Article

Not peer-reviewed version

Marine Macro-Litter (Plastic) Pollution of European and African Marina and City Port Sea Floors

Gerald Schernewski * , Gabriela Escobar-Sánchez , Philipp Wandersee , Xaver Lange , Mirco Haseler , Abdallah Nassour

Posted Date: 25 September 2023

doi: 10.20944/preprints202309.1599.v1

Keywords: recreational harbour; harbor sediment; monitoring; hydrodynamic model; waste water; indicator; policy; Baltic Sea; Hanse Sail Rostock; Kiel Week

Article

Marine Macro-Litter (Plastic) Pollution of European and African Marina And City Port Sea Floors

Gerald Schernewski [1,2*], Gabriela Escobar Sanchez [1,2], Philipp Wandersee [1,3], Xaver Lange [4], Mirco Haseler [1] and Abdallah Nassour [3]

1 Coastal & Marine Management Group, Leibniz-Institute for Baltic Sea Research, Seestrasse 15, D-18119 Rostock-Warnemünde, Germany; gerald.schernewski@io-warnemuende.de (G.S.), gabriela.escobar@io-warnemuende.de (G.E.S.); philipp.wandersee@t-online.de (P.W.), mirco.haseler@io-warnemuende.de (M.H.)
2 Marine Research Institute, Klaipeda University, Universiteto Ave. 17, LT-92294 Klaipeda, Lithuania
3 Waste and Resource Management, Rostock University, Justus-von-Liebig-Weg 6, D-18059 Rostock, Germany; abdallah.nassour@uni-rostock.de (A.N.)
4 Department of Physical Oceanography and Instrumentation, Leibniz-Institute for Baltic Sea Research, Seestrasse 15, D-18119 Rostock-Warnemünde, Germany xaver.lange@io-warnemuende.de (X.L.)
* Correspondence: gerald.schernewski@io-warnemuende.de; Tel.: +49-381-5197207

Abstract: The macro-litter (plastic) sea bottom pollution of 14 city harbors and marinas in North Africa and in the western Baltic Sea was investigated using a new simple mobile underwater camera system. The study was complemented by a harbor manager survey and 3D-hydrodynamic transport simulations. The average pollution in German marinas was 0.1 particles/m² sea floor (0.04–1.75). The pollution in North African marinas on average was 7 times higher (0.7 particles/m²) and exceeded 3 particles/m² in city center harbors. The resulting >100,000 litter particles per harbor indicate the existence of a problem. With 73%-74%, plastic particles are dominating. Existing legal and management frameworks explain the lack of plastic bottles and bags on sea floors in Germany and are one reason for the lower pollution levels. Items that indicate the role of untreated sewage water were not found. Harbor festivals seem not to be quantitatively relevant for open sea bottom pollution. Our method tends to underestimate the pollution level. Model simulations indicate that storms can cause litter reallocations and sediment cleanings. However, marina sea floor monitoring is recommendable, because it addresses pollution hot-spots, is cost-effective and takes place close to emission sources. Further, the effectiveness of land-based pollution reduction measures can easily be assessed.

Keywords: recreational harbour; harbor sediment; monitoring; Baltic Sea; Hanse Sail Rostock; Kiel Week; hydrodynamic model; waste water; indicator; policy

---

1. Introduction

It is estimated that 250,000 metric tons of plastic float in the seas and that macro- and meso-plastic (> 5 mm) has a weight share of 86% in it [1]. Marine macro plastics (>25 mm) can be distinguished into floating and sinking material, depending on the density. Biofouling by marine biota increases the density of plastics and within weeks turns floating into sinking plastic [2]. Floating material can be transported by wind and currents over long distances [3], but a large share is accumulated at beaches in the surrounding of the emission pathways by surface wave activity [4]. Sinking plastics can be accumulated on the sea bottom, especially in sheltered bays or in the deep sea. Canals et al. [5] provide a comprehensive overview about the present global state. However, large shares of plastics that accumulate on sandy coastal sea bottoms are subject to wave induced resuspension and at the end largely end-up at the coastline, as well [6]. The accumulation of amber at beaches visualizes this process [7]. Altogether, near the coast, beaches and sheltered coastal areas, such as bays and harbors/ports, are likely hot-spots for plastic accumulation [8, 9].

The emitted quantities of macro-plastics are correlated to human activities, population densities and modified by human behavior and the effectiveness of waste management systems. Large rivers,

 doi:10.20944/preprints202309.1599.v1

coastal urban areas as well as untreated sewage and stormwater are considered as major pathways for macroplastic to the marine environment [10]. Additionally, intensively used touristic beaches can also serve as a source for macroplastic in the marine environment and not only as a sink [10]. Human activities especially in and around urban coastal areas have to be regarded as of highest importance for marine plastic emissions [11].

In most parts of the Baltic Sea, coastal city centers do not host industrial ports any more, but the city seaside has been transformed into leisure and recreation areas, hosting leisure boat marinas and offering water access for locals and tourists. Further, during the last decades, the Baltic Sea became an inner European Union sea. This development fueled water related tourism and the number of sport boat ports increased. Additionally, many city harbors got additional infrastructures to host the increasing number of cruise ships and ferry lines as well as associated tourism. In 2017, over 5 million passengers visited the Baltic ports onboard cruise ships. The number of calls was about 2500 cruise ships and is still increasing [12]. Additionally, in 2023, 86 regular ferry routes existed in the Baltic Sea [13] and in 2020 about 67 million passengers embarked and disembarked in the over 200 larger commercial Baltic Sea ports [14]. Around the Baltic Sea about 95 coastal cities are located as well as many smaller seaside resorts. The vast majority has a city port and hosts marinas. These number underlines the increasing potential importance of city and sport boat ports as plastic emission and pollution hotspots in the Baltic Sea region, similar to other regions [15].

In the recent assessment of the state of the Baltic Sea, marinas and leisure harbors are considered as a pressure [16] and marine litter is taken into account as indicator. However, reliable data on litter (plastic) sea floor pollution in harbors is scarce [17]. From a fishing port in Turkey over 300 kg of seabed litter extracted in 2017 [18]. In 2020 in Newport harbor (USA) scuba divers collected over 2000 kg of marine litter [19]. In 2022, in Mülheim harbor (Germany) 3 divers collected 200 kg of marine litter within 2 hours [20]. From the city port of Rostock (Germany), 550 kg of marine litter were removed during one day in 2022 [21]. This data indicates that a largely unknown pollution problem in harbors seems to exist.

The question is, why there is no marine litter pollution monitoring in harbors, if harbors are pollution hot-spots? Presently, the marine litter monitoring in the European Union (EU) follows the requirements of the Marine Strategy Framework Directive (MSFD) [22] that aims at a good environmental status of the European regional seas and coasts. As a consequence, the monitoring focusses on open seas and remote beaches and not on pollution hot-spots.

Potentially, several methods exist that are suitable for a marine litter (plastic) monitoring in harbors. Dredging and trawling are mechanical options. Optical methods use videos and images collected by divers, by high resolution cameras installed on remotely operated vehicles or use towed cameras. Acoustic methods use, for example, side scan sonar, synthetic aperture sonar or multibeam echosounder systems. Madricardo et al. [23] and Hanke et al. [24] provide a comprehensive overview about applied methods. Problems of existing approaches are relatively high costs and efforts as well as that they are often not suitable for marinas with a complex shape and large number of boats [25]. Therefore, a new city port and marina pollution screening method is needed that is simple and cost-effective. It should focus on providing data that enables pollution reducing measures and allows assessing their effectiveness.

Our overall objective is to provide an insight into harbor sea floor pollution with macro-litter (plastic) in contrasting areas in the Baltic Sea region and in North Africa by combining field studies and monitoring with literature reviews and modeling. This includes the development and application of a cost-effective harbor bottom plastic screening method.

2. Study sites and methods

2.1. Study area

The sea bottom pollution study was carried out in a total of 14 marinas in North Africa and in the western Baltic Sea. In North Africa, sampling took place in two marinas in the city of Alexandria in Egypt (6.1 million inhabitants) and in three marinas in Tunisia, namely the city of Bizerte (about

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 25 September 2023 doi:10.20944/preprints202309.1599.v1

143,000 inhabitants), Yasmine Hammamet (a tourism resort and part of the city of Hammamet, the latter has about 100,000 inhabitants) and Monastir (about 93,000 inhabitants). The criteria for selecting the harbors were their accessibility and their location in an urbanized area. All African marinas have touristic infrastructure and beaches in the vicinity (Figure 1).

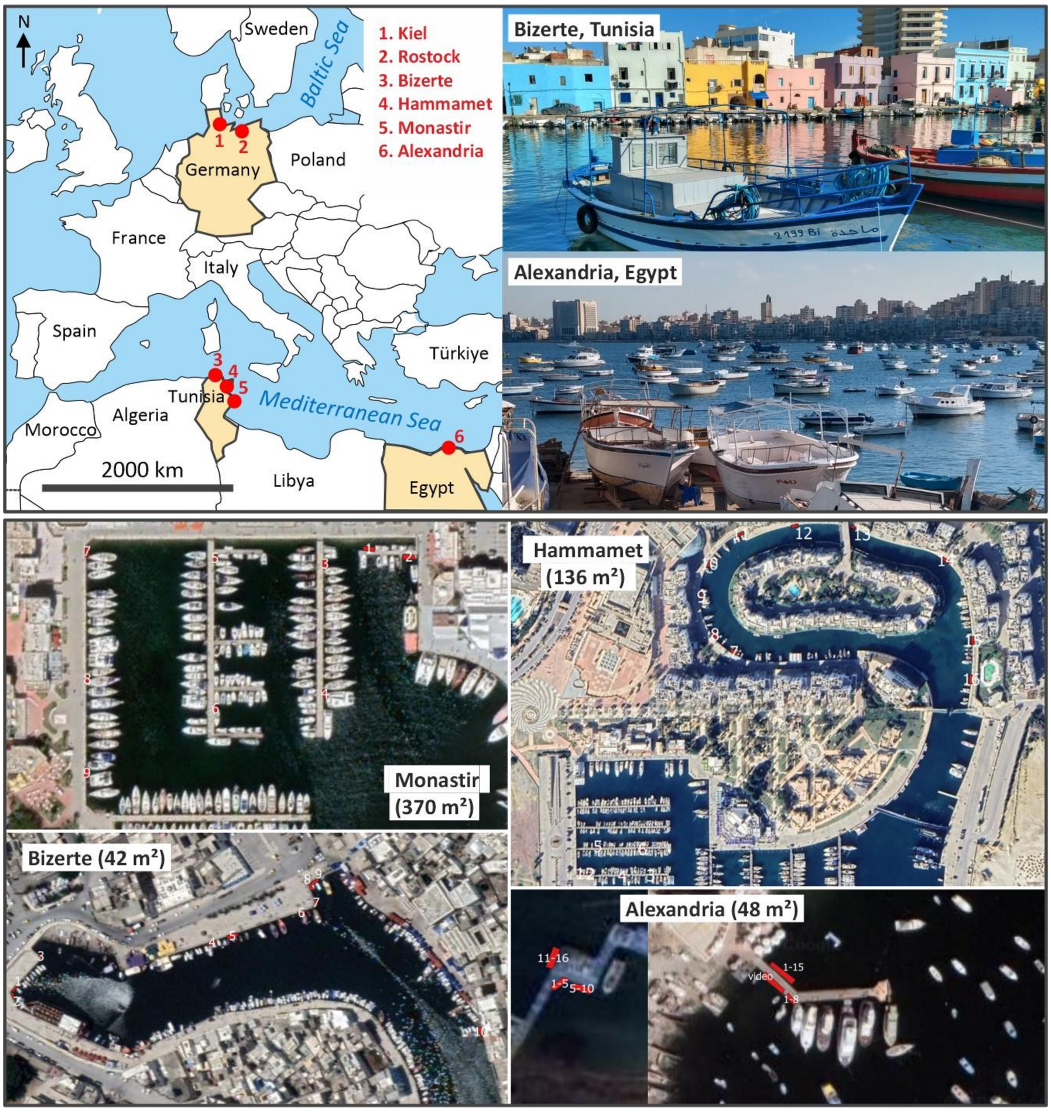

Figure 1. General overview about sampled the sites in Tunesia, Egypt and Germany as well as all North African harbors including name, investigated sea bottom area (m^2) and concrete locations within the harbors (numbered red areas). Satellite images by GoogleMaps.

In the Baltic Sea, the studies focused on harbors in the surrounding of the cities of Rostock and Kiel. Rostock (210,000 inhabitants) and Kiel (246,000 inhabitants) are located in the western Baltic Sea and are the most important Baltic Sea harbor cities in Germany. Both host cruise, cargo, dry and military ports as well as shipyards. In addition, each city has 10 marinas for leisure boats. Sampling took place in four of the marinas in Rostock (Alter Strom, Hohe Düne, Alter Stadthafen and Ludewigbecken) and in five marinas in and around Kiel (Düsternbrook, Seeburg, Strande, Wendtorf and Laboe) (Figure 2).

Figure 2. Details of the harbors in Rostock and Kiel, Germany, including name, investigated sea bottom area (m²) and concrete locations within the harbors (numbered red areas). Satellite images by GoogleMaps.

With the Kiel Week and the Hanse Sail Rostock, the cities host major annual Baltic sailing and harbor events. The Kiel Week is the largest sailing event in the world and the largest summer festival in the Baltic Sea region. In 2023, it attracted 3.8 million visitors over nine days, the highest number ever recorded. More than 100 larger historic steam and sailing ships offered boat trips, over 4000 sport-sailors with about 1500 boats took part in the competitions and 22 cruise ships visited the harbor during the event [26]. The Hanse Sail was founded in 1991. In 2023, the Hanse Sail Rostock counted about 500,000 visitors during four days and about 150 ships offered boat trips for the visitors [27]. Before the COVID-19 pandemic, for example in 2009, the Hanse-Sails counted more than 1 million visitors and in some years more than 200 participating historic ships [28]. The potential role of these events on sea bottom pollution was one aspect of interest.

2.2. Screening method for macro-litter on the bottom of marinas

For the sea bottom screening a fast mobile system was developed, tested and improved in several iteration cycles. An underwater camera (GoPro 8) and an underwater light were installed on a 3 m meter carbon telescope-stick. The camera was connected to a smartphone via a coax cable. The smartphone App GoPro Quick was used to control the underwater camera and to transfer, store and view the photos and videos on the smartphone above the water. During each sampling start- and end-time, cloud cover, wind speed [m/s], estimated wave height [m], water depth [m], water transparency/Secchi depth [m] camera depth and spatial coverage of the underwater photos were protocolled. The system was applied from bridges, catwalks, quay walls and piers. Depending on the structure and size of the marina between 2 and more than 20 different spots in a marina were investigated and the surveyed area ranged from 7-8 m² in Montazah and Ludewigsbecken to 756 m² in Hohe Düne, Rostock. A total of 1938 m² of harbor bottom was sampled in Germany and 596 m² in North Africa. Data collection took place between March and July 2022 [29].

The underwater photos were analyzed visually, by bare eye watching the photos on a large computer monitor, according to Watters et al. [30]. The identified litter items were documented and categorized according to the OSPAR guidelines for monitoring marine litter on beaches [31]. A video-based analysis was tested but not applied for field data collection.

The total costs for equipment were 666 Euros, including the under-water camera (GoPro Hero 8, 225 €) and the smartphone (Huawei P8 Lite, 167 €), an additional underwater light (60 €) and the telescope stick (60 €). The time required to cover one square meter of harbor bottom ranged from 0.3 to 10 minutes (median about 1 minute), depending on the degree of pollution and water transparency (Figure 3).

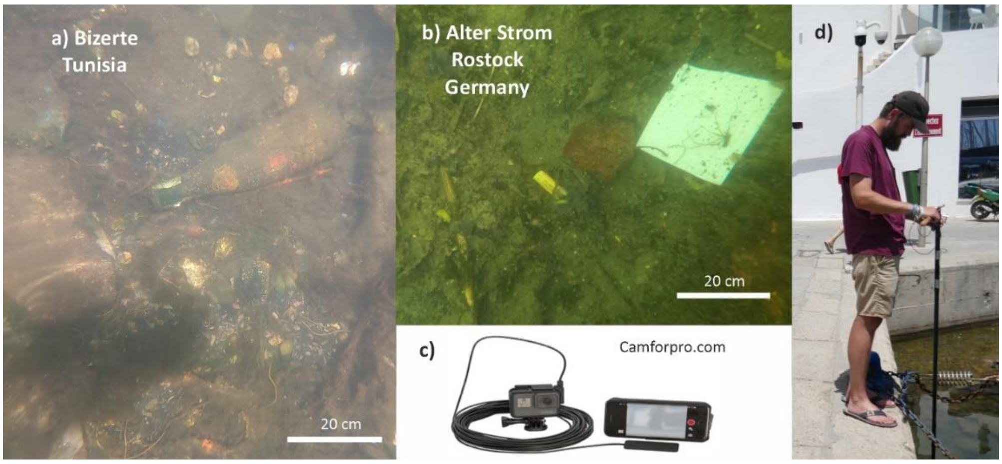

Figure 3. Exemplary underwater photos from a Tunisian (a) (Mediterranean Sea) and a German (b) (Baltic Sea) marina as well as the technical setup (c) and the method field application (d).

2.3. Model approach

Exemplary model simulations were carried out for Rostock harbor covering the entire Warnow Estuary including the coastal parts of the western Baltic Sea. The model simulations covered two Hanse Sail events, because the Hanse Sail is most likely the largest emission event of macro-litter into the Rostock city harbor. The aim was to gain insight into whether sinking litter is deposited locally at the sea bottom near the emission site or is transported over longer distances.

The simulations involved two steps: first, a 3D hydrodynamic model calculated hindcast simulations for the years 2009 and 2010, and second, the results were used for an offline Lagrangian particle tracking approach. For the former, the General Estuarine Transport Model (GETM) [32, 33] with the General Ocean Turbulence Model (GOTM) [34] as the turbulence closure model was used. The study area is numerically discretized on a structured grid with a horizontal resolution of 20m and a vertical resolution of 25 terrain-following sigma-layers. The meteorological forcing is calculated from the output of a reanalysis product of the German Weather Service (COSMO-REA6) with a temporal resolution of one hour and a spatial resolution of 6km. Discharge data of the river Warnow were included as daily mean values. Lange et al. [35] provide details on boundary conditions and model validation.

The main output parameters were staggered horizontal current velocities on an Arakawa C-grid, horizontal eddy viscosity calculated using a Smagorinsky parameterization, and bottom shear stress based on a quadratic drag, stored with 5min resolution each. These were used as forcing inputs for the particle tracking model Ocean Parcels [36]. Diffusion was considered using the Milstein scheme (1st order) and a critical stress condition for near-bottom particles was implemented (see below). Particles were allowed to beach in coastal sections characterized by reeds.

2.4. Scenario simulations

The model simulations addressed only sinking litter (plastics). The most relevant sinking plastic polymers are rigid polyvinyl chloride (PVC, density 1.3-1.45 g/cm³) and polyethylene terephthalate (PET, density 1.38 g/cm³).

In the shallow city harbor, with a water depth of about 2.5 - 3.5 m near the harbor wall and up to 6 m in the shipping channel, common sinking plastic particles such as PVC or PET settle to the harbor bottom within minutes. At the bottom, the particles were assumed to be transported with the 50 cm layer of bottom water. Particles deposited on the sediment require a higher bottom shear stress to be remobilized and transported. We assumed that only the highest 25% of the bottom shear stresses, calculated during the simulation period, would cause a transport. These optimistic assumptions generally favor a near-bottom transport.

The model and Lagrangian plastic transport simulations covered the Hanse Sail years 2009 and in 2010. Background is that Hanse Sails are likely causing pollution and that several events were accompanied by intensive data collection and field activities on litter emissions. The years 2009 and 2010 were chosen because they had contrasting weather conditions and were among the years with the highest number of visitors. The particle tracking simulations always started at the beginning of the Hanse Sail and ended after 10 days. Additionally, one simulation assumed that the strongest storm of the year 2009 (strong gale; maximum wind speed of 21.9 m/s) occurred immediately after the Hanse Sail. Aim was to gain insight into the potential reallocation of bottom litter under extreme conditions.

The field data of several Hanse Sail years allowed an estimation of floating litter emissions, but were too weak to provide data on sinking litter emissions into the estuary. For the model simulations we assumed (expert guess) an emission of litter (plastic) with a density above 1 g/cm^3 of 0.3 emitted macro-litter particles per 1000 visitors per day.

The scenario hypothetically assumed the emission of one sinking plastic particle per 300 Hanse Sail harbor coast-line (about 2.1 km), emitted hourly during the Hanse Sail opening hours (Thu. to Sun. between 12:00-24:00 o'clock). That means 91 particles were emitted per day and 364 particles altogether during the whole event.

3. Results

3.1. Litter pollution in harbors – concentrations

The marinas in Rostock differ in location and framework conditions. The Alter Strom in Rostock-Warnemünde is a former fishing harbor in the center of the seaside resort Warnemünde. The Alter Stadthafen is the oldest harbor basin in Rostock city center and the Ludewigsbecken is an old but recently restored harbor area. In principle, all harbors already exist for over 500 years are nowadays used for leisure boats. All of them are affected by major harbor events, namely the Warnemünde Week and the Hanse Sail. While the Alter Stadthafen and the Alter Strom show a pollution of 0.12-0.14 litter particle/m^2 the Ludewigsbecken shows a higher pollution (1.75 particle/m^2). The Baltic Sea marina in Hohe Düne, opened in 2005, shows a lower pollution of 0.02 particle/m^2 (Table 1).

Similar to Rostock, the city harbor in Kiel exists for over 500 years. The tradition of the leisure boat harbors Düsterbrook and Seeburg, near the city center, go back to the Olympic Games of 1936. Similar to the city harbors of Rostock, both show a pollution of 0.07 - 0.18 litter particles/m^2. Both harbors are principally affected by the Kiel Week. In contrast, the Baltic Sea marinas in the surrounding of Kiel show a pollution of less than 0.1 litter particles/m^2. Overall, the average pollution in German marinas is 0.28 particles/m^2 resp. 0.1 particles/m^2, if the total investigated area is divided by the total number of particles.

Table 1: Results of the marina bottom marine litter screening.

	Marina	Analysed area (m²)	Harbor area (m²)	Number of items	Items per m²	Analysed harbor area (%)	Items per harbor
Rostock	Alter Strom	765	38,000	105	0.14	2.01	5,216
	Alter Stadthafen	82	10,000	10	0.12	0.82	1,220
	Ludewigsbecken	8	11,000	14	1.75	0.07	19,250
	Hohe Düne	340	250,000	6	0.02	0.14	4,412
Kiel	Düsterbrook	286	30,000	21	0.07	0.95	2,203
	Seeburg	51	3,000	9	0.18	1.70	529
	Laboe	194	110,000	7	0.04	0.18	3,969
	Strande	109	30,000	6	0.06	0.36	1,651
	Wendtorf	112	65,000	13	0.12	0.17	7,545
Egypt	Montazah	7	190,000	21	3.00	0.00	570,000
	Yachtclub	41	700,000	23	0.56	0.01	392,683
Tunisia	Bizerte	42	40,000	156	3.71	0.11	148,571
	Yassim Hammamet	136	160,000	59	0.43	0.09	69,412
	Monastir	370	75,000	168	0.45	0.49	34,054
	Germany	**1947**	**547000**	**191**	**0.28**	**0.71**	
	North Africa	**596**	**1165000**	**427**	**1.63**	**0.14**	

In Egypt and Tunisia, the harbors are old, still partly host traditional fishing activities and are located close to the city centers. The only exception is Yassim Hammamet, which represents a new sport boat harbor built in the late 1990s in a tourism center. The pollution in Montazah (Alexandria, Egypt) and Bizerte (Tunesia) exceeds 3 particles/m² (Table 1). The average pollution in African marinas is about 1.6 particles/m² resp. 0.7 particle/m², if the total investigated area is divided by the total number of items. The pollution is about 7 times higher than in German harbors. The extrapolation of the data to the entire harbor area visualizes the dimension of the pollution problem. In the large African harbors, the total number of particles is above 100,000. However, these extrapolations are associated with very high uncertainties, because, apart from the Alter Strom in Germany, less than 1% of the total harbor areas were investigated.

3.2. Litter pollution in harbors – items

In German city harbors, cigarette butts have the highest share of all item classes with 32%. This indicates the dominant role of social activities in the harbors (Table 2). In contrast, in sport boat marinas, ropes and textiles dominate with 42%. The latter represent classical items related to leisuer boats. Plastic items account for 74% of all items.

The low absolute numbers of particles in harbors in Egypt do not provide a reliable insight into the item distribution. In harbors in Tunisia, cigarette butts (20%) also play an important role. In general, plastic bags and bottles have a higher share in African harbors than in Germany. Similar to Germany, plastic items account for 73% of all items. This means that in all harbors, plastic is the dominating material.

Table 2. Item distribution of the marina bottom marine litter screening.

Location	Plastic: Cigarette butt	Plastic: Undefined item	Plastic: Rope & textile	Plastic: Bag	Plastic: Bottle	Metal can	Glass bottle	Wood, paper etc.	Total number
Germany									
City harbors	32%	16%	21%	4%	0%	3%	4%	19%	113
Sport boat marinas	10%	24%	43%	0%	0%	0%	5%	19%	21
Egypt									
City harbors/marina	0%	42%	12%	15%	4%	0%	0%	27%	26
Tunisia									
City harbors/marina	20%	10%	29%	7%	8%	9%	3%	15%	241

3.3. Factors controlling pollution – harbor bottom cleaning

In general, the observed pollution level and spatial differences are influenced and/or controlled by the emission level, possible harbor bottom cleanings, resuspension and reallocation of particles to other areas by wave action and bottom currents and, last but not least, our data collection methods.

A survey and interviews with harbor managers were carried out to get an insight into harbor waste management and the potential role of harbor bottom cleanings. Only four surveys including additional interviews were obtained. In Strande, Germany, and Marina Cap Monastir, Tunisia, floating litter is removed with nets, in Yasmine Hammamet, Tunisia floating litter is removed manually and Schilksee, Germany, uses a Seabin. All four harbors have appropriate waste collection systems in place and floating litter appears to be removed as needed.

Two interviewees mentioned direct rainwater outlets discharging into the harbor. Kiel and Rostock have combined sewer systems [37]. Waste- and stormwater are treated jointly in wastewater treatment plants and discharge into different parts of the city harbors. Heavy rains can temporary cause sewer overflows and the discharge of untreated water. For other harbors, such as Bizerte, it is known that waste water can enter the harbor temporary. This means that waste- and stormwater discharge can potentially play a role for harbor bottom pollution. Hygienic items, such as cotton sticks, can be indicators of untreated sewage water. However, a detailed analysis of all items for each harbor does not indicate an important role of untreated sewage on sea bottom pollution.

None of the interviewees were aware of any harbor bottom cleaning. It seems that harbor bottom cleaning is rare and most likely does not influence our data collection and the observed sea bottom pollution.

3.4. Factors controlling pollution – litter resuspension and reallocation

The observed pollution levels potentially might be affected by resuspension and reallocation of pieces by wave-induced turbulence and currents. This question can be addressed exemplary with 3D-hydrodyamic model simulations. Further, the simulations provide an insight into the spatio-temporal behavior of sinking litter, especially plastic.

Figure 4 shows the transport of hypothetical litter emitted to the sea during the Hanse Sails in August. As said before, it can be assumed that the Hanse Sail is a major pollution event. The Hanse Sail years 2009 and 2010 show contrasting wind directions and wind speeds temporally exceeding 7 m/s (4 Beaufort; moderate breeze). The wind velocities in 2009 and 2010 where above the average that is usually observed during Hanse Sails. Therefore, it can be expected that the transport is more intensive compared to common Hanse Sail years.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 25 September 2023 doi:10.20944/preprints202309.1599.v1

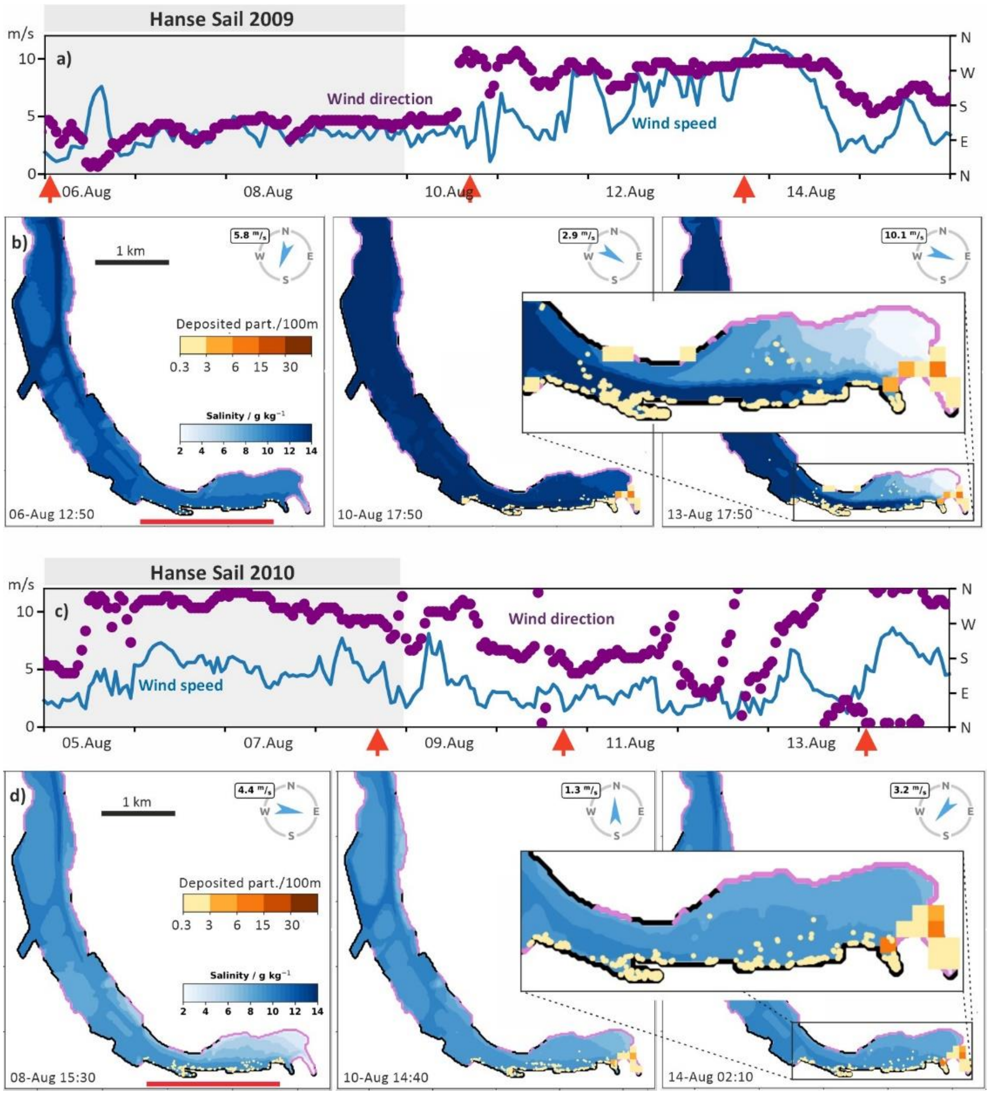

Figure 4. (a) Wind speed and direction during Hanse Sail 2009 that lasted from 6th to 9th August. The red arrows indicate the date and time of figure series (b). (b) Shows the model simulation of sinking litter and the litter deposition at the bottom or along the shoreline for three dates. It is assumed that altogether 300 particles were emitted during the event. (c, d) Show the same for the Hanse Sail 2010.

The model simulations for Hanse Sails 2009 and 2010, do not indicate any significant transport of particles deposited on the sediment. Some of the emitted particles are transported along the shoreline and remain in the city harbor area. Under normal summerly wind conditions, resuspension and reallocation of particles at the bottom does not play a relevant role. Since the sinking particles largely remain very close to the emission spot, a local pollution is likely to occur, especially during events, such as the Hanse Sail. Especially in very sheltered areas located in the center of the event, such as the Alter Stadthafen, (Figure 2), it seems that a long-term accumulation of litter above the sediment can take place. However, the observed litter concentration at the bottom of the Alter Stadthafen was, with 0.12 particles/m², relatively low.

The marinas Seeburg and Düsterbrook in Kiel (Figure 2) are located close to the Kiel Week. They are other marinas where a strong sediment pollution with litter is to be expected due to the Kiel Weeks. However, here too, the observed concentrations of litter on the sea floor were relatively low, with 0.18 resp. 0.07 particles/ m².

The bottom transport is a complex interaction between external forcing from the Baltic Sea, estuarine circulation, harbor morphometry and wind shelter effects and can hardly be predicted without a model. Therefore, a model simulation was carried out to get an insight whether heavy storms have an effect on bottom litter re-allocation.

Figure 5 shows how the most severe storm observed in the year 2009, with wind speeds above 20 m/s from westerly directions, would have affected bottom litter transport. The model suggests a resuspension of most litter and a transport towards up to 4 km north-west. During the storm, the model suggests a strong reallocation of bottom litter and an accumulation in the shipping channel and at the coastline. During the Hanse Sails 2009 and 2010 the average bottom current velocity hardly ever exceeded 0.07 m/s. During the storm the model calculated an average bottom velocity up to 0.12 m/s at times when the wind speed was close to or above 20 m/s. A reallocation of litter at the sea floor can happen and it is likely that this affects our data and our observed litter concentrations.

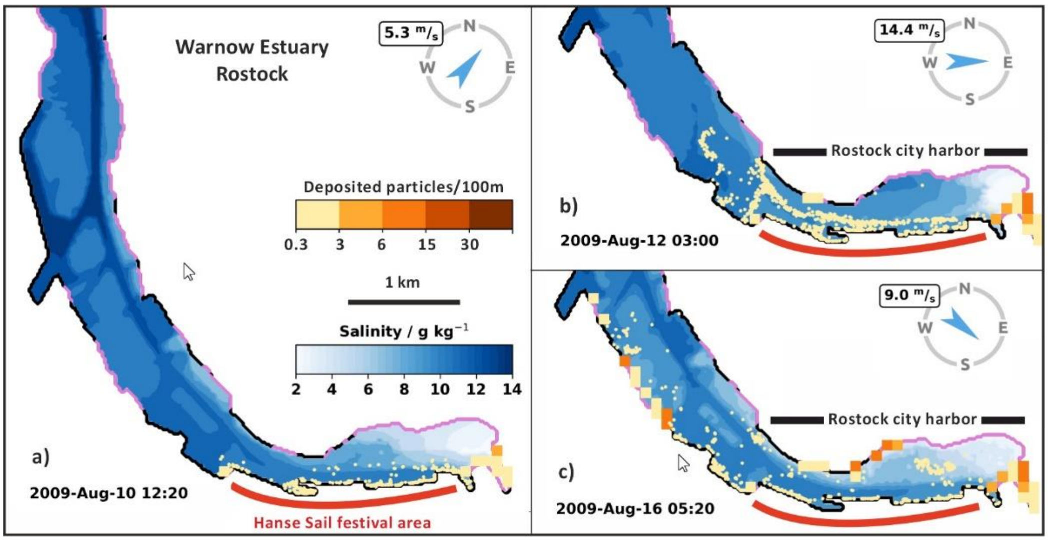

Figure 5. Emission of litter with a density above 1 g/cm³ during the Hanse Sail festival and bottom litter transport in the Warnow Estuary. It is assumed that altogether 300 particles were emitted during the event. (a) Transport of emitted litter in the Rostock city harbor after Hanse Sail (6th to 9th August 2009). (b,c) Litter resuspension and transport during a hypothetical storm after the Hanse Sail.

According to the model results, in the Warnow Estuary, it is very unlikely that any sinking litter emitted near the city center will reach the mouth to the Baltic Sea, in a distance of 11 km. The same is probably true for the Kiel Week and the Kiel Fjord because the framework conditions are comparable. A pollution of the open Baltic Sea bottom resulting from events in the city harbors is very unlikely. However, many of the 150 ships, participating in the Hanse Sail Rostock, transport visitors several times a day between the city harbor and the Baltic Sea. The emissions from boats are not included in the simulations.

4. Discussion

4.1. Evaluation of the methodology

Our sea bottom screening method has several advantages: The total costs for equipment were, with 666 Euros, relatively low. With 0.3 to 10 minutes (median around 1 minute), the time required to cover one square meter of harbor bottom is relatively short. The system is simple, easy to learn and easy to apply. It is mobile and portable, and allows relatively fast comparative studies in very different environmental and regional settings. Several minor technical improvements could further improve the method, such as a stronger underwater light, an increased stick length, or an automatic distance measurement between camera and bottom.

However, the method also has several weaknesses: Objects are often overgrown or covered with organic material. Therefore, a manual analysis of the photos with bare eyes is recommendable. Going into detail, this is time-consuming and the identification of objects is biased, because it depends on the size, color, state and material of the object. Consequence is that not all objects have the same likelihood to be found. Larger colorful and freshly deposited items are favored. In addition, the

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 25 September 2023 doi:10.20944/preprints202309.1599.v1

method and the quality of the resulting data is highly dependent on the water transparency. It is more suitable for clear water seas, such as the Mediterranean Sea, and problematic and time-consuming in turbid systems, such as coastal lagoons. How well and how long an object can be identified after deposition, depends on how fast it is overgrown or buried by sediment. This depends on environmental conditions, such as light conditions, nutrient availability and productivity as well as sediment reallocation. These factors vary greatly from harbor to harbor. Therefore, for how long an identified object was located on sediment can hardly be determined. The method, how we applied it, does allow the calculation of deposition rates, e.g. the number of pieces per squaremeter and month. Despite a considerable time-effort, the number of particles found in several harbors was too low to allow a detailed item analysis.

The method is fast because it is carried out from solid harbor walls, wooden bridges or fixed floating pontoons. The resulting weakness is that only the nearby bottom pollution is assessed which can hardly be considered as spatially representative. We have tried to compensate for this effect by using a large number of sampling locations within each harbor. However, in most cases less than 1% of the total harbor areas was sampled.

For a spatially representative sampling a boat or a float could be used, but this would increase the time required. Further, it would increase the difficulty to get permissions for field studies in harbors and marinas. Permissions were a major challenge in all African harbors and restricted the choice of harbors and the extent of our field studies. This was a major reason, too, for not applying underwater drones for our purpose. We tested the use of different underwater drones in German harbors but faced additional problems that made the approach ineffective [25].

4.2. Harbor pollution – monitoring and model simulations

Madricardo et al. [23] and Canals et al. [5] provide a comprehensive overview about sea bottom monitoring methods and Hanke et al. [24] defines detailed requirements for a monitoring that addresses trends in the amounts of litter deposited on the seafloor as part of the European Marine Strategy Framework Directive. Presently the official monitoring focusses on shallow coastal waters, marginal seas and the deep sea floor. Our approach, focusing on sea floors in urban areas, addresses a complementary area and pollution hot-spots.

For shallow waters, underwater visual surveys by scuba divers are recommended and detailed protocols exist [24]. Presently, the scuba diver method delivers the most reliable data for harbors and marinas, as well. Recently, it has been applied to detect lost fishing gear on harbor sediments in the Baltic Sea. This method is associated to high efforts and costs, which do not allow its integration into regular monitoring programs.

Usually, a monitoring is intended to provide an insight into the pollution process, meaning how much litter is deposited per area and time-unit. A combination of scuba divers and our method could meet this demand. Scuba divers could be used to clean harbor floor areas from litter. Afterwards, the ongoing pollution process on these areas could be observed with our method. A combination with dredging methods could also be beneficial. However, our approach is certainly suitable as a screening method to get a first insight into pollution levels and major items. The results allow the definition of pollution reduction measures and can serve for assessing the effectiveness of these measures.

For the model simulations we used an advanced spatially high resolved 3-D flow model that is very well adapted to the Warnow Estuary [35]. In contrast, the assumption that a litter resuspension and bottom transport takes place at a bottom shear stress of $8.25*10^{-7}$ Pa is a strong simplification. This does not take into account important factors, such as the different shape, size or density of litter particles. Therefore, the model simulations are only a first step towards a better understanding of bottom transport and have to be treated with caution. If we assume that what the model suggests is close to reality, we see that under common wind conditions, the resuspension and transport of litter above the sediment does not play an important role. During storms a resuspension and reallocation of litter can take place even in sheltered harbor areas (e.g. Alter Stadthafen). Therefore, the observed litter concentrations above the sediment are likely to be affected by storms and represent an uncertain pollution time period. The low observed bottom litter concentrations in city harbors suggest, that

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 25 September 2023 doi:10.20944/preprints202309.1599.v1

events, such as the Hanse Sail or the Kiel Week, are not important pollution events. This can be misleading because during storms a litter reallocation and a sediment cleaning may have taken place. All harbor monitoring methods suffer from this uncertainty. The lack of comparable data and literature does not allow us to critically reflect on our results in more detail.

4.3. Harbor pollution – state, causes and management

All harbors in and around Kiel and Rostock have sea floor litter concentrations below 0.2 particles/m². Marinas in semi-urban surroundings of the cities show concentrations below 0.1 particles/m². The only exception is the relatively small Ludewigsbecken in Rostock, which shows a higher pollution (1.75 particles/m²). It is likely that this higher concentration is still the result of recent reconstruction work. Centuries of human activities in and around the city harbors of Rostock and Kiel, frequent social activities as well as large scale harbor events such as the Hanse Sail and the Kiel Week with millions of visitors annually, do not seem to significantly increase the observed harbor floor litter pollution. In all these harbors, bottom cleaning activities are not known and certainly do take place regularly. Our monitoring method certainly underestimates the present pollution, as only recently deposited items can be identified.

In 2019, Tunisia counted 9.4 million tourist arrivals [38]. Tourism focusses on a several coastal resorts and the season is between June and September. The three Tunisian harbors of Yasmine Hammamet, Monastir and Bizerte, are tourism focus spots throughout the summer season. These intensive human activities are reflected in the observed sea floor pollution which is about 7 times higher compared to German harbors. In city harbors, such Bizerte and Montazah, the concentration exceeds 3 particles/m² sea floor. In Tunesian touristic harbors, measures to reduce emissions are implemented, but especially in cities, deficits in waste management and an insufficient public awareness of the litter problems seems still to exist. Our concentrations observed in marinas are in the range of 100 to far above 1000 times higher compared to macro-litter studies in Baltic and Mediterranean coastal sea-floors [10, 29, 40]. An overview in Vlachogianni et al. [41] shows areas, such as the Gulf of Aqaba in the Red Sea, with bottom litter concentration up to 2.8 pieces/m². However, our results indicate that harbor bottom pollution is a problem especially in the African city harbors.

In the cities Kiel and Rostock in Germany an improved waste management system has been implemented in recent years. This especially affected the harbor events (Hanse Sail, Kiel Week). It includes a deposit system for cups, the mandatory use of degradable tableware, free waste deposit containers for all ships, reusable fence fasteners, low-emission fireworks, nightly ground cleaning and an optimized waste bin distribution and emptying system [42]. These activities are largely a result from the European Union ban on single-use plastic items such as plastic plates, cutlery, straws, balloon sticks and cotton buds which entered into force in 2021 [43]. Further, the Kiel Week received the Platinum Level Certification of the Clean Regatta Program. The 20 criteria include the elimination of single-use items (e.g. elimination of single-use water bottles, plastic straws, bags, dinnerware, water refill stations) and a responsible waste management (e.g. green team, proper waste bin placement and signage paper-less event management). The Kiel Week aims at a sustainable events certification according to ISO 20121 [44] and Rostock is following a similar pathway. In Germany, already since 2003, a deposit for plastic bottles exists. It was expanded in 2021. Before, only 1 litre bottles were charged with a 0.25 € deposit. Today, a deposit of at least 0.15 € exists for the vast majority of all plastic bottles. From 2022, certain types of plastic bags became prohibited and customers have to pay for most thicker plastic bags. These laws may explain the lack of plastic bottles and bags on sea floors in Germany.

Our results suggest that the existing waste management systems and the legal frameworks are suitable to reduce emissions and reduce harbor bottom litter pollution. An improved environmental awareness and the recognition of the litter problem have certainly reduced the emissions, as well. However, this needs to be explored in more detail.

5. Conclusion

In general, sea floor monitoring in marinas and city harbors has advantages. It addresses pollution hot-spots, is cost-effective and is close to the emission sources. Further, the effectiveness of land-based pollution reduction measures becomes visible at an early state and the monitoring results provide a fast feedback towards improved measures. A screening of the littering process on the harbor landside is hardly possible, because of an extreme spatio-temporal variability and many controlling factors. Litter on the sea floor shows only a very limited temporal variability and is much less affected by disturbing factors (e.g. cleaning). In smaller, largely closed and wind-sheltered harbors a reallocation deposited litter by bottom currents may not be frequent, but in larger harbors storm-induced litter removal processes have to be taken into account.

Supplementary Materials: The following supporting information can be downloaded at: www.mdpi.com/xxx/s1, Video S1: Model_simulation_HanseSail2010.mp4. Video S2: Model_simulation_Storm.mp4

Author Contributions: Conceptualization, G.S., G.E.S., and P.W; methodology, P.W. G.S., G.E.S., validation, G.S., G.E.S., P.W; model simulations, X.L.; formal analysis, P.W. G.S.; writing, G.S; P.W.; visualization, G.S., P.W., X.L.; review and corrections M.H., A.N.; supervision, G.S, G.E.S.; project administration, M.H., A.N.; funding acquisition, M.H., A.N., G.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the BMU/ZUG project TouMaLi (Beitrag der nachhaltigen Abfallwirtschaft im Tourismus zum Schutz der Meeresökosysteme), grant number 65MM0001. Minor funding was provided by the German Federal Ministry of Education and Research project Coastal Futures, grant number 03F0911B, as well as by Interreg South Baltic project COP, grant number STHB.02.03.-IP01-0006/23. GES also received support by the Doctorate scholarship program in Ecology and Environmental Sciences at Klaipeda University, Lithuania.

Acknowledgments: We like to thank Dr. Miriam von Thenen and Ester Robbe for supporting the field campaigns in Africa and Margaux Gatel-Rebours for graphical support.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Eriksen, M.; Lebreton, L. C. M.; Carson, H. S.; Thiel, M.; Moore, C. J.; Borerro, J. C.; et al. Plastic pollution in the world's oceans: more than 5 trillion plastic pieces weighing over 250,000 tons afloat at sea. *PLoS One*, **2014,** *9:e111913. https://doi.org/*10.1371/journal.pone.0111913.
1. Fazey F.M.C.; Ryan P.G. Biofouling on buoyant marine plastics: An experimental study into the effect of size on surface longevity. *Environ Poll*, **2016**, *210*, 354-360. https://doi.org/10.1016/j.envpol.2016.01.026.
2. Lebreton, L.C.M.; Greer S.D.; Borrero J.C. Numerical modelling of floating debris in the world's oceans. *Marine Pollution Bulletin*, **2012**, *64, 3*, 653-661. https://doi.org/10.1016/j.marpolbul.2011.10.027.
3. Andrady, A. L. Persistence of plastic litter in the oceans. In Marine anthropogenic litter; Bergmann, M.; Gutow, L.; Klages, M. (Eds.), Berlin, Springer Open, **2015**, 57–72. https://doi.org/10.1007/978-3-319-16510-3.
4. Canals, M.; Pham, C.K.; Bergmann, M., Gutow, L.; Hanke, G.; van Sebille, E.; Angiolillo, M., et al. The quest for seafloor macrolitter: a critical review of background knowledge, current methods and future prospects. *Environ. Res. Lett.* **2021**, *16*, 023001. https://doi.org/10.1088/1748-9326/abc6d4.
5. Schernewski, G.; Radtke H.; Hauk R.; Baresel C.; Olshammar M.; Osinski R.; Oberbeckmann S.. Transport and behavior of microplastics emissions from urban sources in the Baltic Sea. *Front. Environ. Sci.*, **2020**, *8, 579361*. https://doi.org/10.3389/fenvs.2020.57936
6. Chubarenko, I.; Stepanova, N. Microplastics in sea coastal zone: Lessons learned from the Baltic amber,
7. *Environ Poll*, **2017**, *224*, 243-254. https://doi.org/10.1016/j.envpol.2017.01.085.
8. Compa, M.; Alomar, C.; Morató, M,; Álvarez, E.; Deudero, S. Are the seafloors of marine protected areas sinks for marine litter? Composition and spatial distribution in Cabrera National Park, Sci Total Environ, 2022, 819, 2022, 152915, doi: /10.1016/j.scitotenv.2022.152915.
9. Azaaouaj, S.; Nachite, D. Fishing for litter at the port of Fnideq (NW Morocco). **2019**. http://jisdelmar.uma.es/ficheros-contribuciones/1561671124/1561671124.pdf
10. Galgani, F.; Hanke, G.; Maes, T. (2015) Global Distribution, Composition and Abundance of Marine Litter In Marine anthropogenic litter; Bergmann, M.; Gutow, L.; Klages, M., Berlin, Springer Open, **2015**, 57–72. https://doi.org/10.1007/978-3-319-16510-3.
11. Schernewski, G.; Radtke, H.; Hauk, R.; Baresel, C.; Olshammar, M.; Oberbeckmann, S. Urban Microplastics Emissions: Effectiveness of Retention Measures and Consequences for the Baltic Sea. *Front. Mar. Sci.* **2021** *8: 594415*. https://doi.org/10.3389/fmars.2021.594415

12. Urbanyi-Popiołek, I. Cruise industry in the Baltic Sea Region, the challenges for ports in the context of sustainable logistics and ecological aspects, Transportation Research Procedia, **2019**, 39, 544-553, doi: /10.1016/j.trpro.2019.06.056
13. Megalist of Baltic Sea Ferry Routes 2023. https://www.ferryscan.com/info/megalist-of-baltic-sea-ferry-routes. (accessed on 06 August 2023).
14. HELCOM. Thematic assessment of spatial distribution of pressures and impacts 2016-2021. Baltic Sea Environment Proceedings **2023** 189. https://helcom.fi/post_type_publ/holas3_spa
15. Maglic, L.; Maglic, L.; Grbčić, A.; Gulić, M. Composition of Floating Marine Litter in Port Areas of the Island of Mallorca. J mar sci eng, **2022** ,10, 1079. https://doi.org/10.3390/jmse10081079.
16. HELCOM. Thematic assessment of hazardous substances, marine litter, underwater noise and non-indigenous species 2016-2021. Baltic Sea Environment Proceedings, **2023**, 190. https://helcom.fi/post_type_publ/holas3_spa
17. Valois, A. Developing a citizen science monitoring programme for Te Awarua-o-Porirua Harbour and catchment. https://ref.coastalrestorationtrust.org.nz/site/assets/files/10419/developing_a_citizen_science_monitoring.pdf, **2020.**
18. Yılmaz, Ö.; Erbaş, C.; Gökçe, M. Investigation of benthic marine litter in the Yumurtalık Fishing Port. *Turkish JAF Sci. Tech*, **2021,** *9,2*, 272-276, doi: /10.24925/turjaf.v9i2.272-276.3619
19. New Port underwater cleanup. **2020**. https://www.facebook.com/NHUnderwaterCleanUp/ (accessed on 06 September 2023).
20. WDR. **2022.** **https:**//www1.wdr.de/nachrichten/ruhrgebiet/taucher-sammeln-muell-aus-ruhr-in-muelheim-100.html, (accessed on 06 September 2023).
21. Stadtgestalten. **2022**. https://stadtgestalten.org/rostock-muellfrei/muell-aus-dem-stadthafenbecken/, (accessed on 06 September 2023)
22. DIRECTIVE 2008/56/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32008L0056. **2008**. (accessed on 06 September 2023)
23. Madricardo, F.; Ghezzo, M.; Nesto N.; Mc Kiver, W.J.; Faussone, G.C.; Fiorin, R. et al. How to Deal With Seafloor Marine Litter: An Overview of the State-of-the-Art and Future Perspectives. Front. Mar. Sci. **2020**, 7 doi: /10.3389/fmars.2020.505134.
24. Hanke, G.; Galgani, F.; Werner, S.; Oosterbaan, L.; Nilsson, P.; Fleet, D.; Kinsey, S.; Thompson, R.; Palatinus, A.; Van Franeker, J.; Vlachogianni, T.; Scoullos, M.; Veiga, J.; Matiddi, M.; Alcaro, L.; Maes, T.; Korpinen, S.; Budziak, A.; Leslie, H.; Gago, J.; Liebezeit, G. Guidance on Monitoring of Marine Litter in European Seas. Luxembourg, Publications Office of the European Union; **2013**. https://publications.jrc.ec.europa.eu/repository/handle/JRC83985
25. Escobar-Sánchez, G.; Markfort, G.; Berghald, M.; Ritzenhofen, L.; Schernewski G. Aerial and underwater drones for marine litter monitoring in shallow coastal waters: factors influencing item detection and cost-efficiency. *Environ. Monit. Assess.*, **2022**, 194, 863, doi: /10.1007/s10661-022-10519-5.
26. Die Kieler Woche 2023 in Zahlen. **2023**. https://www.kieler-woche.de/de/medien/meldung.php?id=128091 (accessed on 06 September 2023).
27. Hanse Sail Rostock. Maritimes Spektakel in Rostock: 500 000 Menschen besuchten die 32. Hanse Sail. **2023**. https://www.hansesail.com/news/detail/maritimes-spektakel-in-rostock-500-000-menschen-besuchten-die-32-hanse-sail.html (accessed on 06 September 2023).
28. Augsburger Allgemeine. Rekordverdächtige Besucherzahl bei Hanse Sail. **2009.** https://www.augsburger-allgemeine.de/panorama/Rekordverdaechtige-Besucherzahl-bei-Hanse-Sail-id6276271.html (accessed on 06 September 2023).
29. Wandersee, P. Assessment of the marine litter seafloor pollution in sport boat harbors. Master-thesis. University of Rostock, Umweltingenieurwissenschaften, pp 67.
30. Watters, D.; Yoklavich, M.; Love, M.; Schroeder, D. Assessing marine debris in deep seafloor habitats off California. *Mar. Pollut. Bull.*, **2010**, *60, 1*, 131-138. https://doi.org/10.1016/j.marpolbul.2009.08.019
31. OSPAR Commission. Guideline for Monitoring Marine Litter on the Beaches in the OSPAR Maritime Area. **2010**. https://www.ospar.org/ospar-data/10-02e_beachlitter%20guideline_english%20only.pdf
32. Burchard, H.; Bolding, K. GETM: A General Estuarine Transport Model - Scientific Documentation; Joint Research Centre: Ispra, Italy, **2002**. https://getm.eu/files/GETM/doc/GETM2002.pdf
33. Klingbeil, K.; Burchard, H. Implementation of a direct nonhydrostatic pressure gradient discretisation into a layered ocean model. *Ocean Modelling*, **2013**, *65*, 64–77, doi: org/10.1016/j.ocemod.2013.02.002
34. Umlauf, L.; Burchard, H. Second-order turbulence closure models for geophysical boundary layers. A review of recent work. *Cont. Shelf Res.* **2005**, *25*, 795–827, doi: /10.1016/j.csr.2004.08.004.
35. Lange, X., Klingbeil, K., & Burchard, H. (2020). Inversions of estuarine circulation are frequent in a weakly tidal estuary with variable wind forcing and seaward salinity fluctuations. J Geophysical Res.: Oceans, 125, e2019JC015789, doi: /10.1029/2019JC015789.

 doi:10.20944/preprints202309.1599.v1

36. Lange, M.; van Sebille, E. Parcels v0.9: prototyping a Lagrangian ocean analysis framework for the petascale age, *Geosci. Model Dev.*, **2017**, *10*, 4175–4186, doi: /10.5194/gmd-10-4175-2017.
37. Piehl, S.; Hauk, R.; Robbe, E.; Richter, B.; Kachholz, F., Schilling, J. Lenz, R., Fischer, D., Fischer, F., Labrenz, M., Schernewski, G. Combined Approaches to Predict Microplastic Emissions Within an Urbanized Estuary (Warnow, southwestern Baltic Sea). *Front. Environ. Sci.* **2021** *616765*, doi: /10.3389/fenvs.2021.616765.
38. Graefe, L. Gästeankünfte in Tunesien von 2010 bis 2019. https://de.statista.com/statistik/daten/studie/441840/umfrage/ankuenfte-in-tunesien/ (accessed on 06 September 2023).
39. Urban-Malinga, B.; Wodzinowski, T.; Witalis, B.; Zalewski, M.; Radtke, K.; Grygiel, W. Marine litter on the seafloor of the southern Baltic, *Mar. Pollut. Bull.*, **2018**, 127, 612-617, doi: /10.1016/j.marpolbul.2017.12.052.
40. Segal, Y., Lubinevsky, H. Spatiotemporal distribution of seabed litter in the SE Levantine Basin during 2012–2021,
41. *Mar. Pollut. Bull.*, **2023**, 188, 114714, doi: /10.1016/j.marpolbul.2023.114714.
42. Vlachogianni, T.; Anastasopoulou, A., Fortibuoni, T.; Ronchi, F. Marine Litter Assessment in the Adriatic and Ionian Seas.IPA-Adriatic. DeFishGear Project, **2017**, pp 168. https://mio-ecsde.org/project/5054/https://mio-ecsde.org/wp-content/uploads/2017/02/Final-MLA-salonia_final.pdf
43. Rathaus Rostock. Nachhaltig und Barrierefrei: Auf dem Weg zur Hanse Sail der Zukunft https://rathaus.rostock.de/de/rathaus/aktuelles_medien/nachhaltig_und_barrierefrei_auf_dem_weg_zur_hanse_sail_der_zukunft/346922 (accessed on 06 September 2023).
44. European Union. EU restrictions on certain single-use plastics. https://environment.ec.europa.eu/topics/plastics/single-use-plastics/eu-restrictions-certain-single-use-plastics_en#:~:text=The%20EU%20is%20acting%20against,of%20the%20EU%20Member%20States (accessed on 06 September 2023).
45. ISO 20121. Sustainable events. https://www.iso.org/iso-20121-sustainable-events.html (accessed on 06 September 2023).