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Original Research Article

EMPORAL AND SPATIAL VARIABILITY OF RAINFALL IN MODELLING OF STORMWATER OUTFLOWS

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A b s t r a c t

The article presents issues related to modeling of the rainfall-runoff phenomenon. As factors influencing the simulation results, the velocity and direction of precipitation relative to the drainage basin were indicated. The possibility of underestimating the cross-sections of rainwater channels as a result of overlapping rain wave directions and the dominant flow direction in the rainwater channel network was pointed out. The research results to date indicate a reduction in the symptoms of this phenomenon as the complexity of the channel network increases. The final verification was based on the actual catchment. Calculations were made using the Epa SWMM 5.1.013 software. The results are presented in a graphic form to illustrate the variability of stormwater outflow.

Keywords: drainage, modeling, runoff, storm water, SWMM

1. INTRODUCTION

Modern engineering practice requires the use of modern computational methods, primarily due to legal provisions. The use of computational methods taking into account the variability of precipitation over time for a catchment area of a significant area becomes standard. The use of software enabling the inclusion of the phenomenon mentioned allows to bring the simulation results obtained closer to real phenomena occurring in the catchment. The method of limiting

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intensities, which is often used in practice, allows quick and easy calculation to determine reliable rainwater flow rates [3, 4]. This method adopts an important and often far from the truth [4] assumption that the maximum flow rate in the considered channel cross-section will occur when the duration of rain is equal to the sum of flow times along the longest route and taking into account the time of field concentration on runoff from the catchment and channel retention time for triggering stormwater flow in the network. In the method of limiting intensities, it was also assumed that the rain begins and ends at the same time throughout the catchment. This means that it covers the entire basin under consideration and has a constant intensity at one time. This assumption is often made when hydrodynamic models are used. Simplification does not correspond to reality and may result in significant design errors [6]. It can also cause problems at the stage of implementing the hydrodynamic model, as many authors have shown. The issue of the impact of outflow variability, taking into account the spatial and temporal variability of precipitation, was discussed in the literature in addition to the already mentioned Dziopak and the Starzec [3], also other authors [2, 5, 7], mainly for very simplified systems. The aim of this study was to confirm the impact of spatial and temporal variability of precipitation on outflow via a sewer network for a system with side channels at various speeds of precipitation relative to the catchment. The results will be verified based on the real catchment model. All models were implemented using the Epa SWMM program [9], also used by other authors [3, 7, 8].

2. MATERIALS AND METHODOLOGY

The analysis was carried out in two stages. The simplified analysis using the symmetrical model catchment was the first to be carried out. A catchment area of 288 ha was adopted, divided into 72 partial catchments of 4 ha each. The catchment has a rectangular shape with a ratio of sides 2:1 and real dimensions: length 2400 m, width 1200 m [8]. The main collector consisting of six sections and seven nodes runs through the longer axis of the catchment. Four subcatchments were connected to each node except the outflow. Two symmetrically placed side channels are connected to each node of the main collector. Four unit catchments are connected to the initial computational nodes of the side channel.

The scheme of the catchment area together with the method of connecting partial catchments and the duct system is shown in Figure 1.

All sections of the main collector are run with an equal drop of 0.25%. Circular cross-section ducts with a diameter of 1000 ÷ 1400 mm were adopted (Figure 1).

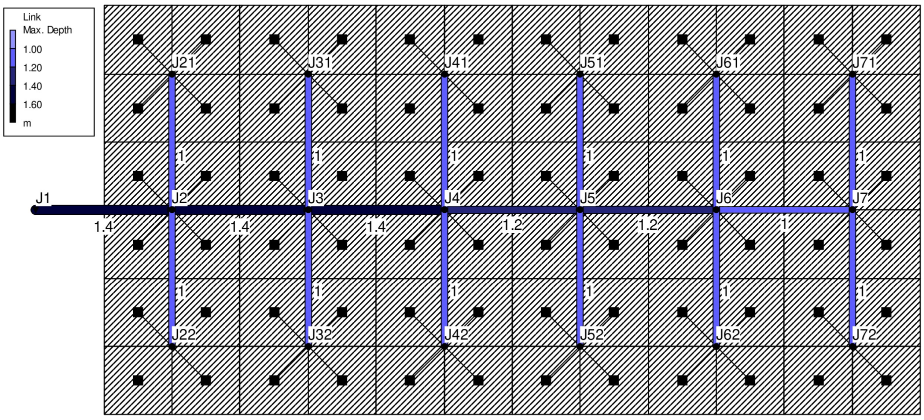

Fig. 1. Diagram of rainwater catchments - node designations and channel diameters

The sizes of the main collector sections were selected on the basis of flow rates obtained using a calculation variant in which precipitation occurs simultaneously in all partial catchments, so that there is no complete filling.

The side pipelines in the catchments were designed as channels with a diameter of 1000 mm and a slope of 0.25%. Similarly to the main collector, there is no full cross-section flow.

The hydraulic widths of the unit catchment were estimated using formula 2.1 [1]:

$$W = (F_i)^{1/2} \tag{2.1}$$

where:

- W is the width of the overland flow path [m];
- F_i - catchment area [ha].

The analysis was based on the following assumptions:

- Type II Euler model precipitation with a frequency of occurrence of F = 2 years (calculated rain according to PN-EN 752 [4]) and F = 3 years (for verification of overcurrent acc. to DWA-A118 [10]) was used. Model precipitation with a duration of t = 30 min was used in the paper. Model precipitation was developed on the basis of the Bogdanowicz-Stachý model [4] (Figure 2);
- a dynamic wave model was used with a time step of 60 seconds and a routing step of 30 seconds.

The calculations were carried out for two calculation variants:

- the rain wave travels along the main collector in the opposite direction to the flow of the main collector - J1-J7;

- the rain wave travels along the main collector in a direction converging to the direction of flow of the wave with the main collector - J7-J1.

In both cases rain velocity was taken into account equal to: 20, 50 i 100 m·min^{-1}.

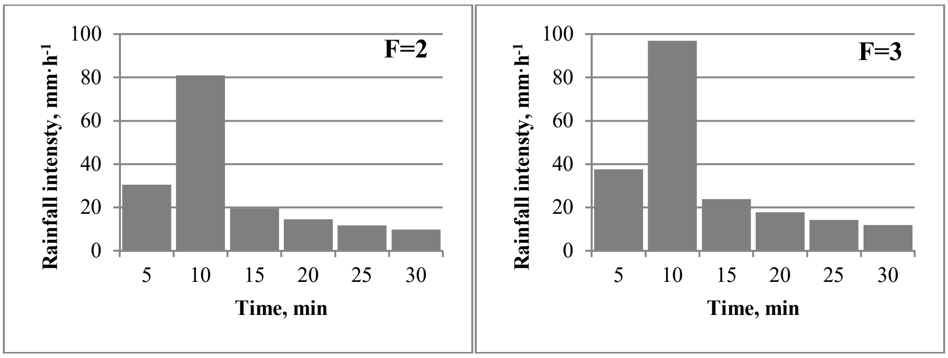

Fig. 2. Characteristics of model rainfalls (F – rainfall frequency in years)

In the second stage, calculations were carried out on the example of a real catchment with the following parameters:
- total catchment area - 71.2 ha;
- impervious catchment - 25.75 ha;
- number of partial drainage catchments - 86 with areas from 0.02 to 9.8 ha;
- number of computing nodes - 112;
- number of calculation conduits - 113 with diameters 0.4 to 1.0 m; locally there are 1,0x1.5 egg channels; the emergency overflow was made of pipes with a diameter of 0.15 and 0.2 m.

The spatial variability of precipitation has been taken into account by dividing the catchment into 13 zones (Figure 3) with a width of 200 m. Partial catchments have been assigned to the zone if most of its surface is within the area bounded by the zone's outline. A Raingage type object has been assigned to each zone. This allowed the simulation of precipitation from west to east. It is the dominant wind direction recorded during the year in the analyzed area. At the same time, the results of earlier simulations indicate the occurrence of the least favorable conditions in the case of a converging direction of rain wave movement and flow direction in the channel network. Two calculation variants were implemented taking into account Euler type II model precipitation (duration t = 30 min) with the following frequencies:
- F = 2 years (calculated rain according to PN-EN 752);
- F = 3 years (for verification of damming up according to DWA-A118).

In both cases, the calculations were made assuming that the rain wave travels from west to east, converging to the predominant direction of wave runoff by the main collector.

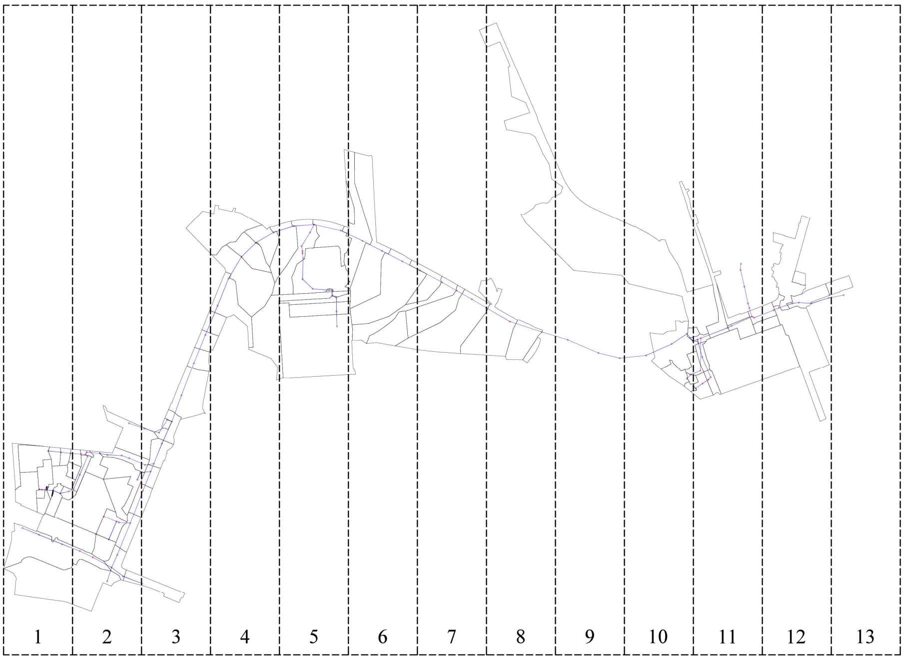

Fig. 3. Diagram of division of rainwater catchments into zones of extent of rain moving towards the west-east

3. RESULTS AND DISCUSSION

The results of the model catchment analysis in graphic form are presented in Figures 4 to 9. The presented data was limited to a full four hours, during which the majority of the runoff occurs through the sewage system.

For all calculation variants, the outflow from precipitation occurring simultaneously throughout the entire analyzed catchments was assumed as the comparative conditions.

In the case of the smallest speed of rain wave movement over the catchment, the maximum outflows from the catchment were significantly reduced in relation to the outflow obtained for uniform precipitation for the J1-J7 direction. For direction J7-J1, the maximum outflow is about 6-7% larger (Tables 1 and 2). The assumed 20 $m \cdot min^{-1}$ is a speed much lower than the flow velocity in the collector channels, therefore the differences are not significant.

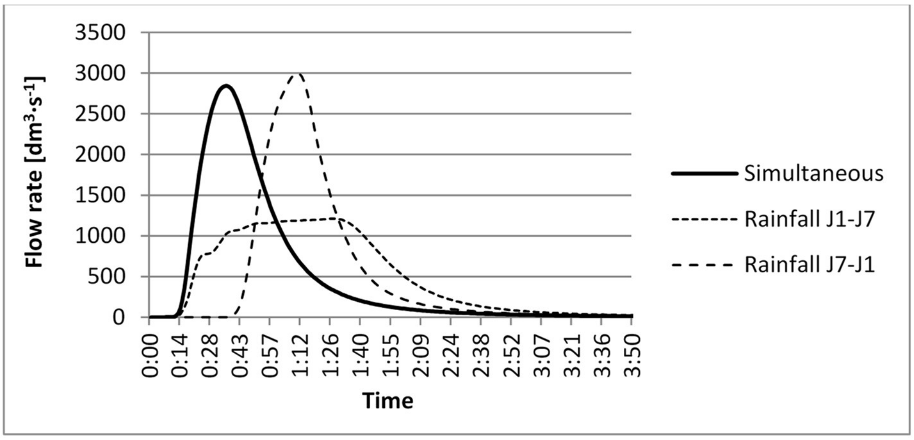

Fig. 4. Outflow from the catchment - rain wave speed 20 m·min^{-1} - rainfall frequency F = 2 years

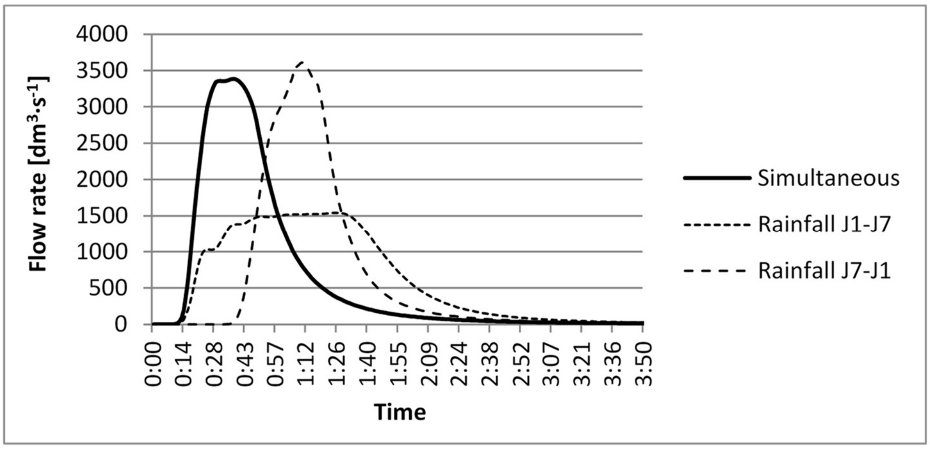

Fig. 5. Outflow from the catchment - rain wave speed 20 m·min^{-1} - rainfall frequency F = 3 years

In the case of the speed of movement of the rain wave over the catchment equal to 50 m·min^{-1}, the maximum outflows from the catchment were also significantly reduced in relation to the outflow obtained for uniform precipitation for the direction J1-J7. For direction J7-J1, the maximum outflow is approximately 12-16% larger (Tables 3 and 4). The assumed 50 m·min^{-1} is lower than the flow velocity in the collector channels. Failure to consider the impact of an increase in the maximum drain may cause local overflow of some of the channels.
In the case of the speed of movement of the rain wave over the catchment equal to 100 m·min^{-1}, the maximum outflows from the catchment were also

significantly reduced in relation to the outflow obtained for uniform precipitation for the direction J1-J7.

Table 1. Drainage intensity from the model catchments at a speed of 20 m·min^{-1}

Rainfall frequency F	Simultaneous	Rainfall J1-J7	Rainfall J7-J1
[years]	[dm^3·s^{-1}]		
2	2844.07	1211.79	2999.73
3	3384.50	1541.39	3610.84

Table 2. Percentage increase in the outflow intensity from the model catchments at a speed of 20 m·min^{-1}

Rainfall frequency F	Rainfall J1-J7	Rainfall J7-J1
[years]	[%]	
2	-57.39	5.47
3	-54.46	6.69

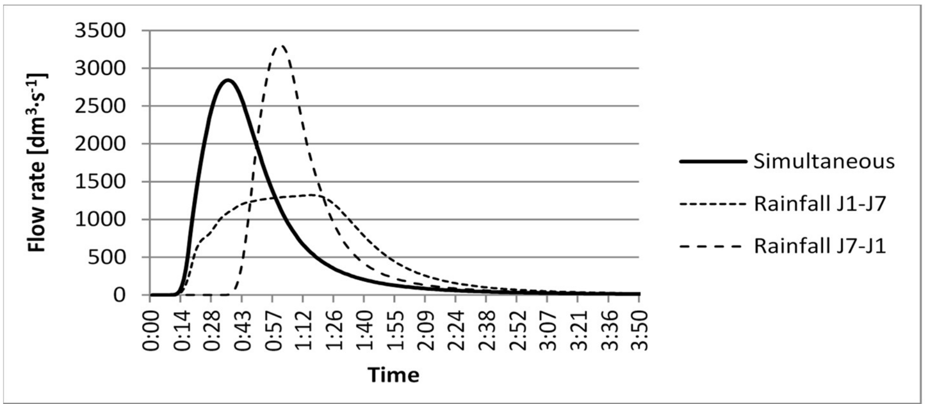

Fig. 6. Outflow from the catchment - rain wave speed 50 m·min^{-1} - rainfall frequency F = 2 years

For direction J7-J1, the maximum outflow is approximately 10-20% larger (Tables 5 and 6). The assumed 100 m·min^{-1} is similar to the flow velocity in the collector channels, and the increase in the maximum outflow value may cause local overflow of some channels and in extreme cases local flooding of the catchment area.

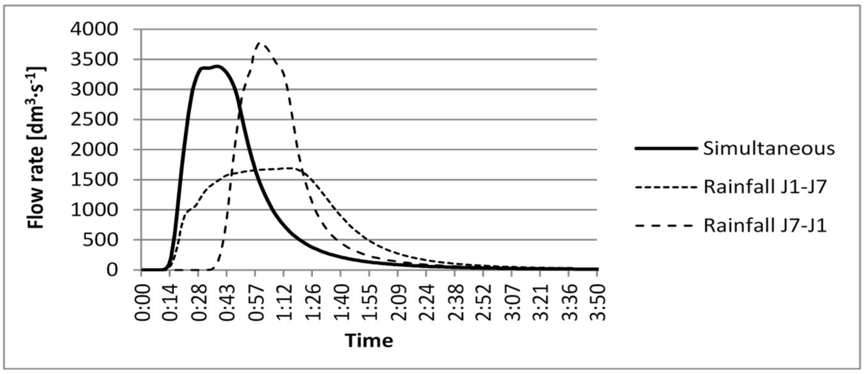

Fig. 7. Outflow from the catchment - rain wave speed 50 m·min^{-1} - rainfall frequency F = 3 years

Table 3. Drainage intensity from the model catchments at a speed of 50 m·min^{-1}

Rainfall frequency F	Simultaneous	Rainfall J1-J7	Rainfall J7-J1
[years]	[dm^3·s^{-1}]		
2	2844.07	1321.93	3313.76
3	3384.5	1690.97	3788.47

Table 4. Percentage increase in the outflow intensity from the model catchments at a speed of 50 m·min^{-1}

Rainfall frequency F	Rainfall J1-J7	Rainfall J7-J1
[years]	[%]	
2	-53.52	16.51
3	-50.04	11.94

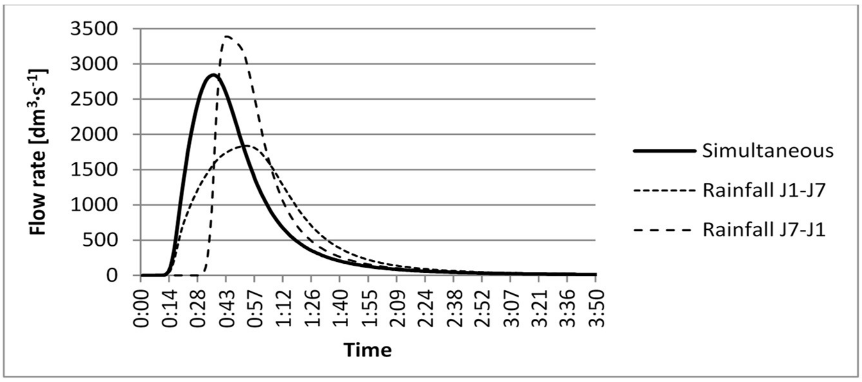

Fig. 8. Outflow from the catchment - rain wave speed 100 m·min^{-1} - rainfall frequency F = 2 years

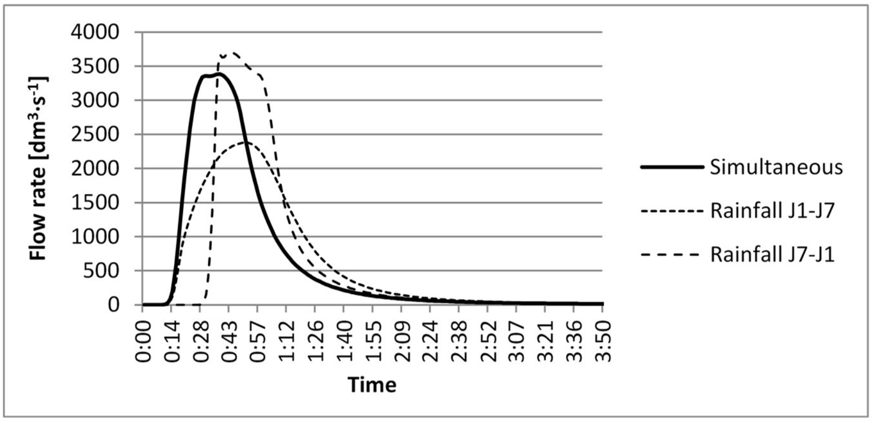

Fig. 9. Outflow from the catchment - rain wave speed 100 m·min^{-1} - rainfall frequency F = 3 years

Table 5. Drainage intensity from the model catchments at a speed of 100 m·min^{-1}

Rainfall frequency F	Simultaneous	Rainfall J1-J7	Rainfall J7-J1
[years]	[dm^3·s^{-1}]		
2	2844.07	1838.25	3389.35
3	3384.5	2378.54	3701.89

Table 6. Percentage increase in the outflow intensity from the model catchments at a speed of 100 m·min^{-1}

Rainfall frequency F	Rainfall J1-J7	Rainfall J7-J1
[years]	[%]	
2	-35.37	19.17
3	-29.72	9.38

The analysis carried out on the basis of the model catchment confirmed the choice of direction J7-J1, in which the directions of movement of the rain wave is close to the dominant direction of flow in the channel network. Therefore, the analysis of the actual catchment only takes into account the west-east direction taking into account the mentioned relationship.

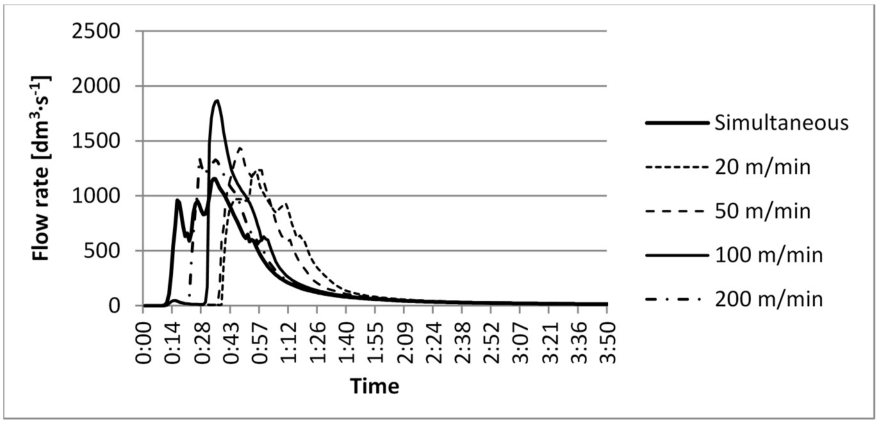

Fig. 10. Outflow from real catchment - rainfall frequency F = 2 years

Table 7. The outflow intensity from the real catchment as a function of rain wave speed

Rainfall frequency F	Simultaneous	20 $m \cdot min^{-1}$	50 $m \cdot min^{-1}$	100 $m \cdot min^{-1}$	200 $m \cdot min^{-1}$
[years]	[$dm^3 \cdot s^{-1}$]				
2	1153.91	1226.08	1434.09	1866.30	1351.05
3	1544.06	1565.60	1744.60	2148.38	1739.81

Despite the increase in the complexity of the sewage system, the adverse impact of spatial and temporal variability of rain is greater than in the case of the model catchment. In the range of speed of rain wave movement from 50 to 200 $m \cdot min^{-1}$, the impact is so significant that the designed or analyzed rainwater drainage systems should be checked for the impact of spatial and temporal rain variability on the hydraulic load of the channel network.

Table 8. Percentage increase of the outflow intensity from the real catchment as a function of rain wave speed

Rainfall frequency F	20 $m \cdot min^{-1}$	50 $m \cdot min^{-1}$	100 $m \cdot min^{-1}$	200 $m \cdot min^{-1}$
[years]	[%]			
2	6.25	24.28	61.74	17.08
3	1.40	12.99	39.14	12.68

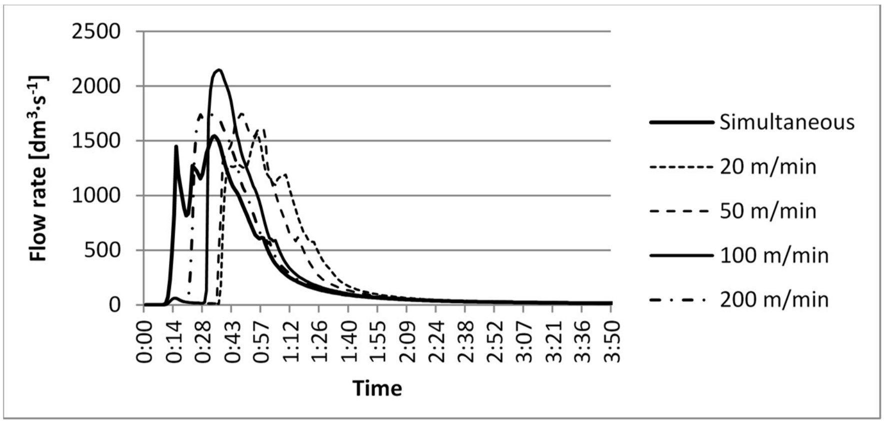

Fig. 11. Outflow from real catchment - rainfall frequency F = 3 years

The impact of the accumulation of the outflow wave in the rainwater network may be the reason for the occurrence of local flooding of the catchment area in the event of precipitation with an intensity that is usually considered safe. Such precipitation (usually with a larger range) usually occurs in combination with a warm front or occlusion front with a warm front character. Lower temporary intensity of precipitation causes outflows in such specific conditions similar to those observed during torrential precipitation.

4. CONCLUSION

As a result of the analysis it was confirmed that the intensity at the outflow increased for specific conditions in relation to the assumed largest outflow for even precipitation. This increase can be as much as 60% of the comparative outflow, usually used in practice. Regardless of the method used, both traditional and based on hydrodynamic modeling, there is a significant probability of occurrence of flows exceeding the values estimated using a simplified solution. Failure to consider the analyzed phenomenon may result in local flooding in potentially non-threatened areas. The literature pointed out that in the event of complications of the drainage system, the differences presented will be blurred. The simulation results obtained do not confirm this thesis. A computational example based on a real catchment is proof that the simplified conditions used at the design stage can lead to a situation where local flooding occurs despite the theoretically correct implementation of the investment. It should be stated that one of the conditions for safe dimensioning of storm water drainage is checking the correct operation of the designed or analyzed network in the conditions of spatial and temporal variability of model precipitation.

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