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Catchment management influence on the magnitude of the total solids load conveyed by the stormwater sewer system – a comparative case study

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Abstract. The aim of the investigations was to make a comparative analysis of TSS concentration and variability in TSS loads as well as to analyse first flush phenomena. That issue is related to the characteristics of two urban catchments located in the city of Kielce. The runoff events observed in the period of investigations (years 2009 – 2016) showed a great diversity. The analyses performed for the study revealed substantial differences in the values of TSS concentration and loads in stormwater from the catchments of concern. The highest TSS concentration in the stormwater for the catchment located at the city outskirts was 252 $mg{\cdot}dm^{-3}$, whereas for the catchment in the city centre that value was almost 30 – fold higher and amounted to 7432 $mg{\cdot}dm^{-3}$. The analysis of the runoff first flush with respect to the mass of total solids in individual rainfall events showed substantial differences in the course of the process depending on the type of catchment management. In the densely built-up area, the initial 25% and 30% of the volume of runoff transported 25-41% and 30-48% of the solids mass, respectively. In the other catchment, with low and sparsely located buildings, the maximum values of TSS mass were considerably higher and amounted to 22-83% and 28-87%.

1 Introduction

As urban agglomerations tend to grow continuously over time, water from atmospheric precipitation is an ever increasing problem in urban areas. The separation of sanitary and storm sewers showed a negative impact of stormwater, carrying large amounts of pollutants from the catchments, on the aquatic and soil environments of the receivers. It was noticed that pollutant load and concentration in stormwater depend on many factors. They include, among others, the depth and intensity of rainfall, the event duration, season of the year, the length of the no-rain period that precedes precipitation, wind direction, direction of the migration of the precipitation front, the level of atmospheric pollution, topography, type and humidity of the catchment area (the percentage of impermeable surfaces, in particular), street cleaning procedures, vehicular traffic volume, the quantity and kind of dry deposits accumulated on paved surfaces, and even type of roof cover material [1-3]. The factors mentioned above determine the content of pollutants accumulated and washed off the catchment surface. The parameters that characterise stormwater include the following: pH, total suspended solids (TSS), petroleum-derived substances, heavy metals, chlorides, chemical oxygen demand (COD), biochemical oxygen demand (BOD_5), and biogenic compounds [1,3,4]. Investigations conducted in Poland [1,3,5,6] and abroad [7-15] report that the concentration of pollutants in stormwater from urban catchments vary substantially, even if the areas have similar land use. The statement above can be used to form a hypothesis that it is not possible to produce an estimate of the typical composition of stormwater.

It is characteristic of stormwater collection systems that pollutant load discharge over a unit of time is not uniform. The initial period of stormwater runoff, during which the concentration of pollutants is substantially higher than during later periods is called the first flush phenomenon (or simply the first flush) [16-18]. Investigations conducted in many countries, including Australia [19], Japan [20], USA [21], Korea [22], Italy [23] and Poland [1] provided different conclusions as regards causes, profile and magnitude of the first flush phenomenon in various sewage systems. In stormwater drainage system, the first flush phenomenon can occur quite often, although not in all rainfall events [24]. The results of investigations [17,25,26] indicate that strong first flush occurs in small catchments that have a significant portion of impervious surfaces, which is reflected in the runoff coefficient level of 0.7-0.8. Conversely, in vast catchments, the first flush phenomenon is much milder, if it occurs at all. That results from the mixing of various portions of runoff flowing from the catchment over a long-time interval.

Relying exclusively on solids concentration for the definition of the first flush phenomenon [27] is insufficient. When designing stormwater treatment plants, this criterion does not correctly represent the load

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on the facilities in the technological sense. The definitions of the first flush phenomenon that have been developed involve a comparison of the total load of pollutants with cumulative runoff volume. They give a percentage content of the pollutant mass in a specified assumed stormwater volume (%M/%V). Saget et al. [28] made an assumption that the first flush phenomenon occurs when 80% of pollutants is transported in 30% of the total runoff volume (80/30). Other researchers proposed slightly different ratio values, namely 80/20 [29], 40-60/25 [30], 40/20 [24] and 50/25 [2, 31].

In accordance with regulations that are in force in Poland [32], stormwater and snowmelt water from polluted impermeable surface that enter sewer systems, and are then discharged into water or soil, should not contain more than 100 $mg \cdot dm^{-3}$ of total solids and 15 $mg \cdot dm^{-3}$ of petroleum-derived hydrocarbons. Thus, emphasis is mainly put on typical pollutants, generally associated with the maintenance and use of travelway space (streets, carparks, pavements). The ranges of variation in concentration of suspended solids are so large that their proper estimation becomes of key importance when sizing stormwater treatment plants (SWTPs). Depending on the load (weight) of deposited solids, and also on basis of the computed values of surface runoff, it possible to optimally select the type and size of the devices (settling tanks).

The aim of the investigations was to make a comparative analysis of concentration and variability in the load of total suspended solids. Additionally, the first flush phenomena were examined on the example of two different urban catchment areas.

2 Materials and methods

2.1 Characteristics of the study area

The investigations into stormwater quality and quantity were conducted on two urban catchments in the city of Kielce, which differ in land use. The first catchment (IX Wieków Kielc SWTP – Fig.1b), having the total area of F = 62 ha., is located in the central-eastern part of the city. It holds main transportation routes, service sector areas, and high-rise residential buildings. In the catchment, six characteristic surface types with respect to runoff were identified: asphalt road surfaces (17.66%), pavements (8.41%), car parks (11.20%), roofs (14.27%), greenery (47.17%) and school playground (1.29%) [1, 6]. Overall, paved areas with a high runoff coefficient constitute 51.54% of the total area of the catchment, which indicates its typically urban character. The stormwater from the catchment area is collected by the existing stormwater sewer system and conveyed by main sewer to the stormwater treatment plant (SWTP) in IX Wieków Kielc Street (Fig. 1d). After treatment, wastewater is discharged to the receiving body, i.e. the river Silnica. The diameter of the main sewer, which is over 1.5 km in length, ranges from 600 mm to 1250 mm, and the diameters of 17 lateral sewers vary from 300 mm to 1000 mm [1, 6].

The other catchment (Witosa SWTP – Fig. 1c), which has an area of 83 ha, is located at the outskirts of the city. On the east, and partially north side, the catchment is surrounded by an open ditch collecting stormwater flowing from a dense forest area. The ditch turns into a ø800 mm closed sewer which is connected to sewer conveying effluent from the Witosa treatment plant (Fig. 1e). All the stormwater is piped (ø1400 mm) to the receiving water of the river Silnica. The land use in this catchment includes mainly green areas (uncultivated land, grassland, orchards – 56.6%), whereas single-family houses and multi-family residential buildings constitute the remaining part of the catchment, namely 43.4% of its area [33]. The sewerage system consists of the main sewer (ø1200 and 1400 mm), approx. 760 m in length, and lateral sewers (ø300 - 800 mm), currently collecting stormwater from Dąbrowa I housing settlement. The system is also intended to serve Dąbrowa II settlement, which is at the design stage and which is included in the city's land use plan [33].

2.2 Measurement apparatus

The measurement apparatus was installed in the separation chambers (Fig. 1) of both treatment plants. The ISCO AV 2150 module flow meters by Teledyne ISCO were used to measure stormwater quantity. The instrument operation is based on the measurements of water column pressure and average velocity in the sewer cross-section. Those quantities were recorded with AV probe mounted on the bottom of the inflow channel (5) – Fig. 1. The wastewater flow was calculated as the product of the wetted area of the sewer cross-section and the mean velocity of the wastewater flow. The measurement frequency during the peak runoff event ranged 15 - 30 s, and prior to the event 1 - 5 min, depending on the instrument setup. Stormwater samples were collected using ISCO 6712 portable sampler*s* by Teledyne ISCO which satisfies the requirements of the United States Environmental Protection Agency EPA. The devices were set up in a way to be activated as soon as the pre-set level of the wastewater in the sewer (~ 3÷5 cm) was exceeded. The wastewater level was recorded by the filling measurement probe, coupled to the device. The level of sampler triggering was adjusted to the season. Wastewater sewer, related to the season, is a sewer filling in rainless weather, which is the result of ground water infiltration. The number of wastewater samples (max. 24 bottles, each with capacity of 0.5 dm^3 –IX Wieków Kielc SWTP, and 1.0 dm^3 –Witosa SWTP) and the time interval between those (5–15 min) was set separately depending on expected duration of spring thaw event. Samples were not fixed but directly transported to the laboratory to determine selected parameters. The concentration of total suspended solids was determined using gravimetric analysis according to PN standard 72/C-04559/03. It is possible to relate the quantity of stormwater to the depth and course of precipitation owing to the analysis of the data recorded by rain gauges installed in both catchment areas. RG 50 Tipping Bucket Rain Gauge by SEBA Hydrometrie was installed in 2009, and Total Rain weighing Sensor TRwS by BMsonic in 2014. The measurement frequency of the first instrument was 2 min at 0.1 mm resolution, and for the second rain gauge, 1 min and 0.001 mm.

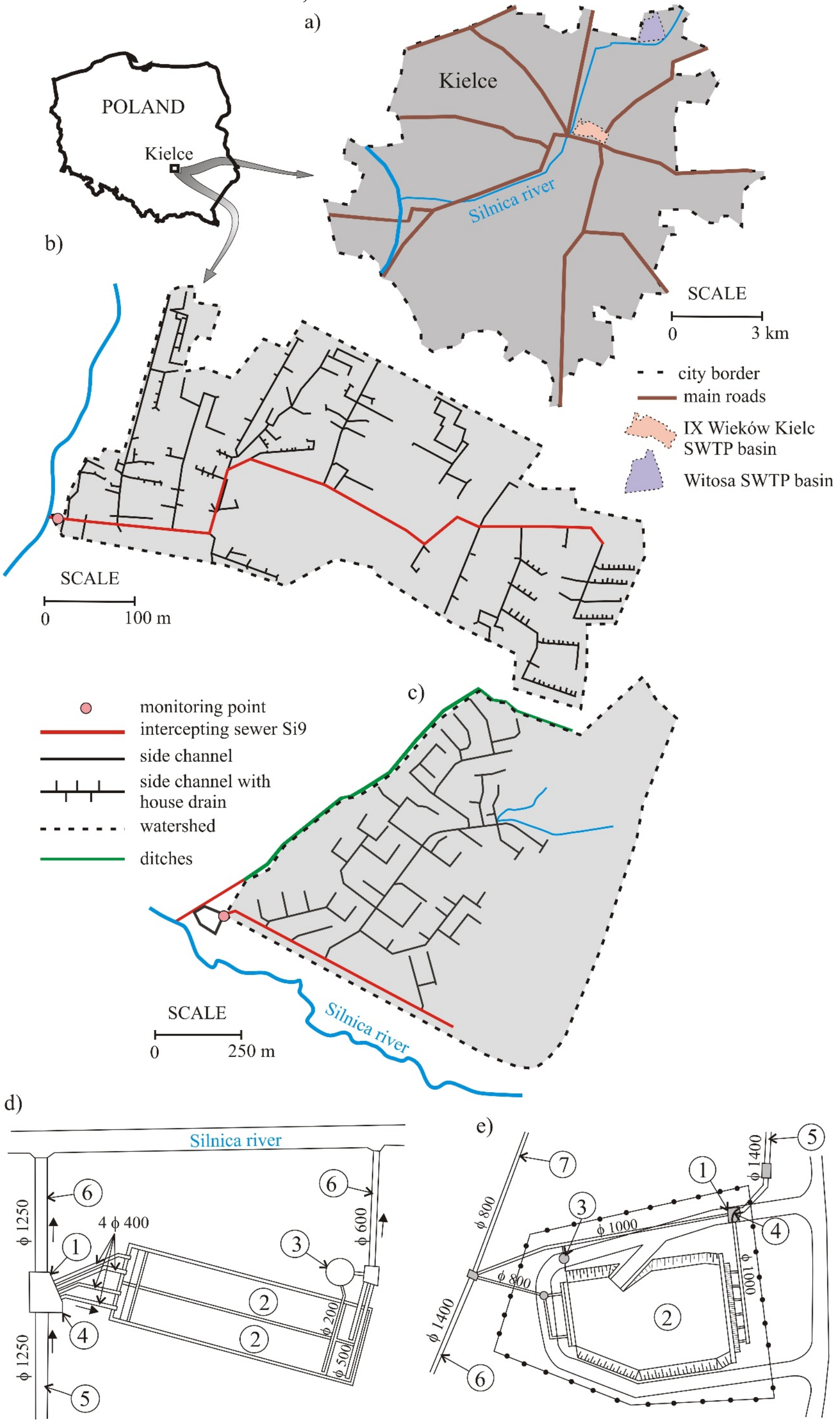

Fig. 1. Study area: a) location in the city of Kielce, b) IX Wieków Kielc SWTP catchment, c) Witosa SWTP catchment, d) scheme of the IX Wieków Kielc SWTP, e) scheme of the Witosa SWTP; 1 - separation chamber; 2 - horizontal settling tank; 3 - coalescence separator; 4 - regulated stormwater overflow; 5- inflow of stormwater, 6- outflow to the river Silnica, 7- inflow from the ditch.

2.3 Computational methodology

On the basis of measurement results and analyses of stormwater quantity and quality in observed runoff waves, the following were determined: concentration, loads and mass of total suspended solids, and also volume of runoff waves. Instantaneous loads of total suspended solids specified in sapling were calculated from the formula:

$$l = c_m \cdot Q, \quad g \cdot s^{-1} \qquad (1)$$

where: c_m – measured concentration of TSS ($g \cdot m^{-3}$), Q – stormwater flow rate ($m^3 \cdot s^{-1}$).

To calculate cumulative loads of total suspended solids in the peak runoff wave, it is necessary to know concentration at an arbitrary moment of the event duration. To this end, the measured values of concentration of total suspended solids were smoothed using the equation of the form: $c_a = f(t^m)$ and $c_a = f(e^{mt})$, where t is the time from the event beginning, and m is the exponent. That allowed the determination of concentration values beyond the time intervals in which stormwater was sampled for analyses. The measure of the accuracy of the regression fit to empirical data was the coefficient of determination R^2. The values of approximated loads of total suspended solids in time t_i of the peak runoff event were calculated from the formula:

$$l_{a\,i} = c_{a\,i} \cdot Q_i, \quad g \cdot s^{-1} \qquad (2)$$

$c_{a\,i}$ – approx. concentration of TSS in time t_i ($g \cdot m^{-3}$),
Q_i – stormwater flow rate in time t_i ($m^3 \cdot s^{-1}$).

The cumulative mass of total suspended solids M_{sum} which flew during the peak runoff event was determined from the formula:

$$M_{sum} = \sum_{i=1}^{n} \left(\frac{l_{a\,i} + l_{a\,(i+1)}}{2} \right) \cdot \frac{\Delta t}{1000}, \qquad kg \qquad (3)$$

where: $l_{a\,i}$, $l_{a\,(i+1)}$ – approximated load of TSS for time t_i and time t_{i+1}, respectively ($g \cdot s^{-1}$), calculated from formula (2), n – number of time steps, Δt – time step, $\Delta t = t_{i+1} - t_i$ (s).

The cumulative volume of a given whole wave event was calculated from the formula:

$$V_{sum} = \sum_{i=1}^{n} \left(\frac{Q_i + Q_{i+1}}{2} \right) \cdot \Delta t, \qquad m^3 \qquad (4)$$

where: Q_i, Q_{i+1} – flow rates in time t_i and time t_{i+1}, respectively ($m^3 \cdot s^{-1}$).

As regards time steps in Eqs. (3) and (4), the number n and the quantity Δt are 110 – 603 and 15 – 300 s, respectively. Those values are related to two different rates of data recording by flowmeters, which depended on the fill level of the sewer.

Mean concentration of total suspended solids for a given peak runoff event was determined from the formula:

$$c_{avg} = \frac{1000 \cdot M_{sum}}{V_{sum}}, \qquad g \cdot m^{-3} \qquad (5)$$

To assess the dependences between individual parameters characterising precipitation events (presented in Table 1), and the characteristics of peak runoff events and of stormwater quality with respect to total suspended solids (Table 2), Kendall's Tau coefficient of rank correlation, was employed. It was determined using the STATISITCA program.

In order to describe the phenomenon of the first flush, dimensionless curves were plotted that show the relation between the cumulative mass of total solids M/M_{sum} and the cumulative volume of the runoff wave V/V_{sum}. Figure 4 shows the curves for all the events analysed. The criterion of the occurrence of the first flush was the definition given by Saget et al. [28] and also by Sansalone and Buchberger [2], namely the ratio the cumulative mass of total suspended solids to the cumulative volume of the runoff wave (M/V) of 80/30 and 50/25, respectively.

3 Results and discussion

Measurements of quantities, and quality investigations into snowmelt runoff event were conducted in the years 2009-2010 for the catchment of IX Wieków Kielc SWTP, and in the years 2015-2016, for the catchment of Witosa SWTP. The analyses included spring peak runoff of the rainfall events (April – June) and runoff of one snowmelt event (February 2010) observed in the first facility, in which the highest concentration of total suspended solids was noted. As regards the catchment of Witosa SWTP, the lack of data on the winter event makes it impossible to determine and compare the concentration in winter peak runoff events in the catchments.

Peak runoff events, selected for the study, resulted from rainfall events that had diversified characteristics (Table 1). As regards IX Wieków Kielc SWTP catchment, the cumulative precipitation depth ranged from 1.3 to 6.6 mm, and the maximum values of rainfall intensity were from 0.1 to 0.8 $mm \cdot min^{-1}$. The highest average rainfall intensity was noted on 30 May 2010, when the rain lasted less than 56 min (I_{avg} = 0.049 $mm \cdot min^{-1}$).

In Witosa SWTP catchment, precipitation depth ranged from 1.35 to 7.76 mm, and the values of the maximum rainfall intensities were 0.23 to 1.16 $mm \cdot min^{-1}$. Like previously, the highest average rainfall intensity was identified during a short event (t_r = 7 min) which occurred on 31 May 2016 (I_{avg} = 0.286 $mm \cdot min^{-1}$).
The rainfall lower than 2 mm was taken to analyze (floods of 21 April 2010 and 29 April 2015 - Table1), although this value is taken as the retention capacity of the catchment. However, the flow measurements carried out in the inflow channels to the given SWTP indicate an increase in filling even with low rainfall. This is explained by the emergence of surface runoff from impermeable areas (roads, parking lots, roofs), whose retention capacity is at the level of 0.2 mm.

When analysing the parameters of precipitation that preceded the observed peak runoff event, it is necessary to account for the length of the inter-event time that affects the amount of pollutant deposition in the catchment area. That is of particular importance in the early spring when sand, used in the road and pavement winter maintenance, is found lying around. Magnitude and intensity of the precipitation event are also significant as they influence the quantity of mineral particles that are washed out.

In the catchment of Witosa SWTP, in which low-rise single-family and multi-family residential buildings are located, the highest maximum concentration of suspended solids was found as 70.6 and 252 g·m^{-3} (Table 2). That occurred for the events of 09 June 2016 and 30 May 2016 which were preceded by the longest inter-event time (t_{ie} = 155 and 379 h). Comparably maximum concentration of suspended solids (70.0 g·m^{-3}) was recorded for the event of 20 May 2015. In this case, the length of the inter-event time was as short as 8.2 h, which suggests the concentration of solids in the peak flow wave was supposedly related to the great intensity of the rainfall (I_{max} = 1.16 mm·min^{-1}). In heavy rainfall, soil particles were washed out of the green areas that constitute almost 57 % of the total area of the Witosa SWTP catchment.

Table 1. Selected precipitation characteristics

Date	Parameters of the precipitation of concern				Parameters of the precipitation that preceded the precipitation of concern				
	P (mm)	t_r (min)	I_{avg} (mm·min^{-1})	I_{max} (mm·min^{-1})	t_{ie} (h)	P (mm)	t_r (min)	I_{avg} (mm·min^{-1})	I_{max} (mm·min^{-1})
IX Wieków Kielc SWTP									
09.05.09	2.60	122	0.021	0.10	581.3	3.50	77	0.045	0.20
06.06.09	2.10	50	0.042	0.60	152.2	3.20	155	0.021	0.10
21.04.10	1.30	78	0.017	0.10	158.1	3.10	311	0.010	0.10
05.05.10	6.60	298	0.022	0.30	13.7	8.10	544	0.015	0.20
30.05.10	5.40	56	0.096	0.80	71.2	2.80	22	0.130	0.80
31.05.10	4.00	168	0.024	0.20	8.2	5.40	56	0.096	0.80
Witosa SWTP									
29.04.15	1.35	65	0.021	0.23	54.5	2.33	150	0.016	0.30
14.05.15	2.07	37	0.056	0.42	2.0	2.08	19	0.110	0.45
20.05.15	7.76	138	0.056	1.16	8.2	9.31	597	0.016	0.23
26.05.15	2.70	103	0.026	0.25	58.1	3.53	488	0.007	0.06
09.06.15	4.67	90	0.052	0.37	155.0	5.89	13	0.453	0.93
30.05.16	3.84	75	0.051	0.31	379.0	4.73	714	0.007	0.09
31.05.16	2.00	7	0.286	0.83	18.5	3.84	75	0.051	0.31

Notations: P – cumulative precipitation depth during a rainfall event t_r, I_{avg} – mean precipitation intensity for time t_r, I_{max} – maximum precipitation intensity, t_{ie} – the inter-event time

Table 2. Concentration, loads and mass of TSS and basic parameters of runoff events

Date	Number of samples	Measured concentrations				Loads and mass		Parameters of runoff events		
		Min. (g·m^{-3})	Max. (g·m^{-3})	Mean (g·m^{-3})	Median (g·m^{-3})	$l_{a\ max}$ (g·s^{-1})	M_{sum} (kg)	Q_{max} (m^3·s^{-1})	t (min)	V_{sum} (m^3)
IX Wieków Kielc SWTP										
09.05.09	8	765	1735	630	978	185.0	399.0	0.313	150	633
06.06.09	7	540	790	554	611	230.0	283.0	0.361	185	511
23.02.10*	12	4181	7432	4457	5422	225.0	2995.0	0.042	515	672
21.04.10	8	100	145	108	140	6.1	22.9	0.046	278	212
05.05.10	24	70	169	89	89	13.2	104.0	0.101	442	1174
30.05.10	9	120	125	122	122	34.5	83.7	0.277	162	685
31.05.10	14	80	296	119	89	24.8	69.3	0.140	257	580
Witosa SWTP										
29.04.15	9	0.1	4.0	1.8	2.3	0.37	0.42	0.060	110	239
14.05.15	5	8.6	38.7	13.7	15.7	4.02	2.25	0.104	97	164
20.05.15	19	1.6	70.0	20.9	10.1	10.00	14.00	0.542	140	670
26.05.15	8	1.4	33.7	18.5	10.7	1.25	2.64	0.063	110	143
09.06.15	22	1.5	70.6	38.2	30.2	15.00	20.70	0.239	203	543
30.05.16	15	38.6	252.0	44.2	39.8	18.10	18.70	0.413	110	423
31.05.16	9	38.9	40.7	39.6	40.0	6.62	6.92	0.166	93	175

Notations: Q_{max} – maximum stormwater flow rate, t – total duration of the flow, V_{sum} – cumulative volume of the whole wave event;
* snowmelt runoff event

For the other facility, namely IX Wieków Kielc SWTP, the findings on the impact of inter-event time on the magnitude of concentration and loads of suspended solids are inconclusive. It could suggest that the number of factors that influence the runoff quality is greater than expected, and it is difficult to specify a typical stormwater composition.

The observations are confirmed by the results of analyses of Kendall's Tau coefficient of rank correlation. For the peak runoff events observed in the Witosa SWTP catchment, a very strong, statistically significant (significance at the level of 5%) correlation holds between the length of the inter-event time, and mean (r = 0.81) and maximum (r = 0.71) concentration of TSS in

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the rainfall events, and also the mass of suspended solids washed off the area surface (r = 0.71). Such dependences were not found for IX Wieków Kielc SWTP.

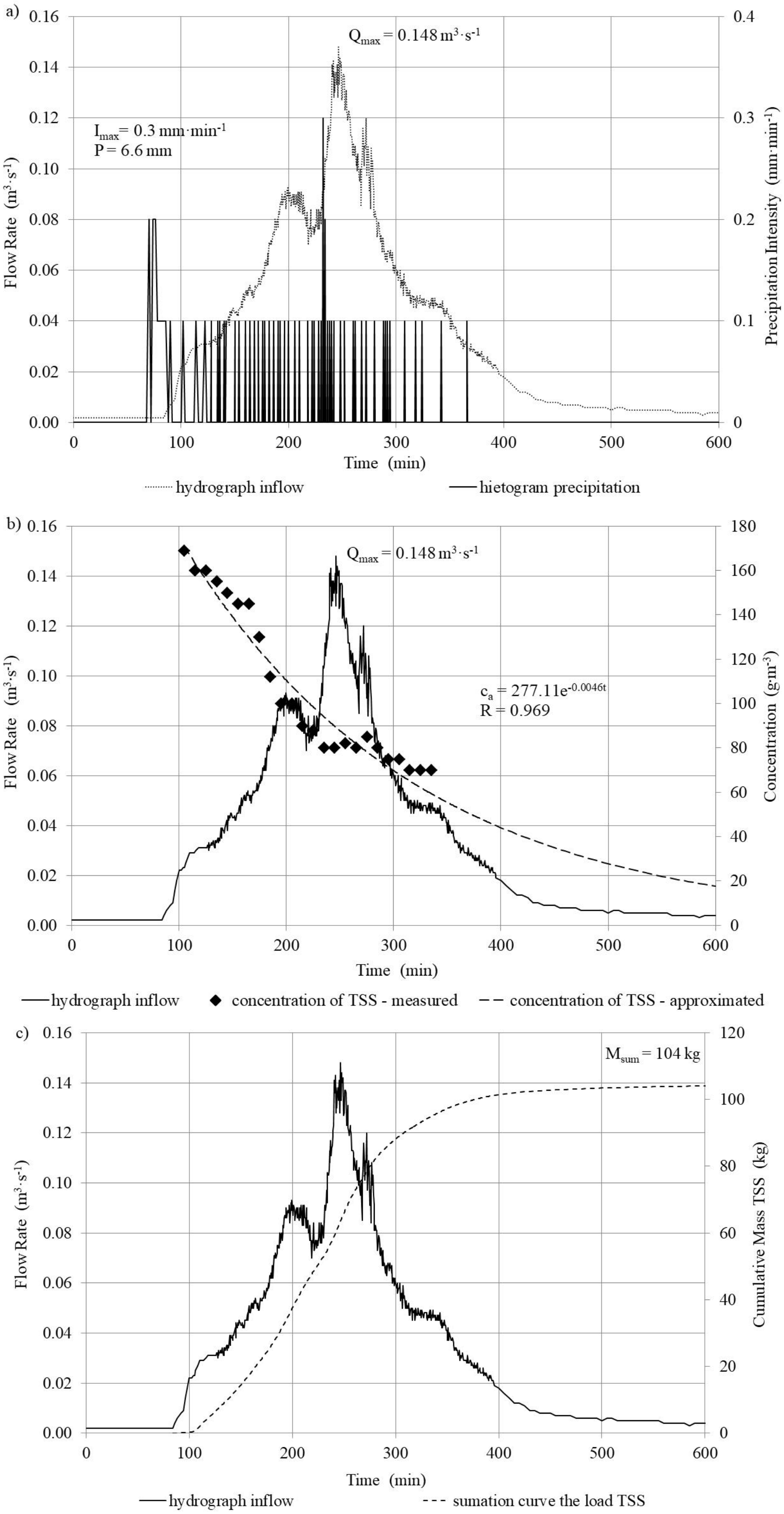

Fig. 2. Characteristics of selected peak rainfall runoff event of 05 May 2010 for IX Wieków Kielc SWTP catchment with respect to stormwater flow rate, precipitation intensity, and also concentration and mass of TSS.

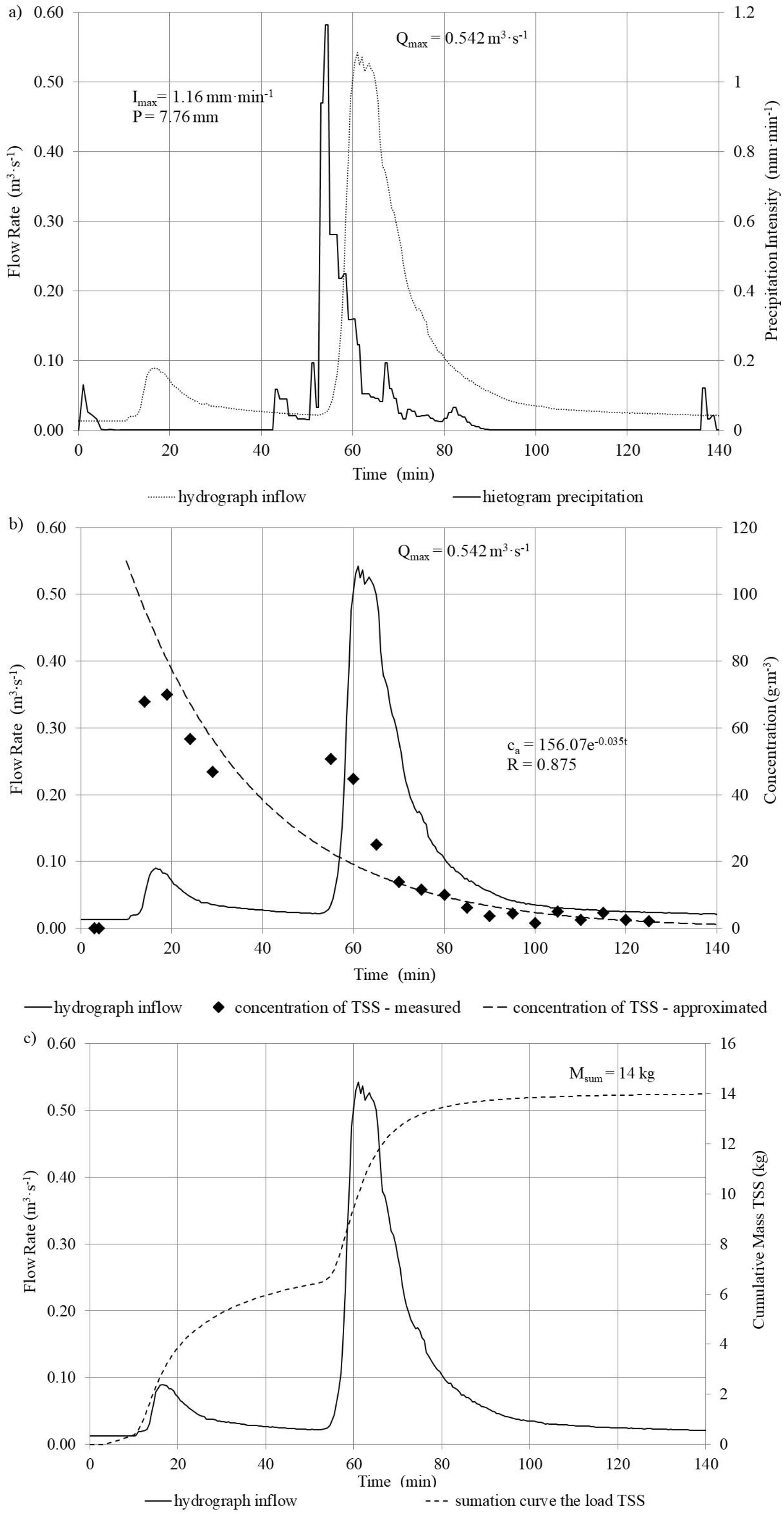

Fig. 3. Characteristics of selected peak rainfall runoff event of 20 May 2015 for Witosa SWTP catchment with respect to stormwater flow rate, precipitation intensity, and also concentration and mass of TSS.

The differences in land use between the two catchments are manifested in the characteristics of the peak flow events and mass of suspended solids deposited in the items of the stormwater treatment plant (settling tanks). For Witosa SWTP, the computed cumulative mass of suspended solids did not exceed 20.7 kg, which seems to be a very small quantity when compared with the value of up to 399 kg reported for IX Wieków Kielc SWTP. Generally, much higher quantities of suspended solids are conveyed to the sewerage systems in snowmelt events. For instance, during the peak flow event of 23 Feb. 2010, which lasted 515 minutes, 2995 kg of mineral and organic suspended solids flew into the settling tanks of IX Wieków Kielc SWTP.

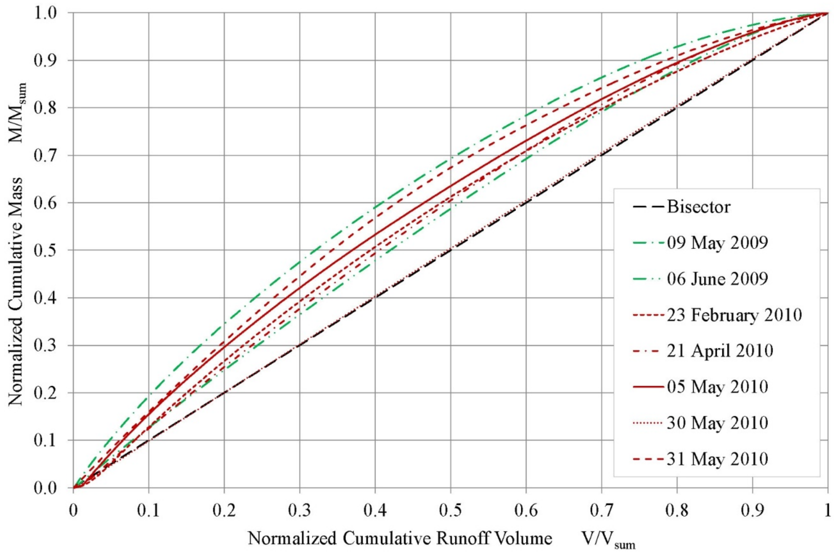

Fig. 4. Dimensionless curves of cumulative TSS mass vs. cumulative discharged volume for IX Wieków Kielc SWTP catchment.

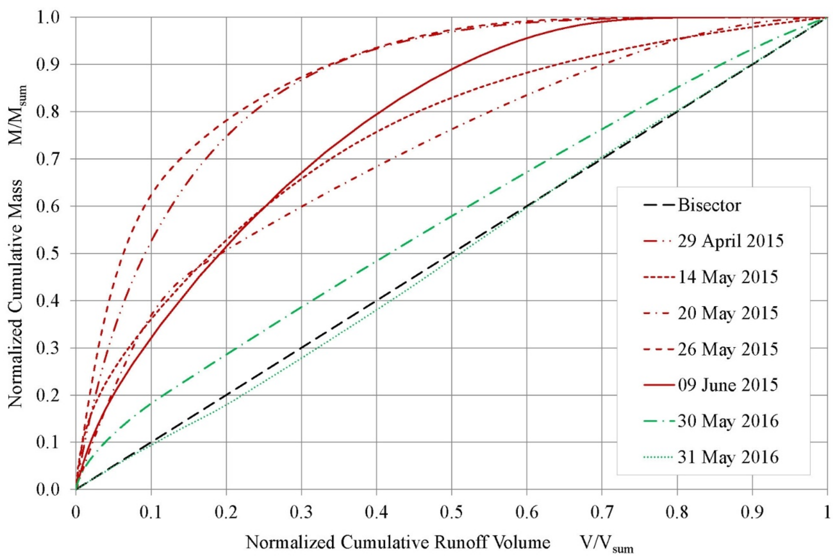

Fig. 5. Dimensionless curves of cumulative TSS mass vs. cumulative discharged volume for Witosa SWTP catchment.

The pattern of variation in the concentration of suspended solids in the peak runoff events reveals certain characteristics (Fig. 2 and Fig. 3). At the initial stage of the flow event (rising limb of hydrograph), concentration of suspended solids is generally much higher that at the final stage of the event (recession limb of hydrograph). That is related to the washing out of mineral and organic pollutants lying on the catchment surface, which occurs during the first phase of precipitation. The peak runoff events of 21 April 2010 and 30 May 2010 (IX Wieków Kielc SWTP), in which observed ranges of suspended solids concentration was low (Table 2) are exceptions to rule quoted above.

On the basis of the analysis of concentration of suspended solids (Table 2), it can be stated that the computed mean values do not always reflect the level of stormwater pollution. It seems reasonable to rely on the values of medians. For instance, for the peak flow events

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of 09 May 2009 and 20 May 2015, the mean values and medians were 630 and 978 g·m^{-3}, and also 20.9 and 10.1 g·m^{-3}, respectively. The reason are outlier values that most often overrate, and occasionally underestimate, mean concentration of pollutants. The instant of sample collection during the peak flow event and the number of samples are extremely important for the estimation of the pollution level of stormwater. That value is necessary at the design stage of the treatment plant, and also to evaluate the operational efficiency of the existing facility.

The analysis of the first flush phenomenon shows a clearly distinct pattern of the curves that express the content of the mass of pollutants in the specified adopted stormwater volume (Fig. 4 and Fig. 5) for both catchments of concern. As regards the IX Wieków Kielc SWTP catchment, the curves are smoother in shape, approaching a straight segment (bisector) which expresses uniform M/V ratio. For the peak flow event of 30 May 2010, the curve practically coincides with a straight segment (Fig. 4). Adopting the 80/30 criterion [28] and the 50/25 one [2], it can be stated that the first flush did not occur in any of the peak flow events. The first 30% and 25% of the runoff transported from 30% to 48%, and also from 25% to 41% of the solids mass, respectively.

The dimensionless curves plotted for the Witosa SWTP catchment show quite a different pattern (Fig. 5). In a majority of cases, in the first phase of the peak event, the flow of pollutants is much higher than during the later stages. The initial 30% and 25% of the cumulative volume of the runoff transported from 28% to 87%, and from 22% to 83% of the mass of the total solids, respectively. In accordance with the criterion formulated by Saget et al. [28], it can be stated that the first flush occurred twice, namely on 29 April 2015 and 26 May 2015. Conversely, when the criterion established by Sansalone and Buchberger [2] is applied, 5 out of 7 peak flow events would be classified as including first flush. Only two events, namely those of 30 May 2010 and 31 May 2010 would not be categorised as such.

The results of investigations indicate that strong first flush phenomenon does not necessarily occur in small catchments having a high share of impervious surfaces. Although the IX Wieków Kielc SWTP catchment with an area of 62 ha shows a high proportion of impervious surfaces (51.54%) and a substantial value of runoff coefficient, namely above 0.8, the first flush phenomenon was not observed. In the other catchment having a similar total area (82 ha), but much lower content of impervious surfaces (low-rise single- and multi-family buildings, and runoff coefficient below 0.7), the phenomenon was observed a few times. That situation can be affected by the length of inter-event period that preceded the peak flows of concern, and also by the dynamics and course of the events. Additionally, it should be emphasized that in the Witosa SWTP catchment, the total mass of TSS transported during the peak flow events was many-fold smaller than in IX Wieków Kielc SWTP catchment, which produced a direct effect on the results. Small amounts of solids deposited on the area surface were, in a majority of cases, washed out during the initial phase of the precipitation event.

4 Conclusions

For the peak runoff events observed in Witosa SWTP catchment, a strong, statistically significant (significance at the level of 5%) correlation holds between the length of the inter-event time, and mean (r = 0.81) and maximum (r = 0.71) concentration of TSS in the rainfall events, and also the mass of suspended solids washed off the area surface (r = 0.71). With respect to the remaining precipitation characteristics (P, I_{avg} t_r, I_{max}) such relations were not found for either catchment. That confirms the catchment characteristics, in particular the percentage of impervious surfaces and their type (which decides the cleaning procedures and winter maintenance) are the basic factors that influence the values of concentration and loads of TSS. When the share of low-rise single-family and multi-family residential buildings and green areas is high, and when local roads outnumber main transportation routes, the maximum concentration of TSS can be even several dozen lower than for the catchment with opposite characteristics. That is directly translated to the mass of TSS ($Ł_{sum}$) deposited in the settling tanks of the stormwater treatment facilities. With respect to rainfall peak flows, TSS mass did not exceed 21 kg for Witosa SWTP, whereas for IX Wieków Kielc SWTP it reached almost 400 kg.

It seems reasonable to use median values instead of mean concentration of TSS when estimating the level of pollution in stormwater. TSS concentration medians ranged 89 - 978 g·m^{-3} for IX Wieków Kielc SWTP, while for Witosa SWTP they were much lower (2.3 - 40 g·m^{-3}). Thaw peak flows resulted in much higher values of TSS concentrations (mean 4457 g·m^{-3}, median 5422 g·m^{-3}, max. 7432 g·m^{-3}) in the IX Wieków Kielc SWTP catchment compared with rainfall peak flows. That needs to be taken into consideration in the design of the active volume of settling tanks and in calculations of the efficiency of pre-treatment facilities.

In hydraulic dimensioning of stormwater treatment plants, TSS loads should be primarily accounted for to calculate the optimal load on technological facilities. Relying exclusively on TSS concentrations can be misleading. Maximum loads of TSS ($ł_{a\ max}$) ranged from 6.10 g·s^{-1} to 230 g·s^{-1} (IX Wieków Kielc SWTP) and from 0.37 g·s^{-1} to 18.1 g·s^{-1} (Witosa SWTP).

In a majority of the peak rainfall runoff events, the first flush carried higher concentration of TSS than it was the case in the final stage. For IX Wieków Kielc SWTP catchment, the values were twice higher on average, whereas for Witosa SWTP catchment, even more than 20-fold higher, reaching the levels of 1735 g·m^{-3} and 252 g·m^{-3}, respectively.

As regards the two catchments under consideration, the first flush phenomenon was observed solely in the area with a much smaller share of impervious surfaces, which is expressed by low runoff coefficient (Witosa SWTP). When the 80/30 criterion is adopted, it can be stated that the phenomenon occurred twice, whereas for the 50/25 criterion, 5 out of 7 events would be classified as first flush. For the sake of design and operational procedures for the entities that deal with stormwater drainage systems, it is recommended that pollution diagrams should be used on practical basis. Readings of the percentage load of TSS for a given percent of the whole wave volume should be taken. The diagrams could be applicable to the design of holding tanks and stormwater treatment plants.

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