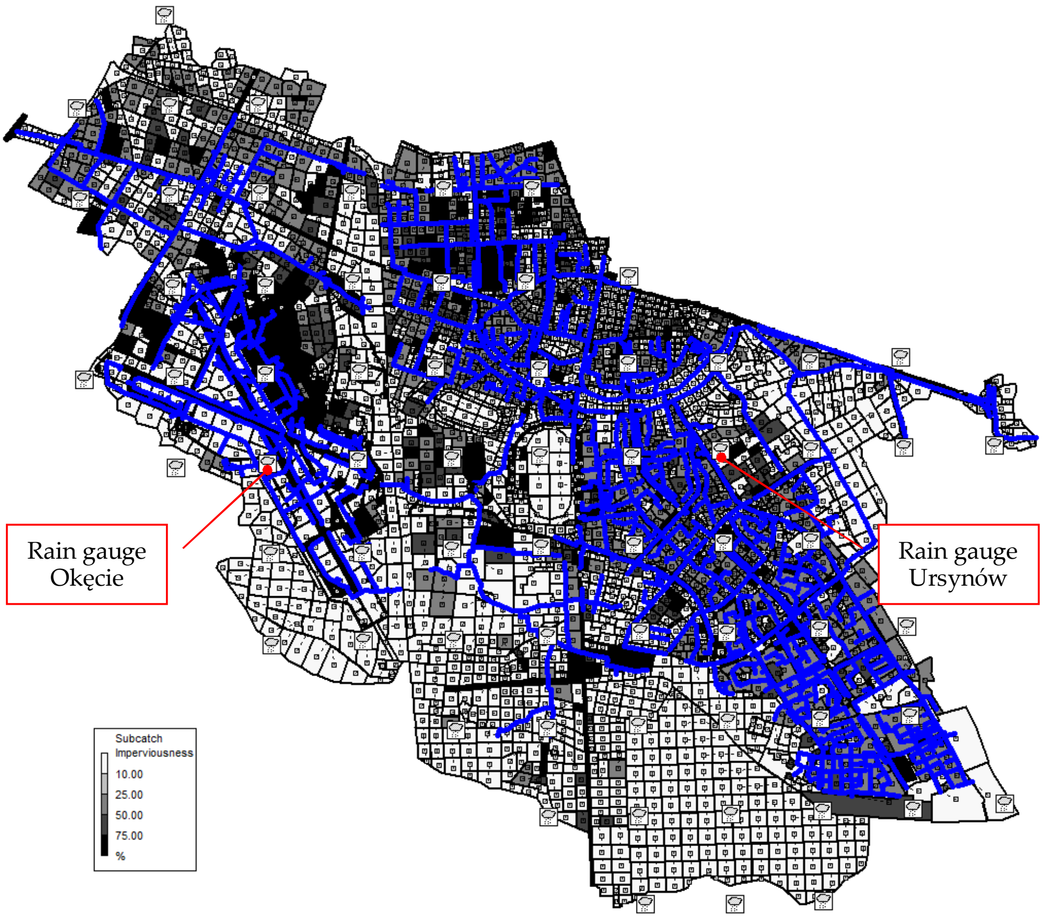


**Figure 2.** The storm drainage system, subcatchments and rain gauges (two existing and 64 virtual objects) in the SWMM model for the studied area.

The following objects were accounted for in the SWMM model, which had been adapted for the analysed catchment (see Figure 2):

- the existing rain gauges at the Okęcie and Ursynów rainfall station (assigned to two rainfall cells with an area of 1 km$^2$, which correspond to appropriate pixels on the map in the SRI radar product);

Peer-reviewed version available at *Water* **2018**, *10*, 1007; doi:10.3390/w10081007



- virtual rain gauges, in which the rainfall depths were estimated on the basis of radar data (assigned to 64 rainfall cells covering the area of the catchment);
- subcatchments, which had been distinguished in the catchment in order to account for the spatial diversity of land use in the catchment and the share of impermeable surfaces connected with this (4,565 objects);
- open channels, watercourses and drainage pipes (2,271 objects);
- road culverts and bridges;
- retention tanks, pumps and valves used to regulate flow, working together with the tanks.

### *2.3. Methods of radar data analysis*

Upon processing values of radar reflectivity registered by the radar, we obtain different meteorological and hydrological products. One of these products is SRI (Surface Rainfall Intensity), which presents a picture of rainfall intensity $R$ in a layer characterized by a constant height above the surface of the ground [31]. The Institute of Meteorology and Water Management - National Research Institute, which carries out measurements in Poland using radars and makes SRI products available, when calculating precipitation (rainfall) rate $R$ on the basis of registered radar reflectivity $Z$, makes use of Equation (1) – presented in inverse order, i.e. expressing $Z$ by $R$, based on $a$ and $b$ coefficients determined by Marshall and Palmer [32], which equal 200 and 1.60 respectively [31].

$$Z = aR^b, \tag{1}$$

where $Z$ is radar reflectivity ($mm^6 \cdot m^{-3}$), $R$ is the rainfall rate ($mm \cdot h^{-1}$), $a$ and $b$ are constants.

The work used the SRI product obtained as a result of processing reflectivity data derived from the C-Band Doppler radar located approx. 30 km north of the Okęcie and Ursynów rainfall stations (in the town of Legionowo). The applied SRI product presents values of rainfall intensity in the area covered by the radar in a layer located at a height of 1 km above the surface of the ground, with 1 km resolution and 10-minute intervals.

A specialized programme – RAPOK (developed at the IMGM-PIB) was used to analyse the values of rainfall intensity on the basis of the SRI product, making it possible to generate radar data in the form of a file compatible with the Microsoft Excel format for the area covering the analysed catchment (fields in a shape close to a square, containing 156 pixels with 1 km resolution). From data for 156 pixels, values of rainfall intensity for 66 pixels located in the Służewiecki Stream catchment were selected and used for analyses in accordance with the scope of the present work. Figure 3 shows a sample SRI product map in the RAPOK programme, corresponding to one of the analysed rainfall events which occurred on 02.07.2007 at 21:40. On the basis of rainfall intensity values $R$ derived from the SRI product for 66 pixels, the corresponding values of radar reflectivity $Z$ were calculated for each of the analysed events (at individual time intervals of rainfall duration). The calculations were carried out on the basis of relation (1) based on $a$ and $b$ coefficients amounting to 200 and 1.6, respectively, determined by Marshall and Palmer.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 1 June 2018 doi:10.20944/preprints201806.0006.v1

Peer-reviewed version available at *Water* **2018**, *10*, 1007; doi:10.3390/w10081007



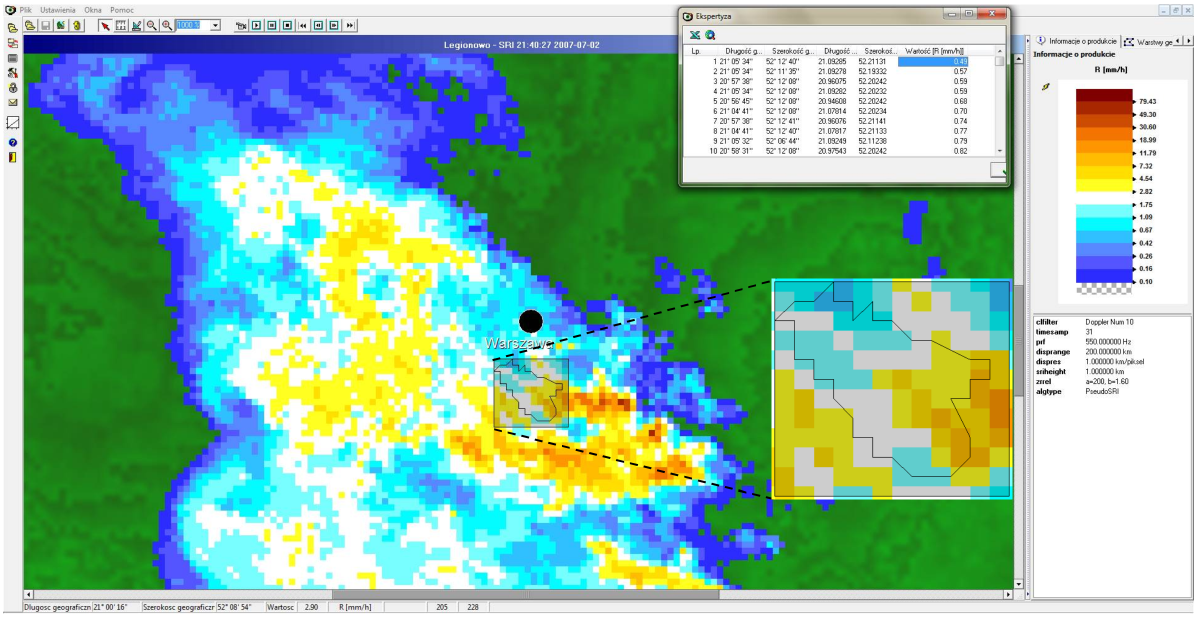


**Figure 3.** SRI product (map of rainfall intensity) and area covering the analyzed catchment (156 pixels).

Next, regression analyses were applied in an effort to establish the values of parameters *a* and *b* in *Z-R* relationship (Equation (1)) for the investigated catchment area of the Służewiecki Stream in Warsaw. The analysis was carried out on the basis of values of rainfall intensity measured at the Okęcie and Ursynów rainfall stations for 18 events and corresponding values of radar reflectivity. A regression line in a logarithmized variable *logZ* and *logR* set was obtained. In this analysis, in order to establish the calculational values of radar reflectivity for each of the events in relation to the points in the catchment corresponding to the locations of the Okęcie and Ursynów rainfall stations, five different methods were applied. They differed in terms of the number of data (ranging from 1 to 4 values of radar reflectivity, corresponding to nodes in pixels in which rainfall stations are located) on the basis of which the calculational values of radar reflectivity were established at individual time intervals of rainfall duration. To establish them, the following were assumed: 1) one value of radar reflectivity obtained in two pixels for the node located nearest with regards to the point where the given rainfall station is located; 2) the lowest value of reflectivity for nodes in a given pixel; 3) the highest value of reflectivity; 4) the average value of reflectivity calculated on the basis of data for four nodes; 5) the value of the median for data from four nodes in corresponding pixels. The influence of each of these methods on the values of parameters *a* and *b* in Equation (1) was analysed, and thus, the compatibility of the estimated rainfall totals for the analysed events with the corresponding data measured at rainfall stations.

Rainfall depths measured using rain gauges as well as obtained on the basis of the SRI product for 18 rainfall events were used to establish the ratio of these data in individual time intervals of rainfall duration (10 minutes), and next, their values of the average (correction coefficient) for all data. The established value of the correction coefficient amounting to 3.6 was used to calculate rainfall depths for the analysed events on the basis of data from the SRI product, which were compared with data measured using rain gauges.

Peer-reviewed version available at *Water* **2018**, *10*, 1007; doi:10.3390/w10081007



## 3. Results and discussion

### *3.1. Radar reflectivity-rainfall rate relationships*

The *Z-R* relationship (Equation (1)), with coefficients derived by Marshall and Palmer, is commonly used for radar rainfall estimation. In a further part of the work, it was indicated that rainfall totals calculated for the analyzed events using this relationship were much lower than those measured using rain gauges. As a result of this, an attempt was made to establish *Z-R* relationships which offer better rainfall rate estimation in the investigated catchment area as compared to that of Marshall-Palmer. Eighteen rainfall events, which were measured simultaneously at the Okęcie and Ursynów rainfall stations (6 and 12 events respectively) as well as using a weather radar, were accepted for this analysis. The events were characterized by different rainfall totals, ranging from 8.6 to 52.6, and 6.2 to 43.6 (see Table 1), registered respectively at the Okęcie and Ursynów rainfall stations. Five various methods of establishing calculational values of radar reflectivity for each of the events in reference to the points in the catchment corresponding to the location of the Okęcie and Ursynów rainfall stations which had been described in the previous chapter were used. Five *Z-R* relationships (differing in terms of the values of $a$ and $b$ coefficients) were obtained in reference to each of the rainfall stations. On the basis of these relationships and calculational values of radar reflectivity, the rainfall depths (totals) for the analysed events were estimated and compared with corresponding data measured at the rainfall stations. The application of Equations (2) and (3), established using only 12 events measured at the Ursynów rainfall station was found to result in the highest compatibility of these data in reference to all analysed events. The relationships were characterized by correlation coefficients amounting to 0.84 and 0.83 respectively. These relationships were assumed for calculating rainfall depth on the basis of radar data corresponding to the Okęcie and Ursynów rainfall stations.

$$Z = 64R^{1.23}, \tag{2}$$

$$Z = 66R^{1.23}, \tag{3}$$

Symbols designated as in Equation (1).

Equations (2) and (3) were obtained using two methods in which the calculational values of radar reflectivity were established respectively on the basis of one value of reflectivity (determined for the node located nearest in terms of the point where the Ursynów rainfall station is located) as well as the value of the median for data from four nodes of the pixel in which the Ursynów rainfall station is located. *Z-R* relationships, which were established applying three remaining methods (in reference to events measured at the Ursynów rainfall station), were characterized by correlation coefficients in the range of 0.80 to 0.85. Values of $a$ and $b$ parameters in these relationships, which were established on the basis of the lowest value of reflectivity for nodes at a given pixel, the highest value of reflectivity and the average value of radar data for four nodes in the pixel, were $a$ = 42 and $b$ = 1.17, $a$ = 86 and $b$ = 1.32, $a$ = 65 and $b$ = 1.25 respectively.

In literature, there is high variability of the *Z-R* relationship (Equation (1)) coefficients. The value of coefficients $a$ and $b$, established in many analyses in different regions of the world, fall within ranges from 16.6-730 and 1.16-2.87 respectively [31]. The values of parameter $a$ can change from a few dozen to a few hundred, whereas values of parameter $b$ are usually limited to the range of 1 ≤ b ≥ 3 [33-35]. According to other data [36, 22], values of *a* and *b* fall within the respective ranges of 31-500 and 1.1-1.9. The values of coefficients established in this study are within the ranges obtained by other authors.

### *3.2. Comparison of radar estimates with rain gauge measurements*

Rainfall totals for 18 events which were obtained directly from the SRI product (in which the values of rainfall rate were calculated based on parameters *a* and *b* determined by Marshall and Palmer) as well as were calculated applying correction coefficient for data from the SRI product (equal to 3.6) and estimated on the basis of *Z-R* relationships (2) and (3) established in this work, compared with corresponding data measured using rain gauges at the Okęcie and Ursynów rainfall stations (see Table 1-2).

Compatibility assessment of the rainfall totals for the analysed events obtained on the basis of radar data and measured using rain gauges was carried out with the use of values of relative error (Equation (4)). A value of 25% was assumed as limiting for acceptance. The results were further assessed using the Nash-Sutcliffe Efficiency coefficient - NSE [37, 28-29]. 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) [38].

$$RE = \frac{x - x_0}{x_0} \cdot 100\%, \tag{4}$$

where *RE* is the relative error, $x$ is the calculated value, $x_0$ is the measured value.

**Table 1.** Rainfall totals using rain gauges and SRI product data.

| **Date of the event (y-m-d)** | **Rainfall totals (mm)** Rain gauges O [1] | U [2] | SRI product O | U | **Relative error (%)** O | U |
|---|---|---|---|---|---|---|
| 2006-10-01 | 14.8 | 7.0 | 3.3 | 1.6 | -77.7 | -77.7 |
| 2006-08-06 | 52.6 | - | 17.6 | - | -66.5 | - |
| 2007-07-02 | 8.6 | 11.0 | 1.9 | 3.6 | -77.8 | -67.6 |
| 2007-07-22 | 9.4 | 14.5 | 3.6 | 3.1 | -62.2 | -78.4 |
| 2008-08-02 | 8.8 | 6.2 | 2.1 | 1.5 | -76.6 | -76.3 |
| 2008-08-15 | 22.8 | 43.6 | 6.6 | 10.1 | -71.0 | -76.9 |
| 2008-08-16 | - | 15.2 | - | 2.5 | - | -83.6 |
| 2009-05-30 | - | 13.5 | - | 5.0 | - | -62.7 |
| 2009-06-16 | - | 10.5 | - | 2.6 | - | -75.0 |
| 2009-06-23 | - | 7.8 | - | 3.4 | - | -56.9 |
| 2009-06-25 | - | 41.4 | - | 10.1 | - | -75.6 |
| 2009-07-05a | - | 21.8 | - | 2.3 | - | -89.6 |
| 2009-07-05b | - | 33.6 | - | 7.8 | - | -76.9 |
| Median value | 12.1 | 14.0 | 3.4 | 3.2 | 73.8 | 76.6 |

[1, 2] Rain gauges: O – Okęcie, U - Ursynów

Rainfall totals for the analysed events which were determined directly from the SRI radar product (for the pixel node closest to the points at which the rainfall stations are located) were much

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 1 June 2018 doi:10.20944/preprints201806.0006.v1

Peer-reviewed version available at Water 2018, 10, 1007; doi:10.3390/w10081007



lower than corresponding data measured using rain gauges (see Table 1). In regards to 18 events at the Okęcie and Ursynów rainfall stations, the values of the median of relative error were 73.8 and 76.6% respectively (calculated for absolute values of relative error). The estimation accuracies of rainfall totals using SRI radar product, as assessed by the NSE values, were -0.19 and -0.89, respectively for data at the Okęcie and Ursynów rainfall stations. These values indicate an unacceptable level of performance.

The results of this analysis indicate that a calibration step that compares radar predicted rainfall to "true rainfall" is still needed. Radar users are required to modify, on their own, the radar data by means of rain gauges located within the target catchment in order to remove the bias [39-41]. Relatively few tests of gauge-based adjustment methods have been conducted on small urban scales and all of them have concluded that, on these scales, more dynamic and localized adjustments are required [12, 42]. In studies carried out in Northern France for a long, heavy rainfall event that resulted in flooding and heavy damage, strong underestimation of the estimated rainfall total based on radar data was observed, despite considerable improvement in radar technology and algorithms [43]. In an analysis carried out in Malaysia using hourly rainfall data, more than 80% of data obtained from the radar were overestimated when compared to rain gauge observations [44]. As described in the work [45], when comparing the C-band and X-band rainfall totals to those resulting from tipping bucket rain gauges, one may note that the X-band radar tends to underestimate, while C-band radar generally overestimates them.

**Table 2.** Rainfall totals using rain gauges and SRI product data.

| Date of the event (y-m-d) | Rainfall totals (mm) | | | | | | Relative error (%) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Eq. (2) | | Eq. (3) | | SRI · 3.6 | | Eq. (2) | | Eq. (3) | | SRI · 3.6 | |
| | O [1] | U [2] | O | U | O | U | O | U | O | U | O | U |
| 2006-10-01 | 15.8 | 5.0 | 16.5 | 4.4 | 11.9 | 4.2 | 6.7 | -29.0 | 11.6 | -36.7 | -19.7 | -40.6 |
| 2006-08-06 | 61.6 | - | 62.1 | - | 63.5 | - | 17.1 | - | 18.1 | - | 20.6 | - |
| 2007-07-02 | 5.6 | 12.6 | 6.3 | 11.7 | 6.9 | 12.8 | -35.2 | 14.2 | -27.3 | 6.2 | -20.1 | 16.5 |
| 2007-07-22 | 20.1 | 14.9 | 19.6 | 15.5 | 12.8 | 11.3 | 114 | 3.0 | 109 | 6.8 | 36.1 | -22.3 |
| 2008-08-02 | 7.0 | 4.2 | 7.4 | 5.7 | 7.4 | 5.3 | -20.2 | -32.9 | -15.5 | -7.7 | -15.7 | -14.7 |
| 2008-08-15 | 24.7 | 37.2 | 30.2 | 35.6 | 23.8 | 36.2 | 8.1 | -14.6 | 32.5 | -18.3 | 4.4 | -17.0 |
| 2008-08-16 | - | 10.7 | - | 12.0 | - | 9.0 | - | -29.4 | - | -20.9 | - | -41.1 |
| 2009-05-30 | - | 20.7 | - | 21.0 | - | 18.2 | - | 53.0 | - | 55.3 | - | 34.5 |
| 2009-06-16 | - | 8.1 | - | 8.3 | - | 9.5 | - | -23.2 | - | -20.8 | - | -9.8 |
| 2009-06-23 | - | 10.5 | - | 10.8 | - | 12.1 | - | 34.0 | - | 38.5 | - | 54.9 |
| 2009-06-25 | - | 46.1 | - | 53.7 | - | 36.3 | - | 11.3 | - | 29.7 | - | -12.3 |
| 2009-07-05a | - | 10.1 | - | 12.5 | - | 8.2 | - | -53.7 | - | -42.6 | - | -62.6 |
| 2009-07-05b | - | 31.2 | - | 27.1 | - | 27.9 | - | -7.1 | - | -19.4 | - | -16.8 |
| Median val. | 18.0 | 11.6 | 18.1 | 12.3 | 12.3 | 11.7 | 18.7 | 26.1 | 22.7 | 20.8 | 19.9 | 19.7 |

[1, 2] Rain gauges: O – Okęcie, U - Ursynów

Values of the median of relative error determined on the basis of the sum of rainfall measured using rain gauges and calculated using *Z-R* relationship (Equation (2)) for the analysed events at the Okęcie and Ursynów rainfall stations amounted to 18.7 and 26.1% respectively (see Table 2). The

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 1 June 2018 doi:10.20944/preprints201806.0006.v1

Peer-reviewed version available at Water 2018, 10, 1007; doi:10.3390/w10081007



estimation accuracies of rainfall totals using this equation, as assessed by the NSE values, were, in both cases, 0.85. This value indicates a very good level of performance. The values of the median of the relative error, established in the analysis using *Z-R* relationship (Equation (3)) for events at the Okęcie and Ursynów rainfall stations, were 22.7 and 20.8% respectively. The NSE coefficients were 0.82 and 0.78. For this statistic, model performance can be evaluated as very good. The established Equations (2) and (3), the application of which requires the identification of calculational values of radar reflectivity on the basis of data for one and four nodes in a given pixel, offer better rainfall rate estimation in the investigated area compared to Marshall-Palmer`s relationship. Using three other *Z-R* relationships, which were established on the basis of the lowest value of reflectivity for data in nodes in a given pixel, the greatest value of reflectivity and the average value for data in four nodes of a pixel (described in greater detail in the previous chapters), the values of the median of relative error for events at Okęcie and Ursynów rainfall stations of 27.6 and 27.9%, 28.0 and 26.6% and 23.8 and 23.4% were obtained. The values of the median of relative error established using the correction coefficient for data from the SRI product (SRI · 3.6) were 19.9 and 19.7% respectively for the Okęcie and Ursynów rainfall stations, The obtained values of NSE, i.e. 0.90 and 0.80, indicate a very good level of performance. In this study, carried out using various methods, both underestimation and overestimation of the estimated rainfall total based on radar data was observed. The highest agreement between rainfall totals which were estimated for the analyzed events based on radar data and using rain gauges were noted when the correction coefficient for data from the SRI product was used and upon applying *Z-R* relationships (Equation (2) and (3)).

### 3.3. Simulation of flow using different rainfall data

Rainfall depths measured at rain gauges and estimated from weather radar data for two selected events were applied to simulate hydrographs in two cross-sections of the Służewiecki Stream using the SWMM model. The results of simulations of peak flows and outflow volumes, obtained in the Kłobucka and Rosoła cross-sections (see Figure 1), have been compiled in Tables 3 and 4. Rainfall-runoff events occurring on 2 July 2007 and 15 August 2008 were used for these analyses. The events are characterized by diverse values of parameters. The rainfall totals for these events were 8.6 and 22.8 mm and 11.0 and 43.6 mm, which were measured respectively at the Okęcie and Ursynów rainfall stations. Values of peak flow and outflow volume of direct hydrographs measured in the Kłobucka and Rosoła cross-sections have been given in Table 3.

**Table 3.** Results using rainfall depths measured at rain gauges.

| Date of the event (y-m-d) | Measured values | | | | Simulated values | | | | Relative error (%) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Peak flow ($m^3 \cdot s^{-1}$) | | Volume ($m^3 \cdot 10^3$) | | Peak flow ($m^3 \cdot s^{-1}$) | | Volume ($m^3 \cdot 10^3$) | | Peak flow | | Volume | |
| | R [1] | K [2] | R | K | R | K | R | K | R | K | R | K |
| 2007-07-02 | 6.06 | 0.76 | 46.0 | 14.7 | 4.95 | 0.80 | 44.8 | 16.8 | -18.3 | 5.3 | -2.5 | 14.5 |
| 2008-08-15 | 21.51 | 1.31 | 369.2 | 69.5 | 20.84 | 1.44 | 342.6 | 74.5 | -3.2 | 9.7 | -7.2 | 7.2 |

[1, 2] Cross-sections (outlet-profiles): R – Rosoła, K – Kłobucka

Assessment of the agreement between measured (observed) and simulated values of parameters of the hygrogram was carried out using relative error (Equation 4), recommended by

ASCE [46] for single events. A value of 25% was assumed as the cut-off level for model acceptance [47].

The values of relative error (RE) which were calculated for the analyzed events in two cross-sections of the Służewiecki Stream in response to rainfall depths measured at two rain gauges (uniformly distributed over two adequate areas in the catchment), ranged from -18.3 to 9.2% and -5.5 to 14.5% (see Table 3) respectively in relation to peak flows and outflow volumes. The simulated values of parameters of the hydrograph obtained from the SWMM model were lower than the assumed level of model acceptance (25%).

Different scenarios were applied to investigate the stream response to changes in rainfall depths estimated from radar data for the analyzed events. Six scenarios in which rainfall depths for two single events (in individual time intervals of the rainfall duration) were established according to the following methods:

- Scenario 1: directly on the basis of data from the SRI radar product (values of the intensity of rainfall in a given node of a pixel which had been calculated based on the *a* and *b* coefficients determined by Marshall and Palmer) for 66 rain gauges, which correspond to the pixels on SRI product maps (including for 64 virtual and 2 existing rain gauges at the Okęcie and Ursynów rainfall stations, located in cells with a surface area of 1 $km^2$ covering the area of the analysed catchment);
- Scenario 2: upon applying *Z-R* relationship (Equation 2) and calculational values of radar reflectivity for 66 rain gauges (obtained for one specified node in 66 pixels, the location of which in each pixel corresponded to that established in two pixels for nodes located closest in terms of the points at which the Okęcie and Ursynów rainfall stations are located);
- Scenario 3: on the basis of data from the SRI product for 66 rain gauges and correction coefficient amounting to 3.6;
- Scenario 4: upon applying *Z-R* relationship (Equation 3) and calculational values of radar reflectivity for 66 rain gauges (values of the median established in 66 pixels on the basis of data for four nodes in each pixel);
- Scenario 5: upon applying *Z-R* relationship (Equation 2) and calculational values of radar reflectivity (established in two pixels for the node located nearest to the points at which the existing rainfall stations are located) for rain gauges in Okęcie and Urysnów rainfall stations (the point rainfall depths established for these rain gauges were uniformly distributed over two adequate areas in the catchment);
- Scenario 6: on the basis of data from the SRI radar product for 2 rain gauges at existing rainfall stations and a correction coefficient amounting to 3.6 (the rainfall inputs were assumed to be uniformly distributed over two areas).

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 1 June 2018 doi:10.20944/preprints201806.0006.v1

Peer-reviewed version available at Water 2018, 10, 1007; doi:10.3390/w10081007



**Table 4.** Results using rainfall depths estimated from radar data.

| Date of the event (y-m-d) | Simulated values: Peak flow ($m^3 \cdot s^{-1}$) | | Simulated values: Volume ($m^3 \cdot 10^3$) | | Relative error (%): Peak flow | | Relative error (%): Volume | |
|---|---|---|---|---|---|---|---|---|
| | R [1] | K [2] | R | K | R | K | R | K |
| | | | | Scenario 1 | | | | |
| 2007-07-02 | 0.82 | 0.10 | 6.0 | 1.6 | -86.5 | -87.5 | -87.0 | -88.9 |
| 2008-08-15 | 2.48 | 0.78 | 47.4 | 16.9 | -88.5 | -40.2 | -87.1 | -75.7 |
| | | | | Scenario 2 | | | | |
| 2007-07-02 | 5.83 | 0.82 | 52.4 | 14.5 | -3.8 | 8.4 | 14.0 | -0.9 |
| 2008-08-15 | 22.03 | 1.66 | 394.2 | 90.3 | 2.4 | 26.4 | 6.8 | 29.9 |
| | | | | Scenario 3 | | | | |
| 2007-07-02 | 5.35 | 0.77 | 50.2 | 15.5 | -11.7 | 1.7 | 9.1 | 5.7 |
| 2008-08-15 | 19.68 | 1.64 | 331.8 | 82.2 | -8.5 | 25.3 | -10.1 | 18.3 |
| | | | | Scenario 4 | | | | |
| 2007-07-02 | 5.21 | 1.00 | 56.0 | 19.1 | -14.1 | 31.7 | 21.8 | 30.4 |
| 2008-08-15 | 22.95 | 1.85 | 441.3 | 94.8 | 6.7 | 40.8 | 19.6 | 36.5 |
| | | | | Scenario 5 | | | | |
| 2007-07-02 | 5.55 | 0.70 | 46.3 | 12.6 | -8.5 | -7.5 | 0.7 | -14.3 |
| 2008-08-15 | 17.35 | 1.58 | 273.5 | 71.6 | -19.4 | 20.8 | -25.9 | 3.0 |
| | | | | Scenario 6 | | | | |
| 2007-07-02 | 5.40 | 0.78 | 46.6 | 14.9 | -10.9 | 3.4 | 1.3 | 1.6 |
| 2008-08-15 | 16.90 | 1.55 | 261.0 | 69.3 | -21.4 | 18.2 | -29.3 | -0.2 |

[1, 2] Cross-sections (outlet-profiles): R – Rosoła, K – Kłobucka

Values of peak flow and outflow volume in the Rosoła and Kłobucka cross-sections obtained using the SWMM model in simulations carried out on the basis of data from the SRI radar product (Scenario 1), were much lower than respective values measured in these cross-sections. In response to the above-mentioned hygrogram parameters, the values of relative error were from -88.5 to -40.2%, and from -88.9 to -75.7% respectively (see Table 4). For a small urban catchment, large differences are observed in the peak flows simulated by radar and rain gauges due to the inherent uncertainties from both rainfall estimates [14], which is confirmed by the results of this analysis. As described in the work [48], the quality of radar-derived precipitation data without gauge-adjustment is insufficient for use in flood risk management. Adjusting radar data son that it more closely resembles the observations of rain gauges will consequently improve the results obtained with distributed simulation models [49]. The results of flow simulations for five above-mentioned scenarios in which the *Z-R* relationships established in this work along with the correction coefficient were applied are described in a further part of the work.

Upon applying rainfall depths estimated on the basis of *Z-R* relationship (Equation 2) and calculational values of radar reflectivity (established on the basis of radar data for a single given node in each pixel), peak and total flow values obtained from the SWMM model were, in most cases, similar to the measured values. The values of relative error calculated in scenario 2 ranged from

*Preprints* (www.preprints.org) | NOT PEER-REVIEWED | Posted: 1 June 2018 doi:10.20944/preprints201806.0006.v1

Peer-reviewed version available at *Water* **2018**, *10*, 1007; doi:10.3390/w10081007



-3.8 to 26.4% and from -0.9 to 29.9%, respectively. For two out of eight cases, the errors were higher than the value of 25%, which had been assumed as the limiting value for acceptance. Good agreement between measured and simulated values of parameters was also obtained in reference to Scenario 3 in which the values of rainfall were calculated on the basis of data from the SRI product for 66 rain gauges accounting for the correction coefficient. The relative error was higher than 25% in only one case. In the analysis for Scenario 4, carried out applying rainfall depths estimated on the basis of the *Z-R* relationship (3) and calculational values of radar reflectivity (established on the basis of radar data for four nodes in each pixel), a lower agreement between the measured and simulated values of the parameters of the hydrograph were obtained than for Scenario 2 (in which the calculational values of reflectivity were established only on the basis of data from one node in each pixel). The values of relative error ranged from -14.1 to 40.8% and 19.6 to 36.5% respectively in regards to peak flows and outflow volumes. In four cases, the errors were higher than 25%.

In the analysis carried out for Scenario 5, in which the *Z-R* (2) relationship and calculational values of radar reflectivity established for pixels in which the Okęcie and Ursynów rainfall stations were located (calculated point rainfalls were uniformly distributed over two adequate areas) were applied to calculate rainfall depths, high agreement between simulated and measured peak flow and outflow volumes was obtained. The values of relative error were found to be from -19.4 to 20.8% and from -25.9 to 3.0% respectively. Only in one case was the relative error slightly higher than 25%. In a respective analysis carried out for Scenario 2, in which the calculational values of radar reflectivity were determined for 66 pixels (applied to calculate the amount of rainfall for 66 rain gauges), similar results of the simulation were obtained – the relative errors were higher than the level of acceptance in two cases. Good agreement between the analysed parameters of the hydrograph was also obtained in regards to Scenario 6, for which the rainfall depths were calculated on the basis of data from the SRI product for 2 rain gauges and the correction coefficient. Only in one case was the relative error higher than the value marking the level of acceptance. The obtained relative errors (compiled in Table 4) indicate that the results of this analysis are comparable to those obtained for corresponding Scenario 3, in which radar data for a much higher number of rain gauges in the analysed catchment were used to carry out the simulation.

## 5. Conclusions

Different methods have been applied to estimate rainfall depths (totals) from radar data for 18 analysed single events. Calculated rainfall totals were compared with corresponding data measured using rain gauges at two rainfall stations located in the analysed urban catchment. The hydrodynamic SWMM model was used to simulate peak flow and outflow volume of hydrograph in two cross-sections of the Służewiecki Stream in response to radar rainfall depths estimated for two selected events using six methods.

The conducted analyses enable the following conclusions to be drawn:

1. Rainfall totals for the analysed events obtained directly from the SRI radar product (in which the values of rainfall rate are calculated based on parameters *a* and *b* determined by Marshall and Palmer) were much lower than the rainfall totals measured for these events at rainfall stations. The values of the relative error ranged from -89.6 to -56.9%. The results of this analysis indicate that a calibration step that compares radar estimated rainfall and rain gauge rainfall is necessary. Respective values of relative error, ranging from -88.9 to -40.2%, were calculated for parameters of the hydrograph simulated in response to rainfall depths obtained from the SRI product.

2. Based on rainfall depths measured at rainfall stations and obtained from the SRI radar product for the analysed events (in individual time intervals of rainfall duration), the average value of the ratio between these data amounting to 3.6 was determined. Rainfall totals which had been calculated for individual events applying this correction coefficient and data from the SRI product were characterized by an absolute value of the relative error median of 20%. The obtained values of the NSE coefficient indicate a very good level of performance.
3. The *Z-R* relationships (2) and (3) determined in this study, the application of which requires the identification of calculational values of radar reflectivity on the basis of data in one and four nodes of a given radar map pixel, offer better rainfall rate estimation in the investigated area as compared to Marshall-Palmer`s relationship (the values of coefficients $a$ and $b$ determined by Marshall and Palmer differ significantly from those established in this work). The values of the median of relative error, determined in the analysis using these relationships for events in two rainfall stations, were between 11.6 and 18.1% respectively. The calculated rainfall totals were both underestimated and overestimated.
4. Relative errors, which were obtained in a similar analysis using three other *Z-R* relationships (established on the basis of the lowest and highest values of radar reflectivity as well as the average value for data in four nodes of a given pixel), were significantly higher than those calculated in the analysis applying *Z-R* relationship (Equation (2) and (3)). The absolute values of the median of the relative error calculated on the basis of rainfall totals for events analysed at individual rainfall stations ranged from 23.4 to 28.0%. As the values of relative error indicate, the method applied to determine the calculational values of radar reflectivity was important.
5. In simulations carried out using the SWMM model in reaction to rainfall depths which had been calculated for the analysed events using the correction coefficient for data from the SRI product and estimated on the basis of the determined *Z-R* (Equation (2)) relationship, relatively good agreement was achieved between the measured and simulated peak flow and outflow volume values. The values of the relative error were, in most cases, lower than the assumed cut-off level of model acceptance (25%). In this analysis, about 56% of peak flow and outflow volume values obtained from simulations were overpredicted when compared to flow gauge observations. For some events, radar data input resulted in better flow simulations than using rain gauge data input.
6. The estimation errors of hydrograph parameters in some cases were not in agreement with values of errors which had been calculated for respective rainfall totals, e.g. when rainfall total error was relatively large and negative, the respective peak flow error was small and positive.
7. Using rainfall depths estimated from radar data for only 2 existing rain gauges (cells with 1 km resolution) as well as 66 (including 64 virtual) rain gauges in the catchment, a similar range of relative error values for simulated peak flows and outflow volumes was found, but different values of errors in individual corresponding cases were obtained.

**Acknowledgments:** Information regarding radar data: The source of data is the Institute of Meteorology and Water Management - National Research Institute. Data from the Institute of Meteorology and Water Management - National Research Institute were processed.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. He, X.; Sonnenborg, T.O.; Refsgaard, J.C.; Vejen, F.; Jensen, K.H. Evaluation of the value of radar QPE data and rain gauge data for hydrological modeling. *Water Resour. Res.* **2013**, 49, 5989–6005, DOI:10.1002/WRCR.20471.
2. Li, Z.; Yang, D.; Hong, Y.; Qi, Y.; Cao, Q. Evaluation of radar-based precipitation estimates for flash flood forecasting in the Three Gorges Region. In Proceedings of the International Association of Hydrological Sciences, Guangzhou, China, August 2014, DOI:10.5194/piahs-368-89-2015.
3. Bouilloud, L.; Delrieu, G.; Boudevillain, B.; Kirstetter, P.-E. Radar rainfall estimation in the context of post-event analysis of flash-flood events. *J. Hydrol.* **2010**, 394, 17–27, DOI:10.1016/j.jhydrol.2010.02.035.

4. Jatho, N.; Pluntke, T.; Kurbjuhn, C.; Bernhofer, C. An approach to combine radar and gauge based rainfall data under consideration of their qualities in low mountain ranges of Saxony. *Nat. Hazards Earth Syst. Sci.* **2010**, 10, 429-446, DOI:10.5194/nhess-10-429-2010.
5. Mittermaier, M.P. Introducing uncertainty of radar-rainfall estimates to the verification of mesoscale model precipitation forecasts. *Nat. Hazards Earth Syst. Sci.* **2008**, 8, 445-460, DOI:10.5194/nhess-8-445-2008.
6. Abon, C.C.; Kneis, D.; Crisologo, I.; Bronstert, A.; David, C.P.C.; Heistermann, M. Evaluation the potential of radar-based rainfall estimates for streamflow and flood simulations in the Philippines. *Geomatics, Natural Hazards and Risk* **2015**, 7, 1390-1405, DOI:10.1080/19475705.2015.1058862.
7. Atencia, A.; Mediero, L.; Llasat, M.C.; Garrote, L. Effect of radar rainfall time resolution on the predictive capability of distributed hydrologic model. *Hydrol. Earth Syst. Sci.* **2011**, 15, 3809-3827, DOI:10.5194/hess-15-3809-2011.
8. Berne, A.; Krajewski, W.F. Radar for hydrology: Unfulfilled Promise Or unrecognized potential?. *Adv. Water Resour.* **2013**, 51, 357-366, DOI:10.1016/j.advwatres.2012.05.005.
9. Borga, M. Accuracy of radar rainfall estimates for streamflow simulation. *J. Hydrol.* **2002**, 267, 26-29, DOI:10.1016/S0022-1694(02)00137-3.
10. Yang, D.; Koike, T.; Tanizawa, H. Application of distributed hydrological model and feather radar observations for flood management in the upper Tone River of Japan. *Hydrol. Process.* **2000**, 18, 3119-3132, DOI:10.1002/hyp.5752.
11. Somorowska, U. Annual and seasonal precipitation patterns across lowland catchment derived from rain gauge and weather radar data. *Journal of Water and Land Development* **2012**, 17, 3-10, DOI:10.2478/v100025-012-0001-4.
12. Wang, L.-P.; Ochoa-Rodríguez, S.; Van Assel, J.; Pina, R.D.; Pessemier, M.; Kroll, S.; Willems, P.; Onof, C. Enhancement of radar rainfall estimates for urban hydrology through optical flow temporal interpolation and Bayesian gauge-based adjustment. *J. Hydrol.* **2015**, 531, 408–426, DOI:10.1016/j.jhydrol.2015.05.049.
13. Wang, L.N; Simões, M.A.; Rico-Ramirez, S.; Ochoa, J.; Leitão, J.; Maksimović, Č. Radar-based pluvial flood forecasting over urban areas: Redbridge case study. In Proceedings of IAHS on Weather Radar and Hydrology, Exeter, UK, April 2011.
14. Schellart, A.N.A.; Shepherd, W.J.; Saul, A.J. Influence of rainfall estimation error and spatial variability on sewer flow prediction at a small urban scale. *Adv. Water Resour.* **2012**, 45, 65-75, DOI:10.1016/j.advwatres.2011.10.012.
15. Rafieeinasab, A.; Norouzi, A.; Kim, S.; Habibi, H.; Nazari, B.; Seo, D.-J.; Lee, H.; Cosgrove, B.; Cui, Z. Toward high-resolution flash flood prediction in large urban areas—analysis of sensitivity to spatiotemporal resolution of rainfall input and hydrologic modeling. *J. Hydrol.* **2015**, 531, 370–388, DOI:10.1016/j.jhydrol.2015.08.045.
16. Villarini, G.; Smith, J.A.; Baeck, M.L.; Sturdevant-Rees, P.; Krajewski, W.F. Radar analyses of extreme rainfall and flooding in urban drainage basins. *J. Hydrol.* **2010**, 381, 266-286, DOI:10.1016/j.jhydrol.2009.11.048.
17. Thorndahl, S.; Einfalt, T.; Willems, P.; Nielsen, J.E.; Veldhuis, M.-C.; Arnbjerg-Nielsce, K.; Rasmussen, M.R.; Molnar, P. Weather radar rainfall data in urban hydrology. *Hydrol. Earth Syst. Sci.* **2017**, 21, 1359-1380, DOI:10.5194/hess-2016-517.
18. Peleg, N.; Ben-Asher, M.; Morin, E. Radar subpixel-scale rainfall variability and uncertainty: lessons learned from observations of a dense rain-gauge network. *Hydrol. Earth Syst. Sci.* **2013**, 17, 2195-2208, DOI:10.5194/hess-17-2195-2013.
19. Krajewski, W.F.; Villarini, G.; Smith, A. Radar-rainfall uncertainties. *Bull. Am. Meteorol. Soc.* **2010**, 91, 87-94, DOI:10.1175/2009BAMS2747.I.
20. Kirstetter, P.E.; Delrieu, G.; Boudevillain, B.; Obled, C. Towards an error model for radar quantitative precipitation estimation in the Cévennes-Vivarais region, France. *J. Hydrol.* **2010**, 394(1-2), 28-41, DOI:10.1016/j.jhydrol.2010.01.009.
21. Delrieu, G.; Bonnifait, L.; Kirstetter, P.-E.; Boudevillain, B. Dependence of radar quantitative precipitation estimation error on the rain intensity in the Cévennes region, France. *Hydrol. Sci. J.* **2014**, 59 (7), 1308-1319, DOI:10.1080/02626667.2013.827337.
22. Dhiram, K.; Wang, Z.H. Evaluation on Radar Reflectivity-Rainfall Rate (Z-R) Relationships for Guyana. *Atmos. and Clim. Sci.* **2016**, 6, 489-499, DOI:10.4236/acs.2016.64039.

23. Gires, A.; Onof, C.; Maksimović, Č.; Schertzer, D.; Tchiguirinskaia, I.; Simoes, N. Quantifying the impact of small scale unmeasured rainfall variability on urban runoff through multifractal downscaling: A case study. *J. Hydrol.* **2012**, 442-443, 117-128, DOI:10.1016/j.jhydrol.2012.04.005.
24. Schellart, A.; Liguori, S.; Krämer, S.; Saul, A.; Rico-Ramirez, M.A. Comparing quantitative precipitation forecast methods for prediction of sewer flows in a small urban area. *Hydrol. Sci. J.* **2014**, 59:7, 1418-1436, DOI:10.1080/02626667.2014.920505.
25. Rossman, L.A. *Storm water management model user`s manual version 5.0*; National Risk Management Research Laboratory, U.S. Environmental Protection Agency: Cincinnati, OH, USA, 2010.
26. Hsu, M.H.; Chen, S.H.; Chang, T.J. Inundation simulation for urban drainage basin with storm sewer system. *J. Hydrol.* **2000**, 234(1), 21-37, DOI: 10.1016/S0022-1694(00)00237-7.
27. Barszcz, M. Influence of applying infiltration and retention objects on the runoff of rainwater on a plot and catchment scale - case study of the Służewiecki Stream subcatchment in Warsaw. *Pol. J. Environ. Stud.* **2015**, 24, 57-65, DOI:10.15244/pjoes/29197.
28. Li, Ch.; Liu, M.; Hu, Y.; Gong, J.; Xu, Y. Modeling the quality and quantity of runoff in highly urbanized catchment using storm water management model. *Pol. J. Environ. Stud.* **2016**, 25, 1573-1581, DOI:10.15244/pjoes/60721.
29. Wu, J.Y.; Thompson, J.R.; Kolka, R.K.; Franz, K.J.; Stewart, T.W. Using the Storm Water Management Model to predict urban headwater stream hydrological response to climate and cover change. *Hydrol. Earth Syst. Sci.* **2013**, 17, 4743-4758, DOI:10.5194/hess-17-4743-2013.
30. Krebs, G.; Kokkonen, T.; Valtanen, M.; Koivusalo, H.; Setala, H. A high resolution application of a stormwater management model (SWMM) using genetic parameter optimization. *Urban Water J.* **2013**, 10, 394-410, DOI:10.1080/1573062X.2012.739631
31. Moszkowicz, S.; Tuszyńska, I. *Meteorologia radarowa. Podręcznik użytkownika informacji radarowej IMGW (Radar Meteorology. IMGW Radar Information User's Manual)*; Instytut Meteorologii i Gospodarki Wodnej: Warszawa, Poland, 2006. (In Polish)
32. Marshall, J.S.; Palmer, W.McK. The distribution of raindrops with size. *J. Meteorol.* **1948**, 5, 165-166, DOI:10.1175/1520-0469(1948)0052.0.CO;2.
33. Morin, E.; Krajewski, W.F.; Goodrich, D.C.; Gao, X.; Sorooshian, S. Estimating Rainfall Intensities from Weather Radar Data: The Scale-Dependency Problem. *J. Hydrometeorol.* **2003**, 4, 782-797, DOI:10.1175/1525-7541(2003)004<0782:ERIFWR>2.0.CO;2.
34. Battan, L.J. *Radar Observations of the Atmosphere*; The University of Chicago Press: Chicago, USA, 1973, DOI:10.1002/qj.49709942229.
35. Smith, J.A.; Krajewski, W.F. A modeling study of rainfall rate-reflectivity relationships. *Water Resour. Res.* **1993**, 29, 2505-2514, DOI:10.1029/93WR00962.
36. Chumchean, S. Improved Estimation of Radar Rainfall for Use in Hydrological Modelling. PhD Thesis, University of New South Wales, Sydney, 2004.
37. Nash, J.E.; Sutcliffe, J.V. River flow forecasting through conceptual models. Part I: a discussion of principles. *J. Hydrol.* **1970**, 10(3), 282-290, DOI:10.1016/0022-1694(70)90255-6.
38. Moriasi, D.N.; Arnold, J.G.; Van Liew, M.W.; Bingner, R.L.; Harmel, R.D.; Veith, T.L. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the ASABE* **2007**, 50, 885-900.
39. Emmanuel, I.; Andrieu, H.; Tabary, P. Evaluation of the new French operational weather radar product for the field of urban hydrology. *Atmos. Res.* **2012**, 103, 20-32, DOI:10.1016/j.atmosres.2011.06.018.
40. Gires, A.; Tchiguirinskaia, I.; Schertzer, D.; Schellart, A.; Berne, A.; Lovejoy, S. Influence of small scale rainfall variability on standard comparison tools between radar and rain gauge data. *Atmos. Res.* **2014**, 138, 125–138, DOI:10.1016/j.atmosres.2013.11.008.
41. Libertino, A.; Allamano, P.; Claps, P.; Cremonini, R.; Laio, F. Radar estimation of intense rainfall rates through adaptive calibration of the Z-R relation. *Atmosphere* **2015**, 6, 1559–1577, DOI:10.3390/atmos6101559.
42. Borup, M.; Grum, M.; Linde, J.J.; Mikkelsen, P.S. Dynamic gauge adjustment of high-resolution X-band radar data for convective rain storms: Model-based evaluation against measured combined sewer overflow. *J. Hydrol.* **2016**, 539, 687-699, DOI:10.1016/j.jhydrol.2016.05.002.

*Preprints* (www.preprints.org) | NOT PEER-REVIEWED | Posted: 1 June 2018 doi:10.20944/preprints201806.0006.v1

Peer-reviewed version available at *Water* **2018**, *10*, 1007; doi:10.3390/w10081007



43. Pauthier, B.; Bois, B.; Castel, T.; Thévenin, D.; Smith, C.C.; Richard, Y. Mesoscale and local scale evaluations of Quantitative Precipitation Estimates by Weather Radar Products during a heavy rainfall event. *Advance in Meteorology* **2016**, Volume 2016, DOI:10.1155/2016/6089319.
44. Ramli, S.; Tahir, W. Radar Hydrology: New Z/R Relationship for Quantitative Precipitation Estimation in Klang River Basin, Malaysia. *Int. J. Environ. Sci. and Develop.* **2011**, 2, DOI:10.7763/IJESD.2011.V2.128.
45. Paz, I.; Willinger, B.; Gires, A.; Ichiba, A.; Monier, L.; Zobrist, C.; Tisserand, B.; Tchiguirinskaia, I.; Schertzer, D. Multifractal comparison on reflectivity and polarimetric rainfall data from C- and X-Band radars and respective hydrological responses of a complex catchment model. *Water* **2018**, 10(3), 269, DOI:10.3390/w10030269.
46. American Society of Civil Engineers (ASCE). Criteria for evaluation of watershed models. *J. Irrig. Drain. Eng.* **1993**, 119(3), 429-442, DOI:10.1061/(ASCE)0733-9437(1993)119:3(429).
47. Ozga-Zielińska, M.; Brzeziński, J. *Applied hydrology*; Wydawnictwo Naukowe PWN: Warszawa, Poland, 1997. (In Polish).
48. Winterrath, T.; Rosenow, W.; Weigl, E. On the DWD quantitative precipitation analysis and nowcasting system for real-time application in German flood risk management. In Proceedings of IAHS on Weather Radar and Hydrology, Exeter, UK, April 2011.
49. Löwe, R.; Thorndahl, S.; Mikkelsen, P.S.; Rasmussen, M.R.; Madsen, H. Probabilistic online runoff forecasting for urban catchments using inputs from rain gauges as well as statically and dynamically adjusted weather radar. *J. Hydrol.* **2014**, 512, 397-407, DOI:10.1016/j.jhydrol.2014.03.027.