

Marine Litter in the Russian Gulf of Finland and South-East Baltic: Application of Different Methods of Beach Sand Sampling



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Abstract The chapter combines an overview of several studies of marine litter distribution on beaches and in sediments for two Russian parts of the Baltic Sea: the Gulf of Finland and the South-East Baltic for a period of 2016–2020. Various methods for sand sampling on beaches have been applied, including the OSPAR method, NOAA methodology, and IOW beach litter sampling methods (Frame and Sand Rake methods). The results of field research for the period of 2016–2020 showed both the applicability and some limitations of some methods. Results showed an overall high level of contamination with marine litter and its polymer

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components, microplastics in particular, of the Russian Baltic beaches – both regularly cleaned and “wild” isolated beaches. However, in comparison to the Neva Bay and beaches around the world the beaches of the South-East Baltic are quite clean and there is no obvious difference in the contamination of beaches with high (near resort cities) and low (less-visited coastal areas) anthropogenic load. The largest amount of litter of all fractions was found on the beaches of the inner part of the estuary in the Neva Bay. At the same time a high variability of types of litter was shown: the predominant type of litter in the South-East Baltic is foamed plastic (foam/polystyrene foam), together with paraffin, coming from the tank waters from ships, and a specific pollutant-geosynthetic materials that are a new contaminant emerging from coastal engineering protection activities. In the Gulf of Finland region, the most common litter items are plastic pellets, broken glass, cigarette butts, rusty metal, and pieces of building plaster, together with synthetic napkins and cotton bud sticks, that are not retained by the wastewater treatment facilities.

Keywords Gulf of Finland, Marine litter, Methods of monitoring, Microplastics, Sandy beaches, South-East Baltic

1 Introduction

Ecosystems of enclosed seas such as the Baltic Sea with a high anthropogenic load can be especially vulnerable to accumulations of plastic particles along the coast, in lagoons and estuaries. Marine litter is very mobile, especially in the coastal zone: it is carried by currents, deposited on coastal underwater slopes, and accumulates in waters relatively protected from currents and winds, including inland coastal water bodies, like large gulfs and lagoons. Therefore, it is important to assess the anthropogenic pollution of the sea coast based on information on the pollution of all components of this “litter rim.”

Despite the numerous studies and monitoring campaigns carried out around the world in the last 10 years there is currently no single unified methodology for sampling and analysis of litter pollution of the coastal and marine environment. One of the problems associated with monitoring of marine litter is the difference in the applied methods and tools in different regions of the world, which complicates the comparison of monitoring results.

The international OSPAR project “Marine Beach Litter” on monitoring marine beach litter (2000–2006) (OSPAR – Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) dated September 22, 1992) became the first in Europe to develop a standardized method for monitoring marine macro-litter on beaches in the North Atlantic region, in which more than 600 surveys were conducted on 51 beaches in eight countries. This project identified the main sources of pollution on European coasts (fishing, waste water, shipping, tourism). The most common items were plastic and polystyrene [1].

The developed marine litter monitoring methodology is reflected in the Marine Strategy Framework Directive Guidance, as well as in the OSPAR Guidelines.

According to the MSFD recommendations, beaches should be selected based on different types of anthropogenic pressure (urban and suburban beaches, etc.) and meet the OSPAR criteria [2]. The survey is recommended to be carried out on at least two 100-m strips on one beach. However, there are still no specific recommendations on the optimal number of such areas for beaches, depending on the level of pollution.

Marine litter is usually classified by the size: “macrolitter” – particles >25 mm in diameter, “mesolitter” – 5 to 25 mm, and “microlitter” – <5 mm [3]. Macrolitter is the most visible for human eye on beaches or floating on the surface. Thus, there is yet much more information on macrolitter campaigns and monitoring. Some data on the amounts of litter on the coasts of the Baltic Sea is available already from the late twentieth century. This information is based on campaigns carried out by various non-governmental organizations or on observations by coastal municipalities. It is not, however, possible to quantitatively compare the results between the campaigns because different methods have been used for collecting litter and estimating their amounts. It also very important to select the most representative beaches for the campaign considering meteorological (storm events frequency), hydrographical, and geomorphological processes.

OSPAR recommendations are widely used in Europe, and on their basis volunteers from different countries participate in beach surveys using standard protocols. In the Baltic region, project MARLIN has united efforts of volunteers and scientists in Sweden, Finland, Estonia, and Latvia, with a total of 120 beach litter assessments throughout 2011–2013 who conducted beach litter surveys in 20 key areas [4]. This project aimed at obtaining new knowledge about marine litter in the Baltic Sea, as well as raising public awareness. For the first time around the Baltic Sea area, all the countries collected and categorized the litter using the same harmonized method based on the protocol of UN Environment Programme on beach litter [5]. The results of this project showed that most of the beach litter in the Gulf of Finland was composed of plastic: 59% on urban beaches, 50% on rural beaches, and 53% on semi-urban beaches, with the highest amount of litter on the Finnish beaches: urban beaches tended to contain more litter than the rural ones. The snow melting period affected the accumulation of litter on beaches as well [4]. Finland and Estonia have continued the monitoring of these beaches in 2014–2015, and Finland has also adopted this protocol into its national monitoring program.

Beach litter accumulation is now the most studied in the Baltic region as compared to plastics distribution in water and on the seafloor; however, the methods for an adequate and harmonized assessment of the distribution and sources of marine litter are still under development. The sources of marine litter here are mainly land-based and are associated with poor waste management including littering, wastewater, and rain drainage management. In European seas over 60% of all marine litter are plastic packaging, predominantly plastic bottles and bags [1]. Previous assessments show that in the Baltic Sea the main sources are considered to include transport, fisheries, household activities, as well as coastal recreation and tourism [6].

The OSPAR method of beach litter survey has also been adopted by HELCOM as a methodology for monitoring beaches in the Baltic Sea, and is described in Recommendation 29/2 in order to obtain comparable results [7]. However, it became

obvious that this method is only suitable for wide open beaches of the Atlantic coast, and for closed marine ecosystems, this method must be adapted and refined.

An adaptation of the OSPAR method of beach monitoring was completed by the Leibniz Institute for Baltic Sea Research, Warnemünde, IOW (Leibniz-Institut für Ostseeforschung Warnemünde, IOW) [8, 9]. Authors have developed a special tool for sieving the sand – “Sand Rake” for open-type Baltic beaches, while using the sand sieve inside a frame for lagoon-type Baltic gulfs and estuaries.

This chapter combines an overview of several studies of marine litter distribution on beaches and in sediments for two Russian parts of the Baltic: the Gulf of Finland, where studies were started in 2018 and the South-East Baltic with longer period of monitoring – since 2016. Various methods for sand sampling that have been applied during the period of 2016–2020 and the results of these studies are discussed briefly.

2 Marine Litter Study in the Eastern Part of the Gulf of Finland

2.1 Study Area: Neva River Inner Estuary and Outer Part of the Gulf

The Gulf of Finland is a water area shared by the three countries (Fig. 1): Finland, Russia, and Estonia and is one of the most unique and fragile ecosystems in the

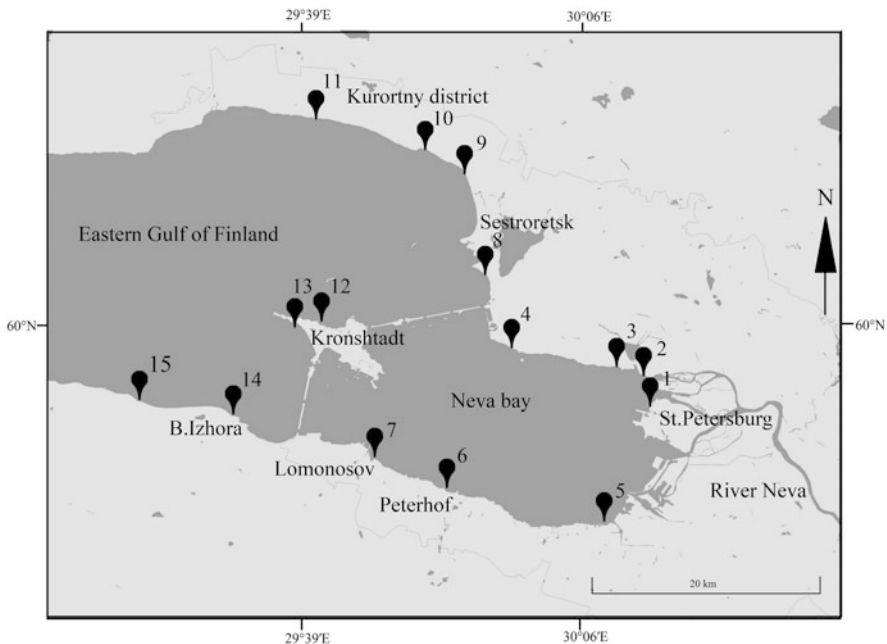


Fig. 1 The Gulf of Finland and Neva Bay, sampling stations in 2018–2019

Baltic Sea due to its special hydrophysical and geomorphological characteristics and pronounced estuarine effects, caused by the inflow of the largest Baltic river – the Neva, with the average annual discharge of 2,500 m³/s. It is a shallow and brackish ecosystem with a low but unique biodiversity [10]. The intense anthropogenic activity in the highly populated area around the Gulf of Finland is the reason of its main environmental problems: eutrophication, oil and hazardous substances pollution, underwater landscape degradation due to dredging and resources extraction, etc. making this ecosystem very sensitive to the growing human impact.

St. Petersburg is the largest city in the North-West of Russia at the easternmost tip of the Gulf of Finland with over 5,200,000 of permanent residents [11]. Large area of the Russian Gulf of Finland coast is situated in the Leningrad Region with a total number of permanent residents over 1,900,000 people [11]. High population density creates a significant pressure on the Gulf's environment.

The plastic litter problem has never been investigated for the Russian sector of the Gulf of Finland. Thus, during the period of 2018–2019 a pilot study of the problem of marine litter pollution of the coasts of the eastern Gulf of Finland was carried out by the Russian State Hydrometeorological University [12, 13] taking into account the existing experience of marine litter monitoring in the Baltic lagoons and estuaries.

The high population density in the region of the Gulf of Finland together with production of large amounts of plastic wastes poses a high risk of marine litter pollution. The metropolitan area of St. Petersburg together with the Leningrad Oblast produces annually about 112,000 tons of plastic wastes including municipal and industrial wastes [15]. However, due to the absence of any regular monitoring activities here it is not possible to give a quantitative estimate of beach litter pollution levels. An important source of plastic litter in the eastern part of the Gulf of Finland before the construction of the Flood Protection Barrier of St. Petersburg (FPB) was a network of waterways in St. Petersburg and suburbs including over 220 rivers, canals, and streams of various length, as well as reservoirs. From the start of FPB operation there is a constant threat of accumulation of floating litter on the east side of the dam. Entering the water environment, the litter is eventually accumulated and buried on the muddy seafloor of the Neva Bay, but can be released again during the permanent dredging works in the Neva Bay and near harbors of St. Petersburg. This can serve as a secondary source of litter pollution that enters the environment and reaches the coasts after storm events.

The coastline of the Russian part of the Gulf of Finland is very diverse and was formed by subaerial and tectonic processes (skerries), non-marine processes (alluvial plains), by waves (marine erosion, accretion, abrasion coasts) as well as technogenic processes (embankments, hydrotechnical constructions, etc.) [16]. The most active erosion processes occur in the coastal zone of the easternmost part of the Gulf – which is the most valuable recreation area. The easternmost part of the coastline within the Neva River mouth is completely transformed by the technogenic processes.

In terms of the recreation potential the most visited sandy beaches of the Russian part of the Gulf of Finland are located in the Kurortny District (northern coast) and

near Peterhof and Lomonosov area (southern coast). Also, long sandy beaches are found further south in the Narva Bay, but due to their remoteness they are not so popular among the local residents. Kurortny District hosts 12 the most popular and visited public beaches in the region that are regularly cleaned by the municipal services (major cleaning before each summer season and then waste is removed twice a day in summer) [11]. However, there are many of the so-called wild beaches in between, that are cleaned randomly throughout the season due to inability of the municipal services to cover the entire 60 km long coastal strip in this district.

For the Russian part of the Gulf of Finland, no deep scientific research on marine litter has been carried out yet, except for several beach cleaning campaigns in 2013–2015 held by the St. Petersburg Administration and local municipalities to increase awareness of marine litter issues amongst the citizens.

2.2 Monitoring Methods for Litter on Sandy Beaches

The Russian coast of the Gulf of Finland in general is characterized by the limited amount of suitable sandy beaches according to recommendations of MSFD and OSPAR (without regular cleaning, exposed sandy beaches without vegetation, little tourism). So, in order to make an assessment of litter pollution in most of the accessible parts of the coastline of the Russian part of the Gulf of Finland an IOW approach [8] was used for different types of beaches in the summers 2018–2019 [12, 14] with application of two beach sand sampling methods – Rake and Frame method. The Rake method and the Frame method focus on large-micro (>2 mm) and mesolitter (5–25 mm) in the 30–50 mm upper sediment layer and were applied at 58 surveys at 15 sandy beaches of the German and Lithuanian Baltic Sea coast between 2014 and 2016. The first rake experiments on the German coast of the Baltic Sea showed that the use of a mesh size of 5 and 2 mm is sufficient. Accordingly, the sand only needs to be sieved twice to the smallest mesh size of 2 mm.

Both methods were developed for sandy beaches, including regularly cleaned ones, and tested during 2014–2016 to monitor 15 beaches in lagoons and estuaries in the southeastern Baltic region (Germany and Lithuania, about 60 samples) [8]. Most of the litter was represented by cigarette butts, plastic, and paraffin wax. These methods have shown the possibility of assessing the “hot spots” accumulation of marine debris on the beaches. An important advantage of these methods is that they do not require elaborated equipment or a laboratory, are low in costs, and can be carried out by volunteers.

The Frame method is used for the coasts of lagoons, closed bays, river estuaries, and always includes the wave wrack line (i.e., the zone of influence of waves and material accumulation). The method was the main one for surveying the coasts of the Neva Bay – the enclosed estuary of the River Neva separated from the outer part of the Gulf by the Flood Protection Barrier (FPB).

The Sand rake method in contrast to the OSPAR method is applied vertically between the water line and the vegetation line along the entire width of the beach

from the water line to the beginning of vegetation. The entire transect is divided on 5 m segments that are then sieved individually. For getting reliable results for most of the beaches two or three 0.5 m wide stripes will be sufficient to reach the minimum area of 50 m² or the total amount of litter found in all segments not less than 20 items, however at some beaches more stripes are needed. If two or more replicate samples are taken, there must be at least 120 m distance between the samples points to ensure that the rake sampling procedure fits to the 100 m distances as recommended for the selected point approach by OSPAR. (Fig. 2). The Rake method is aimed at surveying large areas of beaches that are regularly cleaned by municipal services from macrolitter. This method was chosen to survey the beaches of the outer part of the Gulf (the Kurortny District, the beaches of Kronstadt, and the southern coast near the FPB).



Fig. 2 Application of Frame and Rake methods on the beaches of the Neva Bay (photo by A. Ershova)

2.3 *Marine Litter in the Eastern Part of the Gulf of Finland: Results and Discussion*

During the summers of 2018–2019, surveys were carried out for seven lagoon-type beaches (Neva Bay) and eight beaches outside the Flood Protection Barrier on the northern and southern coasts of the eastern Gulf of Finland. In general, the number of litter particles of different types differs depending on the type of sampling method, which is primarily associated with the sampling area. The Frame method is aimed at examining the wave wrack-line zone, and the Sand rake method is aimed at the entire width of the beach from the water line to the vegetation line.

In both years the amount and distribution of anthropogenic litter along the coasts varied significantly depending on the location of the beaches, weather conditions, hydrological and morphometric characteristics of the studied coasts.

In 2018 in the Neva Bay, the concentration of litter (of all categories) was: average – 8.3 pcs/m², minimum – 1.6 pcs/m², maximum – 14 pcs/m²; the average concentration of microlitter – 3 pcs/m², mesolitter – 3.8 pcs/m². The main types of litter found on the beaches of the Neva Bay and the eastern part of the Gulf of Finland (both in the inner estuary and in its outer part) were plastic pellets, broken glass, cigarette butts, rusty metal, and pieces of building plaster (Fig. 3). Also, among the mesolitter there were many synthetic napkins, cotton bud sticks, and other polymer products that were being flushed down the drain and are often not caught by treatment facilities and go directly into the waters of the Gulf of Finland.

The largest amount of litter of all fractions is found on the beaches of the inner estuary in the Neva Bay, despite regular beach clean-ups in the area. In the outer part of the estuary, microlitter predominates, while in the Neva Bay meso- and macrolitter prevails, and pollution with microlitter is less pronounced. The prevalence of meso- and macrolitter here can be explained by the fact that most of the beaches are located within the city limits, where large urban areas with a high population density are located and, therefore, with a higher level of anthropogenic pollution. In addition, in general, beaches are not cleaned thoroughly enough, which leads to the accumulation of meso- and macrolitter in the inner estuary in the Neva Bay [17].

In general, the northern and southern coasts of the Neva Bay differed significantly in the amount and composition of litter (particle size, composition, quantity, etc.). In 2018 on the northern coast, the amount of litter was lower, but the most of it was plastic – 50–60% of the total amount of litter of all fractions. In the outer part of the estuary, the predominant type of litter was microplastic, the average amount of which is 0.8 pieces/m² in the wrack-line and 0.5 pieces/m² – using the Sand Rake method. Thus, the maximum amount of litter, both in mass and in the number of items, was found on the beaches of the southern coast of the Neva Bay (Fig. 4a) The southern coast of the Neva Bay is also significantly different in the composition of the collected waste – more than 50% is broken glass, plaster, and pieces of rusty metal. Plastic here accounted on average up to 10–12% of the total litter amount [14].



Fig. 3 Types of macro-, meso-, and microlitter collected on the sandy beaches of the Gulf of Finland in 2018 and 2019 (plastic pellets, glass, metal pieces, cotton bud sticks, etc.). Photo by A. Ershova

In the outer part of the Gulf in 2018 the concentration of microparticles in general, and plastic in particular, on the northern coast in the Kurortny area, as well as on the northern beach of Kotlin Island, was 5–6 times higher than on the southern coast of the Gulf of Finland (B. Izhora and Lebyazhye), showing accumulation of microplastics on beaches mainly in the outer estuary, while in the inner estuary – in the Neva Bay microplastics are contained in small amounts (Fig. 4b).

Our studies have shown that the selected methods are applicable on the coasts of the Gulf of Finland (both the outer part of the estuary and the Neva Bay). At the same time, these methods should be applied in parallel, and the research results can complement each other, since these methods are aimed at examining different functional zones of the coast: the wave wrack-line zone for analyzing the litter

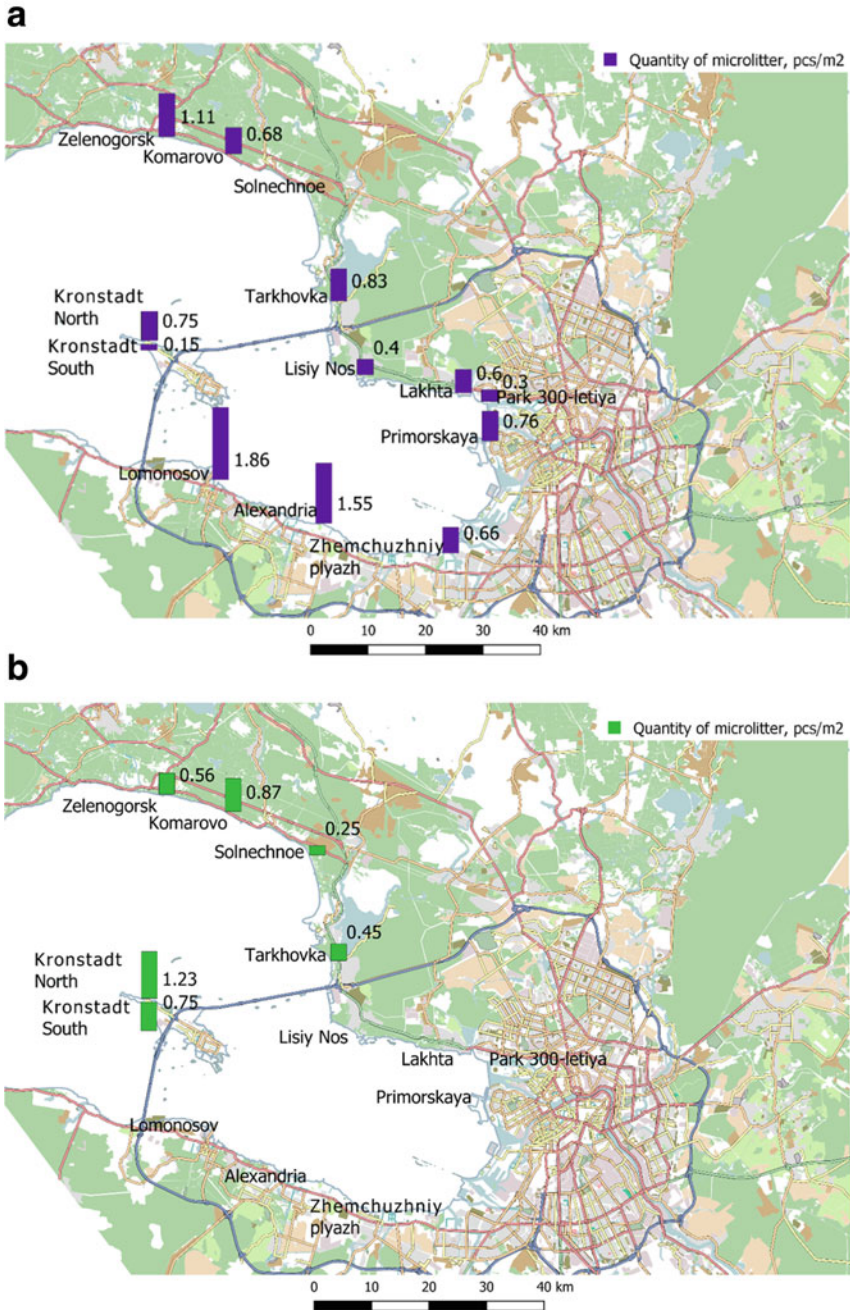


Fig. 4 (a) Concentration of marine microlitter, pcs/m² in the wave wrack-line zone on the coasts of the Neva Bay and the outer part of the Gulf of Finland (Frame method) in 2018. (b) Concentration of marine microlitter, pcs/m² on the beaches of the eastern part of the Gulf of Finland (Sand Rake method) in 2018

carried to the beach by sea waves, and on the other hand, the total accumulation of litter on the entire beach width (taking into account seasonal accumulation, the effect of storms, snow melting, etc.) and their sources (the sea, tourists, etc.).

3 South-East Baltic: Kaliningrad Region

The southeastern part of the Baltic Sea is a populated area with developed ship traffic, fishing industry, and a rather high recreation activity. Wide sandy beaches attract lots of visitors in all the seasons, and, at the same time, allow for application of various methods of monitoring of marine litter, e.g. OSPAR method [2], Rake and Frame methods [8], etc. In this section we focus on the results of assessment of beach pollution by anthropogenic litter collected by the Rake and Frame methods for large litter items (macro-, meso-, and large microparticles – > 2 mm), and the modified NOAA method for microplastics (MP, 0.5–5 mm) during the summers of 2015–2020.

3.1 Studies of Beached Marine Litter by Various Methods

Marine litter on the beaches of the South-East Baltic was studied along all the (potentially different by contamination) shores of the Kaliningrad region (see map on Fig. 5): the western shore, open to the prevailing winds in the region, the northern shore, prone to the most severe N/NW storms, and unpopulated shores of the UNESCO National Park at the Curonian Spit.

3.1.1 Beaches of the Curonian Spit National Park

Quantitative estimates of marine anthropogenic litter and MPs in the Curonian Spit National Park and two adjacent popular urban beaches, Klaipeda (Lithuania) and Zelenogradsk (Russia) (Fig. 5) were performed in spring 2018 [18, 19]. The 100-km-long sandy Curonian Spit on the eastern coast of the Baltic Sea is shared by Russia and Lithuania, and both parts of the spit are National Park, with sea beaches 20–80 m wide [21]. The timeframe of the screening (early May, i.e. after the windy winter and well before the beginning of the tourist season) ensures that the vast majority of plastic waste found during sampling on the beaches has been brought ashore by the sea.

In order to understand the “instantaneous” picture of beach contamination, the sampling was carried out as a single effort, during May 1–2, 2018. Macro- (>25 mm), meso- (5–25 mm), and microlitter (2–5 mm) was studied at 5 points, while sand samples were collected at 6 points along the coast for further analyses of large MPs (L-MP, 2–5 mm) and small MPs (S-MP, 0.5–2 mm) particles. Since

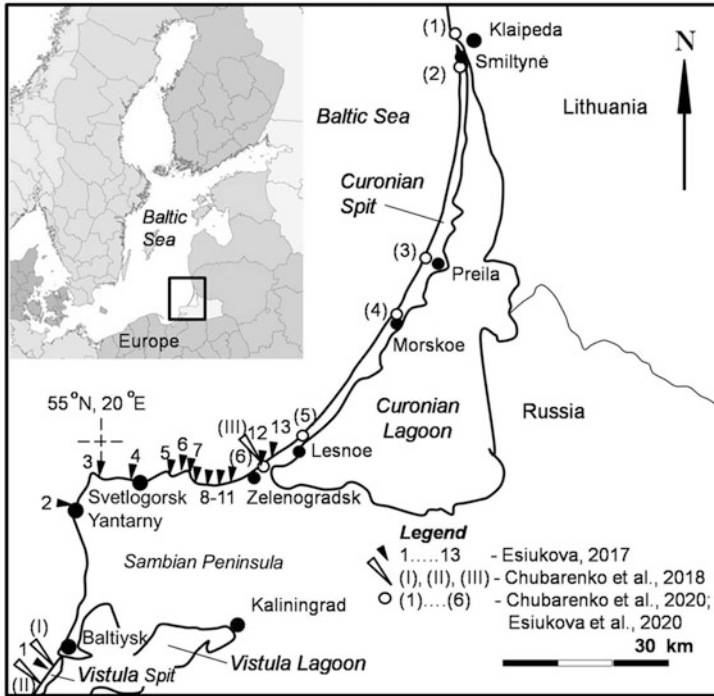


Fig. 5 Sampling locations in the southeastern part of the Baltic Sea in 2015–2020

significantly different fractions of plastic litter were of interest, two sampling methods were applied simultaneously: (1) the Sand Rake method for litter larger than 2 mm [8] and (2) the frame sampling method on the MP (0.5–5 mm) (see details in [19, 20, 22]) (a total of 50 sand samples were taken). 432 anthropogenic particles of litter were collected from a sample area of 135 m², resulting in an average surface concentration of litter of 3.2 items/m². It turned out that there is a 17-fold difference in the concentration of litter between the Klaipeda beach located in the industrial zone (249 objects of litter found on 10 m²) and the beaches of the National Park (183 objects collected from 125 m²), which gives the average surface concentration of litter (and per 1 m of shore length) of 24.9 items/m² (498 items/m) and 1.46 items/m² (77 items/m), respectively (Table 1). Artificial polymers accounted for 84% of all types of litter (363 items). The distribution of litter types (including paper, metal, glass, and other non-plastic anthropogenic litter) of various sizes was obtained [19, 20]. The Klaipeda beach was the most polluted, where microlitter (2–5 mm) makes up 60% of all items of anthropogenic litter (14.9 items/m² out of 24.9 items/m²), and the abundance of meso- and macrolitter is about an order of magnitude higher than in other sampling points.

Western and northern shores showed the following contamination pattern. During 12 surveys (600 m²) the amount of litter found was 1,164 items (mean 1.94

Table 1 Abundance of anthropogenic macro-, meso-, and microlitter (items/m² and items/m), collected by the Sand Rake method

| Station no. | Macrolitter >25 mm | Mesolitter 5–25 mm | Microlitter 2–5 mm | Mean items/ m ² /items/m | Sampled area, m ² | Beach width, m |
|-------------|-----------------------|-----------------------|-----------------------|--|---------------------------------|----------------------|
| (1) | 15.1 | 6.6 | 3.2 | 24.90/498 | 10 | 20 |
| (2) | 1.1 | 0.3 | 0.4 | 1.82/100 | 27.5 | 55 |
| (3) | 0.4 | 0.5 | 0.3 | 1.17/35 | 30 | 35 |
| (4) | 0.9 | 1.0 | 0.5 | 2.34/152 | 32.5 | 65 |
| (5) | 0.1 | 0.3 | 0.1 | 0.63/22 | 35 | 35 |
| Mean ± SD | 3.5 ± 4.6 | 1.7 ± 1.9 | 0.9 ± 0.9 | | | |
| Median | 0.9 | 0.5 | 0.4 | | | |

items/m² ± 0.94; median 2.48 items/m²), with a minimum of 0.58 items/m² and a maximum of 3.26 items/m². The size distribution of the litter was as follows: 370 microlitter items (0.62 items/m²–31.8%), 497 mesolitter items (0.83 items/m²–42.7%), and 297 macrolitter items (0.50 items/m²–25.5%). On 6 beach areas with 2 surveys each, the small-scale spatial variation of litter per beach area was between 0.18 and 1.72 items/m² (mean 0.61 ± 0.52 items/m²; median 0.44 items/m²). Along the northern shore, the top contamination (3.26 items/m² and 2.76 items/m²) was somewhat higher than along the southern shore (2.78 items/m² and 1.10 items/m²). This was mostly due to high amounts of paraffin (mean 1.03 ± 0.81 items/m²; median 0.68 items/m²), contributing along the northern shore versus lower amounts of paraffin (mean 0.07 ± 0.03 items/m²; median 0.08 items/m²) along the southern shore. The lowest number of litter items along the southern shore was 0.58 items/m² and along the northern shore – 2.38 items/m². Mesoplastic items, paraffin, and industrial pellets were predominant, and artificial polymers accounted for 54% of all the litter items [14].

Sand samples for analysis for MPs content (0.5–5 mm) were additionally taken using a wooden frame 18 cm × 18 cm to a depth of 2 cm in four beach zones, with two replicates (about 5 m apart) in each zone: (I) the shore face, (II) the current wrack line, (III) the middle of the winter berm, and (IV) the storm wrack line (i.e., the line left after a storm of the past winter season). Briefly, the stages of extraction and identification of MPs (the modified NOAA method [23] based on the NOAA recommendations [24]) are as follows: sample drying → sieving (cascade of sieves 0.5 mm, 1 mm, 2 mm, 5 mm) → selection of MPs from a fraction of 2–5 mm (optical microscope + UV lamp) → density separation (400 g sample + artificial reference particles, ZnCl₂ solution, ρ = 1.6 g/cm³) → filtration (mesh size 174 μm) → liquid oxidation (H₂O₂, 30% + Fe (II) at 75°C) → removal of the calcite fraction (HCl solution) → filtration (mesh 174 μm) → flotation in a separator (ZnCl₂, ρ = 1.6 g/cm³) → filtration (mesh 174 μm) → filter drying (Petri dish) → MPs selection (optical microscope × 10 – × 40) → identification (Raman spectrometry). To allow for comparison, the results are reported in (1) items/kg of sediment dry weight (further in the text *items/kg DW*), (2) items/m², and (3) items/m of the coastline length [19, 20].

For MPs 0.5–5 mm, variations in abundance were studied both as a whole and with refinement for two size classes (S-MPs (0.5–2 mm) and L-MPs (2–5 mm)) for 4 beach zones. MPs (0.5–5 mm) were found in all 50 beach sand samples from 6 stations, with variations both between and within the station locality. On different beaches, the mean (for the beach zone) values for MPs (0.5–5 mm) range from 1,038 to 7,070 items/m² (both stations are located within the National Park area), with the global mean for all stations of $3,155 \pm 1,308$ items/m² ($n = 50$). The MPs distribution does not correlate with those of meso- and macrolitter. Most of the detected particles (74.3%) are various fibers and threads. Fragments and films were 23.1% and 2.6%, respectively. The global mean MPs concentration (0.5–5 mm) per sediment mass is 115 ± 61 items/kg DW ($n = 50$), which is well comparable to the average value of 108 items/kg DW found in [18] for the beach sands of the neighboring Vistula Spit. A deeper analysis of the distribution between MPs size fractions and beach zones at different stations showed that out of the total number of 5,127 particles detected in the size range from 0.5 to 5 mm, 5,102 items (99.5%) belong to the range of 0.5–2 mm (S-MPs).

L-MPs (2–5 mm) were found exclusively within wave wrack lines, while they are absent in the upper sands and on the berm. The difference between stations and beach zones in the range of S-MPs (0.5–2 mm) is obvious, and the analysis shows that the outliers (identified by quartile analysis) – i.e., the areas with extremely high contamination – are found in all the beach zones except of the wet beach face. The 95% confidence intervals of the means are 119 ± 86.8 items/kg DW for the wrack line, 57.5 ± 51.2 items/kg DW for the berm, 30.2 ± 15.6 items/kg DW for the current wrack line, and 52.7 ± 35.7 items/kg DW for the shore face. With (and without) statistically confirmed outliers, the median abundance for the entire dataset is 45.5 ± 22.4 (41.6 ± 22.2) items/kg DW, and the average is 114.8 ± 61.4 (73.9 ± 22.6) items/kg DW.

Thus, the contamination by S-MPs is larger on the dry part of the beach, and is heterogeneous there, with a large standard deviation and the presence of outliers. The largest contamination is associated with the wrack line, which is consistent with other studies for this area (e.g., [18, 22, 24]). The closer to the waterline, the smaller the difference between the mean and median values, and at the wet beach face they become equal: at all stations and in all replicates, the contamination by S-MPs is the same. Moreover, the content of S-MPs in sands of the beach face (52.7 ± 35.7 items/kg DW) is close to the median value $45.5 \pm 22.4/41.6 \pm 22.2$ items/kg DW for the entire S-MPs dataset covering all the sampled locations and all the beach zones. The general picture of contamination in the MPs range (0.5–5 mm) is quite similar for the Vistula Spit area (about 100 km to the southwest), the values are very close [18]: the peaks are about several hundred of items/kg DW, while the mean for all samples (excluding the peak values/outliers) is about 56 and 74 items/kg DW, respectively.

Thus, it was found that, while contamination by the MPs as a whole (0.5–5 mm) is variable both along the shore and across the beach, the MPs concentration at the wet beach face (the shoreline) is practically the same in all the areas and in all the replicates. The concentration of S-MPs (0.5–2 mm) at the beach face can potentially be used as an indicator for monitoring purposes: it provides (1) a benchmark for

plastic contamination of the marine environment in a relatively large region (with more or less similar environmental conditions) and (2) an indicator to monitor rising levels of plastic pollution.

3.1.2 Beach Sediment Studies

An assessment of the degree of contamination by MPs (as well as macro/mesoplastic and paraffin) of beach sediments in the Russian sector of the South-East Baltic was carried out in June 2015 to January 2016 with sampling (60 samples) from the upper layer of the beach (up to a depth of 2 cm) in 13 areas of the Kaliningrad coast with different anthropogenic load (see map on Fig. 5). It was performed using a wooden frame with an area of $S = 0.15 \text{ m}^2$ and a metal scoop. In each of the 13 areas, 2–7 samples were taken from different points of the storm wrack line at some distance from each other [22].

The samples were dried, weighed, and sieved through a cascade of sieves (5, 1, and 0.5 mm). Fragments of macro- and mesoscopic litter ($>25 \text{ mm}$ and $> 5 \text{ mm}$, respectively) were collected manually using tweezers, counted and weighed. Particles of large MPs ($>1 \text{ mm} - 5 \text{ mm}$) were sampled using an optical microscope and a UV lamp. A more detailed analysis method, the NOAA method, was additionally applied to 20% of the samples [25]. In short: density separation of a 400 g sample (ZnCl_2 , $\rho = 1.6 \text{ g/cm}^3$) → filtration (174 μm mesh size) → liquid oxidation (H_2O_2 , 30% + Fe (II) at 75°C) → removal of the calcite fraction (HCl solution) → filtration (174 μm mesh) → flotation in a separator (ZnCl_2 , $\rho = 1.6 \text{ g/cm}^3$) → filtration (174 μm mesh) → filter drying (Petri dish) → MPs selection (optical microscope). The analysis was carried out on a stereomicroscope (Micromed MC2 Zoom Digital) with a magnification from $10 \times$ to $40 \times$ on the filter surface in accordance with the recommendations for determining the MPs [26]: (1) the cell structure and other organic forms are absent in the particles, (2) the fibers must be uniform in color and thickness along their entire length, not segmented, (3) colored particles are uniformly colored, (4) particles must have a clean and uniform color. Macro/mesoplastics, MPs, paraffin wax, amber were counted as separate categories (Fig. 6). Analysis has shown that plastic litter is found at all sampling points and in all seasons. The level of contamination of the Kaliningrad beaches with MPs is indicated in Table 2.

A comparative analysis with beaches around the world showed that the beaches of the Kaliningrad region are quite clean and there is no obvious difference in the contamination of beaches with high (near resort cities) and low (in fairly deserted, less-visited coastal areas) anthropogenic load. The predominant type of the detected MPs contamination is foamed plastic (foam/polystyrene foam). Paraffin, widely present in the area, the source of which is mainly the discharge of tank waters from ships, contributes to the accumulation of MPs: it is an effective “accumulator” of various types of contamination.

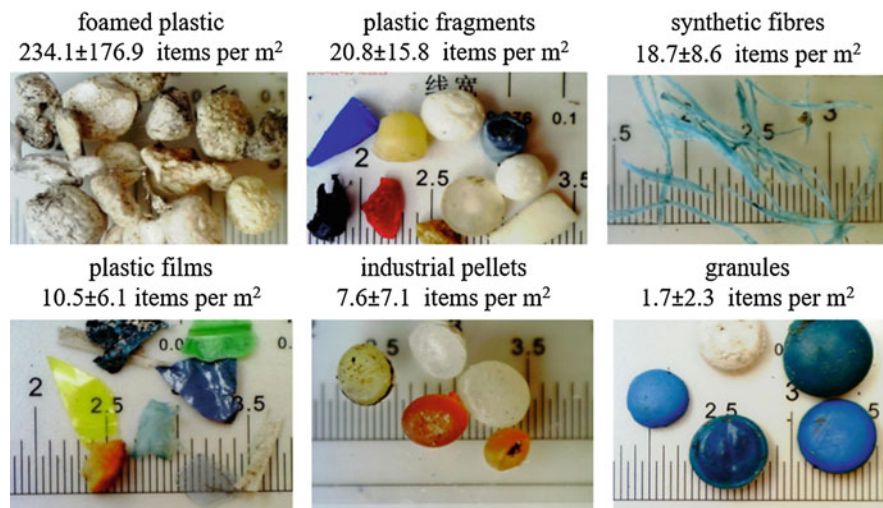


Fig. 6 Different types of MPs in beach sediments in the south-eastern Baltic (items per m²), photo by E. Esiukova

Table 2 Abundance of MPs in sand samples from various Kaliningrad beaches

| | mg/g DW | mg/m ² | items/m ² | items/kg DW |
|---------|---------------------|-------------------|----------------------|-------------|
| Minimum | 80·10 ⁻³ | 67 | 7 | 0.2 |
| Maximum | 8.38 | 16,000 | 5,560 | 175.3 |
| Mean | 0.05–2.89 | 370–7,330 | 42–1,150 | 1.3–36.3 |

3.2 Specific Pollutants: Geosynthetics, Paraffin, Foamed PS

Wrack of *geosynthetic materials* is a new contaminant emerging from coastal engineering protection activities [27]. There are several main categories of geosynthetics: geotextiles, geogrids, geonets, geomembranes, clay mats (bentonite mats), geopenes, geocells, drainage/infiltration cells, geocomposites [27], as well as woven containers (big-bags). Deformation and destruction of coastal and hydraulic protective structures (gabions, reinforced slopes, retaining and protective walls, protective berms, etc.) containing such components lead to the leakage of remnants of geosynthetic materials into the marine environment. When migrating along the shore, fragments of geosynthetics undergo additional degradation, which leads to their destruction down to macro/meso/microparticles. In water samples collected in the economic zone of the Russian Federation in the Baltic Sea (within the Kaliningrad region), microplastic fibers were found, similar to those obtained during the degradation of geotextile materials such as Dornit [29]. The samples taken from the beach surface also showed the presence of fragments of plastic sheathing from gabions [27].

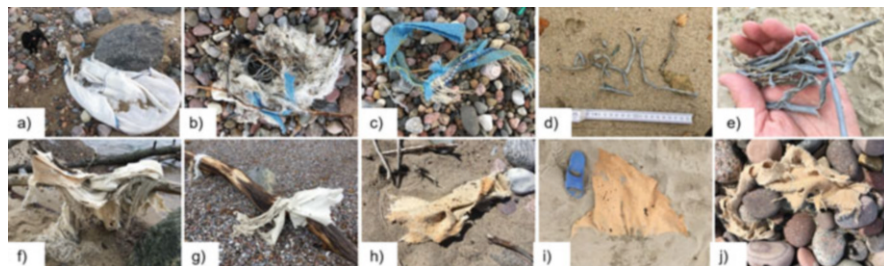


Fig. 7 Examples of geosynthetic materials found on the beaches: (a–c) fragments from woven big-bags used in the construction of a promenade in Svetlogorsk and other engineering and coastal protection structures on the northern coast of the Sambian Peninsula, (d–e) braids from gabions, (f–j) Domit-type geotextiles. (Photo by E. Esiukova)

Thanks to the international project of the ERA.Net RUS Plus program “Environmental impact of geosynthetics in aquatic systems” (No RUS_ST2017-212, <http://ei-geo.com/>), attention was paid to this hot problem. Several local potential sources of beach contamination by geosynthetics (coastal protection structures) were identified in 2018–2020 on the shores of the Sambian Peninsula (Kaliningrad region), and the contamination of sandy beaches by such material was surveyed [27, 28], see Fig. 7. It turned out that the patchy distribution of degraded geosynthetic residues on the beach does not allow the use of well-known methods for assessing the degree of contamination with macro- or MPs (i.e., selected-area methods for their search, such as the OSPAR method, etc.).

A new technique of continuous visual scanning was tested [30, 31] for accounting of the remnants of geosynthetic materials (mega/macro/mesofragments) during the survey of the beach strip. According to the proposed technique of continuous visual scanning, observers must pass along the entire shore, covering the entire width of the beach – from the coastline to the foredune or cliff. The beach is divided into zones (stripes) along the sea, and a group of several people (2–4, depending on the width of the beach and the number of zones) follows along their zones. Each person visually inspects the strip of his/her zone so as to capture the edge of the neighboring zone – for a complete scanning of the entire beach. Each section is being studied (several kilometers – 5–10 km in one effort) with fixing the position (by GPS) and collecting samples of geosynthetics. Participants are equipped by prepared in advance palettes with samples of geosynthetics previously found in local sources (structures) or collected during a preliminary survey of beaches [30, 31]. The main difficulties and problems with such monitoring arise when the sample is not noticed and not taken into account due to: (1) the sample being covered with sand or being in a heap of pebbles/boulders/algae; (2) the sample being smeared or covered with algae or dirt; (3) an unknown type of geosynthetics or modified to the point of impossibility of identification; (4) the sample being located in an inaccessible place (under water, or at a distance from the shore on groins and reinforcement/remains of technical structures, on trunks and branches of trees fallen into the sea, etc.); (5) inattention or fatigue of the person. However, such a technique of continuous visual scanning is the

only way (at the moment) to get a sufficiently complete visual picture of not only the level of contamination and distribution of geosynthetic fragments along the coast, but also to identify the features and characteristics of the collected samples, and, if possible, associate this garbage with a local source of beach contamination. Active alongshore transport of fragments of geosynthetics (for example, containers/big-bags) is proved by the observation of the remains of these bags along the entire northern coast of the Sambian Peninsula, and farther north – along the Curonian Spit, including the territory of Lithuania (according to the results of monitoring in 2019). This way, MP particles (fibers) from big-bags were found in sand samples collected on the beaches of the Curonian Spit [20, 21].

Paraffin of various fractions and types is often carried ashore, contaminating the beaches of the Baltic Sea. The exact source of the contamination remains usually unknown, however international experts have established that it comes from washing of tanks and the unauthorized discharges of cargo residues, contaminated ballast water [32, 33]. Experts admit that the reason for the contamination of beaches with paraffin may be emergencies during the development of offshore oil and gas fields and the transportation of oil products by tankers and pipelines, man-made accidents on ships engaged in underwater work near the coast. During winds and storms, paraffin is thrown ashore. Given the system of currents in the Baltic Sea, the source of contamination may be far enough from the point where the paraffin is washed out onto the beach. During the expeditions [22], rather large pieces of paraffin (up to 100–300 g) were found, which can lie everywhere on the beach. However, most of it is dispersed along the wrack lines.

Most often, pieces of paraffin are mixed with sand, particles of organic origin, adhering litter. In order to assess how contaminated the paraffin is with MPs, paraffin samples were taken from 13 areas of the sea coast of the Kaliningrad region [22]. Each piece was weighed, poured in hot water; it melted and floated like a film to the surface of the water, while the adhered sand remained at the bottom. The sample was then cooled at room temperature for 24 h, then the paraffin was collected from the surface, dried and weighed, then examined with an optical microscope and a UV lamp for the presence of plastic particles [22]. In paraffin, microplastic particles were found in 92% of the samples (12), together with organic particles (algae, grass, insect, and zooplankton fragments), amber, and charcoal particles. The sand that fell to the bottom was about $31.0 \pm 5.8\%$ of the initial weight of the paraffin sample. MPs were mainly represented by fragments of foamed plastic (expanded polystyrene), synthetic fibers, and plastic films. Analysis shows that the content of MPs in paraffin samples averages at 31.1 ± 18.8 items per sample, or $11,479 \pm 10,785$ items per kg of a paraffin sample, or $47,628 \pm 47,567$ items per kilogram of sand from paraffin samples [22]. These values for the MPs content in the paraffin are three orders of magnitude higher than in the surrounding beach sediments. This indicates that the light and rather sticky paraffin (especially aged items that are uneven, in cracks), collected from the wrack line on the beach, is an effective “accumulator” of various types of contamination. The analysis showed that all of the surveyed beaches were contaminated with plastic, and paraffin was a frequent co-component.

One more specific contaminant revealed in sand samples along the sea shore of the Kaliningrad region is *foamed plastic (foamed PS)*. Sampling sands in 13 locations of the beach (in total 60 sand samples from the upper 2-cm layer) using a frame with an area of 0.15 m² showed contamination by foamed particles from 0 to 5,380 items/m² (mean 234.1 ± 176.9 items/m² – from 7 ± 16 to 1,056 ± 1822 items/m²) [22], mainly in areas with a complex system of currents and eddies along the coast. An increased content of foamed plastic in storm wrack lines was also noted during studies of the three-dimensional distribution of anthropogenic litter in the body of the beach in [18].

3.3 Three-Dimensional Distribution of Marine Microlitter in the Sand Body of the Beach

Level of contamination by anthropogenic microlitter and its distribution in the body of a sandy beach on the shore of the Kaliningrad region was examined on May 5 (St. I), May 6 (St. II), and May 27 (St. III) 2016 [18], see Fig. 5. Beaches with significantly different anthropogenic load were selected for this study: (I) a visited beach near a village on the Vistula Spit, (II) a sandy coast in a remote and deserted area of the Vistula Spit, and (III) a coast near the city beach of the resort town of Zelenogradsk. Sampling was carried out (1) from vertical pits (from 48 to 143 cm in depth) made on a storm wrack line in the middle of the winter berm (8–17 m from the shoreline), (2) from the beach face, and (3) on the beach surface out of wrack lines. Sampling was carried out layer by layer using a cylindrical sampler (metal pipe Ø 15 cm, H = 8 cm) and a sapper blade with a handle installed at an angle of 90° to the shovel handle – from the surface to the level of the appearance of sea water at the bottom of the pit. A long, rigid level bar and a folding wooden building meter were used to measure the depth. At point (Ib), from a ladder on a slope near the waterfront (seven steps were dug up to the sea water level), sand samples (100–170 g each) were taken from the vertical walls of five steps using a metal scoop from visually different layers (sands of different colors and grain size composition). Additionally, sand samples were taken from an area of 0.15 m² on the storm wrack lines near the location of the pits (upper layer up to a depth of 2 cm), using a wooden sampling frame and a metal scoop. Moreover, samples were taken from the upper 8 cm layer using a cylindrical sampler at four points with an interval of 10 m along the middle of the beach (16–18 m from the shoreline), regardless of the location of the storm wrack line. All samples were packed in new plastic bags with a string lock and delivered to the laboratory.

In the laboratory, the samples were dried at room temperature, weighed (with the precision 0.1 g), and sieved through a cascade of sieves (5, 1, and 0.5 mm). Those parts of the sample that passed through a 0.5 mm sieve were discarded. The MPs particles, visually identified in sand on a 1 mm sieve, were selected with tweezers, and the remains of sand from 1 and 0.5 mm sieves were combined for further

processing. All material collected from 1 and 5 mm sieves was sorted by hand to separate MPs particles from various inclusions (algae, shells, charcoal, paraffin, etc.) using a magnifying glass, optical microscope, and UV lamp. The following types of litter were identified: meso/macroplastic (>5 mm/>25 mm), microparticles (<5 mm), paraffin, amber, organic matter, charcoal, slag, mica, shells, pebbles. Litter of anthropogenic origin (most of which is plastic) was weighed (accuracy 0.1 g); other ingredients were only assessed qualitatively (no/little/much). At this stage, rather large particles were collected, and the putative plastics were visually examined using a UV lamp, mechanical action [34, 35], hot needle testing [36]. The modified NOAA method for extracting MPs from samples (according to [23]), developed on the basis of NOAA recommendations [25], was applied to the part of the sample that remained between the 5 and 0.5 mm sieves (see short description above). Final analysis was performed on a stereomicroscope (Micromed MC2 Zoom Digital) with a magnification of 10× to 40× on the filter surface in accordance with the recommendations for determining MPs [26].

All the collected 52 samples from different horizons of the beach stratum contained MP particles: fragments, films, and flakes, as well as fibers. This classification is based on the general shape of the particles: 3-dimensional (all three main sizes are comparable), 2-dimensional/flat (flexible films and more or less rigid flakes), and 1-dimensional/long (fibers, threads, lines). MP abundancies in the samples (see Table 3) range from 2 to 572 items/kg DW, the average value is 108 items/kg DW, and the average value excluding samples from storm wrack lines and layers with peak concentrations is only 56 items/kg DW.

The maximum MPs abundance in all three areas was found within the range of storm wrack lines on the beach surface – about 400–600 items/kg DW. Two distinct layers with the same level of contamination (about 300 items/kg DW) were found in the thickness of the beach in area (II) at a depth of 40–48 cm and 64–72 cm below the beach surface. These values are followed by the MPs concentration on the bench in the area of the current wrack line – about 150–450 items/kg DW. In the body of the beach sands (excluding obviously peaking points), the average concentrations are an

Table 3 Quantitative distribution of various forms of MP particles in the samples. Locations see on Fig. 5

| Location | Sampling from | Fibers, items/kg DW | Films and flakes, items/kg DW | Fragments, items/kg DW |
|----------|--------------------------|---------------------|-------------------------------|------------------------|
| (I) | Wrack line | 5–14 | 3–8 | 31–365 |
| (II) | Wrack line | 307–325 | 8–17 | 14–60 |
| (III) | Wrack line | 241–335 | 19–92 | 124–218 |
| (III) | 8 cm surface layer | 13–117 | 0–2 | 0–1 |
| (Ia) | Pit | 8–132 | 0–14 | 0–6 |
| (Ib) | Pit/stairs at shore face | 117–393 | 6–19 | 0–19 |
| (II) | Pit | 11–316 | 1–30 | 0–27 |
| (III) | Pit | 2–15 | 0–2 | 0–1 |

order of magnitude lower (about 10–20, and up to 100 items/kg DW), with similar contamination levels characteristic of the beach surface outside the storm wrack lines (15–118 items/kg DW). The average MP concentrations for the beach strata (with the exception of several peak layers) are of similar order in all three areas: 28 items/kg DW on the beach near the village on the Baltic Spit, 63 items/kg DW in a remote rarely-visited beach, and 7 items/kg DW on a popular city beach (with cleaning of the territory). In particular, in absolute values, the most polluted beach is the most remote and deserted one, while the most visited beach has the lowest contamination. This difference obviously has a non-anthropogenic cause and should be attributed to natural factors.

The distribution of MP particles by depth is uneven and does not show any tendency. It is important that surface contamination does not reflect the MPs content in the sediment stratum: only about 3% (I), 1.5% (II), and 4.5% (III) of the total number of MP particles in the pits was located within the 8-cm thick surface layer. MPs abundance in the surface 2-cm layer of storm wrack lines (i.e., in the most contaminated samples) is also not related to the average concentrations in the beach body: their ratio is about 7,300% for a city beach (III), 400% for a deserted beach (II), and 600% for an ordinary beach (I). That is, a heavily contaminated storm wrack line (mean MPs concentration of 513.5 items/kg DW) rests on the surface of a relatively clean sand (on average 7 items/kg DW) of area (I), while at the remote beach (II), with the mean contamination of 90.5 items/kg DW, a storm wrack line has “only” 365.5 MPs items/kg DW [18].

In the size distribution of MPs particles found in the body of the beach, as many as 98% are in the range of 0.18–3.5 mm, while only 2% are in the range of 3.5–10 mm. This size distribution resembles that reported by Cozár et al. [37] for particles floating at the ocean surface; moreover, there, maximum of the distribution is close ~0.8 mm, while in our case 18% of particles are in the 0.6–0.8 mm range. All our samples contained fibers that were classified as colored and colorless. Colorless translucent fibers dominated. Colored fibers are mainly lustrous pink, blue, red, and green with a range of lengths from ~0.5 mm to several centimeters. Films and flakes were predominantly translucent gray, black, white, and beige, as well as opaque, matte, blue, green, and yellow in the size range from 0.5 mm to 1–3 mm in length. Films were mostly abraded with traces of strong degradation and/or biofouling. The wrack lines in all three regions (I, II, III) show an increased content of foam/expanded polystyrene particles, which is in good agreement with observations at other shores of the Kaliningrad region [22].

Summing up the results of this analysis: (1) The oceanographic reasons for the three-dimensional distribution of MPs in the thickness of the sandy beach are confirmed. (2) Sands from the beach and coastal underwater slope have the same background contamination by MPs. Thus, beach and underwater slope exchange particles of anthropogenic litter, as it happens to natural sediments, especially under the influence of stormy waves. (3) The spots of peak contamination in the body of the beach are associated with influence of stormy events. (4) Coarse-grained sands of dynamically active beach zones/layers are more contaminated. (5) The size

distributions of MPs particles in the body of the beach and on the ocean surface are unexpectedly similar.

4 Conclusions

In general, the conducted studies have shown that the methods for beach litter survey (Frame and Sand rake methods) for assessing the composition of marine litter on sandy beaches (from large micro- (2–5 mm), meso- (5–25 mm) to macrolitter (>25 mm)) should be applied in parallel, and the research results can complement each other, since these methods are aimed at examining different functional zones of the coast: on the one hand, the wave wrack-line zone for analyzing the litter carried to the beach with sea waves, and on the other, for analyzing the total accumulation of litter on the entire beach (including seasonal accumulation, storm events, snow melting, etc.) and the sources of their supply (the sea, tourists, etc.). Testing of beach litter methods in the Gulf of Finland and the South-East Baltic revealed certain limitations of the applicability of these methods in changing weather conditions, as well as their dependence on the granulometric composition of beach sand and the level of eutrophication of the water area.

Results of studies held in 2018–2019 showed an overall high level of contamination with marine litter and its polymer components, microplastics in particular, on the Russian beaches – both regularly cleaned and “wild” isolated beaches. The largest amount of litter of all fractions was found on the beaches of the inner part of the estuary in the Neva Bay. The outer part of the estuary is dominated by microlitter, and in general, the coasts of the Neva Bay differ significantly in the amount and composition of marine litter: there is more heavy glass and metal microparticles in the southern shores, and northern shores tend to accumulate lighter microplastic particles. Microplastics averaged up to 10–12% in total amount of marine litter accumulating to a greater extent in the open part of the Gulf of Finland than in the Neva Bay.

As for South-East Baltic, microplastics pollution as a whole (0.5–5 mm) is variable both along the shore and across the beach and microplastics concentration (0.5–2 mm) at the beach face can potentially be used as an indicator for monitoring purposes: it provides (1) a benchmark for plastic contamination of the marine environment in a relatively large region (with more or less similar environmental conditions), and (2) an indicator to monitor rising levels of plastic pollution. A comparative analysis with beaches around the world showed that the beaches of the Kaliningrad region are quite clean and there is no obvious difference in the contamination of beaches with high (near resort cities) and low (in fairly deserted, less-visited coastal areas) anthropogenic load.

However, the predominant types of litter differ significantly among these two Baltic regions: predominant type of litter in the South-East Baltic is foamed plastic (foam/polystyrene foam), together with paraffin, widely present in the area, and the source of which is mainly the discharge of tank waters from ships. There is also a

specific pollutant in this area: *geosynthetic materials* that are a new contaminant emerging from coastal engineering protection activities. In the Gulf of Finland region, the most common litter items are plastic pellets, broken glass, cigarette butts, rusty metal, and pieces of building plaster. Also, among mesolitter there were many synthetic napkins, cotton bud sticks, and other polymer products that being flushed down the drain are often not caught by treatment facilities and go directly into the waters of the Gulf of Finland.

The data collected during these studies will be included in the Baltic Sea marine litter database for lagoons and estuaries and urban and suburban beaches. Based on the obtained results general recommendations for the national program of marine litter monitoring will be developed for the Russian coasts of the eastern part of the Gulf of Finland, harmonized with the international monitoring programs in the Baltic region.

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