Analysis of suspended solids emissions from a combined sewage system using the Stormwater Management Model (SWMM)

Grażyna Sakson

Lodz University of Technology, Faculty of Civil Engineering, Architecture and Environmental Engineering, Lodz, Poland, e-mail: grazyna.sakson-sysiak@p.lodz.pl, ORCID ID: 0000-0002-6022-7771

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Abstract: The protection of water bodies requires the reduction of pollutant emissions from all major sources. In urbanized areas, these include: wastewater treatment plants (WWTPs) and (depending on the type of sewage system) combined sewer overflows (CSOs) and stormwater drainage outlets. WWTPs are usually monitored and emitted pollutant loads are known, but it is more difficult to assess the pollutant load discharged by CSOs and stormwater drainage systems. The article attempts to use the Stormwater Management Model (SWMM) to assess emissions of suspended solids from a large urban combined catchment. Suspended solids are the main pollutant of stormwater runoff in urban areas, and the dynamics of their emission from catchments is very diverse. The amount of suspended solids discharged by CSOs functioning in the given city was assessed in comparison with emissions from a wastewater treatment plant. The results show that CSOs discharge a pollutant load to the receiver which is comparable to WWTPs, but in a much shorter time and in a violent manner which can lead to the severe deterioration of receiving water quality. The modelling took into account the quality of dry weather sewage, the build-up of suspended solids, wash-off processes in the catchment area, and local precipitation characteristics. Factors affecting the quality of the obtained model and the accuracy of the emission level assessment were analysed.

Keywords: sewerage, modelling, SWMM, suspended solids, pollutant emission, water protection

INTRODUCTION

The development of urban areas leads to an increase in the emission of pollutants directed to water receivers (Blumensaat et al. 2012, Fletcher et al. 2013, Liu et al. 2015). Depending on the solutions adopted by the sewage system, these pollutants can be discharged by the wastewater treatment plant (WWTP), combined sewer overflows (CSOs), stormwater drainage outlets or directly via surface runoff. Effective protection of water bodies requires an integrated approach, which means the control and reduction of pollutant emissions from all sources. In general, the operative monitoring of wastewater quality is carried out in treatment plants, where pollutant emissions to receiving water is reduced to the required extent. In urban areas, WWTPs are most often the main source of pollutant emissions, but their proper functioning does not guarantee sufficient water protection, especially in the case of combined sewage systems. In periods of wet weather, discharges from stormwater overflows and outlets from separate drainage can have a significant share of the loads of pollutants discharged to water receivers (Benedetti et al. 2013, Keupers & Willems 2013, Sakson et al. 2017, Zawilski et al. 2017). City centres in Central Europe usually are equipped with such systems, and CSOs discharge a mixture of untreated sanitary and industrial wastewater and stormwater to receiving water. The expansion of cities, catchment transformation, the increase in impervious surfaces, and climate change manifesting itself, among others, in an increase in rainfall intensity all cause the more frequent activation of CSOs and a greater pollutant load being discharged into the receiving water. Stormwater drainage outlets are another important source of emissions through which pollutants washed-off from the catchment area are usually discharged into the receiving water without treatment. CSO design criteria and regulations regarding their operation in European countries have varied (Dirckx et al. 2011, Brzezińska 2019). The legal regulations currently in force in Poland concerning CSOs only limit the maximum number of spillages per CSO to 10 per year, without limiting the volume and load of discharges (Rozporządzenie 2019). The method of calculating the frequency of CSO activity has not been specified either. However, it can be expected that, due to the need for more effective protection of water receivers, the regulations will be changed and it will be necessary to limit the emitted pollutant load. According to a new proposal for a Directive of the European Parliament and of the Council (Directive 2022) concerning urban wastewater treatment, storm water overflows should not represent more than 1% of the annual load of urban wastewater, as calculated in dry weather conditions. This document introduces the obligation to establish locally integrated urban wastewater management plans to combat pollution from urban runoff and storm water overflow, and provides for stricter requirements for the emission of organic substances, suspended solids, nutrients and micropollutants to surface waters.

The monitoring of CSOs and pollutant emission assessment is difficult (similarly as in the case of stormwater drainage outlets) due to the considerable number of overflow activations, the irregularity and unpredictability of rainfall phenomena and the high variability of wastewater composition. The analysis of the sewerage functioning can be carried out with the use of modelling, for example according to Regulation of the Minister of Maritime Economy and Inland Navigation (Rozporządzenie 2019) in the case of sewage systems above 100,000 PE the number of CSOs should be determined on the basis of simulation models. Using modelling may limit quantitative and qualitative research on the catchment, but the model calibration also requires data on the wastewater flow and quality. It is therefore necessary to simultaneously develop both monitoring and modelling methods and, due to the size of the sewage systems, a safe level of model simplification should be defined to guarantee the credibility of the results.

The article attempts to assess the amount of total suspended solids (TSS) emissions from CSOs in comparison with emissions from WWTPs for a sewage system serving over 100,000 PE. TSS are the main contaminant of stormwater runoffs from impervious surfaces. They are build-up on the catchment during dry weather periods and wash-off during precipitations. The concentration of suspended solids in CSO discharges, due to the multitude of factors affecting them, may be comparable, higher or lower than in dry weather wastewater. The increased concentration of suspended solids has a negative impact on the aquatic environment, causing the deterioration of water taste and smell, reduction of dissolved oxygen content, reduction of sunlight penetration, and consequently inhibition of the photosynthesis process, reduction of the aesthetic and recreational value of watercourses and reservoirs, deterioration of the living conditions of aquatic organisms and the disappearance of vulnerable species (Kerr 1995, Berry et al. 2003). In addition, toxic substances, e.g. heavy metals, may be associated with them and suspended solid concentration is generally well correlated with indicators of organic pollutant content and nutrients (Brzezińska et al. 2018, Silva et al. 2022). Therefore, this parameter can be one of the basic indicators of threats to surface waters that are recipients of municipal sewage and stormwater runoff from urban areas.

MATERIAL AND METHODS

Study area

The analysis was carried out for the Lodz (in Polish: Łódź) catchment, which is equipped with a hybrid sewer system: it is combined in the central part of the city and separate in other districts. The catchment area of the combined sewage system is 4,240 ha.

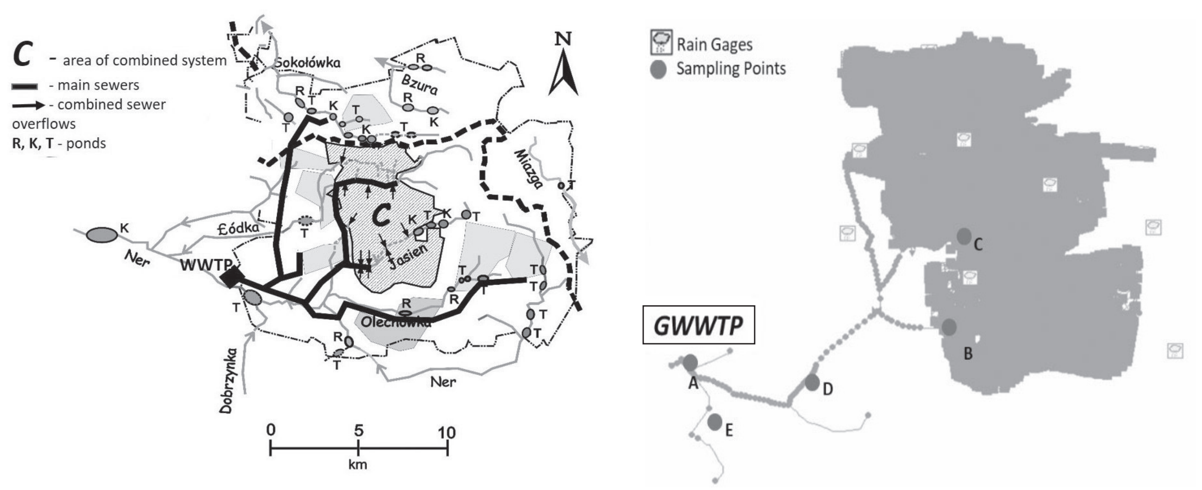

Fig. 1. Combined sewerage catchment in Lodz – plan and scope of the SWMM, A–E – sampling points

The system is equipped with 18 CSOs that discharge excess untreated wastewater and stormwater into four small urban rivers during periods of wet weather (Fig. 1). The activation of most CSOs significantly exceeds the formally admissible number (10 per year). Permissible concentration or discharge load of suspended solids are not formally defined. Urban wastewater is treated in the group WWTP. Maximum sewage inflow to WWTP during dry weather for a probability of 85% is 166,000 m^3 per day. The maximum concentration of suspended solids in treated wastewater discharged to the receiving water should not exceed the limit according to Regulation of the Minister of Maritime Economy and Inland Navigation (Rozporządzenie 2019): 35 mg/L. The sewer system is equipped with devices for online measurement of wastewater flow located near each CSO, flow measurement is also carried out at the inlet to the WWTP. The city has a municipal pluviometric network with 18 rain gauges.

Modelling data and tools

The analysis of emissions of suspended solids from the catchment area was carried out using US EPA software Stormwater Management Model (SWMM). SWMM is one of the most frequently used tools in sewage system modelling. It is a dynamic rainfall-runoff simulation model used for single event or long-term (continuous) simulation of runoff quantity and quality from primarily urban areas (Rossman 2015). Hydrodynamic flow modelling is based on the complete one-dimensional Saint-Venant flow equations and therefore produces the most theoretically accurate results. The quality of stormwater runoff is determined on the basis of the pollutant build-up model in the catchment area and the wash-off model, but in-sewer processes are not taken into account. In the pollutant build-up model, the exponential, power, or saturation formula can be used, while, as indicated in the literature, the exponential function is most often used, and was also used in these analyses.

Build-up (B) follows an exponential growth curve that approaches a maximum limit asymptotically:

$$B = C_1\left(1-\exp\left(-C_2 \cdot t\right)\right) \quad (1)$$

where:
- C_1 – maximum build-up possible [kg/ha],
- C_2 – build-up rate constant [1/d],
- t – antecedent dry weather period [d].

Pollutant wash-off from a catchment occurs during wet weather periods and is described in the exponential function. The wash-off load (W) is proportional to the product of runoff raised to some power and to the amount of build-up remaining:

$$W = C_3 \cdot q^{C_4} \cdot B \quad (2)$$

where:
- C_3 – wash-off coefficient,
- q – runoff rate per unit area [mm/h],
- C_4 – wash-off exponent.

Values of parameters in Formulas (1) and (2) according to literature data are presented in Tables 1 and 2. For the Lodz combined catchment, a model covering 9,137 subcatchments, 1,648 conduit links, 1,631 junction nodes, and 19 outfall nodes (18 are CSOs and one is WWTP) was created with the use of SWWM. The general scheme of the model is presented in Figure 1.

Table 1
Accumulation of suspended solids in an impervious area

Build-up [mg/m²]	Antecedent dry weather period [d]	Surface type	Reference
55–1,098	7	streets	Mahbub et al. (2010)
123–272	13	concrete and asphalt coarse	Wicke et al. (2012b)
18.2–29.2	per day	concrete and asphalt coarse	Wicke et al. (2012a)

Table 2
Parameter values in the suspended solids build-up and wash-off model according to literature data

Build-up		Wash-off		Reference
maximum build-up possible [g/m²]	build-up rate constant [1/d]	wash-off coefficient	wash-off exponent	
C_1	C_2	C_3	C_4	
7.3	0.52	0.014	1.65	Gaume et al. (1998)
1.8[a]	0.3	0.13	1.2	Barco et al. (2005)
1.75	0.3	1.811	1.0	Temprano et al. (2006)
2.6–5.3[b] 0.85–1.2[c]	0.21–0.382 0.122–0.188	0.0015–0.0135 0.051–0.213	0.608–0.914 0.3333–0.603	Hossain et al. (2010)
0.276[d] 0.134[e]	0.2 0.23	0.24 0.24	1.0 1.0	Wicke et al. (2012b)
15.0[f] 6.0[g] 4.0[h]	0.5 0.5 0.5	0.012 0.07 0.04	1.8 1.8 1.2	Gong et al. (2016)
0.2–30.0	0.03–20.0	0.01–10.0	0.2–3.0	Bonhomme & Petrucci (2017)
3.0–10.0	0.7–0.8	0.2–0.6	1.2–1.5	Maharjan et al. (2017)
0.003–47.046	0.09–5.54	1.64–16.73	1.76–9.16	Tu & Smith (2018)

[a] for the impervious surface; [b] streets; [c] roofs; [d] concrete; [e] asphalt; [f] road; [g] roof; [h] green space.

Table 3
Suspended solids concentration [mg/L] in combined sewer system in Lodz (based on Sakson et al. 2022)

Sampling point	Catchment characteristic	Min.	Max.	Median	Standard deviation	Coefficient of variation [%]
A	inflow to the GWWTP	78	2,240	390	332.2	71.58
B	inflow from central and eastern parts of the city (domestic and industrial sewage, stormwater)	152	1,984	346	436.1	82.57
C	inflow from central parts of the city (domestic and industrial sewage, stormwater)	114	556	214	108.0	28.88
D	inflow from combined catchment (central districts)	80	5,004	420	974.8	135.67
E	inflow from Pabianice city (domestic and industrial sewage, stormwater)	138	1,882	342	285.2	71.38

For the model quantitative calibration, rainfall data from seven rain gauges located in the catchment area or in its vicinity were used, as well as data on flows from the CSOs and at the inlet to the WWTP of sixteen rainfall-runoff events from 2012–2018. The calibration of the water quality model was carried out using data from the monitoring campaign conducted in 2018–2022, e.g. at five combined sewer sampling points and at the inlet to WWTP (Sakson et al. 2022). The suspended solids measurement results are presented in Table 3.

RESULTS

Examples of model calibration based on measurements of CSOs spillage flow and at the inlet to the WWTP are presented in Figure 2. The main parameters used in the calibration process were depth of depression storage on impervious and pervious area (D-store imp. = 0.5–1.5 mm, D-store per. = 20–40 mm).

Other model parameters were adopted on the basis of previous studies (Zawilski & Sakson 2010, 2011).

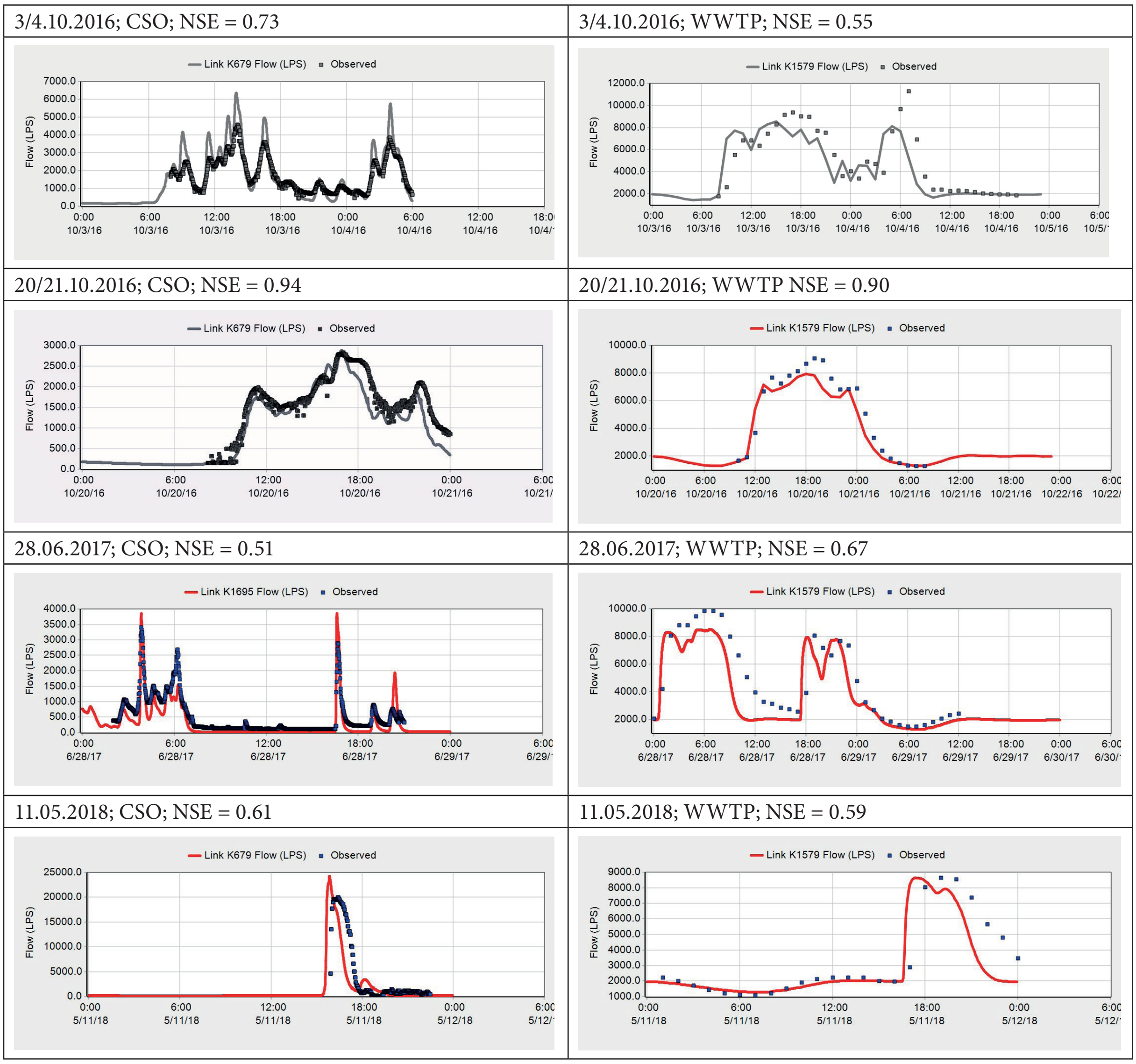

Fig. 2. *Examples of model calibration effects for flow measurements at CSOs and at the inlet to the WWTP; NSE – Nash–Sutcliffe efficiency*

The performance modelling was evaluated by applying a widely used goodness-of-fit tests the Nash–Sutcliffe efficiency (NSE). According to the literature, the following criteria are usually used to assess the degree of fit (Table 4).

Table 4
Model's performance rating in terms of goodness-of-fit scores (Hossain et al. 2019)

Performance rating	Goodness-of-fit test used in the rating
Very good	NSE > 0.75
Good	0.65 < NSE < 0.75
Satisfactory	0.5 < NSE < 0.65
Unsatisfactory	NSE < 0.5

Due to the limited database of concentrations of suspended solids in wet weather sewage, the modelling parameters of the quality model were also based on previous results regarding the suspended solids build-up and wash-off on the catchment equipped with a separate stormwater drainage system (Zawilski & Sakson 2013, 2014, Sakson-Sysiak 2019). The adopted parameters are presented in Table 5, and exemplary modelling results compared to the measurements in 2019 are shown in Figure 3.

Table 5
Parameters of suspended solids catchment build-up and wash-off used in SWMM

Parameter	Value	Unit
Rain concentration	20	mg/L
Dry weather flow concentration	200	mg/L
Maximum build-up possible	10.0[a]; 3.5[b]	g/m^2
Build-up rate constant	0.1	1/d
Wash-off coefficient	0.3	–
Wash-off exponent	1	–

[a] heavily contaminated surfaces; [b] less contaminated surfaces.

Using the prepared model, a simulation of the sewage system functioning in 2019 and 2020 was carried out (Table 6). Suspended solid loads discharged by all CSOs was determined and compared with the load emitted by the wastewater treatment plant. The load for WWTP was calculated on the basis of maximum sewage inflow to WWTP and the permissible suspended solid concentration in treated wastewater according to the water law permit (35 mg/L) and also based on the observed values of treated wastewater volume and TSS concentration.

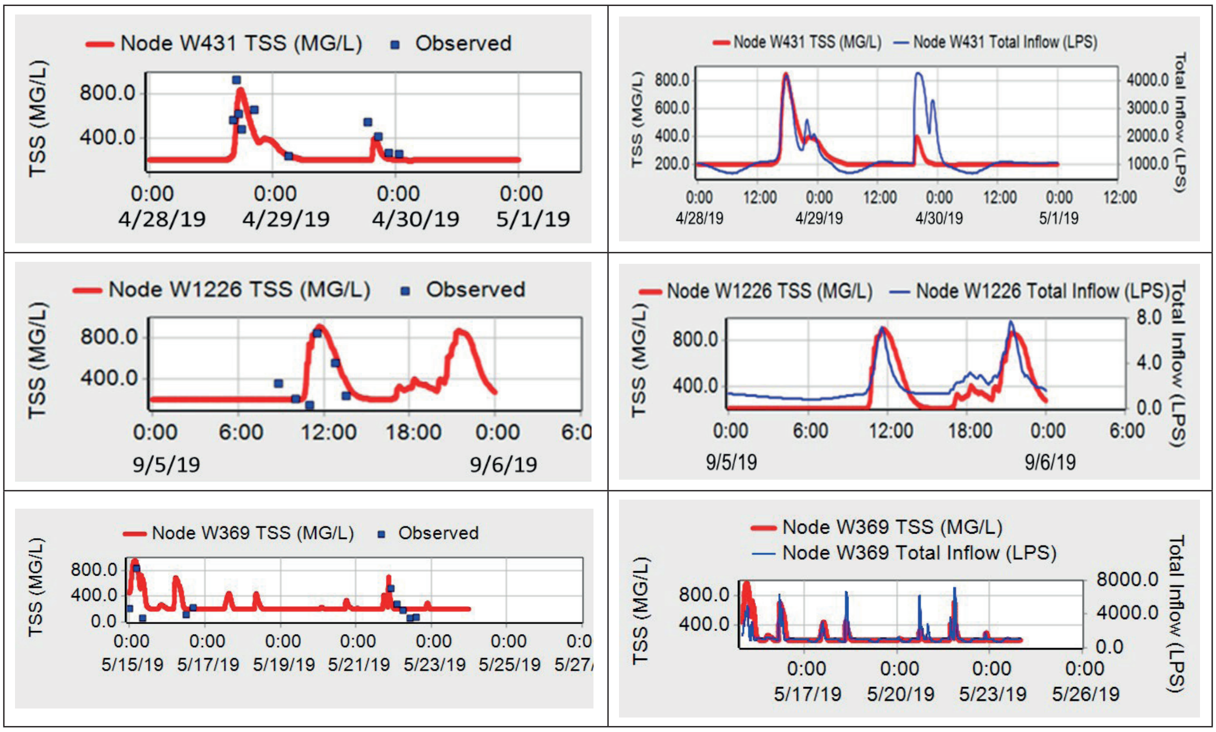

Fig. 3. *Exemplary modelling results compared to the observed TSS concentration in 2019*

Table 6
Annual load of TSS discharged in 2019 and 2020 to the receiving water from WWTP (according to law permit and observed data) and CSOs (according to the model)

Parameter		Unit	2019	2020
Annual precipitation		mm	470	559
WWTP water law permit	wastewater flow	m^3/d	166,000	
	TSS concentration	mg/L	35	
	TSS annual load	Mg	2,120	
WWTP observed*	wastewater flow	m^3/d	164,930	163,269
	TSS concentration	mg/L	15.4	10.5
	TSS annual load	Mg	927.0	625.7
CSOs model	TSS annual load	Mg	730	688

* Data based on: http://www.gos.lodz.pl [access: 5.01.2023].

The data presented in Table 6 indicates that CSOs discharge very large loads of pollutants to water receivers. In Lodz, the annual load of suspended solids emitted by CSOs was similar to that produced by WWTP. However, the emissions from the WWTP take place relatively evenly throughout the year, while CSOs usually operate 20–30 times a year. About 2.5 Mg TSS in 2019 and 1.7 Mg in 2020 per day was emitted by WWTP, and the TSS load discharged during one phenomenon by CSOs can be up to several dozen megagrams. This is of great importance for the quality of the receiving water. Examples of CSO operation in 2019 (sewage flow and TSS load histograms) are shown in Figure 4. The number of discharges was established for a separation time of 6 hours.

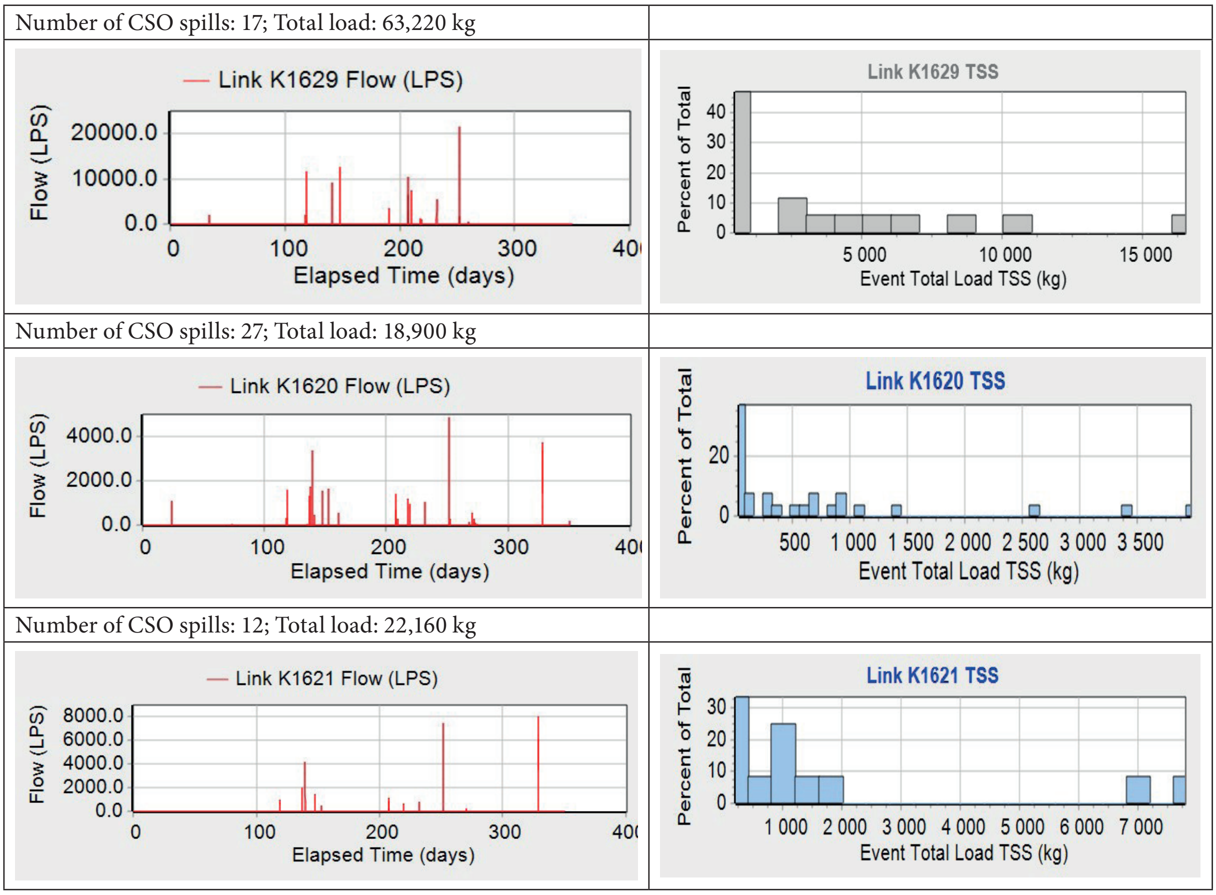

***Fig. 4.** Examples of the operation of three different CSOs in 2019*

DISCUSSION

Protection of water reservoirs requires limiting pollutant emissions, e.g. from urbanized areas, where stormwater overflows are one of the main sources. Estimating the loads of emitted pollutants is still problematic. This can be done based on outlet monitoring – manual sampling and laboratory testing or continuous monitoring using online sensors or using modelling. In this case, in order to calibrate the models, it is also necessary to study the composition of wastewater, but to a much lesser extent.

In this article, quality modelling was used to estimate pollutant fluxes emitted from CSOs. It should be emphasized that the presented analysis is only a preliminary recognition of the possibilities and conditions of using this modelling for such purposes, and the results are indicative. The main reason is the extensiveness of the sewage system and a very limited database of TSS concentrations in wastewater. Model calibration should be based on a measurement campaign planned for this purpose. The quality of stormwater runoff during a precipitation event undergoes a very rapid change and depends on many factors (Sakson-Sysiak 2019, Silva et al. 2022). The so-called first flush phenomenon is often observed, when 30% (or 40%) of the sewage volume contains 70% (or 60%) of the pollutant load (Brzezińska 2019). Samples for testing should therefore be taken very often, and it is best to use online sensors for this purpose. Online monitoring is generally considered to be a good solution for evaluating the quality of stormwater and wastewater discharges (Brzezińska et al. 2016, Maruéjouls & Binet 2018).

The pollutant load emitted by CSO is the sum of the load contained in dry weather flow, washed-off from the catchment and derived from sewer deposits. Its level is also influenced by in-sewer processes – pollutant transformations over the transport of sewage. During the monitoring campaign carried out in Lodz in 2018–2021, the significant spatial and temporal differentiation of TSS concentrations in dry weather wastewater were observed. This was related, among other things, to the characteristics of catchment development and location of industrial plants. However, typical daily or weekly variability that could be taken into account in the model was not found. Sometimes very high concentrations of TSS were observed, significantly exceeding the permissible concentrations for industrial sewage discharged into the sewer system according to the local regulations in Lodz (Sakson et al. 2022). It was probably related to illegal discharges of industrial sewage. It is difficult to include such cases in the model, but spatial and temporal differentiation of dry weather sewage quality in the case of such a large catchment area would certainly improve the model.

The conducted analysis did not take into account in-sewer processes, which, due to the possibility of TSS sedimentation at low flows and sewer deposits flushing by stormwater, may significantly affect the TSS load discharged to the receiver. According to research conducted by Hannouche et al. (2014), the contribution of sewer system deposits can vary between 20 and even 80% of the TSS load observed at the outlet during a rain event.

Two common conceptual processes in suspended solids modelling are the build-up on catchment surfaces, and wash-off by rainfall (Morgan et al. 2020).

Model's goodness-of-fit depends on many factors:

- functions describing pollutants build-up and wash-off,
- calibration processes for the methodology adopted,
- calibrated parameters.

It is extremely important to collect a sufficiently large measurement database, including such aspects as the qualitative characteristics of precipitation and dry weather flows, the accumulation of pollutants in the catchment area and their critical assessment. Collecting data on the build-up and wash-off pollutants in the catchment area is difficult, with experimental studies on artificial surfaces or very small catchments are often used. This can be a cause of uncertainty in the modelling of TSS build-up and wash-off processes, as can the size of pollutant particles, which changes over time (Wijesiri et al. 2016). The creation of an appropriately large database of quantitative and qualitative monitoring of the network and catchment area for various precipitation phenomena makes it possible to determine the parameters of build-up and wash-off in the process of model calibration, which is a technically difficult, long-term, and costly task.

The calibration results will also be affected by factors such as:

– characteristics of the catchment area: surface development (residential, commercial, industrial areas), existing sources of pollution, type of surface (roughness determining the ease of retaining pollutants), slope of the terrain,
– schedule and efficiency of street sweeping,
– type and amount of substances used for road and sidewalk maintenance in winter,
– climate characteristics: air humidity, wind direction and speed, precipitation,
– local accidental/random pollution of the catchment, e.g. as a result of failures and renovation works.

An important reason for the differences between the observed and modelled pollutograms may be, among others, the fact that the streets sweeping was not taken into account, which may significantly affect the current TSS build-up on the catchment area (Chang et al. 2005). Sweeping may be included in the SWMM: the frequency and effectiveness should be declared for the type of land use of the catchment. This would require the collection of accurate data on the efficiency of the sweeping equipment used, and the knowledge of the granulometric composition of the accumulated solids. However, incorrect assumptions about the sweep schedule can cause additional modelling errors.

Nowadays, it is assumed that all strategies for mitigating the impact of stormwater runoff directed towards receiving water should be based on the knowledge of the processes of build-up during dry weather and wash-off during precipitation. This results in the rapid development of modelling methods and tools (Bach et al. 2014). It should be remembered that in the case of water quality modelling there is a much greater variability of calibrated parameters and measurement data regarding the quality of runoff than in the case of quantitative models. Qualitative models are characterized by greater uncertainty, therefore a larger database is needed to calibrate them (Mannina & Viviani 2010). However, the models are not universal and even a well calibrated model in one catchment cannot be directly applied to another. The use of modelling in the development of integrated urban wastewater management plans requires a lot of action in advance. Currently, many cities in Poland already have (or are currently working on the creation of) a hydraulic model of the sewage system with a system for monitoring precipitation and flows in the network. The next step should be to create a system for monitoring the quality of wastewater in the sewage system and discharging it into the water receiver. A broad analysis of the available solutions is necessary here, but it can be assumed that the best solution will be the use of online sensors. The choice should concern the range of measured parameters, the location of stations, taking into account potential operational problems, purchase and operating costs. The additional monitoring activities also may be helpful/necessary: assessment of the sweeping effectiveness, type and consumption of materials for winter road maintenance, identification of pollution sources in the catchment, illegal discharges into the wastewater collecting system, assessment of the technical sewer condition and the level of sewer deposits.

Pollutant emission assessment from urbanized areas, possible thanks to the development of modern measurement techniques and modelling tools (Liu et al. 2015, Bertrand-Krajewski et al. 2021), is only the first step in protecting water bodies. It should be the basis for determining the necessary degree of contaminant removal and the selection of optimal technical solutions, so there is also a need to create digital models of devices and facilities for wastewater/stormwater treatment. Furthermore, it should be emphasized that the emission criterion should not always be applied in the protection of water bodies, especially in the case of small urban rivers like is the case in Lodz. In this case, the emission criterion is more effective, as discussed in a previous study (Sakson et al. 2017).

CONCLUSIONS

1. The result of the analysis carried out is the estimation of suspended solids emission from the Lodz catchment area by CSOs, which made it possible to compare it with the emission from the wastewater treatment plant. The results show that CSOs discharge to the receiver have a pollutant load comparable to WWTP, but in a much shorter time, and more violent manner.

2. Computer modelling can be used in the assessment of pollutant emissions from an urban catchment, reducing the scope of costly and cumbersome continuous monitoring. The condition for obtaining reliable modelling results is the calibration of the model based on a wide database of wastewater quality, precipitation, and flows in sewers. These requirements stem from the high variability of the calibrated parameters and measurement data used for modelling.
3. Qualitative modelling can be used as a basis for wastewater system optimization and reducing the emissions of pollutants into receiving water, provided that a monitoring system is set up early enough, and the data necessary to create the model and its calibration are collected.

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