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Microplastics upstream and downstream dam-reservoirs

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ABSTRACT

The occurrence of microplastics in the aquatic ecosystems, especially in the oceans, is a matter of public record. It is estimated that about 80% of microplastic particles found in oceans and seas are discharged via rivers. But on many rivers especially in Poland, there are dam-reservoirs. The authors wanted to research the role of dam-reservoirs in microplastic removal from the watercourse in this study. The research was done on three rivers were dam-reservoirs are localized. Samples of suspended matter (containing microplastic particles) were taken upstream of the reservoir and as near as possible under the dam. Results showed that the majority of plastic particles are accumulated in the area of the lake, but the presence of microplastics in samples taken under the dam points to the processes that microplastics are transported to the lower parts of the water column.

Keywords: Microplastics; Surface water; Dam-reservoir

1. Introduction

Plastics are synthetic or semi-synthetic organic polymers that are relatively cheap, lightweight, durable, strong, and corrosion-resistant [1,2]. For these reasons, polymers are willingly and commonly used in many branches of industry. The most commonly used polymers: low-density polyethylene (LDPE), high-density polyethylene (HDPE), polyvinyl chloride (PVC), polystyrene (PS), polypropylene (PP), and polyethylene terephthalate (PET). They together account for approximately 90% of the total worldwide plastic production [3]. These polymer wastes are also the most commonly found plastics in the environment. They are dangerous to the natural aquatic ecosystems because organisms can ingest the plastic or can entangle in plastic [4,5] and microplastics can absorb some specific organic micropollutants [6]. Microplastics (MPs) are usually defined as plastic particles smaller than 5 mm. MPs are often manufactured in small sizes (e.g., microbeads in personal care products). They are called primary microplastics [7]. Very often microplastic particles are generated as the effect of larger particle fragmentation. These plastic particles are called secondary microplastics [8]. Plastic particles have the potential to adsorb persistent organic micropollutants (polycyclic aromatic hydrocarbons, polychlorinated biphenyls, as well as trace metals) from the water [9,10]. Scientists noticed that all kinds of water (seas, oceans, rivers, lakes, etc.) are polluted by microplastics [1,11–14]. The presence and consequences of microplastics pollution in the marine environment were firstly described in 1972 [12]. Microplastics are also present in rivers; it especially concerns rivers, which flow through highly urbanized and anthropogenically changed areas [13,15]. Microplastics were also found in lakes [16]. Concentrations of microplastics in freshwater determined by various researchers were usually at the range of 30 to more than 100 particles/m^3 [17].

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Wastewater treatment plants (WWTPs) have been identified as an important source of microplastics in surface water it was stated that the mean concentration of MPs downstream of WWTPs could be 100%–300% higher than upstream one [14,18]. As sources of microplastics in surface water also such as runoffs from agricultural, industrial, urban, and recreational areas, beach litter, or atmospheric fallout were identified [17]. As it was mentioned above, the problem of the accumulation of microplastics particles has been observed and widely described primarily concerning the seas and oceans. The occurrence of microplastics in samples from around the world makes it worth considering how it can affect the environment. The presence of microplastic particles can have a negative effect. Large amounts of this pollution can change the properties of sediments on beaches, which negatively affects, for example, the functioning of crustaceans. Microplastic particles suspended in the water column can affect the propagation of the sun's rays and limiting access to energy for various organisms [19]. There are more and more pieces of evidence that microplastic can increase the incidence of cancer among fish, lower the chance of reproductive success, and shorten the life span of worms inhabiting bottom sediments [20]. Consumption of microplastics may also lead to physical impairment such as nutritional problems, due to filling the stomach with plastics and pseudo saturation [21]. Many microplastic particles can adsorb on their surface other impurities or toxic substances. One particle can show concentrations of some impurities up to a million times higher than in the surrounding waters [22]. The surface of the particles can also be colonized. Microorganisms and pathogens can settle on it.

Microplastics presence in freshwater ecosystems was well illustrated by Eerkes-Medrano et al. [23] who emphasized these micropollutants' role in contamination and properties of the water body and sediments – Fig. 1.

One of the factors which are important for the spread of microplastics is water flow. It carries these pollutants on varying distances. Also, the concentration of other pollutants or organisms, such as suspended solids or microalgae can affect the fates of microplastics. The factors mentioned affects mainly mobility and sedimentation of plastics. In scientific literature also shapes and sizes of particles are mentioned as important in their fates [24].

A more detailed description of processes playing a role in the transport of microplastics was presented by Kooi et al. [19] – Fig. 2a. Dam reservoirs can modify natural processes by promoting some of them because generally, various functions of dam reservoirs mean that water can flow out of them both overflowing through the dam and below the crown of the dam, at various depths, including the bottom zone (Fig. 2b). There are also tanks subjected to the reclamation process, in which, despite the application of an overflow through the dam's crown, water is drained from the bottom zone – hypolimnion.

In Poland first studies and estimations of microplastics concentration in surface water were conducted in the Kłodnica River basin. Nocoń et al. [13] showed, that microplastics contamination was observed in all rivers flowing through Upper Silesia Agglomeration. But it can be noticed that in the case of other river contaminations like suspended matter and trace metals, in the river basins there are places where the concentration of them can be observed.

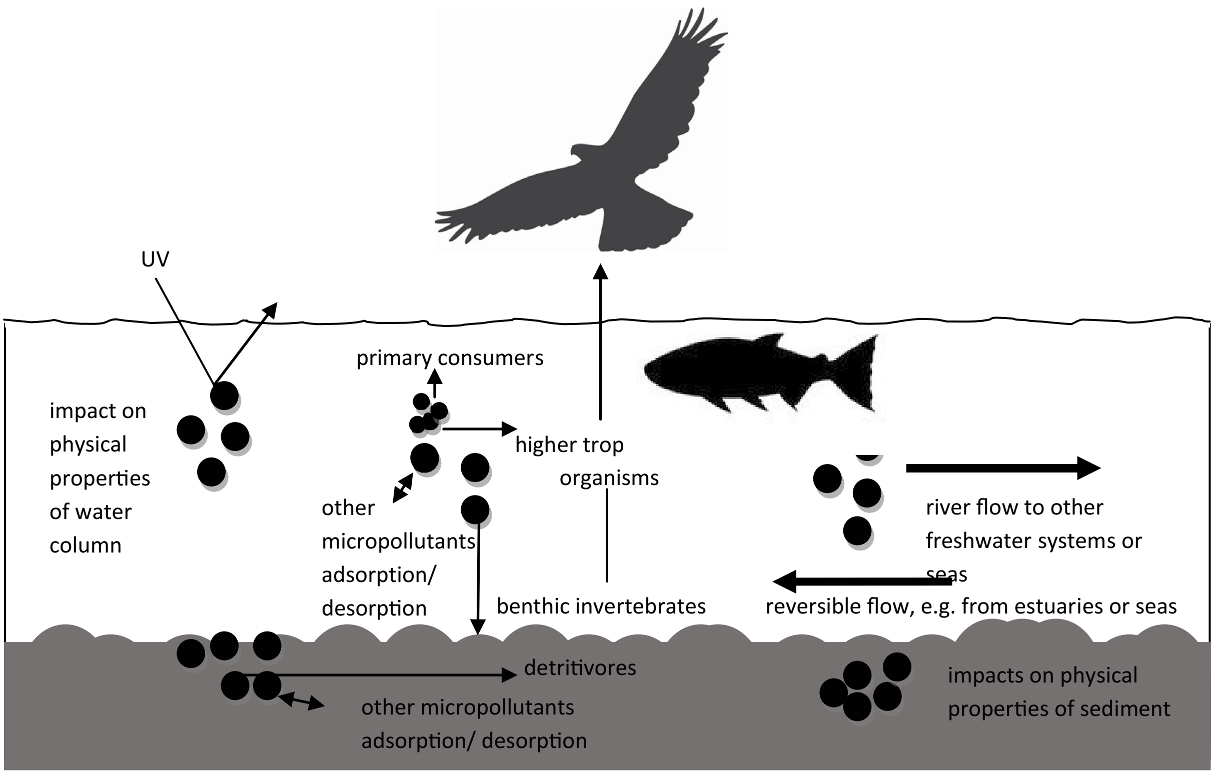

Fig. 1. Fates of microplastics in freshwater ecosystems (based on the figure designed by Eerkes-Medrano et al. [23]).

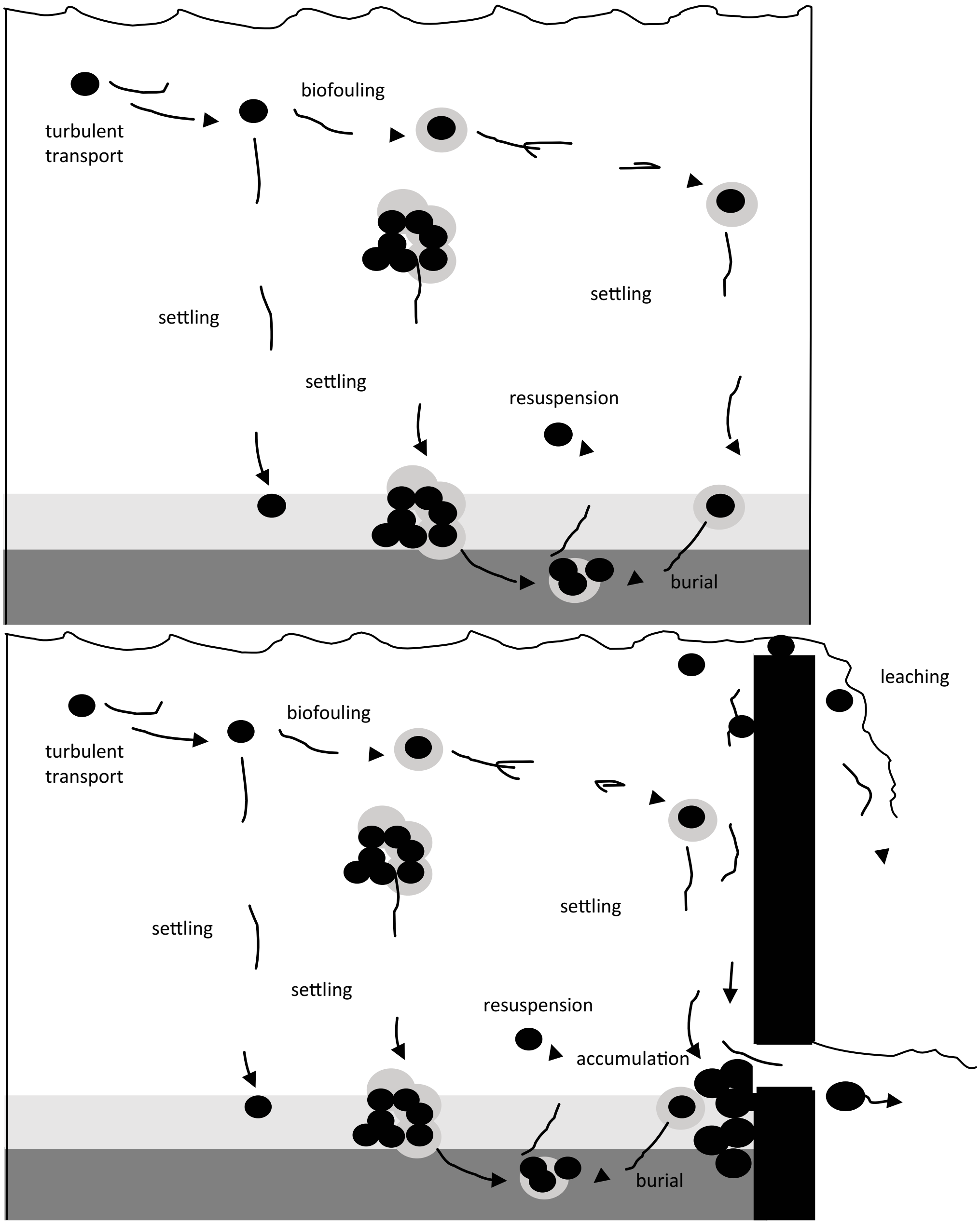

Fig. 2. Processes playing an important role in the transport of microplastics in (a) river or lake (based on Kooi et al. [17] and (b) dam reservoirs.

It especially concerns all kinds of lakes and dam-reservoirs. It was confirmed among others by Watkins et al. [25] who have observed that in dam reservoirs microplastics can accumulate in the sediments. They have found that microplastic concentrations in sediments within reservoirs were significantly higher than in sediments above the dams. What was surprising, in water samples taken from dam reservoirs, the concentration of microplastics was relatively low. Zhang et al. [24] have demonstrated that important regulators for microplastic accumulation and distribution are water level regulated hydrodynamic conditions and input of nonpoint sources of these micropollutants. Their study has been indeed done on the tributaries of the Three Gorges Reservoir, but it is valuable to understand the fate of microplastics in surface water systems. The role of dam reservoirs in the retention of microplastics present in surface water has not been well-recognized since now because the research on this matter worldwide is rare. Some conclusions and thesis can be worded based on the results obtained for water estuaries.

The thesis of the present research is that dam-reservoirs can play an important role in removing microplastics from the river waters. The present research aimed to recognize the role of selected dam-reservoirs in the retention and accumulation of microplastic particles. The main question of the study is the estimation of microplastic removal from the surface layer (0–13 cm) of the water body of the river in the area of an artificial reservoir.

2. Materials and methods

2.1. Study area

The Upper Silesia Agglomeration in Poland is one of the most transformed regions in Europe. The heavy industry (especially coal-mining) has had a significant impact on environmental degradation. There are no natural lakes and a constant lack of freshwater. Upper Silesian Agglomeration lies within the upper and middle basin of the Kłodnica River. With its tributaries, the river flows through densely populated and heavily industrialized areas [13]. But in the western part of this region, on the tributaries of this river, there are localized two dam-reservoirs – the Pławniowice on the Toszecki Stream and the Dzierżno Małe on the Drama River. Their main role is flood protection, but they also perform recreational functions and due to their proper functioning in the hydraulic system of the Gliwicki Canal they also perform the function of leveling flows in this most important waterway in Poland. The third dam-reservoir and river belong to the Vistula basin. It is called the Łąka and is localized on the Pszczynka River.

Although the rivers and dam-reservoirs have different basins and belong to different basin areas, the common feature is the bottom outflow in two of them (Dzierżno Małe and Łąka). The Pławniowice dam-reservoir is constantly reclaimed using drainage of hypolimnion waters. So, the water origin in the outflow is the deepest part of it.

The comparison of the total area and the total capacity of these three dam-reservoirs is shown in Table 1. As it is mentioned above, all water dam reservoirs have bottom outflows, which should be emphasized because it can have an important effect on the results obtained during the research study.

2.2. Sampling

Samples were taken from the rivers in three series. They were taken upstream and downstream dam-reservoirs as well as from the water body of dam-reservoir.

The authors tried to localize downstream sample points as near the dam as possible (10–20 m under the dam). The localization of sampling places was chosen to avoid sample contamination by microplastics from other sources (e.g., air or surface run-off from the river basin under the dam). The localization of all sample points is presented in Figs. 3–5.

Samples were collected from sampling points with a circular polyamide plankton net (0.26 m diameter with 250 µm mesh size). Samples were taken in three series from

Table 1
Total area and capacity of dam-reservoirs researched in the study

Dam-reservoir	Total area (km^2)	Total capacity (m^3)	Type of water outflow
The Pławniowice	2.6	29×10^6	Bottom outflow
The Dzierżno Małe	1.2	10×10^6	Bottom outflow
The Łąka	3.5	11×10^6	Bottom outflow

Fig. 3. Localization of sample points: P1 – inflow, P2 – outflow, P – sample point from dam reservoir (the Pławniowice dam-reservoir) (www.googlemaps.com).

Fig. 4. Localization of sample points D1 – inflow, D2 – outflow, D – sample point from dam reservoir (the Dzierżno Małe dam-reservoir) (www.googlemaps.com).

Fig. 5. Localization of sample points L1 – inflow, L2 – outflow, L – sample point from dam reservoir (the Łąka dam-reservoir) (www.googlemaps.com).

March to June 2018 from 0.13 m surface layer. The net was fixed perpendicular to the flow of the river surface, with half of the net opening submerged to collect floating particles. During the sampling, water velocity was measured using hydrometric grinder Hega-2. Based on the measurement results made with the hydrometric grinder, the time necessary to provide the flow of 2 m^3 of water through the plankton net was calculated; 2 m^3 of water flowed through the net during each sampling which was enough to collect appropriate samples to count microplastic particles.

In the case of samples taken from the water body of the dam reservoir, they were also taken from the 0.13 m surface layer. Using mathematical calculations there was appointed the distance of 18.83 m for 0.5 m^3 of water capacity (half the volume of the cylinder with a base diameter of 0.26 m). The sampler moved along the rope four times.

2.3. Analysis

To isolate microplastic particles, samples of suspended solids were replaced to a laboratory jar fulfilled with distilled water. The most important part of the sample preparation was the removal of natural organic matter which was present in the probe. The preparation was the same as it was described in [13]. The first step was the Fenton's reaction and heating to 85°C–90°C to accelerate and support the decomposition of natural organic substances from the suspended solids. Next, each sample was evaporated to a volume of 20 cm^3. The sedimentation process separated the sand and other mineral components of the specific gravity greater than water. There were still not degraded plant parts after the gravitational separation in the samples. Therefore, the autochthonic suspended material was distinguishable from the microplastics particles and was not counted during the microscopic observation. The same sample volumes (1 mL) were then taken by automatic pipette and fed into the Sedgewick–Rafter's Chamber. Recovered particles were visualized under Delta Optical SZH-650 B/T microscope and the exact number of particles in the precise volume of 1 mL of the sample. Microplastics particles were counted directly.

3. Results and discussion

The results of the research are presented in Tables 2 and 3.

In the Toszecki Stream, upstream the dam-reservoir 1–11 foils/m^3 were recognized. Under the dam, there were 1–4 foils/m^3. There almost were no fibers. During the research, we noticed 0–4 fibers/m^3 upstream the dam-reservoir and only during one sampling, a single fiber under the dam. Granules were recognized in the amounts of 1–5 particles/m^3 upstream of the dam-reservoir and 1–3 particles/m^3 downstream of the dam. Similar amounts of foils and granules in the Drama either upstream the reservoir or under the dam were observed, in comparison to the Toszecki Stream. There were slightly higher amounts of fibers (2–11 fibers/m^3 upstream the reservoir and 0–4 fibers/m^3 under it). The highest concentrations of microplastics upstream the dam-reservoir in the Pszczynka were observed. Mainly fibers and granules, but as it is shown in Table 1, we can notice, that in the Łąka reservoir the highest level of microplastics accumulation was observed.

Table 2
Microplastics particles in rivers upstream and downstream dam-reservoirs

The Toszecki Stream (Pławniowice dam-reservoir)				
	Upstream (P1)		Downstream (P2)	
	Range	Average	Range	Average
Foils (particles/m^3)	1–11	8.7	1–4	2.3
Fibers (particles/m^3)	0–3	1.3	0–1	0.3
Granules (particles/m^3)	1–5	3.3	1–3	2.0
The Drama River (Dzierżno Małe dam-reservoir)				
	Upstream (D1)		Downstream (D2)	
Foils (particles/m^3)	1–8	5.0	1–3	2.0
Fibers (particles/m^3)	2–11	7.3	0–4	2.0
Granules (particles/m^3)	0–3	1.7	0–1	0.3
The Pszczynka River (Łąka dam-reservoir)				
	Upstream (L1)		Downstream (L2)	
Foils (particles/m^3)	1–13	7.0	0–1	0.7
Fibers (particles/m^3)	20–28	23.7	0–4	2.0
Granules (particles/m^3)	18–21	19.7	1–2	1.7

Samples from the dam-reservoirs were taken to check if the microplastics accumulation can be observed in the water body (surface layer) of the dam reservoir. As it is shown in Tables 2 and 3, we have found microplastics particles in higher amounts than in rivers downstream of the dam.

Microplastic in the aquatic environment has been present for many years. However, only recently has this problem been seen in inland waters. The constantly increasing production of plastics is the reason for the steady increase in the number of plastics and all types of ecosystems.

On Fig. 6, images of selected samples taken during the study are presented.

The lack of comprehensive legal solutions so far and the scope of limiting emissions of these pollutants for many years will cause an uncontrolled increase in the amount of this type of pollution. As the researchers show, in all surface waters around the world this problem is observed (Table 4).

During our study, the highest concentrations of microplastics were observed in the Pszczynka River. The Pszczynka River flows mainly through the agricultural areas and seems not to be so much exposed to the increasing load of microplastics. However, research has shown the opposite – the highest level of microplastic contamination was observed in the Pszczynka above the dam-reservoir. Due to the agricultural nature of the catchment, it can be concluded that agriculture could be an important source of microplastics in surface waters. Even though Upper Silesia is highly industrialized also a lot of arable grounds and meadows are in this area. It is even more likely that all materials used in the broadly understood agriculture (fertilizers, animal feed, seeds, etc.) are packed in plastic packaging. Quite often fibers in different colors were recognized (Figs. 6a and b).

Granules (Fig. 6c) were observed at the same level and the origin could be similar. The consequence of this is the emission of microplastics to arable land and its further transport with the help of wind or water into the riverbed. It cannot be excluded that the relatively high number of microplastic particles in the Pszczynka are caused by sewage sludge managed in agricultural areas. This is likely that very

Table 3
Average amount of microplastics in dam-reservoirs

	The Pławniowice (P)	The Dzierżno Małe (D)	The Łąka (L)
Foils (particles/m^3)	14	7	15
Fibers (particles/m^3)	7	12	22
Granules (particles/m^3)	4	4	9

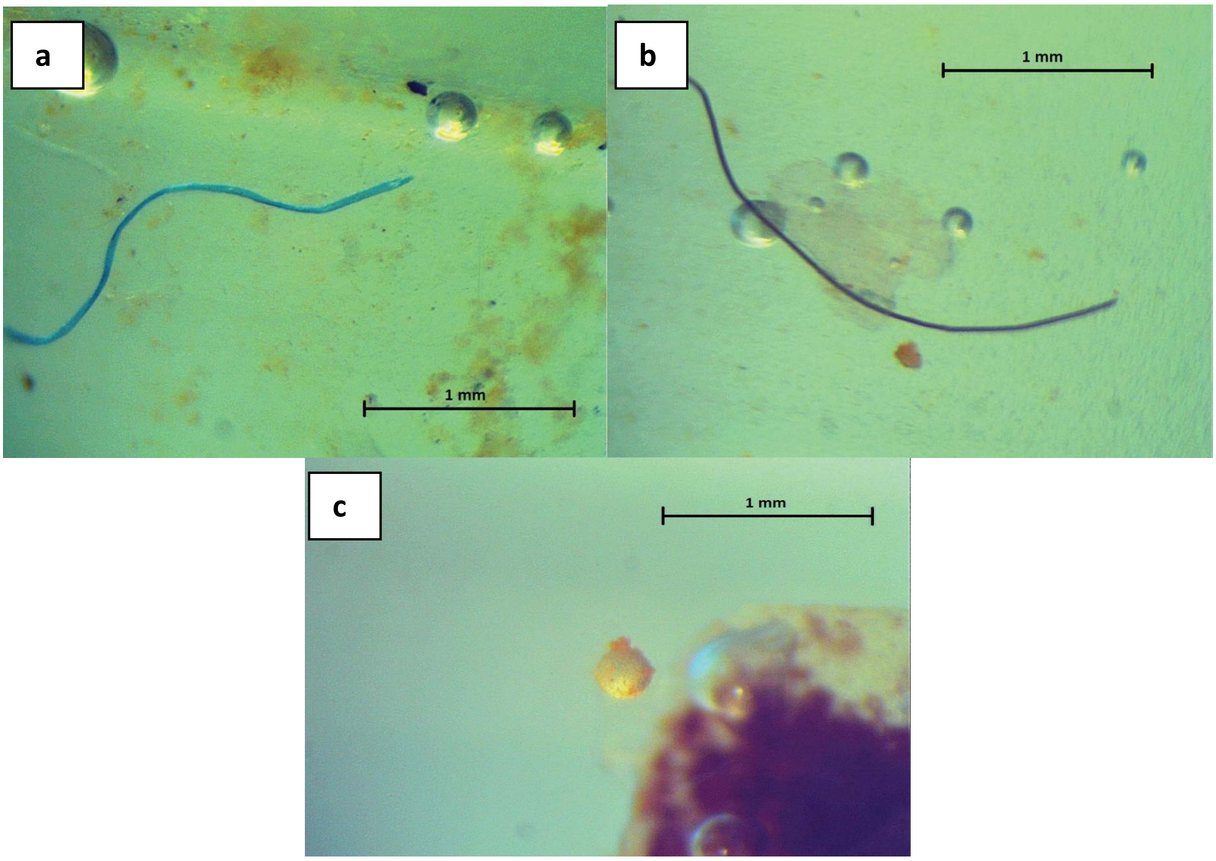

Fig. 6. (a) fiber – upstream the Łąka dam-reservoir, the Pszczynka River, (b) fiber – upstream the Łąka dam-reservoir, the Pszczynka River, and (c) granule – upstream the Łąka dam-reservoir, the Pszczynka River.

high concentrations of microplastics are observed in sewage sludge, mainly in the form of fibers [15]. Sources of microplastics in rivers may vary in time. Identification of them requires detailed inventory.

Compared to the results obtained by other authors (Table 4) concentrations of microplastics upstream the dam reservoirs were at rather low levels even though the rivers examined during our research flew through the urbanized area. One of the reasons for this could be the fact that in the present study only surface layer of water was taken into consideration. This layer is usually recognized as the one which contains the highest microplastics load, however, these microplastics are also observed in the water body [39]. What is important there is no evident correlation between the degree of industrialization and pollution of river water by microplastics.

The main aim of the study was, however, to define the role of an artificial reservoir in the removal of microplastics from the surface layer of water. Based on our research it was stated that dam reservoirs have stopped part of microplastics from the surface layer of water. A significant decrease in microplastics amount downstream of the dam reservoirs was observed in all cases. Simultaneously, compared to both downstream and upstream amounts of microplastic particles, the concentration of microplastics in water taken from the dam reservoir was high (Tables 2 and 3). It concerned especially foils and fibers, whereas granules concentrations were lower or at more or less the same level. It suggests that dam reservoirs examined in the study can act as a trap for microplastics present in the 0–13 cm layer of surface water. It probably was connected with the fact that all examined reservoirs had bottom outflows. As a result, microplastic particles are not leached with outflowing water. This thesis can be supported by the research done by Weideman et al. [44] for dams on the Orange – Vaal River system in South Africa. This system did not trap floating microplastics. It could be just caused by the type of dam construction – in case of the dams in South Africa, there are gravity ones (water flows from the surface layer where the majority of microplastics are observed). As it was mentioned above on the rivers taken into account in our research, the origin of water under the dam is water from the bottom layers. Similar results obtained in our study were obtained by Hartlage et al. [45] who have also stated that the concentration of microplastic particles was higher upstream dam reservoirs and within the water body of dam reservoirs. They have conducted their research in three dam reservoirs in Indiana, USA.

According to the results obtained by Watkins et al. [25] microplastics in dam reservoirs can be accumulated in sediments. It probably depends on the type of dam and kind of microplastics. Contrary to the results obtained during our study, Watkins et al. [25] have observed a decrease in the concentration of microplastics in the water body of the

Table 4
Microplastics is surface waters

River/Lake	Country/Region	Concentration	Reference
The Bytomka River	Poland/Upper Silesia	29–49 particles/m^3	[13]
The Kłodnica River	Poland/Upper Silesia	21–51 particles/m^3	[13]
Tuhikaramera Stream	New Zealand/Waikato	44.8 particles/m^3	[26]
Waiwhetu Stream	New Zealand/Wellington	8.3 particles/m^3	[26]
Lake Ulansuhai	China/Yellow River Basin	1,760–10,120 particles/m^3	[27]
Vltava, Laba (Elbe)	Czech Republic	1,000–4,000 particles/m^3	[28]
Danube, Po, Rhine	European countries	0.03–0.05 particles/m^3	[29]
Yangtze River	China	2,514 ± 912 particles/m^3	[30]
Ottava River	Canada	50–1,999 i particles/m^3	[31]
Ebro River	Spain	3.5 particles/m^3	[32]
Seine River	France	3–108 particles/m^3	[33]
No data	Italy (urban river)	3.52–14.53 particles/m^3	[34]
Haihe River	China	0.7–75 particles/m^3	[35]
Xindian River, Dahan River	Taiwan	0.7–154 particles/m^3	[36]
Ofanto river	Italy	0.9–13 particles/m^3	[37]
Manas River Basin	China	21,000–49,000 particles/m^3	[38]
Han River	South Korea	0–43 particles/m^3 at Surface layer 20,000–180,000 at depth 2 m	[39]
Headstreams of the rivers	Tibet Plateau, Tibet	489–967 particles/m^3	[40]
Ciwalengke River	Majalaya, Indonesia	5,850 ± 3,280	[41]
Marne River	France	100.6 ± 99.9 particles/m^3	[42]
Amsterdam canal	Amsterdam, The Netherlands	48,000–187,000 particles/m^3	[43]

dam reservoir. This could be affected also by physicochemical properties of water, for example, with a concentration of suspended solids which could promote sedimentation of microplastic particles. It was confirmed by Hoellein et al. [46] who concluded that seasonality influences temperature, organic matter inputs, riparian vegetation, and benthic biological community succession (i.e., presence of biofilms and submerged aquatic vegetation), all of which can affect microplastic deposition patterns. Observations of microplastic particles in the river directly below the dam made during the present study indicate that these impurities are subject to certain processes in water that cause the occurrence of microplastics in the water column and even its penetration into the bottom layers. The biofouling process is pointed out as the mechanism responsible for the vertical transport of microplastics from the surface of the lake to its deeper layers. Sedimentation of microplastic particles, in the vast majority with a specific gravity lower than the specific gravity of water, is confirmed by the presence of plastic particles in the water drained from the lake. The Pławniowice dam-reservoir is reclaimed by draining hypolimnion waters. Water drainage pipes are installed in the deepest part of the lake, therefore it is practically impossible for water from other layers to appear in the drain. It is also noted that the other dam-reservoir is located a few kilometers above the Pławniowice reservoir. As a consequence, the microplastic particles observed in the Toszecki Stream, which are less, compared to the other reservoirs, may come primarily from a short section of the river.

Slightly more microplastics were observed in the Drama River above the Dzierżno Małe reservoir, although they are still clearly smaller than for example in the Kłodnica [13]. On the one hand, this is probably due to the nature of the river basin (agricultural catchment, but mainly pasture areas), on the other, the occurrence of emerged vegetation on a significant section of the river, which is a kind of filter for many types of pollution. The depth of the Dzierżno Małe reservoir (exceeding 15 m) and the diverse shoreline mean that all kinds of contaminants, including microplastics, will be retained in the reservoir. However, also, in this case, individual plastic particles were isolated from the suspended matter collected below the water sluice.

As it results from the presented research, dam reservoirs with bottom sluice can stop even over 90% of the total amount of microplastics introduced into them. However, it is worth noting that samples of suspensions were collected during periods of low and medium river flow when the water retention time in the reservoirs is relatively long. Due to the lack of flood surges during the study period, it was not possible to state whether this situation also occurs during emergency water discharges.

4. Conclusions

The conclusions are as follows:

- Studies have confirmed that dam reservoirs may contribute to the retention of microplastics flowing into them along with their inflows. The rivers downstream the dam contained significantly fewer microplastic particles than above the dam reservoirs.

- Microplastic particles appearing in outflows may indicate inside tank processes that cause the microplastic particles to enter deeper and bottom layers of water.
- Biofouling can be one of the factors responsible for microplastics transport into deeper layers of the lake. However, it should be noted that the literature data on this subject are extremely different, which may be associated with, among others, various constructions of dams and changing hydraulic conditions in the reservoirs.
- Research on the presence of microplastics in inland waters should in the future help to develop effective ways of reducing emissions of these pollutants into the environment and should also enable the removal of these pollutants from the environment.
- Currently, in Poland and other European countries, there are no clear guidelines for monitoring the occurrence of microplastics in the aquatic environment. The need for research on a much broader scale is indicated. Reference methods for sampling and the presentation and interpretation of test results should also be developed.

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