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ABSTRACT

Catchment-scale plastic pollution assessments provide insights in its sources, sinks, and pathways. We present an approach to quantify macroplastic transport and density across the Odaw catchment, Ghana. We divided the catchment into the non-urban riverine, urban riverine, and urban tidal zones. Macroplastic transport and density on riverbanks and land were monitored at ten locations in December 2021. The urban riverine zone had the highest transport, and the urban tidal zone had the highest riverbank and land macroplastic density. Water sachets, soft fragments, and foam fragments were the most abundant items. Our approach aims to be transferable to other catchments globally.

1. Introduction

Rivers have been highlighted to play a key role in the transport of plastics into the ocean (Meijer et al., 2021). Riverine plastic pollution is strongly impacted by humans who dispose litter on land, at riverbanks or into the river channel (Nihei et al., 2020). Along their movement from source to sink, several natural (hydrometeorological, topography, land-use types) and anthropogenic (urbanisation, hydraulic structures) factors influence its spatial and temporal abundance (Talbot et al., 2022). Previous research focusing on several rivers in South East Asia and Europe highlights the temporal and spatial variability of micro and macroplastics (Tramoy et al., 2019; van Emmerik et al., 2019) to be attributed to meteorological conditions (wind, precipitation) (Mellink et al., 2023, preprint; Bullard et al., 2021), hydrodynamics (Castro-Jiménez et al., 2019), channel characteristics (presence of vegetation, hydraulic structures, river morphology) (Schreyers et al., 2021; Honingh et al., 2020), and catchment characteristics (land use, slope) (Bond et al., 2022). As these factors vary across a range of spatial and temporal scales, it is relevant to understand the extent to which these factors relate to the variability of micro and macroplastic pollution across a river catchment.

Plastic transport at the catchment scale helps in identifying sources and sinks, because the different spatial features in the catchment influence the transport of litter (Windsor et al., 2019). In recent years, there has been effort on either conceptualising macroplastic transport at the catchment scale or estimating the macroplastic transport at the river outlet of a catchment from field data. For example, Treilles et al. (2021) focused on macroplastic transport at the outlet of a small urban catchment in Paris, France to estimate the mass fluxes. Another study by Weideman et al. (2020), sampled plastic and anthropogenic debris from the runoff of three catchments representing different land-use types to assess how they affect plastic loads in rivers. Despite these previous works, the understanding of macroplastic at the catchment scale is still inadequate because the estimation of micro and macroplastic transport from these previous studies did not consider sampling at all environmental compartments (land, riverbank, and river) at different spatial scales within the catchment. This is important to show how the characteristics (geology, land cover, anthropogenic activities) relate to the variation in macroplastic abundance and composition at each of these environmental spatial scales.

Our paper focuses on macroplastic pollution in the Odaw catchment in Accra, Ghana. This catchment is particularly interesting as it is subject to intense environmental pollution due to it being densely populated and characterized by the presence of commercial (trading) and industrial (plastic packaging, auto mechanics, etc.) activities (Ntajal et al., 2022). Combined with inadequate waste management in this catchment, most

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sections of the river in the catchment are used as garbage dumping receptacles (Larmie, 2019). Therefore, the Gulf of Guinea is highly exposed to marine litter pollution (Van Dyck et al., 2016). Previous study by Pinto et al. (2023) estimated the average hourly transport of macroplastics from the downstream section of this catchment to be 2.7 $\times 10^2$ to 2.4 $\times 10^3$ items/h. The estimated range (3.5 $\times 10^1$–6.5 $\times 10^1$ kg/d) of plastic mass transport stated in this paper was one and two orders of magnitude lower for the lower (5.17 $\times 10^2$ kg/d) and upper (3.1 $\times 10^3$ kg/d) estimates of modelled plastic mass transport in Meijer et al. (2021). In this paper, we extend the previous work by presenting a catchment-scale assessment of plastic pollution at the river surface, on riverbanks and on land, for ten locations ranging from the river mouth to the most upstream reaches of the Odaw basin.

This study aims to provide data on the spatial distribution of macroplastic pollution at three environmental compartments (land, riverbank, and river) across the Odaw catchment. This was done by sampling macroplastic abundance and composition on land, riverbank, and river channel environments at ten locations along the catchment over three days between 11 and 23 December 2021. To correlate the macroplastic distribution in the catchment to the land-use type and macroplastic transport processes in the river, the catchment was sub-divided into three zones: (1) non-urban riverine, (2) urban riverine, and (3) urban tidal. This catchment sub-division is essential to show how macroplastic spatial variations (abundance and composition) relate to the varying spatial geographical characteristics (geology, land-use type) in the catchment. The results from this study are expected to provide insights on the spatial variation in abundance and composition of macroplastics at all environmental compartments in the Odaw catchment.

2. Methods

2.1. Study area

The study was carried out in the Odaw catchment, which covers an area of 270 km^2 (Fig. 1a). This basin is in the coastal savannah region with two seasons, i.e., the dry and wet season. The dry season is from November to April and the rainy season from May to October with an average annual rainfall of about 730 mm (Bogerd et al., 2023). Within the catchment is a 30 km long river and its tributaries Nima, Onyasia, Dakobi, and Ado, which drain the major urbanized areas of Accra into the lagoon and then into the ocean. The land-use for this catchment is largely urban and densely populated including informal settlements at the downstream part (southern). About 57 % (2.7 million) of the population in the Accra Metropolitan Area (AMA) live in this part of the catchment. Within the downstream part of the Odaw catchment, the riverbank characteristics within the city centre is bare and unvegetated (Fig. 1c), whereas close to the river mouth it is either vegetated or covered by stones (Fig. 1d) (Ackom et al., 2020). The upstream part on the other hand is less intensively used with quite some agriculture (Larmie, 2019). The riverbank at this upstream part is vegetated (Fig. 1b) with the slopes generally gentle (below 11 %) (Ackom et al., 2020).

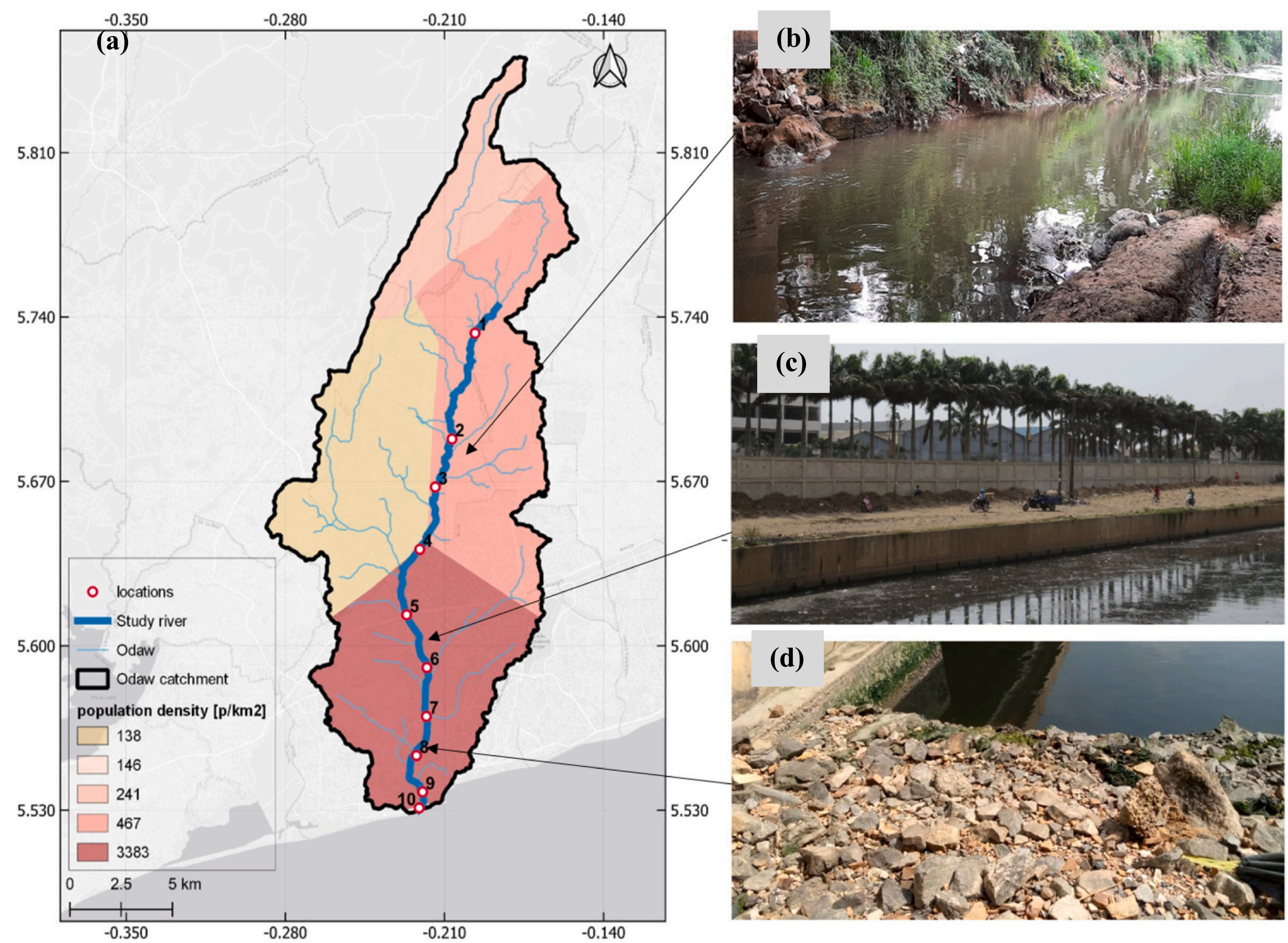

Fig. 1. (a) Map of the Odaw catchment with the 10 sampling locations indicated (Source: ESRI Gray) and riverbank characteristics in the (b) non-urban riverine zone (locations 1–4) (c) urban riverine zone (locations 5–7) (d) urban tidal zone (locations 8–10). (picture credit: Rose Pinto 2021)

2.2. Catchment zones delineation

The catchment, comprising ten macroplastic sampling locations, was sub-divided into three zones based on the common land-use type (anthropogenic characteristics) and the river's physical transport processes that affect the floating macroplastic (Fig. 2a). First, the catchment was divided into two land-use types, non-urban (upstream: locations 1–4) and urban (downstream: locations 5–10) based on the population density variation in the catchment (Fig. 1a). Secondly, the river's physical transport processes were defined: riverine transport was identified for the non-tidal region of the river and tidal transport for the tidal region (river mouth) of the river. The riverine transport zone was identified between bridges 1 and 7 and the tidal zone between bridges 8 and 10 (Pinto et al., 2023). Based on both sub-divisions in land-use and the river's physical transport processes, the land and riverine environments around bridge locations 1–4, 5–7, and 8–10 were grouped and assigned to the non-urban riverine, urban riverine and urban tidal zones respectively for this catchment.

2.3. Conceptual macroplastic transport model in Odaw catchment

We developed a conceptual model for macroplastic transport in the catchment (Fig. 2b). This model considered the macroplastic transport between the different environmental compartments (land, riverbank, and river) and between the catchment zones. A unidirectional transport of macroplastic from the land to riverbank was assumed, because most macroplastic is generated on land (Constant et al., 2020) with its transport to the riverbank controlled by natural factors (rain, wind) (Bullard et al., 2021). From the riverbank to river, a bi-directional macroplastic link was considered, due to the lateral two-way connectivity between a river and its floodplains (Cienciala et al., 2020).

No transport was hypothesised between the riverbank and land environments from one catchment zone to the other. This is due to the variation in geographical characteristics (topography, land-use cover) between the environmental compartments found in these catchment zones (Bond et al., 2022), creating limited hydrological connectivity. For instance, natural barriers such as dense vegetation or artificial structures (buildings) due to urbanisation can limit the transport (Price, 2011) between the sub-catchment zones. Unidirectional transport of floating macroplastic from the non-urban riverine (upstream) to urban riverine (downstream) was assumed. This unidirectional transport was hypothesised for this section due to the down slope freshwater discharges within this section. However, due to the tidal influences at the urban tidal zone, a bi-directional macroplastic transport was indicated between the urban riverine and urban tidal zones.

2.4. Monitoring and sampling of macroplastic

2.4.1. Floating macroplastics

The visual counting approach (González et al., 2016) was used to monitor floating macroplastic in the Odaw river (Fig. 3). Sampling was done on three days in December 2021 (11, 16, and 23) on ten bridges along the river (Table 1). Each sampling day fell within each of the weeks in December, except the last week. The cross-section of a river at each identified bridge was divided into two or three sections (4–28 m) based on the river width and number of floating macroplastics. For each of these sections, the number of identified floating macroplastic within 2 mins was counted and categorised according to the aggregated plastic polymer types (PET, PO soft, PO hard, multilayer, PS, EPS, and Other plastics) (van Emmerik et al., 2020) (see supplementary material for translation table). The specific items could not be categorised for this protocol due to the high abundance of the plastics transported in this river over a short period. Observation at all sections of each bridge was indicated as a sweep. Four sweeps were done at each bridge on each

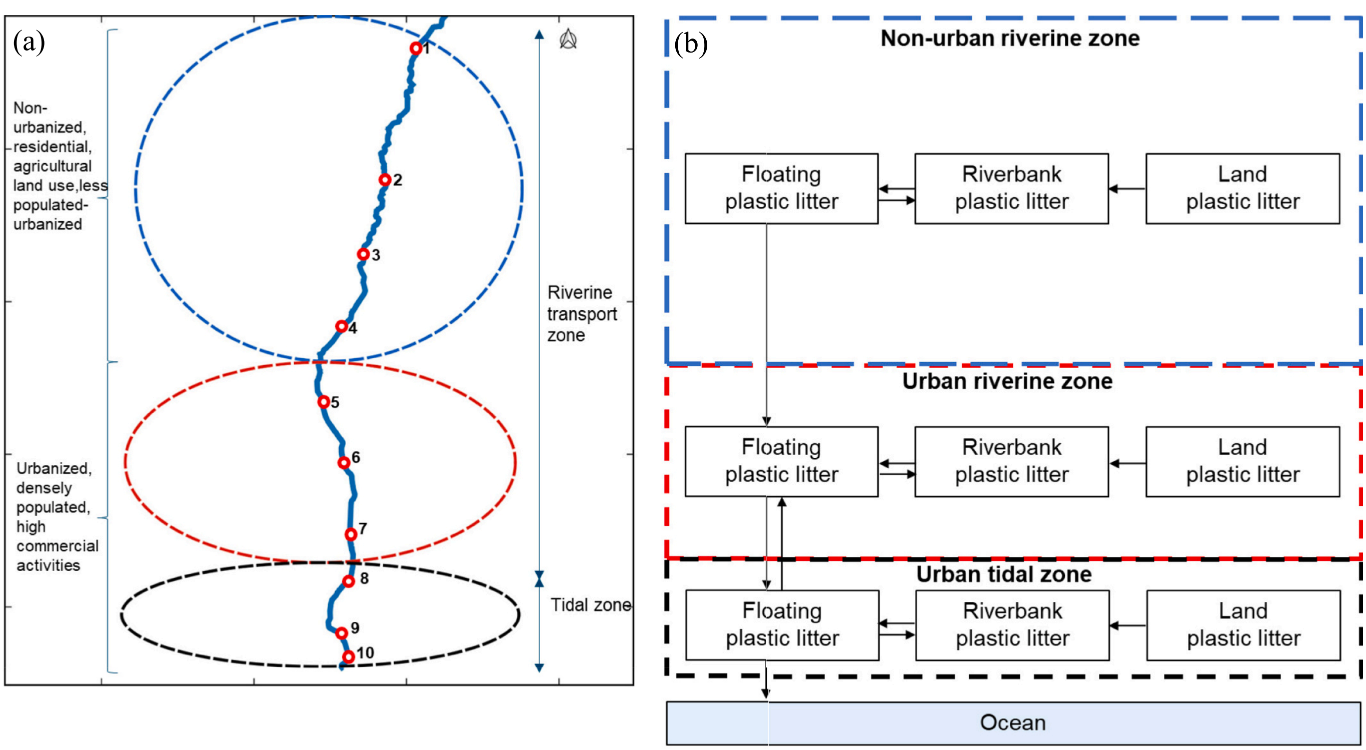

Fig. 2. (a) Catchment zone delineation into non-urban riverine (locations 1–4), urban riverine (locations 5–7) and urban tidal (locations 8–10) (b) macroplastic conceptual transport model in the Odaw catchment. The blue, red and black dashed lines show the non-urban riverine, urban riverine and urban tidal zones delineated for the Odaw catchment. The arrows between the environments (land to riverbank, and riverbank to river) at each of the zones indicate the hypothesised directional macroplastic transport link between the environments and the catchment zones in the Odaw. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

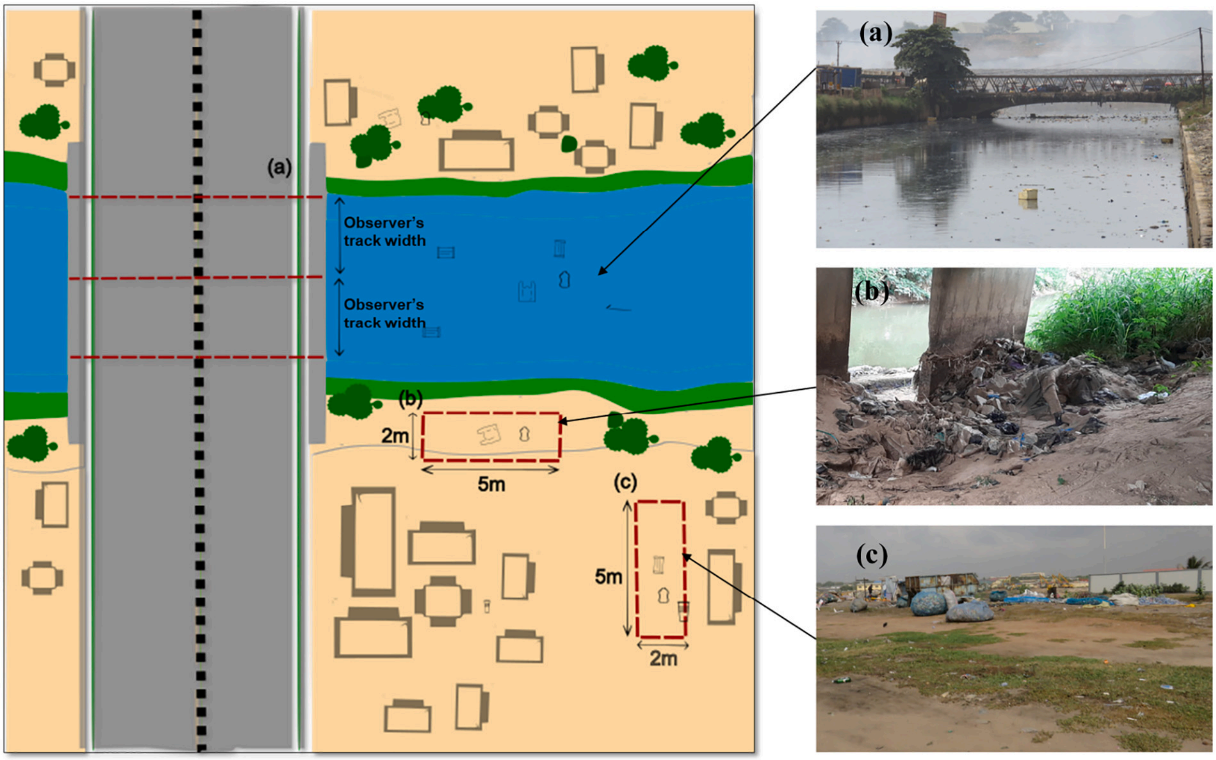

Fig. 3. Overview of a typical monitoring location at the three different compartments: (a) river, (b) riverbank, and (c) land. Although two bridge sections are illustrated (indicated by the red dashed lines) for floating macroplastics monitoring (a), the number of sections depends on the river width (number of sections per bridge location is indicated in Table 1). The orientation of the sampling area illustrated for the riverbank and land changed per location depending on accessibility. Additionally, the three pictures provide an indication of (a) floating litter in a river (picture taken at location 8, picture credit: Tim van Emmerik 2021), (b) litter on a riverbank (picture taken at location 3, picture credit: Rose Pinto 2021), and (c) litter on land (picture taken at location 10, picture credit: Linda Bogerd 2021) within the Odaw catchment.

Table 1
Details of the sampling locations identified for this study and the measurements that were carried out at each of the locations.

Measurement location	Sub basin	Distance from river mouth (km)	River channel type	River width (m)	Visual counting at bridge	No. of sections on bridge	Riverbank sampling of litter	Land sampling of litter
1	Non-urban riverine	22.70	Natural	5	Yes	1	Yes	Yes
2		19.50	Natural	10	Yes	2	Yes	Yes
3		16.90	Natural	11	Yes	3	Yes	Yes
4		13.60	Canalized	9	Yes	2	No	Yes
5	Urban riverine	10.00	Canalized	22	Yes	3	Yes	Yes
6		7.40	Canalized	24	Yes	3	Yes	No
7		5.10	Canalized	33	Yes	2	Yes	Yes
8	Urban tidal	3.50	Canalized	59	Yes	3	Yes	Yes
9		0.90	Natural	68	Yes	3	Yes	Yes
10		0.10	Natural	62	Yes	3	Yes	Yes

sampling day. Approximately 30 mins was spent at each bridge daily. Total macroplastic transport, (P_{F_j}) [items/h] over the river width of each bridge location, (j) was calculated by summing the average macroplastic transport, $(\overline{P}_i)$ [items/2 mins] for each section (i) of a bridge and multiplying it by a scaling time factor of 30 to express it as items per hour (Pinto et al., 2023).

2.4.2. Land and riverbank macroplastics

A 5 by 2 m^2 area was indicated as the standard survey area for each land and riverbank location in the catchment. However, at the downstream sampling locations, the location and area of the sampling section varied over the sampling days due to the insanitary, inaccessible, or unsafe conditions at these locations (Fig. 3). Additionally, riverbank and land sampling was not done at locations 4 and 6 respectively due to inaccessibility. The riverbank locations were <2 m away from the river and the land >10 m away from the river. Sampled litter was collected, counted, and categorised according to the River-OSPAR list (de Lange et al., 2023). This River-OSPAR list allows for the detailed categorisation of 110 litter items. Some litter items were added (water sachet, glue small bottle, pieces of rubber carpet, electronics, ceramics, and facemask) or removed (nurdles) from the River-OSPAR checklist during the field work to fit the mismanaged litter found in this catchment. Litter in the marked area was collected in a trash bag and later disposed of at an appropriate disposal site. Macroplastic density at each location, (j) on either land, (P_{L_j}) [items/m^2] or riverbank, (P_{R_j}) [items/m^2] on a sampling day was then estimated by dividing the macroplastic counts by the area surveyed [m^2] at a location. All locations and their three environmental compartments were measured on the same days. In the analysis presented in the "Results" section, the OSPAR litter types are also aggregated into the seven macroplastic polymer types i.e., PET, PO soft, PO hard, multilayer, PS, EPS, and Other plastics (see supplementary material).

2.5. Macroplastic hotspots definition

We determined macroplastic hotspot locations using the data collected during the study period (Fig. 4). At each environmental compartment, the 75th percentile was estimated using all macroplastic density or transport measurements at each bridge location over the sampling period (Step 1). This percentile was chosen as the threshold for defining hotspots in this study because the number of hotspot locations identified for each compartment at this percentile did not change. This indicates that this percentile is not impacted by outliers (see supplementary material) which makes it a good choice as the threshold for defining hotspot for this study. The total data points used for the estimation of the 75th percentile was 27 (i.e., 9 locations by 3 days) for the land and riverbank compartments and 30 (i.e., 10 locations by 3 days) for the river compartment. Macroplastic density or transport estimated for each location of an environmental compartment was then compared to the estimated 75th percentile (Step 2). An environmental compartment at a location with its macroplastic density or transport per each sampling day above the 75th percentile was noted (Step 3). However, in identifying a hotspot location, a consistency approach was used. Since sampling was done on three days, any environmental compartment at a sampling location with its macroplastic density or transport above the estimated 75th percentile for that environmental compartment on at least two sampling days was indicated as a macroplastic hotspot location, otherwise a macroplastic non-hotspot (Step 4).

2.6. Spatial variation of macroplastic polymer and item composition

Macroplastic composition were analysed separately for the river, land, and riverbank due to the different macroplastic categorisation methods. Floating plastics were analysed by estimating the fraction of each macroplastic polymer category found at a sampling location and within each sub-catchment zone relative to the total number of macroplastic items monitored from all sampling locations along the river during the sampling period. The specific floating items could not be categorised according to the OSPAR list due to the high abundance of the plastics transported in this river over a short period.

For the riverbank and land, we identified the top 10 specific plastic items in the catchment and sub-catchment zones based on the estimated fraction of each identified plastic item at a land/riverbank location relative to the total land/riverbank macroplastics over the sampling period in the catchment and at each sub-catchment zone.

The results from both analyses provides information on the spatial variation of each macroplastic polymer/item along the catchment and sub-catchment zones, indicating where in the catchment a particular macroplastic polymer/item is most abundant.

3. Results

3.1. Macroplastic transport and density spatial variation

Over the sampling period, a total of 6076 litter items were counted across all monitored environmental compartments in the catchment, out of which, 5070 items (83 %) were classified as macroplastics. Specifically, 2311 litter items were visually counted on the river surface, of which 2149 (93 %) were identified as macroplastics. Along the riverbanks, 1653 items were sampled, with 1178 (71.3 %) categorised as macroplastics. Finally, on land, 2112 litter items were sampled, and 1743 (82.5 %) were identified as macroplastics.

Macroplastics transport and density measured at the three environmental compartments (river, riverbank, and land) varied across the ten different locations within the catchment (Fig. 5). No macroplastic transport was recorded at bridge 1, which is located at the most upstream of the Odaw river. Macroplastic transport gradually increased from bridges 1 to 6 (0 to 1125 items/h). From bridge 6 to 7 (1125 to 890 items/h), the macroplastic transport decreased by about 21 %, while from bridge 7 onwards there was no clear trend. Peak macroplastic transport was observed at bridge 6 (1125 items/h).

The mean macroplastic density at the riverbank gradually increased from locations 1 to 3 (2.3 to 12.8 items/m^2) with no clear trend from locations 5 to 10. The highest riverbank macroplastic density was found at location 9 (17.5 items/m^2) and the least at location 1 (2.3 items/m^2). Although the density of macroplastics gradually increased from the upstream riverbank locations towards the downstream locations, the density sharply decreased by 13.3 items/m^2 between locations 9 and 10.

Macroplastic density on land sharply increased between locations 9 (3.1 items/m^2) and 10 (32.4 items/m^2). The highest macroplastic density on land within the catchment was also recorded at location 10. The least macroplastic density on land was recorded at location 2 and 3 (1.5 items/m^2).

Across the catchment zones, the largest macroplastic transport was observed in the urban riverine zone (937 items/h). The lowest macroplastic transport was observed at the non-urban riverine zone (66 items/h). Macroplastic transport in the urban riverine zone was 14 times larger than that in the non-urban riverine zone and 1.2 times larger than that in the urban tidal zone. Land and riverbank macroplastic density was highest closest to the river mouth (urban tidal). The lowest macroplastic

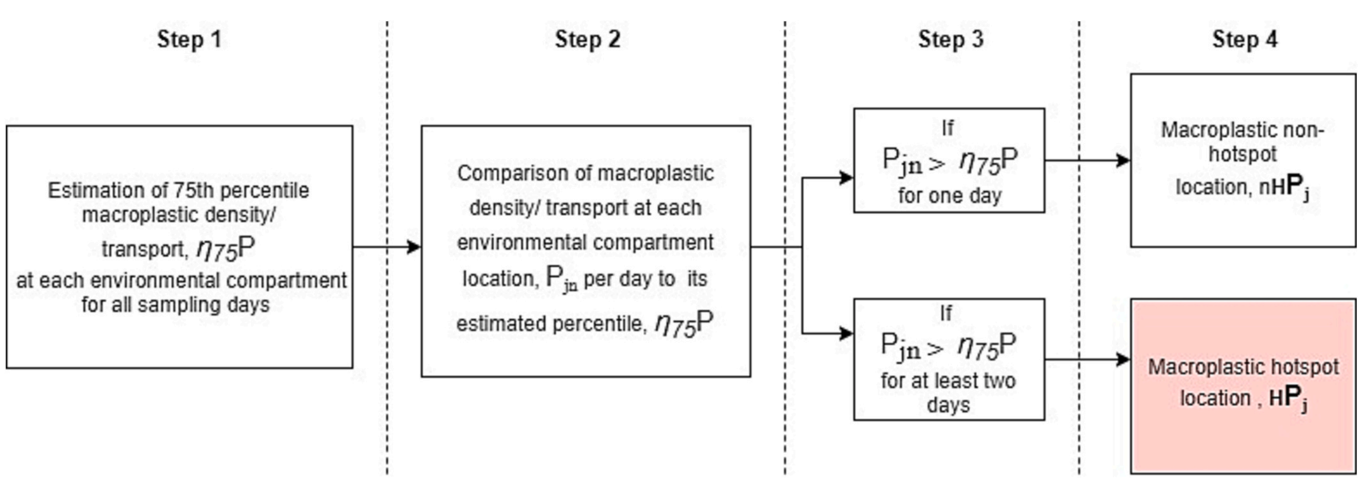

Fig. 4. The four-step framework for the identification of macroplastic pollution hotspot locations at the environment compartments sampled within the Odaw catchment.

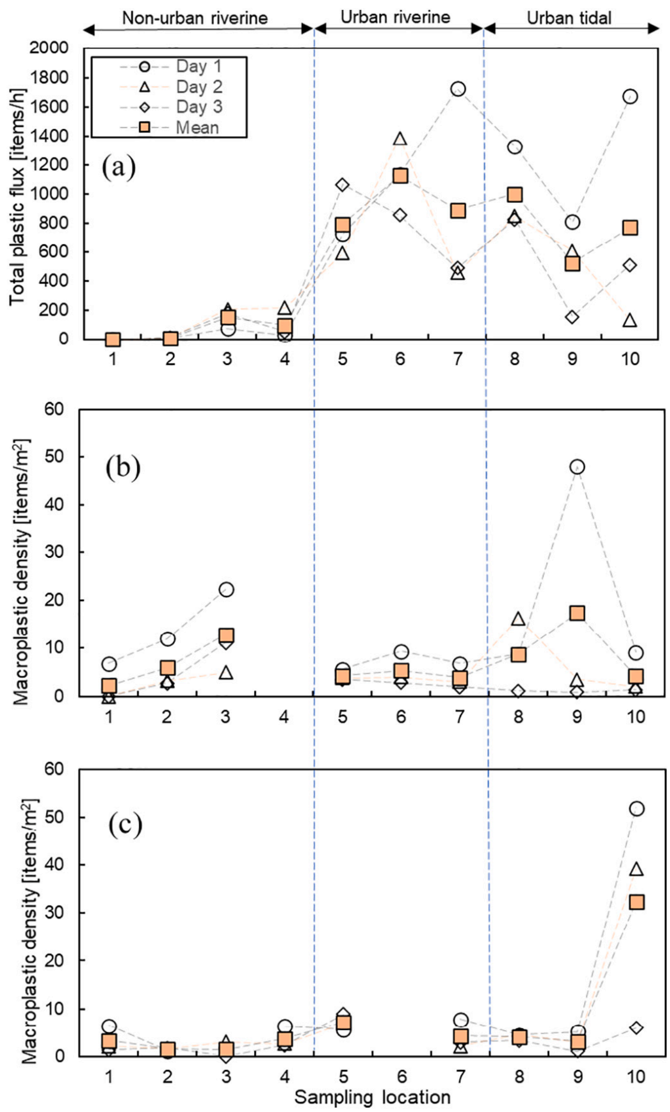

Fig. 5. Spatial and temporal variation of (a) macroplastic transport [items/h] (b) riverbank macroplastic density [items/m^2] and (c) land macroplastic density [items/m^2] along the Odaw river over the sampling period.

density at the land and riverbank environments in the catchment were found in the non-urban riverine and urban riverine zones. The macroplastic density on land and riverbank in the urban tidal zone was twice as high as that in the urban riverine zone (Fig. 6). Furthermore, comparing the most upstream (non-urban riverine) and downstream (urban tidal) catchment zones, the macroplastic density on land and riverbank in the urban tidal zone was four and two times higher, respectively, than in the non-urban riverine zone.

3.2. Macroplastic hotspot locations in the Odaw catchment

Five locations within the catchment were identified as macroplastic hotspots. Each of these locations had only one environmental compartment as a hotspot, except location 8, which had both its riverbank and river identified as hotspot locations (Fig. 7). At the non-urban riverine zone, only one hotspot location (R3) was identified. Additionally, most hotspot locations (3) in the catchment were found in the urban tidal zone (R8, F8, and L10).

3.3. Floating macroplastic polymer variation

The most abundant macroplastic polymer types identified from the total macroplastic items recorded in the river during the study period (Fig. 8a) were PO soft (61.3 %), multilayer (12.2 %), and EPS (9.4 %). 'Other plastics' was the least abundant macroplastic polymer type (1.7 %) found in the river. The dominance of PO soft followed by multilayer was found in all three zones (Fig. 8c).

The relative contribution of each macroplastic polymer type found in the river varied spatially (Fig. 8b). Bridge 6 had the highest transport of macroplastic polymers, accounting for 21 % of the total macroplastic items found in the catchment. Bridges 1 and 2 recorded the least macroplastic polymer transport, at 0 % and 0.2 % respectively.

The catchment's highest fraction of PO soft (15.4 %) and EPS (4.2 %) was found at bridges 6 and 10 respectively. Bridge 7 had the highest fraction of PET (1.7 %) and multilayer (2.8 %) plastic types. The highest fraction of PO hard (1.5 %), PS (1.7 %), and Other plastics (0.6 %) were found at bridge 8. At the river hotspot locations (6 and 8), the most dominant polymer type was PO soft. These findings highlight the spatial variability of macroplastics polymer found in the river within the catchment. Though some polymers (PO Soft, multilayer, EPS) were consistently dominant across all the spatial points in the catchment, their percentage composition was variable. This composition variation provides insights into the sources of these dominant plastic polymers within the catchment.

Between the sub-catchment zones (Fig. 8c), the two urban zones showed the highest fractions of the catchment's most abundant macroplastic polymer types. PO soft (33.9 %) and multilayer (6.7 %) were most abundant in the urban riverine zone, while EPS (6.5 %) was most abundant in the urban tidal zone. The urban riverine zone exhibited the largest macroplastic transport, contributing 52.3 % of the total macroplastics in the catchment, with the non-urban riverine zone contributing <5 %. The highest abundance of each macroplastic polymer type to the total number of macroplastic items counted within the catchment were found in the urban catchment zones. Four of these macroplastic polymer types (PO soft: 33.9 %, multilayer: 6.7 %, PO hard: 3.1 %, and PET: 3.1 %) in the urban riverine zone and the other three polymer types (EPS: 6.5 %, PS: 2.4 %, and Other plastics: 0.8 %) in the urban tidal zone.

The results highlight that the urbanized areas within the catchment, especially the urban riverine zone, are significant contributors to the distribution of macroplastic polymer types. The concentration of these polymers in the urban areas' river sections suggests a link between urbanisation and macroplastic pollution within the catchment.

3.4. Top 10 plastic item variation - land and riverbank

The top 10 plastic items found on land (Fig. 9a) and at all riverbank (Fig. 9b) locations in the catchment made up 87.7 % and 83.9 % of the macroplastics sampled at these environmental compartments respectively. The topmost specific macroplastic item found on land was 'foam fragments (< 2.5 cm)' (28.3 %), whereas these foam fragments were the least on the top 10 list for riverbank (4.3 %). At the riverbanks, 'soft fragments (< 2.5 cm)' (16.2 %) ranked highest whereas was the 2nd most abundant item found on land (14.5 %). Similar plastic items were found among the top 10 list for both land and riverbanks indicating shared pollution sources. However, 'small bags' (7.5 %) were exclusive to the riverbank (Fig. 9b) while 'labels that are wrapped around bottles' (3.4 %) and 'bottle (<= 0.5l)' (3.0 %) were present only in the list for land (Fig. 9a). The dominant macroplastic polymer in the top 10 plastic items found on land was EPS (44.6 %), while on the riverbank was PO soft (54.3 %).

In the non-urban riverine zone, the top 10 most abundant plastic items found on land (Fig. 10a) and at the riverbank (Fig. 10b) locations made up 89.7 % of the total macroplastics sampled at each of these environmental compartments. The largest plastic item on both land (19.7 %) and riverbank's (19.6 %) top 10 list was 'water sachet'. Many

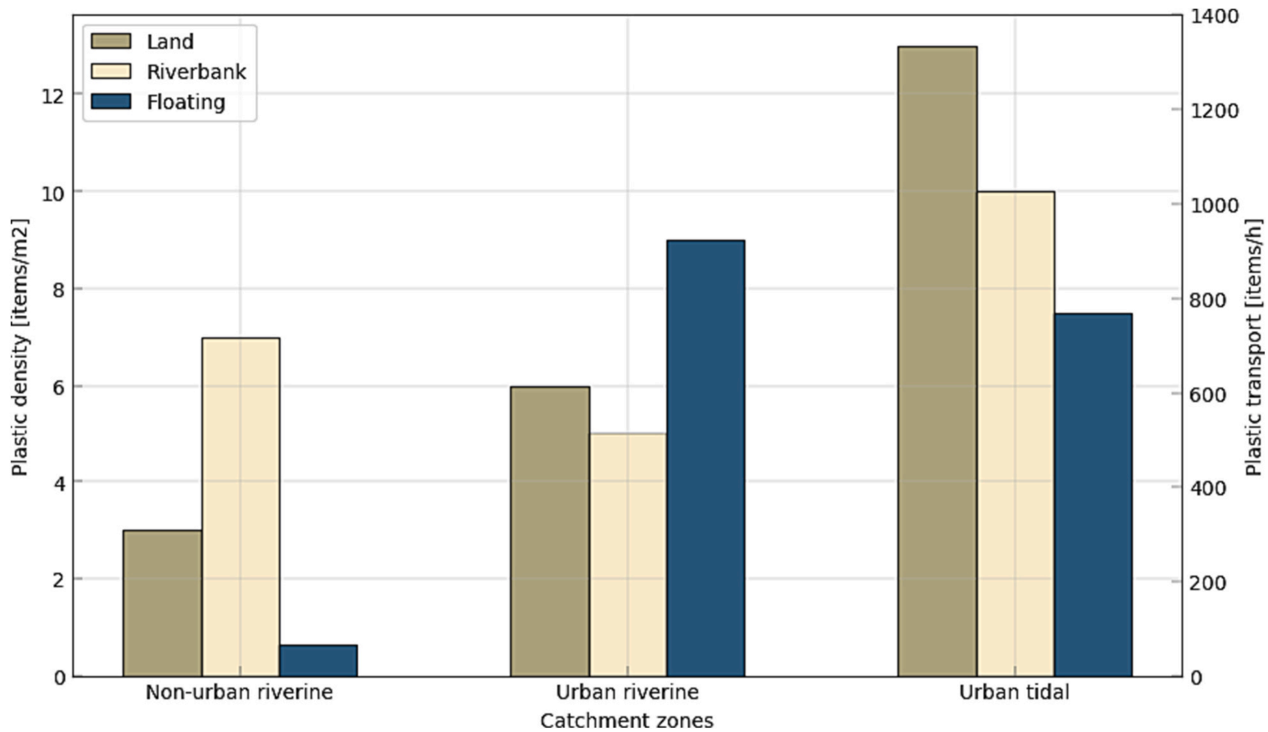

Fig. 6. Variation of mean macroplastic density and transport at the land, riverbank, and river environments respectively across the catchment zones.

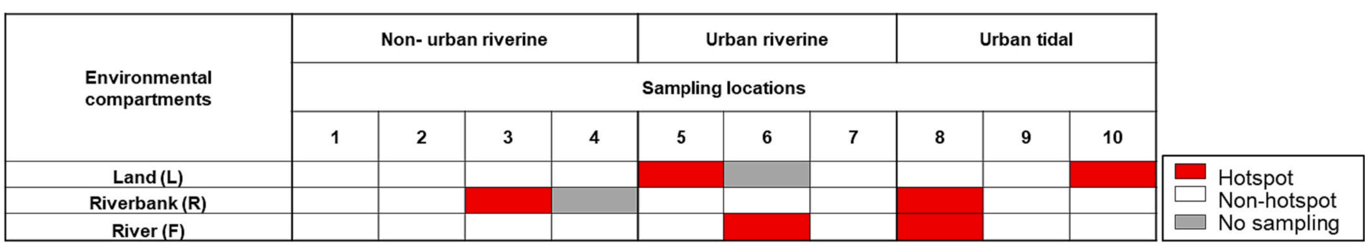

Fig. 7. Macroplastic hotspot locations within the Odaw catchment.

plastic items were common to both land and riverbank top 10 lists. However, some items like 'food packages', 'caps and lids', and 'foam food packages' were unique to the riverbank, while 'hard fragments (< 2.5cm)', 'labels wrapped around bottles', and 'alcohol sachets' were only found on land. The most abundant macroplastic polymer for both land (71 %) and riverbank (75.7 %) top 10 list was PO soft.

Within the urban riverine zone, the top 10 plastic items found on land (Fig. 10c) and at the riverbank (Fig. 10d) locations made up 85 % and 87.8 % of the total number of macroplastics sampled at these environments compartments respectively. The highest ranked top 10 item on land was 'soft fragments (< 2.5 cm)' (27.6 %), whereas that for the riverbank was 'caps and lids' (22.7 %). Many plastic items were common to both the land and riverbank top 10 list, except 'small bags' which were only found in the riverbank list, and 'other unidentifiable plastics' in the land list. The most abundant macroplastic polymer for both land (58 %) and riverbank (43.1 %) top 10 list was PO soft.

The top 10 plastic items found on land (Fig. 10e) and riverbank (Fig. 10f) locations in the urban tidal zone made up 92.8 % and 89.8 % of the total macroplastics sampled at these environmental compartments respectively. The highest ranked top 10 item on land for this zone was 'foam fragments (< 2.5 cm)' (41.3 %), while that for riverbank was 'soft fragments (< 2.5 cm)' (21.8 %). The dominant macroplastic polymer found on land and riverbank varied for this zone with EPS (61.5 %) as the highest on land and PO soft (46.2 %) the highest at the riverbank.

Across both environmental compartments (land and riverbank) in all the sub-catchment zones, water sachets, soft fragments, and food wrappers consistently appeared in the top 10 list. The dominant plastic polymer in both environmental compartments across all sub-catchment zones was PO soft except in the urban tidal zone where EPS was the most dominant polymer on land. EPS was exclusively found in the top list for land in the urban tidal zone (Fig. 10e).

4. Discussion

4.1. Spatial variation in catchment characteristics as an indicator for macroplastic concentration

The characteristics within a catchment have important implications on the transport of plastics once introduced into the environment. Factors such as topography, land-use, level of anthropogenic activities, and channel characteristics have been mentioned and identified in previous studies to influence the input and storage of plastics in river systems (Liro et al., 2020; Nihei et al., 2020; Tramoy et al., 2019). These factors influenced the macroplastic transport and density at the various environmental compartments within the catchment. An example is the sharp increase in plastic transport from the non-urban zone to the urban zone. This result shows the influence of the urban population on the abundance of macroplastics in this zone.

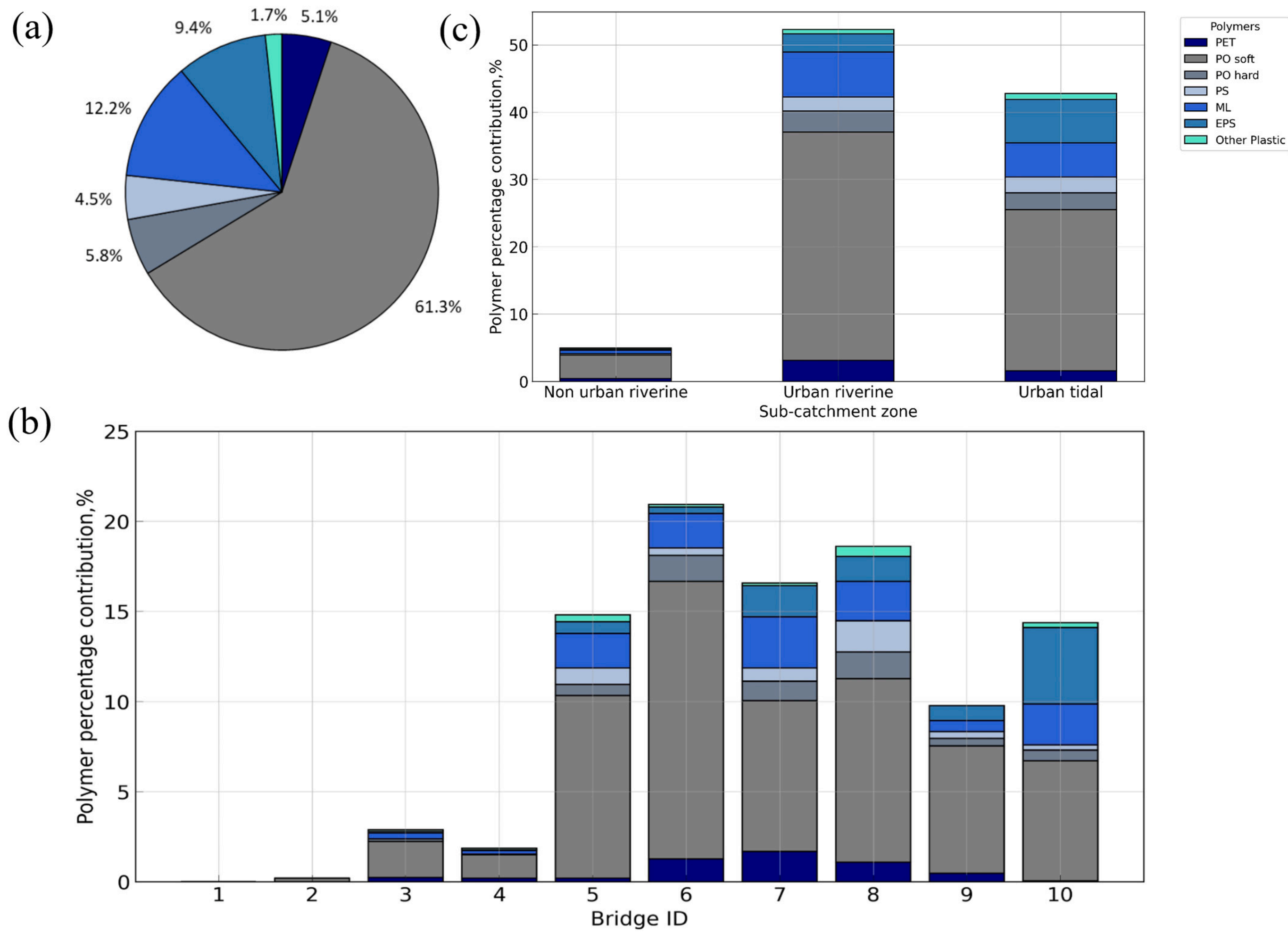

Fig. 8. Floating macroplastic polymer type variation (a) in the entire catchment, (b) at each bridge sampling location along the river in the catchment, and (c) between the sub-catchment zones.

4.2. Urban areas as a source of macroplastic pollution

The sharp increase of floating macroplastic transport from the non-urban riverine to the urban riverine zone, the highest concentration of the macroplastic polymer types, and the identification of most of the macroplastic hotspot locations within the urban catchment zones can be linked to urban activities. Within these urban catchment zones are several commercial (bus stations, open markets) and industrial (food packaging company) activities (Ntajal et al., 2022) situated close to the flood plains of the river. These activities are associated with high litter generation. However, the abundance of the mismanaged litter from these activities is dependent on an adequate waste management infrastructure. According to Larmie (2019), littering is common in this catchment because of the insufficient waste management system. Due to this, the activities of the urban population in these zones contribute to the abundance of macroplastics on land and subsequently increases its chance of transport to the riverbank and river. An example is the dominance of EPS in the urban tidal zone associated to the industrial production of EPS food packaging products coupled with its extensive use in commercial enterprises, particularly in the fast food sector. The results emphasize the role of urbanized activities in the distribution of macroplastic polymer types, highlighting the urban tidal zone as a significant contributor to EPS pollution in the catchment. The link of urbanisation to the increased presence of plastics is supported by Meijer et al. (2021), Crew et al. (2020), Grabowski et al. (2022), Mani et al. (2016), Kwon et al. (2020), and van Emmerik et al. (2023) who show that increase in plastic concentrations in rivers is associated to its proximity to populated or urban areas.

4.3. Retaining factors influence macroplastic transport

The decrease in macroplastic transport between the urban riverine and urban tidal zones means there are retaining structures or mechanisms between the two zones. Between these zones, a hydraulic structure (weir) and estuary were identified. This weir is currently not functional and as such impedes the flow of water through it (Larmie, 2019). The low river flow at this weir traps floating macroplastics thus reducing the number of floating macroplastics that move further downstream. This finding corresponds to the observations in Tasseron et al. (2020), who found that most macroplastics are trapped at locations where the water flow is hindered, such as bridges. Another reason to account for the reduction in macroplastic transport is the role of the tides at the Odaw river estuary. During low freshwater discharge, the tidal dynamics at the estuary causes the upstream movement of floating macroplastics which reduces the number of macroplastics that are transported further downstream the river and into the ocean (Blondel and Buschman, 2022; Schreyers et al., 2023; van Emmerik et al., 2020). The results correspond to the recent studies by Cheng et al. (2021) and Stead et al. (2020) who demonstrated the tidal trapping of microplastics within the estuary.

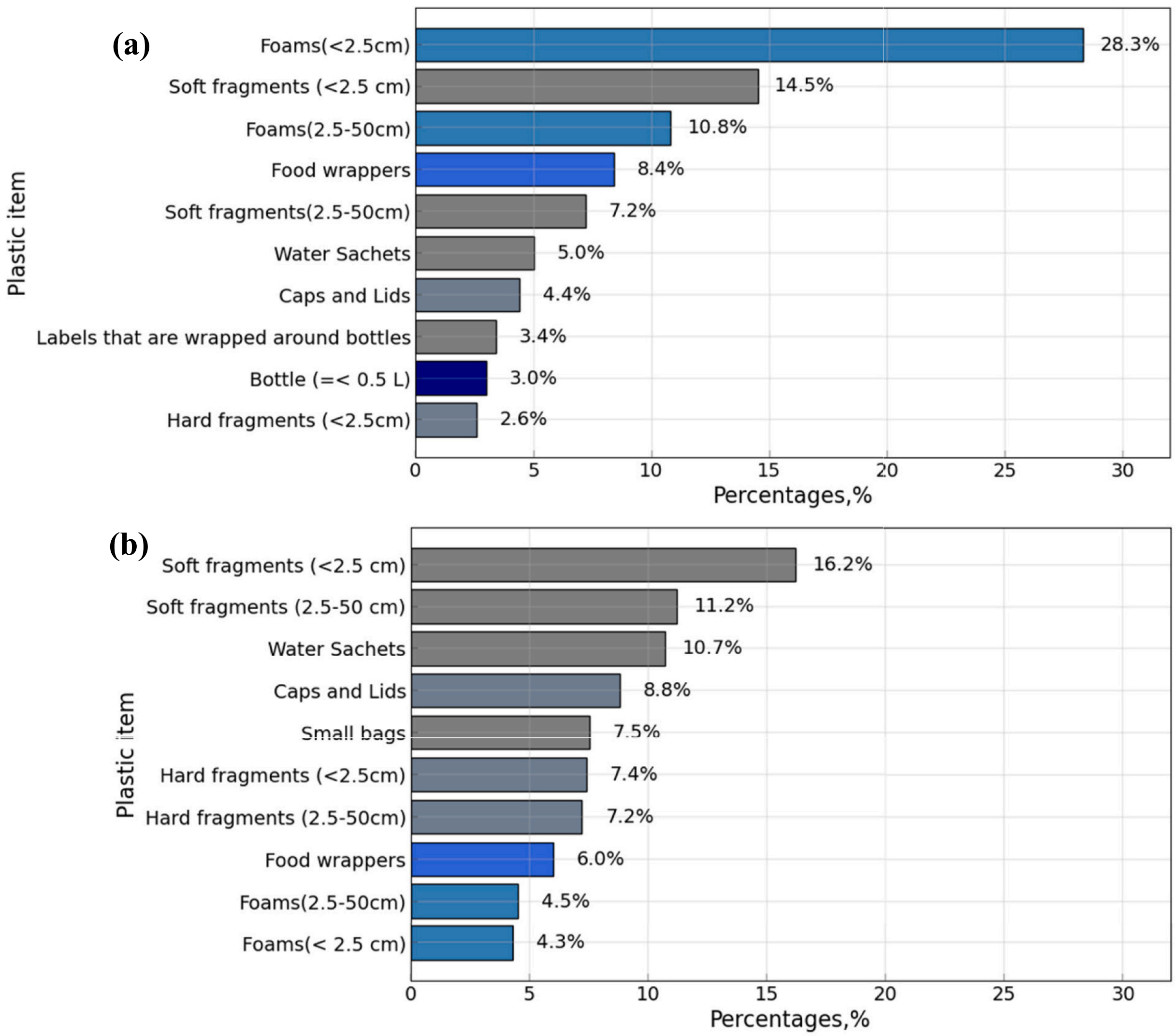

Fig. 9. Top ten most abundant plastic items on (a) land and (b) riverbank in the Odaw catchment over the entire sampling period.

4.4. *Riverbank and land characteristics influence macroplastic density variation*

The topography and geometry of the land and riverbank around a river influences the introduction, transport, and accumulation of macroplastic (Liro et al., 2020; van Emmerik et al., 2022). Unlike the riverbank at the urban riverine zone, which is bare (Fig. 1c), and exposes the litter to wind erosion transport from the banks to the river (Bullard et al., 2021), the riverbanks found at the non-urban riverine (Fig. 1b) and urban tidal (Fig. 1d) zones are covered with vegetation and rocks. This could be the likely reason for the lower macroplastic density at the urban riverine zone as compared to the non-urban riverine zone. It is previously stated (Windsor et al., 2019) that vegetation at floodplains play a role in trapping litter which can affect the macroplastic accumulation at these locations. Cesarini and Scalici (2022) in their study reported high macroplastic density at vegetated riverbanks and stated their role in retaining more macroplastics easily than unvegetated riverbank types.

Despite the hypothesised macroplastic trapping effect at the vegetated and rocky riverbanks within the non-urban and urban tidal zones, differences were observed in the macroplastic density at the non-urban riverine and urban tidal zones. One reason to explain the high macroplastic density at the riverbank in the urban tidal zone is due to the beaching of macroplastic at the banks from the ocean during high tides. In the Seine river, recent work demonstrated that the riverbanks along the estuary are hotspots for deposited (macro)plastic (Tramoy et al., 2020). Since the riverbank in the urban tidal zone is covered with stones and vegetation, a number of these macroplastics are trapped and are not remobilised when the water level is lower during ebb tides. The opposite is true during high flows (floods), which will enable the remobilisation of the macroplastics into the river. The results support the work of Krelling and Turra (2019) who showed that more quantities of plastic items were found at the shorelines of the tide-dominated environment as compared to the other gradient of the river.

4.5. *Soft plastics as the most dominant item type*

At most of the locations within the catchment, PO soft was found to be the most dominant. This result fits into the European and Asian macroplastic polymer categorisation data as the most abundant as demonstrated by van Calcar and van Emmerik (2019). A large share of PO soft found at these locations was fragments of single-use plastic bags and water sachets which can be explained by its affordability and high demand for use by the citizens (Dasgupta et al., 2022). Due to the high demand for usage of the above mentioned plastics, most of these plastics are mismanaged and found littered in the environment. A study by Dasgupta et al. (2022) showed that these single-use plastic water sachets are major sources of macroplastic pollution in Ghana. Wardrop et al.

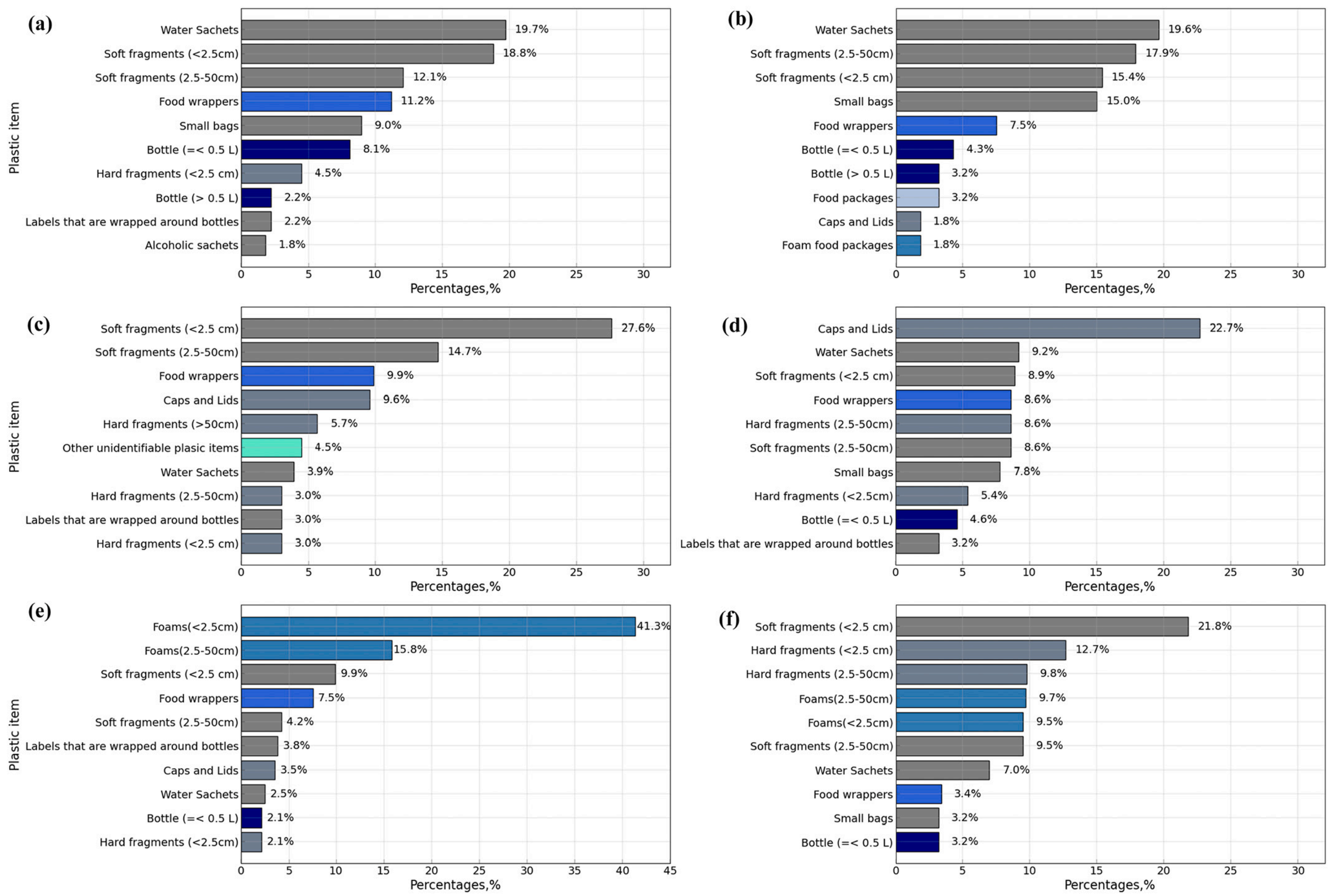

Fig. 10. Top ten most abundant plastic items found in the non-urban riverine (a) land and (b) riverbank, urban riverine (c) land and (d) riverbank, and urban tidal (e) land and (f) riverbank locations in the catchment. Note the difference in x-axis for 10(e). This figure provides a sub-catchment breakdown of Fig. 9.

(2017) also estimated that these single use plastic items represent 14,000 and 13,600 tons/year of plastic waste which is the largest share (63 %) generated by households in Accra. This therefore explains the high fraction and dominance of PO soft as the most common macroplastic polymer category found in the catchment.

5. Outlook for future catchment scale macroplastic pollution assessment

This study provides results from a catchment scale assessment of macroplastic pollution, taking into consideration three environmental compartments (i.e., land, riverbank, and river). This we expect will promote future studies in small urban catchments. Firstly, it is necessary to expand the spatial and temporal scale at which this catchment scale assessment was done. The spatial scale expansion should capture the monitoring of macroplastics at the outlets of tributaries that flow into the main river of the catchment as shown in the study by Tibbetts et al. (2018). The monitoring at these tributaries will increase the understanding of the contribution of macroplastics from point sources into the main river. The timescale expansion should capture monitoring macroplastics in the catchment at the various seasons found within the catchment. This was demonstrated in the study by van Emmerik et al. (2022b), with a one-year monitoring of floating macroplastics to quantify the seasonality and the spatial variation in the Dutch rivers. Hence, the monitoring over a longer timescale will help answer the question of seasonality of the macroplastic pollution in the catchment.

It is also necessary to look at weighing the individual mass of the collected items that were found at the land and riverbank environments. This will yield the mass statistics of specific macroplastic items and their polymer types which can then be used in the estimation of macroplastic density. Expressing the macroplastic density in terms of mass, rather than the counts alone, allows for comparison with floating macroplastic. This was demonstrated in the study by de Lange et al. (2023), who showed the mass distribution statistics of 14,052 macroplastic items collected from 8 riverbanks in the Netherlands. Another thing worth mentioning was the change in orientation and location of the surveyed sampling area at the most downstream locations (7–10) in the catchment due to accessibility constraints on each sampling day. These changes we believe affected the observations, which could have contributed to the lack of trend in macroplastic density on land and riverbank at this part of the catchment.

For this study, the visual counting approach was used. Though for this study, two field volunteers (one observer and one scribe) were at a bridge for the monitoring, we believe the use of cameras will provide a more convenient way of counting the macroplastics. Several studies have demonstrated the use of this advanced technology to monitor macroplastics in rivers (Kataoka and Nihei, 2020; van Lieshout et al., 2020). Finally, we provide a framework for defining macroplastic hotspot locations by first estimating the 75th percentile of macroplastic transport or density at each environmental compartment, comparing the macroplastic transport or density at each of these locations to the defined threshold and checking its consistency above the specified threshold over the sampling period. Due to the short sampling period in this study, we may not have identified definitive hotspot locations within the catchment. It's important to note that the season during which the sampling occurred may introduce some bias on the hotspots identified. Therefore to address these limitations, extensive, long-term sampling is recommended to provide a better understanding on the definitive hotspots and their variability between the seasons in the catchment. Nonetheless, we expect our approach to be replicable for analysis in other catchments or study areas. We also see the need for a harmonised macroplastic hotspot definition framework for global comparison across catchments.

6. Conclusion

Macroplastic density, transport, and composition varied across locations within the Odaw catchment, with peak transport (937 items/h) and density (land: 13 items/m^2; riverbank: 10 items/m^2) occurring in the urban zones of the catchment.

The transport of plastic was highest at the urban riverine zone, while the urban tidal zone had higher plastic density on land and riverbank. Our findings indicate the influence of urban activities and tidal effects on macroplastic transport and density spatial variability.

The most common macroplastic items in this catchment were fragments of single-used plastic bags, water sachets, and foam fragments, with the majority of the foam fragments found on land within the urban tidal zone. This data can be helpful in identifying pollution sources which can guide future policy strategies on reducing the release of these specific items in the catchment.

We show how relatively simple monitoring methods can be used to assess macroplastic distribution across river surfaces, riverbanks, and land within the Odaw catchment over a short time period of three days in December 2021 (11, 16, and 23). The main implication is to show that not all plastics transported through the river reaches the ocean. Spatial variables, such as land-use type, channel characteristics play a role in the variability (flow and accumulation) of these macroplastics towards the ocean. Furthermore, we shed light on catchment-scale macroplastic spatial variability in the Odaw and provide a replicable approach for similar studies in other catchments.

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CRediT authorship contribution statement

Rose Boahemaa Pinto: Conceptualization, Methodology, Data curation, Formal analysis, Visualization, Investigation, Writing – original draft. **Linda Bogerd:** Investigation, Writing – review & editing. **Martine van der Ploeg:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Kwame Duah:** Investigation. **Remko Uijlenhoet:** Writing – review & editing. **Tim H.M. van Emmerik:** Conceptualization, Methodology, Investigation, Supervision, Writing – review & editing.

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.

Data availability

The datasets analysed for this study can be found on the 4TU Research repository [https://doi.org/10.4121/22274980].

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2023.115813.

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