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APPLICATION OF NUMERICAL MODELING IN ANALYSIS OF THE OPERATION OF A STORM SEWAGE SYSTEM

ZASTOSOWANIE MODELOWANIA NUMERYCZNEGO W ANALIZIE PRACY FRAGMENTU SIECI KANALIZACJI DESZCZOWEJ

Abstract: The increase in area of paved surfaces in cities, in relation to the natural permeable areas, results in increased loads of pollutants transported by the storm sewage system directly to the natural receivers. Storm wastewater, as it was reported in literature, in dependence to the type of urbanized basin and manner of drainage, contains significant concentration of pollutants, mainly: Total Suspended Solids (*TSS*), Total Nitrogen (*TN*), Total Phosphorus (*TP*), heavy metals and oil derivatives. In accordance with the Water Framework Directive, in many European countries, the alternative methods of managing rain sewage are being developed, allowing retention and purification of storm water at the place of its formation. In the case of existing storm swage networks, the numerical analysis of hydraulic conditions and quantitative assessment of transported pollutants may support actions taken to protect the natural ecosystems against the exceeding the permissible concentrations of pollutants.

This paper presents the results of modeling of hydraulic parameters and quality conditions of storm wastewater in a selected part of the urban storm sewage system. The USEPA's (United States Environmental Protection Agency) software SWMM 5 was applied to our studies. Three different rainfall events of various intensity and time duration were studied in our research. The conducted simulation tests enabled the analysis of the sewage flow rate, the canals filling height as well as the concentrations and loads of *TSS, TP, TN* at the outlet from the sewage system to the receiver.

The results of the performed calculations showed that in the case of low-intensity rainfall, the unfavorable hydraulic conditions are present in the studied network. At the same time, the occurrence of storm event or extreme rainfall can lead to the flushing of deposits collected at the basin surface as well as at the bottom of pipes and the increase in loads of pollutants transported to the receiver.

Keywords: storm sewage system, Storm Water Management Model, quantitative and qualitative analysis of storm sewage

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Introduction

Development of cities related to the rapid development of their infrastructure leads to increase in share of sealed and paved surfaces which, in turn, causes the increased stream of surface runoff and accumulation of pollutants on the paved areas, resulting in greater load of pollutants discharged by drainage systems to the natural aquatic reservoirs [1–3]. The main pollutants included in surface runoff, in relation to the type of sealed surface from which they are being washed off, manner of operation and characteristics of rainfall event, are *TSS* (Total Suspended Solids), *TN* (Total Nitrogen), *TP* (Total Phosphorus), oil derivatives and heavy metals [4–8]. These pollutants transported by stormwater and entering the natural surface reservoirs affect their chemical and ecological conditions [9]. Literature suggests that 5 % increase in surface sealing degree of catchment causes negative changes in waterbodies, i.e. reduces their biodiversity (number and type of living organisms) [10]. The biding Polish statutory regulation considering conditions required for discharge of wastewater to water or soil and the substances particularly harmful for aquatic environments [11] defines only the permissible concentration of *TSS* (max. $100\ \mathrm{mg} \cdot \mathrm{dm}^{-3}$) and oil-derivative hydrocarbons (max. $15\ \mathrm{mg} \cdot \mathrm{dm}^{-3}$) in stormwater delivered to waterbodies and presents the minimal volume of surface runoff which should undergo treatment (max. $Q = 15\ \mathrm{dm}^3 \cdot (\mathrm{s} \cdot \mathrm{ha})^{-1}$).

Prediction of amount and quality of stormwater delivered to the waterbodies is a very complicated and difficult task, because of random characteristics of rainfall events As well as processes of buildup and washoff of pollutants gathered on the surface of catchment. Application of numerical modeling to quantitative and qualitative assessment of stormwater system operation, both at the stage of design and for real operational systems, may improve exploitation of network and allow undertaking actions allowing protection of the natural ecosystems by limiting the possibility of exceeding the allowable concentrations of pollutants by, i.e. the proper selection of stormwater treatment devices [12–16].

This paper presents results of modeling studies of hydraulic conditions and pollutants transport in the selected part of stormwater network. The numerical studies were performed in SWMM 5 (Storm Water Management Model) software with the assumption of variable characteristics of the selected rainfall events. Our studies allowed the analyses of stormwater flow velocity and height of pipe filling inside the system as well as calculations of concentrations and loads of *TSS*, and the outflow of the system to the receiver.

Materials and methods

Object of study

The studies concerning hydraulic conditions and quantitative and qualitative analyses of transported stormwater were performed for the urbanized catchment of area 89.6 ha located in the city of Chelm, Poland. The studied catchment covers the single-family housing of districts XXX-lecia and T. Kosciuszko as well as parts of Bazylany and Klin. The selected catchment covers area from which stormwater is delivered to the Uherka river (see Fig. 1).

Fig. 1. Spatial development of the studied catchment area [17]

The tested stormwater system consists mainly of concrete pipes, diameters from 150 mm at the house connections to 1700 mm at the main stormwater collector pipe.

Hydraulic model

Our numerical studies were performed in SWMM 5 computational software, by EPA, USA. The data required to build the model of network including materials, diameters and length of pipes and elevation of manholes were accepted after the geodesic map. The studied catchment was divided into 950 subcatchments (see Fig. 2), borders of which were determined using plans containing geodetic data of the studied terrain, type of urban development, routes of individual collecting sewers of the network and the main streets. The developed model consisted of 1100 nodes, 1099 pipelines and one discharge receiver (Fig. 2).

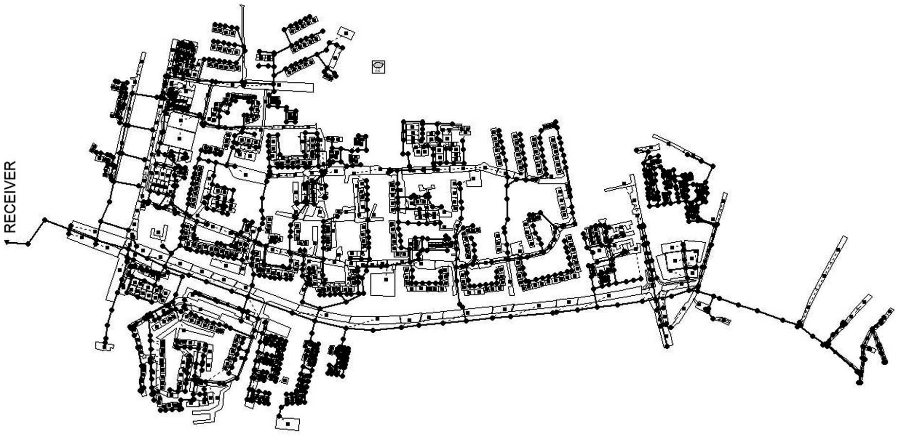

Fig. 2. Scheme of developed model

For separate subcatchments the runoff strip width (*W*) was determined using equation (1) [18]. The increased width of runoff strip results in increase of runoff, while with the decreased values of parameter *W*, the surface runoff from the catchment area would cease.

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

where: A_{red} – reduced catchment area [m^2]
L_d – calculation length of flow path from partial catchment area [m].

The remaining parameters of catchment are presented in Table 1.

Table 1

Parameters of catchment

Parameter	Unit	Value
Land slope	[%]	0.1–25
Runoff strip width	[m]	1.8–21.5
Minimum infiltration rate	[mm · h^{-1}]	0.5
Maximum infiltration rate	[mm · h^{-1}]	3.0
Infiltration intensity decay constant	[h^{-1}]	4
Manning coefficient for impermeable surfaces	[-]	0.012
Manning coefficient for permeable surfaces	[-]	0.15

There were three variants of calculations performed for the selected catchment, with different intensity and time duration of the applied rainfall (Fig. 3). The assumed

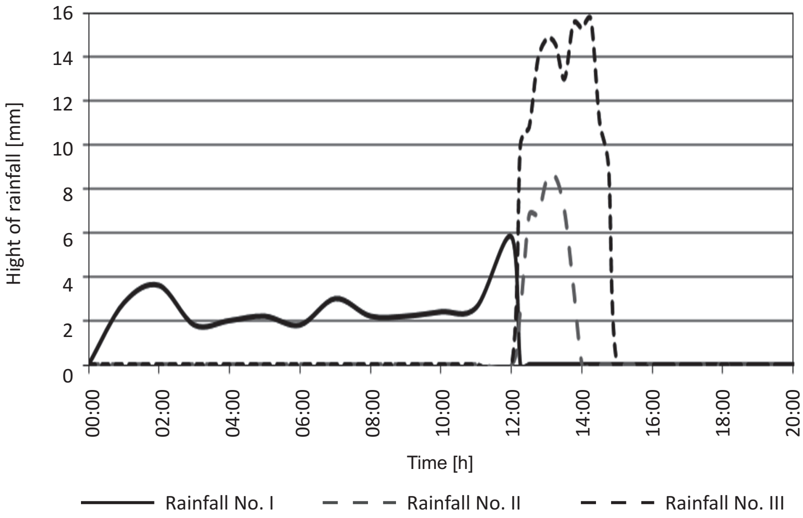

Fig. 3. Distribution of applied rainfall events in time

rainfall events were based on data previously reported by Widomski at al. [14] and measurements performed locally at Lublin University of Technology, Poland (see Table 2).

Table 2

Parameters of accepted rainfall events

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

Our studies considered the existing network, constructed in late nineties of last century for which computational rate of flow was based on the Blaszczyk's formula, which, according to recent knowledge, commonly results in underestimation of rainfall intensity [19]. Underestimation of rainfall output at the stage of network designing may results in numerous cases of stormwater flooding. According to PN-EN 752 [20] standard, flooding in the residential area shouldn't occur more often than once per 20 years.

The developed model of stormwater system was not calibrated because the necessary observations of volume and quality of precipitation water in the catchment as well as characteristics of the rainfall events were not performed.

Qualitative model

Our qualitative calculations were based on quality models available in SWMM 5, including equations of buildup and washoff of pollutants of the surface of the catchment. The exponentials models (2, 3) implemented into SWMM 5 [21–23] and *EMC* (4) (event mean concentration) based models were selected [16, 24, 25].

$$B = C_2(1 - e^{C_2 t}) \tag{2}$$

$$W = C_1 Q^{C_4} \tag{3}$$

$$EMC = \frac{\sum C_i Q_i}{\sum Q} \tag{4}$$

where: B – pollutant surface buildup concentration [$mg \cdot dm^{-3}$];
C_1 – maximal pollutant concentration [$mg \cdot dm^{-3}$];
C_2 – time required for reaching half of the maximal concentration of pollutant [d^{-1}];
t – time [d];
W – concentration of pollutant in surface runoff [$mg \cdot dm^{-3}$];

C_3 – washoff coefficient equal to EMC;
C_4 – the wash-off exponent [-];
Q – surface runoff volumetric flow rate $[\mathrm{dm}^3 \cdot \mathrm{s}^{-1}]$;
C_i – pollutant concentration $[\mathrm{mg} \cdot \mathrm{dm}^{-3}]$;
Q_i – rainfall water volumetric flow rate $[\mathrm{dm}^3 \cdot \mathrm{s}^{-1}]$.

The required input data, presented in Table 3, were assumed after literature studies [4, 14, 24–27] for two types of spatial development: residential (paved and asphalt areas, roofs) and undeveloped (green) including gardens, greenstones and grasslands.

Table 3

Input data applied to qualitative calculations

Type of catchment	Pollutant bildup		Pollutant washoff	
Residential area	*TSS*	$C_1 = 50\ \mathrm{mg} \cdot \mathrm{dm}^{-3}$, $C_2 = 2\ \mathrm{d}^{-1}$	*TSS*	*EMC* = 101
	TP	$58\ \mathrm{mg}TP \cdot \mathrm{kg}^{-1}TSS$	*TP*	*EMC* = 0.34
	TN	$550\ \mathrm{mg}TN \cdot \mathrm{kg}^{-1}TSS$	*TN*	*EMC* = 2.64
Undeveloped area	*TSS*	$C_1 = 100\ \mathrm{mg} \cdot \mathrm{dm}^{-3}$, $C_2 = 3\ \mathrm{d}^{-1}$	*TSS*	*EMC* = 70
	TP	$49\ \mathrm{mg}TP \cdot \mathrm{kg}^{-1}TSS$	*TP*	*EMC* = 0.12
	TN	$460\ \mathrm{mg}TN \cdot \mathrm{kg}^{-1}TSS$	*TN*	*EMC* = 1.51

Results

The performed analysis of hydraulic and quantitative conditions inside the selected part of stormwater system in Chelm was based on calculated values of flow velocity, height of pipe filling as well as on concentrations and loads of *TSS, N* and *P* at the outflow from the system to the receiver. The obtained results of numerical calculations for the applied different variants of rainfall events are presented in Table 4.

Table 4

Results of numerical calculations for different rainfall events

Studied factor	Unit	Rainfall event No. I	Rainfall event No. II	Rainfall event No. III
Flow velocity < 0.3 $[\mathrm{m} \cdot \mathrm{s}^{-1}]$	[%]	27.2	16.8	15.8
Flow velocity > 0.6 $[\mathrm{m} \cdot \mathrm{s}^{-1}]$	[%]	31.8	62.1	64.9
Number of chambers endangered by flooding	[-]	3	10	32
TSS max. concentration	$[\mathrm{mg} \cdot \mathrm{dm}^{-3}]$	128.00	114.20	123.22
TP max. concentration	$[\mathrm{mg} \cdot \mathrm{dm}^{-3}]$	0.43	0.37	0.40
TN max. concentration	$[\mathrm{mg} \cdot \mathrm{dm}^{-3}]$	3.39	2.99	3.23

The obtained results of numerical simulations showed that in case of rainfall event No. I in almost 70 % of pipelines the calculated velocity of flow was lower than required $0.6\ \mathrm{m} \cdot \mathrm{s}^{-1}$, but for over 27 % of pipelines velocity was lower even than

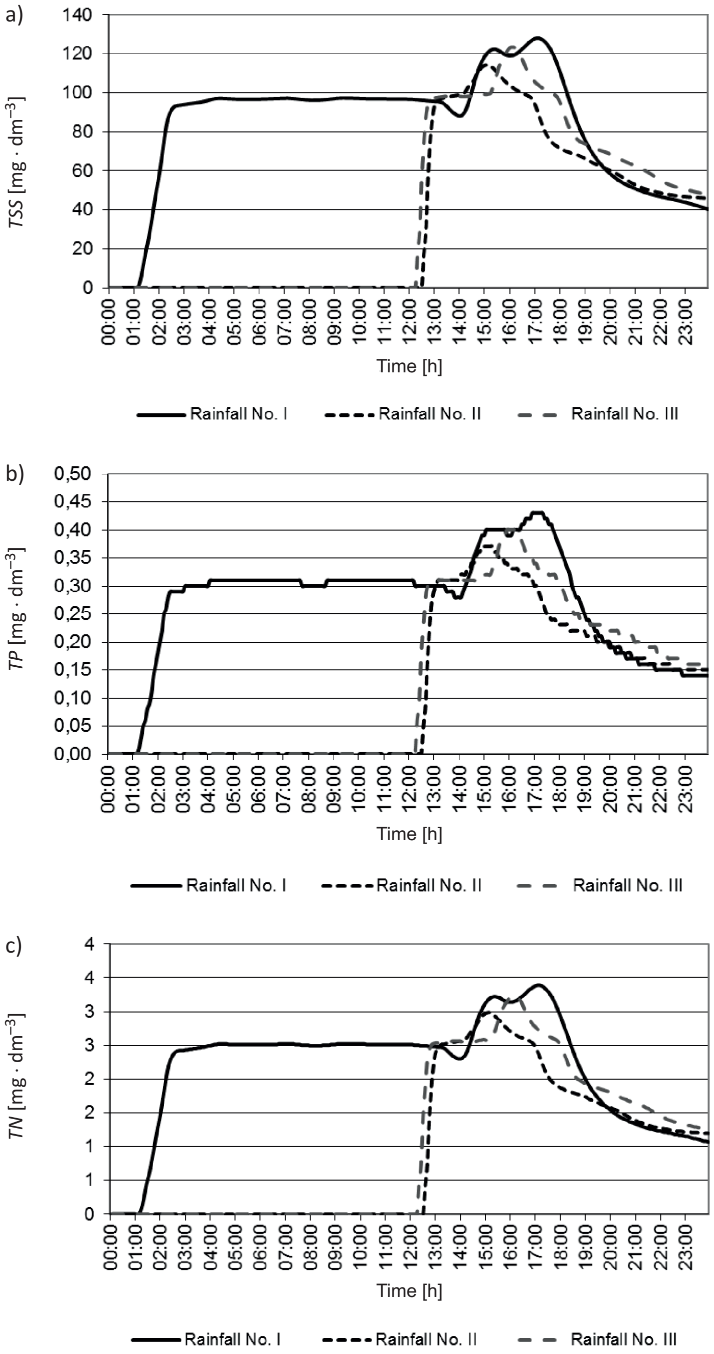

Fig. 4. Concentrations of a) *TSS*, b) *TP* and c) *TN* discharged to storm sewage receiver for different rainfall events

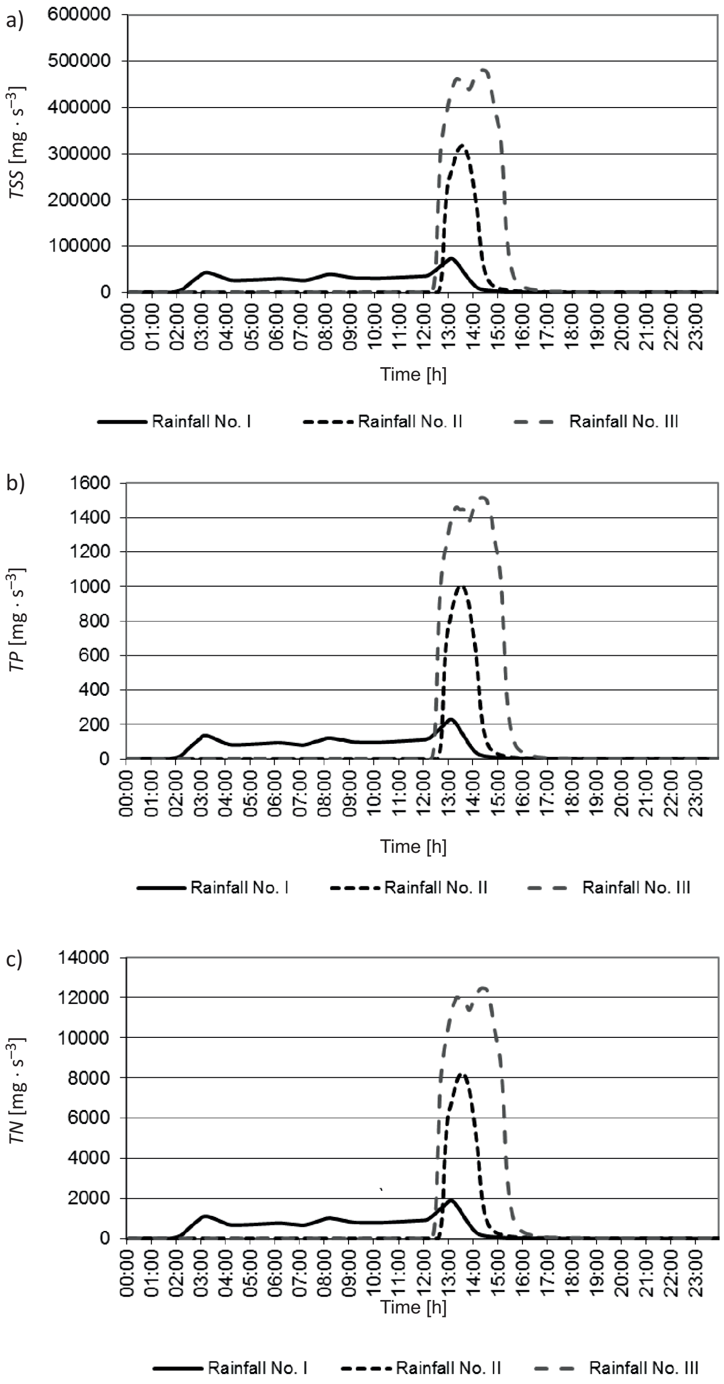

Fig. 5. Loads of a) *TSS*, b) *TP* and c) *TN* discharged to storm sewage receiver for different rainfall events

$0.3\ m \cdot s^{-1}$. The more favorable hydraulic conditions were observed for two remaining short-lasting rainfall events of greater intensity. For these cases (No. II and No. III) velocity of flow greater than $0.6\ m \cdot s^{-1}$ was noted in 62 % and 64 % pipelines, respectively. However, it was also observed that increase in rainfall height for shorter rainfall time duration results in increase in number of flooding cases, from 3 for rainfall No. I to 32 for rain No. III.

The presented results of *TSS* calculations (table 4) show the possible exceeding the allowable concentration of $100\ mg \cdot dm^{-3}$ [11] in water discharged to the waterbody of the receiver. The determined maximal concentrations of *TSS* were equal to $128.00\ mg \cdot dm^{-3}$, $114.20\ mg \cdot dm^{-3}$ and $123.22\ mg \cdot dm^{-3}$ for rainfall events I, II and III, respectively. The highest contravention of the required value, by 28 %, was noted for the rainfall No. I. According to the biding statutory requirements [11] the determined volume of surface runoff for the rainfall event No. I is lower than the required for the obligatory wastewater treatment, so, taking into account the significant increase in *TSS* concentration, it is advised to consider the additional treatment of wastewater before discharge to the receiver.

Figures 4 and 5 present results of qualitative studies covering concentrations and loads of modeled pollutants delivered from the network to the stormwater receiver.

The observed distribution of pollutants' concentrations and loads (Fig. 4 and 5) reflects the distribution of tested rainfall event (Fig. 3). The highest concentrations of *N* and *TP*, as fraction of *TSS*, were obtained for rainfall event I ($0.43\ mg \cdot dm^{-3}$ and $3.39\ mg \cdot dm^{-3}$, respectively). On the other hand, the lowest concentrations of all tested pollutants were determined for rainfall event II. Taking into account the intensity and height of tested rainfalls the highest loads of pollutants (Table 1) delivered to the receiver were noted for rainfall event III (Fig. 4).

The obtained results of pollutants concentrations are comparable to values reported in the literature for different regions, characterized by various structure and population. Taebi et al. [24] obtained the following values of concentrations in Siosepol, Iran: *TSS* 43–467 (mean 161) $mg \cdot dm^{-3}$, total nitrogen 1.22–22.35 (mean 6.65) $mg \cdot dm^{-3}$, total phosphorus 0.064–0.790 (mean 0.274) $mg \cdot dm^{-3}$. The research performed by Goonetilleke et al. [27] for a catchment localized in Australia showed the following values of concentrations: *TSS* $356.7\ mg \cdot dm^{-3}$, total nitrogen $1.9\ mg \cdot dm^{-3}$, total phosphorus $0.8\ mg \cdot dm^{-3}$.

Conclusion

The obtained results of numerical calculations showed that the unfavorable hydraulic conditions were observed in the studied stormwater system, designed with application of Blaszczyk's formula. The noted low values of velocity of flow in pipelines may result in increased deposition of sediments, significantly affecting conditions of flow and capacity of the system. On the other hand, appearance of torrential rainfalls may result in increased cases of flooding from the system. The performed qualitative analysis of stormwater at the outflow from the tested system to the Uherka river showed the possible exceeding of the allowable values of *TSS* concentration. The obtained results should induce to undertaking the actions aimed in improved protection of aquatic ecosystem of sewerage receiver by the proper selection of technology and devices of treatment. According to the lack of model calibration the presented studies should be treated as preliminary.

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ZASTOSOWANIE MODELOWANIA NUMERYCZNEGO W ANALIZIE PRACY FRAGMENTU SIECI KANALIZACJI DESZCZOWEJ

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Abstrakt: Wzrost udziału powierzchni utwardzonych w stosunku do naturalnych powierzchni przepuszczalnych miast powoduje wzrost ładunków zanieczyszczeń przenoszonych przez system kanalizacji deszczowej bezpośrednio do odbiorników. Ścieki deszczowe, jak wykazują badania literaturowe, w zależności od sposobu wykorzystania odwadnianej powierzchni zurbanizowanej przenoszą znaczne ładunki zanieczyszczeń, głównie zawiesiny ogólnej, metali ciężkich czy związków ropopochodnych. Zgodnie z Ramową Dyrektywą Wodną w wielu krajach europejskich podejmowane są działania mające na celu rozwój alternatywnych metod zagospodarowania ścieków deszczowych, umożliwiających ich zatrzymywanie i oczyszczanie w miejscu ich powstawania. W przypadku istniejących już sieci deszczowych numeryczna analiza warunków hydraulicznych oraz ocena ilościowa transportowanych zanieczyszczeń może wspomóc działania podejmowane w celu ochrony naturalnych ekosystemów przed wzrostem/przekroczeniem dopuszczalnych stężeń zanieczyszczeń. W pracy zaprezentowano wyniki badań modelowych warunków hydraulicznych oraz jakościowych transportowanych ścieków deszczowych w wybranym fragmencie sieci deszczowej. Badania przeprowadzono w programie SWMM 5 przy założeniu zróżnicowanego natężenia deszczu oraz czasu jego trwania. Przeprowadzone badania symulacyjne umożliwiły analizę prędkości przepływu ścieków, wysokości napełnienia ścieków w przewodach, a także stężeń i ładunków zanieczyszczeń zawiesiny ogólnej, fosforu i azotu na wylocie z układu kanalizacyjnego do odbiornika. Wyniki przeprowadzonych obliczeń wykazały, iż w sieci kanalizacji deszczowej w przypadku opadów o niewielkim natężeniu panują niesprzyjające warunki hydrauliczne. Jednocześnie występowanie deszczów burzowych czy ekstremalnych może prowadzić do wymywania osadów zgromadzonych na dnie przewodów i wzrostu zanieczyszczeń przenoszonych do odbiornika.

Słowa kluczowe: sieć kanalizacji deszczowej, SWMM, analiza ilościowa i jakościowa ścieków deszczowych