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ORIGINAL ARTICLE

Analysis of the impact of the degree of catchment sealing on the operation of drainage system

Anna Musz-Pomorska[1] · Marcin K. Widomski[1]

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Abstract

With increasing sealing of the catchment surface, the time of outflow of water from the catchment decreases and the volume of surface water flowing out increases. This phenomenon has a negative impact on the water balance of the catchment area, and results in an increase in the frequency of flooding, related to inability of the existing drainage systems to collect the surface waters. This paper presents the results of modeling of hydraulic conditions in a selected part of the storm sewage system. The US EPA's software SWMM 5 was applied to our studies. Three different rainfall events of various intensity and time and variable sealing degree of the catchment surface were studied in our research. The conducted simulation tests enabled the analysis of the sewage flow rate, the canals filling height as well as assessment of the impact of changing the degree of surface sealing on the amount of rainwater discharged and the frequency of outflows.

Keywords Stormwater drainage system · SWMM · Quantitative analysis of rainwater · Sealing the catchment area

Introduction

Development of infrastructure (construction of shopping center, services, parking lots, street and pavements) in urbanized regions triggers increase in sealing degree of surfaces and significantly affects changes in the water balance of catchment. According to water balance equation some part of precipitation intercepted by green cover and retained by soil is subsequently being evaporated (process of evapotranspiration). Another part of surface water may infiltrate groundwater in deeper aquifers. The increase in catchment surface sealing limits bioretention and infiltration, thus, increases the surface runoff and shortens the time of surface run off (Yang et al. 2018; Chen et al. 2015; Hammond et al. 2015; Słyś and Stec 2012; Qin et al. 2013). Additionally, during recent years, according to climate changes, the significant increase in number of extreme climatic event has been observed, i.e., storms of short duration but significant height. The existing stormwater systems are commonly unable to intercept the increased surface run off from the urbanized catchment, which leads to overflow of the pipelines and numerous flooding events, exceeding the acceptable flooding frequency (Arnbjerg-Nielsen et al. 2013; Morris et al. 2017; PN-EN 752. 2008; Kotowski and Kaźmierczak 2010; Rubinato et al. 2013; Jacobson 2011; Michalczyk et al. 2016).

The increased problem of flooding from the existing stormwater management systems triggers research of methods allowing to reduce this adverse phenomenon (EPA SWMM 2004; Rossman 2009; Burger et al. 2014). The software allowing hydrodynamic numerical modeling of stormwater systems may be a useful tool. Freely or commercially available models (e.g., SWMM, Hykas, Hystem-Extran, Mike Urban) allow calculations of operational conditions of stormwater network under the real actual conditions, as well as, for different hypothetic rainfall events. The hydrodynamic models of storm management systems performance under different conditions allow application of space and time variable real surface run off intensity and variable, unsteady stormwater flow inside the system (Rossman 2009; Park et al. 2009; Laouacheria et al. 2019; Haris et al. 2016; Hasan et al. 2019; Chen and Adams 2005; Kaźmierczak and Kotowski 2012; Rabori and Ghazavi 2018; Gülbaz and Kazezyılmaz-Alhan 2017; Szeląg et al. 2015; Bisht et al. 2016; Jiang et al. 2015; Junaidi et al. 2018).

This paper presents results of modeling studies of hydraulic conditions of stormwater flow inside the selected section of municipal drainage system. Numerical calculations were

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✉ Anna Musz-Pomorska
a.musz-pomorska@pollub.pl

[1] Faculty of Environmental Engineering, Lublin University of Technology, Nadbystrzycka, 40B, 20-618 Lublin, Poland

performed in SWMM 5 software under the assumptions of changes in catchment surface sealing as well as variable height and duration of rainfall. The performed simulation studies allowed analyses of stormwater flow velocity inside the pipelines, pipes filling height as well as assessment of increased surface sealing influence on volume of intercepted stormwater and frequency of surface flooding.

Materials and method

Object of study

The studied urbanized catchment is localized in Chelm, Poland and covers the Dyrekcja Dolna district (see Fig. 1). The total area of selected basin equals 17.83 ha and consists mainly, in approx. 70%, of industrial area. The remaining area is occupied by single-family housings. Stormwater from the area of studied catchment is delivered to the Uherka River.

The total length of pipelines in the studied segment of the network is equal 4019 m, from which 60.6% are network pipelines and 39.4% households connections. This network utilizes concrete pipes of diameters from range 250–1200 mm. The largest part are 1200 mm pipes, 1222 m (50%), while the smallest share are 300 mm pipelines, 225 m (9%). The remaining diameters, i.e., 250, 400 and 800 mm constitute 10%, 19% and 12% of network total length, respectively. The percentage share of particular diameters in the total length of the network is presented in Fig. 2. The pipelines layout of the studied network (see Fig. 3) is directly related to the spatial development of the urbanized area. The typical linear system of stormwater collectors with four branches was applied. The diameter 250 mm was in agreement with biding law during construction of the network, in the last decades of the XXth century. Nowadays, since 2003 according to biding Polish guidelines, the minimal allowed diameter of stormwater pipeline is 300 mm (PN-EN 752. 2008; Płuciennik and Wilbik 2003).

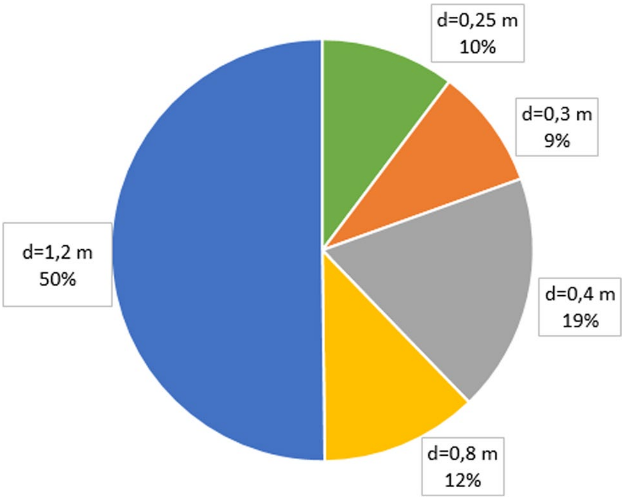

Fig. 2 Percentage of each pipe diameters in the total network length

Hydraulic model

The numerical model of studied section of stormwater management network was prepared in SWMM 5 computational software, developed and distributed by EPA, USA (EPA SWMM 2004).

The studied basin was divided on 153 subcatchments, characterized by the similar degree of surface sealing and slope. For separate subcatchments the runoff strip width (*W*) was determined using Eq. (1) (Rossman 2009). The increased width of runoff strip results in increase in runoff, while with the decreased values of parameter W, the surface runoff from the catchment area would cease.

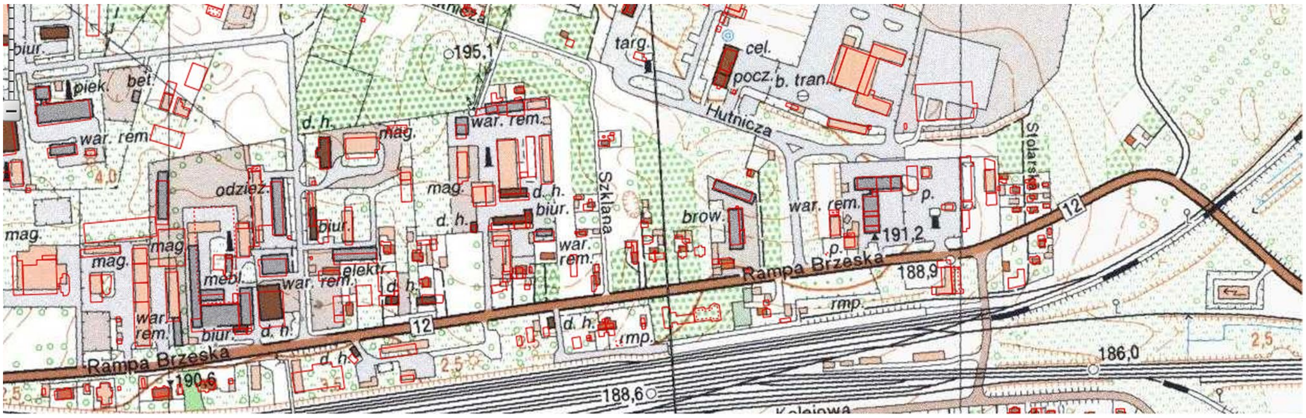

Fig. 1 Spatial development of the studied area (http://www.umchelm.bip.lubelskie.pl. xxxx)

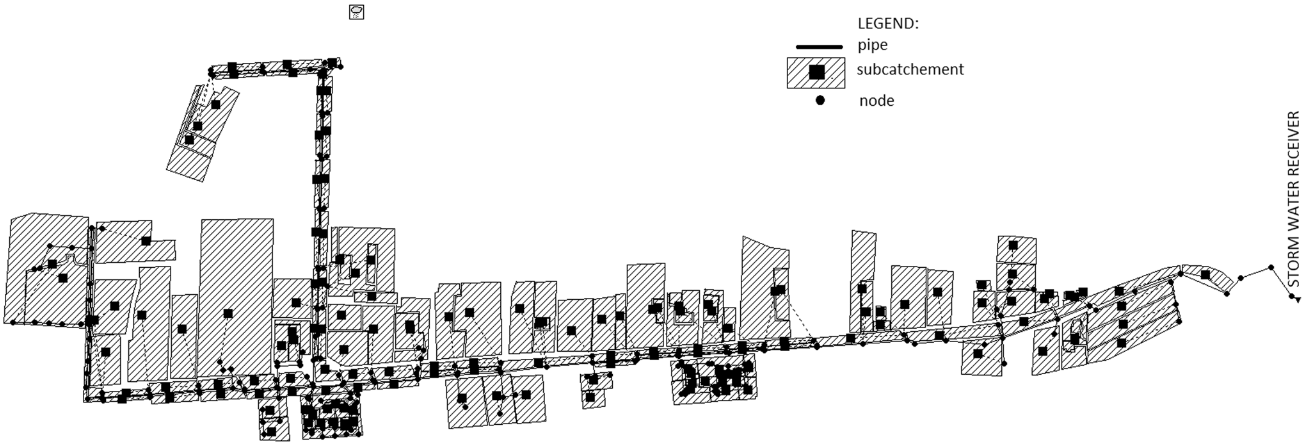

Fig. 3 Scheme of developed model (Wolska 2019)

$$W = \frac{A_{\mathrm{red}}}{L_d} \tag{1}$$

where A_{red}– reduced catchment area [m2], Ld – calculation length of flow path from partial catchment area [m].

The physical characteristics of pipes and nodes, such as pipeline material, diameter, inclination and depth were assumed after the data available in the technical design of the studied network. Due to lacking results of the direct measurements, values of roughness coefficient were assumed as provided by the pipelines producers. The characteristics of catchment were determined using the network technical design and orthophotomap. The orthophotomap was also used for particular subcatchments to determine the percentage share of surface on which surface retention does not occur.

The developed model (Wolska 2019), presented in Fig. 3, consisted of 205 lines, 205 nodes and one stormwater receiver.

Detailed parameters, covering i.e., slope inclinations, infiltration ratio values, Manning's roughness coefficients as well as retention characteristics of the investigated catchment are presented in Table 1.

The following formula was accepted in the model to determine the outflow value (Rossman 2009):

$$Q_o = W\frac{\left(d - d_p\right)^{5/3}}{n} i^{0.5} \tag{2}$$

where Qo—rainwater outflow from the catchment [m^3/s], W—hydrologic width of runoff stripe [m], n—roughness coefficient according to Manning for the particular surface [s/m$^{1/3}$], d—depth of runoff stream [m], d_p—depth of surface retention [m], i—subcatchments surface slope inclination [%].

Table 1 Parameters of catchment

Parameter	Unit	Value	
Catchment slope	[%]	0.1–15.5	
Catchment width	[m]	2.57–97.1	
Minimal infiltration ratio	[mm·h−1]	0.5*1	4.0*^{2}
Maximal infiltration ratio	[mm·h−1]	3.0*1	25*2
Infiltration intensity ratio	[h−1]	4*	
Manning's roughness for impervious surface	[−]	0.012*	
Manning's roughness for pervious surface	[−]	0.15*	
Retention depth for impervious surface	[mm]	0.5*	
Retention depth for pervious surface	[mm]	2.0*	

*Data assumed after the literature, (Rossman 2009), ^{1}—values for an impermeable surface, ^{2}—values for a permeable surface (Zhu et al. 2020)

The numeric calculations in SWMM software were based on the dynamic wave model allowing the best mapping of the stormwater system real operation (Rossman 2009). This model includes: (i) pressure flow in stormwater pipelines, (ii) stormwater back-flows, (iii) possible stormwater retention inside the pipelines, (iv) local flooding.

The presented simulations were performed with the following assumptions: (i) outflow type OUTLET, the runoff is realized from both types of catchments, impervious and previous, directly to the stormwater system, (ii) infiltration of rainwater into soil according to Horton's model. The minimal and maximal values of infiltration ratio were assumed after the literature reports (Rossman 2009; Zhu et al. 2020) for each modeled surface sealing cover.

Table 2 Characteristics of accepted rainfall events (Musz-Pomorska et al. 2019; Chmielewska et al. 2013; Widomski et al. 2012)

Variant	Time duration of rainfall event [h]	Surface runoff [$dm^3 \cdot s^{-1} \cdot ha^{-1}$]	Total height of rain [mm]
Rainfall No. I	12.0	8.0	32.40
Rainfall No. II	1.5	80.0	43.60
Rainfall No. III	2.5	159.5	143.55

Three variants of rainfall event were applied to the performed studies, with different height and duration. Table 2 and Fig. 4 present characteristics of rainfall events used. Due to unavailable results of rainfall measurements for the tested catchment, the literature data for Chelm, Poland were used (Wolska 2019; Musz-Pomorska et al. 2019; Chmielewska et al. 2013; Widomski et al. 2012).

Taking into account that the studied network was built in the second half of XXth century and diameters of pipelines were selected basing of computational flow rates determined by Blaszczyk formula, the same formula was assumed to determine outflows in the model. Recent studies show, that Blaszczyk formula gives understates results, in relation to values observed in reality (Kotowski and Kaźmierczak 2010).

The presented analyses included influence of surface sealing change in the volume of flow inside the existing network, so two variants of calculations were assumed: A—analysis for real, actual share of surface, B—calculations for hypothetic increase in impervious surfaces area, due to development of urbanization. The assumed increase in sealed surfaces area, from 15 to 40% for particular subcatchments, included in variant B covered both, residential and industrial, zones. Table 3 presents area of particular types of surface sealing for both modeling variants, A and B, respectively.

Table 3 Area of particular types of surface sealing for both modeling variants, A and B, respectively

Sealing type	Sealing degree [%]	Variant A Area [ha]	Variant B Area [ha]
Asphalt	98	2.38	2.38
Roof	98	1.63	1.63
Pavement	80	3.46	4.84
Sidewalk	70	0.98	1.13
Green	3	3.37	1.35
Local soil	10	2.20	1.20
Semi-permeable	50	3.81	4.30

Taking into account that the presented modeling studies are based on the past observed rainfall events, for which no measurements results of runoff and stormwater volumetric flowrate in the pipelines are available, calibration of the developed model was impossible. Moreover, our studies present also the hypothetical scenario of stormwater outflow alter alerting the surface sealing. So, the presented results should be treated as preliminary but comparable to each other because the modeling assumptions were the same for both tested variants.

Results

Analysis of hydraulic conditions inside the pipelines was based on calculated values of velocity, volumetric flow rate and number of manholes endangered by flooding. The maximal stormwater flow rate was determined at 13:00, 13:30 and 14:30 for Variant I, II and III, respectively.

Tables 4 and 5 present results of numerical studies of hydraulic conditions inside the tested section of stormwater system for variable rainfall characteristics, for two types of catchments, actual and with increased area of impervious surfaces. Columns 3, 5, 7 give the number of pipes, while columns 4, 6, 8 show percentage share of the pipes.

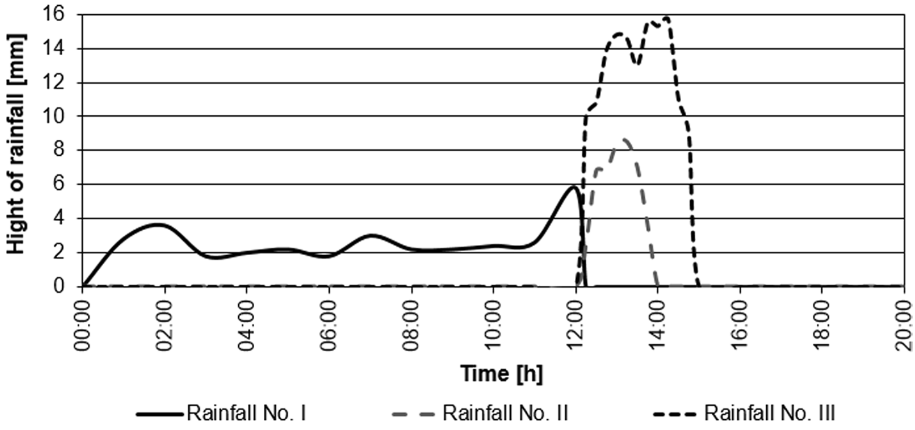

Fig. 4 Distribution of applied rainfall events in time

Table 4 Results of numerical calculations for different rainfall events – real catchment

Studied factor	Unit	Rainfall No. I		Rainfall No. II		Rainfall No. III	
1	2	3	4	5	6	7	8
Velocity of flow $v < 0.3$ [m·s^{-1}]	[number] [%]	76	37.3	41	20.1	26	12.7
Velocity of flow $0.3 < v < 0.6$ [m·s^{-1}]	[number] [%]	51	25.0	46	22.6	21	10.3
Velocity of flow $v > 0.6$ [m·s^{-1}]	[number] [%]	77	37.7	117	57.3	155	76
Number of manholes endangered by flooding	[number]	0		1		9	

Table 5 Results of numerical calculations for different rainfall events—catchment with an increased proportion of the sealed surface

Studied factor	Unit	Rainfall No. I		Rainfall No. II		Rainfall No. III	
1	2	3	4	5	6	7	8
Velocity of flow $v < 0.3$ [m·s^{-1}]	[number] [%]	73	35.8	42	20.6	20	9.8
Velocity of flow $0.3 < v < 0.6$ [m·s^{-1}]	[number] [%]	35	17.1	33	16.2	29	14.2
Velocity of flow $v > 0.6$ [m·s^{-1}]	[number] [%]	96	47.1	129	63.2	155	76
Number of manholes endangered by flooding	[number]	0		4		9	

The calculated values of velocity of flow indicate, than along with the increase in rainfall intensity the hydraulic conditions of flow improve and number of pipelines with velocity of self-purification (min 0.6 m·s^{-1} according to Polish guidelines) increases. In case of calculations performed for the real, actual catchment the calculated velocity of pipelines self-purification was observed in 37.7%, 57.3% and 76% pipelines, for Variant I, II and III, respectively. The same relation was observed at Variant B, after increase in sealed surfaces area the increased share of pipelines with velocity greater than 0.6 m·s^{-1} was observed. At the same time, along with increased rainfall intensity and share of area impervious surfaces, the increased threat of flooding from the stormwater system (Tables 4 and 5), for rainfall event number of endangered manholes increased to 4. Flooding for rainfall No II was observed for manholes installed on pipelines of diameter 200 mm (households connections). In case of rainfall even No III modeled flooding was observed for both, network pipes (250 mm) and households connection pipes (200 mm). Figure 5 shows selected profile of pipeline for which flooding from manholes occurs during rainfall event No II.

As it may be noted in pipelines profiles presented in Fig. 5, at the great part of pipe length stormwater flow is under pressure. Besides the manholes from which flooding may be expected, there are also visible chambers with highly elevated stormwater table.

Figure 6 presents distribution of time-related volumetric flow inside the final pipeline of the system for various variants of rainfall intensity for real, actual surface sealing as well as after the assumed increase in share of impervious surfaces area.

The obtained results of numerical calculations indicate increase in volumetric stormwater flow along with the increased share of sealed surface in the catchment. In case of rainfall events No I and II the maximal value of volumetric flow was observed at the same time for both tested scenario (unaltered and alerted surface sealing), whereas in case of rainfall No III, the increased share of impervious area caused shift of the stormwater flow peak 2 h earlier, in comparison to the actual, unaltered surface of the basin. The shape of curves representing stormwater flow in the final pipeline of the studied system is almost identical for rainfalls No II and III at both applied scenarios. The increase in volume of outflow from the catchment with increased share of sealed surface at the hour of maximal flow, in relation to the actual sealing, was observed. In case of rainfall No I the increased volumetric flow rate of stormwater from catchment with increased sealed area is visible for the opening hours of rain duration. The curves' shape is similar for the second phase of outflow, after the rainfall cease.

The maximal calculated value of volumetric stormwater flow for the real catchment reached the level of 161 dm^3·s^{-1}, 806 dm^3·s^{-1} and 2229 dm^3·s^{-1} for rainfall events I, II and III, respectively, while for the catchment with alerted degree of sealing the maximal calculated value of stormwater outflow equaled 181 dm^3·s^{-1}, 950 dm^3·s^{-1} and 2448 dm^3·s^{-1} for rainfalls No I, II and III, respectively. The highest increase in calculated volumetric stormwater outflow, reaching approx. 17.9%, was observed for rainfall No II characterized by the longest time duration (see Table 2).

Figure 7 presents time-related distribution of stormwater velocity of flow in pipeline delivering stormwater to the Uherka River.

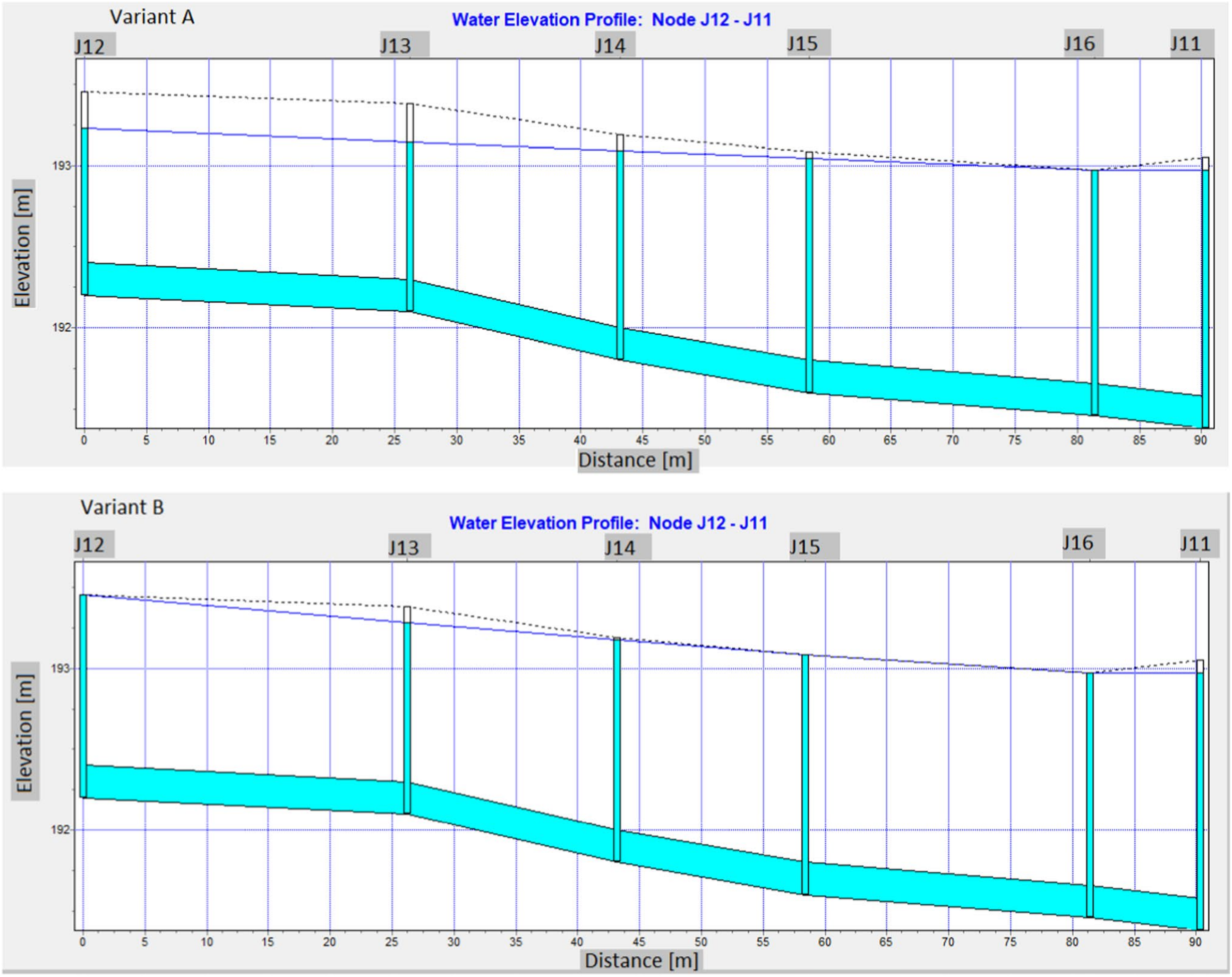

Fig. 5 Profile of the pipe section for rain No. II—variant A and variant B calculations

The maximal calculated velocity of flow in the final pipeline, determined for both applied types of catchment were 2.84 m·s^{-1} and 2.87 m·s^{-1}, 4.6 m·s^{-1} and 4.67 m·s^{-1}, 6.13 m·s^{-1} and 6.1 m·s^{-1} for rainfall events I, II and III, respectively. The maximal calculated capacity of final pipeline, determined for both applied types of catchment were 9% and 10%, 22% and 23%, 33% and 35% for rainfall events I, II and III, respectively. Despite the increased volumetric flow rate the observed changes in calculated velocity of flow and capacity of pipelines were inconsiderable. The maximal allowed velocity of flow, 7 m·s^{-1} for stormwater pipelines, was not exceeded in none of the tested variants (Kotowski and Kaźmierczak 2010).

The results of the presented studies are in agreement with the previous literature reports suggesting clear link between increase in urbanization of the catchment and changes in runoff and stormwater characteristics (Musz-Pomorska et al. 2019; Chmielewska et al. 2013; Widomski et al. 2012). Numerical studies of urbanization impact on stormwater runoff for city of Swinfon, UK and period 1960–2010 showed that increase in total impervious area from 32 to 46% resulted in increase in the peak flow from 0.76 to 1.12 m^{3}·s^{-1} for the same representative modeled rainfall event (Miller et al. 2014). The increase in build-up area in Xiamen, China, from 14.2 to 27.9%, during the period 1980–2015 caused approx. 98% increase in runoff volume (Shrestha et al. 2021). The similar results were also reported for selected urbanized catchments in Beijn, China by Yao et al. (Yao et al. 2017) and Hu et al. (2020) where influence of land use changes and development of urbanization affected total runoff volume in its maximal peak value was observed. The linear relation between rainfall magnitude and modeled runoff volume from increased sealed cover was also noted for City of Espo, Finland (Guan et al. 2016). Finally, the

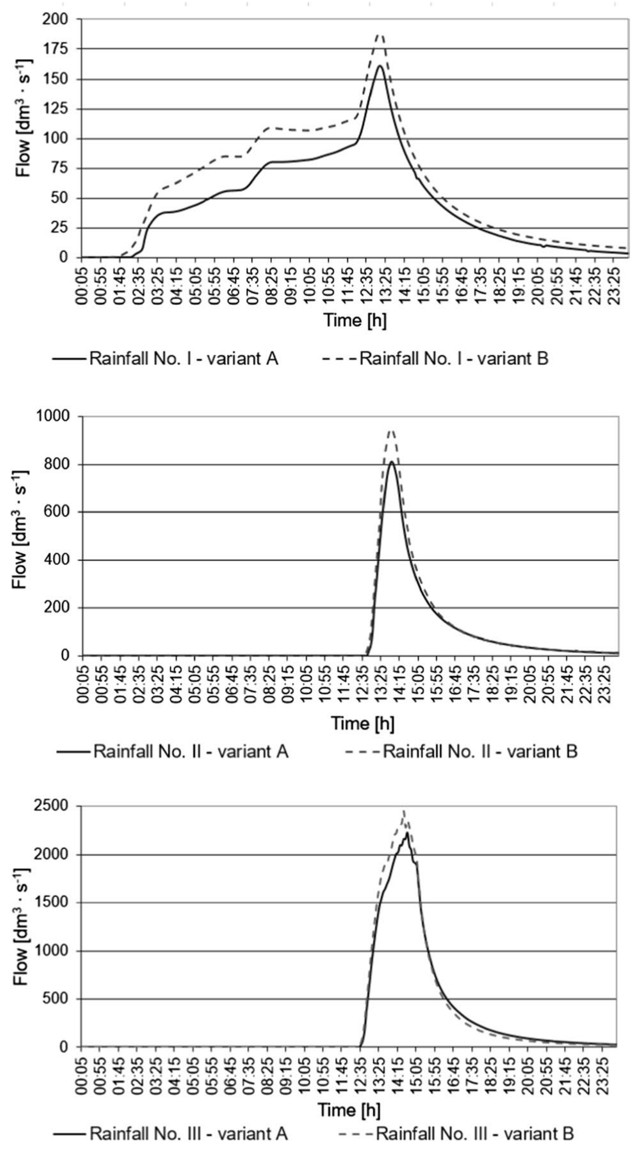

Fig. 6 Flow distribution change in time for different variants of rain for the real surface and after the surface change

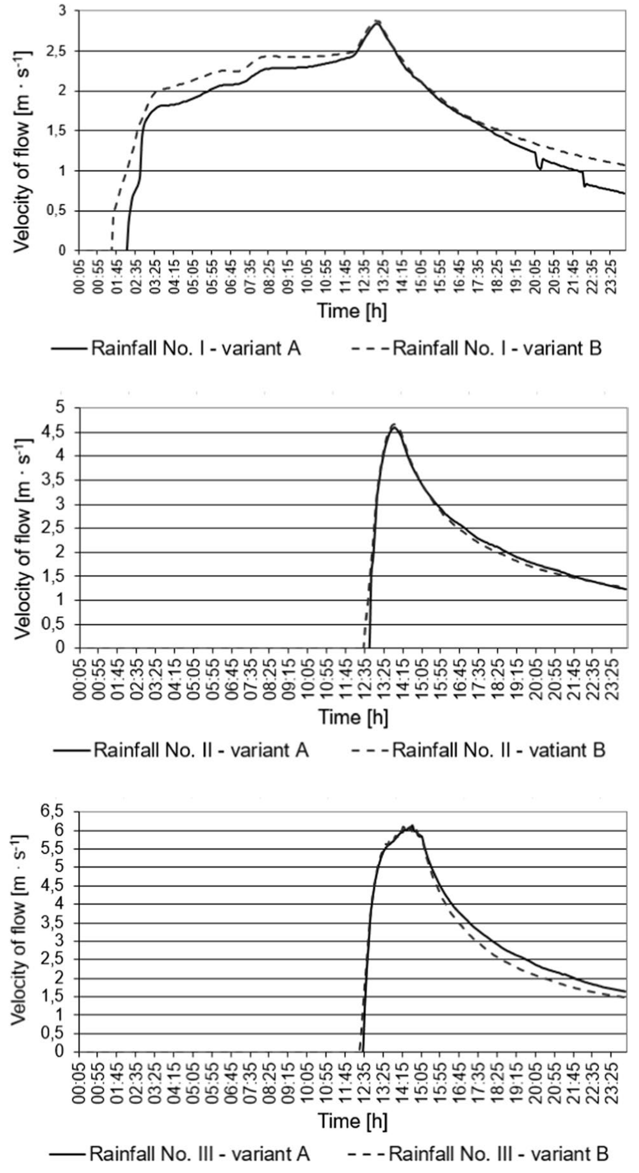

Fig. 7 Velocity of flow change in time for different variants of rain for the real surface and after the surface change

modeling studies concerning possible development of the existing stormwater system in Chelm, Poland (Widomski et al. 2012; Michalczyk et al. 2016) resulting in increased area of impervious surfaces also showed increased runoff volume.

Conclusions

The performed numerical calculations of hydraulic conditions inside the selected part of stormwater system showed that the studied drainage system is unable to sustain possible rapid extreme rainfall events characterized by high intensity. This problem considers mainly pipelines of diameters below 300 mm. In case of rainfalls No II and III the modeled flooding and numerous elevated stormwater tables, even to the ground level, in many manholes were observed. During the increased rainfall intensity many pipelines operated under pressure. This disadvantageous situation was noted for both types of tested catchment surface sealing, the actual and with increased share of impervious area (variant B). Thus, the analyzed section of stormwater system requires modernization and adjustments of its diameters to the actual requirements of PN-EN 752:2008 (2008). As it was determined during the presented calculation, the further urbanization of the catchment, leading to the increase in the share of impervious area at catchment, triggers increased volume of run off outflow. The existing stormwater drainage systems may be unable to adequately collect and transport the increased stormwater volume, expected especially during extreme and rapid rainfall events.

Author contributions (optional: please review the submission guidelines from the journal whether statements are mandatory).

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Data availability The data were collected and analyzed primarily by us.

Code availability Not applicable.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Human and animal Right Not applicable

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