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OCCURRENCE OF FIRST FLUSH PHENOMENON IN DRAINAGE SYSTEM OF CZĘSTOCHOWA

Definition of the first flush phenomenon in urban drainage systems is still a controversial problem. Scientists agree neither on its reality, nor on its influence on the size of treatment devices. This paper presents the overview of the available definitions and investigations on the first flush phenomena investigated at the urban site in Częstochowa. The measurements of total suspended solids (TSS) have been done for 3 catchments characterized by different land use (i.e. imperviousness) and 6 rainfall events. The results obtained have been used to calibrate the hydrodynamic model for the urban catchment (120 ha) at Częstochowa, developed with the use of EPA SWMM5. The analysis of the data obtained shows that this 30/80 first flush is rare. It occurs only once per 6 rainfalls in the catchment area.

1. INTRODUCTION

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*). It was reasoned that the store of pollutants that had accumulated on a paved surface in dry weather was quickly washed off during the beginning of the storm. At this period, an enormous quantity of pollutants is discharged into the receiving waters, degrading their quality. Practical significance of the first flush is clear – if most of the urban pollutant load is transported at the beginning of a storm, then a much smaller volume of runoff water would be needed to treat and remove urban pollutants [1], [2]. The main problem is to select the parameter to quantify the first flush.

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2. FIRST FLUSH DEFINITION

According to many authors, the first flush effect is the fact that a more or less significant concentration peak occurs at the beginning of storm events. THORNTON and SAUL label the first flush as the initial period of a storm, during which pollutant concentrations are generally higher than those occurring later in the event [3]. The first flush volume would then correspond to the volume discharged during the concentration peak period. All definitions based only on concentration peaks are inadequate and it is necessary to confront this with pollutant mass. For the same reasons, it is not enough to observe concentration peaks earlier than flow rate peaks to get the first flush. Other widely accepted definitions are developed from the comparison of a cumulative pollutant load with the cumulative runoff volume ($M(V)$). The studies by SANSALONE and BUCHBERGER [1] have utilized the definition of the first flush as an event with a normalized cumulative pollutant mass load curve that lies above the normalized cumulative volume curve. A more rigorous definition has been presented by GEIGER [4], who has considered that there is a significant first flush if the maximum gap between the $M(V)$ curve and the bisector is wider than 0.2 (figure 1a). The problem is that a gap wider than 0.2 may occur anywhere on the $M(V)$ curve. Therefore, it does not correspond to the "first" proportion of the total volume.

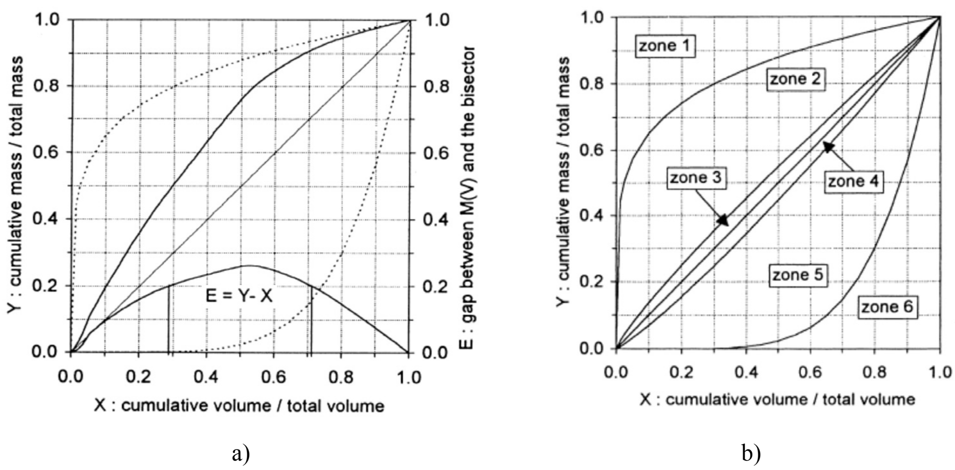


Fig. 1. First flush definitions: a) gap between $M(V)$ curve and bisector as defined by Geiger, b) zones of $M(V)$ curves depending on parameter b (by BERTRAND-KRAJEWSKI), [8]

For GUPTA and SAUL [5], the first flush is the part of the storm up to the maximum divergence between the dimensionless cumulative percentage of pollutant mass and the cumulative percentage of volume plotted against the cumulative percentage of time. More precise definitions of the first flush have been provided on a numeric basis. SAGET et al. have assumed that an event has the first flush when 80% of the pollutant mass is transported in 30% of the total runoff volume [6]. A similar definition proposed by VORREITER and HICKEY describes the phenomenon as transporting 80% of the pollutant load in 25% of the flow [7]. BERTRAND-KRAJEWSKI et al. [8] establish the cumulative pollutant-loading curve equation using a power law function that utilizes the exponential value (b) as a comparative tool for quantifying the first flush. The value of (b) characterizes the gap between the $M(V)$ curve and the bisector, allowing the $M(V)$ curves to be divided into 6 zones (figure 1b). These definitions based on $M(V)$ curves seem to be the most appropriate to describe the first flush.

3. FIRST FLUSH INVESTIGATION AT CZĘSTOCHOWA

The observations of the first flush phenomena were carried out in the catchment located in the central district of Częstochowa. Although the town is fully equipped with the separate system, there are no data about stormwater discharge quality in the catchment area. Therefore, the research was firstly focused on the variability of TSS concentration during rainfall events. The main task was to determine the pollutant mass distribution vs. the volume and to find some factors responsible for the distributions observed.

Three subcatchemnts have been selected for the experiment:

- industrial site (Ind) – area, 3.14 ha; imperviousness, 72%; average slope, 0.5%,
- typical old urban site (OU) – area, 2.38 ha; imperviousness, 56%; average slope, 4.0%,
- single residential site (SR) – area, 2.0 ha; imperviousness, 22%; average slope, 1.0%.

Table

Description of rainfall events

Event	Rainfall (mm)	Duration (h:mm)	Days since last storm	Measuring site
May 26	22.3	0:30	9	Ind., SR
June 21	44.8	4:00	5	Ind., SR
July 20	12.4	1:40	7	Ind., OU
August 12	15.5	3:00	9	Ind., OU
September 18	7.1	3:20	7	SR, OU
November 7	5.3	1:50	1	SR, OU

The samples were collected during 6 rainfall events (see the table) using a tipping bucket rain gauge with 0.1 mm resolution and at 10 min time interval. Flow rates were measured using flow meter PCMPro with a triple redundant level measurement (air-ultrasonic, water-ultrasonic and hydrostatic). The quality samples were collected from the manholes manually, then were filtered, dried at 103–105 °C and weighed. TSS concentrations and flow rates were measured at discrete time intervals throughout the duration of each event. Sampling intervals varied between events and, in many cases, within them as well. For every sample collected, a concentration (C_n) and a flow rate

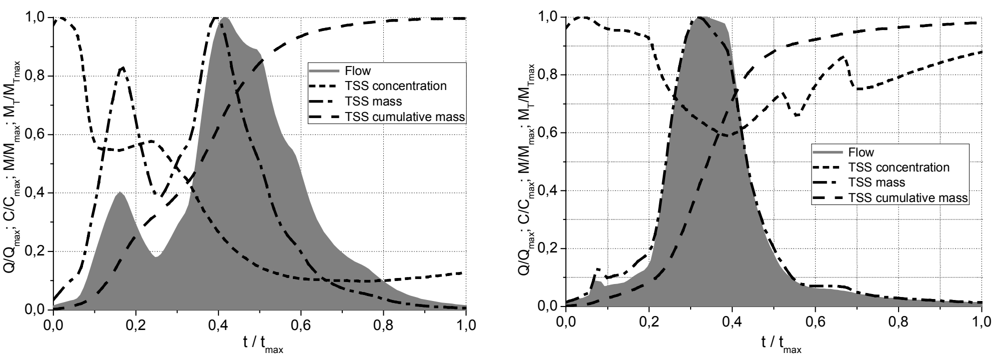
(Q_n) were measured (n is the sample number). Incremental volumes were determined based on the measured flow rates as follows:

$$V(t) = 0.5 \cdot (Q_n - Q_{(n-1)}) \cdot t_i \quad \text{and} \quad t_i = t_n - t_{n-1}.$$

Assuming a linear relationship between all measured points, an incremental mass was determined by the following equation:

$$M(t) = 0.5 \cdot (C_n - C_{(n-1)}) \cdot t_i \,.$$

Incremental flow rates, concentration, and masses were normalized to their maximum concentrations and plotted against normalized time for each event. A plot of cumulative mass was also included to investigate the degree of constituent delivery as a function of normalized flow. Figure 2 shows sample hydrographs and pollutographs for the catchments.



a) b)

Fig. 2. Temporal comparisons of normalized incremental pollutant concentration, mass, cumulative mass and flow at: a) single residential site, rainfall 07.11.2007, b) old urban site, rainfall 12.08.2007

For each catchment, the dimensionless curves of the cumulative pollutant mass vs. the cumulative discharged volume were plotted (4 rainfall events per catchment). As can be seen in figures 3, the first flush effect is the most pronounced for the sites that are highly impervious, and is much weaker at lower levels of imperviousness. For example, on the single residential catchment, 2 of 4 rainfall events had a proportional distribution of TSS load (the first flush phenomena did not occur), while on the industrial site, one rainfall caused a strong first flush effect (over 90% of TTS load in 30% volume) and the next 3 events brought about a "weak" first flush (80% of TSS load in 42%–58% volume). Considering the criteria proposed by Bertrand-Krajewski in order to quantify the first flush (figure 1a), the following results were obtained: one event in zone 1; nine events in zone 2; two events in zones 3 and 4, and no event in zones 5 and 6. The results clearly show that the 30/80 first flush is a rare phenomenon and is not as strong and universal as was previously thought to be.

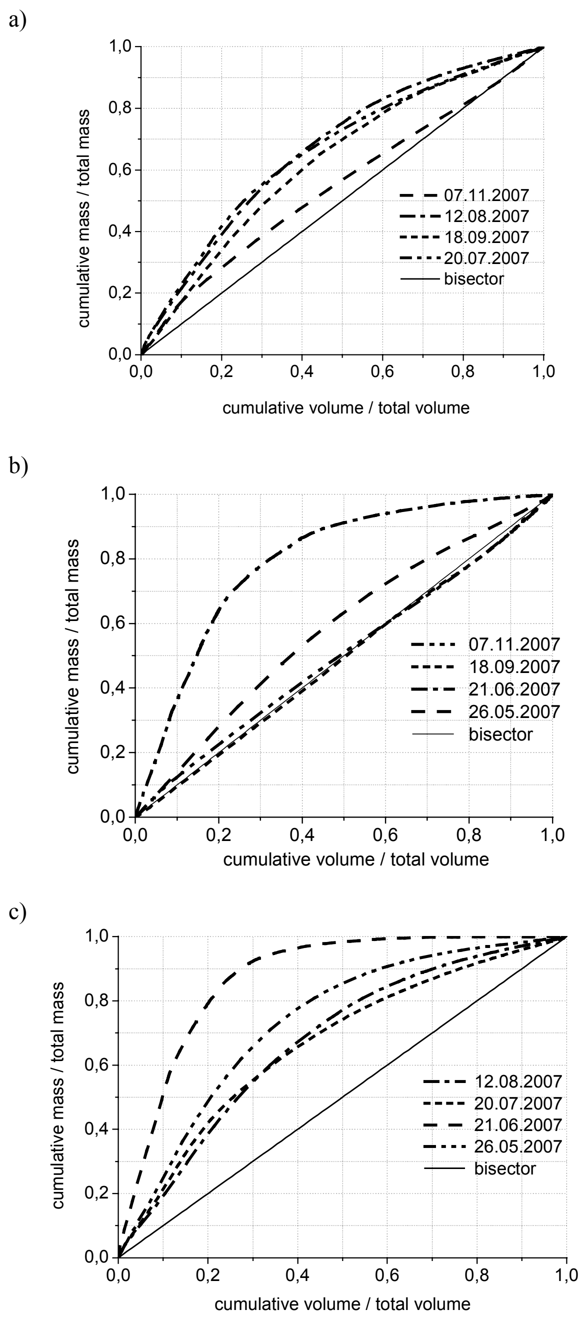


Fig. 3. Dimensionless curves of cumulative pollutant mass vs. cumulative discharged volume for: a) old urban site, b) single residential site, c) industrial site

4. SIMULATION MODEL OF FIRST FLUSH

A hydrodynamic model has been developed using the EPA Storm Water Management Model (SWMM). SWMM5 is a dynamic rainfall-runoff simulation model used for single event or long-term simulation of runoff quantity and quality from primarily urban areas. Based on numerical maps and aerial photographs, the whole catchment area (120 ha) was divided into 155 homogeneous subcatchments (area from 0.2 to 2.8 ha), taking into account their shape, slope, land-use type (on average 30% imperviousness) and soil conditions. Due to some lack of necessary data from the numerical maps of drainage system, the analysis was completed by a field survey. The whole network consists of nearly 150 links (diameters between 250 mm and 800 mm). The Horton infiltration equation was used to estimate the infiltration of stormwater on the pervious portions of the catchment. Dynamic wave was selected as a routing method with a time step of 5 sec.

For the hydraulic validation, a very accurate adjustment in terms of time and variation of flows was obtained, and the total volume simulated presented only a difference of 5% with respect to the measured volume. However, the observed peak flows were greater than the simulated ones by 10–15%.

The previously presented TSS concentration data was used to calibrate the quality component. The SWMM structure recognized the existence of three major model components that can be described as:

- accumulation of pollutants (exponential equation was selected),
- wash-off of pollutants by rainfall transformed to runoff (exponential equation was selected),
- pick up of accumulated pollutants by street cleaning (component treated as marginal).

There are several significant problems with the exponential equations within SWMM, i.e.: the wash-off coefficient can vary dramatically from one storm to the next and there is no apparent way to accurately predict this variation; there is no spatial effects both on buildup and wash-off; the program does not differentiate between impervious and pervious area pollutants and wash-off. Considering the abovementioned inconveniences, the calibration process have been conducted with differences no greater than 30% between measured and simulated values of TSS concentration, and no greater than 20% for total TSS load. Simulations done for the whole catchment allow us to plot the $M(V)$ curves for 6 rainfall events. As can be seen in figure 4, the first flush phenomena for large catchment are less distinct than for the previously presented subcatchments, mainly because an average imperviousness of the catchment is closer to a single residential site. However, even for this configuration only one rainfall met the requirements of 80/30 definition (77% to be precise). The rest of the events belong to zone 2 (four events) and zone 3 (one event). Considering median cumulative load, 50% of the total TSS mass is transported in the first 35% of the total volume, and 80% of the total pollutant mass is transported in the first 67% of the total volume.

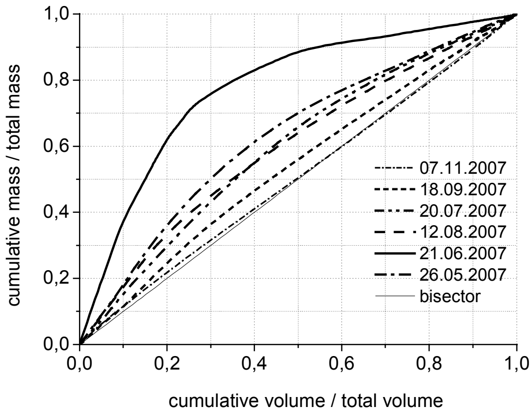


Fig. 4. Curves of cumulative pollutant mass vs. cumulative discharged volume for urban catchment at Częstochowa (six rainfall events)

5. CONCLUSIONS

According to the above-mentioned definitions, a strong first flush is present when 30% of the runoff contains 80% of the pollutants. The analysis of the data obtained in the urban catchments at Częstochowa proves the rarity of the 30/80 first flush – for six rainfalls it occurs only once in one catchment. The distribution of TSS load depends greately on the rainfall intensity and temporal variability, as well as on catchment imperviousness and the antecedent dry weather period. Simulations performed with SWMM show its quite good correlation with the measured values of flow rates as well as TSS concentration for single events. As a result of the authors' research, it is not appropriate to assume that most of the pollutants will be captured by merely capturing the first flush. Without field investigation, it is safer to assume that there is no first flush. If local investigations do find a significant first flush, then it will be necessary to define its volume and duration.

ACKNOWLEDGEMENTS

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WYSTĘPOWANIE ZJAWISKA PIEWSZEJ FALI SPŁUKUJĄCEJ NA PRZYKŁADZIE KANALIZACJI DESZCZOWEJ CZĘSTOCHOWY

Definicja zjawiska pierwszej fali spłukującej nadal stanowi przedmiot dyskusji naukowców zarówno w odniesieniu do kwestii jego występowania, jak i wpływu na wymiarowanie urządzeń oczyszczających. W artykule przedstawiono proponowane definicje pierwszej fali oraz badania tego zjawiska przeprowadzone na miejskiej zlewni w Częstochowie. Badania objęły pomiary stężeń zawiesiny w trzech zlewniach cząstkowych o zróżnicowanym zagospodarowaniu dla 6 opadów deszczu. Dane z pomiarów terenowych wykorzystano do kalibracji modelu, wykonanego przy użyciu programu SWMM5 dla zlewni o powierzchni 120 ha. Wyniki badań pozwalają stwierdzić, że gdy stosuje się definicję 30/80 (80% ładunku zawiesiny w 30% objętości), wtedy zjawisko pierwszej fali w badanej zlewni występuje bardzo rzadko. Nierównomierną dystrybucję ładunku zanieczyszczeń względem objętości obserwuje się w mniejszym stopniu i dla przeciętnego opadu 80% ładunku zawiesiny jest zawarte w 50–60% objętości spływających ścieków deszczowych.