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# Analysis of particle size distribution and concentration of suspended solids in stormwater runoffs

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**ABSTRACT**

Stormwater runoff from urban areas degrades receiving waters by increasing the quantity of polluted water in river systems in a short period of time. The article presents tests of the quality of runoffs (total concentration of suspended solids and particle size distribution (PSD)) from impervious ground in urban areas. The distribution of particles in runoffs was characterized for eight types of urban surfaces (three different types of roof, two parking lots, and three roads) located in Czestochowa City. Variability in median particle size and distribution was considerable between source areas and also in comparison with other studies. The lowest median particle size was found for the roof surfaces (from 40 to 65 μm), followed by parking lots (73–82 μm). PSD and concentration of solids in road runoffs were influenced by average daily traffic for a particular road, with median particle sizes ranging from 100 μm for the local road to 150 μm for the main freeway. Results showed significant variability in data and lead to the question of using one template of particle-size distribution that is representative of stormwater runoffs generated from urban catchments.

*Keywords:* Stormwater; Suspended solids; Particle size distribution

## 1. Introduction

Stormwater discharged from drainage systems degrades the quality of surface water and impairs aquatic habitat. The negative effects of pollutants transported to river bodies can be classified as acute or cumulative. If the effect is acute, the impact of single events is significant, particularly for those of extreme magnitude and a relatively frequent occurrence (i.e., dissolved oxygen depletion caused by biodegradable organic matter will result in an acute effect). If the effect is of the cumulative type, it is important to consider the discharge over a certain period of time, typically a season or a year, to examine nutrients causing eutrophication [1]. Stormwater quality is affected by rainfall, especially depending on the catchment. The sources of pollutants include [2]:

- the atmosphere: pollutants present in the atmosphere exist as gases, suspended solid particles, and aerosols; they may originate from both stationary and mobile sources. The pollutants that are transported to the urban surface are identified as atmospheric fallout,
- human activity in the urban area: the urban areas include in particular roads (highways, freeways, local roads, etc.), parking lots, roofs, and pavements. The polluting activities related to the urban surface are often identified by the term "land use" (i.e., commercial, industrial, residential, etc.). The major sources include vehicle emissions, corrosion and abrasion; building and road corrosion, and erosion; bird and animal feces; street litter deposition, fallen leaves, etc.,
- spills, accidents, and illegal or inappropriate activities: specific input that occurs stochastically; they may result in extreme pollutant loads.

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A characteristic feature of the stormwater pollutant sources is their variability in time and site (depending on the design of the drainage system or land use). These aspects and the stochastic nature of the rainfall result in very large variability of both the quality and the quantity of pollutant contributions [2,3]. The variability of the pollutant load is important in terms of environmental effects and the choice of a treatment process. There are several types of variability:

- variability within an event: the highest concentrations or the largest mass of pollutants transported occur during the initial period of a runoff event compared with the later stages of the same event,
- variability between events at a specific site: the stochastic nature of runoff events including pollutant buildup in drainage systems that affects the volume of pollutants available for transport implies that both pollutant loads and pollutant concentrations may vary between the runoff events at a specific site,
- variability between catchments: the factors affecting the build-up of pollutants on impervious surfaces include: land use, population, traffic flow, effectiveness of street cleaning, season of the year, meteorological conditions, antecedent dry period, street surface type.

A great number of investigations have been performed worldwide to assess the level of pollutants originating from different sources. The variability of these data is very high, with common pollutants in stormwater being mainly heavy metals, and suspended sediments [4,5]. According to research presented by Ellis and Mitchel [3], TSS concentration ranges from 21 to over 2,500 mg/L, but its mean value is around 90 mg/L. Greater spread of results is observed for heavy metals [6]. The following four heavy metals have generally studied in urban drainage systems: cooper, zinc, cadmium, and lead. Results of selected studies are presented in Table 1.

According to the results of many studies, removal of suspended solids leads also to the removal of various quantities of heavy metals because of the tendency for these substances to attach to suspended solids [10]. The efficiency of removal of suspended solids depends mainly on its particle size distribution (PSD). The distance that suspended solids travel and the type and quantity of pollutants transported are strongly influenced by the size and shape of the particles in runoffs. Large particles settle rapidly while particles with smaller size range remain in suspension for long distances. The smaller sized particles have a greater surface area per mass than larger particles, and thus offer more sites on the surface for the adsorption of dissolved constituents like heavy metals. In samples of highway runoff, the authors of the study [11] found a clear association of copper, lead, and zinc to finer particle sizes. Other constituents associated with suspended particles are phosphorus and nitrogen [12], polycyclic aromatic hydrocarbons [13], and also bacteria [14]. These data suggest that treatment options for urban stormwater should be focused on sediments as the primary source of contamination to streams and rivers.

Since many pollutants bind to suspended sediments, TSS concentration is often treated as a measure of the overall quality of stormwater runoffs. Various characteristics are used to describe suspended sediments in stormwater, including:

- suspended sediment concentration—basic method of measurement of suspended solids in stormwater for regulatory purposes and improving removal efficiency,
- PSD characterizes the size fractions of suspended sediments which is important because certain pollutants adhere to specific particle sizes,
- specific gravity—measured to determine the sediment settling characteristics which are important for treatment devices,
- turbidity, as an indirect way to measure suspended solids in stormwaters once a relationship between TSS concentration and turbidity has been established.

If the PSD of suspended solids in a particular stormwater discharge is known, a stormwater treatment device can be designed to remove a specified proportion of the suspended solids and the associated chemical contaminants [15]. The difficulty is that the PSD of stormwater suspended solids varies depending on the physical and chemical characteristics of anthropogenic particulate material in the catchment and on the character of natural soils and rainfalls as well.

Most of the research conducted in Polish conditions concerns on stormwater quality in drainage systems, after mixing of runoffs from different surfaces. Therefore, the results usually refer to the land use category (industrial, commercial, flats, residential, etc.) rather than to specific surfaces (roads, roofs, etc.). Ociepa [16] studied quality of stormwater runoffs from different surfaces (local roads, highway, roof) but analysis covered mainly chemical parameters (pH, suspended solids, heavy metals (As, Pb, Cd, Ni, Cu), biological and chemical oxygen demand) without evaluation of PSD and rainfall characteristics. Wiercik and Berger [17] analyzed samples taken directly during rainfall and as runoff from the roof to identify the shape and size of particles forming polydisperse suspensions in stormwater. The samples were collected in the village, so it is not representative of urban areas.

Table 1
Heavy metals concentrations [3,7–9]

| Heavy metal (mg/L) | Ellis and Mitchell [3] | Gasperi et al. [7] | Järveläinen et al. [8] | Lee et al. [9] |
|---|---|---|---|---|
| Total copper | – | 15–138 | 11–59 | 0–280 |
| Total lead | 140 | 2.5 | 1.1–33.4 | 0–255 |
| Total cadmium | – | 0.3 | – | 5–20 |
| Total zinc | 300 | 126–240 | 41.6–260.9 | 43–449 |

The primary objective of this paper is to reduce the uncertainty in stormwater management planning in cities by improving the characterization of particle-size distributions in stormwater runoff from specific land-use categories. This information can be used to assist engineers in designing the most appropriate control devices for the reduction of sediment in urban stormwater runoff. Special attention was paid on sample collection during intensive rainfalls that produce high peak flows, volumes, and pollution loads released to the aquatic environment.

## 2. Methods

There are many factors affecting the PSD and it would be an excessively time-consuming task to determine the PSD of stormwater suspended solids site of every stormwater event. A realistic compromise is to define a number of PSD patterns for the main surfaces and select the most appropriate PSD for their particular source of suspended solids to use for design purposes. Therefore, the aim and scope of the research were to analyze total suspended solids (TSS) concentration and its PSD for runoffs originating from different types of urban surfaces.

### *2.1. Site description*

The place of research was an urban catchment located in the northern part of Czestochowa, Poland. Considering the structure of impervious surfaces in the city, the research was focused on areas that dominate in urban landscape: roofs, roads, and parking lots. In the case of sidewalks, it was assumed that they are part of the road lane because in most cases runoffs are flowing to street gully pots. Street type was categorized by traffic volume, defined by the term average daily traffic (ADT, expressed in the number of vehicles per day). A short description of the monitored sites is presented in Table 2.

To minimize the effect of local factors (i.e., industry emissions), all the sites are located near each other (less than 1 km), except for the collection point at main freeway (F3), located 2 km away from other monitored points (Fig. 1). Rain gauge station is located at a distance of 1,600 m from the furthest point.

Table 2
Characteristics of monitored sites

| Type of site | Characteristics of surface |
|---|---|
| R1 – Roof of a commercial building | Bitumic |
| R2 – Roof of a block of flats | Bitumic |
| R3 – Roof of an individual house | Metal roof panels |
| P1 – Parking lot, commercial building | Pavement |
| P2 – Parking lot, city center | Asphalt |
| F1 – Local street (ADT = 4,000) | Local road, asphalt |
| F2 – Freeway (ADT = 23,000) | Regional road, asphalt |
| F3 – Freeway (ADT = 55,000) | Main national road, asphalt |

### *2.2. Sample collection*

The choice of a sampling method is crucial and can be a source of errors and discrepancies in the analysis of stormwater quality. The effect of the sampling method on the results has been demonstrated in many publications [18–20]. There are two basic stormwater sampling techniques: samples can be taken manually or collected using automatic samplers [21,22]. Obtaining manual samples involves sending a person to the sampling location before the rain event occurs and physically capturing samples as the stormwater effluent leaves the pipe or downspout. This requires good prediction of precipitation and waiting for the beginning of rainfall, otherwise, the first flush phenomenon may be missed [23]. For this reason, each monitoring station was equipped with automated stormwater quality samplers and instruments to measure discharge. Stormwater samples were collected by automatic samplers interfaced to rainfall loggers using flow proportional sampling. Between 5 and 7 events were sampled at each site and between 22 and 30 samples for each site were analyzed for PSD.

Precipitation data were collected by means of a SEBA RG50 tipping bucket rain gauge connected to a data logger. Resolution was calibrated to 0.1 mm, while the time step was equal to 5 min. Samples were collected during rain events between May 2016 and September 2018. It was assumed that the precipitation height should be higher than 10 mm and that the dry weather period preceding the event (precipitation) should be at least 36 h (the precipitation in this period should be lower than 1 mm). Assumption of the minimum rainfall depth resulted from the fact that rainfalls of depths less than 10 mm do not cause a hydraulic overload of treatment devices and discharges through combined sewer overflows. A summary of all rainfalls analyzed in the study is presented in Table 3.

Due to the availability of only two sets of automated samplers, the tests were conducted at two locations during one rainfall event. Runoff from roads and parking lots was collected using a shaped orifice mounted instead of a gully grate. It allows for catching the stormwater before it reaches the pipe and mixes with inflows from other surfaces. Roof runoffs were collected at the outlet of gutters, using orifice plate to increase the water depth.

### *2.3. Analytical methods*

Several methods exist to report PSD of sediments in stormwater. Particle sizes span four to five orders of magnitude and there is no single instrument or technique that has been proven to characterize the entire range of particle sizes in stormwater runoffs [24]. Historically, the PSD was determined by either dry or wet sieving but the distributions determined with these methods were limited partly by the difficulties of using sieves with pore sizes below 32 μm. The most common sources of errors are: (a) blocking of sieve apertures (too coarse results); (b) old or damaged sieves (too fine results); (c) errors in data transfer. The average real aperture size of a 1 mm sieve, for example, is permitted to deviate about ±30 μm; for a 100 μm sieve, this is ±5 μm. Thus, the sieve becomes effectively larger than the nominal aperture size.

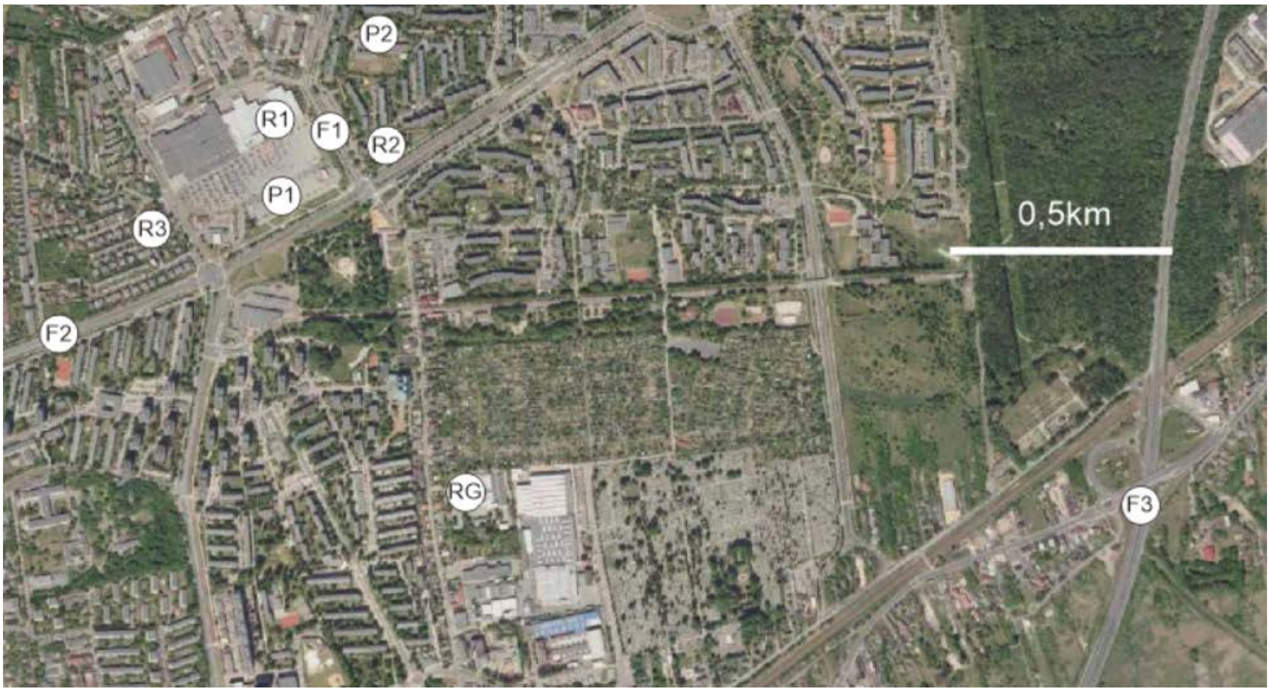

Fig. 1. Location of sample sites (R1, R2, R3, P1, P2, F1, F2, F3) and rain gauge (RG), northern part of Czestochowa, Poland.

Table 3
Characteristics of rainfall events: total depth, duration, antecedent dry period, and monitored sites during given event

| Rainfall date | Rainfall depth (mm) | Rainfall duration (h) | Antecedent dry period (days) | Sites monitored during rainfall |
|---|---|---|---|---|
| 25 May 2016 | 10.3 | 1.9 | 8.3 | R1, P1 |
| 28 May 2016 | 10.4 | 4.1 | 3.2 | R1, P1 |
| 2 July 2016 | 18.2 | 2.4 | 2.5 | R1, P1 |
| 12 July 2016 | 39.5 | 5.8 | 7.3 | R1, P1 |
| 26 May 2016 | 25.7 | 3.5 | 6.2 | R1, P1 |
| 31 May 2016 | 11.3 | 1.7 | 2.1 | R2, P1 |
| 5 August 2016 | 12.5 | 3.6 | 5.5 | R2, P2 |
| 21 August 2016 | 13.5 | 7.3 | 11.6 | R2, P2 |
| 17 September 2016 | 11.9 | 11.3 | 12.1 | R2, P2 |
| 24 May 2017 | 15.7 | 5.2 | 8.8 | R2, F1 |
| 30 May 2017 | 12.3 | 3.0 | 5.7 | R2, F1 |
| 16 June 2017 | 10.8 | 1.7 | 6.2 | R2, F1 |
| 27 June 2017 | 18.0 | 4.1 | 4.8 | F1, F2 |
| 11 August 2017 | 14.1 | 1.7 | 1.6 | F1, F2 |
| 16 August 2017 | 11.7 | 2.5 | 3.5 | F1, P2 |
| 1 September 2017 | 28.5 | 6.8 | 6.7 | F2, P2 |
| 11 September 2017 | 11.9 | 9.3 | 5.8 | F2, P2 |
| 17 September 2017 | 29.7 | 20.4 | 5.2 | F2, P2 |
| 11 May 2018 | 23.9 | 5.4 | 2.0 | F2, F3 |
| 10 May 2018 | 21.2 | 1.8 | 8.2 | F2, F3 |
| 27 July 2018 | 20.9 | 1.5 | 1.5 | R3, F3 |
| 29 July 2018 | 15.0 | 2.8 | 2.1 | R3, F3 |
| 10 August 2018 | 10.6 | 4.2 | 2.4 | R3, F3 |
| 24 August 2018 | 10.4 | 2.3 | 10.0 | R3, F3 |
| 23 September 2018 | 11.6 | 4.0 | 8.7 | R3, F3 |

Researchers often use different analytical techniques, such as laser diffraction, optical sensors, settling rates, or wet/dry sieving when determining the distribution of particles in stormwater. Much of the inconsistency can be attributed to the lack of analytical equipment capable of covering the wide range of particle sizes found in urban stormwater. Therefore, each method has a tendency to produce specific results. Optical laser instruments are now commonly used for measuring the size of particles that can be readily retained in suspension but wet sieving is still used for larger particles [22]. Laser techniques can give a measure of particle shape, but for calculating particle area and volume, the assumption is generally made that the particles are perfect spheres with a diameter equal to the measured particle size, but for example, clay particles are more likely to be flat. With static laser light analysis, also called laser diffraction, particle size is measured indirectly by detecting intensity distributions of laser light scattered by particles at different angles. This technique is based on the phenomenon that light is scattered by particles and the correlation between intensity distribution and particle size is well-known. While large particles produce rather sharp intensity distributions with distinctive maxima and minima at defined angles, the light scattering pattern of small particles becomes more and more diffuse and the overall intensity decreases. It is particularly difficult to measure differently sized particles in a polydisperse sample as the individual light scattering signals of the particles superimpose each other. Other factors that influence the accuracy of PSD are: time from the extraction of the sample, time of its analysis, and the temperature at which the sample is stored [25]. As time elapses, smaller particles reduce in number whereas the number of larger-sized particles grows [26]. Higher storage temperature will also affect PSD due to the biological flocculation or the proximity of particles to each other [22]. Consequently, much of the variability of the results may be attributed to differences in analytical methods or sample collection methods or both.

Considering the abovementioned issues, it was decided that PSD determination will be performed using two methods: dry sieve (particles up to 63 mm) and laser diffraction (particles smaller than 63 mm).The sample was then wet sieved through a series of stacked nylon-mesh sieves, which separated the solid-phase material from the sample into separate particle-size fractions (mm): ≥1,000, 500 < 1,000, 250 < 500, 125 < 250, and 63 < 125. Material retained on each sieve was transferred into a clean tared container and dried at 105°C [27]. The mass of dried material recovered from each sieve was measured and recorded. This process was repeated for each fraction. Particles less than 63 µm in size were quantified by means of laser diffraction (Malvern mastersizer 2000) into three separate particle size fractions: 32 < 63, 15 < 32, 8 < 15 µm.

## 3. Results

The research conducted over a three-year observation period allowed for collecting a sufficient amount of data for their statistical analysis of TSS concentration and PSD for runoffs from roofs, roads and parking lots. The solids concentration and size range of particles found in stormwater differ both due to the type of surface and rainfall parameters (especially storm duration and depth).

### *3.1. TSS concentration in stormwater runoffs*

The results of TSS concentrations in runoffs from different types of surfaces (Table 4) confirmed the general relationship that roof runoffs are characterized by significantly lower concentrations than runoffs from roads and parking lots (this applies to both residential and commercial roofs). In the case of the residential roof, the average difference between TSS concentration from the roof and the local road was 70% (78 vs. 134 mg/L). A similar relationship was observed between runoffs from the roof and a parking lot of a commercial building (107 and 189 mg/L on average, respectively). It should be noted that the differences in maximum values are much higher and in the case of commercial buildings are more than fourfold (198–857 mg/L), while for residential buildings, this was over threefold higher (169–654 mg/L). Therefore, runoffs from road surfaces have a much greater potential for harmful effects on the aquatic environment due to the risk of significant pollution loads.

Comparison of the quality of runoffs from different road surfaces showed a proportional relationship between the average suspension concentration and their traffic load (ADT): an increase in average concentration values from 134 mg/L for a local road to 302 mg/L (freeway) and even 401 mg/L is observed in the case of the highest traffic loads. In the case of heavy traffic, very high TSS concentrations were recorded, reaching over 1,000 mg/L in five trials (17% of all trials) and the maximum concentration was close to 2,000 mg/L). It was noted that in the case of local roads, the median suspension concentration was slightly higher than for roof drains but lower than that recorded for parking lots, which was a bit surprising. At the same time, the maximum values were more than twice as high as those recorded for roofs, which indicates greater uncertainty for TSS concentration. The explanation for this relationship may be the fact of the accumulation of pollutants in parking lots due to their rare sweeping and the lack of the effect of air mass movement through passing cars.

### *3.2. Particle size distribution of stormwater runoffs*

From 22 to 30 samples were collected for each surface tested and individual PSD curves were plotted. Fig. 2 shows all PSD curves obtained for the roof R1 (Fig. 2a) and freeway F3 (Fig. 2b). They show great variability of PSD between the sites and between the rainfall events. For example, particles finer than 100 mm accounted for from 46% to 82% in runoffs from roofs but for freeway F3, it ranged from 27% to 57%.

Since the PSD curves were characterized by significant variability in minimum and maximum values, the statistical summary is presented in Table 5 (it contains maximum, minimum, mean, median, and standard deviation values). A similar representation of PSD was applied in [28].

Given the degree of variability of the data, the median distribution was chosen as an appropriate representation of particles from each study area. The median PSD for each site was calculated from the sample results remaining after

Table 4
Concentrations of total suspended solids (TSS) measured at test sites

| Types of site | Rainfall events | Number of samples | TSS (mg/L) | | | |
|---|---|---|---|---|---|---|
| | | | Minimum | Mean | Median | Maximum |
| R1 | 5 | 24 | 13 | 107 | 89 | 198 |
| R2 | 7 | 30 | 17 | 92 | 72 | 169 |
| R3 | 5 | 22 | 7 | 78 | 47 | 148 |
| P1 | 6 | 27 | 15 | 189 | 159 | 857 |
| P2 | 7 | 30 | 19 | 233 | 193 | 654 |
| F1 | 6 | 23 | 21 | 134 | 98 | 401 |
| F2 | 7 | 28 | 24 | 302 | 207 | 889 |
| F3 | 7 | 30 | 55 | 401 | 311 | 1,984 |

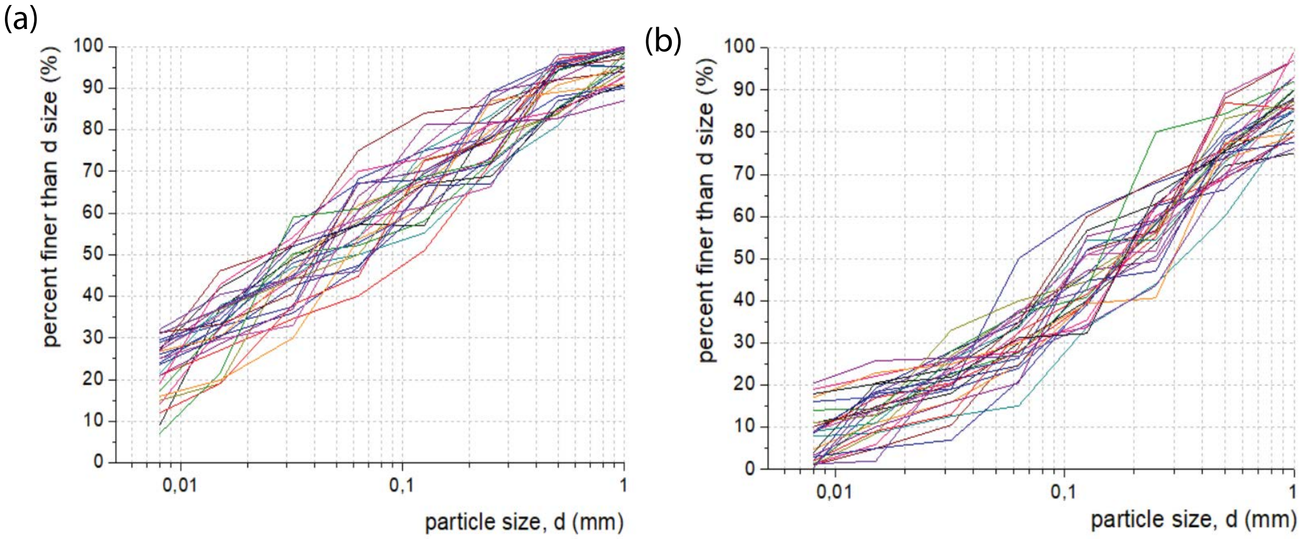

Fig. 2. Particle size distribution for individual samples: (a) roof R1 and (b) freeway F3.

the removal of outliers [29], and then the median values were plotted for each surface presented in the figure. These median PSDs are plotted in Fig. 3 as the cumulative percentage of total particle weight (percentage finer) against the upper size of each particle size band.

Based on developed PSD (Fig. 3), it was possible to determine the characteristic diameter of particles for each surface. The median particle size ($d_{50}$) across all samples ranged from 40 to 160 μm. The suspended solids from roofs were clearly finer than those from the roads and parking lots. Roof study areas (R1, R2, R3) had the lowest median particle sizes (from 40 to 65 μm), followed by the parking lots (73–82 μm) Roads F1 and F2 had similar median particle sizes—from 100 μm for the local road to 115 μm for the regional road. Finally, the freeway F3 showed the largest median particle size of nearly 160 μm. Results show the significant variability in data and lead to the question of using one template of PSD that is representative of stormwater runoffs generated from urban catchments.

In road runoffs, around 30% – 42% (by weight) of the suspended solids particles were smaller than 63 μm in diameter, while particles greater than 1,000 μm accounted for 5%–10% of the total. The comparison between the surfaces reveals that the stormwater runoffs from roads contain substantial proportions of larger and heavier particles, some of which are abraded from the rocks used on road surfaces. This finding is similar to that of [30,31] and Li et al. [25], who found 30%–50% of the particle mass in particles smaller than 50 μm. In general, the fraction of finer particles is rather smaller than those obtained in other studies, especially in comparison to samples containing mixed runoffs from different types of surfaces. Different characteristics of suspended solids (concentration, PSD) in runoffs from roofs and roads justify the concept of flow separation for these surfaces. Runoffs from roofs are clearly enough to be managed locally by infiltration devices or by rainwater reuse for different purposes (irrigation, toilet flushing, etc.). Due to significant contamination, runoffs from roads have to be transported through the drainage system to treatment devices:

- settling tank for a separate sewer system,
- wastewater treatment plant in a combined sewer system.

Table 5
Particle size distribution represented as percent finer than the corresponding particle size (mm)

| Site | Stats | Particle size (mm) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 0.008 | 0.015 | 0.032 | 0.063 | 0.125 | 0.250 | 0.500 | 1.000 |
| R1 | Maximum | 28 | 38 | 48 | 63 | 78 | 90 | 94 | 98 |
| | Minimum | 17 | 24 | 31 | 43 | 53 | 68 | 78 | 89 |
| | Median | 21 | 29 | 39 | 54 | 66 | 82 | 88 | 92 |
| | Mean | 22 | 31 | 39 | 53 | 65 | 79 | 86 | 93 |
| | SD | 11 | 14 | 17 | 20 | 25 | 22 | 16 | 9 |
| R2 | Maximum | 36 | 46 | 61 | 75 | 84 | 92 | 100 | 100 |
| | Minimum | 12 | 19 | 31 | 39 | 52 | 64 | 81 | 90 |
| | Median. | 26 | 32 | 43 | 57 | 64 | 76 | 94 | 97 |
| | Mean | 24 | 32 | 46 | 57 | 68 | 78 | 92 | 96 |
| | SD | 24 | 27 | 30 | 36 | 32 | 28 | 22 | 13 |
| R3 | Maximum | 32 | 42 | 62 | 70 | 79 | 88 | 99 | 100 |
| | Minimum | 10 | 15 | 29 | 35 | 47 | 60 | 75 | 91 |
| | Median | 22 | 27 | 37 | 53 | 67 | 80 | 85 | 93 |
| | Mean | 19 | 24 | 35 | 48 | 62 | 77 | 84 | 94 |
| | SD | 15 | 14 | 20 | 19 | 23 | 19 | 11 | 6 |
| P1 | Maximum | 28 | 32 | 39 | 56 | 73 | 81 | 92 | 99 |
| | Minimum | 11 | 14 | 18 | 33 | 54 | 61 | 77 | 88 |
| | Median | 21 | 23 | 27 | 43 | 60 | 73 | 84 | 93 |
| | Mean | 20 | 23 | 28 | 44 | 63 | 71 | 84 | 93 |
| | SD | 17 | 18 | 21 | 23 | 19 | 20 | 15 | 11 |
| P2 | Maximum | 27 | 36 | 44 | 58 | 70 | 83 | 97 | 100 |
| | Minimum | 13 | 19 | 25 | 38 | 47 | 62 | 82 | 89 |
| | Median | 21 | 29 | 34 | 47 | 58 | 74 | 89 | 95 |
| | Mean | 20 | 27 | 34 | 48 | 58 | 72 | 89 | 95 |
| | SD | 14 | 17 | 19 | 20 | 23 | 21 | 15 | 13 |
| F1 | Maximum | 26 | 34 | 48 | 53 | 68 | 78 | 92 | 95 |
| | Minimum | 10 | 14 | 25 | 28 | 45 | 60 | 78 | 85 |
| | Median | 19 | 26 | 36 | 42 | 54 | 71 | 85 | 90 |
| | Mean | 18 | 24 | 36 | 40 | 56 | 69 | 85 | 90 |
| | SD | 16 | 20 | 23 | 25 | 23 | 18 | 14 | 10 |
| F1 | Maximum | 19 | 26 | 30 | 45 | 59 | 77 | 89 | 100 |
| | Minimum | 10 | 13 | 14 | 25 | 37 | 54 | 74 | 87 |
| | Median | 16 | 19 | 21 | 39 | 46 | 66 | 81 | 94 |
| | Mean | 14 | 19 | 22 | 35 | 48 | 65 | 81 | 93 |
| | SD | 9 | 13 | 16 | 20 | 22 | 23 | 15 | 13 |
| F2 | Maximum | 16 | 23 | 32 | 39 | 57 | 69 | 84 | 91 |
| | Minimum | 3 | 5 | 8 | 17 | 34 | 48 | 69 | 79 |
| | Median | 9 | 16 | 21 | 30 | 47 | 59 | 77 | 85 |
| | Mean | 9 | 14 | 20 | 28 | 45 | 58 | 76 | 85 |
| | SD | 13 | 18 | 24 | 22 | 23 | 21 | 15 | 12 |

### *3.3. Use of PSD for stormwater treatment strategy*

If the PSD of suspended solids in a particular stormwater discharge is known, a stormwater treatment device can be designed to remove a specified proportion of the suspended solids and its associated chemical contaminants [32,33]. There is limited guidance available with respect to the choice and design of treatment devices for the removal of solids of different size classes in stormwater. This is due to the limited number of studies that have investigated PSD. Most investigations on the performance of stormwater treatment devices have documented the removal of only TSS. The removal of solids is largely dependent on the detention time and the settling behavior of the solids. Ideally, settling basins should be designed so that the path length from the inlet to the outlet divided by the detention time is the same as the settling rate of the target grain size to be removed [34]. To determine the settling velocity profiles for each of the tested sites, the results of the average TSS concentration (Table 4) and the PSD curves (Fig. 3) were combined to calculate an average TSS concentration for each fraction. Table 6 contains results of calculations for roads, parking lots and roofs.

Based on the calculated TSS concentrations for each fraction (Table 6), the cumulative distribution of TSS concentrations was plotted against the upper size of each particle size band (Fig. 4). It provides to determine the value of particle diameter that must be removed to obtain the required concentration of the suspended solids in effluent [35]. In Poland, according to the quality regulation for stormwater discharged to rivers, the maximum permissible concentrations of TSS are 100 mg/L. Considering this value as the upper limit for each surface tested, it is possible to select the minimum particle size ($d_t$) which has to be removed in order to meet the requirements.

Settling velocity from the known particle size $d_t$ was calculated using Stokes' law (appropriate for particles with Reynolds number (Re) <1) and Weber equation for Reynolds number from 1 to 1,000. Quiescent settling was assumed, interactions between particles including flocculation were ignored and each particle was assumed to have a perfect sphere with a diameter equal to the particle size.

Two cases were included in the calculations of the settling velocity: constant and variable density. In the first case, particles have a density of sand (2,600 kg/m$^3$), whereas water is assumed to have a density of 998 kg/m$^3$ (at 20°C). A density of about 2,600 kg/m$^3$ is reasonable for unweathered mineral particles but in the natural environment, particles commonly have coatings of amorphous material that would be expected to have a lower density than that of crystalline minerals. As the proportion of organic matter in a particle increases, the density tends towards 1,100 kg/m$^3$, the approximate density of the organic matter [36]. Decreasing density with decreasing particle size is assumed among others in the MUSIC model based on the analysis of PSD by Lawrence and Breen [37]. Settling velocities calculated for the variable density of particles are lower by 10% to 25% in comparison to the constant density of particles (Table 7.). It should be noted that the temperature of stormwater also affects sedimentation efficiency due to the viscosity phenomenon. The effect of water temperature on the settling velocity increases with the increasing particle size. In the case of $d$ = 100 mm,

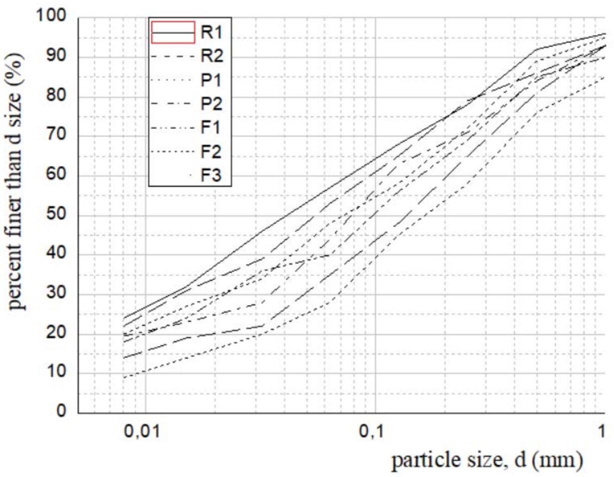

Fig. 3. PSD obtained for selected surfaces based on median values.

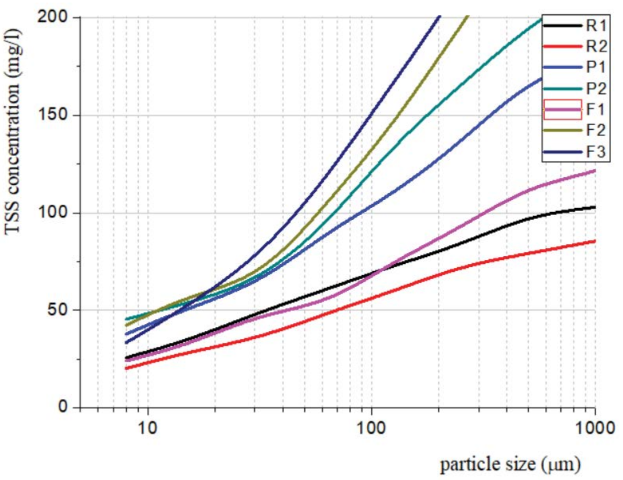

Fig. 4. Cumulative distribution of TSS concentrations against the upper size of each particle size band.

Table 6
Suspended solids concentration calculated for each fraction, based on the median percentage distribution

| Site | TSS concentration (mg/L) in fraction | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 8 mm | 15 mm | 32 mm | 64 mm | 125 mm | 250 mm | 500 mm | 1,000 mm | Over 1,000 mm |
| R1 | 25.7 | 8.6 | 15.0 | 11.8 | 11.8 | 10.7 | 15.0 | 4.3 | 4.1 |
| R2 | 20.2 | 8.3 | 7.4 | 12.9 | 11.0 | 12.9 | 6.4 | 6.4 | 6.1 |
| P1 | 37.8 | 13.2 | 13.2 | 26.5 | 18.9 | 26.5 | 32.1 | 11.3 | 9.4 |
| P2 | 45.4 | 8.2 | 11.7 | 37.3 | 44.3 | 18.6 | 30.3 | 21.0 | 16.3 |
| F1 | 24.1 | 8.0 | 16.1 | 5.4 | 21.4 | 17.4 | 21.4 | 6.7 | 13.4 |
| F2 | 42.3 | 15.1 | 9.1 | 39.3 | 39.3 | 51.3 | 48.3 | 36.2 | 21.1 |
| F3 | 33.4 | 18.6 | 22.3 | 29.7 | 63.1 | 48.2 | 66.8 | 33.4 | 55.7 |

the falling speed in the water at 10°C is about 25 m/h while for 25°C, it is close to 37 m/h, so the difference is near to 50%. The runoff temperature factor is usually not included in the calculations of the settling tanks efficiency as design parameters are usually determined for a standard temperature 20°C.

Analysis of the theoretical settling velocities confirmed the need for a completely different approach to stormwater management in urban areas. Treatment of runoff from roofs requires the removal of only coarse solids, characterized by velocities of above several hundred m/h, so these fractions can be easily removed in simple devices, and then stormwater can be conveyed directly to the infiltration device or reused. According to literature review, harvested rainwater for non-potable use usually requires no more treatment than basic filtration to remove organic debris. Bird and animal feces, as well as decomposing leaf litter on roofs and in guttering, could pose a health risk if washed into a rainwater harvesting system. For this reason, manufacturers of systems recommend to clean gutters and to protect reservoir by application of sieves.

Considering runoff from roads, the settling velocities range from 4.3 to 12.2 m/h, so the treatment process is required, by application of sedimentation tanks with significant unit dimensions (and investment costs). As driveways may be contaminated with oil and more fecal material than roofs, collecting rainwater from these surfaces increases the potential risk. Using oil traps removes some of the oil, but odors may still be a problem. For these reasons, some suppliers advise against using driveways to collect rainwater. The use of a suitable permeable pavement with appropriate substrate below can provide a reasonable level of treatment. Significant variability of treatment requirements for runoffs from roofs and roads clearly indicates the need to separate these streams.

Currently, urban drainage development is moving towards green concepts in mitigating stormwater runoff. The primary goal is to switch from a pipe-engineered system to practices and systems that use and enhance natural processes, that is, infiltration, evapotranspiration, filtration, and re-use [38]. While conventional drainage systems focus only on the stormwater quantity, sustainable development pays attention to all three aspects of quantity, quality, and amenity.

Table 7
Theoretical settling velocities calculated for particle size $d_t$ (have to be removed to keep TSS concentration below 100 mg/L for a particular site)

| Site | $d_t$ (mm) | Settling velocity (m/h), 2,600 kg/m$^3$ | Settling velocity (m/h), varying density |
|---|---|---|---|
| R1 | 630 | 1,245.9 | 1,245.9 |
| R2 | 310 | 301.5 | 301.5 |
| P1 | 102 | 32.6 | 29.5 |
| P2 | 89 | 24.8 | 21.7 |
| F1 | 68 | 14.5 | 12.2 |
| F2 | 58 | 10.5 | 8.2 |
| F3 | 43 | 5.8 | 4.3 |

## 4. Conclusions

The presence of solids in urban runoffs is a major concern for stormwater management. Contaminants from urban areas such as heavy metals and polycyclic aromatic hydrocarbons tend to bind to sediments, leading to aquatic habitat degradation. The article presents the results of quality tests of stormwater runoffs conducted in 2016–2018 on the urban catchment in Czestochowa. The research was focused on measuring TSS concentrations and PSD in runoffs from various impervious surfaces, characteristic for urban landscape: roofs, roads, parking lots). Sampling was limited to 30 rainfall events (total depth from 10.3 to 39.5 mm) and for different antecedent dry days (1.5–12 d). Analysis of the results confirms the large variation of TSS concentrations between different types of surfaces. The road runoff contained an average of 2–3 times (depending on ADT) higher concentrations than the runoff from roofs, while maximum concentrations were even many times higher and reached up to 2,000 mg/L. This justifies the need to separate runoff from roof and road surfaces according to the level of contamination.

PSD plots ranging from <8 to >1,000 μm were highly variable both within and between source areas. The roof areas (R1, R2, R3) had the lowest median particle sizes (from 40 to 65 μm), followed by the parking lots (73 – 82 μm). Roads F1 and F2 had similar median particle sizes from 100 μm for the local road to 115 μm for the regional road. Finally, the main road F3 showed the largest median particle size of nearly 150 μm. The results showed a significant variability which puts into question the validity of using one PSD, representative of rainwater generated from the urban catchment area. The data collected at different sites (TSS concentrations and their PSDs) allowed for deriving theoretical settling velocities based on Stokes and Weber equations. Considering runoffs from roads, the settling velocities ranged from 4.3 to 12.2 m/h, so the treatment process is required by the application of sedimentation tanks while runoffs from roofs require removal of only coarse solids, characterized by velocities of above several hundred m/h. The process of design of stormwater treatment devices should take into account the settling characteristics of runoffs according to Hazen's surface load theory for settling basins. Surface load (usually expressed as m/h) is directly related to the dimensions of the device and to the investment costs. Identical devices located at different sites may have different removal efficiencies as a result of differing relative proportions of fine to coarse solids in runoffs to be treated rather than their ability to function as designed.

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