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Wasting the North Sea? – A field-based assessment of anthropogenic macrolitter loads and emission rates of three German tributaries[☆]

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ABSTRACT

Research into the scope of litter pollution in freshwater systems has shown similar levels to the marine and coastal environment. Global model estimates of riverine emission rates of anthropogenic litter are largely based on microplastic studies as long-term and holistic observations of riverine macroplastics are still scarce. This study therefore aims to contribute a detailed assessment of macrolitter in the transitional waters of three major North Sea tributaries: Ems, Weser, and Elbe. Litter surveys were carried out in four river compartments: along the embankment, on the river surface, in the water column, and on the river bed. The data revealed spatio-temporal variability and distinct pollution levels for each compartment. Beaches had the highest debris diversity and were significantly more littered than vegetated sites and harbors. Stony embankments were least polluted. Benthic litter levels appeared substantial despite rapid burial of objects being likely due to high suspended sediment loads. Two extrapolation approaches were tested to scale daily and annual litter emission quantities of surface- and subsurface-floating litter. Using the mean (median) litter item mass from water column samples, total annual mass discharges were calculated: ~0.9 (0.2) t y^{-1} to ~2.8 (0.5) t y^{-1} emitted via the Ems, ~1.3 (0.2) t y^{-1} to ~12.0 (1.9) t y^{-1} through the Weser, and ~14.7 (2.4) t y^{-1} to ~801 (128) t y^{-1} carried into the North Sea by the Elbe. These rates deviate considerably from previous model estimates of plastic loads discharged by these three rivers. Future studies should therefore ground-truth model estimates with more river-specific and long-term field observations. Overall, the estimated plastic debris discharge quantities account for <1% of the total mass of mismanaged plastic waste per catchment.

1. Introduction

A large body of research on the occurrence of anthropogenic debris has concentrated on the marine and coastal environment (Blettler et al., 2018). More recently, studies have addressed sources and entry pathways of particularly plastic litter in order to estimate input rates on a national and global scale (Jambeck et al., 2015; Geyer et al., 2017; Lebreton et al., 2017; Schmidt et al., 2017; Lebreton & Andrady, 2019). Rivers have been highlighted as conveyors of inland litter pollution into coastal ecosystems but also as potential sinks for man-made debris (Galgani et al., 2000; Araújo & Costa, 2007; Rech et al., 2014). Yet key model-based estimates have been validated by only few field studies, the majority of which quantified microplastics (see Lebreton et al., 2017; Schmidt et al., 2017) whose drifting, beaching, accumulation, and remobilization behavior can be very different to that of macrodebris items.

This bias in modelled estimates and the scarcity of field data on riverine macroplastics and macrodebris has been criticized before (e.g. González et al., 2016; González-Fernández; Hanke, 2017; Blettler et al., 2018; Crosti et al., 2018; van Emmerik et al., 2018; Tramoy et al., 2019). The present study therefore provides an advanced assessment by drawing together data sets with information on litter quantities and composition in four river compartments, i.e. the embankment, river surface, water column, and river bed (Fig. A, Supplementary) of three major North Sea tributaries, i.e. the Ems, the Weser, and the Elbe. Previous riverine studies have generally concentrated on 1–2 compartments (van Emmerik & Schwarz, 2020) and such a holistic approach has, to the best of the authors' knowledge, not been taken before, although

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having been recommended (see KÜFOG GmbH, 2013). The aims were

i) to assess the quantities and composition of litter deposited and transported by the three rivers,
ii) to investigate potential differences in litter abundance and diversity between the river compartments, and
iii) to estimate litter emission rates into the respective estuary from surface-floating litter and negatively buoyant, suspended debris.

Based on past findings (e.g. Schmidt et al., 2017; Cowger et al., 2019; Kiessling et al., 2019), it was generally hypothesized that the larger the river and its respective catchment population, the greater the anthropogenic stress and the higher the litter pollution levels would be, thus resulting in higher emission rates of debris into the coastal environment.

2. Materials and methods

2.1. Study area

Focus of this study were the tidally influenced freshwater and transitional water bodies of the Ems, Weser, and Elbe. From the last weir to the sea, the estuaries are tidal for about 48 km, 65 km and 142 km, respectively (Schulz, 2015). The Ems is the shortest of the three rivers, spanning 371 km from its source in the Senne, Germany, to the Dollart estuary between Emden, Germany, and Eemshaven, Netherlands (FGE Ems, 2017). Its watershed covers an area of ~13,200 km^2 (NLWKN, 2018) with over 2.7 million inhabitants (European Commission – JRC, 2007; Vogt et al., 2007). Between Papenburg and the coast, the Ems is used for freight shipping and also riverine fisheries. It mainly flows through agricultural land, connecting larger urban areas.

The Weser covers 432 km from the joining of the Fulda and Werra in Hannoversch Münden, to its estuary near Bremerhaven (NLWKN, 2018). With a watershed of ~46,300 km^2 (NLWKN, 2018) and over 8.5 million inhabitants (European Commission – JRC, 2007; Vogt et al., 2007) it is the second largest of the three tributaries. While tourism plays a role, centers of shipbuilding, steel production, wind energy, and the automobile industry as well as the ports of Brake and Bremerhaven – the latter being the forth-largest container port in Europe (Bremenports GmbH and Co. KG, 2019)– are also located along the Weser north of Bremen.

The Elbe is the largest of the three rivers, flowing almost 1100 km from the Krkonoš mountain range in the Czech Republic to Cuxhaven (Germany), and spanning a catchment area of over 148,000 km^2 (FGG Elbe, 2019) with approx. 23.5 million inhabitants (European Commission – JCR, 2007; Vogt et al., 2007). With the port of Hamburg being Germany's largest harbor, ranking among the world's top 20 (Hafen Hamburg Marketing e.V., 2019), cargo freight shipping is a key industrial sector as well as agriculture, recreational boating, and tourism.

2.2. River bank surveys

Macrolitter (>0.5 cm) sampling was carried out irrespective of the tides at nine locations per river (green dots, Fig. 1), twice a week for ten weeks (Table A, Supplementary). The surveys followed the Guideline for Monitoring Marine Litter on the Beaches in the OSPAR Maritime Area (OSPAR Commission, 2010) for areas of 100 m in length. The sites were chosen to be representative of the types of embankment generally found: vegetation, stones, sandy beaches, and harbor structures, e.g. boat moorings and quay walls. Along each river, three sites were selected per river bank type. Due to logistical constraints, only three of the four types could be sampled per river: vegetation, stones, and harbor structures along the Ems, and stones, sandy beaches, and harbor structures along the Weser and Elbe.

2.3. Surface litter monitoring

Between October 2017 and January 2019, monitoring of surface-floating debris was conducted 1–2 times per month for approx. half an hour per survey, 1–4 h after high tide, from elevated positions close to the respective estuary: the Ems barrage in Gandersum, the quay wall behind the zoo in Bremerhaven, and the "Alte Liebe" vantage point in Cuxhaven (red dots, Fig. 1; Table A, Supplementary). Any item floating downstream within 20 m of the survey point was recorded using the "River Litter Monitoring" function in the standardized "Floating Litter Monitoring" application for devices with an Android operating system, version 2.0 (González-Fernández and Hanke, 2017). A track width of 20 m was chosen, as this was the maximum distance across which a minimum-sized litter object of 2–2.5 cm, e.g. a cigarette butt, could be clearly identified under different weather and light conditions. This visual limitation may have led to an underestimation of items sized 0.5–2 cm.

2.4. Water column sampling

As part of the Water Framework Directive 2000/60/EC, the abundance and community composition of fish are assessed in estuarine waters using commercial stow net vessels (NLWKN, 2006). Twice a year, i.e. in spring and autumn, and at fixed locations (blue dots, Fig. 1) and 1–2 stow nets with a mesh size of 6–12 mm at the cod end are deployed over the course of one tidal cycle while at anchor, resulting in one ebb and one flow haul. The sampled water column ranges from just below the surface to a maximum depth of 10 m. Each position is sampled once per season, and the respective through-flow volume is documented by a flowmeter. Macrolitter has been recorded and categorized according to the OSPAR Guideline since 2013 (Schulz, 2015); the wet weight was additionally determined for the majority of items. The assessments were carried out annually in the Ems and Elbe, and biannually in the Weser (Table A, Supplementary). Oberhammelwarden (Weser) was only sampled in 2014 (BioConsult, 2015).

2.5. River bed sampling

During research cruise HE527 (RV Heincke) river bed samples were collected using a 2 m bottom trawl with a mesh size of 5 mm that was towed for 10 min with approx. 2 knots at three estuarine positions per river (orange dots, Fig. 1; Table A, Supplementary). After each tow, the net was emptied and the contents searched for macrolitter objects. The net was additionally inspected by two or three experienced staff for any items that had remained inside. The items of each tow were identified according to the OSPAR litter categorization.

2.6. Data analysis

All data were compiled and harmonized in Microsoft Office Excel 2013. Summed litter quantities of the twelve debris classes (plastic, rubber, cloth, paper, wood, metal, glass, pottery, sanitary waste, medical waste, feces, other pollutants) as well as individual abundances of all recorded plastic litter categories were included in comparative composition charts. Otherwise, all items were summed into one "total litter" category. Statistical analyses were conducted in both Excel and IBM SPSS Versions 25 and 26. Reporting

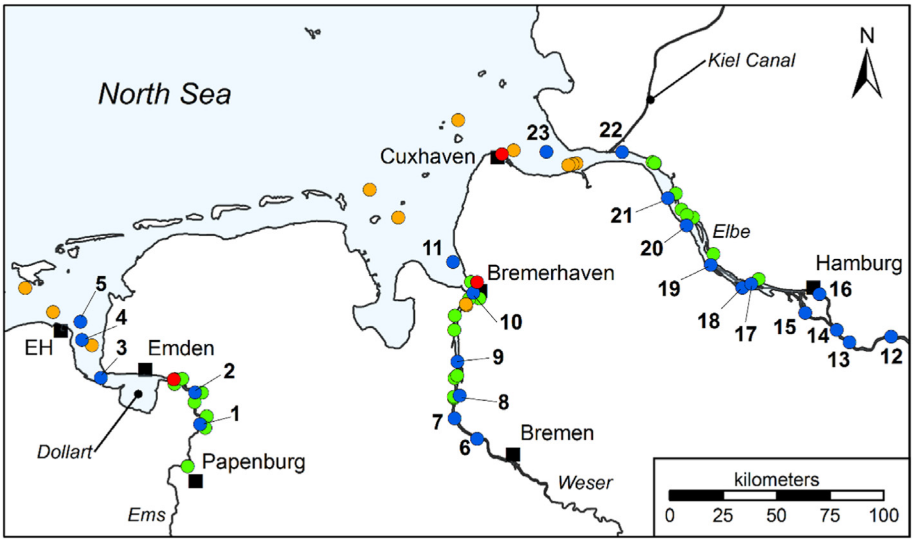

Fig. 1. Overview map of the southeastern German Bight coastline including the Ems, Weser, and Elbe, showing the six stations at which river bed trawl samples were taken (orange dots), the nine river bank locations at which litter surveys were carried out (green dots), the three vantage points at which surface litter monitoring was conducted (red dots), and the 23 stations (see Fig. 2 for the station names) at which water column samples were taken (blue dots). EH = Eemshaven. The map was created in Esri ArcMap Version 10.6 based on coastline data provided by the Marineregions.org initiative (2018) and by the Niedersächsischer Landesbetrieb für Wasserwirtschaft, Küsten- und Naturschutz (NLWKN) via the Niedersächsisches Ministerium für Umwelt, Energie, Bauen und Klimaschutz (2018). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

mean values ± the standard deviation (SD) was preferred over median values due to the large variability in the data and frequent zero counts which would have resulted in several medians of zero. Given the skewed nature of the majority of data (Shapiro-Wilk $p \leq 0.05$), differences between three or more groups of the independent variable were investigated using the non-parametric analysis of variance Kruskal-Wallis-H omnibus test, and differences between two groups with the non-parametric Mann-Whitney U test. River bed litter data and partly the litter diversity data were normally distributed and analyzed using parametric one-way ANOVA, followed by Tukey-HSD post-hoc testing. For all tests a significance threshold of $p \leq 0.05$ was assumed.

2.6.1. *River bank litter calculations*

To test whether litter was equally abundant along the different forms of embankment within each river, the absolute number of litter items per site as well as the daily litter accumulation rates were compared between river bank types. The exact location, i.e. the town or city where sampling had taken place, was not chosen as a variable due to several cases in which different embankments were sampled in the vicinity of the same town/city. For an overall comparison of litter quantities between river bank types, the data were pooled across rivers.

2.6.2. *Surface litter calculations*

Each survey duration was converted from minutes to seconds (s_{survey}). Based on the track width of 20 m, the amount of litter was standardized to number of litter items per meter width per seconds surveyed and extrapolated to the respective total river width at each survey point (n_{survey}), assuming a homogeneous distribution (see also Castro-Jiménez et al., 2019; Tramoy et al., 2019) while acknowledging a growing level of uncertainty with increasing width: 530 m at the Ems barrage, 1420 m at the zoo in Bremerhaven, and 14,550 m at the "Alte Liebe" in Cuxhaven (measured from each vantage point as the shortest distance across the river, using the ruler tool in Google Earth Pro 7.3.2.5776). To estimate the total daily/annual number of floating litter items that enter the respective estuary beyond the survey point, two approaches were taken:

1) The long-term mean flow speed ($v_{river} = m\ s^{-1}$) was calculated by dividing the long-term mean discharge volume of each river ($MQ = m^3\ s^{-1}$) by the area of the respective river cross-section ($A = m^2$), based on digital terrain models of the Ems (WSA Wasserstraßen- und Schifffahrtsamt Emden, 2011), the Weser and the Elbe (WSV and NLWKN, 2016; Table B, Supplementary). The long-term mean discharge volume was selected as the basis for a conservative litter emission estimate in order to avoid strong short-term tidal, seasonal or inter-annual variation as seen in van Emmerik et al. (2018, 2019a,b,c). Given the survey period in seconds (s_{survey}) and the calculated long-term mean flow speed of each respective river ($v_{river} = m\ s^{-1}$), the mean length of river distance that flowed past the survey point per survey duration (d_{survey} in m) as well as within 24 h (d_{day} in m) was calculated. The total daily surface litter discharge was then determined as $n_{day} = d_{day}*(n_{survey}/d_{survey})$. For each river's annual emission estimate (n_{year}), the mean of all n_{day} values (rounded to the nearest full item) was multiplied by 365.
2) Alternatively, d_{survey} was calculated on the basis of the river- and location-specific mean flow speed of the ebb tide (v_{ebb} in $m\ s^{-1}$; Table B, Supplementary) during which the surveys were conducted, while the extrapolations to daily emissions remained based on d_{day}, calculated from the long-term v_{river}. Annual discharge rates were calculated as under 1).

Per approach, the daily emission values were compared between the three rivers. As a wider width could lead to greater input quantities which may therefore bias the result, the daily input rates were also divided by the total river width at the survey points to calculate daily litter emissions per meter river width. These standardized values were also tested for differences.

2.6.3. *Water column litter calculations*

Based on the varying through-flow volume per haul, the mean number of litter items per m^3 of water column was calculated per haul for each station. These standardized quantities were compared between stations within each river, and, pooling all station data, across rivers, between seasons, and between tides. Due to the fact that the Weser surveys were conducted every two years and not all stations within each river were continuously sampled since 2013, annual differences were not tested for, despite the knowledge of inter-annual variation in riverine litter abundances in previous studies (e.g. Lechner et al., 2014; Kiessling et al., 2019). Additionally, the sampled volume and the number of litter items from each back-to-back ebb and flow haul were summed, upon which the mean litter amounts per m^3 sampled at the station closest to the respective estuary were extrapolated to average daily litter emission rates, based on the long-term mean discharge volume of each river (Table B, Supplementary). The river-specific mean of all daily discharge quantities (rounded to the nearest full item) was multiplied by 365 to yield the annual emission estimate. This extrapolation enabled a direct comparison of the litter amounts discharged into the estuary via the river surface and the water column.

2.6.4. River bed litter calculations

The absolute and standardized amounts of litter recorded in the estuarine bottom trawl samples were compared between the three rivers. To standardize the litter quantities per area, the distances trawled (in m) were calculated based on the start and end coordinates of each trawl using the “XY to Line” tool in Esri ArcMap Version 10.6, and the ETRS 1989 projection for UTM zone 32N. The respective distances were each multiplied by the trawl width of 2 m to receive the number of items per trawled area (in m^2). The absolute abundance data were subsequently extrapolated to litter items per km^2.

2.6.5. Riverine litter composition

Lastly, differences in litter diversity were investigated. This was done by counting all unique debris types that had been recorded per survey location, and by comparing these values between rivers, river compartments, and river bank types.

3. Results

3.1. River bank pollution

Along the Ems, stony river banks accumulated significantly less debris per 100 m than sites with harbor structures or vegetation (both $p < 0.001$; Table C, Supplementary) while the litter pollution levels at vegetated sites did not significantly differ from harbors. The same was observed for stony river banks along the Elbe compared to harbors and beaches (both $p < 0.001$). The opposite was noted along the Weser where harbors were significantly less polluted than beaches and stony river banks (both $p < 0.001$), irrespective of absolute quantities or accumulation rates (Table C, Supplementary). Comparing litter amounts and accumulation rates between the embankment types overall, stones collected significantly fewer debris items than harbors and marinas which in turn were less polluted than river beaches. All differences were significant ($p < 0.001$). The cross-river comparison showed that the river banks of the Weser were significantly less polluted than those of the Ems (absolute litter: $p = 0.003$; accumulation rate: $p = 0.007$) and also of the Elbe (both $p < 0.001$). The river banks of the Elbe were in turn the most polluted ($p < 0.001$; Table C, Supplementary).

3.2. Floating litter quantities

Extrapolation approach 1, based solely on the long-term mean flow speed of each river, resulted in emission estimates that were 1–2 orders of magnitude higher than approach 2, based on mean ebb current speeds during the survey and daily emissions extrapolated from the long-term mean velocity (Table 1a). In both cases, the mean rank of the daily quantities estimated for the Elbe at Cuxhaven was significantly greater than that of the Weser at Bremerhaven ($p \leq 0.001$) and of the Ems at the Ems barrage ($p < 0.001$). The difference between the Weser and Ems litter outflow was not statistically significant. Standardized to daily litter discharge rates per meter river width, the pattern remained the same. The data from all three rivers showed a high degree of variability (Table 1a).

3.3. Suspended litter quantities

In the Ems, the two stations upstream of the Dollart showed significantly higher debris loads per m^3 than the three stations between Emden and Eemshaven ($p \leq 0.029$; Figs. 1 and 2a). The mean debris loads at the outflow of the Dollart were the lowest (Oterdum: mean ± SD: $4.0\ 10^{-6} \pm 30.3\ 10^{-6}$ items m^{-3}) and more than doubled again towards the position furthest seaward (Dukegat: $8.5\ 10^{-6} \pm 15.0\ 10^{-6}$ items m^{-3}; Fig. 2a). In the Weser, a similar pattern was observed: With the exception of Oberhammelwarden, the mean litter quantities per water volume generally decreased the further downstream the station (Fig. 2b). The lowest mean litter quantities measured at Bremerhaven ($8.2\ 10^{-6} \pm 14.7\ 10^{-6}$ items m^{-3}) slightly increased again towards the perimeter of the estuary (Wremen: $8.9\ 10^{-6} \pm 14.8\ 10^{-6}$ items m^{-3}). The litter levels of the Elbe water column did not appear to follow any particular pattern (Fig. 2c).

Overall, the mean rank of the litter quantities per m^3 of the Elbe water column was greater than that of the Weser, which in turn was significantly higher ($p = 0.031$) than that of the Ems (Fig. 2). A comparison of the seasonal litter quantities per m^3 revealed neither for the Ems nor for the Weser a significant difference between spring and autumn samples. The Elbe water column however contained significantly higher litter loads in spring (mean rank: 123.5; mean ± SD: $27.4\ 10^{-6} \pm 64.3\ 10^{-6}$ items m^{-3}) than in autumn (99.3; $16.6\ 10^{-6} \pm 24.4\ 10^{-6}$ items m^{-3}; Mann-Whitney U $p = 0.005$). Across all rivers, the incoming tide resulted in hauls that contained on average $2.9\ 10^{-6}$ items more per m^3 than during the outgoing tide ($18.5\ 10^{-6} \pm 26.6\ 10^{-6}$ items m^{-3}), yet this difference was not statistically significant.

3.4. River bed debris

Neither the absolute amount of litter per trawl nor the standardized abundances per km^2 showed any significant differences between the three rivers. However, the trawls of the Elbe estuary (mean n items per station ± SD: 7.6 ± 4.5; mean n items per km^2 ± SD: ~5500 ± 3600) had higher pollution levels than those samples taken in the Weser (2.5 ± 3.3 and ~2700 ± 3600 items, respectively), which were in turn also higher than samples from the Ems estuary (1.7 ± 1.2 and ~1400 ± 1000 items, respectively).

3.5. Litter emissions via the surface and the water column

Calculating daily surface-floating litter emissions based on approach 1, statistically significantly more debris is carried into the Dollart estuary by the water body of the Ems at Terborg (mean rank: 22.0) than via the surface at the Ems barrage (14.5; $p = 0.026$; Table 1a). The opposite observation was made for the Elbe: Significantly greater litter quantities are discharged via the water surface, based on litter observations at Cuxhaven (21.4), compared to the water column samples within the estuarine water body at Medem (11.5; $p = 0.007$). At the Weser estuary, no statistically significant difference was detected between the emission levels of the river surface (13.2) and the water column at Bremerhaven

Table 1
Quantitative daily estimates (a) and extrapolated annual mass discharges (b) of all macrolitter as well as only macroplastics for the Ems, Weser, and Elbe. The mean daily values of items emitted via the surface and the water column (a) were added and extrapolated to a year (365 d) to calculate annual numbers of items. These were in turn multiplied by the mean and median per item weights (in g) to yield annual mass emissions (b). Estimates 1 and 2 relate back to extrapolation approaches 1 and 2 (see Section 2.6.2).

a	daily **macrolitter** emission (n items)												daily **macroplastic** emission (n items)		
	surface (estimate 1)				surface (estimate 2)				water column				surface (estimate 1)	surface (estimate 2)	water column
	min.	max.	mean	SD	min.	max.	mean	SD	min.	max.	mean	SD	mean	mean	mean
Ems	0	3816	507	1003	0	142	19	37	58	391	215	112	507	19	203
Weser	0	10,954	2874	3897	0	452	118	161	36	461	221	162	2515	103	212
Elbe	0	1,571,400	205,389	338,401	0	17,076	2232	3677	290	9395	1564	2489	194,503	2114	1487

b	annual **macrolitter** emission (t)				annual **macroplastic** emission (t)			
	estimate 1		estimate 2		estimate 1		estimate 2	
	based on mean item weight (10.6 g)	based on median item weight (1.7 g)	based on mean item weight (10.6 g)	based on median item weight (1.7 g)	based on mean item weight (6.3 g)	based on median item weight (1.7 g)	based on mean item weight (6.3 g)	based on median item weight (1.7 g)
Ems	2.8	0.5	0.9	0.2	1.6	0.4	0.5	0.1
Weser	12.0	1.9	1.3	0.2	6.3	1.7	0.7	0.2
Elbe	800.7	128.4	14.7	2.4	450.7	121.6	8.3	2.2

(14.5). On average though, consistently more litter enters the North Sea via the water surface of the Ems, Weser, and Elbe than via the water body (estimate 1, Table 1a). Estimating the daily macrolitter discharge from mean ebb velocities and long-term river flow speeds (approach 2), more litter is carried into the sea via the water body of the Ems and Weser than via the surface (estimate 2, Table 1a). In the Ems, this difference is statistically significant ($p < 0.001$). In the Elbe, the river surface in turn emits more litter than the water column, based on both means and mean rank abundances.

Considering the results of approach 1 and 2 as upper and lower estimates, the added annual mean surface and water column pollution levels of the Elbe result in ~1.4 million to ~75.5 million items being emitted into the North Sea. For the Weser, the estimates range from ~124,000 to ~1.1 million items, and for the Ems from ~85,000 to ~260,000 items. Based on the weight of 1991 objects from stow net samples, the mean item mass was 10.6 ± 163.1 g (range: 0.007–6995 g), the median mass 1.7 g. The mean quantities of discharged litter were multiplied by the average (median) item weight. Under estimate 1, the Ems emits ~2.8 (0.5) t y^{-1} of anthropogenic debris into the Dollart, while the Weser carries ~12.0 (1.9) t y^{-1} and the Elbe 801 (128) t y^{-1} into the North Sea. Under estimate 2, the amounts are reduced: 0.9 (0.2) t y^{-1} discharged via the Ems, 1.3 (0.2) t y^{-1} via the Weser, and 14.7 (2.4) t y^{-1} via the Elbe (Table 1b).

For only those objects classified as “plastic/polystyrene” ($n = 1802$), the mean item mass amounted to 6.3 ± 33.0 g (median mass: 1.7 g). Based on the river-specific contribution of surface-floating and suspended debris to the total sum of daily litter outflow, while taking only the compartment-specific proportion of plastics into account (Fig. B, Supplementary), the average macroplastic emissions range from ~0.5 (0.1) to ~1.6 (0.4) t y^{-1} for the Ems, ~0.7 (0.2) to ~6.3 (1.7) t y^{-1} for the Weser, and ~8.3 (2.2) t y^{-1} to ~451 (122) t y^{-1} by the Elbe (Table 1b).

3.6. *Litter composition and diversity*

Plastic generally contributed between 87.5% and 100% of all debris in the four river compartments (Fig. B, Supplementary). The Elbe river bed samples contained a relatively high proportion of glass (15.8%) and other pollutants (7.9%). Along the river banks of the Ems, Weser, and Elbe, plastic and paper items co-dominated the litter composition; the majority of items classified as “paper” were cigarette butts (Fig. B, Supplementary). A large proportion of plastic items were unspecified plastic/polystyrene pieces of various sizes (Fig. 3). Consumer waste, such as bottles, food containers or crisp/sweet packets and lolly sticks consistently made up a quarter to a third of the total litter found on shores, the river surface and in the water column, but were absent from river bed samples. Here, plastic strings, particularly dolly ropes, added the largest proportion; such fishing-related items were also found in the other river compartments (Fig. 3).

Comparing the number of different litter types between the three rivers, the Elbe had the highest macrolitter diversity (mean ± SD: 24 ± 15), followed by the Ems (17 ± 12) and the Weser (15 ± 9). The difference between Elbe and Weser was statistically significant (Tukey-HSD $p = 0.036$). Comparing the four river bank types across all rivers, stones and boulders accumulated an average of 20 ± 6 different litter types per location, harbor structures 24 ± 14, and vegetated river banks almost 30 ± 5; beaches had the most diverse litter composition with a mean of 39 ± 20 categories per site. The difference between beaches and river banks made of stones and boulders was statistically significant (Tukey-HSD $p = 0.029$). Comparing the four river compartments across all rivers, the river bed had the lowest

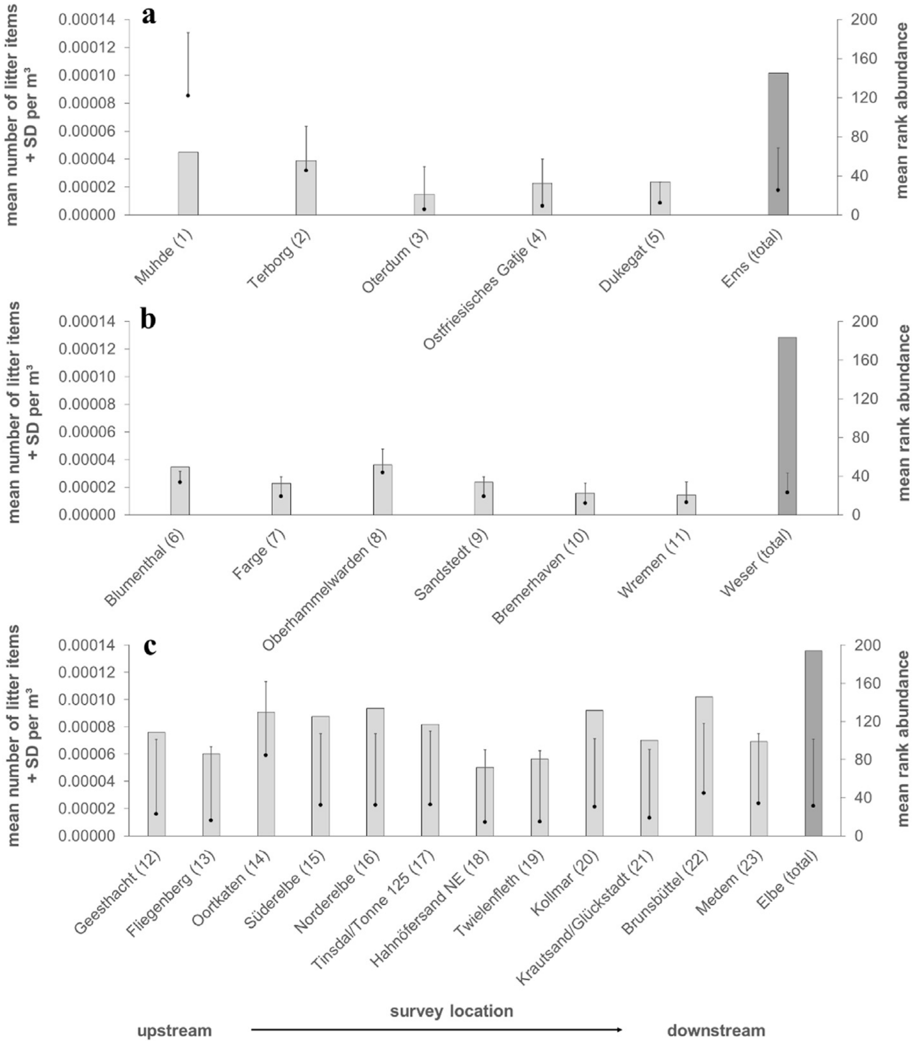

Fig. 2. Mean litter pollution levels + standard deviation (SD) per m^3 of water column (black dots) at each station in the Ems (a), Weser (b), and Elbe (c), as well as the respective mean rank abundance (gray bars) from which the statistical differences were calculated. The locations are placed in geographic order, from left "upstream" to right "estuary" (see also Fig. 1).

litter diversity (mean ± SD: 2 ± 2; mean rank: 6.2), followed by the river surface (8 ± 5; 13.0) and the water column (19 ± 7; 31.4). River banks exhibited the largest variety of debris types (27 ± 13; 42.1) which was significantly more diverse than that of the water column ($p = 0.036$), the river surface ($p = 0.008$), and the river bed ($p < 0.001$). The differences in the litter diversity between the river bed and the river surface, as well as the river surface and the water column were both not statistically significant.

4. Discussion

4.1. Comparison of model- and field-based estimates

Lebreton et al. (2017) estimated that European rivers only account for 0.28% of the global riverine input of plastics, i.e. between 2310 and 9320 tonnes annually. Considering the model-based calculations by Schmidt et al. (2017), the 243 European rivers, for which data were analyzed, are however said to contribute 2.8% or 5.8% of the global riverine microplastics emission, depending on the model, and 9.4% of riverine macroplastics. Among the top 25 of Europe's most plastic litter polluted rivers, Schmidt et al. (2017) rank the Ems 25th, the Weser 12th, and the Elbe 7th. In light of more advanced waste management systems in European states compared to many developing countries, these quantities should still be considered substantial. The general scarcity of field data with which the model estimates were calibrated and the fact that none of those studies provided data on the three river systems that are focused on here, call for ground-truthing.

Although the two extrapolation approaches for surface-floating litter differ in only one aspect, i.e. the calculation of litter items during the survey period based on either the river-specific long-term mean flow speed or the mean ebb current velocity, the numeric quantities vary by up to two orders of magnitude, subsequently shifting the proportional contribution of river surface and water column. Combining litter abundances from both compartments as annual mass emissions, the results of the two estimates also diverge considerably, i.e. 3- to 54-fold for all debris as well as for plastics. The discrepancies are smallest for the Ems, and largest for the Elbe, which may be attributed to the growing level of uncertainty obtained by extrapolating across a wider river. Compared to the previous model-based estimates, the field-based plastic litter discharge quantities of the Ems (0.1–1.6 t y^{-1}) and Weser (0.2–6.3 t y^{-1}) are lower than the macroplastic inputs calculated by Schmidt et al. (2017; Ems: 2 t y^{-1}, Weser: 10 t y^{-1}) and substantially

Fig. 3. Composition chart of all litter categories under the material debris group "plastic" (red bars in Fig. B, Supplementary). For the purpose of improved comparability, the proportion of cigarettes that were recorded as "plastic" in the "Floating Litter Monitoring" app during river surface observations was excluded (Cigarette butts are categorized as "paper" in the OSPAR litter classification used for river bank, water column, and river bed surveys.). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

smaller than the range of estimates by Lebreton et al. who also included microplastics (2017; Ems incl. one sub-tributary: ~7–37 t y^{-1}, Weser incl. five sub-tributaries: ~31–137 t y^{-1}). This is also the case for the Elbe's mean (8.3 t y^{-1}) and median (2.2 t y^{-1}) macroplastic emissions under estimate 2 (see 2.6.2). In contrast, the mean (451 t y^{-1}) and median (122 t y^{-1}) input quantities under estimate 1 are similar to or exceed the highest estimates by Lebreton et al. (2017; Elbe: 72–301 t y^{-1}) and Schmidt et al. (2017; Elbe: 25 t y^{-1}).

The reasons for these noteworthy differences are speculative: Whether it may be the general difference in baseline data from which the estimates were calculated, the potential importance of relating abundance data to river-specific average per-item-masses, shortcomings in the previously published or present methodological approaches, or simply a large degree of remaining uncertainty as to the exact mechanisms influencing litter input, dispersal, beaching, and re-entry in rivers. This ground-truthing exercise therefore highlights the potential discrepancies between and within model- and field-based estimates. Whether such differences also apply to other river systems would have to be investigated by future studies and thus necessitates an increase in comparable field observations that include particularly macroplastics. Unless it is possible to improve the alignment of models and field-data as well as the overall accuracy of estimates, it will remain extremely difficult to adequately identify any reduction of pollution levels due to new laws and regulations or improved enforcement.

However, given the river-specific emission rates calculated here and the estimates of mismanaged plastic waste per catchment from the literature (see Supplementary in Lebreton et al., 2017; Schmidt et al., 2017), the litter quantities discharged overall account for only 0.001–0.76% of the total mismanaged mass. As in van Emmerik et al. (2019a) who found waterways around Jakarta to emit only 3% of all mismanaged plastic waste in the region, this leads to the conclusion that the vast majority of discarded debris in fact likely accumulates on land, along the river banks, and on the river bed, while only a fraction is transported into the sea via the Ems, Weser, and Elbe. If this turned out to be a recurring observation in other river systems, management strategies should preferably target on-land and riverside waste accumulation.

4.2. Compartment-specific pollution levels

Aside from plastic emission estimates, the recorded anthropogenic waste quantities throughout the transitional waters of the

Ems, Weser, and Elbe show great spatio-temporal variability as has been generally noted for riverine debris (e.g. Williams & Simmons, 1996; Gasperi et al., 2014; Rech et al., 2014; Bruge et al., 2018; Bauer-Civiello et al., 2019; Kiessling et al., 2019). This is likely to be influenced by various source points, differences in litter input rates along the river, the tidal movement of the water masses, and small-scale features of the river morphology and hydrology (McCormick & Hoellein, 2016).

River banks are the interface between the terrestrial and the aquatic environment and can act as sources and sinks for anthropogenic debris. In the Ems, river vegetation and harbor structures accumulated the largest litter quantities. The high average diversity of 30 litter types per vegetated site additionally indicates the significance of riverside plants acting as litter traps (Williams & Simmons, 1996; Araújo and Costa, 2007). This may be advantageous when aiming for effective and targeted litter removal by e.g. local authorities or cleanup volunteers. The range of recorded quantities was greater at harbors structures though, suggesting that varying levels of human activities on-site are a point source of litter, adding to the waste that is carried past or washed ashore by the river. Such littering behavior in harbors and marinas, even by sailors whom one may assume to be more environmentally conscious through their sport, was confirmed by field observations (M. Kruse, 2017; pers. comm.; G. Reich, 2018; pers. comm.; Merten, 2019; unpubl.).

Both in the Ems and the Elbe, stone embankments retained the lowest litter quantities, likely due to the fact that they do not act as point sources and that the river current drags floating debris along with few items becoming wedged in between the stones. Suspended sediment loads also fill up the gaps, creating a more even surface that items are less likely to become caught on (pers. obs.). In the Weser however, approx. five times less debris was found at harbor sites than at stone embankments which in turn were similarly polluted to the river beaches. This similarity was also noted in a previous study along the Weser (BioConsult 2015) and may be river-specific. Beaches were the most significantly and diversely polluted of all river bank types, accumulating both litter washed ashore through tidal movements and ships' swash as well as beach visitor waste, particularly cigarette stubs, food containers, caps and lids, cups and cutlery, as well as bottles. This is in line with several previous river studies who also found a large proportion of consumer waste (Gasperi et al., 2014; Blettler et al., 2017; Vincent et al., 2017; Kiessling et al., 2019).

The observed floating litter quantities close to the estuary showed extreme temporal variability between surveys despite the monitoring always having been carried out during ebb tide. This again highlights the heterogeneity in litter dispersal that is also common to coastline observations (see findings and references in Schöneich-Argent et al., 2019). The relatively low diversity in floating waste types can be explained by their nature: Only "persistently buoyant" or "short-term buoyant" items from estuary-near sources are likely to exit into coastal waters (Rech et al., 2014). Direct data comparisons of litter quantities emitted via the river surface are limited due to the small number of publications and differences in the data processing, analysis approach, and reported units therein (Schmidt et al., 2017; van Emmerik et al., 2019b). The observation that generally higher debris loads are found at the river surface than in the water column however corresponds to findings by van Emmerik et al. (2019a, b).

Suspended litter quantities in the water column varied spatially and temporally. The decreasing average pollution levels towards the estuary of the Ems and the Weser were previously noted (Schulz, 2015) and may be due to fewer litter source points towards the estuary, a dilution effect caused by the widening of the river, or river banks and the river bed acting as sinks for debris further upstream. Differences in embankment use and thus local litter source points as well as deposits may also explain the fluctuation of waste amounts recorded at stations in the Elbe, as suggested for the Seine by Gasperi et al. (2014). The increase in average debris abundances in the water column close to the ports of Eemshaven, Bremerhaven, and Brunsbüttel may hint towards harbors not only having an increasing effect on embankment waste amounts but also on suspended litter quantities. Yet while a relatively small proportion was directly fishing-related, only few individual items such as plastic strapping bands, industrial packaging, or industrial gloves indicated possible ship-based sources. The variety of recorded household goods was not conclusive and may have originated either from land or from ship waste, while more than half the recorded plastic litter were unidentified pieces of plastic or polystyrene. This resulted in the water column having the second highest litter diversity on average, but also highlights the continued difficulty in attributing definite sources to waste items, not only along the coast but also in rivers (Williams & Simmons, 1999; Tudor & Williams, 2004; KÜFOG GmbH, 2013; Schäfer et al., 2019).

In comparison to the aforementioned compartment surveys, the river bed samples were only collected at one point in time and at locations that allowed the research vessel to trawl at low speed for several minutes. Therefore the results may be less conclusive. Nonetheless, they offer a first impression of the benthic litter pollution levels which appear to be rather extensive per unit area but also not homogeneous. In contrast to Schwarz et al. (2019) who hypothesized a greater plastic debris abundances at the river floor due to a variety of negatively buoyant polymers sinking, the river bed samples here were the least diverse of all the river compartments. This may be attributed to the high sediment load known from all three rivers (Schuchardt et al., 1999) which can lead to rapid burial of items on the river bed (Galgani et al., 2000). Alternatively, the trawl may not have been able to capture larger items due to the restricted opening, pushing objects aside or losing them whilst being hauled back up. Similarly, some smaller items may have been overlooked in particularly muddy trawl samples despite best efforts.

4.3. Recommendations

Overall, the minimally invasive methodological framework of this study can be applied to rivers elsewhere. Future studies could also aim to reduce the various levels of uncertainty identified: Observations of surface-floating debris should ideally be carried out across the entire width of the river (see van Calcar & van Emmerik, 2019) in order to increase the accuracy of emission estimates, particularly for wider rivers. Without a bridge close to the estuary (as was the case here), cross-river transects by boat or remote sensing using drone technology could provide an option. Water column sampling could also be increased from annually two surveys per site to quarterly or monthly surveys. This would identify year-round variability which could in turn be better linked to external influences. The same applies to river bed sampling. Here, one should also consider whether trawling is the best way to record benthic debris in riverine/estuarine systems with a high load of suspended sediments, or whether grab or 1-m dredge samples may be more suitable. Ultimately though, such add-ons are likely to be more time- and labor-intensive so that their effectiveness should be tested.

5. Conclusions

This study provides the first holistic, field-based assessment of riverine macrolitter pollution as well as abundance and mass discharge estimates in three Northern European rivers. The Elbe exhibited significantly higher litter pollution levels across all compartments than the Weser and the Ems. And while the Ems appeared to have significantly more polluted river banks than the Weser, the Weser had generally higher debris transport via its surface and the water column, as well as larger litter deposits on the river bed than the Ems. This confirms the initial hypothesis that larger rivers with more populated catchments tend to have higher pollution levels and thus also emit more debris into the marine environment.

Comparing mean and median annual plastic emission rates calculated for the Ems, Weser, and Elbe to previous model-based estimates, which were largely validated by riverine microplastic studies, revealed large discrepancies. This does not invalidate the model calculations but highlights the need to ground-truth such estimates. Small-scale local and regional factors along each river course that were not included in such large-scale models may have a substantial influence on the river-specific levels of litter input and retention, and will affect the actual amount of riverine litter discharged into the coastal environment. As such, spatial and temporal variability in the recorded litter quantities has been noted by several past studies and appears to be a common phenomenon also along the rivers in this research. Future studies should therefore be cautious to extrapolate litter data from just one stream compartment, short-term sampling, or a selected item size range to litter loads and emission rates for the entire river system as this may lead to a distorted assessment of the scope of pollution. Ultimately, the aim should be to adequately evaluate the effectiveness of waste management and reduction strategies inland and on water that will ideally become visible by a significant, long-term decrease in riverine pollution levels.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Rosanna Isabel Schöneich-Argent: Conceptualization, Methodology, Investigation, Validation, Data curation, Formal analysis, Visualization, Writing - original draft, Writing - review & editing. **Kirsten Dau:** Funding acquisition, Conceptualization, Investigation, Validation, Data curation, Writing - review & editing. **Holger Freund:** Funding acquisition, Supervision, Conceptualization, Writing - review & editing.

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Appendix A. Supplementary data

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