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Capture of plastic litter by sluice gate and trash racks

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Abstract: This pilot study investigated the amounts of plastic litter captured by water structures. It is based on hydraulic experiments using flume models of the sluice gate and trash racks. Plastic elements of different shapes and sizes were introduced to the flume upstream of the water device. The study measured the number of plastic elements captured by the device. The outcomes of the study suggest that for each device, it should be possible to determine the size of elements beyond which they can capture plastic elements in substantial quantities. The findings should be helpful in designing future experiments on the capture of plastic elements by water structures.

Introduction

Plastic litter is a significant pollutant in urban basins. The first professional reports on such water contamination appeared at the end of the 20th century (Sosinski, 1990). Systematic studies were started in the last 20 years, as water pollution with plastic waste became an important problem in developing countries. From a practical approach to the conservation of sewer system, the distinction between plastic and non-plastic contamination is not crucial, and in most studies on gross pollutants in sewer waters, they were considered jointly. The available reports, presented in a recent review of Alam et al. (2017), shows that litter, both plastic and non-plastic, constitutes an important part of gross pollutants in urbanized basins, ranging from 10% up to 70% of the total mass. According to estimates by e.g., Marais et al. (2001), plastics make up most of the litter in urban waters.

Plastic pollution occurs in water of various chemical compositions and sizes. In the water environment, polymers such as polyethylene, polypropylene, polystyrene, polyester, polyvinylchloride, polyamide, polyvinyl acetate are most commonly reported (Enders et al., 2015; Shim et al., 2018). Most studies have focused on microplastics, usually defined as particles smaller than 5 mm. Their presence in the aquatic environment has been analyzed in various studies (e.g. Hitchcock & Mitrovic, 2019; Kaliszewicz et al., 2020; Li et al., 2018; Tibbetts et al., 2018; Yin et al., 2019). Gross plastic pollutants, often called macroplastics, have been studied much less frequently. Al-Zawaidah et al. (2021) in their review point out the differences in particle size, which are site specific. Depending on their size and method of production, they exhibit different buoyant and hydrodynamic behaviors.

Contamination of water with plastic litter is particularly concerning, as gross plastic pollutants are considered as source of mircoplastics (Eerkes-Medrano et al., 2015; Li et al., 2018). Current studies focus on developing efficient methods to capture plastic pollutants from sewer waters (Allison et al., 1998; Armitage & Rooseboom, 2000; Helinski et al., 2021; Madhani & Brown, 2015) and ways to measure the flow of gross plastic pollutants in urban waters. The latter is crucial for assessing the extent of this pollution from urban basins reaching marine ecosystems (Emmerik & Schwarz, 2020; van Emmerik et al., 2019). One promising method is analysis of gross pollutant captured by artificial water structures (González et al., 2016). Measuring the content of plastics captured in such structures as dams and weirs should allow us to estimate the flow of these pollutants in rivers. However, it is unknown how efficient water structures are at intercepting plastic litter. Without this information, it is impossible to determine what portion of the total pollution load was captured and, as a result, to assess the plastic flow. Up to now, the only study that directly addressed this problem was by Honingh et al (2020).

The goal of the presented research was to investigate the interception of plastic elements by a common device: the sluice gate. For comparison trash racks were also analyzed. The efficiency of the devices was determined based on experiments conducted in hydraulic laboratory using plastic elements of different in sizes and chemical composition. This pilot study aims to provide an initial understanding of the transport of plastic elements through the two analyzed devices. Its outcomes should help design future experiments.

Study materials and methods

Study materials

The flume experiments (Dąbrowska, 2021; Gałka, 2021) were performed in the Hydraulic Laboratory of Warsaw

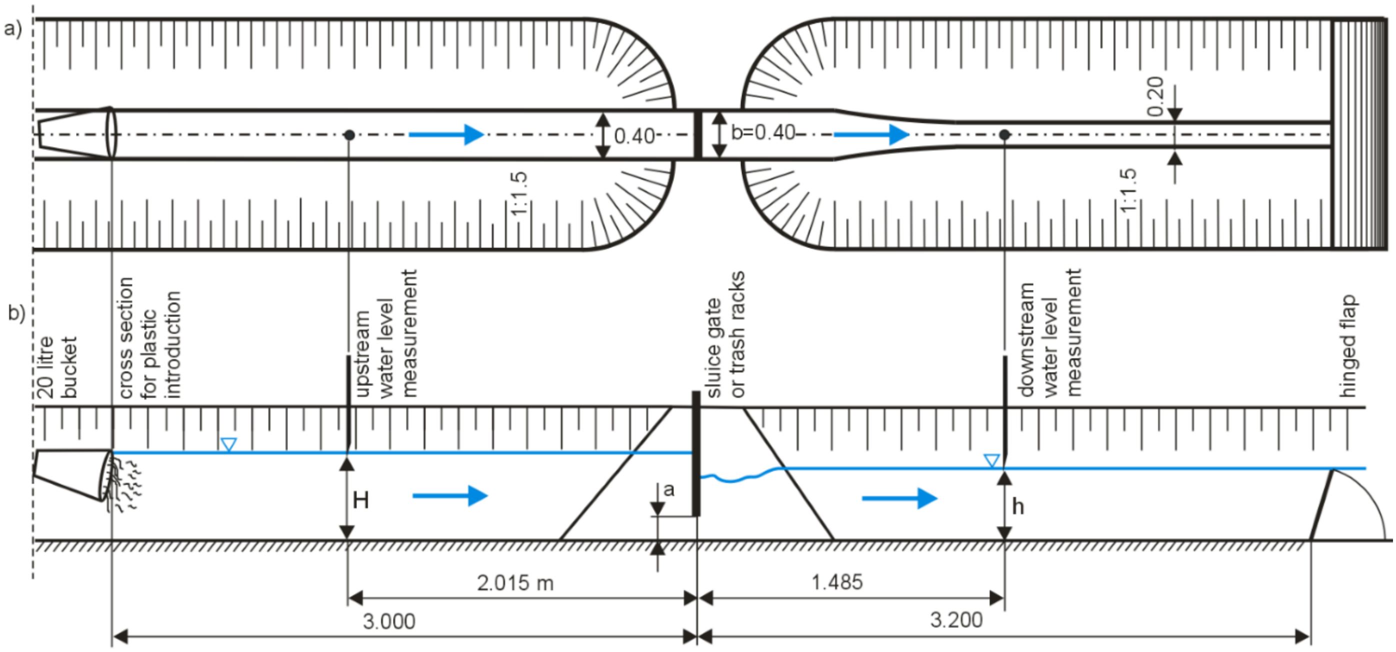

Figure 1. The location of measurement points of water levels upstream and downstream sluice gate and trash racks.

University of Life Sciences (WULS-SGGW), using a model of a standard irrigation gate in the trapezoidal channel. Earlier studies performed with this model focused on the hydraulic characteristic of the sluice gate (E. Kubrak et al., 2020; J. Kubrak et al., 2019). The gate is placed in the flume throat section on vertical guides. In the present study, experiments were performed in two scenarios: (1) with the sluice gate mounted in guides and (2) trash racks installed instead of the gate. The gate (1) was made of PVC with dimensions of 0.40 x 0.50 m and a thickness of 0.018 m. The trash rack (2) had same dimensions, with bars diameters of 3 mm and a mesh size of 5 cm x 5 cm.

The flume was supplied from a closed water cycle. The water flow rate was measured using an induction flow meter. The downstream water level was controlled using a hinged overflow gate, located 3.20 m downstream from the sluice gate/trash racks (Figure 1). Water levels were measured using a pin gauge with an accuracy of 0.1 mm. The upstream measurement stand was located 2.015 m from the gate guides, and the downstream measurement stand was located1.485 m below. The width of the flume in the rectangular section, where the devices were mounted, was 40cm.

Experiments with plastic elements were performed for a steady flow rate and a fixed position of the overflow gate. Before introducing the plastic elements, upstream and downstream water levels were recorded for the undistributed flow.

Experiments with plastic elements

The experiments involved introducing plastic elements of a known size, number, and with a fixed water flow into the upper station. Plastics were introduced into the water approximately 3 m upstream of the sluice gate or trash racks from a 20-liter bucket. Each experiment was run as long as all plastic elements reached a stable position upstream of the sluice gate or trash racks, or flowed downstream to the overflow gate. A stable position was defined as remaining unchanged for more than 5 minutes. Observations showed that changes in the position of the plastic element were unlikely. Due to the flow conditions, no element was retained in the trapezoidal section of the flume upstream of the sluice gate or trash rack. The plastic elements were either captured at the sluice gate/trash rack or flowed through it. The outcome of the experiment was the number of elements captured at the trash racks/sluice gate in each group. In order to analyze the reproducibility of the results, each experiment for each group was repeated appr. 10 times for two different flow rates, resulting in 20 repetitions. The discharge values were selected to obtain conditions of small and larger flows.

The plastic elements were made from widely available materials, listed along with their composition and density in Table 1. Except for the bags, the elements were cut into rectangular strips with dimensions given in Tables 2 and 3. The bags used in the experiment were unpacked, washed with water, and then manually vented to better resemble used bags commonly found in waste. In the sluice gate experiments, torn garbage bags were also used. They were prepared by tearing regular bags to simulate their degradation as bags are carried by flowing water.

Table 1. Materials used to obtain plastic elements.

Material	Density (kg/m³)	Composition
Warning tape	915 - 935	polyethylene
Garbage bag 25 l	915 - 935	polyethylene
PP bags	920	polypropylene
Cover tarpaulin	942-965	HDPE polyethylene
Stretch foil	915 - 935	polyethylene
Bubble wrap	915 -935	polyethylene
Transparent painting foil	918-925	LDPE polyethylene
Insulation and construction foil	918-925	LDPE polyethylene

Table 2. Plastic elements groups used in sluice gate experiments.

Group ID	Material	Elements dimensions (cm)	Elements Mount	Area of as single element (cm²)
1	warning tape	8.5x10	10	85
2	warning tape	8.5x20	20	170
3	warning tape	8.5x10	20	85
	warning tape	8.5x20	20	170
40	warning tape	8.5x50	20	425
41	warning tape	8.5x100	20	850
4	garbage bag 25 l	53x54	25	2862
5	garbage bag 25 l	53x54	12	2862
12	stretch foil	50x150	10	7500
13	garbage bag 25 l	53x54	12	2862
	torn garbage bags 25l	53x54	13	2862
16	PP bags	50x85	15	4250
17	insulation and construction foil	20x400	25	8000
18	bubble wrap	20x100	15	2000

Table 3. Plastic elements groups used in trash racks experiments.

Group ID	Material	Elements dimensions	Elements count	Area of as single element (cm²)
2	warning tape	8,5x10	20	85
3	warning tape	8,5x10	20	85
	warning tape	8,5x20	20	170
21	warning tape	8,5x20	20	170
22	transparent painting foil	10x20	40	200
23	transparent painting foil	20x20	40	400
24	stretch foil	10x50	20	500
25	stretch foil	20x50	20	1000
26	Insulation and construction foil	10x50	20	500
27	Insulation and construction foil	20x50	20	1000
28	bubble wrap	10x50	20	500
29	bubble wrap	20x50	20	1000
30	transparent painting foil	10x20	40	200
		20x20	40	400
31	stretch foil	10x50	20	500
		20x50	20	1000
32	Insulation and construction foil	10x50	20	500
		20x50	20	1000
33	bubble wrap	10x50	20	500
		20x50	20	1000

Figure 2. The sluice gate (a) used in the 1 experimental case and trash racks (b) in the 2 case, mounted in vertical guides

Study methods

To quantify the outcomes of the experiment, the percentage share of elements captured on the trash racks or upstream the sluice gate was used:

$$I_n = \frac{n}{N} \tag{1}$$

where: N – total number of elements, n – number of collected/captured elements.

An interesting practical issue is if different groups of plastic elements (Table 2-3) show similar capturing shares. On the one hand, this might show which features of plastic elements are important for their capturing at water structure. On the other hand, it will also allow investigation of whether the capturing shares are coherent, e.g., if the element groups exhibit similar behavior across different measures.

The similarities were analyzed using the Mann-Whitney U Test. The null hypothesis of this test is that the distributions of the two compared populations (in this case, plastic groups) are identical. The p-statistics as a probability that the null hypothesis is fulfilled is used here as a test output. The computation were performed using the Python SciPy library is used (Virtanen et al., 2020).

Results and discussion

The same flow rates were used for all experiments with each device. For the sluice gate, the flow rates were 7 and 14 ±1 l/s, while for the trash racks, the flow rates ranged from 11 to 24 ±1 l/s . Flow conditions upstream and downstream of the devices were subcritical, with Froude's numbers between 0.1-0.8 for the sluice gate, and between 0.1 and 0.5 for the trash racks.

The outcomes of the experiments, in terms of the percentage share of captured elements for the trash rack and sluice gate in each experiment (Tables 2 and 3), were presented in the form of box-plots (Fig 3). The p-values from the Mann-Whitney U Test for similarities between experimental groups (Fig 4) and relationship between the share of captured elements and their effect on flow through the sluice gate or thrash racks were also analyzed.

The variability seen in the box plots (Fig 3) results from the repetitions (app. 20-30 times) of the experiment for each group. In Figure 3, the percentage share of collected elements is shown. Significant differences can be noticed between the sluice gate (Figure 3a), which has strongly varying capture ratios, and trash racks (Figure 3b), which have much more uniform capture ratios.

Experiments for the sluice gate were also performed with large elements, as the smaller ones mostly passed through the device, as seen in Groups 1, 2, 3 and 40. In the case or larger elements, such as those in groups with garbage bags (e.g., Groups 18, 4, 5, 17 and 13), the capture ratio is high but variable between experiments, with the range of at least 70% to 100% (Figure 3a).

In Figure 3a, Groups 1, 2, 3, 40 and 41 consist of elements made of warning tape cut into sections of various lengths, ranging from 10 cm (Group 1), to 100 cm (Group 41). Up to

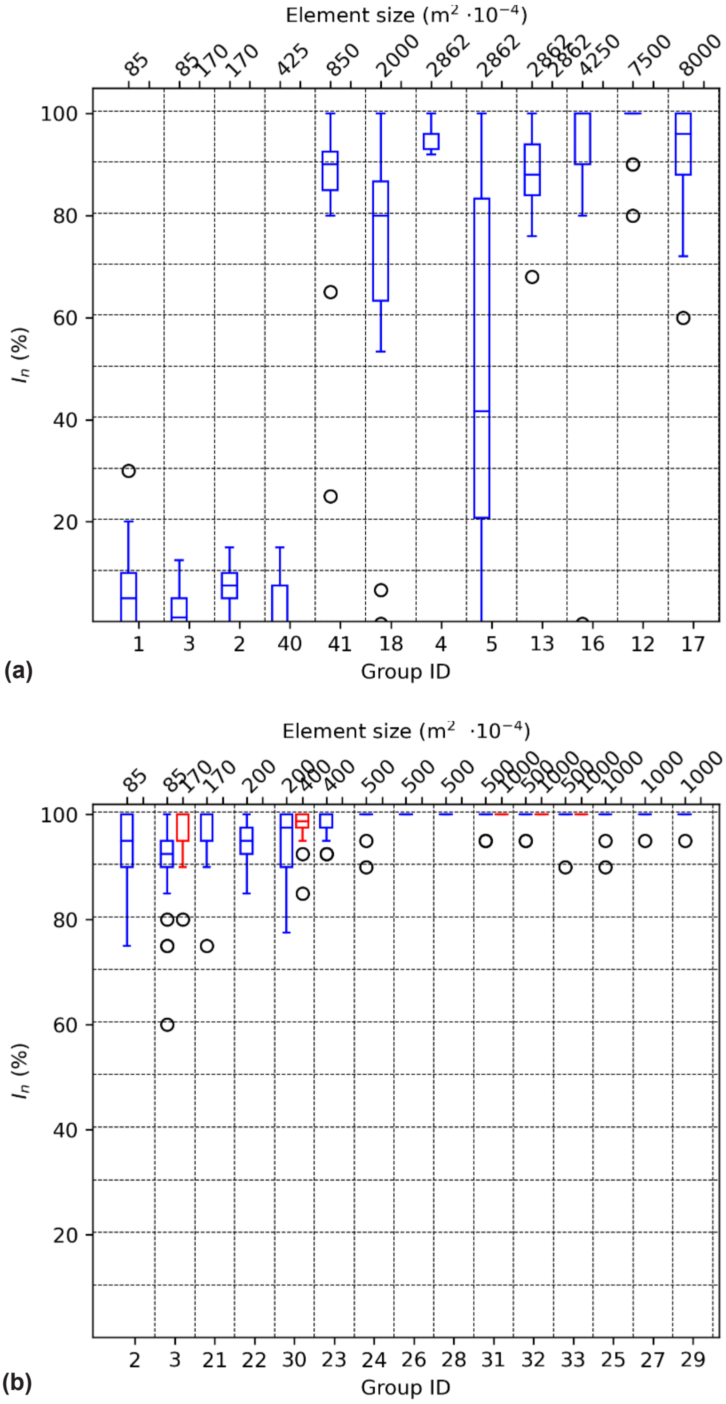

Figure 3. Percentage share of collected elements on (a) - sluice gate, (b) - trash racks. Labels on the lower x-axis specify the plastic elements group (as in Table 2 and 3), on the upper one the area of the single plastic element (averaged if two sizes were used); For Groups with two elements, two values of element area were provided (for the sluice gate, only overall statistics for all elements were available, for trash racks statistics for each element size in a group were also provided).

a tape length of 50 cm, all groups exhibited similar capture ratios, with most elements passing through the sluice gate. However, the tape elements in Group 41, which are 100 cm long, behaved different. In most cases, more than 80% of these longer elements were captured, while for the shorter ones, the capture rate was less than 20%.

The varying capture rate for Group 5 (Figure 3a), ranging from 0% to 100%, is interesting. For same elements but in larger quantity (25 garbage bags comparing to 12) in Group 4, the capture ratio in all experiments was above 90%. This suggests that the number of elements is a significant factor affecting the capturing ratio.

The capture ratio for trash racks is presented in Figure 3b. It shows a clear pattern, with the mean capture ratio increasing with element size. Importantly, it is possible to identify a threshold size of the element, above which all the elements are captured, app. 500 cm^2. The capture ratio for smaller elements included in the experiment varies but remains within 80-100% ranges. In the experiments with trash racks for two element groups (e.g., 3, and 30-33), statistics for different sizes were

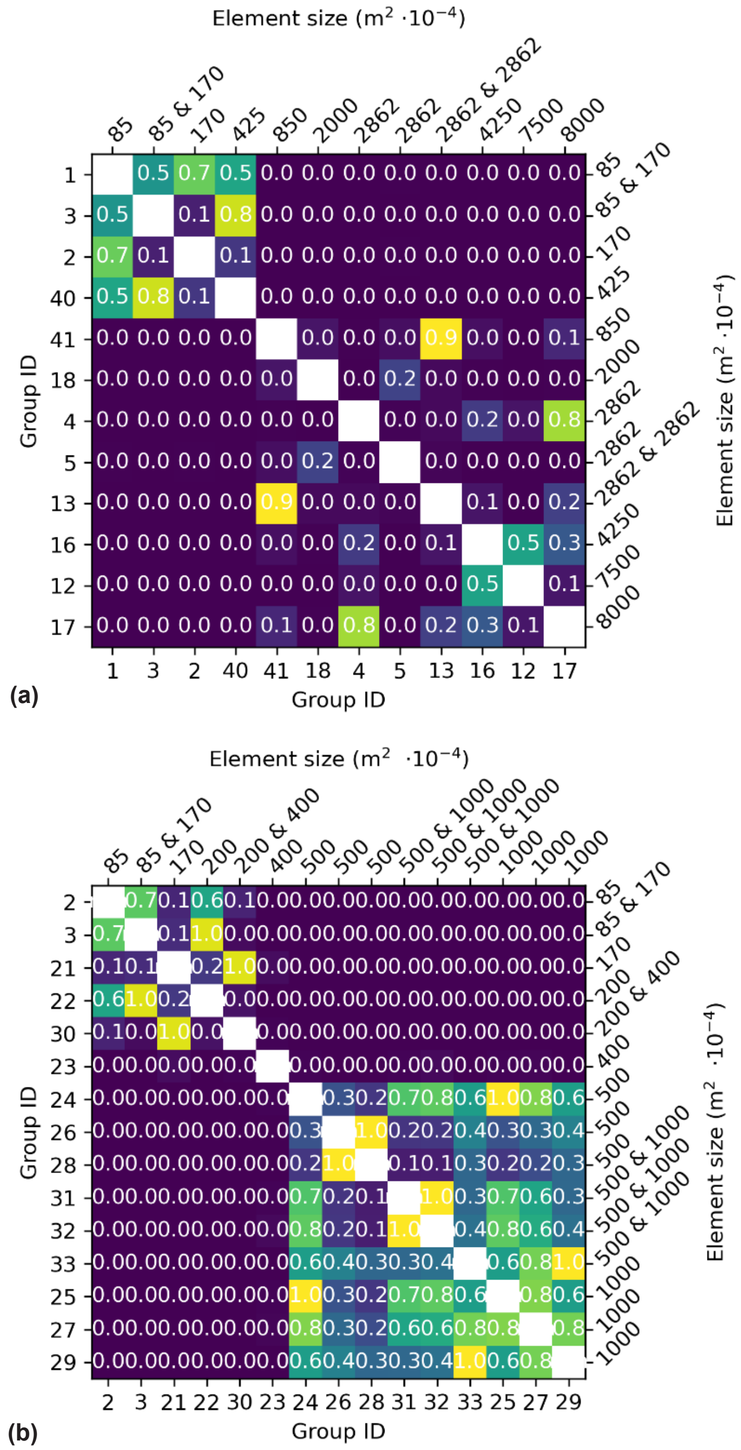

Figure 4. The p-value of the Mann-Whitney U Test for elements groups in terms of percentage share of captured elements In for (a) - sluice gate, (b) - trash racks. Labels on the lower x-axis specify the plastic elements group (as in Table 2 and 3), on the upper one the area of the single plastic element (averaged if two sizes were used).

provided (for sluice gate, only joint statistics were available). For Groups 3 and 4 (for the other two element groups the capture ratio was 100% in experiments) elements have similar ratios, consistent with their single element groups.

The similarity between groups of different elements was analyzed using Mann-Whitney U Test. Figure 4 presents a graph of p-statistics, indicating the probability that the distributions between analyzed groups might be identical. Groups were compared in terms of the percentage share of captured elements, both for the sluice gate (a) and trash racks (b).

For the sluice gate, the percentage share of captured element was similar in groups of smallest elements (Figure 4a). Incidental similarities were also observed for larger elements, such as Group 41 (long strips of warning tape) and Group 13 (garbage bags), or Group 4 (garbage bag) and Group 17 (insulation and construction foil). These similarities results from high capture ratios in these groups.

More straightforward results were obtained for trash racks (Figure 4b). It can be noticed that similarities are present in groups of small elements with low capture ratios and larger elements with high carputer ratios. The interesting regions span between these two groups. Group 23 and 30 are dissimilar to others because the size of the elements in these groups is in the transition between small elements that freely pass through the trash racks and large elements that are captured.

Conclusions

This pilot study provides insights that could be useful in designing future experiments on the effect and capture ratios of basic hydraulic structures, such as sluice gates and trash racks. The main outcomes can be summarized as follows:

1. The results on the capture ratio of plastic elements lead to the obvious conclusion that small elements easily pass through both devices, while large elements do not. This implies that such devices might only be useful for measuring the loads of larger elements, which would likely not provide a reasonable estimation of the overall contamination of river waters with these pollutants.
2. From a hydraulic point of view, the transition region between small elements that freely pass through both devices and large elements that are almost always captured is particularly interesting. With properly designed future experiments, it might be possible to relate capture ratios to element sizes and device properties.
3. The similarity analysis between different groups of plastic element sizes supports the observation from point 2. Particularly for trash racks, it is possible to determine element sizes that are most likely to be captured or to pass through the device.
4. If future experiments can determine the element size that is most likely to be captured, the number of litter items collected upstream of a given device could be used to estimate the pollutant load in the water stream with reasonable accuracy.

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Zatrzymywanie odpadów plastikowych na zasuwie i kracie

Streszczenie: Jest to badanie pilotażowe nad zatrzymywaniem odpadów plastikowych na urządzeniach wodnych. Praca bazuje na eksperymencie hydraulicznym z wykorzystaniem fizycznych modeli zasuwy i kraty. Powyżej urządzeń wodnych do koryta wprowadzano plastikowe elementy o różnych kształtach. Mierzono liczbę elementów plastikowych zatrzymywanych przez zasuwę lub kratę. Wyniki badań wskazują, że dla każdego urządzenia powinno być możliwe określenie progowej wielkości elementów, powyżej której większość z nich ulega zatrzymaniu. Badania powinny być pomocne w projektowaniu przyszłych eksperymentów dotyczących zatrzymywania elementów plastikowych przez urządzenia wodne.