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NUMERICAL MODELING IN QUANTITATIVE AND QUALITATIVE ANALYSIS OF STORM SEWAGE SYSTEM EXTENSION

MODELOWANIE NUMERYCZNE W ILOŚCIOWEJ I JAKOŚCIOWEJ OCENIE MOŻLIWOŚCI ROZBUDOWY SIECI KANALIZACJI DESZCZOWEJ

Abstract: This paper presents the attempt of numerical modeling application to quantitative and qualitative analysis of storm-water sewer system extension in conditions of the selected urbanized catchment in city of Chelm, Poland. The USEPA's (United States Environmental Protection Agency) software SWMM 5 was applied to our studies. Three different rainfall events of various intensity and duration were studied in our research. Our calculations considered hydraulic operational conditions before and after attachment of new pipelines to the existing system. The presented analysis was based on sewage flow velocity, wastewater level along the pipelines and the load of pollutants leaving the sewer system. The visible changes in flow velocity, discharged loads of selected pollutants and sewage outflow from several join or inspection chambers were observed after development of the existing sewer system. Our studies reveals also the fact that the existing system, designed basing on Blaszczyk's formula is partially oversized, the velocity of pipes' self-purification was not assured in the some part of studied network. The quality of our observations may be reduced by the lack of model calibration.

Keywords: storm sewer, numerical modeling, network expansion, quantitative and qualitative analysis

Introduction

According to numerous problems, encountered even on the designing stage, resulting from increase of drainage area, surface runoff rate, storm water flow and loads of transported pollutants, development of existing municipal systems of storm water drainage may be treated as challenging and difficult engineering task [1].

Extension of existing storm water systems may in some cases led to improvement of hydraulic parameters of wastewater flow in drainage canals by ensuring the self-purification velocity of flow. This situation is possible due to the fact that in some

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existing storm water systems applied pipes diameters prevent autogenous pipes flushing by flowing storm sewage [2, 3].

Assumption of incorrect designing inputs during storm water network development may result in periodical water gathering in join and inspection manholes, flooding and increase of concentrations and loads of pollutants delivered to sewage receivers [4–6].

Appearance of periodical flooding should be certainly treated as disadvantageous phenomena, seriously affecting the everyday life of municipal settlement. Increase of concentrations and loads of pollutants transported by storm sewage may negatively influence the quality of water in the wastewater receiver.

Storm wastewater, as it was frequently reported in the literature, in dependence to type and manner of drainaged urbanized basin usage contain significant concentrations of pollutants: *Total Sewage Sludge* (TSS), *Chemical Oxygen Demand* (COD), *Biochemical Oxygen Demand* (BOD), *Total Nitrogen* (TN), *Total Phosphorus* (TP), heavy metals and oil derivatives [6–8]. Considering the above, in many European countries, according to European Water Frame Directive [9], the application of storm water drainage is being limited in favor of solutions based on collection and treatment of storm sewage in location of their generation [10,11].

Hence, the analysis of increased discharge of storm sewage effect on receiver's water quality conducted at the stage of storm water network extension designing seems to be requisitive.

Application of numerical modeling, allowing designing variant analyses for different rainfall events and various possible manners of network development for basins of different degree of sealing, may be a considerable help for designers and local authorities. One of the most popular pieces of software applicable in multivariate calculations is model SWMM 5 (*Storm Water Management Model*) by *United States Environmental Protection Agency* (USEPA). This model allows dynamic quantitative and qualitative calculations of storm water network operation – the quality of offered calculations were repeatedly positively verified [5, 12, 13].

Presented study focused on quantitative and qualitative analysis of storm water sewer system extension for selected municipal in Chelm city, Poland. Our researches were based on numerical calculations conducted by SWMM 5. Flow velocity of storm wastewater, canals filling height as well as concentrations and loads of TSS, TP and TN at discharge location, before and after development of stormwater network were selected as factors of our analyses.

Materials and methods

The 17.23 ha basin located in NW part of Chelm city, Poland, covering streets Szpitalna, Wygon and Ceramiczna was selected to our studies. Private housings and municipal hospital are located at the selected catchment. The existing storm water system of 1300 m length is constructed of concrete pipes of diameters from 100 to 1000 mm. Storm wastewaters are delivered to the surface retention tank of surface equal to 0.62 ha and mean depth of 1.9 m, and then diverted to the Uherka river. The proposed extension of modeled system covers new sanitation collectors in the region of

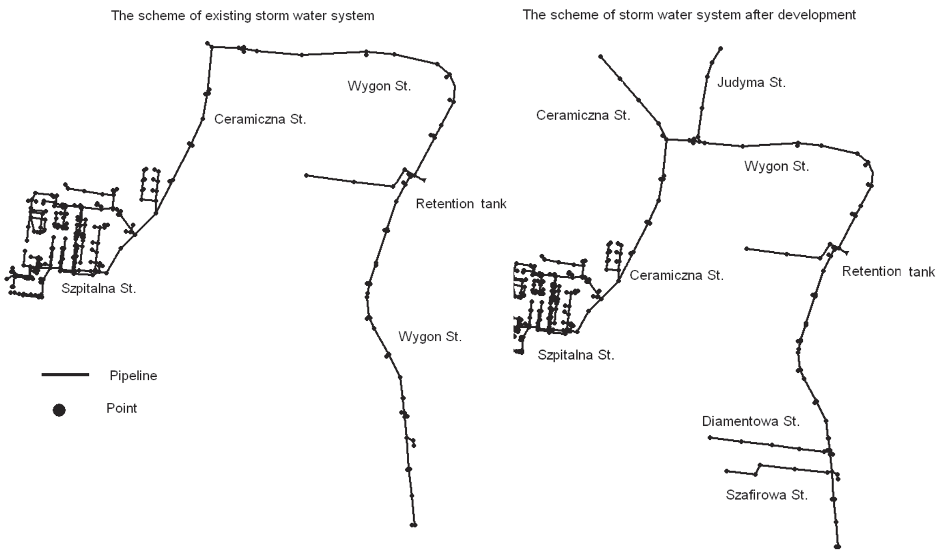

Fig. 1. Modeled storm water system – existing and after development

Szafirowa, Diamentowa, Judyma and Ceramiczna St. Development of network will result in increase of drainaged area of approximately 6.66 ha.

Numerical calculations of studied storm water network before and after extension were conducted by SWMM 5 [14]. The numerical model of existing network, based on documentation accessed by system operator, is consisting of 289 subcatchments, 284 nodes, 283 lines and sewage receiver. The model containing new collectors, in turn, consists of 404 subcatchments, 304 nodes and 303 lines and a receiver. Geometrical characteristics of the existing system and hydraulic parameters of pipes were read from the map and selected from SWMM 5 documentation [15]. The designed part of network was based on actual standards and literature guidelines [16, 17].

Our numerical calculations were conducted for the three different rainfall events (various intensity and duration of rain). Parameters of applied rainfall events, according to lack of suitable meteorological station in Chelm, were based on available literature and daily weather news: observations during 2002–2003 at measurement station in Olszanka, Poland (35 km from Chelm), reported daily sums of precipitation for the Wieprz river, Poland and archival characteristics of extreme rainfall events from 6 stations located in eastern Poland [18, 19]. Unit runoff for rain No. I of duration $t = 12$ h was accepted as 3 $dm^3 \cdot s^{-1} \cdot ha^{-1}$, rainfall event No. II $t = 1.5$ h 65 $dm^3 \cdot s^{-1} \cdot ha^{-1}$, and event No. III $t = 2.5$ h 90 $dm^3 \cdot s^{-1} \cdot ha^{-1}$.

Our qualitative numerical calculations were based on implemented in SWMM 5 equations of pollutants buildup and washoff on the catchment surface. The linear model of pollutant buildup and *event mean concentration* (EMC) model of pollutant washoff were accepted [14, 15]. Input data were applied according to literature studies for two various types of land use (residential and undeveloped) distinguished in the studied catchment [6, 20, 21].

The Event Mean Concentration is a flow-weighted average value of selected pollutant concentration. Definition of EMC may be described as follows [22]:

$$\mathrm{EMC} = \frac{\sum C_i Q_i}{\sum Q} \tag{1}$$

where: C_i – concentration of studied pollutant,
Q_i – storm water volumetric flow rate.

Input data for TSS, TP and TN modeling were also based on literature studies [6, 19, 20, 23–25].

Table 1

Models and input data applied to qualitative calculations

		Pollutant buildup		Pollutant washoff	
Model		$B = C_2\,(1 - e^{C_2 t})$ B – pollutant buildup [$\mathrm{mg \cdot dm^{-3}}$] C_1 – maximum buildup possible [$\mathrm{mg \cdot dm^{-3}}$] C_2 – buildup rate constant [$\mathrm{d^{-1}}$] t – time [d]		$W = C_3 \cdot Q^{C_4}$ W – concentration of pollutant in surface runoff C_3 – washoff coefficient, equal to EMC [–] C_4 – exponent, $C_4 = 1$ [-] Q – surface runoff flow rate [$\mathrm{dm^3 \cdot s^{-1}}$]	
Applied values	Residential area	TSS	$C_1 = 50$ [$\mathrm{mg \cdot dm^{-3}}$] $C_2 = 2$ [$\mathrm{d^{-1}}$]	TSS	EMC = 101 [-]
		TP	Co-pollutant to TSS 58 mg TP per kg TSS	TP	EMC = 0.34 [-]
		TN	Co-pollutant to TSS 550 mg TN per kg TSS	TN	EMC = 2.64 [-]
	Undeveloped area	TSS	$C_1 = 100$ [$\mathrm{mg \cdot dm^{-3}}$] $C_2 = 3$ [$\mathrm{d^{-1}}$]	TSS	EMC = 70 [-]
		TP	Co-pollutant to TSS 49 mg TP per kg TSS	TP	EMC = 0.12 [-]
		TN	Co-pollutant to TSS 460 mg TN per kg TSS	TN	EMC = 1.51 [-]

The developed numerical model of selected part of storm water network in Chelm, Poland requires empirical calibration based on multiple *in situ* measurements of the qualitative and quantitative characteristics of studied system.

Results and discussion

Possibility assessment of storm water network development in selected catchment in Chelm, Poland was conducted basing on calculated velocities of flow, collector fillings and concentrations and loads of TSS, TP and TN at the entrance to wastewater receiver, before and after the system extension. The results of our calculations were presented in Fig. 2–4 and in Table 2.

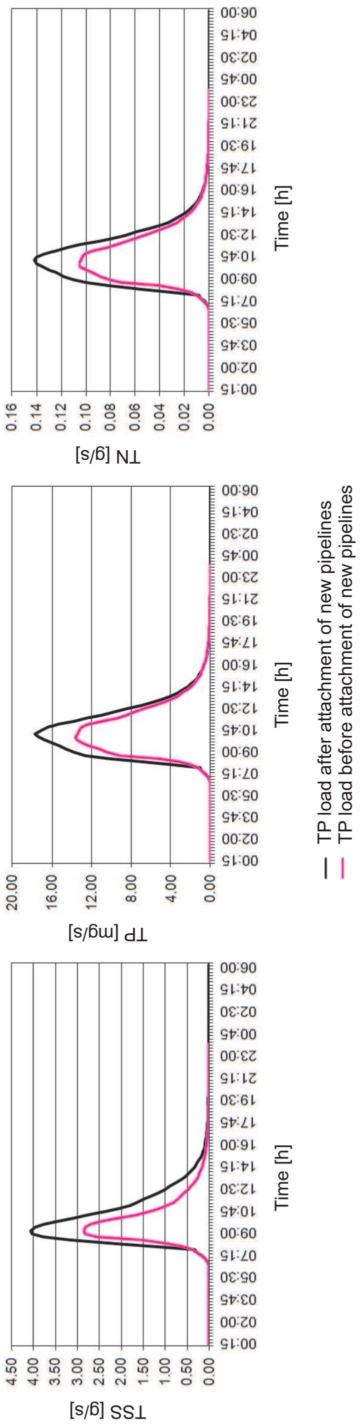

Fig. 2. Loads of TSS, TP and TN discharged to storm sewage receiver for Rainfall event No. I

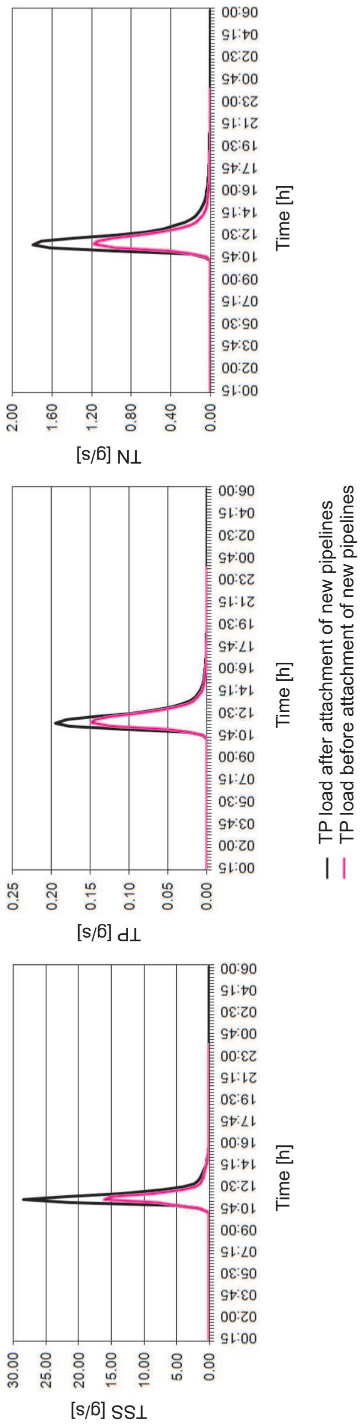

Fig. 3. Loads of TSS, TP and TN discharged to storm sewage receiver for Rainfall event No. II

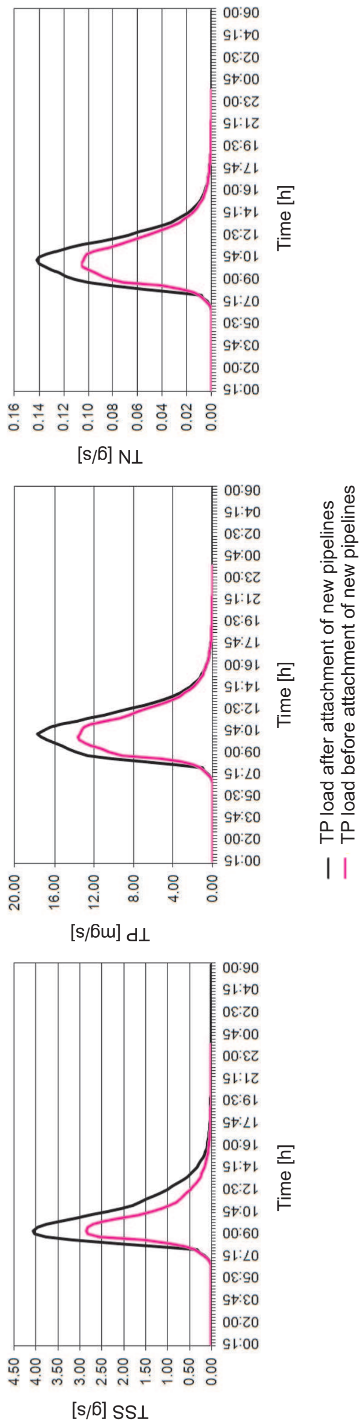

Fig. 4. Loads of TSS, TP and TN discharged to storm sewage receiver for Rainfall event No. III

Table 2

Results of quantitative and qualitative calculations for existing and planned storm water network

Studied factor	Unit	Rainfall event No. I		Rainfall event No. II		Rainfall event No. III	
		Existing network	Network after develop-ment	Existing network	Network after develop-ment	Existing network	Network after develop-ment
Flow velocity $[m \cdot s^{-1}] < 0.3$	[%]	57.80	53.13	11.66	10.89	8.48	7.92
Flow velocity $[m \cdot s^{-1}] > 0.6$	[%]	10.60	10.23	50.18	53.80	57.95	60.73
Number of chambers endangered by flooding	[-]	0	0	15	19	27	33
TSS max concentration	$[mg \cdot dm^{-3}]$	97.01	93.43	84.76	84.62	73.48	69.28
TP max concentration	$[mg \cdot dm^{-3}]$	0.34	0.31	0.32	0.29	0.32	0.29
TN max concentration	$[mg \cdot dm^{-3}]$	2.65	2.52	2.54	2.65	2.55	2.36

Our calculations, for conditions before and after development, showed that in case of rainfall event No. I velocity of flow in over 50 % of pipes is lower than $0.3\ m \cdot s^{-1}$ (Table 2). The significant improvement was observed for rainfall events No. II and III characterized by higher intensity. Calculated velocity of flow, even in case of rainfall event No. III, in 8 % of all pipes is lower than $0.3\ m \cdot s^{-1}$. After network development recommended speed of storm sewage flow higher than $0.6\ m \cdot s^{-1}$ was observed in approx. 53 % and 60 % of pipes, for variant No. II and III, respectively. However in this case, the numerous flooding were noted: for rainfall event No. II from 15 chambers in case of existing network model and 19 after development and respectively from 27 and 33 chambers for rain No. III. The clear majority of chambers endangered by flooding is located at southern part of Wygon St., at existing pipes of 0.3–0.5 m diameter and newly designed side collectors in Diamentowa and Szafirowa St. of diameter 0.3 m. Our studies showed that addition of new drainaged catchments in the region of Diamentowa and Szafirowa St. should be preceded by alternation of existing collector diameter in Wygon St.

The results of qualitative calculations of storm water network development were presented in Fig. 2–4, as well as at Table 3. The visible in all studied cases increase of transported TSS, TP and TN loads is caused, in our opinion, by increase of drainaged area and share of undeveloped and unurbanized subcatchments – bare soil parking lot and building parcels in Szafirowa, Diamentowa, Judyma and Ceramiczna regions.

The observed increase of TSS loads reached the level of, respectively, 42.96 %, 76.98 % and 72.70 % for all tested rainfall events. Increase of TP may be described by 30.15 %, 33.33 % and 31.82 % for each tested rainfall, while increase of calculated maximum loads of TN reached the level of 27.27 %, 51.69 % and 39.53 %. The decreased values of tested pollutants loads in case of rainfall event No III, in our opinion, result from the noticeable flooding observed in calculations. The excess of allowed by standards [4] value of TSS concentration in surface water delivered to the receiver was not observed. The maximum calculated value of TSS reached the level of 97.01 mg · dm^{-3}, when the maximum admissible value is equal 100 mg · dm^{-3}. Usage of open retention tank located between end of the storm drainage network and receiver to preliminary treatment of storm wastewater before discharge to the Uherka river seems to be reasonable.

Table 3

Results of qualitative modeling of tested storm water system in Chelm

Pollutants	Maximum calculated loads					
	Rainfall event No. I		Rainfall event No. II		Rainfall event No. III	
	Existing network	Network after development	Existing network	Network after development	Existing network	Network after development
TSS [g · s^{-1}]	2.84	4.06	16.07	28.44	11.21	19.36
TP [g · s^{-1}]	$13.6 \cdot 10^{-3}$	$17.7 \cdot 10^{-3}$	0.15	0.20	0.22	0.29
TN [g · s^{-1}]	0.11	0.14	1.18	1.79	1.72	2.40

Results of our qualitative calculations were compared to the reported values of observed concentrations of studied pollutants in the storm water discharged from various residential basins. Table 4 presents comparison of maximum calculated values of TSS, TN and TP concentrations for studied storm water system in Chelm, Poland to minimal, maximum and mean values of appropriate pollutants presented by literature reports [6, 22, 24, 25].

Table 4

Comparison of calculated maximum TSS, TN and TP concentrations to values reported in literature

Catchment	Concentration [mg · dm^{-3}]		
	TSS	TN	TP
Chelm, calculated maximum values, Poland	97.01	0.34	2.65
High density residential basin, combined sewer Chongju, S. Korea [22]	33.0–2796.0 (552.2)	0.11–39,51 (11.09)	2.9–10.8 (7.2)
Residential area, Twin City, MN, USA [24]	2–3577(184)	0.43–19.4 (3.08)	0.03–9.40 (0.58)
Residential area Siosepol, Iran [6]	43–467 (161)	1.22–22.38 (6.65)	0.064–0.790 (0.274)
Birdlife, high-socio-economic single detached-dwelling area, Australia [25]	356.7 (Mean)	1.9 (Mean)	0.8 (Mean)

Comparison of concentration values presented in Table 4 shows that our results are comparable to values of tested pollutants concentrations for several various residential watersheds of different structure, populations number and inhabitants habits, presented in literature reports. Moreover, calculated maximum values of TSS, TN and TP concentrations for studied catchment in Chelm, before and after development of storm sewer system are in good agreement to EMC values for various low and medium density urban catchments compiled by Park et al [13].

Summary

Our studies proved suitability of numerical modeling application to quantitative and qualitative analysis of storm water network development in conditions of Chelm city, Poland. Thus, studies of existing and designed network operational conditions were possible. The obtained results showed that in case of low intensity rainfall events, the adverse conditions of flow occur inside the network designed on the basis of Blaszczyk's formula. The insufficient wastewater flow velocity may result in sediments deposition inside the system pipes. Simultaneously, the possibility of major flooding, significantly disturbing the life of urbanized community during the extreme rainfall events was noted during simulations of both existing and developed network.

The conducted qualitative calculations showed the clear increase of TSS, TN and TP loads after eventual development of the studied network. The excess of acceptable load of tested pollutant in storm water discharged to the receiver was not observed.

According to the lack of model calibration the presented researches should be treated as preliminary studies. We consider further studies focused on assessment of retention tank application as location of introductory wastewater treatment as well as monitoring of exiting storm water system allowing the future model calibration.

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MODELOWANIE NUMERYCZNE W ILOŚCIOWEJ I JAKOŚCIOWEJ OCENIE MOŻLIWOŚCI ROZBUDOWY SIECI KANALIZACJI DESZCZOWEJ

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Abstrakt: W pracy przedstawiono próbę zastosowania modelowania numerycznego do ilościowej i jakościowej oceny możliwości rozbudowy systemu kanalizacji deszczowej. Model wybranego fragmentu sieci kanalizacyjnej miasta Chełma wykonano w programie SWMM5. W badaniach przeanalizowano trzy warianty charakteryzujące się różną intensywnością oraz czasem trwania opadu. Obliczenia hydrauliczne wykonano dla warunków przed i po rozbudowie sieci. Przedstawiona analiza została oparta na prędkościach przepływu ścieków, napełnieniu kanałów oraz stężeniach i ładunkach transportowanych zanieczyszczeń. Po wykonaniu obliczeń symulacyjnych sieci po jej rozbudowie otrzymano wyniki, w których zaobserwowano zmiany w prędkości przepływu, napełnieniach kanałów, ładunkach badanego zanieczyszczenia. Odnotowano także w wynikach symulacji wypływ ścieków ze studzienek połączeniowych lub rewizyjnych na powierzchnię odwadnianego terenu. Przeprowadzone badania wskazują również, iż istniejący system zaprojektowany na podstawie wzoru Błaszczyka, w obecnych warunkach jest częściowo przewymiarowany. W związku z tym prędkość samooczyszczania przewodów nie została osiągnięta w znacznej części sieci. Ze względu na brak kalibracji modelu otrzymane wyniki należy traktować jako wyniki badań wstępnych.

Słowa kluczowe: kanalizacja deszczowa, modelowanie numeryczne, rozbudowa sieci, analiza ilościowa i jakościowa