

Predictive model of pollutant loads discharged by combined sewer overflows

Agnieszka Brzezińska, Grażyna Sakson and Marek Zawilski

ABSTRACT

Effective protection of receiving waters on urbanized areas requires knowledge about the amount of pollutants contained in discharged wastewater, inter alia by combined sewer overflows (CSOs). This involves the need to conduct long-lasting, costly and technically complex studies on the quantity and quality of discharged sewage. Loads of pollutants emitted by CSOs depend on many factors, inter alia on very variable characteristics of precipitations. This paper attempts to develop a simplified predictive model of pollutant loads for two basic parameters: total suspended solids (TSS) and chemical oxygen demand (COD). Studies were conducted in Lodz (Poland) between 2012 and 2015 on an urban catchment. Obtained data were analysed using the Pearson's correlation and principal component analysis method which enabled selection of the key parameters forming the model (depth and maximum intensity of rainfall and CSO volume). A good fit for the developed model was obtained ($R^2 = 0.79$ for TSS and $R^2 = 0.80$ for COD). The model was verified for two other catchments in the same city. Results indicate that the load of TSS and COD can be sufficiently precisely determined by using the proposed model for the studied city without the need to perform long-term continuous quality research of wastewater.

Key words | combined sewer overflow, emission of pollutants, pollutant load, predictive model, urban drainage

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INTRODUCTION

Operation of combined sewer systems in the urbanized areas still is associated with the functioning of sewer overflows, which emit large quantities of untreated sewage to receiving waters under wet weather conditions. This is especially true in the central districts of large cities, which were equipped with combined sewer systems more than 100 years ago, and since then have undergone numerous changes associated with the progress of urbanization and increase in built-up areas and their impermeability. These transformations enhanced the problem of functioning combined sewer overflow (CSO) facilities which discharge more often and with increasing volume of wastewater. Furthermore observed climate change can intensify these phenomena. The composition of wastewater discharged by the CSO is very variable and depends, inter alia, on the nature of land use in the catchment and on hydraulic parameters of the sewer system. Wet weather sewage is a mixture of wastewater and stormwater in different proportions of quantity and quality, especially depending on the characteristics of the rainfall.

According to Gasperi *et al.* (2010) dry weather wastewater constitutes the main source of organic and nitrogenous pollution, while runoff is the predominant source of zinc, copper, polycyclic aromatic hydrocarbons and total suspended solids (TSS). In-sewer processes also play an important role. According to research conducted in Paris and Lyon by Hannouche *et al.* (2014), the contribution of sewer deposits to wet weather suspended solid discharges is between 20 and 80% of the mass at the outlet, depending on the event. Knowledge of the characteristics of discharges of pollutants by a CSO is essential to protect the receivers. It is known that CSO impact on the receiving water body can be short-term (acute) and long-term. A short-term CSO impact depends on the type of river and is most significant in the case of small streams (Matzinger *et al.* 2012; Riechel *et al.* 2016). In the case of the River Spree (Berlin), the degradation of organic matter, reduced photosynthesis due to turbidity increase and mixing with CSO spill water poor in dissolved oxygen (DO) were identified as major

CSO-induced processes in the water body (Riechel *et al.* 2016). In many countries there are national recommendations and approaches to the CSO impact assessment. They are usually based on the use of concentration–duration–frequency thresholds for DO and NH₃ to take into account the highly dynamic nature of CSO events (Matzinger *et al.* 2012). Continuous monitoring of CSOs is expensive and sometimes complicated due to technical reasons. Therefore methods of similar accuracy but lower cost have been analyzed (Lacour *et al.* 2009; Hannouche *et al.* 2017; Montserrat *et al.* 2017). As noted by Dirckx *et al.* (2011) water quality modeling and monitoring are labour-intensive and/or very complex; thus water quantity monitoring seems a best option to characterize CSO spill behavior at an acceptable price. Hence, simplified methods to assess pollutant emission from CSOs and to reduce impact of overflows, based on rainfall and flow measurements in the sewage network, are being sought (Schroeder *et al.* 2011; Isel *et al.* 2014; Montserrat *et al.* 2015).

The main factor determining the occurrence of CSO events is the depth of precipitation on the catchment (Schroeder *et al.* 2011), but there are also other important factors such as previous meteorological and hydrological conditions, and watershed and sewer network characteristics (Mailhot *et al.* 2015). For example analysis carried out by Engelhard *et al.* (2008) showed a correlation of some emission-based indicators with discharged loads. However, none of the emission-based indicators were correlated to acute effects. Research conducted by Casadio *et al.* (2010) has shown good correlation between the concentration of TSS and the chemical compounds analyzed (biochemical oxygen demand, chemical oxygen demand (COD), heavy metals, total phosphorus) in CSO fluxes, suggesting that the greatest part of such substances is somehow linked to suspended solids. According to Sandoval *et al.* (2013) maximum and average rainfall intensities are the most influential variables to describe CSO water quantity and pollutant loads whereas the duration of the rainfall event and the rain depth seem to be the most important variables to describe CSO pollutant concentrations.

In consequence, assessment of load emitted from catchments is a complex problem. Depending on the methods, significantly different results may be obtained. In research conducted by Gamerith *et al.* (2011) for a built-up wash-off model a good correlation ($R^2 = 0.87$) was achieved for runoff volume and TSS. Kim *et al.* (2009) estimated pollutant load emitted from CSOs based on total rainfall depth, CSO volume and antecedent dry period (ADP) of each separate single event. According to Engelhard *et al.* (2008) the best fitted CSO performance indicator to describe receiving

water quality indicators (except acute impacts) is the mean annual overflow volume. If data of annual overflow volume are missing, the indicator of CSO efficiency defined as the percentage of the total rain runoff treated at the sewage treatment plant could be used.

The difficulty in developing CSO emission forecasts is mainly due to two factors. The first is the variation in precipitation characteristics and the second the possibility of occurrence of the ‘first flush’ of pollutants. Brezonik & Stadelmann (2002) determined that simple correlations between parameters of rainfall, catchment area and stormwater loads and event mean concentrations (EMCs) were weak. Rainfall amount and intensity and drainage area were the most important variables in multiple regression models to predict event loads, but uncertainty was high. Li *et al.* (2015) indicated that the mean rainfall intensity, the imperviousness rate, and maximum 5-min intensity were the critical parameters of EMCs in stormwater.

Generally, during CSO events in the case of intense rainfall events the first-flush effect is observed (Skipworth *et al.* 2000; Lee *et al.* 2004); however, this is not the case during prolonged rainfalls due to lower wash-off rate unless the accumulation prior to rainfall is high. Therefore, during the latter precipitations the dilution of wastewater in sewers is mainly observed. But if the accumulation of pollutants in the catchment area is large, a mass-limiting phenomenon may occur, where runoff is contaminated during the whole rain event. Therefore, the development and calibration of a credible model of flushing contaminants from the catchment surface can cause problems, in particular in the case of unrepeatable character of the rainfall and many other factors interlinked in some way.

The prediction of loads of CSO discharges based on rainfall data and volume of discharges may be a useful tool in selecting effective methods of CSO abatement and receiving water protection. In this paper a model of pollutant load emissions from a CSO (TSS and COD) based on parameters of precipitations on the catchment and measurements of wastewater level in sewers is presented. The model was developed for one real catchment and validated on two other real catchments in Lodz (Poland).

MATERIALS AND METHODS

Study site

Lodz is one of the largest cities of Poland with area of 293 km² and population of 706,000 inhabitants. The central

part of the city (area of 43 km², coefficient of catchment imperviousness equal to 0.43) is equipped with a combined sewer system. Other parts of the city have a separate system. The receivers of discharged wastewater from CSOs and stormwater drainage were identified as 18 small urban rivers. The presented research was carried out between 2012 and 2015. Studies were conducted on the catchment area corresponding to the CSO J1, by which a part of wet weather runoff is discharged to the river Jasień. This CSO is equipped with online measurements of flow as well as TSS and COD concentration. For this CSO based on results of quality analysis of sewage, measurements of flow in sewers and rainfall data, a predictive model of pollutants' emission was developed. Next, the model was verified for another two catchments – J4 and B1, also equipped with combined sewerage with CSOs. Location of all catchments is presented in Figure 1 and their characteristics in Table 1.

Rainfall characteristics

Lodz is equipped with a monitoring system of 30 rain gauges. One is located on each of the analysed catchments. During 2012–2015 there were 362 events with depths from 0.1 to 38.5 mm, 212 rain events had depth greater than 1.0 mm, 45 rain events greater than 10 mm and only 10 events over 20 mm. Maximum intensity (i_{\max}) of rainfalls varied from 0.11 to 78.01 mm/h, for 80% of events i_{\max} was above 1 mm/h, and for 10% of events, above 18 mm/h.

Characteristics of rain events for which CSO J1 discharges were studied are presented in Table 2. During the study period 38 rain events were analysed. Precipitation phenomena were defined as independent if the interval

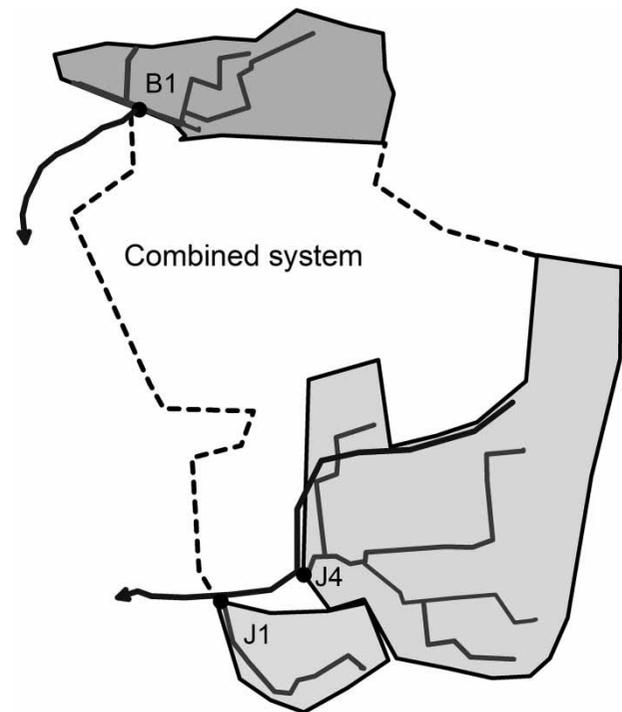


Figure 1 | Lodz urban catchments connected with the analysed CSOs; J1, J4, B1 – identifiers of the CSOs.

between next rain events was longer than 4 hours. The event threshold (separation time) was established based on the characteristics of the catchment area and time of rain water flow to and through the sewer system. The critical rainfall threshold causing the wastewater discharge from the CSO J1 is 2.9 mm (Table 1). This is the sum of the catchment and sewer retention, which must be exceeded in order to initiate overflow activity. The rainfall thresholds for analysed

Table 1 | Basic characteristic of the monitored catchments and CSO

	Parameters	Unit	J1	J4	B1
Catchment	Total area	(ha)	211	1,714	609
	Imperviousness	(%)	33	30	42
	Land use (order of decreasing share of surface)		MFR, G, IND	MFR, IND, G	MFR, SFR, IND, C, G
	Mean slope of terrain	(%)	0.58	0.73	0.63
	Mean slope of sewerage	(%)	0.45	0.76	0.53
CSO	Type of weir		side	side	side
	CSO weir length	(m)	4.92	12.00	12.74
	Mean dry weather flow	(m ³ /s)	0.09	0.82	0.47
	Critical flow ^a	(m ³ /s)	0.38	2.99	2.06
	Minimum dilution of sanitary flow		4.2	3.6	4.3
	Rainfall threshold for overflow	(mm)	2.93	1.79	2.97
	Frequency of overflow per year		23	13	19
	Average annual volume of overflow	(thousand m ³)	60	117	3812

MFR, multi-family residential; SFR, single-family residential; IND, industrial; C, commercial; G, green.

^aActivating the overflow.

Table 2 | Characteristics of rainfalls for which CSO J1 discharges were studied

Parameter	ADP [day]	Rain depth [mm]	Rain duration [min]	$i_{\max 5 \text{ min}^*}$ [mm/h]	i_{mean} [mm/h]
Minimum	0.2	3.1	25	2.4	0.4
Maximum	30.0	38.5	670	51.6	11.0
Median	4.0	9.9	197.5	14.8	2.6
Mean	6.0	12.0	293.7	17.8	3.4
Standard deviation	6.5	9.3	204.7	12.8	2.4

$n = 38$ (number of events).

$i_{\max 5 \text{ min}^*}$ – maximum intensity for 5 minute interval.

CSOs are presented in Table 1. The different values of this parameter result mainly from the above mentioned retention in the catchment area and in the sewer system as well as the overflow construction (its edge height above the sewer bottom). These values has been established from several years' observation of CSOs' activity and rainfall monitoring. Apart from many other factors, both the duration and the depth of precipitation have an impact on the flow volume and composition of wastewater discharged by the CSO into the environment.

Methodology of sampling and laboratory tests

Each of the studied CSOs is equipped with an automatic flowmeter which allows determination of the volume of sewage discharged into the receiving water. The flow was measured directly in the overflow and outflow sewers based on water level and flow velocity. For the online analysis of the loads emitted by the CSO J1, sensors from Hach Company called SOLITAX sc and UVAS plus, designed for monitoring TSS and dissolved chemical oxygen demand (COD_{sol}) were respectively used. The sensors were calibrated with an average R^2 value equal to 0.87 for both the dissolved COD and TSS (Brzezińska et al. 2016). The COD indicator was established based on:

$$\text{COD} = \text{COD}_{\text{sol}} + 0.86 \text{ TSS}^* \quad (1)$$

*according to experimental linear correlation.

For the J1 overflow an automatic sampler (6712 FR ISCO) collecting samples proportionally to the wastewater flow was used. In the case of J4 and B1 overflows the samples were manually collected at 5 minute intervals during the first part and at 15–20 minute interval in the second part of the runoff (depending on the depth observed in the sewer overflow).

The samples were refrigerated and analysed within less than 8 h after collection. For the collected samples ($n = 38$), TSS, COD and COD_{sol} , using standard methods, were determined. Characteristics of CSO J1 wastewater discharges, caused by rainfalls from Table 2, are presented in Table 3. The total discharge of wastewater was analysed. Taking into account possible breaks in the CSO wastewater discharges into the receiver, resulting from varying precipitation intensity and different wastewater inflow, a few overflows during a single rain event were treated as one, if the break between the rainfalls did not exceed 4 hours. Analyses were made in instantaneous samples and in a total flow-weighted sample (as EMC) from each discharge event.

Analyses of CSO J1 activity conducted for all events in 2012–2015 showed that a single volume of discharge was from 52 to 18,086 m^3 . The largest number of discharges (up to 30% of all events) was observed for the volume of wastewater of 2,000 m^3 .

The collected rainfall data and data of quality and quantity of wastewater discharged from CSO J1 were analysed using Statistica 10.0 and PQStat software.

RESULTS AND DISCUSSION

Wastewater characteristics

The EMC of pollutants and loads of wastewater emitted to the receiver in the period of J1 overflow duration are shown in Figure 2. The median of EMCs was estimated as 578 mg/L for TSS and 560 mg/L for COD. The range of EMCs for single events during the research conducted in CSO J1 varied from 258 to 1,966 mg/L for TSS and 256–1,710 mg/L for COD. The maximum concentration values were observed after the rain events of maximum intensity equal to 41.1 mm/h and duration 2.08 h. The pollutant

Table 3 | Characteristics of analysed discharges from CSO J1

Parameter	V_{CSO} [m^3]	T_{duration} [min]	EMC [mg/L]		
			TSS	COD	COD_{sol}
Minimum	92.0	33.0	224.0	256.0	4.0
Maximum	18,400.0	324.0	1,966.0	1,710.0	280.0
Median	599.5	87.5	578.3	559.7	84.0
Mean	2,540.3	111.8	667.7	668.0	89.5
Standard deviation	4,425.0	76.1	342.7	309.0	49.8

$n = 38$ (number of events).

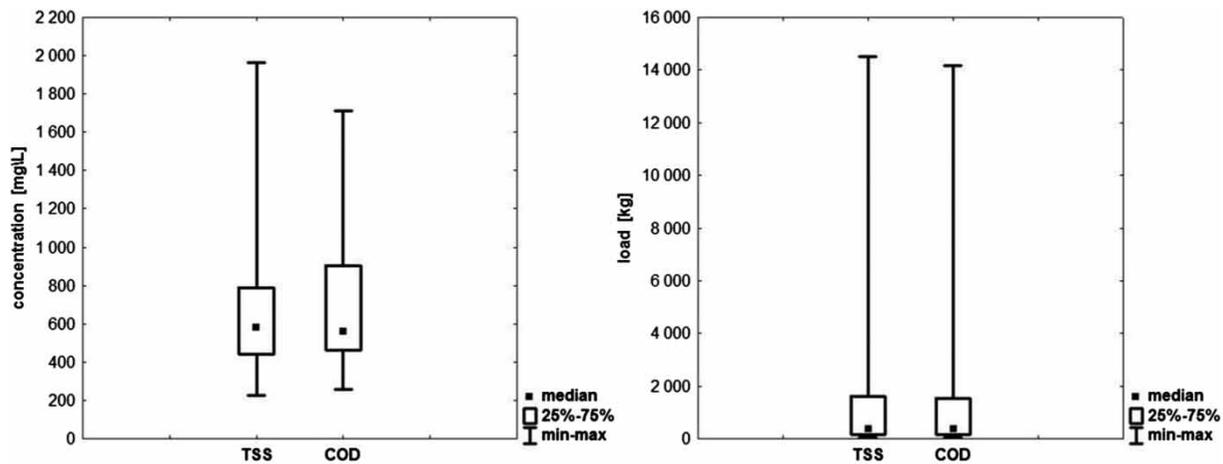


Figure 2 | Characteristics of pollutant concentrations (as event mean concentration of pollutants) and loads of CSO discharged. The central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers show maximum and minimum value from the data.

concentration measured in CSO discharges is usually very variable, which was also observed in researches from other countries. Brombach & Fuchs (2001) stated a range of concentration in the world for TSS of 35.3–661 mg/L (average- 226,7 mg/L) and for COD 33.3–581 mg/L (average- 192.6 mg/L). The research conducted by Gasperi et al. (2012) found a range of concentration of 135–353 mg/L for TSS and 136–446 mg/L for COD. As can be seen in Figure 2 the measured values obtained during the present study period were relatively high.

On the basis of the measured concentration and volume of discharged wastewater (calculated from measured flow rates) the loads of emitted pollutants for the individual events were estimated. The results are shown in Figure 2. The median of pollutant loads was 377 kg for TSS, 364 kg for COD. In some events several times higher load in the discharges was observed. This is believed to be the consequence of precipitations with very high maximum intensity, which probably result in sewer deposits being transported to the CSO. As highlighted by Hannouche et al. (2014), the contribution of

deposits in the system can be very high (up to 80% of TSS load observed at the outlet of the combined sewer system). Other research (Passerat et al. 2011; Caradot et al. 2013) also confirmed the high contribution of resuspension of sewer sediments and runoff to total CSO loads.

In wastewater some correlations were found, e.g. between TSS and COD – $R^2 = 0.87$, also between volume of discharged wastewater (V_{CSO}) and depth of precipitation (R_{depth}) – $R^2 = 0.7$. Other correlations between the analysed indicators were negligible.

Correlations between pollutants' indicators and rainfalls

Obtained data were used to develop a simplified model of pollutant emission from CSOs. First, findings from Pearson correlation analysis allowed determination of the key parameters affecting the amount of pollutant emitted by the CSO. Correlations between pollutants and rainfall parameters are presented in Table 4. These values show a very

Table 4 | Pearson's correlation coefficients between EMCs, loads of pollutants from CSO J1 and rainfall parameters (bold values indicate a certain strength of correlation between the studied variables)

	Parameter	ADP [day]	Rain depth [mm]	Rain duration [min]	$i_{max\ 5\ min}$ [mm/h]	i_{mean} [mm/h]	V_{CSO} [m ³]
Concentration	TSS	0.305	−0.106	−0.214	0.519	−0.05	0.16
	COD	0.370	−0.142	−0.179	0.517	−0.11	0.08
	COD _{sol}	0.179	−0.137	0.086	0.011	−0.12	−0.25
Load	TSS	0.189	0.532	−0.005	0.540	0.30	0.86
	COD	0.185	0.549	0.010	0.534	0.31	0.87
	COD _{sol}	0.092	0.681	0.113	0.367	0.47	0.90

weak correlation between pollutant concentration and rain parameters except for the relationship between TSS, COD and i_{\max} , which is substantial (coefficients moderately positive). Quite strong dependence was only noticed between load of pollutants and V_{CSO} (from 0.86 to 0.90) as well as between COD_{sol} load and rain depth (0.68). Table 4 was the basis for the development of a simple model for estimating the pollutant load discharged by a CSO to the receiver.

The attempt to establish the relationship between the CSO activity parameters and the precipitation parameters showed only a significant correlation between the depth of precipitation and the discharged volume of wastewater for single events ($R^2 = 0.70$). In comparison [Gamerith et al. \(2011\)](#) established significant correlation between overflow volume and annual rainfall runoff ($R^2 = 0.81$), but correlation between annual number of overflow and annual rainfall runoff was low ($R^2 = 0.37$).

In order to identify the major parameters for forecasting pollutant loads discharged to the receiver, the obtained data were analysed using the principal component analysis (PCA) method. Since it was assumed that the predictive model would be based only on the rainfall parameters and flow in the sewers, the pollutant concentrations of wastewater were not taken into account. PCA method determined the primary variables for the eigenvalues of the correlation matrix. The first component corresponding to the largest eigenvalue of 4.477 explained more than 49% of the total variance. The second component corresponding to the second eigenvalue equal to 1.954 explained more than 21%, and the third component corresponding to the third eigenvalue (equal to

1.036) explained over 11.5% giving the accumulated value of approximately 83%. Equations for the three main components were as follows:

$$\begin{aligned} \text{Component 1} = & 0.0339 \cdot \text{ADP} + 0.3376 \cdot R_{\text{depth}} \\ & - 0.0147 \cdot R_{\text{duration}} + 0.3057 \cdot i_{\max} + 0.167722 \cdot i_{\text{mean}} \\ & + 0.4455 \cdot V_{\text{CSO}} + 0.4404 \cdot L_{\text{TSS}} + 0.4450 \cdot L_{\text{COD}} \\ & + 0.4156 \cdot L_{\text{COD}_{\text{sol}}} \end{aligned}$$

$$\begin{aligned} \text{Component 2} = & -0.2786 \cdot \text{ADP} + 0.2488 \cdot R_{\text{depth}} \\ & + 0.5863 \cdot R_{\text{duration}} - 0.4098 \cdot i_{\max} - 0.5465 \cdot i_{\text{mean}} \\ & + 0.0895 \cdot V_{\text{CSO}} + 0.0240 \cdot L_{\text{TSS}} + 0.0396 \cdot L_{\text{COD}} \\ & + 0.1997 \cdot L_{\text{COD}_{\text{sol}}} \end{aligned}$$

$$\begin{aligned} \text{Component 3} = & -0.8128 \cdot \text{ADP} + 0.2466 \cdot R_{\text{depth}} \\ & + 0.0925 \cdot R_{\text{duration}} + 0.2435 \cdot i_{\max} + 0.3832 \cdot i_{\text{mean}} \\ & - 0.0122 \cdot V_{\text{CSO}} - 0.1609 \cdot L_{\text{TSS}} - 0.1619 \cdot L_{\text{COD}} \\ & - 0.1075 \cdot L_{\text{COD}_{\text{sol}}} \end{aligned}$$

These results indicate a good correlation between pollutant loads and rain depth, maximum rainfall intensity, and discharge volume. There was no correlation between pollutant loads and rain duration and ADP; additionally the correlation between pollutant loads and mean rainfall intensity was not significant. It is generally assumed that ADP has significant influence on pollutants washed off from the catchment. However, for the pollution load emitted to the receiver by CSOs ([Figure 3](#)), the major parameters are i_{\max} and R_{depth} probably because they may affect additionally the removal of deposits from the sewers.

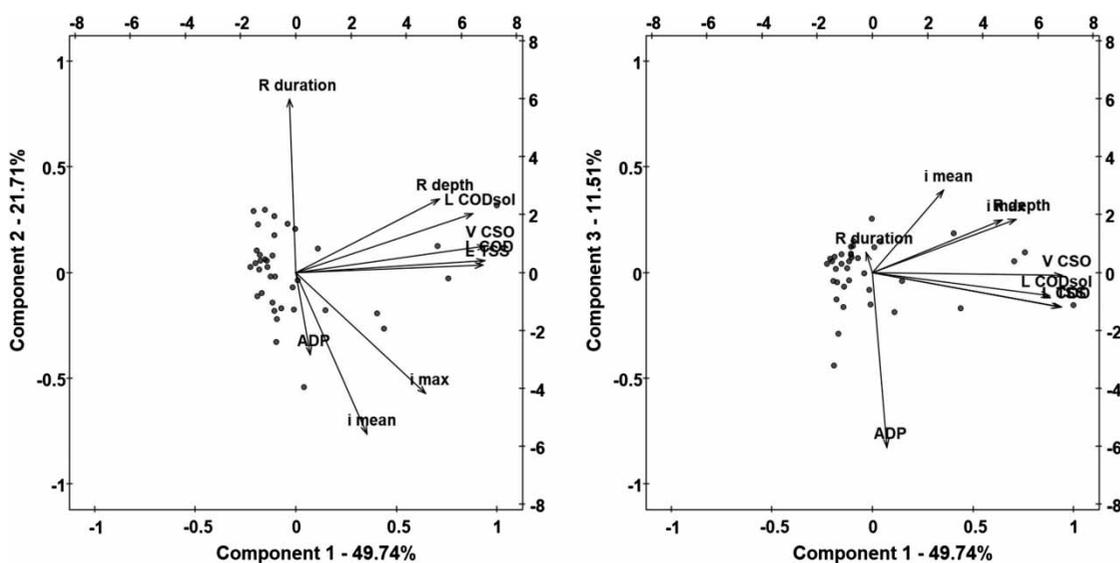


Figure 3 | Biplots for pollutant emissions and rainfalls.

Simplified model of pollutant load emission

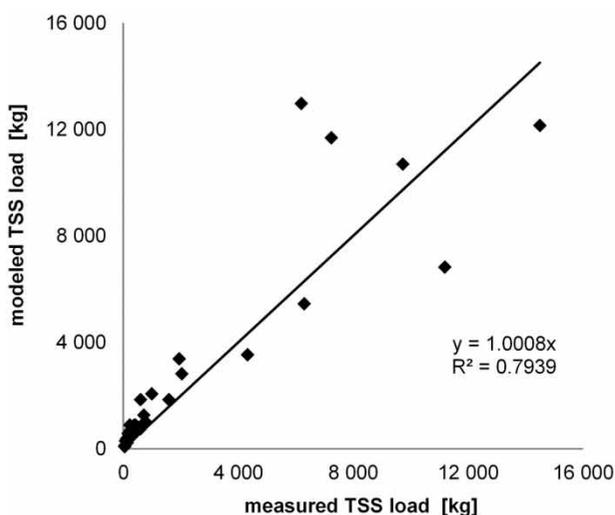
In previous studies (Brzezińska et al. 2014), the authors developed a simplified model for the assessment of pollution loads discharged to the receiving water based on the sum of the load originated by the runoff and dry weather flow. This method requires continuous monitoring of not only precipitation and flow rate in a sewer system but also quality parameters of the wastewater.

Obtained data did not allow development of a reliable predictive model for pollutant concentration in CSO discharges because of negligible correlations between rain parameters and wastewater quality indicators. The prediction of overflow quality is a very complex issue. In the analysis conducted by Sandoval et al. (2013), determination coefficients for prediction of CSO characteristics based on rainfall variables were rather low ($R^2 < 0.6$). However, the crucial point, for effective protection of a receiver, is the load of emitted pollutants, especially for small urban rivers.

The predictive model of pollutant emission from CSOs developed in Lodz was based on the three variables: rainfall depth, maximum rainfall intensity and volume of wastewater discharged from the CSO. For these variables the best correlations were estimated (Table 3, Figure 3). The model was created using the Statistica 10.0 software and multiple regression and is presented below.

$$L_{TSS} = 1.8R_{\text{depth}}^{-0.37} i_{\text{max}}^{0.21} V_{\text{CSO}}^{0.97}$$

estimation error $\pm 0.199 (p \leq 0.05)$ (2)



$$L_{\text{COD}} = 1.6R_{\text{depth}}^{-0.3} i_{\text{max}}^{0.22} V_{\text{CSO}}^{0.95}$$

estimation error $\pm 0.199 (p \leq 0.05)$ (3)

where:

L_{TSS} – load of total suspended solids [kg],

L_{COD} – load of chemical oxygen demand [kg],

R_{depth} – rain depth [mm],

i_{max} – rain maximum intensity [mm/h],

V_{CSO} – quantity of discharged wastewater [m^3],

The values 1.8 and 1.6 are the adjusted proportional coefficients.

These models enable the prediction of pollutant load emitted by CSOs only on the basis of rainfall parameters and volume of overflows without the need to study the composition of wastewater each time. The proposed model provides a reliable prediction, which can be confirmed by Figure 4 that shows the relationships between the measured values and the model results for TSS and COD for all analysed overflow events, according to Equations (2) and (3).

According to the developed model, the forecasted load depends mainly on the volume of wastewater to the power close to 1. It should be remembered that for a single CSO event, the volume of wastewater has a varying importance relative to the load of emitted pollutants. This is due to the fact that the precipitation parameters and a first-flush phenomenon significantly influence the concentration of pollutants in the surface runoff and CSO.

The model does not include ADP before rainfall. ADP was taken into consideration in the predictive model of

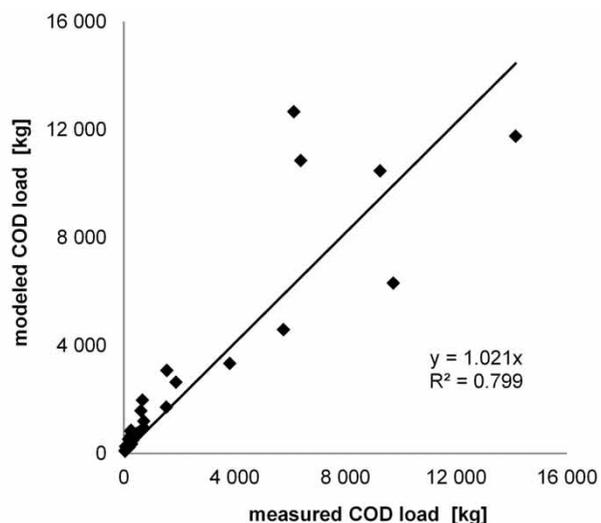


Figure 4 | Relationships between the measured values and model: (a) for TSS, (b) for COD.

pollutant concentration in stormwater runoff (Brzezińska et al. 2014). However, it should be noted that wastewater discharged by a CSO is a mixture of sanitary flow and stormwater, so the prediction of pollutant load discharged into a receiver depends also on other factors such as build-up or wash-off of sewer sediments, and not only on wash-off from the catchment surface of pollutants accumulated during dry weather conditions. The results of analyses carried out using the PCA method and multiple regression indicated that the parameters of rainfall and outflow from the CSO were the main factors in the prediction of the pollutant load emitted by the overflow, and in general ADP turned out to be significantly less important.

The created models have been validated on two other catchments described in Table 1. The results are presented in Figure 5 and show a good fit. The coefficient of determination for TSS was 0.89 for CSO B1 and 0.99 for CSO J4; for COD it was 0.43 and 0.99, respectively. The relatively

low $R^2 = 0.43$ for COD results from the character and spatial variability of precipitation. Rejection of the point which gives the highest load from the validation analysis results in a high value of $R^2 = 0.98$. It should be noted that this phenomenon was very different from other rainfalls because of its height of 15.2 mm and i_{\max} of 52.6 mm/h. The validation still requires a continuation, but it can be seen that the character of single rainfalls may have a significant effect on the final outcome in the case of low number of investigated CSO events. In order to obtain the model's compatibility with the measurements for a given catchment area, it was necessary to adjust the slope (proportional coefficients) in Equations (2) and (3). The proportional coefficient was 1.0 for TSS load for both catchments, and for COD load it was 0.8 for B1 and 0.4 for J4. The correction of these coefficients is required due to the different characteristics of each catchment: the land use, the location of pollutants' source, and the structure of a CSO, especially

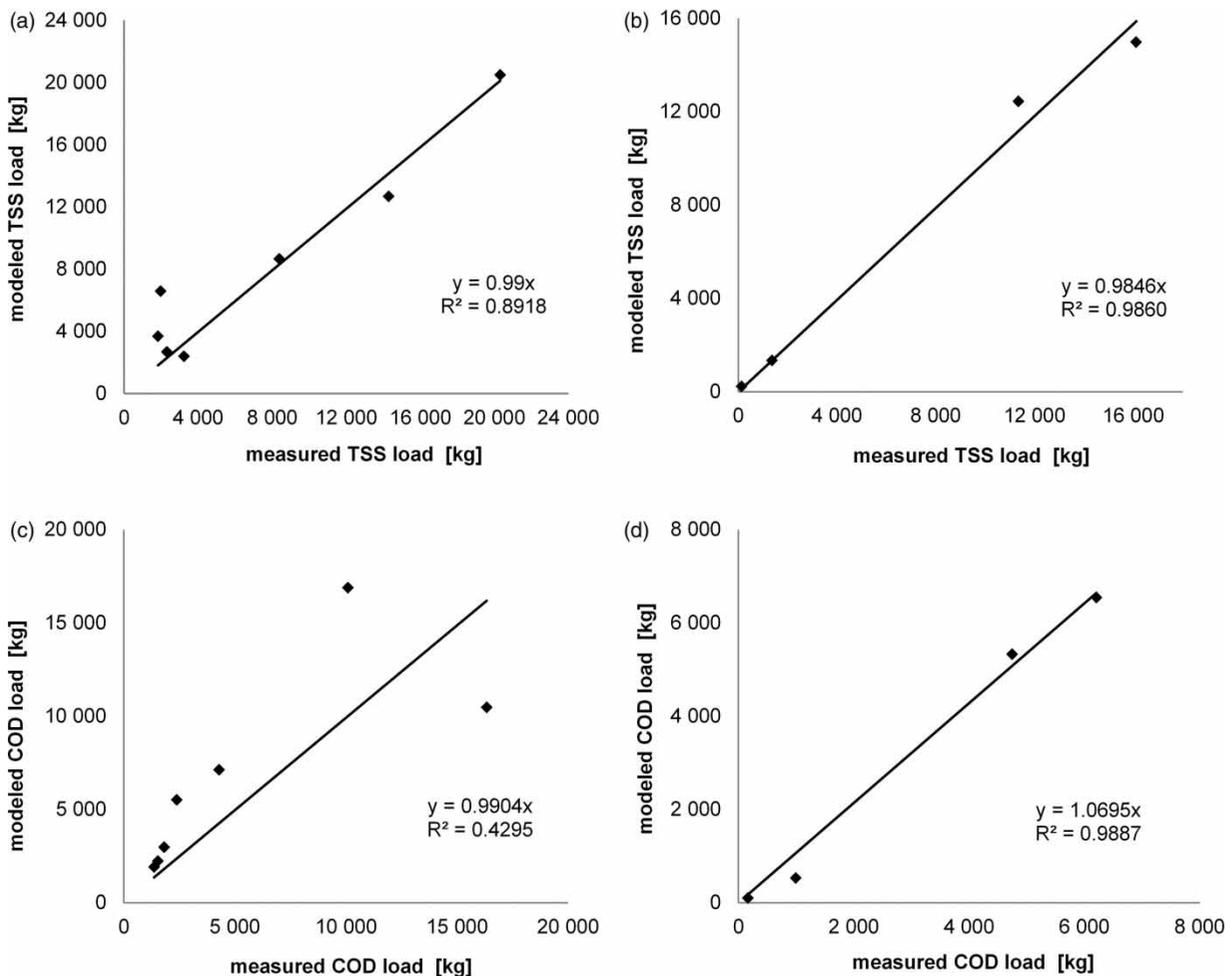


Figure 5 | Validation of created model for TSS and COD: (a) TSS for CSO B1, (b) TSS for CSO J4, (c) COD for CSO B1, (d) COD for CSO J4.

the dilution rate at which a CSO discharges. Hence, the validation confirmed that the developed predictive model of pollutant loads based on volume of overflow and the depth and maximum intensity of precipitation can be considered as universal, provided that it is calibrated at a given catchment.

CONCLUSIONS

CSOs are the main source of pollutants emitted to a receiver in an urban area equipped with combined sewer systems, and the estimation of discharged loads is of great importance. A predictive model of pollutant emission by CSOs is difficult to develop because of a large number of factors, inter alia rainfall parameters, which could have an important effect on the pollutant load transported in sewer systems. Data obtained in research conducted in Lodz were the basis for the simple model for forecasting loads of TSS and COD directed by a CSO to a receiver. The PCA method made it possible to identify the key factors of this model, which was finally based on rainfall parameters and discharged volumes of wastewater. The model allows for forecasting the pollutant emissions without the need for complicated and expensive wastewater quality analyses. The parameters which play a major role in this model are i_{\max} , R_{depth} , and V_{CSO} . Two factors have a significant impact not only on the contaminant wash-off from the catchment but also on the removing deposits from the sewers. In this case of a combined sewer system, ADP turned out to be insignificant, although this parameter had an important impact on the pollutant load emitted from the storm sewer system. The predictive model was developed with the use multiple regression with a progressive step-by-step method. The model fitting results between calculated load based on measured data and the modeled load was sufficiently good ($R^2 = 0.79$ for TSS and 0.80 for COD). The validation process confirmed the possibility of application of the model to other urban catchments provided adjustments are made to the proportional coefficients in the model. The proposed model may be particularly useful in circumstances when the time and funds for detailed analysis of wastewater quality are limited.

ACKNOWLEDGEMENTS

Scientific research has been carried out as a part of the project 'Innovative recourses and effective methods of safety

improvement and durability of buildings and transport infrastructure in the sustainable development – reduction of pollutant emission from urbanized areas into the environment', no. POIG.01.01.02-10-106/09-00 financed by the European Union from the European Fund of Regional Development based on the Operational Program of the Innovative Economy.

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First received 25 July 2017; accepted in revised form 22 January 2018. Available online 7 February 2018