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Article

Riverine Litter Flux to the Northeastern Part of the Black Sea

Maria Pogojeva [1,2,*], Evgeniya Korshenko [1] and Alexander Osadchiev [2,3]

1 N.N. Zubov State Oceanographic Institute, Roshydromet, Kropotkinskiy Lane 6, 119034 Moscow, Russia
2 Shirshov Institute of Oceanology, Russian Academy of Sciences, Nahimovskiy Prospect 36, 117997 Moscow, Russia
3 Moscow Institute of Physics and Technology, Institusky Lane 9, 141701 Dolgoprudny, Russia
* Correspondence: pogojeva_maria@mail.ru

Abstract: Rivers are among the main sources of marine litter, especially for semi-isolated sea areas with high populations and intense economic activity. The semi-isolated Black Sea located in the Eastern Europe is an example of such an area, whose watershed basin is under high anthropogenic pressure. In this study, we report the results of the first long-term monitoring program of floating litter at several rivers inflowing to the northeastern part of the Black Sea. We describe the main characteristics of registered marine litter, including the distribution of its type and size. Based on the obtained results, we reveal the relation between river discharge rate and the litter flux for the considered rivers. Using this relation extended to all rivers of the study area, we assess the total annual flux of riverine litter to the northeastern part of the Black Sea.

Keywords: riverine litter; marine pollution; floating litter; Black Sea; marine environmental monitoring

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1. Introduction

The input of solid waste from terrestrial sources to the World Ocean has become a major environmental threat. Marine litter and plastic pollution nowadays are among the priority issues on the agenda of national and international environmental organizations [1–4]. Rivers act as pathways between land and ocean; they collect litter from their watershed areas and transport it towards the sea. A certain share of litter remains in river catchments (river bottom, shores, backwater areas) and is later released to seas after its physical degradation. Plastics make up the largest proportion of litter in marine regions [5] and are dominant in riverine litter [6]. Non-floating items (e.g., made of glass or metal) are also present in river catchments and transported by river streams in bottom layers. The behavior of litter in riverine systems depends on its sources, pathways, composition and properties (such as size, density and shape) [7].

Sources of marine litter must be identified in order to organize appropriate and accurate measurements of litter fluxes. Possible sources include public littering on riverbanks or directly to rivers; waste from cities and harbors; poor waste management at landfill sites; disposal or loss of products from industrial and agricultural activities; debris from untreated sewage; flooding discharge periods; and entrainment of litter from riverbanks [6,7]. Only during the last decade have researchers started measuring quantities of plastics in rivers and their input to the ocean, which has resulted in very limited data in terms of temporal and geographical coverage [8]. The lack of data on litter fluxes in rivers hinders assessing the effectiveness of environmental measurements and regulations [7].

The Black Sea is a semi-enclosed water body with a very limited exchange with the World Ocean. The Black Sea receives very intense anthropogenic pressure, in particular, from river discharges, including from large rivers (Danube, Dnieper, Dniester, Don, Kuban, Sakarya, Southern Bug, etc.) with large drainage basins and numerous small rivers located along its densely populated coast [9,10]. Due to these factors, the Black Sea is a particularly sensitive area for marine litter pollution [11–13]. Moreover, in the last Black Sea Commission report [14], the level of ML pollution in the Eastern Black Sea was noted to depend mainly on the level of river run-off in this area.

The scope of monitoring of riverine litter consists of the quantification of litter presence, calculation of litter fluxes, and identification/characterization of litter sources to assess the environmental status and to support the development of litter reduction measures. Data on riverine litter needs to be comparable among different monitoring locations at different rivers and during the whole period of observations for accurate analysis. Therefore, harmonized and documented protocols of monitoring are required, along with certain procedures of data quality assurance, unification of units in data reports, provision of metadata, etc. [7].

In this paper, we describe the results of monitoring of the floating litter at several rivers inflowing to the northeastern part of the Black Sea. This monitoring program was designed and launched within the framework of the EMBLAS project [15–18], in close collaboration with the RIMMEL project supported by the Joint Research Centre of the European Commission. After the end of these projects, we continued the monitoring program and extended it to other rivers. Based on the obtained data, we assessed the total flux of riverine litter to the northeastern part of the Black Sea.

2. Materials and Methods

Floating litter was monitored at three rivers, from nearest observation platforms to the estuary (bridges and coastal platforms). One large (the Don River), one medium (the Sochi River) and one small (the Matsesta River) river were chosen in order to cover different types of riverine basins, size, water regime, supply, population, morphology and hydrological conditions, which are crucial for litter behavior in local rivers [4] (Figure 1) (Table 1). The Don River is the fourth largest river in Europe after the Volga, Dnieper and Danube rivers, with a watershed area of 429,400 km^2 and length equal to 1870 km [19]. The water regime of the Don River is typical for the rivers of the steppe and forest-steppe zones. It has mainly snow supply (up to 70%), with relatively weak ground and rain supply. The Don River is characterized by distinct spring freshet and drought during the rest of the year. The Don River flows through 19 large cities, including two cities with a population > 1 million people (Voronezh and Rostov-on-Don) and is regulated with a series of dams. The monitoring at the Don River was performed from the bridge, where the river width was 220 m and the observation track width was chosen as 70 m.

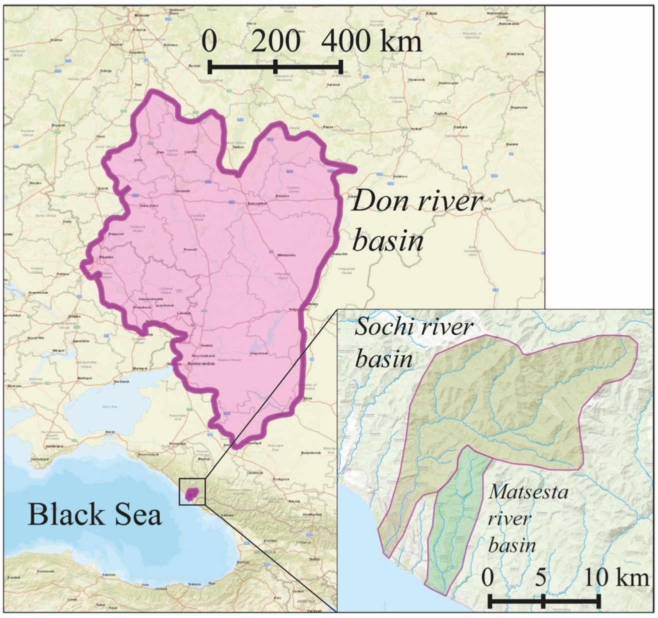

Figure 1. Watershed areas of the Don River (pink area), Sochi River (brown area at the inset), and Matsesta River (green area at the inset).

Table 1. The main parameters of the considered rivers and the number of monitoring sessions and hours.

River	River Bassin Area (km^2)	Average Discharge (m^3/s)	Number of Monitoring Sessions	Hours of Monitoring
Don	429,400	680	21	11
Sochi	296	15.6	50	51
Matsesta	68	2.7	35	36
Total			106	98

The Sochi River is 45 km long, with a basin area of 296 km^2 [19]. It is a medium-size mountainous river with snow and rain supply. The Sochi River has a drought period in autumn and winter and a freshet in spring and early summer. The Matsesta River is relatively small (18 km long), with a drainage basin of 68 km^2 [19]. It is rain-fed, and its annual runoff volume is formed mainly during short-term rain-induced floods, with sharp rises and falls of discharge. Both rivers inflow to the Black Sea at the city of Sochi, which is the largest resort in Russia, with a population of approximately 500,000 people. The monitoring of Sochi and Matsesta rivers were performed from coastal platforms, with a river width 60 m and 30 m, respectively; the observation track width covered the entire widths of the rivers.

The riverine litter monitoring methodology followed an MSFD harmonized approach described in "Guidance on Monitoring of Marine Litter in European Seas" [20,21]. At each river, the observations were performed by trained observers 1–5 times a month during one year from the bridges and coastal platforms located close to the river mouth. The observers identified, from standardized categorization lists, and registered litter items passing by with the river flow and estimated the size range of each item and recorded the related metadata information (observation height, river width, observation track width, river flow speed, weather description). As an example, a separate descriptive file was stored for each observation session (Supplementary Material Table S1). Binoculars were seldom used to confirm identification of the registered items. For the Don River, observations were made from a 30 m high bridge, so it was assumed that the observer could cover only 70 m of the total width of the river. Since the width of the river at the study site was about 220 m, the obtained results were multiplied by 3 to obtain the total litter flux. However, this issue could cause biased results due to possible missing of small items at the water surface, providing underestimated litter fluxes [22]. The width of the observation track for the Sochi and Matsesta rivers covered the entire river widths; the related heights of coastal platforms were less than 5 m. The duration of each session was 30–60 min.

A Floating Macro Litter mobile application developed by the Joint Research Center (JRC) was used for the registration of received data, including metadata, visual observations and common litter categorization according to "Guidance on Monitoring of Marine Litter in European Seas" [21]. According to the methodology, only macrolitter items bigger than 2.5 cm were visually registered with the mobile application; approximate size ranges (2.5–5, 5–10, 10–20, 20–30, 30–50, >50 cm) for each item were also recorded. The analysis did not include non-litter/non-identified items in such categories as "other", "other wood", "feather", "leaves" and "dead fish". The resulting riverine litter flux was calculated as items per hour. In total for the three rivers, 106 monitoring sessions from 2016 to 2022 were performed, which is equal to 98 h of observations. Observation dates on the Don, Sochi and Matsesta rivers are presented on Figure 2. The main parameters of these rivers, as well as the number of monitoring sessions and hours, are summarized in Table 1.

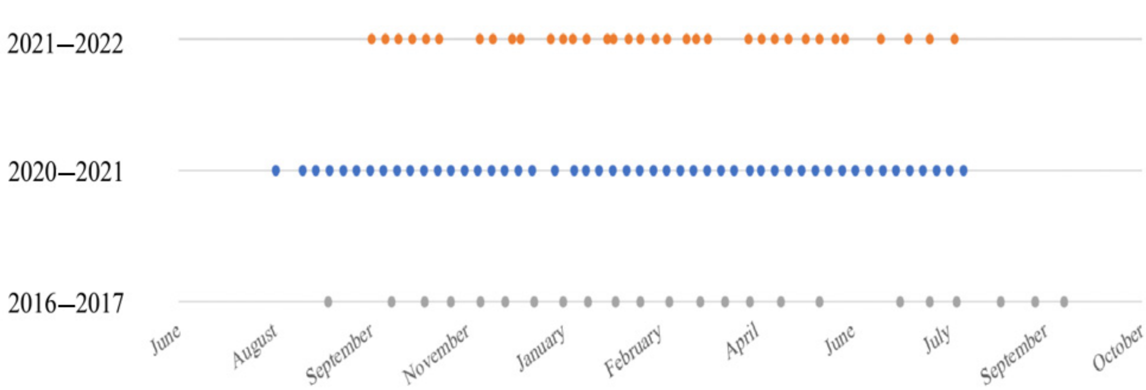

Figure 2. Observation dates on the Don River in 2016-2017 (grey points), on the Sochi River in 2020–2021 (blue points), and on the Matsesta River in 2021-2022 (orange points).

3. Results

Monitoring at the Don River was performed from 3 September 2016 to 20 September 2017. During each observation period, the calculated litter flux varied from 6 to 101 items/h. Monthly averaged values varied from 9 to 59 items/h, while the annual averaged value was 23 items/h. The most common items detected at the Don River were other paper (28.9%), paper packaging (13.3%), plastic bottles (12%), bags (8.4%), pallets (8.4%), cover/packaging (7.2%), polyurethane granules (6%) and plastic pieces (6%) (Figure 2), and the most abundant materials were artificial polymers (45%) and paper/cardboard (42%) (Figure 3). The frequency of size classes is shown in Figure 4. More than 74% of litter items were smaller than 10 cm, while 46% of litter items were 5–10 cm (Figure 4).

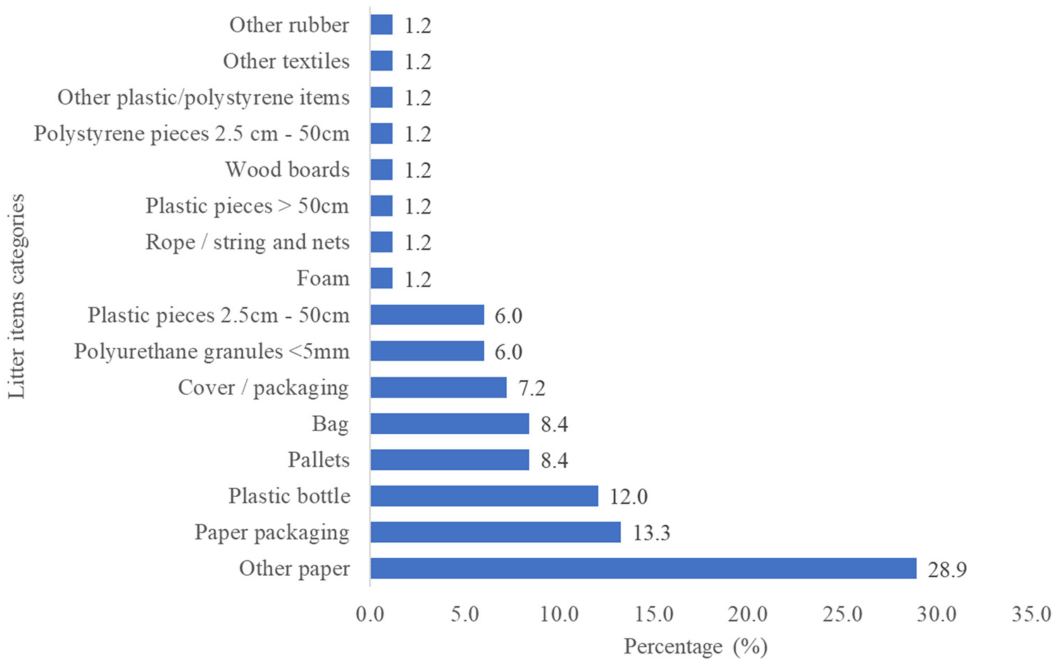

Figure 3. Percentage of recorded litter item categories in the Don River.

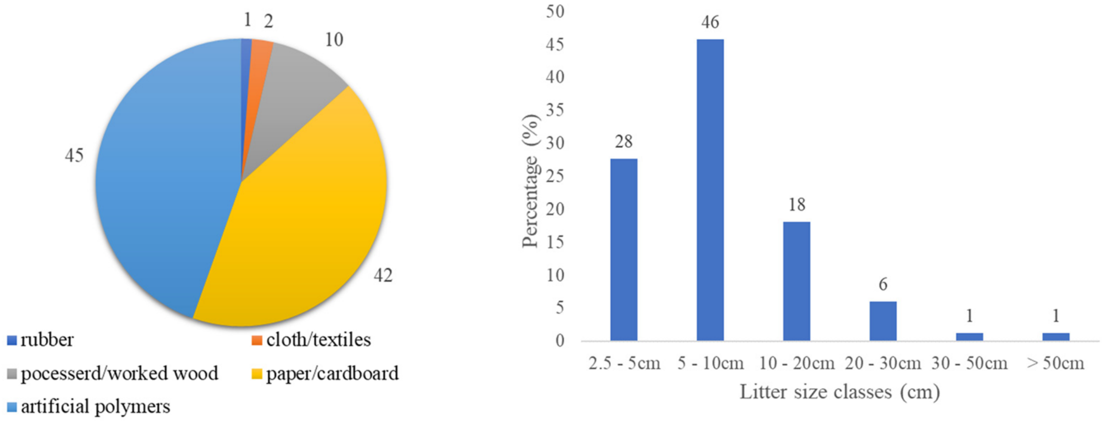

Figure 4. Percentage of materials of litter > 2.5 cm (**left**) and litter size classes (**right**) recorded at the Don River.

Monitoring at the Sochi River was conducted from 7 August 2020 to 30 July 2021. A total of 92.5% of the registered floating items were natural objects (mainly leaves) and were not included in the analysis. During each observation period, the litter flux varied from 1 to 107 items/h. Monthly averaged values varied from 1 to 32 items/h, while the annual averaged value was 10 items/h. The most common detected items were plastic pieces (29.3%), other paper (17.8%), polystyrene items (15%), plastic bottles (8.5%), cover/packaging (4.5%) and bags (3.7%) (Figure 5), and the most abundant materials were artificial polymers (74%) and paper/cardboard (19%) (Figure 5). The frequency of size classes is shown in Figure 6; more than 80% of litter items were <10 cm, while 45% of litter items were 2.5–5 cm (Figure 6).

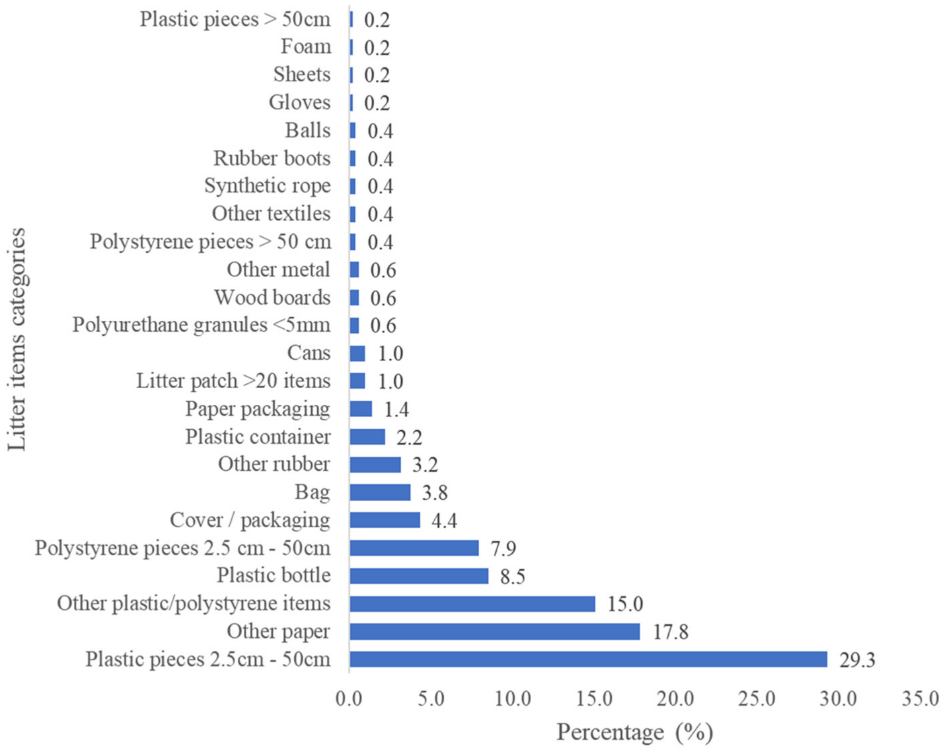

Figure 5. Percentage of recorded litter item categories at the Sochi River.

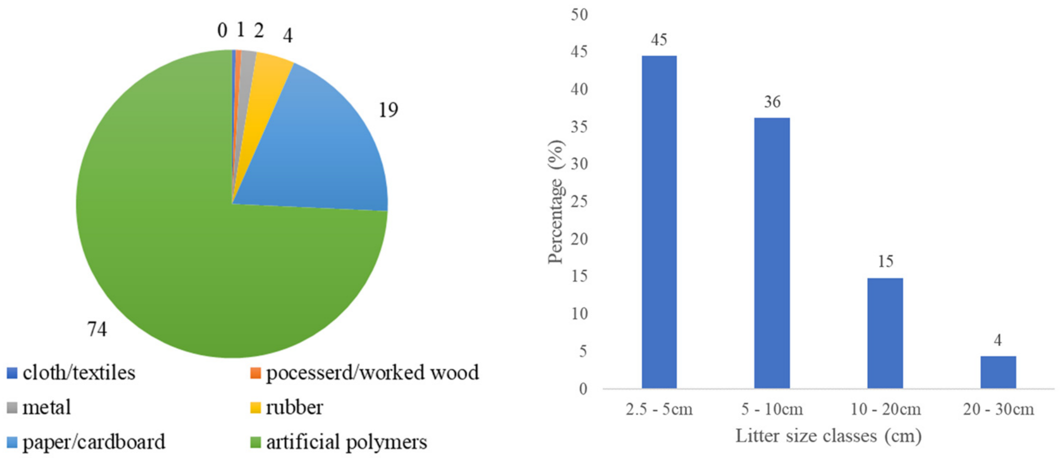

Figure 6. Percentage of materials of litter > 2.5 cm (**left**) and litter size classes (**right**) recorded at the Sochi River.

Monitoring at the Matsesta River was performed from 26 September 2021 to 25 July 2022. Leaves and wood predominated in the results, and (similarly to the other rivers) these non-litter items were not considered during the data analysis. During each observation period, the litter flux varied from 1 to 24 items/h, the monthly averaged values varied from 1 to 9 items/h, and the annual averaged value was 4 items/h. The most commonly detected items were plastic bottles (29.2%), plastic pieces (14.6%), polyurethane granules (13.5%), other paper (9.4%), polystyrene pieces (7.3%), bags (5.2%) and balloons (5.2%) (Figure 7), and the most abundant materials were artificial polymers (73%) and paper/cardboard (11%) (Figure 8). Almost 50% of registered items were 10–20 cm, and 37% were smaller than 10 cm (Figure 8).

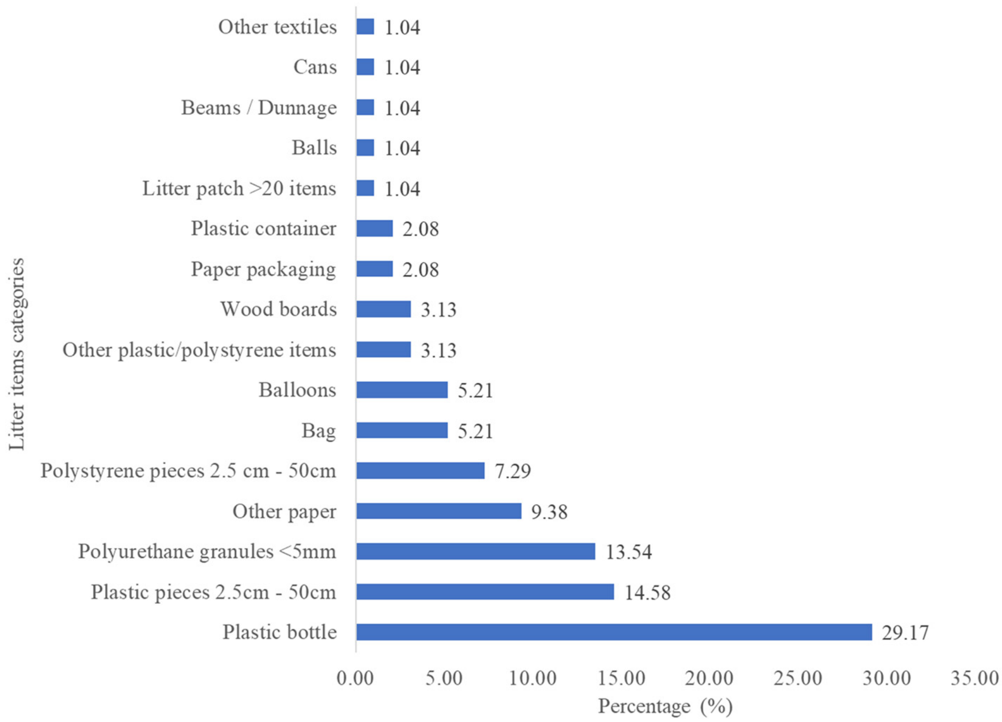

Figure 7. Percentage of recorded litter item categories at the Matsesta River.

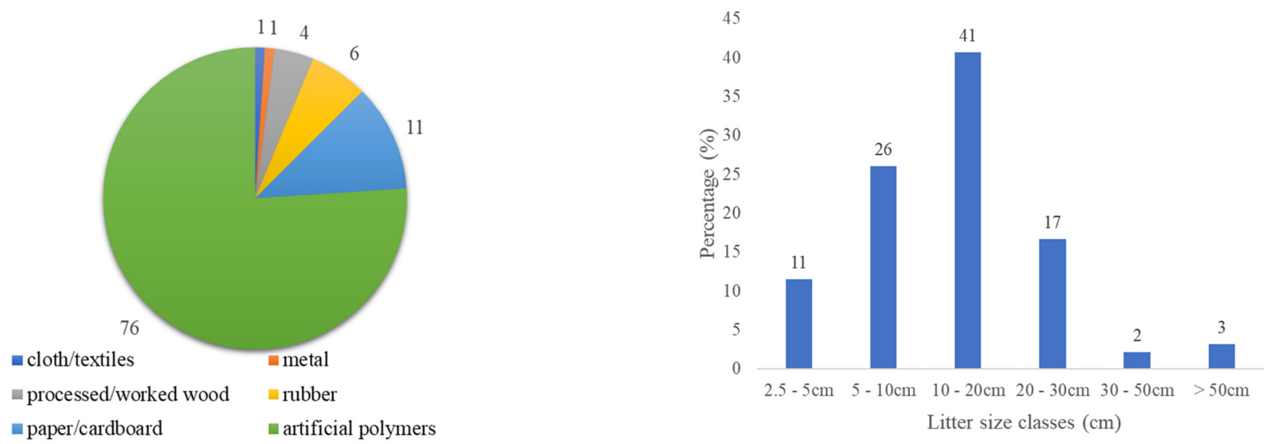

Figure 8. Percentage of materials of litter > 2.5 cm (**left**) and litter size classes (**right**) recorded at the Matsesta River.

In general, during the monitoring period from 2016 to 2022 on the Don, Sochi and Matsesta rivers, 9289 floating objects bigger than 2.5 cm were identified; 92% of them were of natural origin, mainly leaves, while only 8% (714 items) were of anthropogenic origin. Most of identified litter items were smaller than 10 cm, except for the Matsesta River, where the most frequent size range was 10–20 cm. The most common detected items were 'plastic pieces 2.5–50 cm' (24.4%), 'other paper' (18.0%), 'plastic bottles' (11.8%), 'other plastic/polystyrene items' (11.7%), 'polystyrene pieces 2.5–50 cm' (7.0%), 'bags' (4.5%) and 'cover/packaging' (4.4%) (Figure 9).

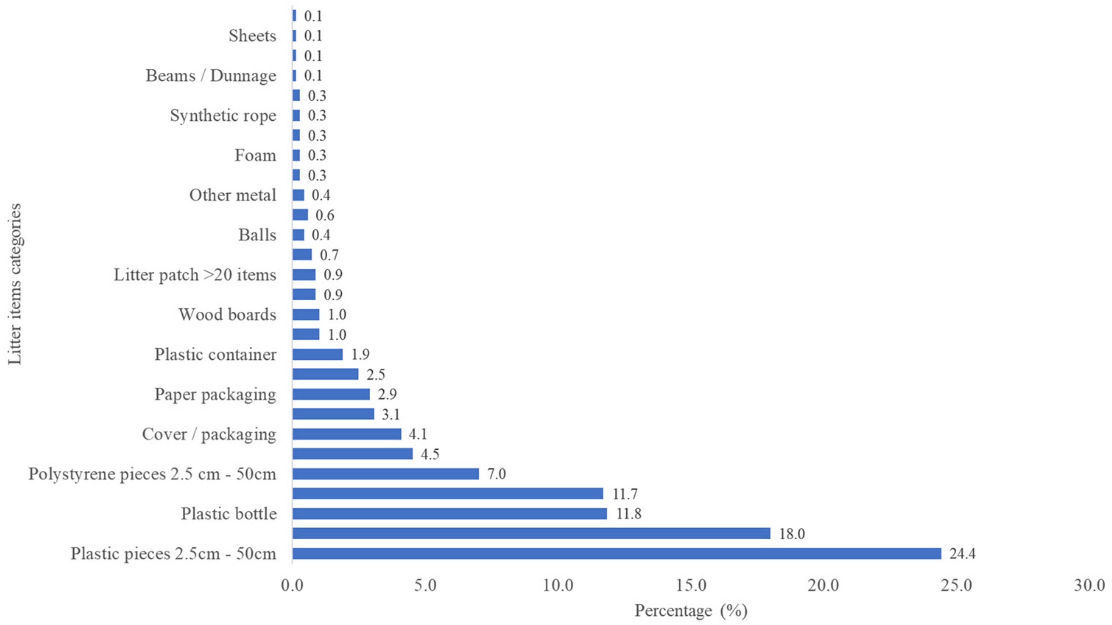

Figure 9. Percentage of recorded litter item categories on observed rivers.

A high proportion of plastic and polystyrene pieces (31.4%) indicates that the process of fragmentation is ongoing in the river basin. Other identified litter categories were mainly single-use items (23.3%) like plastic bottles, bags and cover/packaging and specified the prevalence of consumer goods in the total riverine litter flux [4].

It was estimated that in all monitored rivers, the individual flux range was 1–101 items/h and the annual averaged litter flux varied from 4 to 23 items/h. The proportion of litter item categories on the rivers varied a great deal (Figure 10), which could be explained by the many factors influencing the litter composition, from social-economic reasons (i.e., consumption behavior) to hydrological and weather conditions.

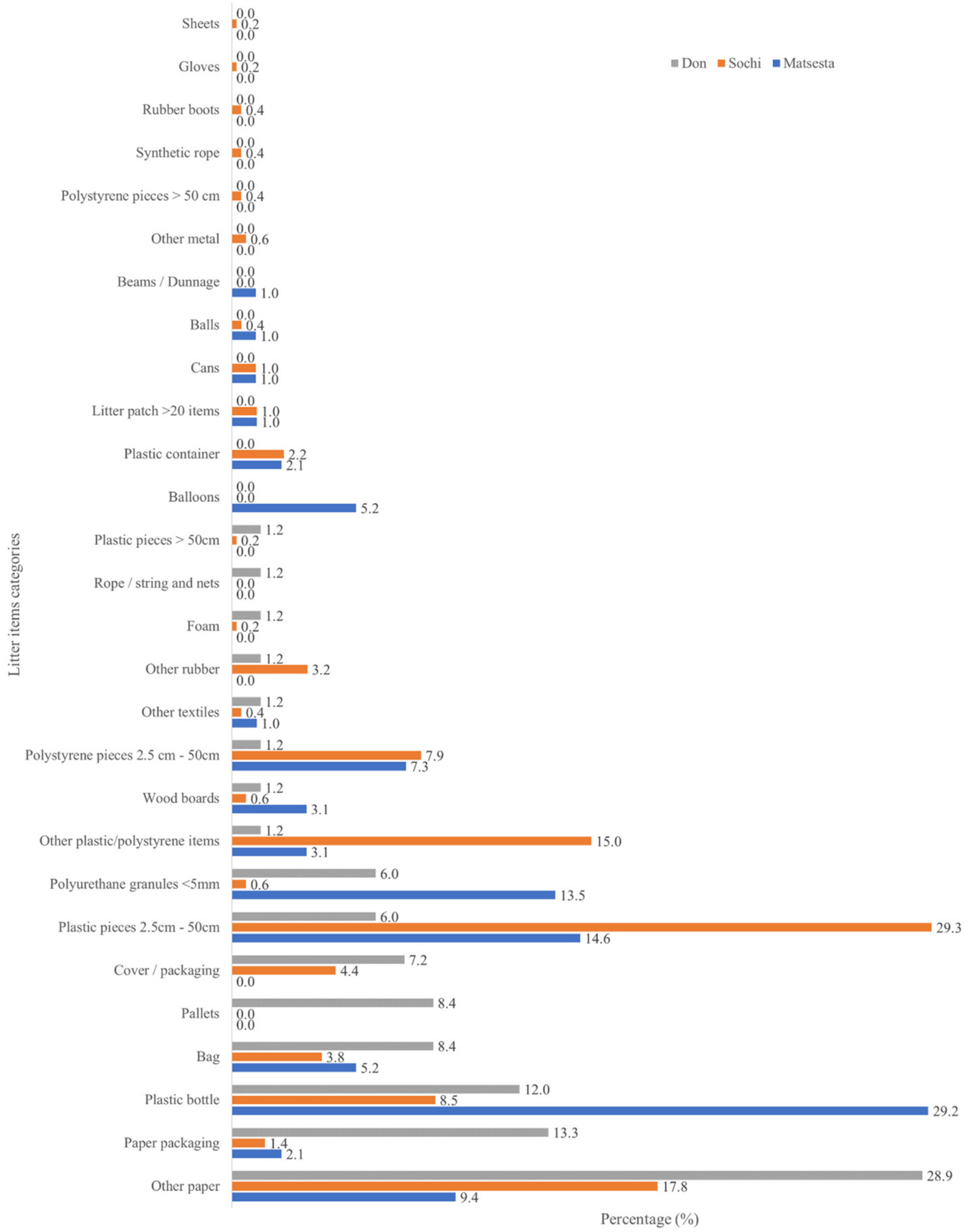

Figure 10. Percentage of recorded litter item categories at the Don, Sochi and Matsesta rivers.

In recent studies, it was assumed that the level of marine litter pollution depends mainly on river runoff in this area. Snowmelt floods and torrential downpours are typical for the study region in late spring and early summer; as a result, numerous mountainous rivers become swollen during this season. It is highly likely that flooding events wash down large volumes of land-based garbage and solid waste and, therefore, constitute crucial sources of pollution in the region [15].

The monitoring observations in the study area provide the baseline for assessment of the main characteristics of litter for the selected rivers. The litter fluxes from the considered rivers (Don, Sochi, Matsesta) were calculated for each observation day as the ratio of the observed litter items (without non-litter) and the observation time. For the Don River, an obtained value was additionally multiplied by three to extrapolate it to the river width (220 m) at the sampling site [23,24]. The Don and Sochi rivers have gauge stations, which provide daily measurements of freshwater discharge. These gauge stations are located

151 and 1 km from the mouths of the Don and Sochi rivers, respectively. Currently, there are no gauge discharge measurements on the Matsesta River; therefore, we analyzed the dependence of litter fluxes on river discharge rates only for the Don and Sochi rivers.

For the Don and Sochi rivers, we calculated the Spearman's correlations to determine the relationship between daily discharge rates during observation dates and the corresponding litter flux values. We did not analyze the influence of other environmental variables (hourly discharge rates, precipitation, wind, etc.), which could affect the litter flux, due to lack of the related data. In future studies, the measurement of these variables at the sampling sites should be performed to check their influence on the litter flux variability.

For both rivers during the observation periods (the Don River in 2016–2017 and the Sochi River in 2020–2021), we observed a significant synoptic variability (Section 2) (Figure 11). Synoptic variability of the Don River discharge rate is caused by river flow regulation by dams, which affects most of the river basin. Synoptic variability of the Sochi River discharge is governed by short-term rain-induced flooding events, which could occur during any time of the year. Therefore, synoptic variability of discharge for both rivers is governed by irregular external forces. As a result, we did not distinguish freshet and drought periods within the analysis of litter fluxes.

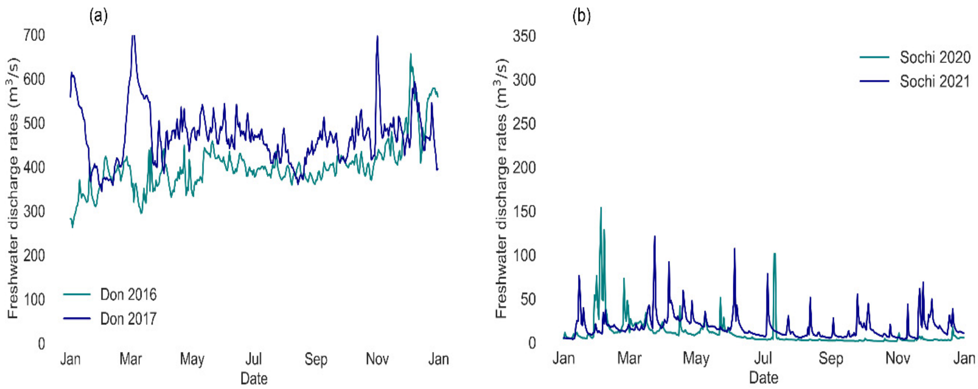

Figure 11. Freshwater discharge rates of the Don River during 2016–2017 (**a**) and Sochi River during 2020–2021 (**b**).

For the Don and Sochi rivers, there was moderate positive correlation between river runoff and litter flux. For the 23 observations on the Don River during 2016–2017, the Spearman's correlation coefficient (r_s) was equal to 0.6 and p-value was equal to 0.002. For the 50 observations on the Sochi River during 2020–2021, the Spearman's correlation coefficient (r_s) was equal to 0.49 and p-value was equal to 0.0003. Considering the obtained correlation values, we used daily discharge rates and litter flux values to determine the linear regression model for the litter flux (L, items/h) and freshwater discharge (Q, m^3/s): $L = 0.17\,Q - 56$ for the Don River, $L = 0.16\,Q + 2.4$ for the Sochi River. The mean and median values of the litter flux (L, items/h) based on these equations were similar to each river (20.8 and 20.5 items/h for the Don River; 4.6 and 4.1 items/h for the Sochi River, respectively). Note that the mean values based on the raw observational data were equal to the mean values based on equations and were significantly different from the raw observational data median values (20.8 and 11.6 items/h for the Don River; 4.6 and 2.4 items/h for the Sochi River, respectively). In previous studies [4,24], the median values were selected against the mean ones, because they minimize the influence of extreme litter flux events. However, such an approach could also underestimate the final annual estimates of litter flux; therefore, both mean and median values were considered in this study. Since the mean values of litter flux were similar to the median values, further research should be carried out to quantify possible overestimation of the obtained equations.

As a result, we quantified the total annual litter flux from the Don (2016–2017), Sochi (2020–2021) and Matsesta rivers using the mean and median values of the litter flux from the raw observational data (L, items/h) $\times$ 24 h $\times$ 365 d, providing the resulting flux in items/year. The estimation assumed that riverine litter is homogeneously distributed at the cross-sections of the considered rivers [24]. The resulting annual litter flux from the Don River ranged from 1×10^5 to 2×10^5 items/year when derived from the median and the mean values, respectively. Similarly, the annual litter flux from the Sochi river ranged from 2×10^4 to 4×10^4 items/year and from the Matsesta, from 0.9×10^4 to 3×10^4 items/year.

Further, we assume that the obtained estimations could provide the first order approximation of litter flux from large and small rivers of the study area. In this case, using the mean values of annual litter flux ranges for the Sochi and Matsesta rivers (3×10^4 items/year and 2×10^4 items/year), we quantified the total annual flux of riverine litter to the northeastern part of the Black Sea as 3×10^5 items/year (from the Sochi and Matsesta rivers and the other small rivers). The total annual flux of riverine litter from the large Don and Kuban rivers to the Sea of Azov (which relates to the northeastern part of the Black Sea) was equal to 2×10^5 items/year.

4. Conclusions

In this study, we describe the results of the first long-term monitoring of floating litter at the rivers inflowing to the northeastern part of the Black Sea. The observations revealed that fluxes of riverine litter at the Don, Sochi, and Matsesta rivers varied, being 6–101, 1–107, and 1–24 items/h, respectively. These fluxes of riverine litter at the observed rivers are comparable with those observed in other European rivers, e.g., the Rhone (0–293 items/h), Rhine (10–75 items/h), Llobregat and Besos (0–429 items/h), and Tiber (10–130 item/h, at Fiumicino canal) rivers [4,8,23–25].

On the basis of the monitoring results of floating litter for the Don, Sochi and Matsesta rivers, we assessed the total annual flux of riverine litter for the considered rivers, which was estimated as 1×10^5 items/year (median) to 2×10^5 items/year (mean) for the Don River, from 2×10^4 to 4×10^4 items/year for the Sochi River and from 0.9×10^4 to 3×10^4 items/year for the Matsesta River. The differences could be partly explained by the total river runoff, but other natural and socioeconomic factors, which were not assessed in this study, could also be valuable. Under the assumption that the relations for the Don, Sochi and Matsesta rivers are representative for all large and small rivers of the study area, we calculated the total annual flux of riverine litter from all rivers in the northeastern part of the Black Sea, which is equal to 5×10^5 items/year. No data on general litter flux are available for other regions, except in [17], where the total input of floating macroplastic from Europe into the ocean was estimated to be 3382 t/year. For the Don, Kuban and small rivers of the study area, the total yearly input is much smaller and is equal to 3 t/year. Further transport of marine litter in the Black Sea is governed by physical processes associated with spreading and mixing of river plumes [26–32] and further processed at the sea [33,34]; however, this issue is beyond the scope of the current work.

The observed differences in characteristics of litter flux at the considered rivers are affected by many factors, including climatological (river watershed basin size, river flow regime, etc.) and socio-economical (population density, land use, waste management, etc.) factors [22]. Most of the research, including this study, shows the prevalence of single-use items in the total litter flux. Therefore, it is recommended to regulate production and consumption of plastic products at all scales, improve local waste management systems, and encourage change in consumption habits and behaviors of coastal populations. Monitoring programs are also essential to control the leakage of waste into the environment and to make further legislative steps to reduce marine litter pollution.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/jmse11010105/s1. Table S1. Data from the first observation on the Don River (an example), conducted on 3 September 2016.

Author Contributions: Conceptualization: M.P.; methodology: M.P., E.K., A.O.; software: E.K., A.O.; formal analysis: M.P.; E.K., A.O.; investigation: M.P., E.K., A.O.; resources: M.P., E.K.; writing: M.P.,

E.K., A.O.; visualization: M.P., E.K.; supervision: A.O. All authors have read and agreed to the published version of the manuscript.

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