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Changes of heavy metal concentration in rainfall wastewater in urban catchment

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ABSTRACT

The article presents the results of a study into rainfall wastewater pollution in a catchment area of 62 ha, located in the central part of the city of Kielce, where the construction of a large-format retail facility was conducted. The samples of stormwater were collected to determine pH, total suspended solids (TSS), and heavy metals (Ni, Cu, Cr, Zn, and Pb). The performed analysis of variance (ANOVA) shows that the average concentrations of TSS in the stormwater samples collected during the construction works (1,913–57,814 mg dm^{-3}) were considerably higher than that recorded in the period preceding these works (106–126 mg dm^{-3}) and after their completion (978–1,089 mg dm^{-3}). The conducted investigation showed that the highest average concentrations of nickel (0.30 mg dm^{-3}), copper (0.43 mg dm^{-3}), chromium (0.33 mg dm^{-3}), and zinc (2.40 mg dm^{-3}) were recorded in stormwater samples taken in 2011. On the other hand, the ANOVA results did not indicate significant differences in the heavy metal concentrations in stormwater samples collected during the freshets in 2010 and 2012.

Keywords: Rainwater; Heavy metals; Total suspended solids; Urban catchment

1. Introduction

Waters of atmospheric origin in urban areas constitute an ever-growing problem due to continuing agglomeration growth. Precipitation waters, collected by means of combined sewage or storm drain systems, are classed as wastewater. The degree of surface sealing affects the volume of precipitation water that appears, while spatial land development affects its quality. It has been observed that pollutant loads and concentrations in precipitation waters depend, among other factors, on rainfall intensity, rainfall duration, the season, dry weather spells preceding the precipitation, the degree of atmospheric pollution, the volume of green areas, the type of paved surfaces, street maintenance methods, the quantity and type of dry deposit collected on paved surfaces, as well as the type of roofing materials [1–5]. The parameters that characterize stormwater include the following: pH, total suspended solids (TSS), petroleum-derived substances, heavy metals, chlorides, chemical oxygen demand, biochemical oxygen demand and biogenic compounds. Investigations conducted in Poland [3,6–8] and abroad [9–18] report that the concentrations 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.

The problem of limiting the harmful influence of precipitation wastewater on soil and water environments is more and more often becoming an integral part of planning and design of sewage systems in anthropogenically affected areas. Nonpoint sources of pollution are among the main reasons for water quality degradation. The greatest influence on

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pollution content in surface runoff comes from transportation and leaching of the sediments deposited in sewage collectors [9,19]. The runoff due to high-intensity precipitation causes hydraulic and pollution loads in sewage systems, which are several times higher than those during dry weather. A typical phenomenon is the first wave of runoff, characterized by occurrence of the highest pollutant loads at the onset of runoff. The phenomenon of the first wave of runoff depends mainly on precipitation intensity and duration, land use, as well as dry weather spells, which in turn affects the quantity of pollution collected in the catchment area [11,20]. The range of factors affecting the composition and type of rainfall wastewater makes it difficult to speak of typical rainfall wastewater composition, and it is only through verification of theoretical assumptions by means of testing the wastewater from a particular catchment that any generalizations can be made.

The research is primarily aimed at determining the impact of construction works on the quality of stormwater. The secondary objective is to assess the degree of contamination of this stormwater with TSS and selected trace elements (Ni, Cu, Cr, Zn, and Pb).

2. Materials and methods

2.1. Study area

The study was conducted at a runoff collector (Si9), located in Kielce, with a wastewater treatment plant situated at the mouth of the Silnica river (Fig. 1). It receives rainwater and snowmelt from the central eastern part of the city—an area of 62 ha. The primary channel is 1.569 m long and its diameter varies from 600 to 1.250 mm. It is joined by 17 side channels (with diameters ranging from 300 to 1.000 mm). The collector has 32 inspection and connection chambers, as well as street 24 inlets. The total length of the sewage system is 5.583 m. The collector gradient in individual sections varies from 0.04% to 3.9%, side channel gradients reaching 2.61%. On average, one street inlet receives water from an area of 0.585 ha.

The highest elevation in the catchment area is 271.20 m, the lowest is 260.0 m above sea level, and the average surface gradient is 0.71%. Within the catchment, six types of surface runoffs have been distinguished: from the roofing (14.3%), pavements (8.4%), roads (17.7%), car parks (11.2%), green areas (47.2%), and school football pitches (1.3%). The paved areas with a high runoff coefficient represent 52.83% of the total catchment area, which testifies to its typically urban character.

The runoff wastewater is collected from the roofs by means of guttering, incorporated directly into storm drain channels (72.5% of all roofs), and from roads and streets—by means of standard street drains, complete with cast iron grates.

2.2. Samples collection

Precipitation wastewater was collected during rainfall with the use of a Teledyne ISCO 6712 portable sampler,

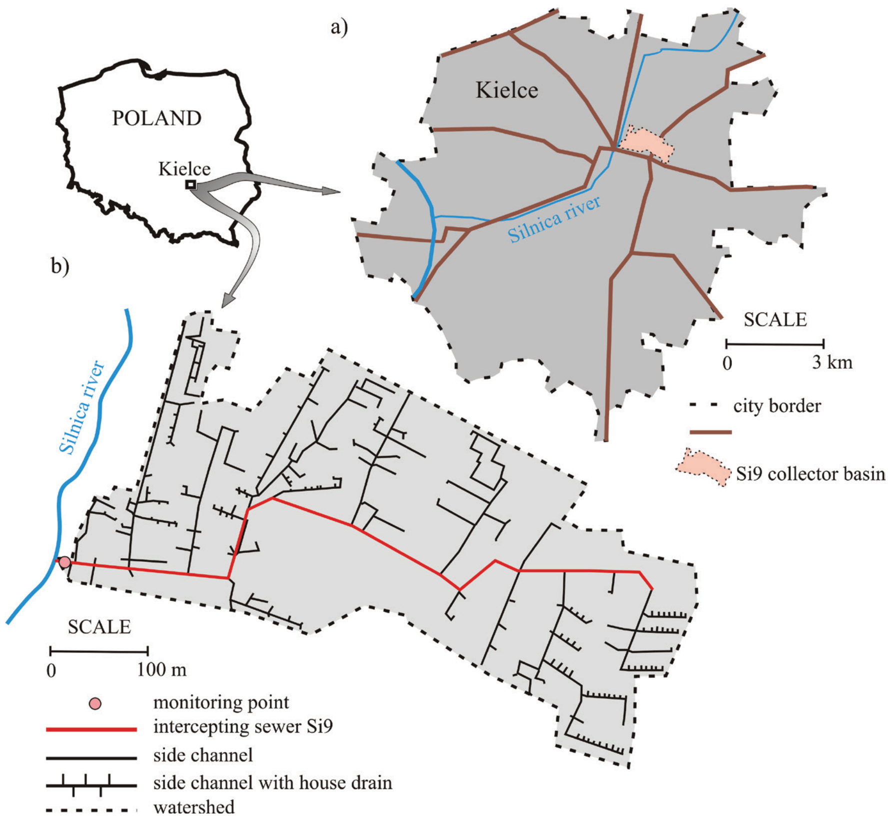

Fig. 1. Study site: (a) city plan and location of the study catchment and (b) Si9 collector catchment together with the system of side channels and location of monitoring point.

equipped with 24 bottles of 0.5 dm^3 volume each, installed at ca. 50 m away from the channel inlet into the collector. The sampler enables automatic sample collection at set volume and frequency during freshets. It is configured to begin operation at wastewater flow reaching the set depth, as registered by a sensor which measures channel filling. In the studied cases, samples were collected at channel filling exceeding 0.08 m at 7-min intervals. This setting enabled the collection of 12 samples, while studied freshet duration was 84 min.

Additionally, in the channel, a Teledyne ISCO 2150 module flow meter was installed. The flow meter's area velocity sensor measured the filling level (according to the principle of water column pressure measurement) and mean flow velocity, which—together with the definition of the channel shape and size—enabled calculation of flow intensity (by means of a built-in microprocessor).

2.3. Wastewater quality analysis

The unstabilized collected samples were immediately transported to a chemical laboratory in order to determine selected indicators. The testing of rainfall wastewater pertained to determination of the following quality indicators: heavy metals (Ni, Cu, Cr, Zn, and Pb), the pH, and TSS. Heavy metal content was determined by atomic adsorption spectroscopy with flame atomization according to PN-EN ISO 8288:2002 Standard [21]. Prior to the sample determination, the samples were mineralized according to the PN-EN ISO 15587-1:2005 Standard [22]. The TSS determination was performed according to the PN-72/C-04559 Standard [23].

2.4. Data analysis

The characteristics of the obtained values of pollution indicators, for each freshet separately, were outlined with the use of the median as well as the upper and lower quantile of ~25% and 75%.

To compare the obtained mean values of pollution indicators for the studied freshets, the analysis of variance (ANOVA) was performed. The analysis was preceded by the check of homogeneity of variance using the Brown–Forsythe test. For the ANOVA results that were statistically significant, the Tukey multiple comparison test was applied, which is most frequently used in the aquatic environment investigations [24]. When the assumption of homogeneity of variance was not satisfied, the Kruskal–Wallis nonparametric test was employed. ANOVAs were preceded by the tests on the normality of distribution of the variables of concern (Lilliefors version of the Kolmogorov–Smirnov test and the Shapiro–Wilk test). When the distribution of a given feature was not compliant with the normal distribution, logarithmic transformation of variables in accordance with the log (Cn + 1) function was performed [25].

3. Results and discussion

3.1. Characteristics of the observed rainfall freshets

The analysis focused on seven freshets from May 2010 to May 2012 with different parameters of freshets and precipitations that led to them (Table 1). The first two freshets of 2010 took place in the period before the intensive construction of a large-scale commercial building in the catchment area, with pavements, access roads, car parks, and the replacement of underground infrastructure. The construction works covered about 10% of the total catchment area and lasted from July 2010 until the end of 2011. Their impact on the concentrations of pollutants, and in particular on the content of TSS, were determined on the basis of three freshets that were observed on 7 and 11 April and 1 May 2011. The last two freshets of 7 and 15 May 2012 occurred after the completion of the abovementioned works.

The freshets recorded between May 2010 and May 2012 were characterized by maximum flow intensity from 79 to 349 $dm^3 s^{-1}$ (Table 1). Each of the presented freshets was formed under different meteorological and hydrological conditions. The freshets in 2010 were caused by rainfall in the range of 4.0–6.3 mm, with the event of 4 June characterized by the highest value of the rainfall intensity of I_{max} = 0.7 mm min^{-1}. F3 and F4 of 2011 were characterized by the highest maximum flow rates of Q_{max} = 0.331–0.349 $m^3 s^{-1}$ among the analyzed freshets and resulted from rainfalls, the height of which was

Table 1
Characteristics of parameters for individual freshets and rainfall causing the freshets

No.	Date	Sample quantity	Freshet parameters			Rainfall parameters		
			Q_{max} ($m^3 s^{-1}$)	t (min)	P (mm)	I_{avg} (mm min^{-1})	I_{max} (mm min^{-1})	t_r (min)
F1	31/05/2010	14	0.140	257	4.0	0.024	0.2	168
F2	04/06/2010	14	0.312	215	6.3	0.060	0.7	106
F3	07/04/2011	12	0.349	240	0.8	0.012	0.2	66
F4	11/04/2011	11	0.079	480	6.0	0.015	0.1	388
F5	01/05/2011	12	0.331	720	12.4	0.029	0.5	432
F6	07/05/2012	12	0.211	195	4.0	0.098	0.3	41
F7	15/05/2012	12	0.251	380	4.8	0.012	0.1	395

Q_{max} is the maximum flow in the channel during the studied freshet ($m^3 s^{-1}$), t is the total duration of the studied freshet (min), P is the total rainfall height (mm) during rainfall t_r (min), I_{avg} is the mean rainfall intensity for t_r (mm min^{-1}), and I_{max} is the maximum rainfall intensity in (mm min^{-1}).

0.8 and 12.4 mm, respectively. It should be noted here that F3 and F4 freshets were preceded by a minor rainfall which did not cause any flow in the storm drain channel, with the height of 0.2–0.4 mm. The maximum flow velocities in the freshets of 7 and 15 May 2012 with 0.211 and 0.251 $m^3 s^{-1}$, respectively, were close to each other, as were the rainfalls which had caused them (P = 4.0 and 4.8 mm). Due to the short duration of the rainfall (t_r = 41 min) the freshet of 7 May had the highest average rainfall intensity of 0.098 mm min^{-1}.

Three of the studied freshets were of complex nature and featured several climaxes. This is connected mainly with the unique characteristics of the studied catchment as well as the complexity of rainfall formation, influenced by local conditions, the spatial range, and variety of rainfall intensity in the studied part of the city of Kielce, together with current retention capacity of the catchment. The influence of elements such as field concentration time, channel retention, as well as external water inflow from the wellpoints draining the shopping centre construction site is not to be underestimated. In the remaining cases, hydrograph plots reflect the rainfall hyetograph, and maximum rainfall wastewater flow intensity values correlate with maximum rainfall intensities (allowances being made for the time shift related to field and channel retention).

3.2. Heavy metals and pH

An important property of rainfall wastewater is the pH value, which results from the presence of acidic and alkaline substances. The pH value is significant for the processes which occur in water solutions, as it conditions redox processes and precipitation reactions, thus influencing the occurring metal forms. Moreover, changes to the pH value can decrease the kinetics of a variety of processes or even inhibit them entirely. That is why this indicator is among major indicators of rainfall wastewater quality. Recorded between March 2011 and May 2011, the freshets displayed pH values which ranged from 7.31 to 7.93 (Fig. 3). These values were close to those recorded in other periods: 2010 and 2012 (pH = 7.30–7.70). The obtained pH values are within the range given in the literature for strongly urbanized catchments situated in city centers with similar land use (Table 2).

Heavy metals, found primarily in the airborne particulate matter, are particularly hazardous substances. They are deposited on the ground together with particulate matter, and then they are washed from the catchment and transported, with the rain wastewater, into the wastewater receiving body. Zinc and lead show the highest concentrations in rain wastewater, but in the most heavily polluted runoff portions, copper and chromium, and also cadmium, nickel, arsenic, cobalt, and iron are found. The transportation routes are the major sources of heavy metal pollution. A high share of zinc, lead, and nickel in the rainfall wastewater results from the widespread use of these elements in the automotive and fuel industries. The presence of copper and chromium in the atmosphere is mainly caused by coal combustion and industrial activity [3,8].

When analyzing the variability of heavy metal concentrations in the various freshets (Fig. 2), it can be seen that only in the case of wave F3 the measured values tend to decrease during the freshet. In other cases, there is no clear uniform tendency of changes or relation to the freshet dynamics. The concentrations of heavy metals are characterized by significant non-uniformity over time, as confirmed by studies conducted in the catchment area by Bąk et al. [6] and Górska et al. [8].

The results of the ANOVA analysis (Kruskal–Wallis test analysis $K > 70.0$, $p < 0.023$—for 95% of the confidence interval) showed that in the case of F3 wave (Fig. 3), the average concentrations of Ni and Zn (0.304 and 2.389 mg dm^{-3}, respectively) were the highest and significantly statistically different from the average concentration of these metals in the remaining waves (F1-F2 and F4-F7). No statistically significant differences ($K > 70.0$, $p > 0.05$) between average concentrations of Ni and Zn were recorded in the waves observed in 2010 (F1 and F2) and 2012 (F6 and F7), in which the average concentrations of the listed metals were relatively small, with the values for Ni being 0.025–0.029 mg dm^{-3} and 0.029–0.076 mg dm^{-3}, respectively, and for Zn ranging from 0.120 to 0.158 mg dm^{-3} and from 0.362 to 0.609 mg dm^{-3}, respectively.

The observed variation range of concentrations of Ni substantially housed within the limits for rainwater (Tables 2 and 3), in addition of wave F3, in which the maximum value of this element (0.612 mg dm^{-3}) was significantly elevated and exceeded even the upper ranges of values given by Brombach and Fuchs [26] (0.426 mg dm^{-3}) and Revitt et al. [35] for runoff from parking lots and shopping areas (0.493 mg dm^{-3}). Similarly, when the maximum content of Zn were observed at wave F3 (5.375 mg dm^{-3}), it was significantly greater than the maximum value given by Gasperi et al. [27] for catchment of similar size and land use. This value corresponds to the results of Królikowski et al.'s research [3] and Djukić et al. [29] (Table 2) for the catchment with a significant part of roads and parking lots and high traffic volume, as well as with the results of surface runoff tests from motorways and major roads [31,33]. The maximum values of Ni and Zn concentration in the F3 wave were also significantly higher than the values given by Bąk et al. [6] obtained during measurements carried out in the catchment area in 2009 and 2010. Therefore, the increased content of Ni and Zn in F3 wave can be linked to the commencement of earthworks in the catchment area at the beginning of 2011 (vehicles movement and operation) and the intensive supply of fine-grained mineral material of the soil top layer to the stormwater system.

While analyzing average Cr concentrations (Fig. 3), it can be seen that in F3-F5 waves they were slightly higher (0.199–0.327 mg dm^{-3}) than in F6-F7 waves of 2012 (after the construction completion: 0.128–0.135 mg dm^{-3}). The lowest average values, ranging from 0.027 to 0.036 mg dm^{-3}, were observed before the construction works in 2010. Minimum (0.060 mg dm^{-3}) and maximum values (0.616 mg dm^{-3}) in waves F3-F5 and F6-F7 were significantly higher than the corresponding values given in Table 2 for different catchments [28,30–32] and in Table 3 for residential area [36]. Similar maxima were observed in Białystok [3] (0.600 mg dm^{-3}), and higher in a small catchment (921 m^2) located in Belgrade [29] (1.350 mg dm^{-3}), in which asphalt and concrete surface was included 73.7% of the total catchment area.

The analysis of the average Pb concentrations (Fig. 3) shows that there is no clear trend of their changes depending on construction works carried out in the studied

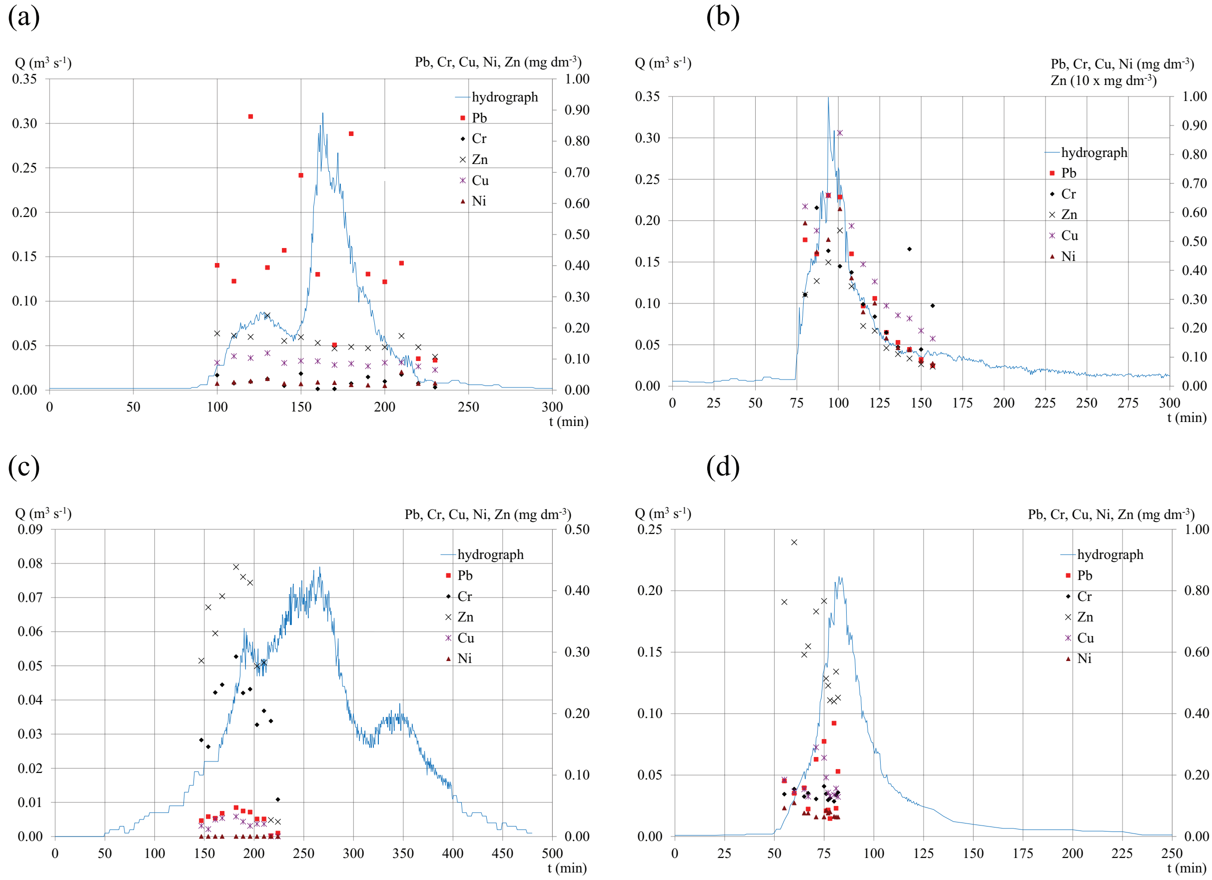

Fig. 2. Variability of heavy metals concentrations in rainfall freshets: (a) F2, (b) F3, (c) F4, and (d) F6.

catchment. These values change in the F3-F5 waves: 0.328, 0.029, and 0.001 mg dm^{-3}, respectively, and in F1-F2 and F6-F7 waves: 0.187–0.416 and 0.169–0.304 mg dm^{-3}, respectively. The maximum Pb concentration (0.879 mg dm^{-3}) was registered for F2 freshet. Obtained values of Pb concentrations in rainwater correspond with the results of studies of other authors for urbanized catchment with high traffic (Table 2).

Public transport is the main source of Pb emissions (50%–98%) in urban areas. Most of the lead compounds are emitted together with the flue gases and come, for example, in the form of lead ammonium halides. All lead compounds are in a high dispersion state and are subject to easy sorption on the surface of atmospheric dust particles, which is deposited on the hardened surfaces, from where it is further washed down to rainfall wastewater [3,8]. The changes in analyzed catchment, consisting in the increased percentage of impervious surfaces, did not lead directly to the increased traffic intensity and the noticeable increase in Pb concentrations. It should be emphasized that the investment under consideration is located in the city center, by the main arterial roads with continuous heavy traffic.

The content of Cu in the studied waves was in the range from 0 to 0.874 mg dm^{-3}, and similarly as in the case of other metals, the maximum concentration of this element was observed in F3. The content of Cu in rainwater from the tested catchment corresponds to the results of research of other researchers (Table 2).

3.3. Total suspended solids

The results of ANOVA analysis (K = 75.3, p = 0) indicate that the average concentration of TSS in stormwater (F3-F5) from the period of infrastructural projects implementation in the investigated catchment was the highest and statistically significantly differed from the TSS content in stormwater typical of other periods (before and after the construction work). The average concentration of suspended solids in F3-F5 waves was respectively: 4,416, 1,913, and 57,814 mg dm^{-3}, while in F1-F2 it ranged within 106–126 mg dm^{-3}, and in the waves F6-F7 it was about 1,000 mg dm^{-3}. The variability of suspended solids concentration in the observed waves is shown in Figs. 4 and 5 and in Table 2, in which the results of research on rain sewage from urban catchments located in various parts of the world were compiled. Analyzing the studies cited, it may be noted that the minimum and maximum values for TSS concentrations wave F1 and F2 are similar to the ranges observed in Genoa [13], Paris [27,28], Isfahan [12], and Lahti [30] and coming from low-residential areas [33,36] (Table 3). In the case of waves F6 and F7, TSS concentrations are within the ranges given for residential high density [36] and industrial areas [33] (Table 3) and significantly exceed the maximums established by Gasperi et al. [27] for catchment Marais (Paryż) with similar characteristics of land use. However, in relation to waves F3 and F5 maximum concentrations of TSS (respectively 21,510 and 199,191 mg dm^{-3})

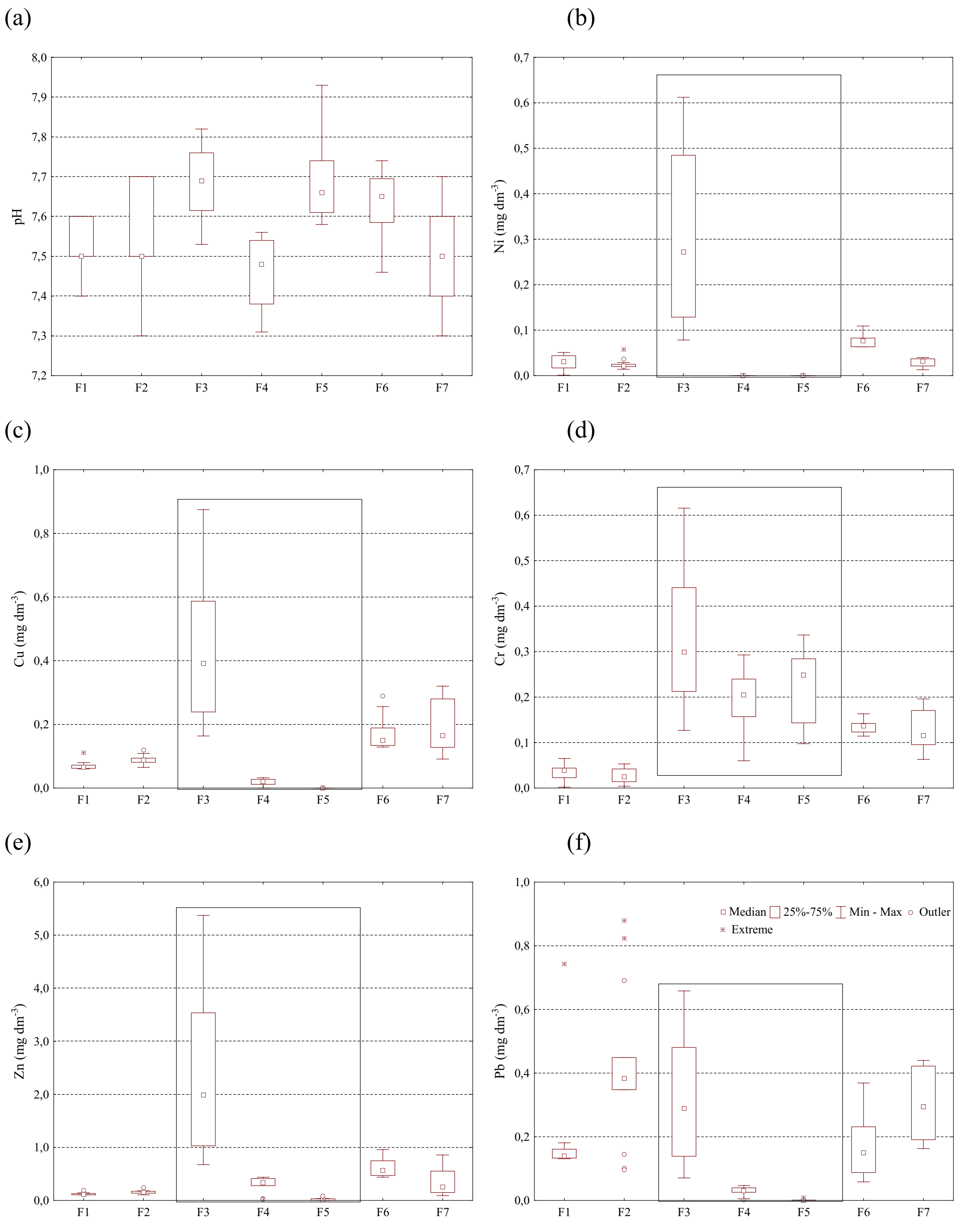

Fig. 3. Box plot of heavy metal concentration and pH for the studied rainfall freshets.

repeatedly exceed the value given by most authors (Table 2), also for studied rainwater coming from motorways and major roads [33] and residential high density areas [33,36] (Table 3). Noteworthy is also the high median value of TSS in waves F3 and F5 (Fig. 4) similar or significantly higher than the maximum characteristic for runoff from highways (Table 3). The causes of such high values of TSS in these waves, with certainty, should be seen in earthworks carried out within the catchment. Studies by Bąk et al. [6] have shown that for the studied catchment, under conditions of standard operation, the volume of TSS for rainfall freshets reached a level several times lower than was the case with the above-discussed freshets. Under standard operation, suspension volumes ranged from 70 to 790 mg dm^{-3} (median 120 mg dm^{-3}).

Table 2
Range of stormwater quality parameters

Event number	TSS (mg dm^{-3})	Ni (mg dm^{-3})	Cr (mg dm^{-3})	Cu (mg dm^{-3})	Zn (mg dm^{-3})	Pb (mg dm^{-3})	pH
F1	80–296	0.001–0.051	0.002–0.065	0.060–0.111	0.103–0.187	0.131–0.743	7.40–7.60
F2	0.070–0.177	0.014–0.058	0.004–0.053	0.065–0.119	0.107–0.240	0.096–0.879	7.30–7.70
F3	898–21,510	0.078–0.612	0.127–0.616	0.164–0.874	0.674–5.375	0.071–0.658	7.53–7.82
F4	1,107–2,847	–	0.060–0.293	0–0.032	0.024–0.439	0.001–0.047	7.31–7.56
F5	2,908–199,191	–	0.098–0.337	–	0–0.084	0–0.009	7.58–7.93
F6	617–1,901	0.064–0.109	0.114–0.163	0.129–0.290	0.439–0.957	0.058–0.369	7.46–7.74
F7	899–1,533	0.013–0.040	0.063–0.196	0.091–0.320	0.091–0.858	0.163–0.440	7.30–7.70
Other researchers							
Source							
[3]	10–40,000	0.010–0.080	0.010–0.600	0.050–0.800	0.200–6.000	0.100–2.000	6.11–9.16
[26]	29–1,535	0.004–0.426	–	0.057–1.143	0.024–3.563	0.007–2.408	–
[13]	15–377	–	–	0–0.053	0.027–0.123	0.006–0.023	–
[27]	119–254	–	–	0.054–0.124	0.128–0.500	0.015–0.042	–
[27][a]	153–252	–	–	0.054–0.104	0.140–0.202	0.021–0.031	–
[28]	11.0–430	–	<0.01–0.045	0.030–0.220	0.130–0.520	<0.01–0.129	6.99–7.87
[29]	189–4,820	0.003–0.010	0.074–1.350	0.067–1.820	0.284–6.200	0.003–0.006	8.74–8.98
[30][b]	50–348	0–0.027	0.002–0.032	0.011–0.059	0.042–0.261	0.001–0.033	–
[12]	43–467	–	–	–	0.015–2.386	0.018–0.558	6.90–7.60
[31][c]	103–836	0.011–0.037	0.002–0.095	0.010–0.250	0.390–4.400	0.012–0.427	6.22–7.63
[32]	12–1,400	0.003–0.040	0.001–0.020	0.009–0.110	0.043–0.690	0–0.035	–

[a]Data from catchment Marais with similar characteristics to the catchment (area 42 ha, with roofs and streets accounting for 80% of the land cover).
[b]The range concerns average values from different types of surfaces (city center, roads, highways, industrial, commercial, residential).
[c]The range concerns the mean values of 11 rainfall events.

Table 3
Range of total suspended solids (TSS) and trace metals concentrations in runoff from different surfaces

Type of surface	Source	TSS (mg dm^{-3})	Ni (mg dm^{-3})	Cr (mg dm^{-3})	Cu (mg dm^{-3})	Zn (mg dm^{-3})	Pb (mg dm^{-3})
Residential high density	[33]	55–1,568	–	–	–	–	0–0.140
	[36]	23–3,359	0.001–0.125	0–0.222	0.002–0.656	0.007–1.937	0–0.098
Residential low density	[33]	10–290	–	–	–	–	0–0.140
	[36]	2.9–384	0–0.030	0–0.018	0–0.087	0–0.400	0–0.010
Motorways and major roads	[33]	110–5,700	0.004–0.070	–	–	0.053–3.550	0.003–2.410
Urban, suburban and residential roads	[33]	11–5,400	0.002–0.493			0.300–0.410	0.010–0.440
	[35]	–	–	–	0.006–0.120	0.020–1.900	–
	[37]	61–794	–	–	–	–	–
Roof	[13]	–	–	–	0.001–0.018	0.212–0.759	0.002–0.007
	[33]	12.3–216	–	–	–	–	0.001–0.030
	[34]	0.1–453	–	–	0.0.2–7.861	0.005–2.369	0–0.108
	[37]	2.1–79	–	–	–	–	–
Car parks and commercial areas	[35]	7.8–270	0.002–0.493		<0.001–0.205	<0.001–700	<0.001–0.010
	[37]	42–2,185	–	–	–	–	–
Industrial	[33]	50–2,582	–	–	–	–	–

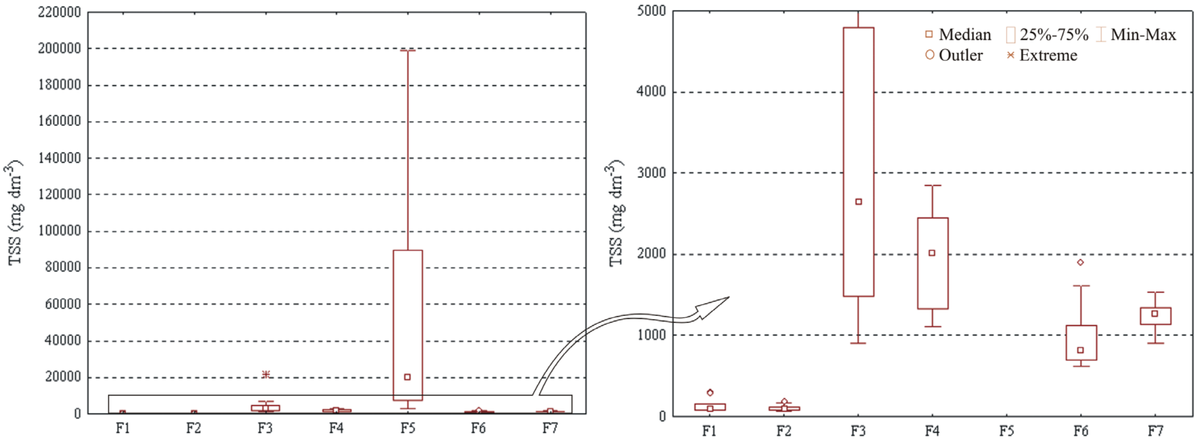

Fig. 4. Box plot of TSS for the studied rainfall freshets.

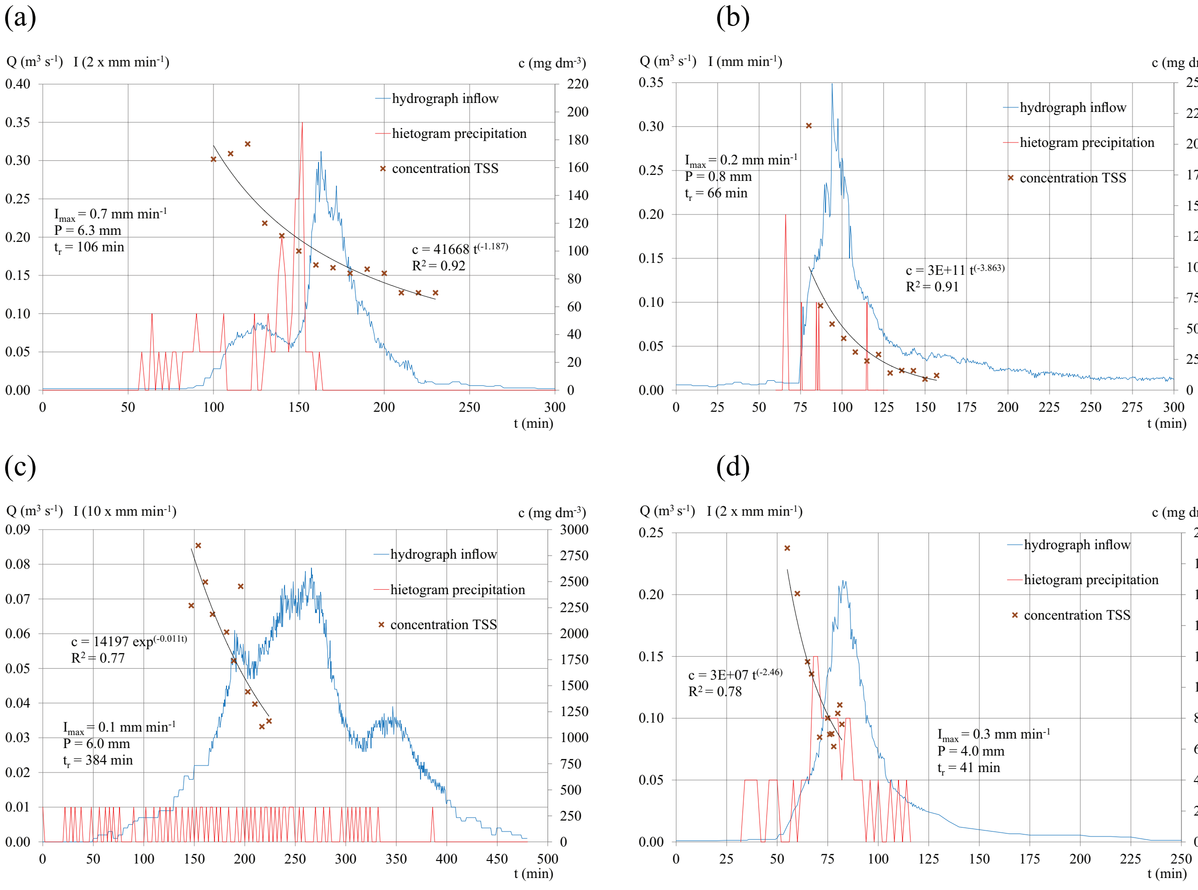

Fig. 5. Variability of total suspended solids concentrations in rainfall freshets: (a) F2, (b) F3, (c) F4, and (d) F6.

The ANOVA analysis ($K = 75.3$, $p = 0.015–0.020$) also shows that the average concentration of TSS in the stormwater samples collected in 2012 was significantly higher than the average values recorded for wastewater outflowing from the catchment in 2010. The increased values of TSS in the rainfall wastewater recorded in 2012 may be related to the gradual leaching of the sludge deposited in the sewers and sewage chambers after the completion of the construction works and probably in a low degree with an increase in the impervious surface in the catchment area.

An important feature of stormwater formed in the phase of surface runoff is the uneven distribution of pollutant load in a unit of time, which in the relevant literature is called the cumulative effect. The results of studies on the concentration of TSS in stormwater confirm this non-uniformity. There is a tendency for the concentrations of TSS to decrease during the freshet, which is reflected in the trend lines described by the regression equations of the exponential and power form with R^2 determination coefficient in the range of 0.77–0.92 (Fig. 5). Similar dependencies were observed in the conditions of the normal operation of the sewage system [6].

4. Conclusions

The problem of limiting the adverse impact of stormwater on the aquatic environment has been a subject of scientific research work for many years and is an increasingly integral part of the planning and design developments of sewage systems in anthropogenically transformed areas. Point sources of pollution are one of the main causes of water quality degradation. The contamination content in precipitation runoff is primarily affected by transport and, as revealed in this paper, a number of temporary factors such as construction, reconstruction of the existing technical infrastructure—resulting in the increase of impervious surfaces in the catchment area. Contamination of waters with heavy metals is particularly dangerous because in the natural processes of the rivers' self-cleaning not only are they non-biodegradable, but by their toxic effect on microorganisms they slow down biodegradation processes. The performed research and analyses allow to formulate the following conclusions:

The heavy metal contents in the stormwater varied widely during particular freshets. The maximum values were from a few to several times higher than the minimum ones.

In the initial period of construction work in the catchment area, the concentrations of Ni, Cr, and Zn observed in the stormwater were distinctly higher than in the course of further work. Only in this case (F3 wave), the concentration of heavy metals decreased with the duration of the freshet.

The results of the ANOVA test do not indicate the existence of statistically significant differences in the concentrations of the examined heavy metals in all the waves from the individual periods: before the commencement of construction works (2010) and after their completion (2012).

The highest concentrations of TSS were observed in 2011 (construction period), when the maximum concentrations in F3, F4, and F5 waves were, respectively, 21,510, 2,847, and 199,191 mg dm^{-3} and significantly exceeded the maximum levels in 2010 (177–296 mg dm^{-3}) and 2012 (1,533–1,901 mg dm^{-3}).

The results of ANOVA indicate the existence of statistically significant differences in average concentrations of TSS in the individual freshets observed in the years 2010–2012. The causes of this situation can be seen, among others, in the dynamics of freshets connected with the course and intensity of precipitation phenomena and to some extent in the increase of impervious surface in the catchment area.

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