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Comparative Analysis of Riverine Plastic Pollution Combining Citizen Science, Remote Sensing and Water Quality Monitoring Techniques

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Abstract: The Tisza River is the longest tributary of the Danube, draining the eastern part of the Carpathian Basin (Central Europe). Five countries share its catchment with different waste production and management practices. Large amounts of waste, including macroplastics (MaPs), are washed into the river. Some of the litter is trapped by the riparian vegetation forming litter accumulations. The study aimed to map the amount of litter by a citizen science program and remote sensing data and to compare the MaP data to the amount of microplastic fragments in sediments. Volunteers reported 3216 riverine litter accumulations from five countries along the entire length of the Tisza (2016–2022). The results suggest that low flow conditions (e.g., impoundment by dams) support litter and MaP trapping. The volume of large accumulations registered by the citizens showed a good correlation with the area of drifting litter revealed on Sentinel-2 images (2016–2022) using machine learning algorithms. Though the MaPs probably fragmentate during their fluvial transport, no clear connection was found between the volume of litter accumulations and the mean microplastic fragment content of sediments (2019–2022). The "Clean Tisza Map" reveals the high degree of stranded pollutants along rivers and supports public cleanup activities.

Keywords: plastic waste; pollution monitoring; citizen science; remote sensing; microplastic degradation; microplastic fragments

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1. Introduction

The composition, distribution and dynamics of marine litter have been studied in detail for decades since the first scientific papers were published in the 1970s, and their number has been growing ever since [1]. Data suggest that 80% of marine litter is transported from land-based sources into the sea by rivers [2,3]. It is difficult to determine the annual plastic influx into the seas, as the rivers in different socio-economic regions transport quite different amounts [4]. However, according to various estimations, it ranges between 0.5–3 million t/y and 12 million t/y [5].

The riverine litter consists of organic materials, like driftwood and leaves, and anthropogenic waste like glass bottles, metal cans and plastics. Various plastic types can contribute up to 75% of the floating litter [6]. Most of the anthropogenic waste transported by rivers originates from residential and industrial sources [7–11], but agriculture and tourism also play role in the pollution [10,12]. The problem with riverine litter is that only a fraction of the pollution is visible. The litter floating on the surface of the water makes up only 15% of the total amount of riverine waste, as ca. 70% sinks to the bottom and 15% is drifted and stranded along the banklines and the floodplain [13–15].

During the transportation and the deposition, the plastic litter is continuously degrading. Thus, the macroplastics (MaP) are gradually degraded into meso- and then to microplastics (MiP). The floating and stranded MaPs are exposed to changes in temperature, photo- and bio-degradation [16–18]. Whereas the MaPs on the bottom are mixed with sediment particles, thus exposed to physical erosion; thus, the quartz grains erode their surface. One of the most common MaP types in rivers is plastic packaging [6], which contributes to producing microplastic sheets and fragments; however, this fragmentation is quite slow [19,20].

Detecting riverine litter accumulations along the banks and on the floodplain is challenging, especially due to the difficult terrain and dense riparian vegetation. The dense canopy of floodplain forests limits the aerial surveys (e.g., UAV and remote sensing data) of the stranded litter under the canopy; in addition, the resolution of the remotely sensed images is often a challenge [21,22]. Therefore, a different approach is needed. However, to map the riverine litter along hundreds of kilometres long sections of rivers by field-work is quite labour intensive. Therefore, a solution could be to involve volunteers. For example, the Plastic Cup initiative launched a multi-year citizen science program ("Clean Tisza Map" [23]) to conduct personal observations along the entire Tisza River and its tributaries (Central Europe). However, the results and efficiency of this citizen science program were not analysed in detail.

The catchment of the Tisza River is located in the eastern half of the Carpathian Basin (Central Europe), and five countries share it with quite different waste management practices. In 2022, the recycling rate was the lowest in Ukraine (2.5%) and the highest in Slovakia at 42.2% [15]. The mountainous sub-catchments are especially exposed to mismanaged MaP pollution, as in these areas, the difficulties in logistics and high cost of waste collection [24] often lead to illegal waste deposition close to rivers [25].

Liro et al. [14,15] mapped the mismanaged plastic waste in the Carpathian region. According to their data, 60–620 tonnes of mismanaged plastic waste got into the mountainous rivers annually. The plastic waste could enter the fluvial system during heavy rainfalls when the run-off and mass movements mobilised the waste along the banks and valley slopes [26]. Along the Tisza River, litter accumulations (containing waste and natural items) were identified based on Sentinel-2 images and machine-learning algorithms [22,27]. Based on the results, the greatest riverine litter accumulations develop upstream of water engineering structures (e.g., dams, bridges and hydroelectric power stations), and the highest litter transport rate occurs during floods. The largest litter spot area was observed at low stages upstream of the Kisköre Dam [22,27]. During floods, the transport rate of plastic litter could be as much as 500 plastic bottles per minute [6]; thus, it is called the "plastic flood" [28]. When the overbank flood enters the floodplain, its flow velocity is drastically decreased by the dense riparian vegetation, so the drifting MaPs are trapped. Smaller flood waves are also important conveyors of MaPs. However, in these cases, the floating plastic is trapped by vegetation along the banklines (Figure 1A), and from these temporary traps, the MaPs could be mobilised by the subsequent flood waves. A non-representative questionnaire survey among inhabitants of the Tisza River Basin [28] shows that the local population is aware of the environmental problem, as 66% of them have witnessed plastic flood events and 83% have seen riverine litter accumulations along the banks or on the floodplain (Figure 1B).

The increased MaP pollution probably contributes to the increased microplastic pollution of the Tisza River. According to the annually repeated (since 2019) monitoring along the river [29–33], the microplastic pollution of the sediments was the highest in 2019 (3177 ± 1970 items/kg). In the same year, the largest MaP accumulation (18.8 thousand m^2) was detected upstream of the Kisköre Dam [22]. Still, the microplastic fragments contribute just to 2–33%, as microfibres dominate in the sediments within the water system of the Tisza [29–31,33].

Figure 1. (**A**) Riverine litter accumulation in the floodplain of the Tisza during wintertime. Most of the pollution originates from regions with poor waste management. (**B**) Riverside communal landfill in the valley of the Tisza at Rakhiv (Ukraine) on a Google Earth image (August 2019).

As the MaPs are widely distributed on the globe but their spatial distribution could change in time, a citizen science approach has been increasingly applied to study marine [4,34] and riverine litter [5,35,36]. The increasing awareness of MaP pollution in the Tisza River initiated the foundation of the Plastic Cup, which has organized international river cleanup actions in the Tisza River Basin since 2013. They successfully removed over 300 tons of riverine litter from the channel and the floodplains. Through preventive measures, the Diageo Call-Action, a cooperative project of the Plastic Cup, has also removed more than 1200 tons of household waste from the river over two years and diverted it back into the waste management system [37]. Proper pollution monitoring can increase the efficiency of river cleanups and help habitat restoration. In 2016, a long-term citizen science-based monitoring campaign was initiated to better understand the distribution of riverine litter, support prevention and help implement river cleanup efforts. The community effort involved schools, NGOs and volunteers, who surveyed more than 4000 km of banklines on foot over seven years. Thus, this project became one of the longest and largest citizen science studies in a large river basin.

The MaP pollution of the Tisza and the mountainous areas of the catchment were documented by Liro et al. [15], Magyar et al. [27] and Mohsen et al. [22]. In addition, one of the longest and most detailed microplastic surveys of the world was performed in the river system of the Tisza, revealing the MiP transport in the river and its accumulation in the sediments [29–33].

The main goal of the research was to compile an online river pollution map along the Tisza River and some of its tributaries, focusing on MaPs in order to help the implementation of river cleanup actions and to evaluate the spatial distribution of plastic pollution using the data collected by volunteers. In addition, we aimed to compare the results of the fieldwork done by volunteers with data on MaP distribution based on remote sensing data to reveal the strengths and weaknesses of the citizen science-based method. Finally, we aimed to compare the MaP data and the microplastic fragment content of the sediments to see whether the actual MaP pollution of a short section influences the MiP pollution of the sediments.

The novelty of the research relies on its spatiotemporal scales. The research was performed in a transboundary river system along the entire length of the main river and covers several years. Therefore, it goes far beyond the snapshot-like surveys common in macroplastic and plastic research. In addition, researchers usually study the MaP and MiP pollutions separately and the connection between them is often neglected, even though the weathering of MaPs could result in increased MiP contamination.

2. Study Area

The Tisza River is the largest tributary of the Danube in Central Europe (length: 966 km, discharge: 58–4346 m^3/s). The catchment (157,200 km^2) is shared by five countries (Figure 2). The sub-catchments in Ukraine (8.1%), Romania (46.2%) and Slovakia (9.7%) are mountainous and hilly, where the run-off is high; therefore, most of the discharge (95.7%) of the Tisza's fluvial system originates from these areas. On the contrary, the Hungarian (29.4%) and Serbian (6.6%) sub-catchments are in the lowland, flat areas; therefore, their contribution to the discharge (4.3%) is limited [38].

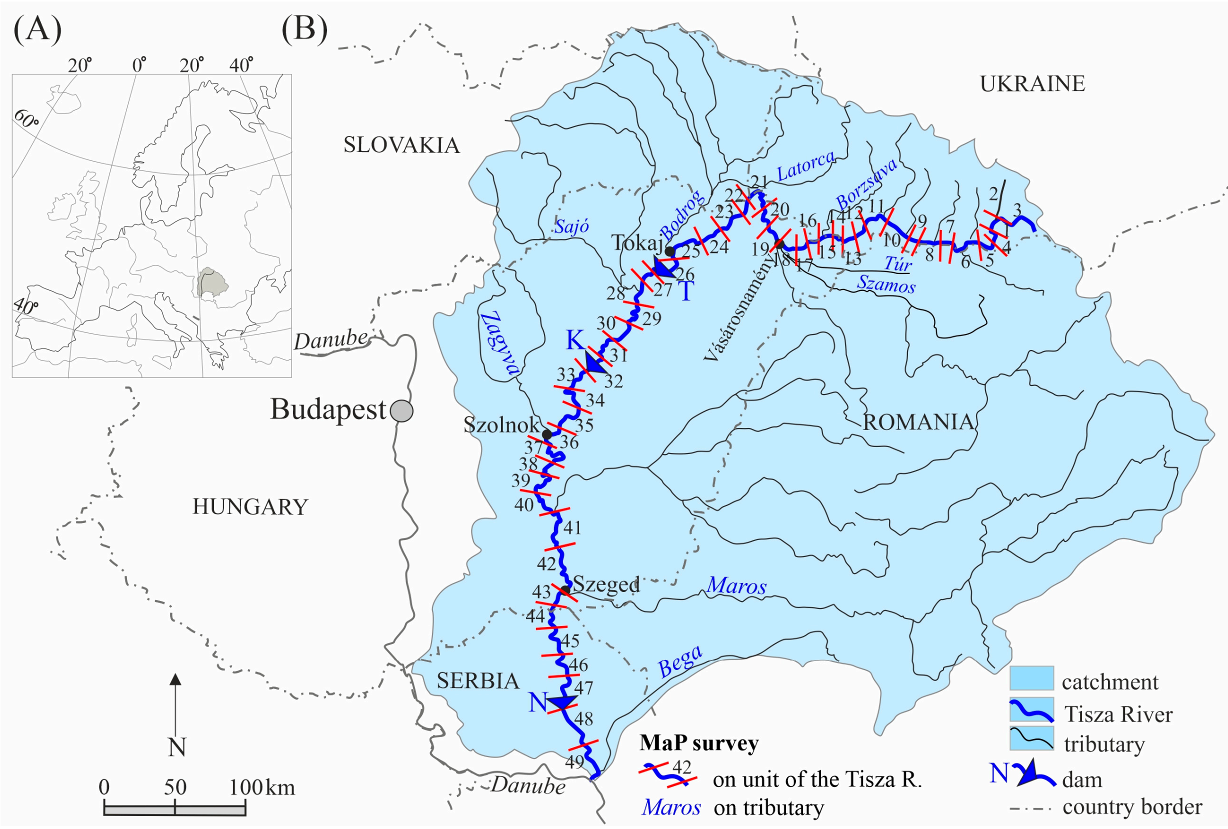

Figure 2. The riverine litter, including the distribution of microplastics, was mapped in the fluvial system of the Tisza River in Central Europe (**A**), which was divided into units (**B**). Macroplastics were mapped in each unit (2016–2022), and sediment samples were collected for microplastic analysis (2019–2022) at the downstream end of the units. T: Tiszalök Dam; K: Kisköre Dam and N: Novi Becej Dam.

The Upper Tisza has a great slope (20–50 m/km) and high flow velocity (2–3 m/s) in the mountainous units (No. 1–6). In the hilly areas (units No. 7–19), the slope gradually drops (from 110 to 13 cm/km); thus, the mean flow velocity decreases to 1.0 m/s [39]. The mean discharge is 330 m^3/s at the downstream end of the Upper Tisza. The slope (1–6 cm/km) and the flow velocity (0.1–0.5 m/s) further decrease in the Middle Tisza (units No. 20–42). Here, the Tiszalök and Kisköre Dams influence the flow conditions. As considerable tributaries join the Middle Tisza, its mean discharge increases to 800 m^3/s at the end of the reach. The Lower Tisza (units No. 43–49) has an even lower slope (1–0 cm/km) and flow velocity (0.0–0.2 m/s), which are influenced by the Novi Becej Dam. As the number of tributaries are limited along the lower reach, its mean discharge remains the same.

In the upstream countries, the settlements are located close to the rivers; thus, any mismanaged waste could easily get to the river. On the contrary, artificial levees were built on the lowland floodplains; thus, there is no direct connection between the settlements and the river.

The annual municipal waste production of the countries (300–478 kg/capita) sharing the catchment was below the average of the European Union (27 countries) in 2022 [40,41]. Most municipal waste was produced in Slovakia and Serbia, but in Ukraine and Romania, it was considerably lower (Figure 3, Table 1). The complex issue of transnational riverine litter pollution is caused by multiple reasons, including the low recycling ratio (5–49.5% in the Tisza River Basin). Thus, most of the countries on the catchment produce more unmanaged municipal waste than the EU average. Waste management is quite advanced in Slovakia; however, the non-EU members Serbia and Ukraine are the greatest unmanaged waste producers. The importance of EU membership is well reflected by the fact that since some of the countries joined the EU (2004: Slovakia and Hungary; 2007: Romania), the waste recycling ratio gradually increased, and in Romania and Hungary, the amount of municipal waste is declining.

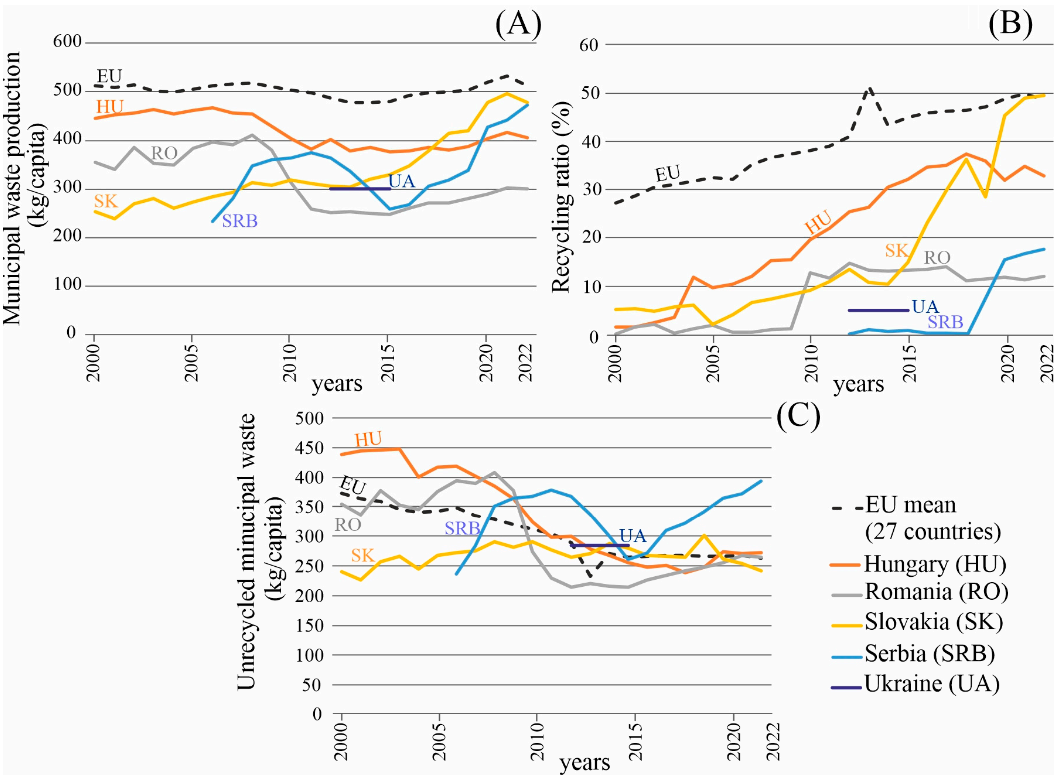

Figure 3. Temporal changes in municipal waste production (**A**), recycling ratio (**B**) and the amount of unrecycled municipal waste (**C**) in the countries of the Tisza's catchment and the average values of 27 countries of the European Union (data source: [40,41]). Note: the dataset provided for Serbia and Ukraine are incomplete.

Table 1. Municipal waste production and management in the countries sharing the catchment of the Tisza River and the average values of the European Union (EU) based on the mean of 27 countries in 2022 (source of data: [40,41]).

	Municipal Waste Production (kg/capita)	Municipal Waste Production in the Mean of the EU (%)	Recycling Ratio (%)	Unmanaged Municipal Waste (kg/capita)
Hungary	406	79.1	32.8	273
Romania	301	58.7	12.1	265
Slovakia	478	93.2	49.5	241
Serbia	472	92.0	17.6	389
Ukraine	300	58.5	5.0	285
EU average	513	100.0	48.6	264

Liro et al. [15] conducted a regional survey on MaP pollution of the mountainous rivers of the catchment. They found that most MaP leakage zones occurred along rivers in Romania, Hungary and Ukraine. In these countries, the waste-collection efficiency is low in the remote areas. Therefore, illegal dumpsites are common in the floodplains and along rivers, and the waste is often transported into the rivers.

Historically, the Tisza River had two main floods during early spring and summer [39], but nowadays they have shifted to the winter months due to climate change. These flood waves mobilise the mismanaged plastic waste from the valley slopes, floodplains and banklines. The MaP transport rate is the highest during flood peaks [22], but also, a large amount of MiP is transported by the floods [31,32]. River cleanup actions can target the floating/drifting riverine litter during flood events, but high discharge makes these operations very risky. To target the stranded riverine litter accumulations along the shorelines and on the floodplain is safer and easier. Former field observations and data suggest that floodplain forests and artificial water engineering structures have great waste retention capacity. Thus, in the upstream sections of the Tiszalök, Kisköre and Novi Becej Dams, large debris patches develop every year [22], removed by the operators of the dams.

The presented citizen science-based monitoring activity was performed along the entire length of the Tisza River on both banklines and on sections of some tributaries: Latorca (Latorica), Borzsa (Borzsava), Túr, Szamos (Someș), Sajó, Bodrog, Zagyva, Maros (Mureș) and Bega. The results of the citizen science-based survey along the Tisza were summed for units (49) between two subsequent MiP sampling points to match these data to the previous MaP and MiP monitoring results. The spatial distribution of litter surveyed along the tributaries was considered non-representative, as only their short sections were surveyed with uneven spacing. Thus, the tributaries were not divided into units.

3. Materials and Methods

3.1. Riverine Waste and Macroplastic Data Collected by Citizens

Volunteers registered and reported stranded riverine litter accumulations following the pollution mapping protocol provided by *The Transnational River Cleanup Handguide* [28]. The survey of the floodplains and banklines lasted for six years (2016–2022) in five countries sharing the catchment. The surveys were mostly performed during winter months, when the canopy lost the leaves, facilitating the detection of stranded riverine litter. The monitoring activity required the dedication of hundreds of volunteers, who spent thousands of hours searching and documenting litter accumulations.

The volunteers registered to the free, multilingual, open-source smartphone application "TrashOut" originally developed to report illegal dumpsites in rural areas. The application uploads substantial data on a polluted site (geolocation, size, description) to an online database via a mobile internet connection. With a lack of mobile signal reception, the device caches the data and transfers it again once it is back online. When making a report, the volunteers had to estimate the volume of the litter, as it was important from the point of view of cleaning-up efforts; thus, they had to suggest the size and capacity of equipment needed to remove the waste by trailer (ca. 10 m^3), wheelbarrow (ca. 1 m^3) and waste bag (ca. 0.1 m^3). The composition of the litter also had to be indicated, whether it contained broken vehicle parts, construction materials, electronic waste, domestic waste, glass or metal, organic materials (e.g., woody debris and dead animals) or plastic. The volunteers did not have to estimate the weight or volume of these components; they just indicated by yes or no whether the litter contained them. If the waste was removed from a site, indicating it in the application was also possible. The volunteers could also add pictures to the reported sites. The saved data were transferred to the server of the online Clean Tisza Map using the JSON format and API endpoint provided by the application. Data visualization was carried out for public users via an automated process, assuring that a newly discovered pollution site appeared on the online map within 15 min (Figure 4). The Clean Tisza Map is accessible at https://tisztatiszaterkep.hu/#/ (accessed on 30 April 2024).

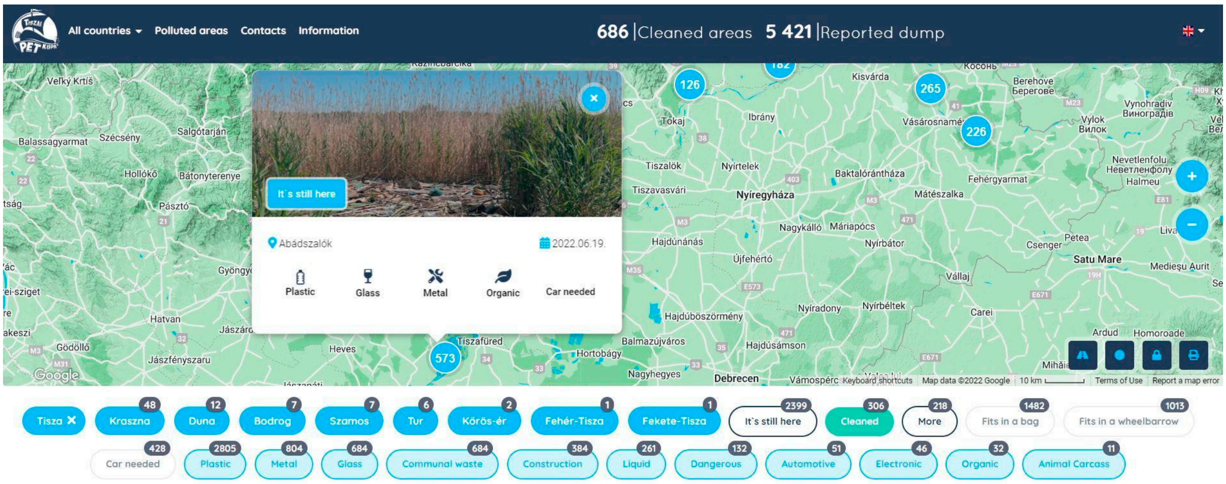

Figure 4. On the online Clean Tisza Map, the registered sites can be grouped based on their country, river, volume, accessibility and pollution composition.

3.2. Former Data on Riverine Litter and Microplastic Fragments in Sediments

Along the Hungarian section of the Tisza River, the distribution of floating riverine litter was mapped using remotely sensed data. The detailed methodology was described by Mohsen et al. [22] and Magyar et al. [27]. In brief, the survey was made based on multispectral satellite images (Sentinel-2) applying various machine learning algorithms (i.e., Artificial Neural Network Support Vector Classifier, Random Forest, Naïve Bayes and Decision Tree). The greatest limit of the riverine litter detection was the relatively low resolution of the Sentinel-2 images (100 m^2); thus, this method could not identify smaller riverine litter accumulations. The research surveyed the floating riverine litter accumulations for 2016–2022. The area of identified litter accumulations on the satellite images was compared with the volume of the registered polluted sites by citizens on a unit scale.

The monitoring of the microplastic content of sediments of the Tisza and its tributaries started later than the survey on MaPs, as it was performed annually since 2019 [29–33]. Each summer, a sampling campaign was performed from the source of the Tisza in Ukraine to its confluence in Serbia and in the near-confluence sections of the main tributaries. Freshly deposited sediment samples were collected from the water line. The samples were treated with 30% hydrogen peroxide solution for 24 h and using a density separation method (zinc chloride), the MiPs were extracted (see in detail in [30,33]). During the sample preparation, strict contamination control was followed [33], and every fourth sample was a blank to check the cross-contamination. The extracted MiP particles (200–90 μm) were identified under a light microscope (magnification: 60×), and the correctness of the identification was tested by FTIR measurements [33]. Most of the identified MiP particles were fibres originating from wastewater. However, in this paper, only the MiP fragment content of the samples was considered, as fragments mainly originate from the fragmentation of municipal plastic waste (e.g., PET bottles, plastic bags and packing materials).

4. Results

4.1. Citizen Science Survey

Volunteers reported 3216 riverine litter accumulations in the Tisza River Basin between 2016 and 2022. Most of the data were from the main river (83%), as its entire length was surveyed. Thus, the mean density of litter accumulations along the Tisza is 3.3 accumulations/river km. During the survey, the tributaries were underrepresented (17%). Substantial data were provided from the Bodrog (8%), Latorca (3%) and Szamos Rivers (2.5%), but on the rest of the tributaries, only ca. 1–1% of the data were collected.

The country-scale data were also inhomogeneous, as most data were collected in Hungary (86%), followed by Ukraine (7%), Romania (2.5%), Serbia (2.5%) and Slovakia (2%).

The total volume of the riverine litter accumulation was 5020 m^3 on the Tisza (5.2 m^3/river km). Most of the data are from Hungary; the average volume along the Hungarian section (597 km) was 8 m^3/river km. The volume of the registered litter was the highest (Figure 5) in popular tourist destinations (at unit No. 18: Vásárosnamény; No. 26: Tokaj and No. 32: Tiszafüred). It should also be noted that a low number of accumulations with large volumes were registered in the Ukrainian and Serbian sections. A longitudinal trend in the plastic transport along the river could be detected, as the volume and the size of riverine litter accumulations is gradually increasing in the Hungarian Upper and Middle Tisza, reaching its peak in the Tisza Lake (unit No. 32), just upstream of the Kisköre Dam and Hydropower Plant (HPP).

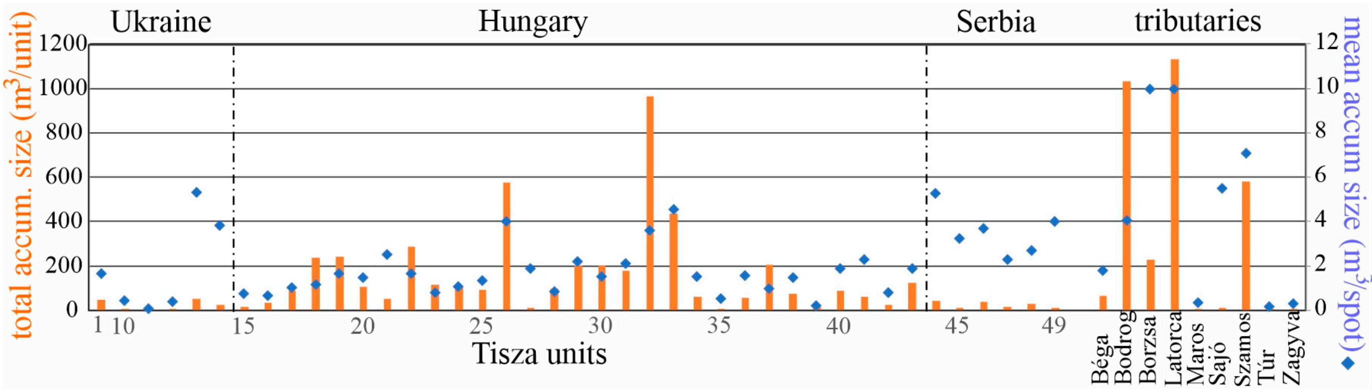

Figure 5. Total and mean volume (m^3) of litter accumulations in the units of the Tisza and its tributaries.

Along the tributaries, a considerable volume (3061 m^3) of deposited riverine litter was also identified. Their density (m^3/r km) could not be calculated precisely, as the surveys represented a limited number of sites rather than a reach or the whole river. The mean accumulation volume of the tributaries (4.3 m^3/accumulation) was considerably higher than that of the Tisza (2.0 m^3/accumulation). The largest accumulations were found along the Ukrainian sections of the Borzsa and Latorca Rivers (10 and 10 m^3/accumulation) and the Romanian section of Szamos (7.1 m^3/accumulation).

During the survey, the volunteers had to register the type of riverine litter accumulation they found on the field (Figure 6). The most common registered litter type was plastic, reported from 95 and 92% of the sites along the Tisza and tributaries. In contrast, organic debris was the least common recorded material on the sites (Tisza: 5.5%; tributaries: 30%). Towards the Tiszalök and Kisköre Dams and Hydroelectric Power Plants (unit No. 33), the variety of the waste increased, and an increasing proportion of the polluted sites contained various other materials (e.g., electric, domestic, glass and metal waste). At the Kisköre HPP, floating riverine litter is removed from the river on a large scale with the application of heavy machinery. Interestingly, downstream of the Kisköre HPP, the proportion of accumulations with plastic litter decreased, and the other litter types became less frequent, too.

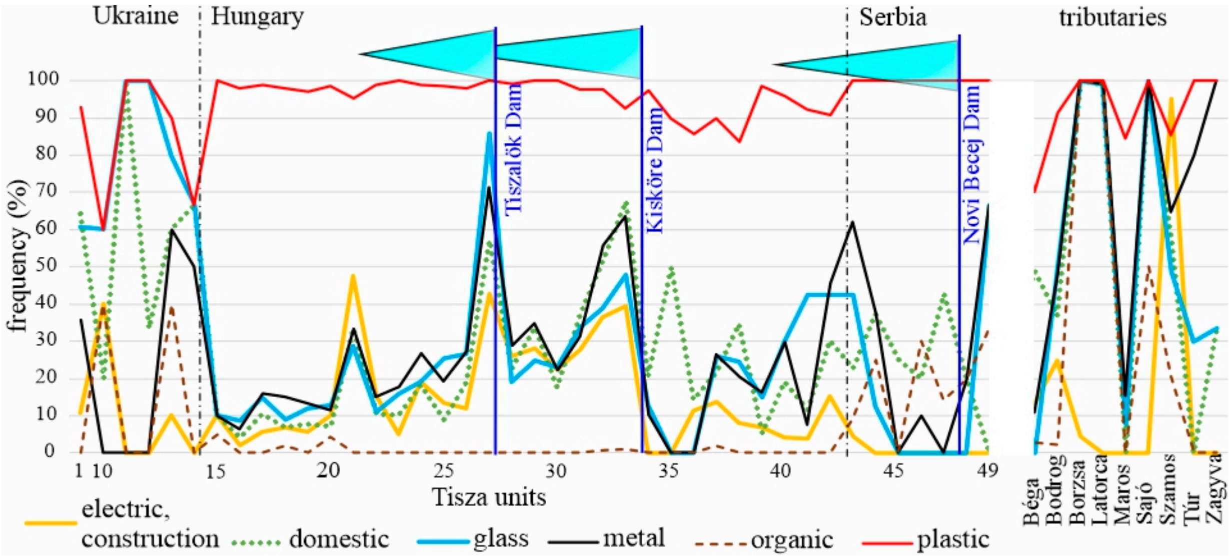

Figure 6. Registered litter types in the surveyed accumulations.

4.2. Comparison of Results of the Citizen Survey and Remote Sensing Methods

The comparison of the citizen-based and Sentinel-based methods is difficult, as the volunteers could register even very small accumulations (≤0.01 m^3), they estimated the volume of waste accumulated at the polluted site, and they performed the mapping on the floodplain and also along the banks. On the contrary, our Sentinel-based MaP survey was suitable for detecting litter accumulation areas larger than the pixel size (≥100 m^2), and just the floating waste on the water was detectable, as the dense riparian vegetation impedes the measurements. Therefore, only those units were considered during the comparison, where the largest (≥10 m^3) volumes were registered by the volunteers (Figure 7). There is a strong positive correlation (R^2 = 0.9) between the two datasets. It suggests that the volunteers performed a reliable survey along the Tisza.

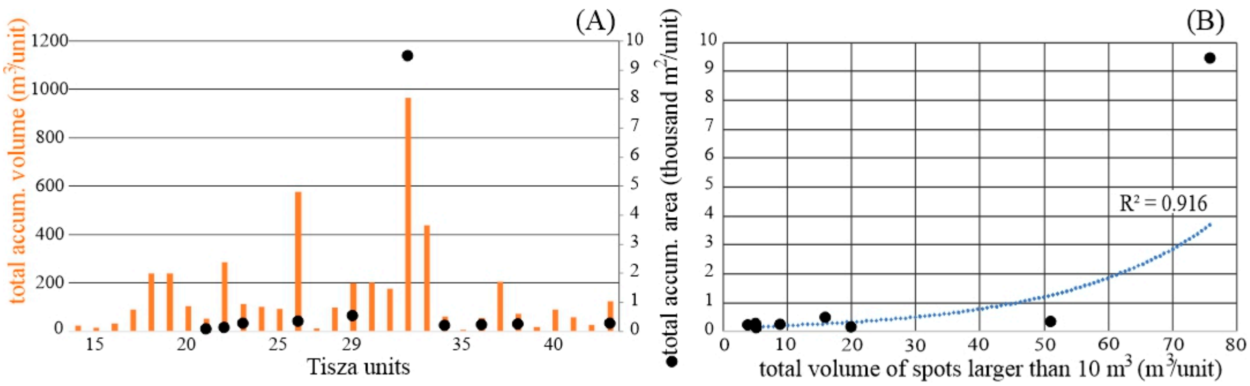

Figure 7. (**A**) Comparison of the total accumulation volume (m^3) registered by volunteers and total area (m^2) of riverine litter accumulations identified on Sentinel-2 images on the Hungarian section of the Tisza. (**B**) Relationship between volume of riverine litter (≥10 m^3) and their total area in those units where both surveys provided data (source of Sentinel-based data: Mohsen et al., 2023b [22]).

4.3. Comparison of Results of the Citizen Survey and Microplastic Fragments in Sediments

The riverine litter accumulations registered by volunteers contained plastic waste in high proportions, and the drifting and stranded MaPs are prone to degradation. A comparative analysis was conducted to determine whether the fragmentation of MaPs is detectable in the form of the appearance of secondary MiP particles. The volume of polluted sites contaminated by plastics was calculated within the units and compared with the MiP fragment content of samples collected at the downstream end of each unit (Figure 8). Statistically, there was no connection between the two parameters ($R^2 < 0.01$).

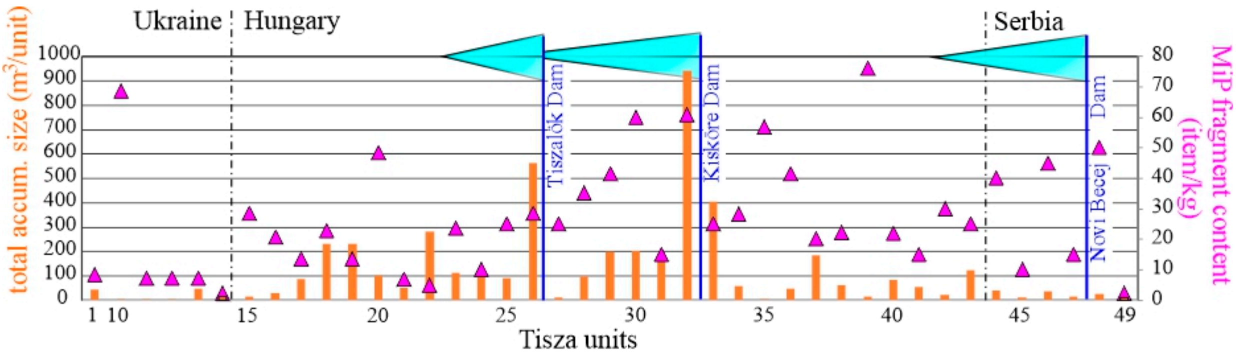

Figure 8. Longitudinal changes in the volume of litter accumulations containing plastics and the mean MiP fragment content of the sediments based on data from 2019 to 2022 (source of MiP data: [29–33]).

The flow velocity is high in the upstream section of the Tisza (units 1–13), and the villages are close to the river in the valley. These circumstances create unfavourable conditions for developing large riverine litter accumulations (mean volume: 16 m^3/unit) and MiP deposition. However, the fragmentation of the plastics could be intensive due to the fast-moving sediments and plastics' movements. Therefore, on the Upper Tisza, the MiP fragment content of the sediments was very low (7–8 items/kg), except for one site (unit No. 10: 68 items/kg).

In the next section (units 14–26), there was no clear downstream trend in the volume of the litter accumulations or the MiP fragment content. However, both parameters increased, as the total litter volume almost increased 9-fold (148 m^3/unit) and the MiP fragments by 2.5-fold (19 items/kg) compared to the previous section. Presumably the higher deposition rate correlates with low-flow conditions in this case. The downstream units (23–26) of this section are impounded by the Tiszalök Dam and HPP, creating favourable conditions for the accumulation of floating debris and the deposition of fragmented MiPs. Therefore, both parameters show an increasing downstream trend in the reservoir.

The same process could be identified in the next section (units 27–32), which is influenced by the Kisköre Dam and HPP. Here, the volume of litter accumulations containing plastic contaminants increased from 13 to 942 m^3/unit (mean: 271 m^3/unit), and the micro-fragment content of the sediments increased from 25 to 61 items/kg (mean: 39 items/kg).

The Kisköre Dam plays an important role in removing floating riverine litter; therefore, downstream of the dam (units 33–49), the volume of litter accumulations containing plastics decreased (mean: 71 m^3/unit). The fragment content of the sediments also became lower (mean: 31 items/kg). However, the Novi Becej Dam impounds the section between units No. 41 and 47; thus, the MiP fragment content of the sediment gradually increases from 15 to 45 items/kg (mean: 25 items/kg), in the same way as in the reservoirs of the upstream dams.

5. Discussion

5.1. Strengths and Weaknesses of Citizen Surveys

To follow the dynamics of plastic transport in rivers and map the riverine litter accumulations along entire river systems are challenging and labour intensive. Dense riparian vegetation hides most of the waste accumulations, mixed with organic debris (e.g., driftwood). Current remote detection technologies are either too expensive or not applicable if the task is to detect the waste composition on these polluted sites with dense vegetation [21,22]. The citizen science approach provides an applicable alternative, especially because the environmental awareness of the citizens is increasing and they could do useful work during their leisure activities (e.g., hiking and canoeing). In this paper, we checked for the reliability and replicability of the citizen science dataset "TrashOut" by comparing the citizen science dataset with remote sensing data [22,27]. The comparison was made for the Hungarian section of the Tisza River, where data were densely registered. Here, the volume of the large riverine litter accumulations registered by volunteers correlated well with the area of the riverine litter identified by machine learning algorithms on Sentinel-2 images, even though they refer to different phases of MaP transport. The remote sensed data represent the floating MaPs. In contrast, the citizen survey presents the stranded ones. Their proportion within the entire MaP budget of a river is very similar according to Hanke et al. [13] and Liro et al. [14,15]; thus, we also achieved similar results. Thus, it could be stated that the presented citizen science dataset on stranded riverine litter accumulations is reliable. The practical and adaptation values of citizen science in plastic pollution surveys were also proven by various authors [12,14,37,42,43].

In the presented survey, mostly plastic waste (e.g., bottles and bags) was surveyed by the volunteers in the form of riverine litter, and they did not necessarily consider other waste types (e.g., construction materials, textiles and agricultural products). However, according to several authors [6–11], industry, agriculture and tourism also play crucial roles in the plastic pollution of rivers. The proportion of registered organic materials (e.g., large woody debris and dead organisms) was especially low. However, according to our experiences, organic debris often creates jams upstream of engineering structures (e.g., dams, groynes and bridge pillars) and at points where the overbank flood enters the floodplain, and the dense riparian vegetation blocks the transport of the drifting materials. Most volunteers did not consider driftwood as litter, so they only registered the anthropogenic waste in the accumulations. This approach related to the survey, as it was organised by the Plastic Cup Society, an NGO organising international community and professional river cleanup campaigns.

Another weakness of the citizen survey is its spatial and temporal representativity. In the given survey, the citizen scientists were more active in Hungary than in the other countries sharing the catchment of the Tisza. Especially, the tributaries had very uneven survey patterns as only their short sections were surveyed, probably by some enthusiastic individuals. It is also interesting to note that a low number of accumulations with large volumes were registered in the Ukrainian and Serbian sections. It could be explained by the fact that almost a continuous litter carpet covers the riverbanks and the gravel bars in Ukraine. Thus, the volunteers registered only the extremely large litter accumulations. In Serbia, the sporadic dataset could be explained by the very dense vegetation on the floodplain and the different approaches applied by citizen scientists. Finally, the age of litter accumulations remained a question, as the volunteers could not estimate the exact deposition time. Thus, they could have been at a given location for years or just since the last flood wave.

5.2. Factors Influencing Macroplastic Pollution

The waste management in the countries of the catchment is gradually improving, as the recycling ratio of municipal waste slowly reaches the average of the European Union. However, some countries (e.g., Ukraine and Serbia) still produce large amounts of untreated or mismanaged municipal waste. In the mountainous and hilly regions, the collection of waste and recycled items is not profitable; therefore, in most of the remote areas, the waste is illegally dumped along waterways [11,14,15,24,25]. It is well reflected by the fact that some tributaries originating in the mountains of Ukraine (Latorca), Romania (Szamos) or Slovakia (Bodrog) were highly contaminated. Along these rivers, the total volume of the litter accumulations containing plastics was $\geq$50 m^3 and their mean volume (7–10 m^3) was much higher than that of the Tisza (2 m^3). Thus, from these upstream catchments with poor waste management, the run-off effectively could mobilise the waste, and the tributaries act as conveyor belts to carry the pollution to the main river. It explains that the heavily polluted river transports up to 500 plastic bottles/minute during floods in the Upper Tisza reach [6]. The importance of upstream rivers in MaP pollution was also proven by Liro et al. [15], who found that the most polluted sub-catchments are probably in the hilly and mountainous regions of Ukraine, Romania, and Hungary.

In the river system of the Tisza, plastics were common in most litter accumulation spots, and the variety of plastic materials increased downstream. This could be related to the greater catchment area with a larger population, their different consuming habitats, and the different transport mechanisms and trapping of MaPs along the river [15,16,44].

The most important conclusion from the combined survey is that engineering structures, especially dams, have substantial waste retention capacity. The total size and number of large riverine litter accumulations, including MaPs, and the MiP fragment concentration of the sediments were higher in upstream sections of dams. They act as barriers, as upstream of dams, the flow velocity drops; thus, the floating debris gradually could be trapped by the riparian vegetation or obstacles in the channel. In all three reservoirs of the Tisza, the volume of riverine litter accumulations containing plastics increases toward the dams, as found on other rivers [7,11].

On the other hand, downstream of dams, the pollution decreased, as only a limited amount of pollutants could get through the dams because local authorities removed the riverine floating debris. In Hungary, 90–10,000 tons/year of debris are removed from the Tisza each year and selected for further use [22,45]. Our citizen survey also reflected the efficiency of this work, as downstream of the Kisköre Dam, the volume of the litter accumulations dropped and their plastic content decreased.

The Tisza is incising, especially downstream of the Kisköre Dam and HPP. Because of the incision, very steep banks were formed, providing an unfavourable depositional environment for riverine litter and plastic waste. This could also contribute to the low number of litter accumulations downstream of the dam. In addition, overbank floods became rare in the last decade due to the combined effects of climate change and incision; therefore, the transported debris and MaP could not be accumulated on the floodplain except during exceptionally high floods.

5.3. Consequences of Macroplastic Pollution: Potential Microplastic Pollution

The results of the long-term MaP survey (2016–2022) and the annual MiP monitoring in sediments (2019–2022) were compared. Lahens et al. [8] found a connection between the number of floating MaPs and MiPs in the water based on their size–spectrum continuum. However, in our case, no clear correlation was found between the volume of the litter accumulations containing plastics and the amount of MiP fragments in the freshly deposited sediments. It could be explained by the fact that the deposition of the MiP fragments is influenced not just by the source but also by the environmental conditions of the deposition. First of all, the fragmentation of macroplastics is quite a slow process [19,20]. In addition, the MiP particles in suspension could be mobilised earlier and travel larger distances than the natural suspended sediments [46]. As the flow conditions change along the river, the sections with declining flow velocities influence the trapping of the MaPs and the deposition of MiPs similarly; however, they are not directly connected. Therefore, in the impounded sections upstream of dams, the volume of the accumulations containing MaPs and the MiP fragment concentration of the sediments increased. They reached their greatest values upstream of the dams and HPPs, where the flow velocity dropped to almost zero.

5.4. Macroplastic Pollution and Cleanup Actions

Macroplastic pollution negatively impacts industries like fishing, shipping, tourism and recreation [14,15,47]. However, the enthusiasm of citizens, combined with eco-awareness and love of water sports could open new views. The Plastic Cup Society regularly organises transnational river cleanup actions in all countries of the Tisza River Basin. As a result, approximately 10% of all polluted sites have already been cleaned (Figure 9) by collecting 367 tonnes of waste by the end of 2023. Most of the collected material was plastic (80%). According to our calculations, at least ca. 1665 tons of riverine litter are still present in Tisza floodplains, and considering the whole fluvial system, it is estimated that at least

2500 tons of litter are stranded or trapped in the channel and the floodplains. Considering that 70% of the plastics sink to the bottom [13–15], it is reasonable to assume that a greater quantity of riverine litter exists in the fluvial system. As plastics are prone to fragmentation and degradation, pollution contributes to the further deterioration of habitats and water supplies.

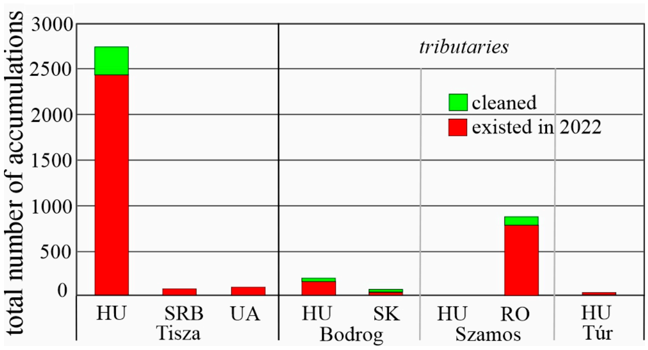

Figure 9. The number of surveyed litter accumulations and the proportion of cleaned sites in 2022 in Hungary (HU), Serbia (SRB), Ukraine (UA), Slovakia (SK) and Romania (RO).

6. Conclusions

The presented citizen science survey has demonstrated that personal observations can accurately and reliably reveal riverine litter accumulations along the riverbanks and in dense riparian forests. However, they can be used for scientific analysis only if the registered data are representative spatially (or temporally). However, the survey method has some disadvantages, including uneven spatial distribution or repeated surveys needed to keep the database up-to-date.

Our study highlighted the potential of an online river pollution map. The Clean Tisza Map's open-access database effectively supports river cleanup actions in all Tisza countries. In addition, it contributed to general calculations on the trapped and stranded riverine litter in the fluvial system of the Tisza River. It is important to note that these results represent only the current situation, as they could change dynamically due to external factors such as new plastic pollution and rearrangement of the stranded materials by flood waves.

In conclusion, the floodplains and the riverbanks, and especially the sections upstream of dams, function as repositories for large amounts of floating riverine litter, including MaPs and MiPs. Our data suggest that the retention capacity of alluvial forests, combined with the low-flow sections of the river formed by natural and artificial causes, leads to the formation of large riverine litter accumulations. These litter accumulations contain natural materials and also waste of human origin (e.g., plastics, communal or construction waste). These findings suggest that rivers serve as a transport route and conveyor belts for marine litter and become increasingly polluted themselves if proper preventive and reactive actions are not taken.

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References

1. Ryan, P.G. A brief history of marine litter research. In *Marine Anthropogenic Litter*; Bergmann, M., Gutow, L., Klages, M., Eds.; Springer: Cham, Switzerland, 2015. [CrossRef]
2. Lebreton, L.; van der Zwet, J.; Damsteeg, J.W.; Slat, B.; Andrady, A.; Reisser, J. River plastic emissions to the world's oceans. *Nat. Commun.* **2017**, *8*, 15611. [CrossRef] [PubMed]
3. Meijer, L.J.; Van Emmerik, T.; Van der Ent, R.; Schmidt, C.; Lebreton, L. More than 1000 rivers account for 80% of global riverine plastic emissions into the ocean. *Sci. Adv.* **2021**, *7*, eaaz5803. [CrossRef] [PubMed]
4. Hidalgo-Ruz, V.; Thiel, M. The contribution of citizen scientists to the monitoring of marine litter. In *Marine Anthropogenic Litter*; Bergmann, M., Gutow, L., Klages, M., Eds.; Springer: Cham, Switzerland, 2015; pp. 429–447. [CrossRef]
5. Lechner, A. "Down by the river": (Micro-) Plastic pollution of running freshwaters with special emphasis on the Austrian Danube. In *Mare Plasticum—The Plastic Sea*; Streit-Bianchi, M., Cimadevila, M., Trettnak, W., Eds.; Springer: Cham, Switzerland, 2020; pp. 141–185. [CrossRef]
6. Gyalai-Korpos, M. *Plastic Pollution of Rivers in the Danube Region—Best Practices towards Reduction of Plastic Pollution*; EUSDR Priority Area 4 and Financed by the Project DTP-PAC1-PA4 (Acronym: PA 04 Water Quality); Ministry of Foreign Affairs and Trade Hungary: Budapest, Hungary, 2019; Available online: https://dunaregiostrategia.kormany.hu/download/3/7f/72000/EUSDR_20191.pdf (accessed on 30 April 2024).
7. Mihai, F.C.; Apostol, L.; Ursu, A.; Ichim, P. Vulnerability of mountain rivers to waste dumping from Neamt County, Romania. *Geogr. Napoc.* **2012**, *6*, 51–59. [CrossRef]
8. Lahens, L.; Strady, E.; Kieu-Le, T.; Dris, R.; Boukerma, K.; Rinnert, E.; Gasperi, J.; Tassin, B. Macroplastic and microplastic contamination assessment of a tropical river (Saigon River, Vietnam) transversed by a developing megacity. *Environ. Pollut.* **2018**, *236*, 661–671. [CrossRef]
9. Eo, S.; Hong, S.H.; Song, Y.K.; Han, G.M.; Shim, W.J. Spatiotemporal distribution and annual load of microplastics in the Nakdong River, South Korea. *Water Res.* **2019**, *160*, 228–237. [CrossRef] [PubMed]
10. He, B.; Wijesiri, B.; Ayoko, G.A.; Egodawatta, P.; Rintoul, L.; Goonetilleke, A. Influential factors on microplastics occurrence in river sediments. *Sci. Total Environ.* **2020**, *738*, 139901. [CrossRef] [PubMed]
11. Mihai, F.C.; Gündoğdu, S.; Khan, F.R.; Olivelli, A.; Markley, L.A.; van Emmerik, T. Plastic pollution in marine and freshwater environments: Abundance, sources, and mitigation. *Emerg. Contam. Environ.* **2022**, *11*, 241–274. [CrossRef]
12. Barrows, A.P.; Christiansen, K.S.; Bode, E.T.; Hoellein, T.J. A watershed-scale, citizen science approach to quantifying microplastic concentration in a mixed land-use river. *Water Res.* **2018**, *147*, 382–392. [CrossRef] [PubMed]
13. Hanke, G.; Galgani, F.; Werner, S.; Oosterbaan, L.; Nilsson, P.; Fleet, D.; Kinsey, S.; Thompson, R.; Palatinus, A.; Van Franeker, J.; et al. *Guidance on Monitoring of Marine Litter in European Seas*; EUR 26113; Publications Office of the European Union: Luxembourg, 2013. [CrossRef]
14. Liro, M.; Zielonka, A.; Hajdukiewicz, H.; Mikuś, P.; Haska, W.; Kieniewicz, M.; Gorczyca, E.; Krzemień, K. Litter Selfie: A citizen science guide for photorecording macroplastic deposition along mountain rivers using a smartphone. *Water* **2023**, *15*, 3116. [CrossRef]
15. Liro, M.; Zielonka, A.; van Emmerik, T.H.M.; Grodzińska-Jurczak, M.; Liro, J.; Kiss, T.; Mihai, F.C. Mountains of plastic: Mismanaged plastic waste along the Carpathian watercourses. *Sci. Total Environ.* **2023**, *888*, 164058. [CrossRef]
16. Li, C.; Busquets, R.; Campos, L.C. Assessment of microplastics in freshwater systems: A review. *Sci. Total Environ.* **2020**, *707*, 135578. [CrossRef]
17. Huang, D.; Li, X.; Ouyang, Z.; Zhao, X.; Wu, R.; Zhang, C.; Lin, C.; Li, Y.; Guo, X. The occurrence and abundance of microplastics in surface water and sediment of the West River downstream, in the south of China. *Sci. Total Environ.* **2021**, *756*, 143857. [CrossRef]
18. Huang, D.; Tao, J.; Cheng, M.; Deng, R.; Chen, S.; Yin, L.; Li, R. Microplastics and nanoplastics in the environment: Macroscopic transport and effects on creatures. *J. Hazard. Mater.* **2021**, *407*, 124399. [CrossRef]
19. Weinstein, J.E.; Crocker, B.; Crocker, A.; Gray, A.D. From macroplastic to microplastic: Degradation of high density polyethylene, polypropylene, and polystyrene in a salt marsh habitat. *Environ. Toxicol. Chem.* **2016**, *35*, 1632–1640. [CrossRef]
20. Ronkay, F.; Molnár, B.; Gere, D.; Czigány, T. Plastic waste from marine environment: Demonstration of possible routes for recycling by different manufacturing technologies. *Waste Manag.* **2021**, *119*, 101–110. [CrossRef] [PubMed]
21. Topouzelis, K.; Papakonstantinou, A.; Garaba, S.P. Detection of floating plastics from satellite and unmanned aerial systems (Plastic Litter Project 2018). *Int. J. Appl. Earth Obs. Geoinf.* **2019**, *79*, 175–183. [CrossRef]
22. Mohsen, A.; Kiss, T.; Kovács, F. Machine learning-based detection and mapping of riverine litter utilizing Sentinel-2 imagery. *Environ. Sci. Poll. Res.* **2023**, *30*, 67742–67757. [CrossRef]

23. Clean Tisza Map: Online River Pollution Map. Available online: https://www.tisztatiszaterkep.hu/#/en/ (accessed on 30 April 2024).
24. Mihai, F.C. Waste collection in rural communities: Challenges under EU regulations. A case study of Neamt County, Romania. *J. Mater. Cycl. Waste Manag.* **2018**, *20*, 1337–1347. [CrossRef]
25. Mihai, F.C. Rural plastic emissions into the largest mountain lake of the Eastern Carpathians. *R. Soc. Open Sci.* **2018**, *5*, 172396. [CrossRef]
26. van Emmerik, T.; Strady, E.; Kieu-Le, T.C.; Nguyen, L.; Gratiot, N. Seasonality of riverine macroplastic transport. *Sci. Rep.* **2019**, *9*, 13549. [CrossRef]
27. Magyar, D.; Cserép, M.; Vincellér, Z.; Molnár, A.D. Waste detection and change analysis based on multispectral satellite imagery. In Proceedings of the KEPAF: Képfeldolgozók és Alakfelismerők társaságának 14. Konferenciája, Gyula, Hungary, 24–27 January 2023; p. 18. [CrossRef]
28. Molnár, A.D.; Hankó, G. *Aquatic Plastic I. The Transnational River Cleanup Handguide*; PET Cup: Budapest, Hungary, 2022; p. 14. Available online: https://dtp.interreg-danube.eu/uploads/media/approved_project_output/0001/56/4fb08d49141573d5aecbea014f841deaa6cb28c7.pdf (accessed on 30 April 2024).
29. Kiss, T.; Fórián, S.; Szatmári, G.; Sipos, G. Spatial distribution of microplastics in the fluvial sediments of a transboundary river—A case study of the Tisza River in Central Europe. *Sci. Tot. Environ.* **2021**, *785*, 147306. [CrossRef]
30. Kiss, T.; Gönczy, S.; Nagy, T.; Mesaroš, M.; Balla, A. Deposition and mobilization of microplastics in a low-energy fluvial environment from a geomorphological perspective. *Appl. Sci.* **2022**, *12*, 4367. [CrossRef]
31. Mohsen, A.; Balla, B.; Kiss, T. High spatiotemporal resolution analysis on suspended sediment and microplastic transport of a lowland river. *Sci. Tot. Environ.* **2023**, *902*, 166188. [CrossRef] [PubMed]
32. Mohsen, A.; Kovács, F.; Kiss, T. Riverine Microplastic Quantification: A novel approach integrating satellite images, neural network, and suspended sediment data as a proxy. *Sensors* **2023**, *23*, 9505. [CrossRef] [PubMed]
33. Balla, A.; Teofilovic, V.; Kiss, T. Microplastic contamination of fine-grained sediments and its environmental driving factors along a lowland river: Three-year monitoring of the Tisza River and Central Europe. *Hydrology* **2024**, *11*, 11. [CrossRef]
34. Schernewski, G.; Escobar Sánchez, G.; Felsing, S.; Gatel Rebours, M.; Haseler, M.; Hauk, R.; Lange, X.; Piehl, S. Emission, transport and retention of floating marine macro-litter (plastics): The role of Baltic harbor and sailing festivals. *Sustainability* **2024**, *16*, 1220. [CrossRef]
35. Popa, C.L.; Dontu, S.I.; Savastru, D.; Carstea, E.M. Role of citizen scientists in environmental plastic litter research—A systematic review. *Sustainability* **2022**, *14*, 13265. [CrossRef]
36. Schneider, F.; Kunz, A.; Hu, C.-S.; Yen, N.; Lin, H.-T. Rapid-survey methodology to assess litter volumes along large river systems—A case study of the Tamsui River in Taiwan. *Sustainability* **2021**, *13*, 8765. [CrossRef]
37. Bitter, Z. Nearly 1200 Tonnes of Waste Collected and Processed Thank to the Call-Action Programme. 2023. Available online: https://petkupa.hu/eng/?cikkId=call-action-reached-1200-tons (accessed on 30 April 2024).
38. Konecsny, K. The effects of environmental changes on the water household of the Great Hungarian Plain. In *A víz szerepe és jelentősége az Alföldön*; Pálfai, I., Ed.; Nagyalföld Alapítvány: Békéscsaba, Hungary, 2000; pp. 27–46. (In Hungarian)
39. Lászlóffy, W. *The Tisza*; Akadémiai Kiadó: Budapest, Hungary, 1982; p. 610. (In Hungarian)
40. Eurostat: Waste Generated by Households by Year and Waste Category. Available online: https://ec.europa.eu/eurostat (accessed on 30 April 2024).
41. IFC. Municipal Solid Waste in Ukraine: Development Potential. Available online: https://documents1.worldbank.org/curated/zh/839801556599035128/pdf/Municipal-Solid-Waste-in-Ukraine-Development-Potential.pdf (accessed on 30 April 2024).
42. Kiessling, T.; Knickmeier, K.; Kruse, K.; Gatta-Rosemary, M.; Nauendorf, A.; Brennecke, D.; Thiel, L.; Wichels, A.; Parchmann, I.; Körtzinger, A.; et al. Schoolchildren discover hotspots of floating plastic litter in rivers using a large-scale collaborative approach. *Sci. Tot. Environ.* **2021**, *789*, 147849. [CrossRef]
43. Özbek, S.E.; Lanzavecchia, A.; Ferrarese, F. Participatory geographic information system based citizen science: Highland trails contamination due to mountaineering tourism in the Dolomites. *Sustainability* **2023**, *15*, 13908. [CrossRef]
44. Gallitelli, L.; Scalici, M. Riverine macroplastic gradient along watercourses: A global overview. *Front. Environ. Sci.* **2022**, *10*, 937944. [CrossRef]
45. Katona, G. Waste pollution of the River Tisza. *Műszaki Katonai Közlöny* **2019**, *29*, 65–80. (In Hungarian) [CrossRef]
46. Waldschlager, K.; Schüttrumpf, H. Effects of particle properties on the settling and rise velocities of microplastics in freshwater under laboratory conditions. *Environ. Sci. Technol.* **2019**, *53*, 1958–1966. [CrossRef] [PubMed]
47. Beaumont, J.; Aanesen, M.; Austen, M.C.; Börger, T.; Clark, J.R.; Cole, M.; Hooper, T.; Lindeque, P.K.; Pascoe, C.; Wyles, K.J. Global ecological, social and economic impacts of marine plastic. *Mar. Pollut. Bull.* **2019**, *142*, 189–195. [CrossRef]