Studia Quaternaria, vol. 38, no. 2 (2021): 85–100 DOI: 10.24425/sq.2021.136825

LITTER SOURCES ON THE POLISH BALTIC SHORE – EFFECT OF INCREASED ANTHROPOGENIC POLLUTION

Tomasz Arkadiusz Łabuz

Institute of Marine and Environmental Sciences, University of Szczecin, Mickiewicza St. 16, PL-70383 Szczecin, Poland; e-mail: tomasz.labuz@usz.edu.pl

Abstract:
The article summarises results of studies on litter concentrations on the Polish sea shore. Origin, mechanism of transport and source of litter are discussed. The main part of the data has been based on litter quality and quantity investigation in post-storm marine sediments. Data were collected in surface sediments since 2001 and in fossil washover fans dated 1988–2000 in different locations on the coast. Litter has been divided according to the material, use, size and origin. Analysis of litter quantity on beaches after storm surges showed an annual increase. The heavier surge, the more debris and mixed litter appear on the coast. A large increase in the amount of litter has been observed after the storm in 2009. The average amount of litter per 1 m^2 has increased from 1.5 in 2001 to 17.5 in 2020. Among litter there is still a similar share of fishery and ship waste. The biggest growth was observed in waste of consumable origin. Plastic litter, including anthropogenic waste left on beaches, has increased to 80% in recent years. Most waste occurred on the coast adjacent to the Vistula River mouth.

sq

Key words: Polish Baltic coast, litter source, beach litter, litter material, post-storm debris.

Manuscript received 24 January 2021, accepted 19 July 2021

INTRODUCTION

Numerous reports state that seas and coastal waters are full of different litter (Pruter, 1987; Gabrielides *et al.,* 1991; Derraik, 2002; OSPAR, 2010; Galgani *et al.,* 2013; Rosevelt *et al.,* 2013; Anfuso *et al.,* 2015; Bergmann *et al.,* 2015; Jambeck *et al.,* 2015; Arcangeli *et al.,* 2017). Marine debris includes all objects, with litter that does not naturally occur in the marine and coastal environment but is nevertheless found (Cheshire *et al.,* 2009). Marine litter is a worldwide enlarging threat to the sea and coastal environment (Cheshire *et al.,* 2009; Bergmann *et al.,* 2015). It is any material (waste, liquid, debris and others) that has been manufactured by man and then intentionally left or lost in the environment. Almost 80% of marine litter is plastic material (Sheavly and Register, 2007; Ryan, 2015; Arcangli *et al.,* 2017).

The main sources of marine litter are land and marine-based (Sheavly and Register, 2007; Cheshire *et al.,* 2009; Thiel *et al*., 2013; Jambeck *et al.,* 2015; Łabuz, 2015). Some of the litter is transported to seas by rivers, some is thrown from vessels and more and more is produced by tourists. Other possibilities are natural storm-related events such as hurricanes, tsunamis, tornadoes and floods. They can create a large amount of material that is washed from coastal areas to the sea (Cheshire *et al.,* 2009; OSPAR, 2010; Rosevelt *et al.,* 2013; Anfuso *et al.,* 2015).

Numerous studies from almost all regions in the world report on plastics debris on beaches (Taffs and Cullen, 2005; Alkalay *et al.,* 2007, Oigan-Pszczol and Creed, 2007; Browne *et al.,* 2010; Rosevelt *et al.,* 2013; Williams *et al.,* 2013; Laglbauer *et al.,* 2014; Aydm *et al.,* 2016; Fernadino *et al.,* 2016; Strand *et al.,* 2016; Zhou *et al.,* 2016; Portman and Brennan, 2017; Watts *et al.,* 2017). Plastics litter is any size from large material 1–2 cm particles to well-known microplastic (Tudor *et al.,* 2002; Taffs and Cullen, 2005; Corcoran *et al.,* 2009; Rosevelt *et al.,* 2013; Thiel *et al.,* 2013; Munari *et al.,* 2016; Arcangeli *et al.,* 2017; Urban-Malinga *et al.,* 2020). On the Baltic Sea coast an increasing amount of marine litter is reported (HELCOM, 2009, 2014; MARLIN, 2013; Balčiūnas and Blažauskas, 2014; Hasler *et al.,* 2018). On the Polish Baltic coast there is also increasing waste pollution (Jóźwiak, 2010), growing amount of litter on the beach (Zalewska *et al.,* 2021) and microplastic in studied beach sand samples (Urban-Malinga *et al.,* 2020). During investigations on marine debris and washover fan distribution on the Polish Baltic coast a lot of anthropogenic artefacts have been observed in sediments (Łabuz and Olechnowicz, 2004; Łabuz, 2007, 2009, 2018). The issue of waste concentration after storm surges is so far not well recognised.

The aim of the study was the determination of litter origin and quantity on the Polish Baltic coast in post-storm

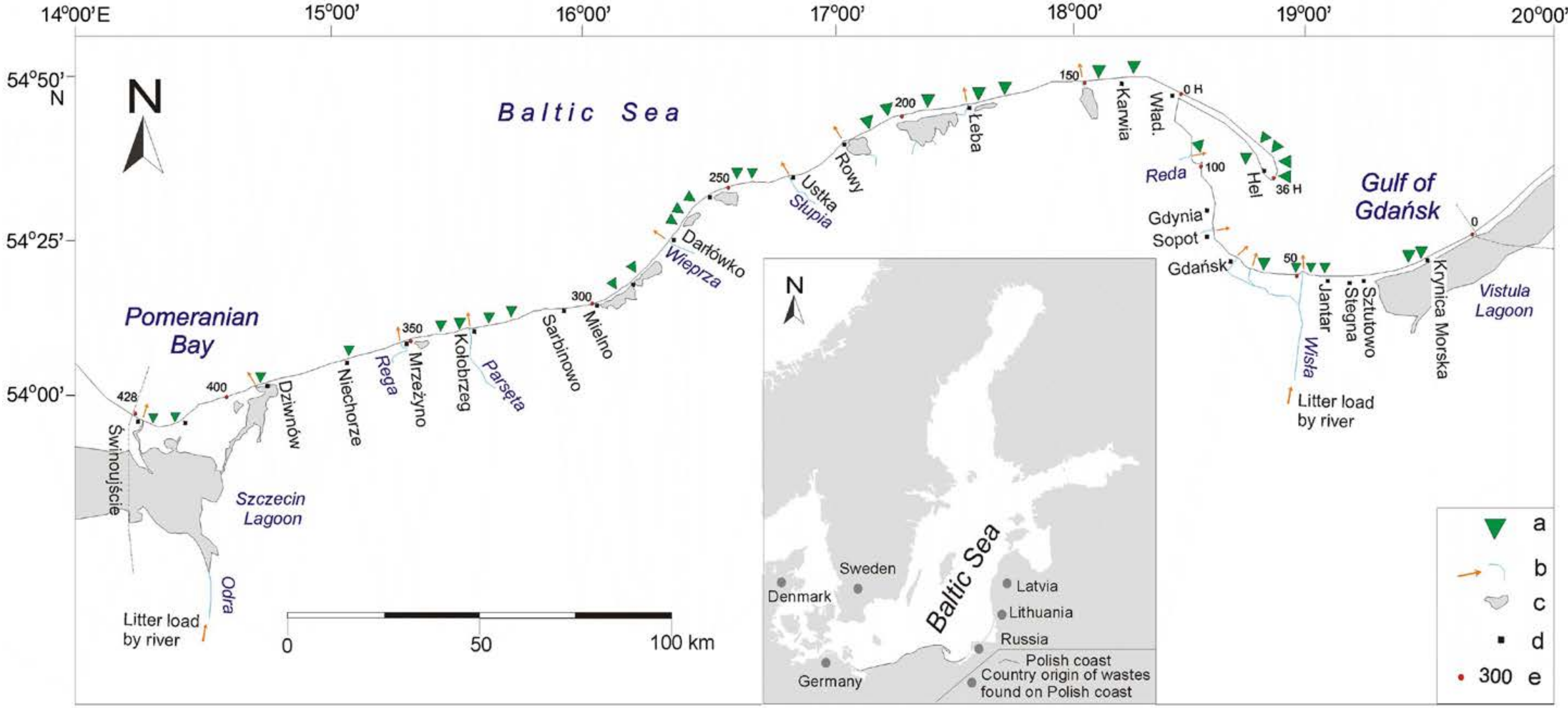

Fig. 1. Localization of permanent washover fans and post-storm sediments with accumulated litter on Polish Baltic coast, also marked country of found waste origin, a – washover fans, b – main rivers and mouths, c – coastal lakes and closed lagoons, d – main urban settlement, e – Polish coast kilometrage (km 0–428).

sediments from 1988 to 2020. In the first step, the sources of litter origin and location on the shore are explained. Then characteristics of litter mechanism transport, kind and type of concentration are presented. The last part of the study contains an analysis of litter quantity and quality in post-storm sediments (mainly washover fans).

STUDY LOCATION, MATERIAL AND METHODS

The study location covers the Polish Baltic Sea coast. Its length is 500 km, stretching from the Świna Gate Sandbar (Uznam Island) in the west to the Vistula Sandbar in the east. The Polish coast is an aligned one and formed of loose sediments only. More than 85% of the coast is covered by sand bars and dunes in various stages of development. The rest consist of moraine cliffs with a short section of reed wetlands in the Puck Bay. The shore is mainly composed of sandy beaches, 20–60 m wide. Along the coast, there are many touristic towns and resorts that produce different type of garbage. Several rivers discharge also waste from the land, including the two biggest: Odra (through Świna channel) in the west and Vistula in the east.

The material has been studied basing on own observations of litter type that have been found on the shore, coming both from direct human action and marine caused accumulation from selected locations along the whole Polish coast. Litter left directly on the beach, dunes and adjacent land during summer has not been counted. This material was used to explain the source and type of litter that primary appears on the beach and adjacent land. It documents places of illegally left litter: viewpoints, along paths and sunbathing areas, coastal waters and rivers. In summer it is hard sometimes to distinguish the primary left litter on the beach and the secondly thrown by water during the previous storm season. The main purpose was to quantify the kind and amount of litter in post-storm sediments, that appears secondly on the beach in the autumn-winter period.

The analysed material has been collected on beaches where post-storm debris is usually accumulated after storm surges. These areas are more or less the same beach sections each year where the sea is accumulating a large amount of debris (Fig. 1). Most of them belong to the accumulation part of the coast with a wider beach. During each stormy season in these areas a sea brings marine debris with anthropogenic artefacts onto the beach and on the lowland. Data were collected in surface post-storm sediments from 2001 to 2020 and from excavated sediments dated 1988–2000. Washover fans found in excavations were studied for other scientific purposes. Some of them included also anthropogenic artefacts. For example, in 6 fans dated to 1988 only an anthropogenic material appeared in one of them. On the other hand, heavy storm surge in January 2017 accumulated artefacts dated to 1980s and washed from eroded dunes. Through 20 years anthropogenic artefacts in post-storm sediments were quantified with different accuracy, because of the primarily different aims of the studies. That is why that only those data with complete information about litter type and amount were selected for this analysis. Among them, 1 to 15 cases from each year with storm surges were selected to further analyses.

The research was made during other coast dynamics measures in debris accumulated on shore, always after the known storm surge. The length of the investigated surface depended on the width and length of the observed post-storm remnants mixed with artefacts. The length of 10 to 100 m for each sampled surface area has been examined. Their width ranged from 2–10 m. In post-storm sediments stretching along the shore over 100 m, sections up to 10 m were studied. Only visible litter particles have been quantified, larger than 1 cm. In some cases, organic debris was separated to count small anthropogenic artefacts. Cigarette butts have been avoided, because they have low survival resistance after strong surges. They have been mainly observed on the beach after the first low surge that is washing the beach after summer.

During field research, a number and type of litter was quantified at each selected location. The material collected annually from each sample site was assigned to each known storm surge that appeared on the studied part of the coast. The recognized artefacts were counted and assigned to classification types. Table 1 presents litter classifications used since 2002 including origin, material, size, location on the coast and concentration characteristics. In recent years the used classifications and monitoring techniques have been improved by comparing to the proposed methods in other works (Silva-Iñiguez and Fisher, 2003; Cheshire *et al.,* 2009; HELCOM, 2009; OSPAR, 2010; MARLIN, 2013; Strand *et al.,* 2016; Hasler *et al.*, 2018). The very detailed

Table 1. Classifications of macro-marine litter on the coast.

Origin	Material	Size (cm)	Location on coast	Concentration
Ships, yachts	Plastic	<5	Shallow water	Way of transport in the sea environment
Fishery	Metal	5-25	Waterline	
Construction, agricultural	Glass	>25	Beach (lower, upper)	Main source
Transportation	Rubber	>100	Lowland, dune	Concentration shape
Chemicals, drugs, cosmetics	Organic fibre		Coastal reeds	Covered surface
Clothes, wear	Processed wood		Lake, channel, river	Density
Touristic, recreation elements	Liquid, oils		Promenade	Layer thickness
Consumption packaging	Organic		Beach entrance	Surface or fossil
Other	Mixed		Protection measure (e.g. band)	Other

classification of plastic waste is proposed in the publication status on beach litter monitoring in Denmark in 2015 (Strand *et al.,* 2016).

The recognised litter of each material type or size group was summarized from each location for each year and presented as its percentage in a total amount of artefacts. The average amount of litter per surface area of the studied location was counted. Then average number for each year with significant storm surge was estimated.

RESULTS

Presented results consist of two separate litter characteristics. In the first part, there is an analysis of litter sources origin at the Polish Baltic seashore, main types, rare and unique artefacts, way of transportation to the beach and separated concentrations. This part is based on almost 25 years of field studies and observations of littering on the coast. The second part is strictly an analysis of quantified and qualified waste found in post-storm sediments as a secondary source of coast littering. Data originated from field studies of surface debris found on the beach after storm surges from 2001 to 2020 and in fossil sediments from 1988 to 2000.

Sources of litter origin

There are two main sources of marine litter that have been observed on the Polish Baltic coast: primarily land-based and secondarily marine-based ones. Among them there are different local sources and way of litter transport to the shore (Fig. 2A). Among the most important there is a river discharge to the sea. This problem should be studied separately due to different origin of litter material use and concentration on beaches near river mouths.

The primary source of litter on the Polish Baltic Sea coast is the human littering of the coastal zone itself or the rivers with mouths in the sea. In the coastal sunbathing areas litter can be found directly on dunes or beaches. Near coastal towns and harbours, there are illegal waste landfills behind the beach. Their origin is mainly household, construction, fishery and ships or production waste. In some countries, dunes that are worthless even for agriculture or animal grazing are used as landfills (Łabuz, 2015). In recent years sunbathing tourists leave more consumption litter or broken recreation tools and items on dunes, cliff viewpoints and beaches (Fig. 3).

The secondary source of waste on the shore is a marine litter. Litter in the sea so far was only of maritime transport and fishery origin. The waste may be thrown from ships to the sea, may be lost due to wave action. Among them, there are a lot of fishery tools: nets, rubber wear, crates, etc. The nets and fishery equipment may be lost or forgotten by fishing vessels. The litter of these origins are distributed by sea currents and waves and are thrown by the sea on the beach during storm surges. Nowadays storm surges can create large amounts of litter that are washed from coastal areas (Cheshire *et al.*, 2009; Anfuso *et al.*, 2015). During a storm surge, the higher sea level and impact on the longer coast section, the bigger coast erosion and the larger number of

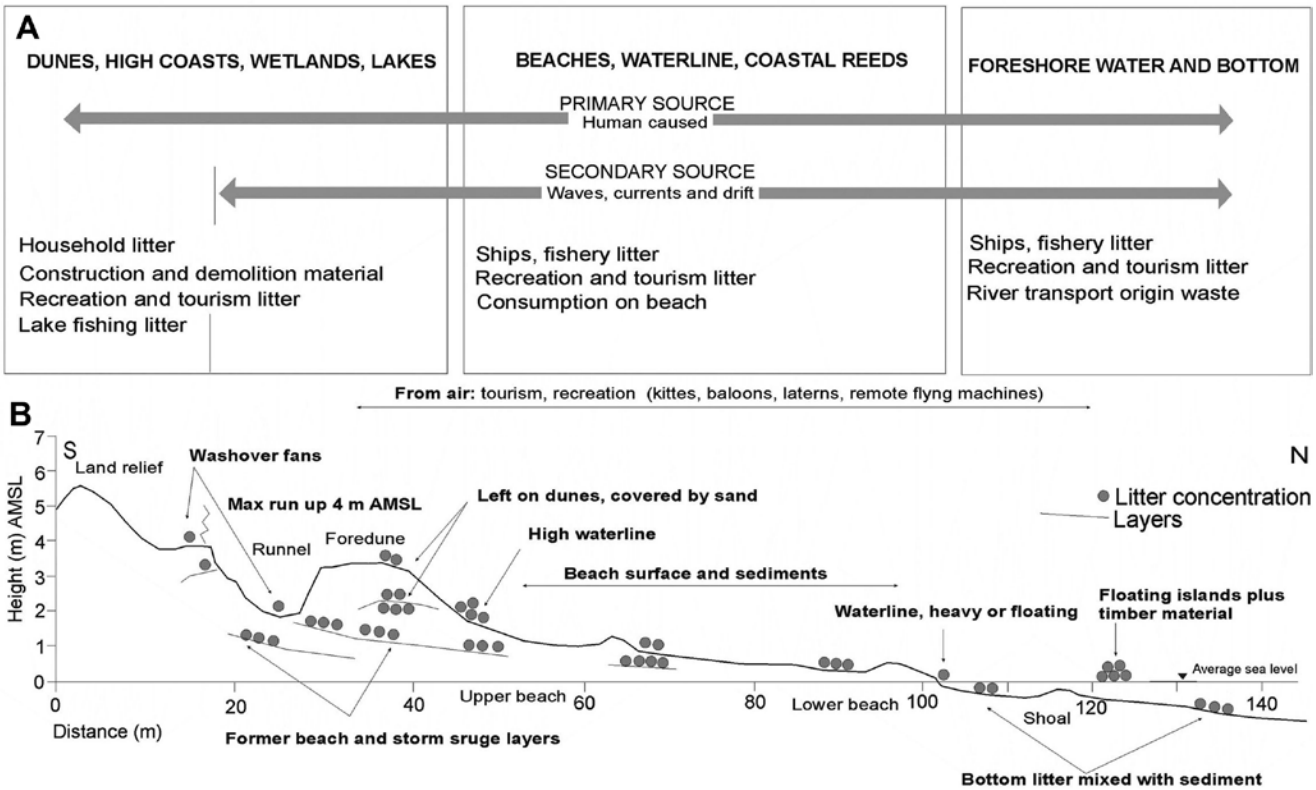

Fig. 2. Scheme of litter distribution on the Polish Baltic coast. A – habitats and source of waste, B – coastal dune profile with marked litter concentrations.

Fig. 3. Example of litter on the coast from sunbathing origin. A – dune view after illegal camping on Świna Gate Sandbar, 06.2012, B – litter collected on sea view on a low cliff in a small village of Wicie, 07.2018.

waste or parts of the broken infrastructure are washed to the sea. The number of litter is a part of infrastructure as waste bins, destroyed benches information boards, railings of beach stairs and others.

There is also much litter in a sea that is transported by rivers. Among tree trunks, branches and parts of vegetation there can be typical floating litter parts, e.g. closed glass bottles and jars, plastic bottles and other plastic materials. Near rivers mouth are plums of waste aggregated on shallow water in reds or on the adjacent beach. The observed larger litter concentrations on the coast of the Gulf of Gdańsk and the Puck Bay has also connected to the large agglomeration of Tricity: Gdynia, Gdańsk and Sopot and other small settlements along the coast. Numerous drainage channels provide rainwater with washed waste from urban areas (chemical substances have been not measured). After flooding, more waste is washed from land areas, even larger particles as refrigerators, electronics, barrels or furniture (Fig. 4B). Those were observed in Odra and Vistula mouths after floods in 2001 on the western Polish coast and in 2010 on the eastern one.

For example, after the flood in the southwestern Poland in July 2001, a large freezer ended up on a beach of the Świna Gate Sandbar. In turn, after the flood in May and June 2010, along with the mouth of the artificial mouth of the Vistula and the 'brave' Vistula, there was a lot of waste in a sludge that covered the shore and the beach; 4 refrigerators were also pulled out in the area of the ferry crossing at Mikoszewo. The largest amount of litter can be found on beaches adjacent to the Vistula Mouth. Among them, there are mainly consumable packages and foil, and transportation and post-production packages. In 2014, at the mouth of the Vistula River, on the 20 m long beach, there were 85 plastic bottles. The beach adjacent to the main Vistula mouth is covered by foils of agriculture, industry and consumable origin.

The new source of beach litter is a beach nourishment that contains usually small plastics particles. Sand pumped from foreshore sediments contains more litter: glass, aluminium cans and mentioned small plastics. Nowadays sludge collected from the seabed and pumped to the beach contains plastics. In 2019, over 5 mln m^3 of sediment was collected from the Gulf of Gdańsk from the dredged and widened nautical channel leading to the port in Gdańsk. The sediment is deposited on the beaches as filling material. The sand that was pumped through the pipes to the beach contained visible amounts of fine and broken plastic, mixed with the sediment of the beache (Fig. 4D). This type of waste cannot be removed and accumulates in the upper part of the beach on the Vistula Sandbar (Stegna), the Hel Spit (Hel, Kuźnica) and the Karwia Sandbar (Ostrowo). Its abundance in the collected sediment indicates serious contamination of the seabed of the bay with plastic in the area of a large urban agglomeration and at the mouth of the Vistula River. These are artefacts washed away from the mainland after heavy rainfalls by rivers and storm sewer systems in Gdańsk, Sopot and Gdynia.

The main sources of litter on the Polish shores are:

– left on beaches, adjacent cliffs or dunes, near river mouths, mainly in busy touristic places (parts of tourist and recreational goods, post-consumption waste, pieces of clothing),
– thrown out to the coastal environment (mainly forest) by residents of local villages, towns (equipment of accommodation centres, debris after renovation),
– carried by rivers (construction and transportation waste; foils; lubricants, medicines or chemicals packaging; parts of household goods and waste from sewage treatment plants),
– washed away or discarded from vessel decks (equipment, nets),
– washed away by storm surges from beaches (parts of tourist and recreational goods, post-consumption waste, pieces of clothing),
– washed away by storm surges from land as a result of erosion (benches, waste bins, information boards),

Fig. 4. Type of litter concentration. A – floating island on the beach, 01.2017. B – floating large size waste. C – fine litter in organic debris, 10.2009 (scale 1 m). D – smallest particles mixed with sand in dredged material on the beach (x – part of cotton buds), 01.2020. E – heavy waste, ammunition washed from the foreshore bottom, 01.2007. F – a broken piece of infrastructure, 11.2004.

– blown by a strong wind from construction sites, towns (mainly foil, styrofoam),
– falling from the air (balloons, kitties, lanterns, fireworks, small aircraft and others),
– pumped on the beach during nourishment by material dredged from sea bottom (mainly small plastic particles, or beverage cans).

Based on the observations, two periods per year were determined for the accumulation of litter on the Polish coast. The first period is the vacation season, from July to

September/October, when post-consumption waste is left on the beaches, dunes and viewpoints of cliffs and dunes. The other period is the time after storm surges in autumn and winter. During longer and severe surges with sea level H > 1.3 m AMSL, encompassing entire coasts, the water washes away from the beaches or lifts from the seabed more artefacts than during shorter ones. As a result of rewashing, the litter is transferred from beaches to further stretches of the shore. Among the waste, product packaging and information boards from other Baltic countries were recorded. This proves that waste is carried by sea currents. More waste from the Baltic countries was observed after storm surges. Most small fragments of plastic cover the beach after the first storm surge since the end of the vacation season (September). Among them, there are plastic consumption packages, spoons, forks, sticks and cigarette butts. The cigarette butts are often waste on beaches (Taffs and Cullen, 2005; Balčiūnas and Blažauskas, 2014; Laglbauer *et al.*, 2014; Aydm *et al.*, 2016; Fernadino *et al.*, 2016; Strand *et al.*, 2016; Hasler *et al.*, 2018). These artefacts were rarely found in post-storm sediments due to their low survival resistance.

Litter transport mechanism to the shore

Wave undulation and storm surges carry various artefacts and leave them as a result of accumulation in different places. Most of the waste, due to its weight and structure, was able to float on water for a long time creating, along with organic debris, floating clusters that were washed ashore during storms. Among the waste, some elements could be earlier settled on a seabed and were washed away by sea waves, as indicated by barnacle or seaweed colonies attached to the surface of the objects. Part of the waste that could not float was also washed ashore along with organic debris from the eroded seabed, including algae and shell accumulations. These were usually small plastic and metal elements, as well as open glass containers and aluminium cans. Some of them were already fragmented as a result of mechanical destruction by water. These elements were most often identified in the sediments of organic matter deposited at the lower beach.

In the upper part of the beach, the most common elements were those that could float freely at the water surface. Knowing the waste transported in a sea environment, it is possible to distinguish various groups of waste that could float on water for a long time and the waste that was washed away from a seabed.

In terms of the transport mechanism in the aquatic environment, the following waste categories were distinguished (Fig. 4):
- homogeneous, floating in a sea and forming clusters along with organic matter (roots and fragments of tree trunks and shrubs) (Fig. 4A),
- single, large waste that can float due to its construction (barrels, TV sets, fridges, chairs) (Fig. 4B, F),
- small floating debris mixed with light organic matter, including algae and shells, washed away from a seabed and forming patches suspended on the sea surface (Fig. 4C),
- non-floating, washed away from a seabed along with sediments and vegetation and mixed with them, carried by strong waves only (Fig. 4E),
- piled up waste caught in nets, forming periodically floating or suspended patches on the sea surface,
- dredged from a seabed for nourishment purposes (Fig. 4D).

Litter location and distribution on the shore

All litter in the coastal zone, both onshore and in water originated from human irresponsible behaviour. A part of it is directly left onshore or thrown into the water (primary origin). Another part is accumulated on beach, low dune (land) or in water channels and coastal lakes by sea, mainly after storm surges (secondary origin).

The litter found on the shore may be located due to its source origin (primary and secondary) everywhere. Their range and main types are presented in Fig. 2. The main spots of litter left by tourists on the coast are shrubs along pathways, viewpoints, runnel behind foredunes and beach. They are left on shores of river mouths and coastal lakes in places of rest or other recreation activities. In terms of the marine litter location, the following waste categories were distinguished (Fig. 5):
- shallow foreshore bottom or floating in water,
- beach and waterline,
- upper beach with sea run-up debris (Fig. 5A),
- coastal landforms: dune, interdune or low land part (Fig. 5B),
- river, channel mouths (Fig. 5C),
- lake or wetland vegetation,
- low coastal pavements adjacent to the beach, entrances to the beach,
- coastal protection structures and piers.

Distribution of litter left directly by humans (primary source)

The primary source of litter on the shore is directly of human origin, left mostly during the holiday season. Those left by tourist can be found on coastal viewpoints, park places, along paths to the beach and on beaches of sunbathing areas, then also in a sea. The forest just near the coastal towns is littered with waste left from household, cars, construction or renovation of the houses or just by tourists (and sunbathers). Non-finished drinks and food remain in the left containers or packages too. Their number is largest at the viewing points (September 2019, Chłapowo cliff on the area 5x5 m in size there were 45 glass bottles, 10 aluminum cans, 18 plastic bottles).

An interesting group of waste in terms of human behaviour are plastic, wooden, metal and cardboard parts of

Fig. 5. Location examples of marine litter. A – longitudinal concentration on the upper beach of former floating islands, Jamno Lake Sandbar, B – typical washover fan on a low-lying dune, Wicko Lake Sandbar, C – concentration in stream mouth, cliff coast Dębina.

fireworks and lanterns set off on the shore each year. After the storm on January 3rd, 2019, a multitude of such artefacts were found in the sediments deposited on a remote beach on the Świna Gate Sandbar. They were washed away with beach sediments after they had been used on December 31st on the beach in Świnoujście and probably in towns on the German side of the Uznam Island, and moved 5 km further east by waves from WNW-NW direction.

The development of construction, including the ones on the coast, results in a new type of rubbish: packaging foam, polystyrene and other plastic construction materials. During strong wind action, these small building materials are blown away from new hotel construction sites and deposited on a beach and dunes.

Coastal dunes located in the touristic resorts are rarely cleaned up. Litter is almost invisible on dunes densely grassed or covered by shrubs. In many places, aeolian accumulation leads to burry litter in the sediment (on the upper beach and foredunes). The waste that remains on touristic beaches in the towns during summer is most often cleaned up and does not pose a major ecological threat (except waste that is buried or covered by accumulated sand). However, what does pose a problem is the waste that is re-washed ashore, and most often covered with sand accumulated in the spring. After autumn-winter storm surges (October/March) and in early spring (March/May), the sediment washed up by a sea on the shore contains organic matter and waste that is washed away from beaches and eroded dunes. After storm surges (secondary source), there is much more waste on the beaches of the entire coast than after the summertime (primary source).

The amount of waste generated by vacationers relaxing on the beach is increasing every year. In vacation resorts, waste bins are emptied daily, and the beaches closest to the largest of them are also cleaned every day. In recent years, waste bins have been placed not only at the entrances to the beach but very often there is a waste bin every 50–30 m. Only in a few places, there are bins for waste segregation. In 2008, the city beaches in Świnoujście and Kołobrzeg started to be cleaned with a machine that removes waste from the sand. In the following years, similar equipment was purchased for towns on the eastern coast, including Gdańsk. Since 2019, such machines are also available in smaller towns, such as Łeba. Another measure, introduced in 2017, is harrowing beaches after cleaning. Without these measures, the amount of waste left in the sand and subsequently washed away by the sea would be much greater.

Distribution of marine caused litter (secondary source)

Litter thrown by a sea onshore appears in beach and interdune sediments and on the whole beach, the waterline and in sediments (Fig. 2B). Part of them is left in coastal river outlets, or streams and wetland vegetation (reeds). Part of the heavier litter is accumulated in the foreshore seafloor.

The beach near the river mouths is covered by light plastic artefacts. On the Vistula Sandbar, one particular type of waste that is very common and present in post-storm surge deposits are cotton swabs used for ear hygiene. These have been found in sediment on the upper beach after each strong surge between Jantar and Mikoszewo (1–2 pieces on each 1 m^2) and in washover fans along the Vistula Sandbar. For example, in the washover fan developed on a low dune after the 2019 surge (25 km to the east from the Vistula Mouth), there were 13 pieces on 5 m^2. The only possible source of origin are bathrooms in households, and the way of transport – water that passes through sewage treatment plants, flows into the Vistula River and then up to the Baltic Sea. On the western coast of Poland, on the beach at the mouth of the Świna channel, which carries water from the Oder River, no such large amount of inland waste was observed, as it is probably accumulated in the Szczecin Lagoon and on its shores, where the mouth of the Oder is.

Some of the identified artefacts were rewashed ashore during a single strong storm surge (2004, 2012, 2017, 2019). These were information boards which, after being pulled out from the ground as a result of erosion, were transferred to other sections of the coastline, even up to 30–40 km away from the place of their origin (identified town, place of origin and place of finding). After the largest storm surges, some of the artefacts in the washover fan sediments were evidently older, covered with organic matter and crustaceans. Such waste came from sediments deposited much earlier. After being washed away from the bottom or from under eroded dunes by a large storm, it was re-accumulated in the sediments of fans and on the beach.

The main litter accumulation spots are storm surge areas (washover fans) with natural and artificial debris located between low and high sea water level. The material of natural or anthropogenic origin that is accumulated by thae sea on the upper beach, behind a dune or on a lowland is named the washover fan (Łabuz, 2009). In the long coast sections, marine debris is accumulated in the water run-up range on a beach/land relief. Since 2001 after each observed storm surge more litter has appeared in washover fans. The rule is, the heavier the storm surge, the more litter after strong erosion appears on the beach or the low-lying land. During slight wave undulation, artefacts tend to accumulate near the waterline or on the lower part of the beach. During storms with high sea level, waves run-up to the upper beach, leaving artefacts in a linear form. The highest storm surges accumulate litter behind the first dune.

In many places, water washes out shell cases and ammunition from the seabed in Kołobrzeg during January 2007 storm surge (Fig. 4E) or near the former military unit in Bagicz (east of Kołobrzeg), as reported in 2019 after the January storm surge. A larger accumulation of shell cases washed out as a result of shore erosion was observed but in the future there is also a threat of barrels with chemical ammunition from the First and Second World Wars that were sunk at the bottom of the Baltic Sea (Vanninen *et al.,* 2020). In 1955, a number of beachgoers suffered burns after contact with the barrels when they washed ashore at Darłówek. In April 2012, storms washed up phosphorus accumulations on the beaches in the region of Ustka, which probably also originated from sunken barrels.

Among other artefacts, a large variety of elements of large-sized tourist infrastructure have been recorded, including benches, information boards and waste bins. Other litter originating from the mainland (or ships) included home furnishings and equipment (e.g. light bulbs, pieces of furniture, refrigerators, construction elements, etc.). Uncommon waste recorded on beach from 2009 included (pieces): toilet seats (2), TV sets and computer monitors (7), wooden and plastic chairs (6), tires (5), refrigerators and freezers (5), as well as fragments of drones and other flying units (electronic parts, wings, etc. – 7).

There are three sources of litter accumulated onshore after a storm surge:
- directly marine origin (originating from ships and land, and recently floating in the sea, that is why litter from other countries appear),
- rinsed and washed from sediment of eroded beach and dune (some of older origin, formerly covered by marine and aeolian accumulation including plastic litter from the 1980s found after heavy surge erosion in January 2017),
- washed from land and damaged infrastructure from eroded part of a coast by the last surge (during its end number of infrastructure parts is being accumulated onshore even several kilometres from their previous location).

As the sea level and wave run-up increase, the higher location of litter on the coast above sea level. The highest elevation with sea debris, up to 3.8–4.1 m AMSL has been observed after surges in 2012, 2017 and 2019. In reference to sea level growth and more often higher sea level during a storm, more litter will appear on low-lying land. These forms are mainly created on accumulative part of the Polish Baltic coast, far from seaside resorts and coastal towns. That is why more litter occurs in this part of the coast where accumulation prevails and storm sure washover fans are created than on touristic ones. Conducted observations show that at the Polish coastline of the Baltic Sea, there are several places where washover fans with waste are formed in the same location after each major storm surge (sea level H >1 m). Besides, as the sea level rises, new washover fans are formed during major storm surges, including the low dune coasts. On the extremely eroded Lake Kopań Sandbar, the entire low dune coast up to the coastal embankment is covered with sediments and artefacts from storms in 2012–2019, including a considerable amount of small and large-sized waste.

On the beach of accumulation areas, waste constantly piles up, gradually forming entire layers of various small debris, which are covered with sand and then with emerging dunes. The thickest layer (up to 20 cm) of permanent waste is formed between Jantar and Mikoszewo on the Vistula Sandbar after each storm (Fig. 4B). A number of artefacts made from plastic foil is the highest there (pieces of foil from packaging, including the ones of industrial origin). Occasionally, there are also car tires, pieces of furniture or electronic devices (as whole refrigerators). As can be deduced, these objects are not post-consumption waste from beaches but are carried by the Vistula River from the land.

On the erosive, low lying coast sections, litter is accumulated on the land behind eroded dunes, in a coastal forest (Fig. 4B) and on meadows (as Beka Reserve). At the accumulation part of the coast litter and debris are seposited on the upper beach or behind foredunes in washover fans. Other heavier material as glass or metal cans can be buried at a foreshore bottom or on the beach. Also, other particles are mixed with shore (beach) sand, because plastic appeared in material dredged for beach nourishment (from Gulf of Gdańsk in 2019).

Higher surges recently leave more remnants on human used structures. At the urbanised coast a large amount of driftwood with litter is accumulated on promenades (Darłówko), as it was in 2017 and 2019 or other longshore paths (bicycle path, Bagicz-Kołobrzeg). There are also separate litter accumulation in traps formed by coastal protection structures (behind bands, among water breaker construction) or coastal infrastructure (piers, stairs, etc). During storms, large amount of waste is carried through water channels to the lakes. The waste also accumulates in the areas overgrown by reeds surrounding the Puck Lagoon and is carried into the coastal lakes through water channels.

Waste washed up on the beaches in coastal towns has been usually cleaned up after storms by municipal cleaning services or maritime office staff. Waste that piled up on low dune coast covered with woods was in turn cleaned up by forest services. On the long stretches of beaches away from towns, artefacts left after autumn and winter storms remained on the beach until they were buried by sand in spring. In many places, the surface layer is formed by waste, including accumulations of oil and other chemicals. Such concentrations can be found on the natural, protected parts of the coast as in: natural reserves, national parks and Natura 2000 areas. On a stretch of over 30 km of beaches in the Słowiński National Park after storm surges only the largest-size waste or hazardous substances (oils, paraffin) are collected. Artefacts in washover fans amidst the dunes are not cleaned and after subsequent storm surges more waste is deposited there.

Characteristics of litter thrown on beaches by storms

The groups established according to the basic characteristics of waste are presented in Table 2. In examined litter concentrations the material and its size are varied. A litter washed on the coast is of varied size. The waste found among the sediments on the beach included occasionally larger objects, 1–5 m long, such as pieces of furniture, boards, freezers, tires, aluminium sun-beds, umbrellas, rails, pieces of benches and waste bins. The average size in the most common group of plastic waste is 20 cm. As mentioned earlier, these are most often bottles, boxes and other items that were often parts of larger objects. In some places, only small fragments of plastic waste, 1–5 cm size, are accumulated. They are quickly buried by sand and cannot be removed from the shore. Their content in beach sediments increases with each major storm surge. Table 3 presents a diversified content of the main litter types in selected washover fans (marine debris concentrations). In the excavations presenting washover fans sediments after storm surges from 1988, 1995, 1997 and 2000 there were more processed wood and metal particles with some plastics from 1980–1990. At the beginning of research in 2001 more wooden and plastic artefacts appeared in sediment accumulated by storm surges. There were also parts of fishing nets and wooden crates. In the fossil sediments after the storms of 1988 only pieces of fertilizer foil bags and

Table 2. Characteristic of different litter type in post-storm surfaces.

Size (m), up to	Origin	Type
0.1–1	Clothes, wear	Shoes, sandals, underwear, items of clothes (coats, pants etc.), including several working clothes and shoes (ships, port industry)
0.1–0.4	Consumption leftover and packaging	Pieces of consumption leftover, various packaging after eat, drink and storage: bottles, jar, stick, foil, cutlery, cigarette filters, straws, sticks, nuts and other
1	Chemicals, drugs, cosmetics, medical	Household chemicals, vials and medicine packaging, hygiene waste, and beach cosmetics, stearin, the concentration of chemicals (oil, petroleum etc.)
1.5	Transportation	Oil and water packaging cans, bags, tapes, foil, containers, boxes and crates (also wooden), tires
2	Construction, agricultural	Mounting foams, styrofoam, plastic room furnishing, pieces of furniture, benches, fertilizer bags
2	Touristic, recreation elements	Pieces or whole: umbrellas, tents, deck chairs, oars, mattresses, balloons, kites, toys, glasses
3	Others, uncommon	Freezers and refrigerators, pieces of furniture, light bulbs, TV receivers, benches, information boards, ammunition and shells, fragments of small flying craft, electronic components, animals tracking transmitters (also with dead animals)
5	Ships, cutters, yachts	Signal flares, gangways, rigging, oils, other
8	Fishery	Whole and twisted nets, ropes, floats, gloves, boxes

Table 3. Change in litter origin and quantity calculated in post-storm beach sediments in years 1988–2020.

Year	Max sea level (m)	No of cases (n)	Artefact percentage					
			Ship and fishery elements	Processed wood	Building and agricultural materials	Chemicals, cosmetics, drugs	Consumption packaging, cutlery	Other
1988	1.21	2	50	0	50	0	0	0
1995	1.86	1	30	60	0	0	10	0
1997	1.12	2	60	20	10	0	10	0
2000	1.01	1	50	15	27	0	8	0
Average			47.5	23.7	21,7	0	7.0	0
2001	1.02	3	40	30	6	6	15	3
2002	1.20	4	35	25	5	7	26	2
2003	1.44	4	36	12	8	8	36	0
2004	1.37	4	36	6	7	6	45	0
2006	1.47	7	37	8	6	4	44	1
2007	1.40	3	27	9	5	3	55	1
2009	1.33	7	33	1	9	2	54	1
2012	1.42	15	23	4	7	7	58	1
2015	1.09	4	17	1	9	9	63	1
2016	1.23	4	0	2	5	7	68	0
2017	1.55	15	12	4	10	7	66	1
2019	1.37	11	17	3	9	3	67	1
2020	0.92	5	11	1	5	5	77	1
Average			27.0	8.7	7.2	5.6	50.5	1.3

fragments of wood with metal elements are found (Łabuz and Olechnowicz 2004). There were mainly pieces of processed wood with metal parts. Untill 2001/02 ships and fishery have been the main source of litter on the coast. In that period people used only aluminium cans or plastic bottles for beach cosmetics. Other plastic comprised bottles of household or car chemicals only. Those found in washover fans dated to 1988 and 1995 have been excavated on the Świna Gate Sandbar. However, after the storm surge in January 2017, a lot of these old litter have been washed out from dune sediments after heavy erosion (Łabuz, 2018).

The ships and fishery origin decreased from 47% to 27%. The industry or building and agriculture waste have also decreased. However, construction elements are still numerous because of styrofoam or montage foams. Agriculture foil, old containers (washed from sediments of eroded part of the coast) have changed due to consumable packaging, industry materials and household tools. As a consumption of the original litter increased, all other groups have been less represented. The consumption packaging among litter has been growing from 10–15% in 2001 to 55% in 2007 and over 60% in 2017.

Wooden waste decreased from 23.7% to 8.7% of the total recorded litter. Its share has gradually decreased untill 2004. Among them there were elements of railings, furniture, construction and finishing materials as well as information boards. Metal waste due to its weight was rare, mainly as part of other material. Its quantity is decreasing over time. Metal waste that was observed included nails, pieces of wire and since 2012 also drink cans. In recent years, the amount of aluminium waste has been increasing, mainly due to increasing consumption by sunbathers. In some areas, water brings ammunition to the coast. Rubber was among the first non-natural materials in debris with older plastic particles. Due to its considerable weight, rubber was rarely found as single pieces of elements. Pieces of glass, due to their higher weight, do not end up in the sediments thrown by the sea onto the upper beach. Glass was usually found as bottles and jars closed with metal lids, less frequently also as light bulbs and fluorescent lamps. Due to its quick decomposition, the paper was not observed among the waste. In rare instances paper waste came as cardboard boxes mixed with plastic used for beverage packaging (the so-called tetra packs). This type of litter keeps increasing.

The largest amount of waste in each washover fan or sediment zone (up to 85% in total) was various plastic waste: bottles and boxes (from soft PP, PET to HDPE hard packaging used for chemicals). Since 2012 various plastics waste including bottles and boxes (up to 85% in total) composed the largest amount of litter in each location. After 2017 storm surge an increasing amount of small plastic <5 cm was observed. Some of them are eroded to small sand-size particles. Small particles of plastic >5 cm are mixed with sand or pressed into coastal vegetation.

Increasingly often, elements combined of various materials are washed ashore, such as: metal packaging and mounting foams, polystyrene and wood, fibres, wood and plastic in pieces of net, or plastic and metal in electronic parts.

Litter quantity change

Analyses proved that in subsequent years the litter volume in storm sediments has been increasing (Fig. 6). In subsequent years, small plastic elements became more common in deposits of washover fans and post-storm sediments, from bottle corks to broken pieces of larger pack-

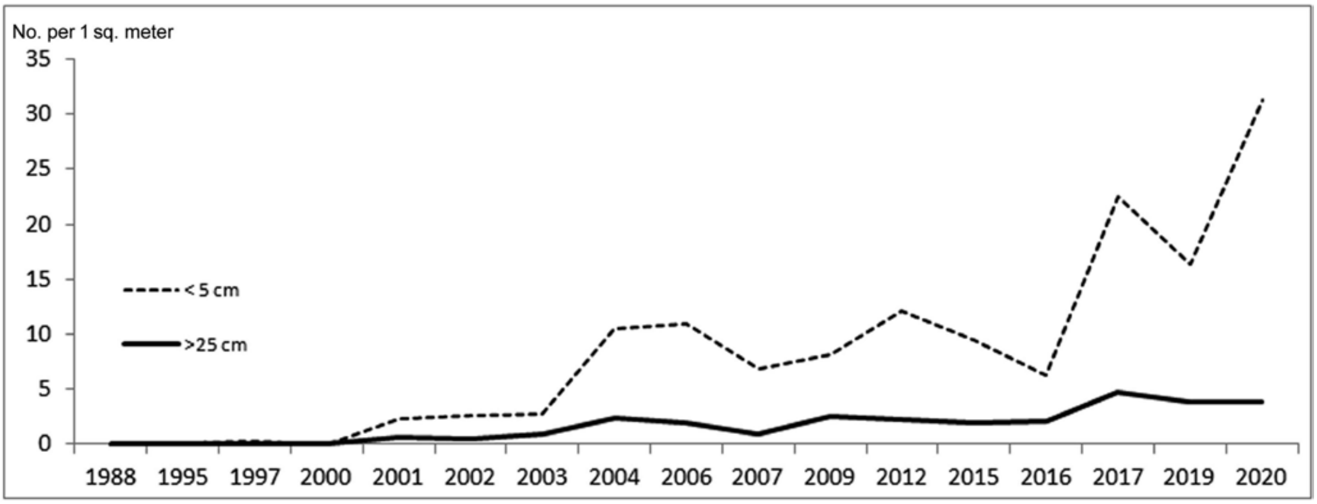

Fig. 6. Annual growth of an average number of litter particles (size <5 cm and >25 cm) in investigated areas of marine accumulation debris on the beach (1988–2020).

ages. In sediments since 2004, a volume of small size particles >5 cm per 1 m^2 doubled. In the storm washover fans of 2009 and 2012, small plastic elements, nuts, sticks and broken elements were dominant. Since 2012 post-storm accumulative surfaces have contained several times more litter than at the end of the 20th century. Table 4 presents a changing percentage of the main origin of litter in investigated marine debris concentrations (1988–2020). The largest amount of it was observed after the storms of 2017–2020. The growth from 10 items to almost 30 per 1 m^2 was observed after strong storm surges in 2012 and 2017. A content of items larger than 25 cm, like bottles and cans, has increased more slowly. However, their quantity changed from 1 to 5 items per 1 m^2 between 2002 and 2017. In 2017 the litter accumulation was the highest in terms of number of small infrastructure elements scattered on the beach. The situation repeated in January 2019 (surge named Zeetje). After 6 smaller storm surges from January to March 2020 still the same amount of larger items as bottles and cans and larger of small plastic were observed.

Figure 7 presents litter material percentage change in washover fans over time (1988–2020). Quantitative analysis of litter in investigated locations from storm surge debris from 1988 to 2020 presents at first, slow increase of plastic material and decrease of processed wood and then, rapid growth of plastic items after 2002–2004. Also, the rubber material was decreasing from 10 to 1–2%. The glass material has dropped from 20% to 5–6%, Almost 40% of average material content was plastic in 2007. This value increased to 70% in 2016 and 80% in 2017/19.

Since the beginning of the 21st century, rubbish of anthropogenic origin was gradually increasing among storm surge debris. From maximum 1.6 per 1 m^2 in 2001 to 4.7 in 2006 and 5–8 items in 2012. The larger increase was observed in 2012 and 2017 after strong storm surges affecting the whole Polish coast. Between 2017 and 2020 a number of

Table 4. Example of washover fans with quantity and quality of found anthropogenic artefacts

No. of fan	1	2	3	4	5	6	7	8	9	10
Year	1995	2001	2001	2002	2004	2006	2006	2009	2012	2017
Location (km)	422	291	421	420	024	389	421	343	192	265
H (m amsl)	0.8–1	1.8	2.2	2.2	1.8	1.9	2.7	2.9	1.8	2.2
Area (m)	1×2	2×5	5×10	10×20	3×8	2×8	2×10	5×10	3×7	6×4
Plastic bott.	1	1	1	9	0	2	2	4	18	32
Glass bott.	0	0	0	0	0	2	0	3	4	11
Alu. can	0	0	0	3	0	1	2	2	8	21
Glass jar	0	0	0	1	0	2	3	5	5	6
Cap	0	0	5	160	24	11	34	42	54	78
Styrofoam	0	3	2	5	1	3	3	6	4	8
Nets	1	4	2	0	1	4	3	4	3	2
Foil	1	3	1	4	2	3	3	6	5	2
Proc. wood	2	5	5	3	6	3	5	4	4	3
Plas. <5 cm	0	0	8	96	24	13	25	42	86	112
Plas. >25 cm	0	0	2	36	0	6	15	11	34	45
SUM	5	16	26	317	58	50	95	129	225	320
SUM/ 1m^2	2.5	1.6	0.50	1.60	2.41	3.10	4.75	2.60	10.70	13.33

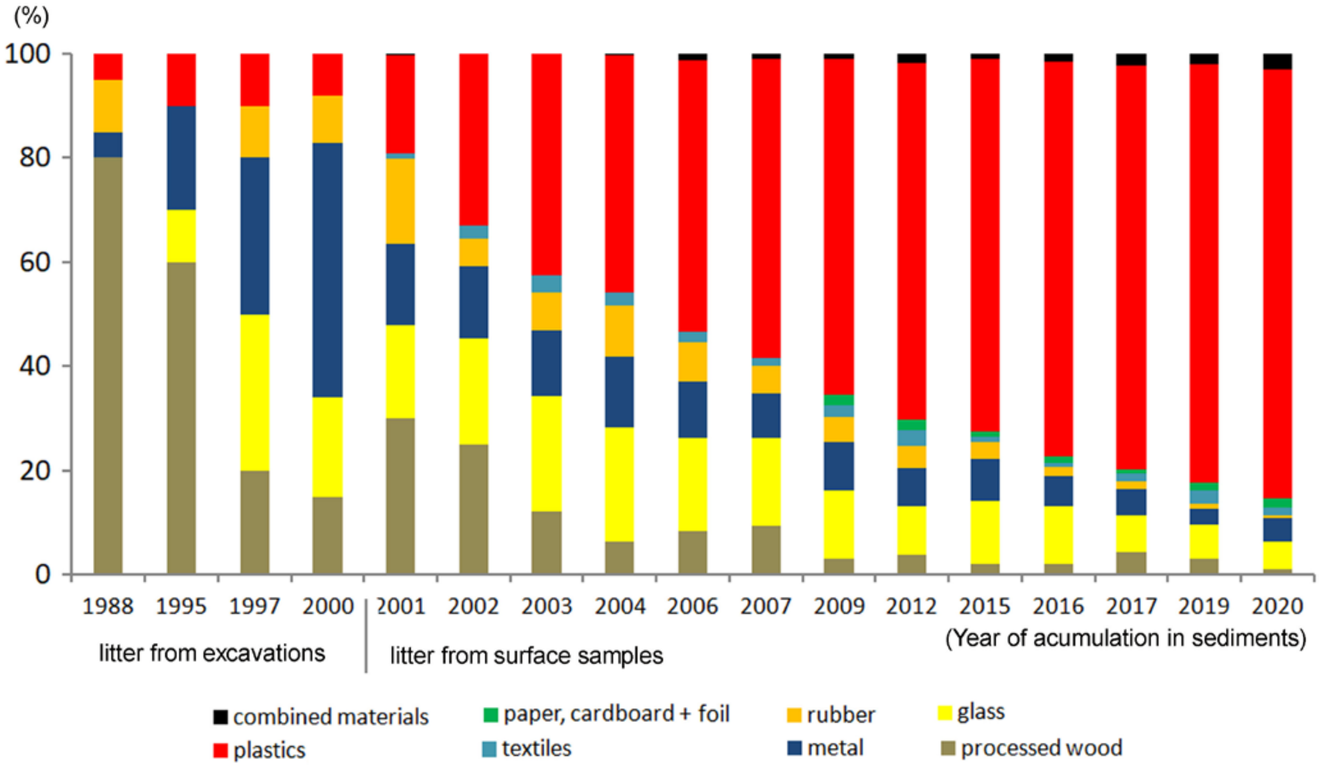

Fig. 7. Percentage distribution of material type in marine accumulation debris on the beach (1988–2020).

items per 1 m^2 exceeded 6–11. Also, there is visible higher number of small plastic particles <5 cm. Among quantified litter, an increase of plastic material and also broken plastic particles are noted.

DISCUSSION

Most marine litter has a very slow rate of decomposition, leading to a gradual, but significant accumulation in the coastal and marine environment (Cheshire *et al.*, 2009). Litter on the beach is an aesthetic and ecological problem (EA/NALG, 2000; Alkalay *et al.*, 2007; Oigan-Pszczol and Creed, 2007; Cheshire *et al.*, 2009; Galgani *et al.*, 2013; Aydm *et al.*, 2016; Fernadino *et al.*, 2016; Strand *et al.*, 2016; Zhou *et al.*, 2016; Portman and Brennan, 2017; Watts *et al.*, 2017 and others). Recent studies present that litter concentrations on beach is a growing problem for the Baltic sea coast (HELCOM, 2009, 2014; MARLIN, 2013; Balčiūnas and Blažauskas, 2014; Strand *et al.,* 2016; Hasler *et al.*, 2018), including the Polish coast (Urban-Malinga *et al.*, 2020; Zalewska *et al.*, 2021). Observation of grooving amount waste in post-storm debris was conducted after each storm surges since 2001 (Łabuz, 2002, 2007, 2018; Łabuz and Olechnowicz, 2004). Data counted for post-storm debris locations from 2001 to 2020 and in fossil sediments since 2002 show an increasing volume of litter per 1 m^2 and rapidly increasing plastic items. The litter amount on Baltic beaches quantified since 2013 exceeds 80–400 pieces / 100 m beach length in Denmark, Germany or Lithuania (MARLIN, 2013; Balčiūnas and Blažauskas, 2014; Strand *et al.*, 2016; Hasler *et al.*, 2018). This is almost 1 to 4 items per 1 m (or 1 m^2). On the Polish coast there is 1–6 items per 1 m^2 (Zalewska *et al.*, 2021). Some number differences are noted between seasons and after summer litter volume is larger. Summary results from the presented research of litter amount per 1 m^2 indicate 0.5 to 4 items and in recent very heavy storm surges up to 10–17 items. These amount is larger but concentrated in a smaller area, usually 20 to 50 m^2. Data quantitated for post-storm debris locations along the Polish Baltic coast from 2001 to 2020 and in fossil sediments since 1988 show an increasing number of litter per 1 m^2 and rapidly increasing plastic items. Since 2002 plastic waste in marine deposited debris increased from 30% to 60% in 2012 and almost 80% in 2017/19 of total waste (to 85% as largest debris waste percentage). The litter from Denmark, Swedish and German coast include 40–55% of polymers /plastic (Strand *et al.*, 2016; Hasler *et al.*, 2018), Lithuanian 70–80% (Balčiūnas and Blažauskas, 2014; Hasler *et al.*, 2018). The other Polish research shows 68.5% of plastic litter on the beach on average (Zalewska *et al.*, 2021). These values seem to be comparable, however there is a lower amount in the western part of the Baltic coast, where there is more effective environmental awareness and recycling.

The other material as processed wood, glass, rubber, metal or cardboard does not exceed 4–8% (MARLIN, 2013;

Balčiūnas and Blažauskas, 2014; HELCOM, 2014; Strand *et al.,* 2016; Hasler *et al.,* 2018; Zalewska *et al.,* 2021). The worldwide plastic in litter concentration on beach exceeds 65–85% (Taffs and Cullen, 2005; Browne *et al.,* 2010; Williams *et al.,* 2013; Laglbauer *et al.,* 2014; Aydm *et al.,* 2016; Fernadino *et al.,* 2016; Strand *et al.,* 2016; Zhou *et al.,* 2016; Watts *et al.,* 2017; Portman and Brennan, 2017). Such values are essentially linked to greater plastic durability and persistence, combined with rising production of plastics and low rates of recovery (Anfuso *et al.,* 2015). A new source of waste ashore is the land reclamation process. Sediment includes heavier non-floating waste and small broken plastics. Small particles of plastic >5 cm are easily mixed with sediment of the nourished beach.

Litter deposited from public use of the beach environment is a growing component of total debris (Gabrielides *et al.,* 1991; EA/NALG, 2000; Derraik, 2002; Taffs and Cullen, 2005; Cheshire *et al.,* 2009; HELCOM, 2014; Bergmann *et al.,* 2015; Jambeck *et al.,* 2015; Portman and Brennan, 2017). Waste from ships and fishery is a decreasing component of beach litter (Balčiūnas and Blažauskas, 2014; Strand *et al.,* 2016; Hasler *et al.,* 2018). In this study recognized waste from ships and fishery industry decreased from 40 to 15–12% through 20 years in the total amount of litter in post-storm debris.

Increasingly, due to increasing consumption and a lack of care for the environment, a sea throws ashore large accumulations of different plastics garbage, including packages, foil, cutlery, sticks, bottles, boxes, cans caps and a small, already broken items (there are granules comparable to the sand grains). The investigated post-storm waste spots show rapid growth of consumption packages and broken touristic equipment.

The amount of waste from the land, including litter left by vacationers on beaches, has increased significantly since 2009, exceeding 85% of the identified waste on average. On the Baltic coast, 40 to 80% of litter originates from touristic behaviour and the other 20–40% from land sources (Balčiūnas and Blažauskas, 2014; Strand *et al.,* 2016; Hasler *et al.,* 2018; Zalewska *et al.,* 2021). A similar litter amount of land origin is observed on other sea coasts (Rosevelt *et al.,* 2013; Laglbauer *et al.,* 2014; Jambeck *et al.,* 2015; Fernandino *et al.,* 2016; Munari *et al.,* 2016 and others).

Another problem on the Baltic coast is a litter from chemical, medical and hygiene use that come directly from the land (Balčiūnas and Blažauskas, 2014; Strand *et al.,* 2016; Hasler *et al.,* 2018). The bottles of chemical liquids, creams and even cotton bud sticks appear on beach sediment (Strand *et al.,* 2016). This material is carried by rivers. It was also observed in other coastal zones that land origin litter is deposited on beaches close to the rivers (Browne *et al.,* 2010; Moore *et al.,* 2011; Rosevelt *et al.,* 2013). Initially, this waste accumulates near the mouths and after storms, and it is scattered on further coast sections. Even more waste flows out of rivers after floods. Such phenomena were observed after flooding near the Vistula river and the Świna channel. The beach near the Vistula mouth, mainly accumulative on the eastern bank has 10–20 cm thick layers of litter covered by aeolian sand. These are washed out after storm surge erosion and then again covered by sand.

Other studies present paper and cigarette butts among the litter (Taffs and Cullen, 2005; Laglbauer *et al.,* 2014; Aydm *et al.,* 2016; Fernadino *et al.,* 2016; Strand *et al.,* 2016). These items are quickly decomposing in the marine environment, therefore are less visible in post-storm sediments (excluding cardboard boxes covered with foil).

An overwhelming majority (60–80%) of each litter type found on the studied beaches was derived from plastic material. The increasing use of plastic instead of more natural metal, wood or leather and larger production of plastic packed consumable items caused a growth of waste made of this material.

A seasonal variability in litter abundance is likely due to physical drivers such as winds and sea currents that may driver debris deposition. More of them are observed during winter (Rosevelt *et al.,* 2013). The studies from the Baltic coast present larger waste on the beach after summer (Balčiūnas and Blažauskas, 2014; Strand *et al.,* 2016), which is related to the sunbathing season.

In this study, an increased volume of waste was observed in two periods. After the holiday season waste remains on beaches, dunes and cliff viewpoints, and it is observed from July to September-October along touristic beaches (resorts). After storm surges from October to March, there is much more waste on beaches of the entire coast than after summer. Litter is washed away from touristic beaches and secondly distributed in remote coastal areas.

In the touristic resorts the waste is collected mainly by raking, but on remote coast, the waste remains on the beach and is buried. Artificial remnants (mainly plastic and glass) stay in sediments for years and do not decompose. After another heavy storm erosion, they can be brought to the surface. During a research after the storm in January 2017, the oldest plastic, metal and glass waste from the 1980s were washed out from under the eroded dunes.

CONCLUSIONS

The article presents sources and types of litter on a beach and shows an increase in the amount of litter in storm surge fans. The material was collected during a long period and only the stands investigated with the same accuracy were compared, where each waste in the fans was counted.

As it is observed during years of the investigation carried over human impact in coastal dune environment, anthropogenic waste is a growing problem on beaches of the Polish coast.

In the last few years, the larger amount of litter accumulated on the beach is a primary source of the waste left on the beach by tourists. Litter can be found in each coastal environment from river mouth and lake, through dunes, beach to foreshore sediment. Large amount of various types of waste, including large-size waste, are carried by rivers after floods.

The origin and type of litter are hanging in time. Processed wood with metal items and fishery litter is decrease, but consumption of plastic packages increases. It results in more waste on beaches during summer holidays. The litter is mostly composed of medium size items 5–25 cm including beverage bottles, cans and boxes, food wrappers, nuts, more and more small and microparticles. These larger items are collected by appropriate services in seaside resorts only. However, a number of them remains buried in a sand. On the natural beaches, remote from resorts, they are not collected. After storm surge litter is washed by the sea and as a secondary source is left on the coast again or in remote sections (mainly natural ones). These artefacts mixed with natural debris form washover fans or heaps of waste. In such places, litter is not collected and the smallest one stays in sediment or is buried in a sand. Among them, there are more and more plastic particles every year. Even after a small surge or sea waving, water is throwing heavier glass or metal that is eroded from foreshore bottom sediments. Plastic found on the beach includes mainly touristic and consumable items. After 2002/04, the first plastic packages from consumption were found in the sediment. A number of consumable items increased and since 2006/2009 has been doubled in post-storm debris.

Each year after storm surges more litter appears in marine debris. Litter quantity in post-storm washover fans is related to a storm surge strength and range along the coast. The higher the storm surge the more litter appears on the beach. Those litter loads include more plastic than at the beginning of the 21st century. The names and types of products also inform about the brand popularity and its presence in the market. On the Polish Baltic coast, one can find litter originating from neighbouring countries and it informs about waste circulation in a sea. The range of waste location onshore depends on storm surge level causing the height of water inflow on the land or coastal lakes and river mouths.

There is an observed decrease in processed wood, glass or metal (iron). Quantity of cardboard and foil packages, aluminium cans and mixed elements (as electronics) is slowly increasing. In recent years a litter amount, mainly of consumable origin, is growing on beaches and adjacent land.

Acknowledgement

The presented material has been collected by the author during research in own financed project focused on anthropogenic pressure on the Polish dune coast titled Anthropogenic Natural Dunes Dynamics ANDDY (http://polishdunes.usz.edu.pl).

REFERENCES

Alkalay, R., Pasternak, G., Zask, A., 2007. Clean-coast index – a new approach for beach cleanliness assessment. Ocean & Coastal Management 50, 352–362.

Anfuso, G., Lynch, K., Williams, A.T., Perales, J.A., Pereira da Silva, C., Nogueira Mendes, R., Maanan, M., Pretti, C., Pranzini, E., Winter, C., Verdejo, E., Ferreira, M., Veiga, J., 2015. Comments on marine litter in oceans, seas and beaches: characteristics and impacts. Annals of Marine Biology Research 2(1), 1008.

Arcangeli, A., Campana, I., Angeletti, D., Atzori, F., Azzolin, M., Carosso1, L., Di Miccolil, V., Giacoletti, A., Gregorietti, M., Luperini, C., Paraboschi, M., Pellegrino, G., Ramazio, M., Sarà, G., Crosti, R., 2017. Amount, composition, and spatial distribution of floating macro litter along fixed trans-border transects in the Mediterranean basin. Marine Pollution Bulletin 129, 545–554.

Aydın, C., Güven, O., Salihoğlu, B., Kıdeyş, A.E., 2016. The Influence of land use on coastal litter: An approach to identify abundance and sources in the coastal area of Cilician Basin, Turkey, Turkish Journal of Fisheries and Aquatic Sciences 16, 29–39.

Balčiūnas, A., Blažauskas, N., 2014. Scale, origin and spatial distribution of marine litter pollution in the Lithuanian coastal zone of the Baltic Sea. Baltica 27, 39–44

Bergmann, M., Gutow, L., Klages, M. (Eds), 2015. Marine anthropogenic litter. Springer International Publishing, Switzerland. 447 pp.

Browne, M.A., Galloway, T.S., Thompson, R.C., 2010. Spatial patterns of plastic debris along estuarine shorelines. Environmental Science & Technology 44, 3404–3409.

EA/NALG, 2000. Assessment of aesthetic quality of coastal and bathing beaches. Monitoring protocol and classification scheme. Environment Agency and The National Aquatic Litter Group, London.

Cheshire, A.C., Adler, E., Barbičre, J., Cohen, Y., Evans, S., Jarayabhand, S., Jeftic, L., Jung, R.T., Kinsey, S., Kusui, E.T., Lavine, I., Manyara, P., Oosterbaan, L., Pereira, M.A., Sheavly, S., Tkalin, A., Varadarajan, S.,Wenneker, B., Westphalen, G., 2009. UNEP/IOC Guidelines on Survey and Monitoring of Marine Litter. UNEP Regional Seas Reports and Studies, No. 186, IOC Technical Serious No. 83.

Corcoran, P.L., Biesinger, M.C., Grifi, M., 2009. Plastics and beaches: A degrading relationship. Marine Pollution Bulletin 58 (1), 80–85.

Derraik, J.G.B., 2002. The pollution of the marine environment by plastic debris: a review. Marine Pollution Bulletin 44, 842–852.

Fernandino, G., Elliff, C.I., Silva, I.R., de Souza Brito, T., da Silva Pinto Bittencourt, A.C., 2016. Plastic fragments as a major component of marine litter: a case study in Salvador, Bahia, Brazil, Revista de Gestão Costeira Integrada. Journal of Integrated Coastal Zone Management 16(3), 281–287.

Gabrielides, G.P., Golik, A., Loizides, L., Marino, M.G., Bingel, F., Torregrossa, M.V., 1991. Man-made garbage pollution on the Mediterranean coastline. Marine Pollution Bulletin 23, 437–441.

Galgani, F., Hanke, G., Werner, S., De Vrees, L., 2013. Marine litter within the European marine strategy framework directive. ICES. Journal of Marine Science 70 (6), 1055–1064.

HELCOM, 2009. Marine Litter in the Baltic Sea Region: Assessment and priorities for response. Helsinki, Finland, 1–20.

HELCOM, 2014. Marine Litter in the Baltic Sea: sources, monitoring approaches, possible common indicators and first lines of thinking on measures. Monitoring and Assessment Group (MONAS) Oslo, Norway, 1–51.

Hasler, M., Schernewski, G., Balciunas, A., Sabaliauskaite, V., 2018. Monitoring methods for large micro- and meso-litter and applications at Baltic beaches. Journal of Coastal Conservation 22, 27–50.

Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R., Law, K.L., 2015. Plastic waste inputs from land into the ocean. Science 347 (6223), 768–771.

Jóźwiak, T., 2010. Parametryzacja stanu sozologicznego wybrzeża południowego Bałtyku w świetle idei rozwoju zrównoważonego. Wydawnictwo Uniwersytetu Gdańskiego, 248 (in Polish)

Laglbauer, B.J.L., Franco-Santos, R.M., Andreu-Cazenave, M., Brunelli, L., Papadatou, M., Palatinus, A., Grego, M., Deprez, T., 2014. Macrodebris and microplastics from beaches in Slovenia. Marine Pollution Bulletin 89, 356–366.

Łabuz, T.A., 2002. Eamples of anthropopresion on the coastal dunes of Swina Gate Sandbar. In: Szwarczewski, P., Smolska, E. (Eds), Zapis działalności człowieka w środowisku przyrodniczym, 77–84, UW, Warszawa, (in Polish with English summary).

Łabuz, T.A., Olechnowicz, P., 2004. Reconstruction of the accumulative dune coast relief on the basis of sedimentological structures – case study from the Świna Gate Sandbar. In: Błaszkiewicz, M., Gierszewski, P. (Eds), Rekonstrukcja i prognoza zmian środowiska przyrodniczego w badaniach geograficznych, 237–248, Prace Geograficzne 200, IGiPZ PAN, Warszawa (in Polish with English summary).

Łabuz, T.A., 2007. A record of contemporary anthropogenic pollutants in sediments and surface relief of the Świna Gate Sandbar. In: Smolska, E., Szwarczewski, P. (Eds), Zapis działalności człowieka w środowisku przyrodniczym, 89–98, Wydawnictwo Szkoły Wyższej Przymierza Rodzin, Warszawa (in Polish with English summary).

Łabuz, T.A., 2009. Distal washover fans on Świna Gate Sandbar. Oceanological and Hydrobiological Studies 38 (Supplement 1), 79–95.

Łabuz, T.A., 2015. Coastal dunes: Changes of their perception and environmental management. In: Finkl, Ch.W., Makowski, Ch. (Eds), Environmental management and governance. Advances in coastal and marine resources series, 323–410, Coastal Research Library 8, Springer.

Łabuz, T.A., 2018. Erosion of sandbar dunes of Koszalin Bay resulting from extreme storm events Barbara and Axel from the turn of 2016 and 2017. Przegląd Geograficzny 90 (3), 435–477, (in Polish with English summary).

MARLIN, 2013. Final report of the Baltic marine litter project MARLIN. Litter Monitoring and raising awareness 2011-2013, http://www.projectmarlin.eu/sa/node.asp?node=3005.

Moore, C.J., Lattin, G.L., Zellers, A.F., 2011. Quantity and type of plastic debris flowing from two urban rivers to coastal waters and beaches of Southern California. Jorunal of Integrated Coastal Zone Management 11 (1), 65–73.

Munari, C., Corbau, C., Simeoni, U., Mistri, M., 2016. Marine litter on Mediterranean shores: analysis of composition, spatial distribution and sources in north-western Adriatic beaches. Waste Management 49, 483–490.

Oigan-Pszczol, S.S., Creed, J.C., 2007. Quantification and classification of marine litter on beaches along Armacao dos Buzios, Rio de Janeiro, Brazil. Journal of Coastal Research 23 (2), 421–428.

OSPAR, 2010. Guideline for Monitoring Marine litter on the Beaches in OSPAR Maritime area. OSPAR Commission, 1–84.

Portman, M.E., Brennan, E., 2017. Marine litter from beach-based sources: Case study of an Eastern Mediterranean coastal town. Waste Management 69, 535–544.

Pruter, AT., 1987. Sources, quantities and distribution of persistent plastics in the marine environment. Review. Marine Pollution Bulletin 18 (6), Suppl. l8, 305–310.

Ryan, P.G., 2015. A brief history of marine litter research. In: Bergmann, M., Gutow, L., Klages, M. (Eds), Marine anthropogenic litter, 1–25, Springer International Publishing, Switzerland.

Rosevelt, C., Los Huertos, M.W., Garza, C., Nevins, H., 2013. Marine debris in central California: Quantifying type and abundance of beach litter in Monterey Bay, CA. Marine Pollution Bulletin 71 (1–2), 299–306.

Silva-Iñiguez, L., Fisher, D.W., 2003. Quantification and classification of marine litter on the municipal beaches of Ensenada, Baja California. Marine Pollution Bulletin 46 (1), 132–138.

Sheavly, S.B., Register, K.M., 2007. Marine debris and plastics: environmental concerns, sources, impacts and solutions. Journal of Polymers and the Environment 15, 301–305.

Strand, J., Tairova, Z., Metcalfe, R. d'A., 2016. Status on beach litter monitoring in Denmark 2015. Amounts and composition of marine litter on Danish reference beaches. DCE – Danish Centre for Environment and Energy, 42 pp. Scientific Report from DCE – Danish Centre for Environment and Energy 177. Aarhus University, p 42.

Taffs, K.H., Cullen, M.C., 2005. The distribution and abundance of beach debris on isolated beaches of northern New South Wales, Australia. Australian Journal of Environmental Managing 12, 244–250.

Thiel, M., Hinojosa, L.A., Miranda, L., Pantoja, J.F., Rivadeneira, M.M., Vasquez, N., 2013. Anthropogenic marine debris in the coastal environment: a multi-year comparison between coastal waters and local shores. Marine Pollution Bulletin 71, 307–316.

Tudor, D.T., Williams, A.T., Philips, M.R., Thomas, M C., 2002. Qualitative and quantitative comparisons of some indices suitable for litter analysis. In: The changing coast. Littoral 2002. EUROCOAST/ EUCC, Porto, Portugal, 367–373.

Urban-Malinga, B., Zalewski, M., Jakubowska, A., Wodzinowski, T., Malinga, M., Pałys, B., Dąbrowska, A., 2020. Microplastics on sandy beaches of the southern Baltic Sea. Marine Pollution Bulletin 155, 111170.

Williams, A., Pond, K., Ergin, A., Cullis, M.J., 2013. The hazards of beach litter. In: Finkl, Ch.W. (Ed.), Coastal Hazards. Springer, Dordrecht, 753–780.

Watts, A.J.R., Porter, A., Hembrow, N., Sharpe, J., Galloway, T.S., Lewis, C., 2017. Through the sands of time: beach litter trends from nine cleaned North Cornish beaches. Environmental Pollution 228, 416–424.

Vanninen, P., Östin, A., Bełdowski, J., Pedersen, E.A., Söderström, M., Szubska, M., Grabowski, M., Siedlewicz, G., Czub, M., Popiel, S., Nawała, J., Dziedzic, D., Jakacki, J., Pączek, B., 2020. Exposure status of sea-dumped chemical warfare agents in the Baltic Sea. Marine Environmental Research 161, 105112, p. 10.

Zalewska, T., Maciak, J., Grajewska A., 2021. Spatial and seasonal variability of beach litter along the southern coast of the Baltic Sea in 2015–2019 – Recommendations for the environmental status assessment and measures. Science of the Total Environment 774, 145716, doi.org/10.1016/j.scitotenv.2021.145716.

Zhou, Ch., Liu, X., Wang, Z., Yag, T., Shi, L., Wang, L., You, S., Li M., Zhang, C., 2016. Assessment of marine debris in beaches or seawaters around the China Seas and coastal provinces. Waste Management 48, 652–660.