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TRANSPORT OF SUSPENDED SEDIMENT DURING FLOOD EVENTS IN A SMALL URBAN CATCHMENT

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ABSTRACT

The aim of this study is to present results of investigations into rainfall–runoff–suspended sediment transport process, based on field measurements conducted in small (A = 28.7 km^2) urban catchment of Służew Creek, located in Warsaw. Hydrological monitoring was carried out by the Department of Hydraulic Engineering at the WULS-SGGW (Warsaw University of Life Sciences). Between 2014–2017, twelve flood events were recorded, during which rainfall, discharge, turbidity, and suspended sediment concentrations were measured. The correlation between the flows and sediment concentration was analysed and clockwise hysteresis for all events was indicated, meaning that sediment concentrations during the increase of water flows were higher than at the same flow values during the fall of the flood wave. Also first flush effect has been noted, that is, most of the sediment loads was washed-off at the beginning of the flood event; whereas the peak concentration occurred prior to the maximum discharge. Statistically significant correlation between direct runoff and suspended sediment has been established.

Keywords: suspended sediment yield, flood hydrograph, urban catchment

INTRODUCTION

The sum of the matter transported by rivers is called ‘river sediment’. Due to the method of transport, Dębski (1955) divided the river sediment into: bed load, rolled load, suspended load, wash load, and dissolved load. Bed load and rolled load are the largest rock fractions, moving along the bottom. Suspended load are fractions of rock material that flow along with water at various depths, whereas in standing water they sink to the bottom.

This division is not rigid, as the same fractions, depending on the velocity and turbulence of the flow, can be lifted in the mass of water or moved along the bottom. As a result of intense rains or snow melting the flow rate and the amount of sediment increase in channels (Hejduk et al. 2006, Michalec 2009). The amount of bed load, flowing away during a single flood may account for more than half of the load yielded from the basin throughout the year (USGS 2016). During the spring thaw, the rivers of Central Europe carry about 600 times more fine particles than in the winter (Falkowski and Złotoszewska-Niedziałek 2005). The amount of sediment in rivers depends mainly on the intensity of the following processes: soil erosion in the catchment area (Banasik et al. 2001, Mitchell et al. 2001, Banasik et al. 2012), erosion of the bottom and the banks of the watercourse (Trimble 1997), and the washing of particles from sealed areas (Chae and Hamidi 1997). In certain special cases, the flow of sediment may also be affected by: mass movements in the catchment area such as landslides and solifluctions (Broeckx et al. 2016), construction of roads and housing estates [NCRS 2000], regulatory works in the watercourse, and discharges of polluted waters (Rossi et al. 2005). The influence of the catchment sealing on

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the sediment effluent is under dispute. Some studies indicate that the load from the agricultural catchment exceeds the load disbursed from the urban catchment (Wolman 1967, Bello et al. 2017), while other studies come to exactly opposite conclusions (Ciupa 2009, Russell et al. 2017).

Excessive sediments in rivers can cause: silting of riverbeds, reservoirs and hydrotechnical constructions, increase of flood risk in estuary sections of rivers, increased flood damage, deterioration of tourist and recreational values of the river valleys, lower water quality, and increase of water treatment costs (Guy 1970). Suspended sediment is particularly inconvenient for the environment. Fine particles affect the colour and turbidity of water, and are also carriers of other pollutants, including: heavy metals (Herngren et al. 2005), radionuclides (Walling 2006), phosphorus compounds (Hejduk 2011), polycyclic aromatic hydrocarbons (Bathi et al. 2012), and pharmaceuticals (Sikorska et al. 2012). Consequently, they can pose a threat to human health, or to the proper functioning of ecosystems, even far away from the place of their creation.

The process of sediment transport and its effects are therefore important for technical, environmental as well as social issues. The aim of this work is to present the results of research into the process of rainfall – runoff – transport of suspended sediment, conducted in a small (A = 28.7 km^2), urban catchment of the Służew Creek in Warsaw.

MATERIALS AND METHODS

The research area is located in the south-western part of Warsaw, the Służew Creek catchment (see: Fig. 1). Since the mid-1980s, the catchment has been periodically monitored by the Department of Hydraulic Engineering at the WULS-SGGW (Banasik 1987, Banasik et al. 1988). The conducted research concerned, among others, the modelling of rainfall and runoff process (Banasik et al. 2008, 2014, Sikorska et al. 2012), the functioning of small retention ponds (Gradowski and Banasik 2008, Pietrak and Banasik 2009, Krajewski et al. 2017a, 2017b), and river sediment transport (Bajkowski 2009, Sikorska et al. 2015).

The catchment area, up to the mouth of the Służew Creek to Lake Wilanów, is 54.8 km^2, whereas the analysed part of the catchment for the Wyścigi profile is 28.7 km^2. The catchment is heterogeneous in terms of land development; the northern part is characterized by high urbanization, with the airport located within

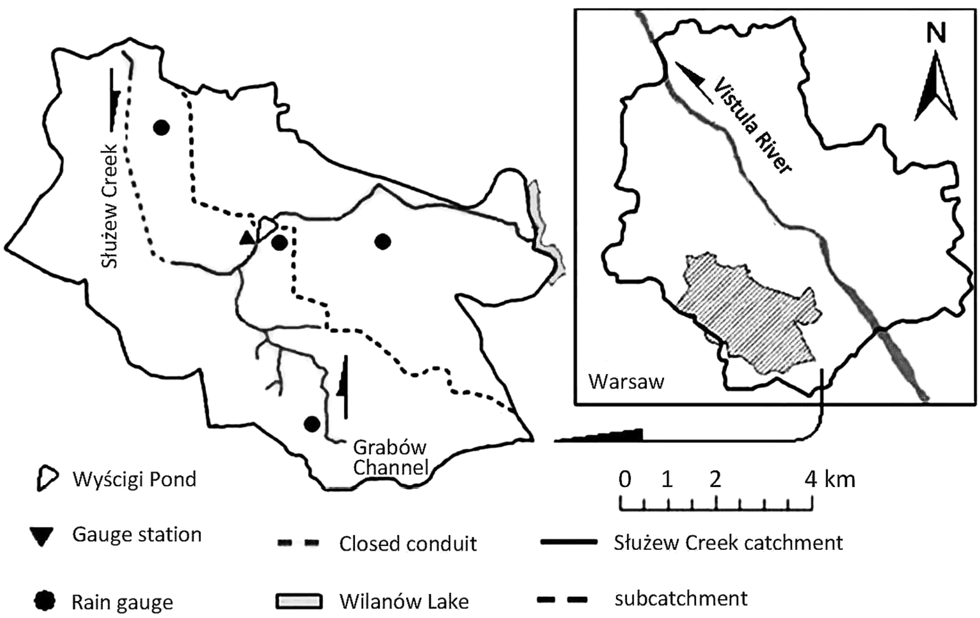

Fig. 1. Location of Potok Służewiecki (Służew Creek) catchment

it, among other infrastructure. Within the airport, the Służew Creek flows encased in a closed channel. In the southern part, which is the catchment of the Rów Grabowski, there are single-family housing estates, fields, wasteland, and forest areas. The catchment area is flat, the difference of land elevation is 30 m, and the average slope of the channel is 1.05 ‰ (MSIP 2017). The soil structure is dominated by clay deposits and fluvioglacial sediments (Metropolitan City of Warsaw 2012). The average annual rainfall for this part of Warsaw in the years 1960–2009 amounted to 541.9 mm (Majewski et al. 2010). The average annual flow in the Wyścigi profile in the period of 2009–2016 was set at 0.157 $m^3 \cdot s^{-1}$ (KIW 2016).

In the Wyścigi profile, a measurement station is located above the Staw Wyścigi reservoir. It is equipped with a level gauge, a pressure water level recorder, and an optical water turbidity recorder (see: Fig. 2). In the stations, there is also the option of taking measurements of the flow rate and manual sampling of the bathometers probes, i.e. a mixture of water and suspended load. In the catchment, four rain gauges are installed, in order to measure the amount of precipitation.

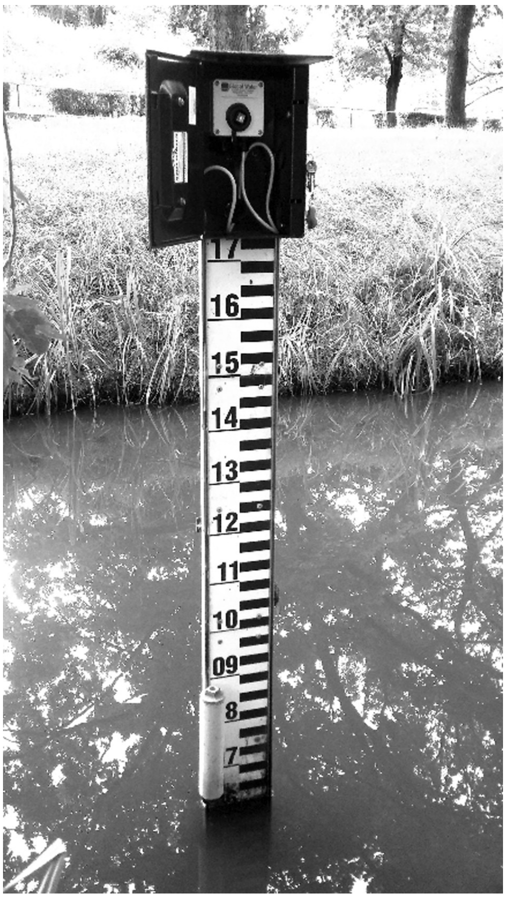

Fig. 2. Gauge Station upstream of the Staw Wyścigi (Pond), optical turbidity sensor with data recorder and gauge staff

The water levels are periodically measured by weekly readings from the water level gauge and in a continuous manner, in 10 minute time intervals, by means of a pressure recorder. Periodic readings from the gauge staff are used to verify the instrument's indications. The dicharge is measured periodically, mainly during freshets using the acoustic method – the ADCP (Hejduk 2008). Based on the measurements of the water level and flow, the ratio between the water level and the flow is determined, i.e. the flow curve. The turbidity of water is determined using the nephelometric method.

A system consisting of an optical sensor and a data recorder was used, which logs the measurement result every 10 minutes. Bathometers probes are taken using a manual bathometer, several times during flood events (see: Fig. 3). The device was constructed at the Department of Hydraulic Engineering at WULS-SGGW, following the pattern of the PIHM-1 bathometer used by the Polish hydrological service (Pasławski 1973). It consists of a one-litre container equipped with appropriately shaped two ducts; the inlet – supplying a mixture of water and suspended sediment as well as the outlet – to release the air. In the samples taken, the concentration of suspended load is determined by gravimetric method. On the basis of the bathometers probes and indications of the turbidity sensor, the shapes of sediment graphs of concentration are determined. Data on flows and concentration of the suspended load are used to determine the mass of the sus-

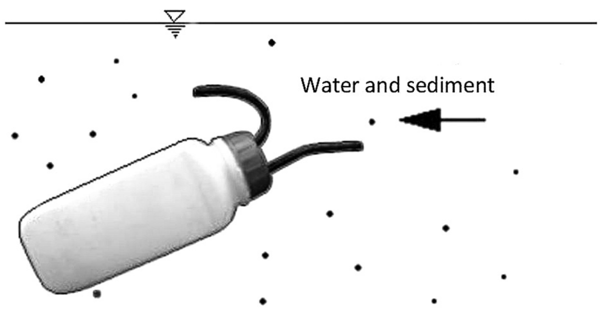

Fig. 3. Manual bathometer

pended sediment, transported in the cross-section in individual floods, according to the following formula:

$$Y = 10^{-6} \sum_{i=1}^{n} Q_i \; C_i \cdot \Delta t \qquad (1)$$

where:
Y – yield of suspended sediment transported during the flood, Mg,
Q_i – flow rate in the *i*-th time interval, $m^3 \cdot s^{-1}$,
C_i – concentration of the bed load carried in the *i*-th time interval, $g \cdot m^{-3}$,
Δt – time interval, s.

RESULTS AND DISCUSSION

In the period of 2014–2017, twelve events of the rainfall–runoff–suspended sediment transport have been registered. The basic characteristics of the measured floods are summarized in Table 1. In the period of 2014–2016, the shape of sediment graphs was determined on the basis of collected bathometric samples, and since 2017, on the basis of the samples coupled with the indications of the turbidity sensor. The events of 24 April 2014 and 27 July 2017 were triggered by the highest rainfall, during which time the greatest runoff of both water and sediment was recorded, amounting to 104 thousand m^3 and 9.66 Mg and 309 thousand m^3 and 23.5 Mg, respectively.

In the case of the remaining 10 events, the transported amounts of water and matter were significantly smaller, on average 37 thousand m^3 and 1.80 Mg. The maximum concentration of the carried suspended sediment in the flood surge varied from 102 to 429 $mg \cdot dm^{-3}$. For the sake of comparison, concentration in the non-flood period is estimated at 4.5 $mg \cdot dm^{-3}$ (Krajewski 2017). Figure 4 shows the yield of the suspended sediment in relation to the direct runoff layer (determined on the basis of the hydrogram of the direct runoff and the size of the catchment area).

The amount of the suspended sediment load increases in proportion to runoff depths, according to the following formula:

$$Y = 2.75\, H \qquad (2)$$

where:
Y – yield of the suspended sediment during flood event, Mg,
H – direct runoff depth, mm.

Table 1. Characteristics of the recorded rainfall-runoff-sediment transport events

No.	Date	Rainfall (mm)	Rainfall duration (h)	Direct runoff (mm)	Max. discharge ($m^3 \cdot s^{-1}$)	Flood volume ($10^3\,m^3$)	Max. suspended sediment concentration ($mg \cdot dm^{-3}$)	Suspended sediment yield (Mg)
1	20.04.14	6.9	5.5	0.48	0.529	25.7	129	1.95
2	24.04.14	23.5	16.7	2.65	1.44	104	214	9.66
3	06.05.15	15.8	8.2	1.24	0.640	46.5	204	2.84
4	25.07.15	8.0	5.0	0.40	0.460	23.0	422	0.74
5	18.11.15	10.9	11.2	1.40	0.967	57.4	208	3.82
6	20.06.16	9.6	6.5	1.50	0.652	64.6	200	1.47
7	24.05.17	9.4	5.0	0.80	0.838	34.7	137	2.54
8	23.06.17	7.5	2.8	0.50	0.737	21.1	109	1.39
9	25.07.17	8.7	5.0	0.81	1.01	37.7	102	1.07
10	28.07.17	39.2	3.5	8.57	6.08	309	429	23.5
11	10.08.17	5.7	1.5	0.49	0.715	28.3	182	1.16
12	19.08.17	11.1	4.5	0.59	0.774	29.6	198	0.96
range		5.7–39,2	1.5–16.7	0.40–8.6	0.460–6.1	21.1–309	102–429	0.74–23.5
Average		13.0	6.3	1.6	1.2	65.2	211	4.3

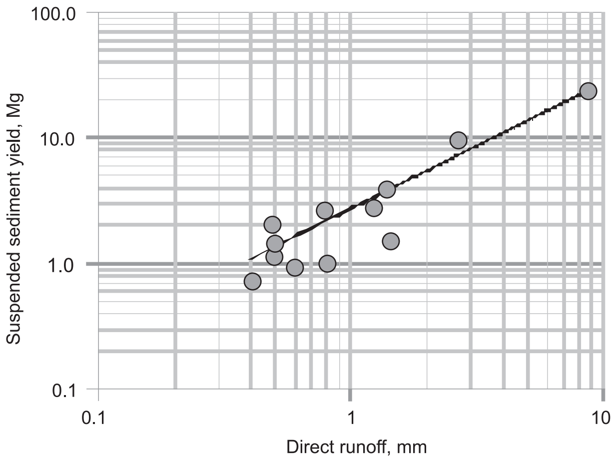

Fig. 4. Suspended sediment yield vs. direct runoff

The above correlation is statistically significant and has a high coefficient of determination, equal to 0.967.

Figures from 5 to 7 present the course of exemplary flood events, together with the relation between the flow and the concentration of suspended sediment. For all events, the phenomenon of the first wave of pollutant runoff was observed, the so-called first flush effect, which often occurs in urbanized catchments, as a result of heavy rains or thaws (Brzezińska et al. 2014). It manifests itself by a rapid increase in the concentration of contaminants in the watercourse, and the occurrence of the maximum concentration value, even before the culmination of the flood hydrogram. A phenomenon of clockwise hysteresis was observed, indicating that sediment concentrations during the increase of the water flows were higher than at the same flow values during the falling of the wave.

The occurrence of the first wave of contamination flow should be considered as an unfavourable process, which causes the deterioration in the quality of the aquatic environment, and which may disturb the functioning of wastewater treatment plants, among other things (Zawilski and Brzezińska 2003). Williams (1989) distinguishes five types of dependencies between the flow and the concentration of the suspended sediment: single-value line, clockwise loop, counterclockwise loop, single line plus loop, and figure eight, which is a combination of two hystereses. Out of all of those listed above, the most common is the dextrorotary hysteresis (Morris and Fan 1998, Kociuba and Stępniewska 2003, Hejduk and Banasik 2010). It appears under specific conditions when the easily eroded material is separated and transported to the channel together with the first runoff. The occurrence of such a phenomenon may be favoured by the presence of sealed areas, such as roadways, car parks, and sidewalks, or by a specific distribution of rainfall above the catchment.

The correlation between the flow and the concentration in a given cross-section is not constant; instead, it can change during the flood and take various courses for other events. Establishing one reliable relation for

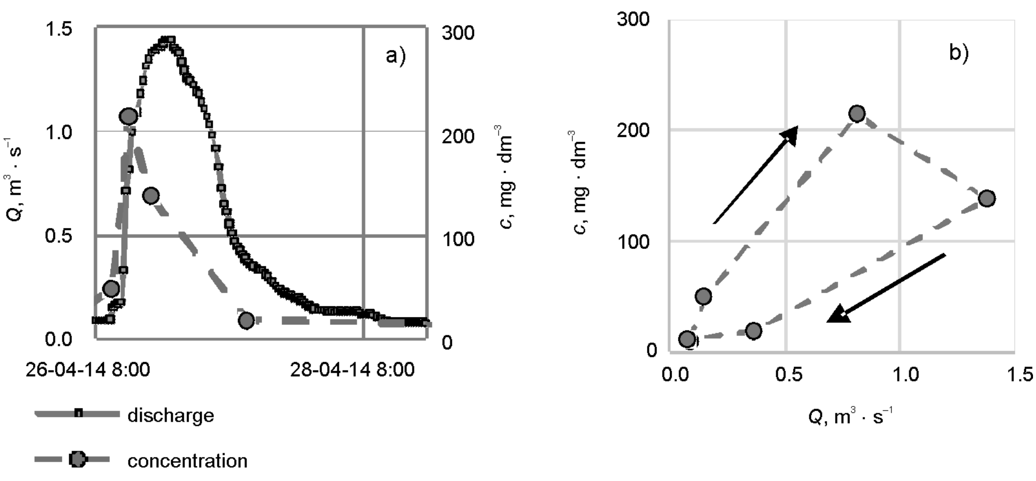

Fig. 5. Flood event of 26 April 2017: a) a hydrogram and a sediment graph, dots representing bathometer samples, b) correlation between the discharge and the suspended sediment concentration; Q – discharge, c – concentration

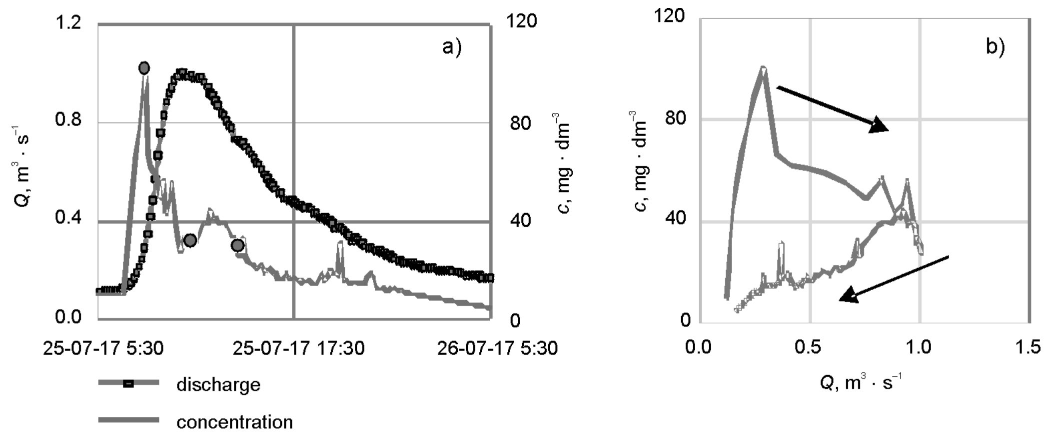

Fig. 6. Flood event of 25 July 2017: a) a hydrogram and a sediment graph, dots representing bathometer samples, b) correlation between the discharge and suspended sediment concentration, Q – discharge, c – concentration

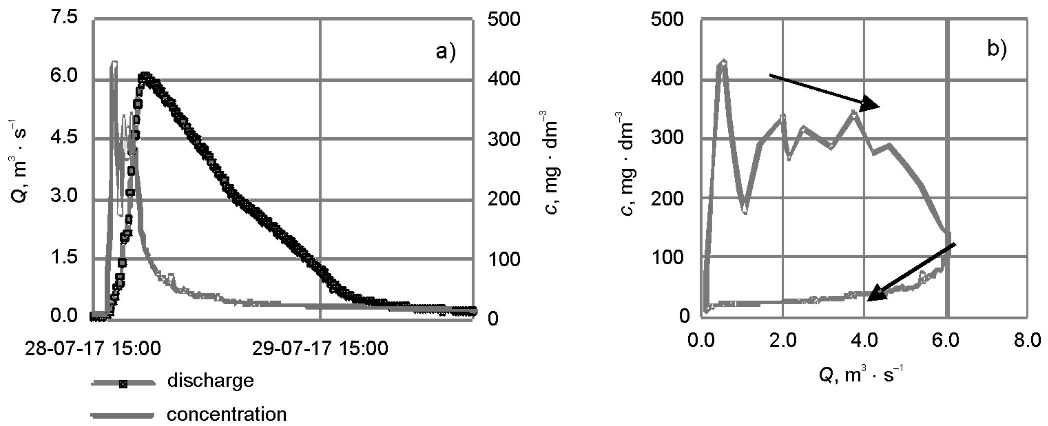

Fig. 7. Flood event of 28 July 2017: a) a hydrogram and a sediment graph, b) correlation between the discharge and the suspended sediment concentration, Q – discharge, c – concentration

the measurement cross section is therefore a difficult task, and it should be done on the basis of multiple measurements carried out in the area of low, medium and high flows. In addition, it may be necessary to determine separate dependencies for the rising and falling phases of the flood wave, due to the occurrence of the hysteresis phenomenon.

CONCLUSIONS

The paper presents the results of hydrological monitoring carried out in the small urban catchment of the Służew Creek in Warsaw by the Department of Hydraulic Engineering at the Warsaw University of Life Sciences (WULS–SGGW). In the period between 2014–2017, 12 events of rainfall-runoff-suspended sediment transport were recorded. A correlation was determined between the yield of the suspended sediment in the flood wave and the depth of direct runoff. The amount of outflowing matter increases in direct proportion to the size of the runoff. For all the measured events, the first flush effect and the occurrence of clockwise hysteresis between the flow rate and the concentration of suspended sediment were observed; and both these processes are typical for small river basins, in particular urban catchments. The recognition of the above relation is important whenever we plan to undertake activities related to the management of rainwater, for example the construction and operation of small reservoirs that detain the runoff and capture excess sediment. The problem of the quantity and quality of flood runoff is of particular importance in the case of the environment in which changes to land use arte taking place, for instance the increase in the proportion of sealed areas. In order to solve this problem, interdisciplinary knowledge is required, based on research in the fields of hydrology, sedimentology, chemistry and water quality, as well as spatial planning and engineering practice.

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TRANSPORT RUMOWISKA UNOSZONEGO W CZASIE WEZBRAŃ OPADOWYCH W MAŁEJ ZLEWNI MIEJSKIEJ

ABSTRAKT

Celem pracy było przedstawienie wyników badań nad procesem opad–odpływ–transport rumowiska unoszonego wykonanych w małej (A = 28,7 km^2) miejskiej zlewni Potoku Służewieckiego w Warszawie. Monitoring hydrologiczny prowadzony był przez Katedrę Inżynierii Wodnej SGGW. W latach 2014–2017 zarejestrowano 12 zdarzeń, w czasie których mierzono wysokości deszczu, przepływy, mętność oraz pobierano próby batometryczne. W pobranych próbach określano koncentrację unosin. Analiza zależności pomiędzy przepływami i koncentracjami wykazała występowanie zjawiska histerezy prawoskrętnej, oznaczającej, że koncentracje rumowiska w czasie wzrostu przepływów wody były wyższe niż przy tych samych wartościach przepływów w czasie opadania fali wezbraniowej. Zaobserwowano ponadto powstawanie zjawiska pierwszej fali spływu zanieczyszczeń (*first flush*), objawiającego się gwałtownym wzrostem koncentracji unosin w cieku oraz wystąpieniem ich wartości maksymalnej przed kulminacją hydrogramu wezbrania. Ustalono, statystycznie istotną zależność pomiędzy ilością rumowiska unoszonego a warstwą odpływu bezpośredniego w wezbraniach.

Słowa kluczowe: rumowisko unoszone, wezbranie, zlewnia miejska