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DOI
10.1016/j.scitotenv.2024.175463

Publication date
2024

Document Version
Final published version

Published in
Science of the Total Environment

Science of the Total Environment 951 (2024) 175463

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Mismanaged plastic waste as a predictor for river plastic pollution

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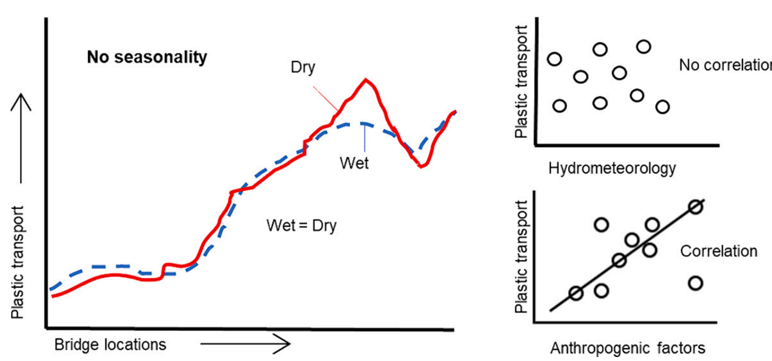
HIGHLIGHTS

- River plastic transport shows no significant differences between the wet and dry season along the catchment.
- Discharge, wind, and rainfall show a limited role on spatial and temporal plastic transport variations.
- Mismanaged plastic waste shows highest correlation with spatial plastic transport variations.
- Water sachet dominates as the most polluting item in all compartments and throughout seasons.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Damià Barceló

Keywords:
Seasonality
Peak plastic transport
Catchment
Specific plastic item
Anthropogenic impact

ABSTRACT

Hydrometeorological processes are often assumed to be key drivers of plastic transport. However, the predominant focus on these factors overlooks the impact of anthropogenic factors, such as mismanaged plastic waste (MPW) on plastic transport variability. Here, we investigate the roles of both anthropogenic and hydrometeorological factors on plastic pollution in the Odaw catchment, Ghana. Data on macroplastic transport and density were collected at ten locations between December 2021 and December 2022. We tested for differences between the wet and dry seasons and applied a multiple regression analysis to examine the separate and combined impact of hydrometeorological variables (rainfall, discharge, and windspeed) on macroplastic transport. Additionally, we analyzed the spatial correlation in macroplastic transport/density with MPW and population density. Data collection involved visual counting of floating macroplastics at 10 river locations and counting litter at 9 riverbanks and land locations. Rainfall data was sourced from TAHMO (Trans-African Hydrometeorological Observatory), discharge was measured during field campaigns, and windspeed data sourced from a global climate data provider. We used globally modelled MPW estimates to represent anthropogenic factors. Contrary to previous studies, we found no seasonal differences in macroplastic pollution and only weak correlations were observed between the hydrometeorological variables and macroplastic transport. However, a strong correlation was observed between MPW and macroplastic pollution. We hypothesize that, the influence of hydrometeorological factors on macroplastic transport depend on the relative impact of anthropogenic factors. Our research highlights the limited role of hydrometeorology, showing the significant role of mismanaged plastic waste to

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https://doi.org/10.1016/j.scitotenv.2024.175463
Received 29 May 2024; Received in revised form 24 July 2024; Accepted 10 August 2024
Available online 15 August 2024

field monitored macroplastic pollution variability in the catchment. This insight is essential for future research as it highlights the importance of holistically investigating both anthropogenic and hydrometeorological factors in explaining plastic transport and retention dynamics. This insight is essential for developing interventions that effectively address plastic pollution in catchments.

1. Introduction

Rivers have been highlighted as the main pathways for the transport of land-based plastic pollution into the marine environment (van Emmerik and Schwarz, 2020), but also as potential temporary and long-term plastic sinks. More recently, rivers have been highlighted as plastic reservoirs because of the effective retention by riverbanks, vegetation, and sediment in the different river compartments (van Emmerik et al., 2022b). This is supported by Rodrigues et al. (2018) who reports the presence of microplastics in the riverbed sediments. Plastic transport variations within rivers are assumed to be driven by various factors including, hydrometeorological factors such as rainfall (Xia et al., 2020), wind (Mellink et al., 2024), discharge (van Emmerik et al., 2019), anthropogenic factors such as population density, land-use type (Dikareva and Simon, 2019), and mismanaged plastic waste (Lebreton and Andrady, 2019), along with river channel characteristics (bed geomorphology, presence of hydraulic structures) (Zhang et al., 2015). The variable presence of these factors influences the transport and retention of plastics in the river leading to their associated role as a source or sink of plastic pollution into the ocean.

Recent studies have primarily focused on the individual contributions of these environmental factors on plastic transport variations with predominant focus on hydrometeorological factors, yielding varied results. For instance, Laverre et al. (2023) show significant correlations between rainfall conditions, and macroplastic transport, particularly at the beginning of flood events. In contrast Mani and Burkhardt-Holm (2020) suggest weak correlations between microplastic abundance and rainfall. Zhdanov et al. (2022) also reports no correlations between discharge and plastic transport. This uncertain discharge-plastic transport relationship was also reported by Roebroek et al. (2024, preprint). The inconsistencies in findings highlight the need for future exploration on the other drivers, particularly anthropogenic and channel characteristics. While some studies (Kataoka et al., 2019; De Carvalho et al., 2021) have explored correlations between anthropogenic activities and plastic concentrations, highlighting the impact of urban areas on plastic transport, other studies have investigated factors like land-use types (Huang et al., 2020), population density (De Carvalho et al., 2021), and mismanaged plastic waste (Lebreton and Andrady, 2019; Meijer et al., 2021). For instance, Meijer et al. (2021) and Lebreton and Andrady (2019) show that MPW generation nearest to a river is more likely to contribute to increased plastic transport. Despite these studies, there still exist a limited understanding on the relative contribution of each anthropogenic factor to plastic transport rates, particularly in the most polluted rivers in developing countries.

The Odaw river in the coastal city (Accra) of Ghana from previous global models have been highlighted as a small polluting river (Meijer et al., 2021), with field-based works indicating peak macroplastic pollution loads of 1.1×10^3 items/h (Pinto et al., 2024). However, these previous studies focused solely on the role of hydrometeorological variables in macroplastic transport variations, suggesting the limited role of discharge (Pinto et al., 2023). Though the ambiguous role of discharge to macroplastic transport was already reported for this river, the study was limited since the observations were done over a short period of time and the discharges were modelled instead of measured. Therefore, extended field observations over time and direct discharge measurements are crucial for understanding macroplastic transport seasonality and confirming previous findings on the discharge-macroplastic transport relationship for this river. Also, given that this river flows through a densely populated urban area with inadequate waste management system, high daily macroplastic means ranging between 5.3×10^2 to 1.1×10^3 items/h (Pinto et al., 2024) were observed at the different sampling locations within the urban area. Though the river's proximity to these urban areas is known to increase macroplastic transport (Pinto et al., 2023, 2024), quantitative results regarding the specific relationship of these anthropogenic factors to plastic emissions into the river remain unclear. The lack of this results also makes it unclear which of the anthropogenic factors predominantly contribute to increased macroplastic pollution in the Odaw river.

Therefore, this study aims to provide a quantitative analysis on the role of anthropogenic factors specifically MPW and population density, on macroplastic transport in the Odaw river. We also provide further evidence on their relative contributions to macroplastic transport, revealing the dominant anthropogenic factor contributing to increased macroplastic pollution in the river. Additionally, we show the discharge-macroplastic transport relationship for this river using field-measured discharges, adding certainty to the previously reported relationship from modelled discharge values. Furthermore, we explore seasonal variations in macroplastic pollution for the catchment. Exploring this will reveal whether there are seasonal variations in macroplastic pollution in the catchment and, if so, assess the differences in abundance between the seasons. Field measurements were conducted at ten locations across three environmental compartments (river, riverbank, and land) from December 2021 to December 2022. Data collection involved visual counting of floating macroplastics and counting macroplastics at the riverbank and land locations. Furthermore, hydrometeorological (discharge, rainfall, and windspeed) and anthropogenic (MPW, population density) variables were collected to analyse their influence on macroplastic pollution variations. Regression and correlation analyses were performed to understand the role of these variables. The study also analyzed the seasonal variations of specific plastic items and examined the occurrence of macroplastic transport peaks in relation to major hydrometeorological events. The findings contribute to understanding the seasonal patterns of macroplastic pollution and highlights the distinct roles of anthropogenic and hydrometeorological factors in macroplastic transport in the Odaw, thereby providing a more comprehensive understanding on the drivers of macroplastic pollution in this river. The study also provides new insights on assessing the relative contributions of each anthropogenic factor to macroplastic pollution. Additionally, we establish a clearer relationship between macroplastic transport and river discharge from direct measurements. This research guides future research in holistically exploring both hydrometeorological and anthropogenic factors in explaining macroplastic transport variations in a river. The study also guides future research on investigating the specific role of each anthropogenic factor to macroplastic transport. These insights not only contribute to scientific knowledge but also inform policy makers and stakeholders on effective mitigation strategies for plastic pollution in the river.

2. Materials and methods

2.1. Study area

The Odaw catchment (270 km^2) located in the southern part of Ghana falls within the Greater Accra Metropolitan Area, the industrial and commercial hub of the Greater Accra region (Fig. 1) (Acheampong et al., 2023). Due to the intensive anthropogenic activities in the urban areas of this catchment, the Odaw river is one of the most polluted rivers in Ghana, with household sewage, industrial effluents (Ntajal et al., 2022), and waste (particularly plastics). The river has many tributaries that contribute to the discharge volumes downstream, especially in the wet season (Acheampong et al., 2023). The catchment is characterised by a tropical climate, experiencing a bimodal rainfall pattern annually, indicated as major and minor rainy season. The major rainy season falls within April to June and the minor between September to October. Rainfall in this catchment is mostly short but intense, resulting in localized flash and riverine floods in this area (Bogerd et al., 2023).

For this study, sampling months were grouped into wet (rainy) and dry seasons based on rainfall data obtained from 11 TAHMO (Trans-African Hydrometeorological Observatory) stations within the catchment (see supplementary material). A wet month was defined as having an average precipitation exceeding the defined threshold of 60 mm/month, as per the Köppen climate classification for tropical climates (Beck et al., 2018). The dry season included December to March and July to August, while the wet season included April to June, and September to November (see supplementary material for rainfall distribution).

2.2. Field sampling

2.2.1. Macroplastic transport

Sampling in the river involved visually counting floating macroplastics (plastic items >0.5 cm) (van Emmerik et al., 2023) at 10 bridges along the course of the river within the catchment between December 2021 and December 2022. Each bridge was divided into sections, *i* based on the river width (Table 1). Monitoring at each section, *i*, of a bridge, *j* (Fig. 1a), involved a 2-min observation repeated four times. Approximately 30 mins was spent at each bridge during a sampling day. Total macroplastic transport, P_{F_j} (items/h) for each bridge, *j*, was estimated by summing the average macroplastic transport (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). 'Peak' macroplastic transport at a bridge was defined as an estimated macroplastic transport equal to or above the 90th percentile of all macroplastic transport recorded at a specific bridge over the entire sampling period.

2.2.2. Land and riverbank macroplastic density

Macroplastic sampling at the riverbank was done within a distance of 2 m from the river water line, while sampling on land was done at a distance of 10 m away from the river. For this study, the riverbank and land locations at bridges 4 and 6 were not sampled due to inaccessibility. At each of these riverbank and land locations, a 5 by 2 m^2 delineated area was identified for sampling (Fig. 1b). However, depending on accessibility and sanitary conditions, the delineated area varied mostly for the downstream locations. The same sampling sections as reported in Pinto et al. (2024) were monitored for this study. Within each delineated section, litter was collected and categorised according to the River-OSPAR list (Pinto et al., 2024) which allows for the detailed categorisation of 110 litter items (see supplementary material). Collected litter was later disposed of at an appropriate disposal site. Macroplastic density at each sampled land, P_{L_j} or riverbank, P_{R_j} location expressed as items/m^2 was estimated by dividing the macroplastic counts by the area of a sampling section (Pinto et al., 2024).

On each monitoring day, macroplastics in the river were visually counted for 30 mins from a bridge, followed by the collection and characterisation of litter at the riverbank and land adjacent the bridge. Monitoring was done twice per month in the dry season and three times per month in the wet season. The frequency of data collection varied between the wet and the dry season because our approach was rainfall event based with the hypothesis of more rainy days in the wet season as compared to the dry season. In total, sampling was done over 33 days between December 2021 and December 2022, across the three environmental compartments: river (10 locations), riverbank (9 locations), and land (9 locations) (Table 1). See supplementary material for the

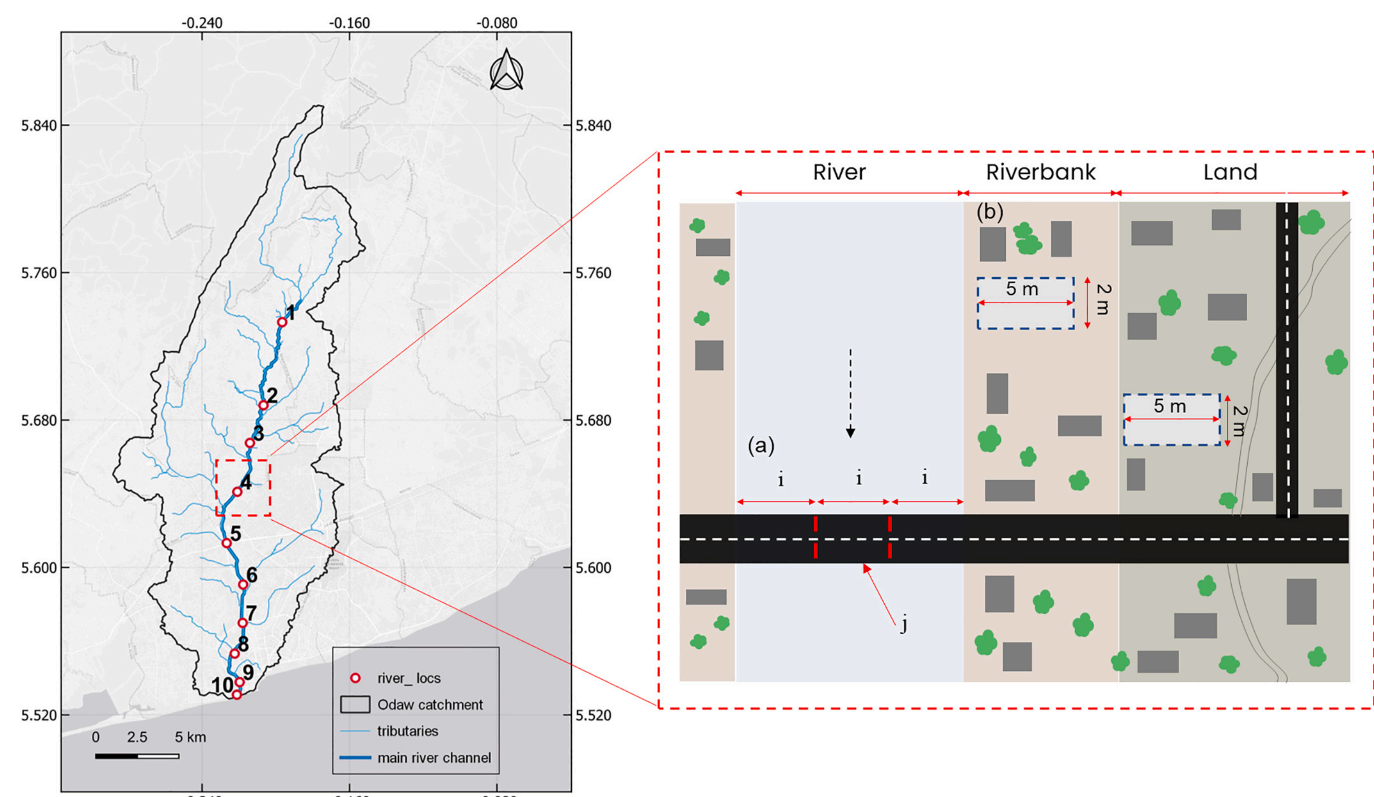

Fig. 1. Left-Map of the Odaw catchment with sampling locations (1-10). Right- Illustration of (a) visual counting of floating litter, and (b) riverbank and land litter monitoring at a sampling location. For (a) '*i*' refers to a section of a bridge, '*j*', and (b), the gray area bounded by blue-dashed lines indicate the designated litter sampling area on riverbank/land. The black-dashed arrow shows flow direction.

Table 1
Details of sampling locations at each compartment along the Odaw river. Y/N is the abbreviated use for Yes/No.

Bridge location	Urbanization level	Distance from river mouth (km)	Tidal effect (Y/N)	River width (m)	Visual counting at bridge (Y/N)	No. of bridge sections	Riverbank litter sampling (Y/N)	Land litter sampling (Y/N)
1	Non-urban	22.7	N	5	Y	1	Y	Y
2	Non-urban	19.5	N	10	Y	2	Y	Y
3	Non-urban	16.9	N	11	Y	3	Y	Y
4	Non-urban	13.6	N	9	Y	2	N	Y
5	Urban	10.0	N	22	Y	3	Y	Y
6	Urban	7.4	N	24	Y	3	Y	N
7	Urban	5.1	N	33	Y	2	Y	Y
8	Urban	3.5	Y	59	Y	3	Y	Y
9	Urban	0.9	Y	68	Y	3	Y	Y
10	Urban	0.1	Y	62	Y	3	Y	Y

coordinates of sampled compartments at each bridge location.

2.2.3. Hydrometeorological variables

In this study, three hydrometeorological variables were quantified (rainfall, windspeed, and discharge). Rainfall data was accessible through the TAHMO website upon login. This data was obtained from 11 rain gauges installed in the catchment all equipped with ATMOS 41 Sensors electronic drop-counting gauges (METER Group, 2021) (see supplementary material). Windspeed data was accessible on the Meteostat platform, an open source global climate data provider (Rahma et al., 2023). Both rainfall and windspeed variables were collected between December 2021 and December 2022. Rainfall is recorded in mm/day and windspeed in m/s.

Discharge was estimated using the velocity-area method (Herschy, 1998). At each section, i, of a monitored bridge, j, velocity ($v_{i,j}$), water level ($h_{i,j}$), and width ($w_{i,j}$) were measured. Velocity was measured using the flow watch meter (JDC Electronic SA, Yverdon-les-Bains, Switzerland), and water level was determined using a marked wooden rod. Velocity and water level measurements were taken four times at each section over time concurrently with the visual counting of plastics. Sectional average velocity, $\overline{v}_{i,j}$(m/s) was then calculated as the average of the four velocity measurements taken across the width of a bridge section.

The discharge at each section, $q_{i,j}$ (m^3/s) of a bridge, j, was first calculated as the product of the sectional average near-surface velocity, $\overline{v}_{i,j}$(m/s), sectional average water level, $\overline{h}_{i,j}$ (m) and width of section, $w_{i,j}$ (m). Since velocity at each section was measured close to the water surface, a default velocity index factor of 0.85 (Hauet et al., 2018) was applied to estimate the depth-averaged flow velocity. Total discharge at a bridge, Q_j was obtained by summing the sectional discharges, $q_{i,j}$. Discharge data were available only for the period between July and December 2022, since this was the period the flow meter was available for field work. Below is the estimation for total discharges at a bridge.

$$q_{i,j} = 0.85\overline{v}_{i,j}\cdot\overline{h}_{i,j}\cdot w_{i,j} \tag{1}$$

$$Q_j = \sum_{i=1}^{i=3} q_{i,j} \tag{2}$$

2.2.4. Anthropogenic variables

Population density and mismanaged plastic waste (MPW) were both obtained from global models. Population density was acquired online as population counts from the LandScan Global 2022 model (Sims et al., 2023) with a high resolution (approximately 1 km^2) distribution of long-term projections of population. Since the resolution is 1 km^2, the acquired population counts were considered as population density for subsequent analysis. MPW were derived from the global MPW projections at approximately 1 km^2 resolution using the model by Lebreton and Andrady (2019). This model is based on country-level data on waste management, gross domestic product (GDP) per country and high-resolution long-term population projections.

To derive population density (Fig. 2b) and MPW (Fig. 2a) from both models for the study area, the Odaw catchment map was extracted from these global raster data in QGIS. Population density and MPW data at each sampling location were determined by averaging data within a one-point pixel buffer zone around the central pixel, C (Fig. 2i), where each sampling location was within. The use of the buffer zone for the estimates accounts for the spatial heterogeneity in population density and the MPW, considering the influences of surrounding areas.

2.3. Statistical analysis

2.3.1. Seasonal difference in transport or density

To assess seasonal variations in macroplastic transport/density between the wet and dry season at each sampling location, the Mann-Whitney U test was used due to the non-normal distribution of the data. For this analysis, the daily mean macroplastic transport/density values at the different locations along the river (10), riverbank (9), and land (9) compartments during the dry and wet seasons were used. These daily means were then compared using the Mann-Whitney U test to determine if there were statistically significant differences in macroplastic transport/density between the two seasons. The test produced a U-statistic which quantifies the magnitude differences between the two seasons, and the significance or non-significance in the seasonal differences of macroplastic transport/density at a location was determined by comparing the p-values with a significance level (α) of 0.05. A p-value $>$ 0.05 indicated no significant difference, while a p-value $\leq$ 0.05 indicated significance (Imbens, 2021).

2.3.2. Hydrometeorological variables to peak macroplastic transport

We assessed whether macroplastic transport peaks were associated to hydrometeorological peaks. Macroplastic peaks at each sampling location were defined using the 90th percentile threshold. The analysis involved checking if the percentile of the corresponding hydrometeorological variable fell below or above its 90th percentile at a location, indicated as upper percentiles in this paper. If a hydrometeorological variable fell within this threshold, it indicated the co-occurrence of both the peak macroplastic transport and the high event of that hydrometeorological factor, suggesting a high probability of that factor influencing the macroplastic transport peak. It is important to note that the data points for discharge are fewer than those for windspeed and rainfall in this analysis. Windspeed and rainfall data was available for all the 33 sampling days, while discharge was only available for 16 days after July 16.

2.3.3. Assessing driving factors on plastic transport

The combined effect of rainfall, discharge, and windspeed on the mean daily macroplastic transport per sampling location across the sampling period was tested using multiple regression, aiming to understand the overall influence of these hydrometeorological variables on macroplastic pollution variations over time and space. Additionally, each hydrometeorological variable was individually correlated with the

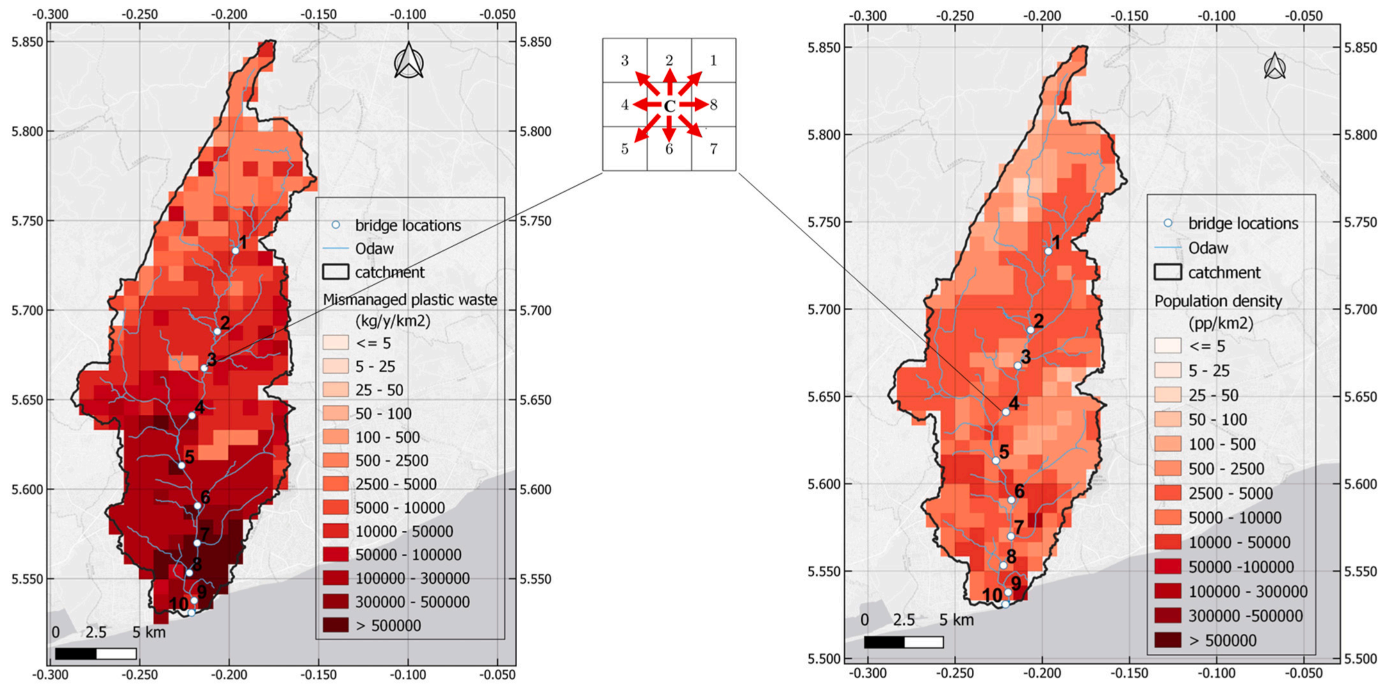

Fig. 2. (a) Mismanaged plastic waste and (b) Population density map of the Odaw catchment. (i) shows the one-pixel buffer zone around the central pixel, *C* used in the estimation of the population density or MPW at each sampling location.

mean daily macroplastic transport.

Since the considered anthropogenic data were not variable over time, spatial correlation was used to assess its relationship across the different sampling locations. Population density and MPW at each sampling location were correlated with both the mean and median macroplastic transport/density. The use of both the mean and median was to provide a more reliable analysis. Considering the sensitivity of the mean to outliers, the use of the median provides additional insight into the correlation results. The correlation analysis used Spearman's rho (r), with coefficients categorised as strong (> 0.65), moderate (0.45-0.65), or weak (< 0.45) (Asuero et al., 2006). Significance was determined by *p*-values <0.05 (Imbens, 2021).

2.3.4. Seasonal variation of top 10 polluting items

At each riverbank and land sampling location, we identified the top 10 polluting plastic items based on the fraction of each identified plastic item relative to the total macroplastics at that specific land/riverbank location over the sampling period. The highest fraction was ranked '1', and subsequent items ranked accordingly based on their contribution level. We also estimated the fraction of a top 10 plastic item at one sampling location recurring in the top 10 list at the other land/riverbank sampling locations. This was aimed to identify the most consistently polluting item across the catchment.

Additionally, we ranked the top 10 plastic items during the dry and wet seasons for both land and riverbank. This ranking was based on the fraction of each plastic item relative to the total items found across all sampling locations in each season. The aim was to highlight variations in the most polluting plastic items across the seasons in the catchment.

3. Results

3.1. Spatiotemporal macroplastic transport and density variations

Mean daily macroplastic transport varied over space and time from 0 to 25,515 items/h, with the largest peak (25,515 items/h) observed at location 8 on 22 December (Fig. 3a). Mean macroplastic density on land was higher than at the riverbanks. Land macroplastic density ranged from 0 to 84 items/m^2 (Fig. 4b), while riverbank density ranged from 0 to 41 items/m^2 (Fig. 4a). The highest macroplastic density on both land (84 items/ m^2) and riverbank (41 items/m^2) occurred at location 10 on the first sampling day (3 January). At locations 8-10, macroplastic density decreased gradually across the sampling days. These findings are consistent with the results stated in Pinto et al. (2023, 2024), indicating higher macroplastic transport and density downstream (locations 5-10) compared to upstream (locations 1-4).

3.2. No significant seasonal variation in macroplastic transport and density

Average macroplastic transport in the dry and wet season was 563 and 333 items/h, respectively. However, statistical analysis revealed no significant seasonal differences across all the sampling locations (see supplementary material). Though most locations (3, 4, 5, 8, and 10) showed higher mean macroplastic transport in the dry season compared to the wet season (Fig. 5a), these differences were not significant.

On land and riverbank, higher macroplastic density was observed in the dry season compared to the wet season, except at riverbank location 3 and land location 5. Despite these variations, significant seasonal differences in land macroplastic density (Fig. 5c) were only identified downstream (locations 8-10), while at the riverbank (Fig. 5b), this was observed only at location 8.

3.3. Hydrometeorological factors to macroplastic transport

The correlation between the combined effect of all hydrometeorological variables and macroplastic transport at bridges 1, 2, and 4 showed a strong significant relationship. At bridge 6, the relationship was significant, but moderately correlated (Fig. 6).

The correlations between each hydrometeorological variable and macroplastic transport varied across the sampling locations. No significant relationship was found between rainfall and macroplastic transport at any location. Bridges 4 and 9 showed significant correlations between discharge and macroplastic transport, with a stronger correlation at bridge 4 (strong) as compared to 9 (moderate). Similarly, bridges

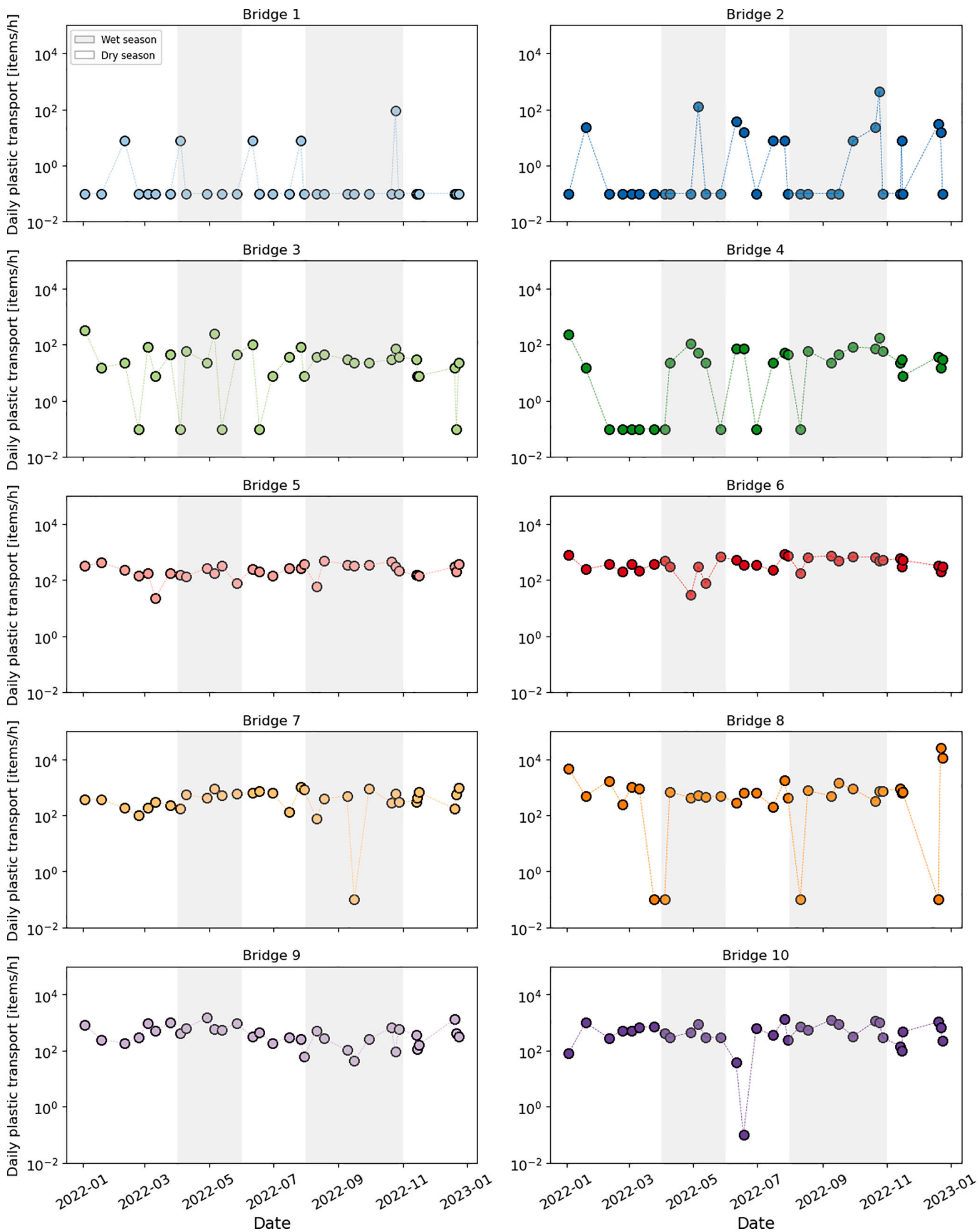

Fig. 3. Spatial and temporal variations of macroplastic transport along bridge locations. The white and gray zones indicate the dry and wet season. 0-values were adjusted by adding 1, ensuring they are displayed in the plot.

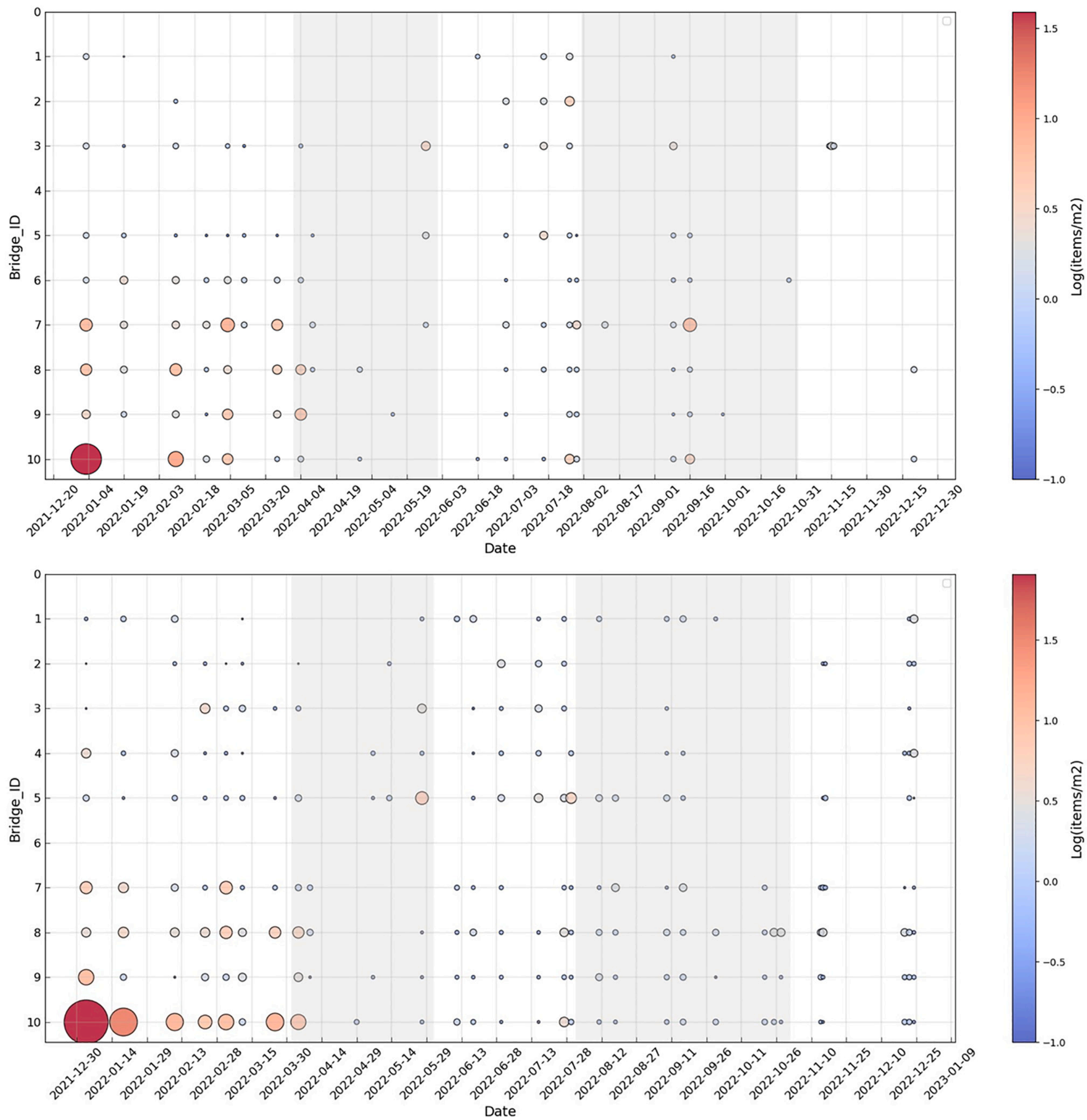

Fig. 4. Spatial and temporal variations of (a) riverbank and (b) land macroplastic density. The white and gray zones indicate the dry and wet season.

6 and 9 exhibited significant correlations between windspeed and macroplastic transport, with a stronger correlation at 6 (strong) compared to 9 (moderate).

3.3.1. *Hydrometeorological factors to macroplastic peak transport*

Of all the daily mean macroplastic transport at all the bridges, 11% were identified as peaks, with a higher occurrence of peak macroplastic transport in the dry season (57%) compared to the wet season (43%). Among these peaks, 18%, 14%, and 16% coincided with the upper percentiles of discharge (Fig. 7a), rainfall (Fig. 7b), and windspeed (Fig. 7c), respectively. Rainfall-coincided peaks were exclusively observed upstream (locations 1-4), discharge-coincided peaks were mostly upstream, and windspeed-coincided peaks were mainly downstream (locations 5-10).

The fractions of macroplastic transport peaks (between the 97th and 99th percentiles) at each bridge location coinciding with rainfall, windspeed, and discharge peaks were 9%, 27%, and 13%, respectively. These findings highlight low co-occurrence rates of different macroplastic transport peaks with the peak events of each of the hydrometeorological variables. The results show the limited role of peak rainfall events on the occurrence of macroplastic transport peaks in this river. This suggests that high rainfall events may not necessarily be an indicator of a high flux of plastic pollution as indicated in previous research (Wong et al., 2020).

3.4. *Significant role of anthropogenic factors on macroplastic transport and density*

Macroplastic transport exhibited a stronger association with MPW (mean: 0.810; median: 0.830) compared to its correlation with

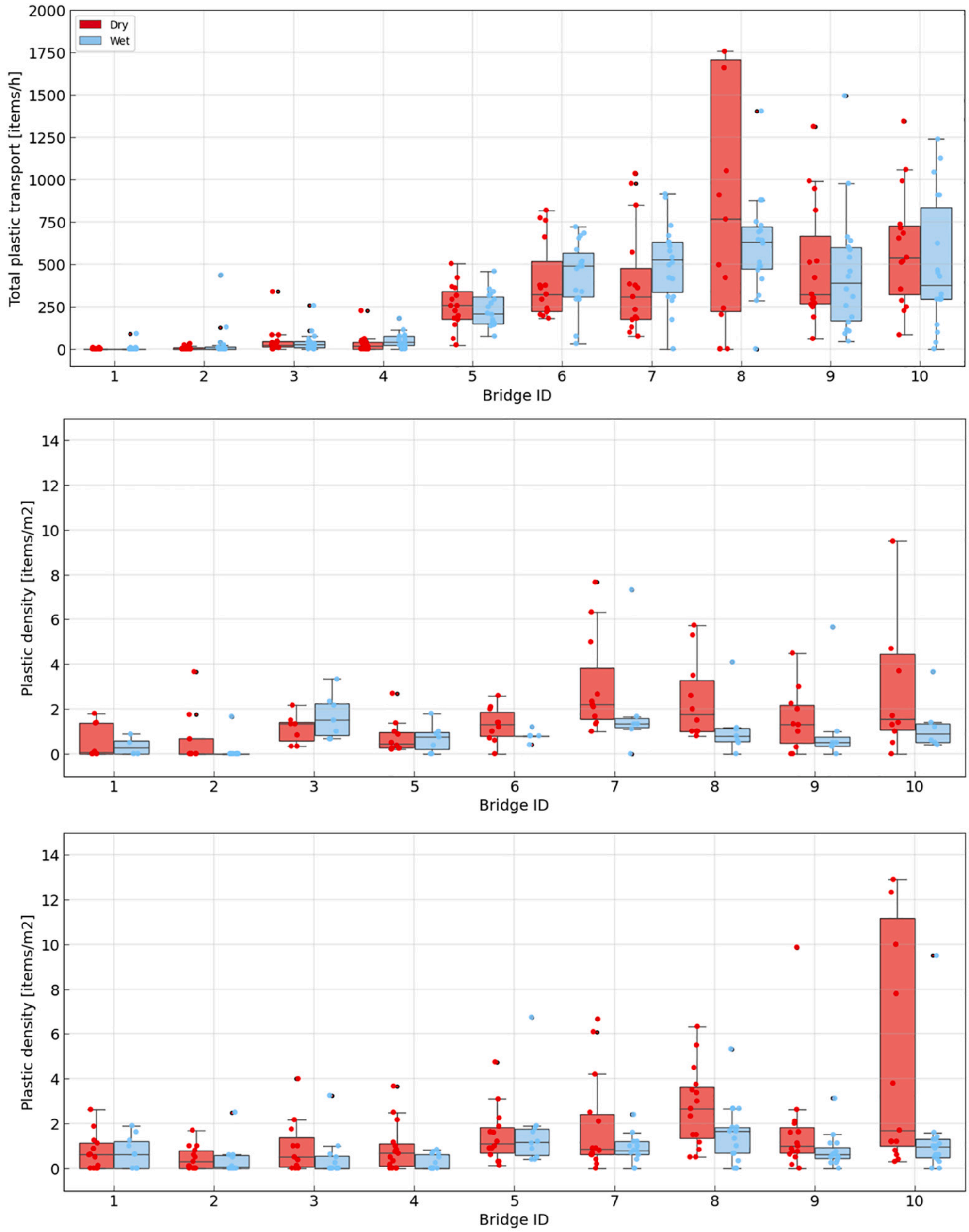

Fig. 5. Boxplot of observed (a) macroplastic transport, (b) riverbank, and (c) land macroplastic density in the dry (red) and wet (blue) seasons at locations (1-10). The y-axis in subplot (a) is capped at 2000 items/h but includes an outlier (25,515 items/h) at bridge 8.

population density (mean: 0.400; median: 0.580). Similar correlation patterns were observed for both land (MPW: 0.710; PD: 0.450) and riverbank (MPW: 0.600; PD: 0.300) median macroplastic density. However, the correlation between mean land (MPW: 0.210; PD: 0.510) or riverbank (MPW: 0.350; PD: 0.440) macroplastic density and both anthropogenic factors was low. All correlation coefficients were statistically significant (Table 2). In contrast, spatial correlations between the hydrometeorological factors and macroplastic transport were weak, negative, and insignificant. These findings suggest the limited influence of hydrometeorology on macroplastic transport variations, both temporally and spatially.

3.5. Top 10 plastic items spatial and seasonal trends

The fraction of representation in the Top 10 list for most of the plastic items was similar for both compartments (riverbank and land). Water sachets (rank 1) consistently dominated as the most prevalent plastic item on both land and riverbank throughout the wet and dry seasons (Fig. 8-left). The fraction of water sachets compared to the other plastic items was higher on riverbanks (33%) than on land (31%). In both compartments, the fraction of water sachets was higher in the wet season (land: 34%; riverbank: 37%) as compared to the dry season (land: 27%; riverbank: 28 %). However, water sachets ranked higher at the upstream locations compared to the downstream locations. The top 3 polluting plastic items (water sachets, bottles $\leq$0.5 l, and caps and lids) at the riverbank was consistent in both seasons (wet and dry), while that on land was more diverse (Fig. 7-right). Items exclusively found in one season, either on land or riverbank were generally less polluting, ranging between positions 7-10, with exceptions like drinking cups and foam packages having higher representation at riverbank during the wet season (No.4) and on land during the dry season (No.5) (Fig. 8-right). These findings highlight both the seasonal and location-specific

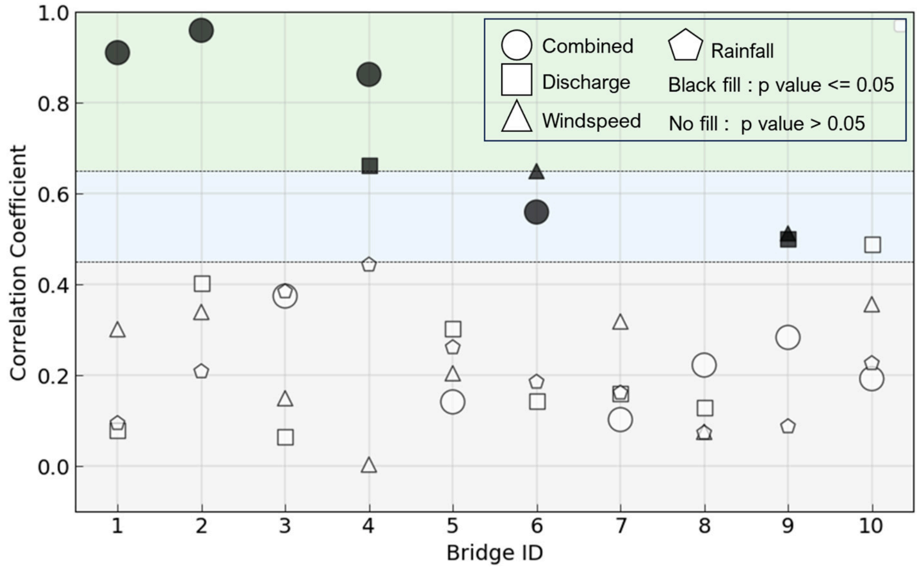

Fig. 6. Correlation coefficients of discharge, windspeed, and rainfall to macroplastic transport across all bridges. The shaded areas show correlation strength: green for strong (> 0.65), blue for moderate (0.45-0.65), and gray for weak (< 0.45).

dynamics of plastic pollution.

4. Discussion

4.1. No seasonality in plastics transport and density

Contrary to common assumptions, our study on the Odaw catchment reveals no significant seasonality in macroplastic transport. Similar observations were reported in other studies (Rodrigues et al., 2018; Zhdanov et al., 2022), though focused on microplastics. The reported non-seasonal patterns could be related to the hydrological conditions in the river in both seasons. Though the dry season is characterised with low flow conditions, it still allows for macroplastic transport downstream the river, due to outflows from household sewers/drains, facilitating macroplastic transport in a manner similar to the wet season, though slower in the dry season as compared to the wet season (Dralle et al., 2016). Another reason expected for this result could be due to the lack of seasonality in anthropogenic activity patterns (Rodrigues et al., 2018) in this catchment, except during specific festive periods (e.g., Christmas) with a peak in macroplastic pollution as observed in this study. This could therefore result in the continuous input of plastic waste into the river throughout the year, therefore likely limiting the influence of rainfall, discharge, and windspeed on potential seasonal variations. Plastic mobilisation by these factors can only occur after the release of plastic waste in the environment influenced by anthropogenic factors (Moses et al., 2023). This emphasizes the larger role of anthropogenic activities in driving seasonal plastic pollution variations than hydrometeorology. Recognizing the dominance of other factors beyond hydrometeorological variables highlights the complexity of plastic pollution in riverine environments. Moving forward, research efforts should prioritize investigating anthropogenic factors to develop more comprehensive numerical models and strategies for mitigating plastic pollution, incorporating data on waste management practices and socio-economic factors.

While our study found insignificant differences in macroplastic transport between seasons, our findings revealed higher transport in the dry season at most locations compared to the wet season (Fig. 9). The reduced water level in the dry season limits vertical transport of plastics, causing plastic items that would normally suspend under normal flow conditions to be more influenced by horizontal transport (van Emmerik and Schwarz, 2020) along the river surface, resulting in increased macroplastic pollution. However, in the wet season, increased water discharges and higher water levels are expected to lead to the frequent submersion of floating plastics. Consequently, with our research focused on floating macroplastics, these submerged items may have been missed, potentially underestimating the observed macroplastic transport in the wet season.

4.2. Limited role of hydrometeorological on macroplastic transport

While rainfall and discharge events have been associated to increased plastic transport (Wong et al., 2020; Xia et al., 2020), recent research findings challenge this, revealing weak correlations between plastic transport and discharge (Mikusheva et al., 2023; Roebroek et al., 2024 [preprint]), or no correlation between rainfall and microplastic concentrations (Mani and Burkhardt-Holm, 2020). van Emmerik et al. (2022a) observed inconsistent correlations between discharge and macroplastic transport at different river locations, indicating the non-triviality of generalizing this relationship for a river. Additionally, Roebroek et al. (2022) found discharge as a poor predictor of plastics in rivers under normal conditions. Nonetheless, its important to note that extreme events such as floods have been found to have an impact on the mobilisation and transport of plastics in rivers (van Emmerik, 2024). The limited role of these variables in the Odaw could be explained by the river's local characteristics. The Odaw river is characterised by sedimentation, exposed riverbeds, vegetation, and hydraulic structures (bridge piers, weir) along the downstream sections (bridges 5-8). These features in rivers, have being indicated in previous studies (Zhang et al., 2015) as temporary sinks, limiting the influence of hydrometeorological processes on macroplastic transport. For instance, the weir after bridge 8 retains some macroplastics flowing downstream, resulting in higher macroplastic transport values at bridge 8 as compared to 9 and 10. This is supported by Kapp and Yeatman (2018), stating the easy accumulation of macroplastics at dams, thus acting as a sink zone for plastics in rivers. Han et al. (2022) also stated the role of vegetation in enhancing the retention of plastics by about 20%. The ability of highly sedimented riverbeds as sinks, as stated for this river, is supported by Ockelford et al. (2020), who mentioned the accumulation of plastics in riverbeds with a high vertical extent. The presence of these sediments depending on their properties and quantity influences the hydraulics at the water-sediment interface. Thick riverbeds drag flow, thus allowing accumulation of plastics in transport (Ockelford et al., 2020). While our study did not

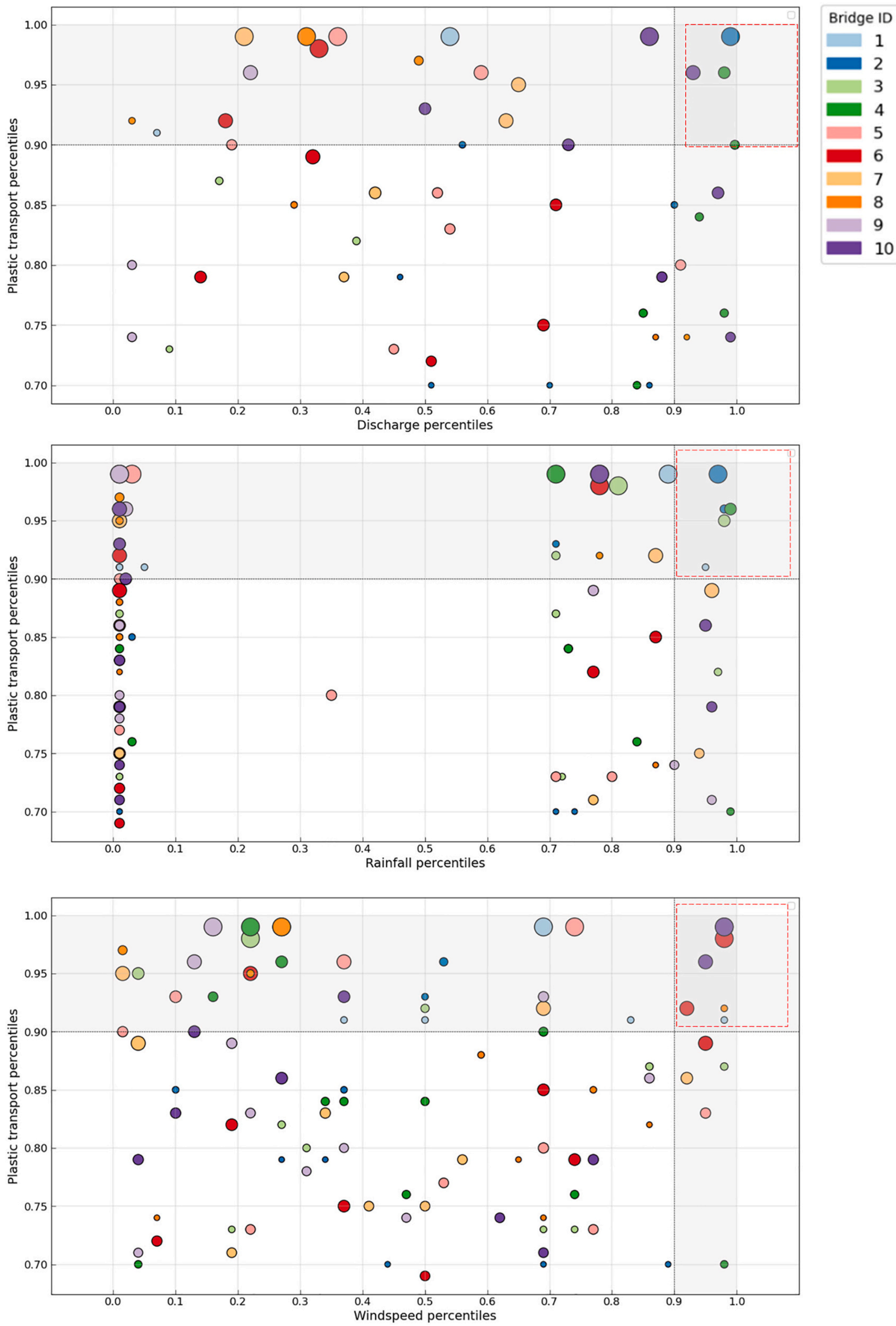

Fig. 7. Relationship between macroplastic transport percentiles (≥70th) and their corresponding (a) discharge, (b) rainfall, and (c) windspeed percentiles. The bubble colours in all plots represent sampling locations (see legend). The dashed lines at 0.9 on the x and y axis represent the threshold to define the upper percentiles of the hydrometeorological variables and macroplastic transport, respectively. The gray shaded area indicates the identified peaks, and the red-dashed box shows macroplastic transport peaks coinciding with the upper percentiles (≥90th) of each hydrometeorological variable. The data point sizes are scaled relative to the macroplastic transport values at each location, with larger data points indicating higher transport values compared to others at the same location.

Table 2
Spatial correlation results between macroplastic transport/density and anthropogenic/hydrometeorological factors across all compartments. The * and ** on each of the correlation coefficients indicates significance and non-significance, respectively.

		Anthropogenic factors		Hydrometeorological factors		
		Mismanaged plastic waste (t/y)	Population density (p/km^2)	Rainfall (mm/day)	Discharge (m^3/s)	Windspeed (m/s)
Environmental compartment	Macroplastic transport/density	Correlation coefficient				
Floating	Mean transport	0.810*	0.400*	−0.002**	−0.005**	−0.003**
	Median transport	0.830*	0.580*	< −0.001**	0.042**	−0.020**
Riverbank	Mean density	0.350*	0.440*	–	–	–
	Median density	0.600*	0.300*	–	–	–
Land	Mean density	0.120*	0.510*	–	–	–
	Median density	0.710*	0.450*	–	–	–

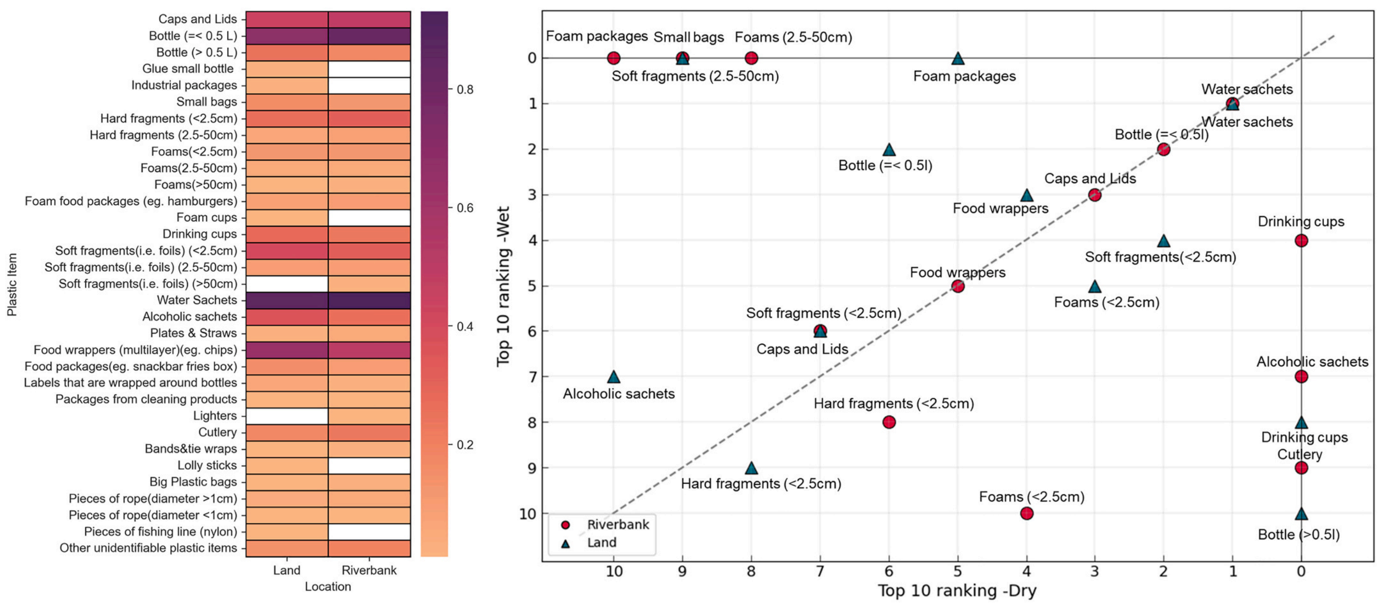

Fig. 8. Left- Fraction of an identified top 10 plastic item occurring at all land and riverbank locations top 10 lists; Right- Top 10 ranking of plastic items in the dry and wet seasons for land and riverbank.

specifically investigate the role of these factors, their potential impact on plastic accumulation may be applicable to the Odaw river, given its sedimentation and vegetation patterns. Future research should therefore consider investigating the role of the river's local characteristics (vegetation, sedimentation, hydraulic structures) in plastics retention to enhance understanding on plastic accumulation dynamics.

4.3. *Anthropogenic factors correlate to plastic pollution variability*

Sources of plastic waste in freshwater systems can be closely related to human activities, as the magnitudes of plastics have been reported to show strong correlations with population density, urbanization (De Carvalho et al., 2021), and waste mismanagement (Lebreton and Andrady, 2019). Downstream locations along the Odaw are characterized by slums, commercial, and industrial activities, situated <5 m away from the river. In these sections, where waste management is inadequate, most generated wastes are often littered along the riverbanks or directly into the river (Acheampong et al., 2023), thereby contributing to localized plastic litter in the river. This is evident in the results, where the increase in MPW strongly correlates with the increased macroplastic transport along the different spatial points as compared to population density, highlighting MPW as a more explanatory factor to macroplastic transport variations.

The weak correlation between population density and macroplastic pollution aligns with findings by Dikareva and Simon (2019) and Wong et al. (2020). Wong et al. (2020) specifically show that population density in a catchment does not correlate with microplastic pollution. These results suggest that direct or diffuse sources of plastic pollution (such as MPW, wastewater treatment plants) are not necessarily linked to population density or related activities such as commuting and commercial activities. These potential source factors have been associated with socio-economic status, impacting behaviour and waste management practices (Schuyler et al., 2018). Schuyler et al. (2021) highlighted that globally, areas with high socio-economic status often have better waste management systems, resulting in lower levels of MPW, despite generating more waste than areas with lower socio-economic status. Despite the inadequate waste management practices in the Odaw catchment, the densely populated areas experience higher removal rates of plastics through frequent collection of littered recyclables for recycling and occasional clean-up exercises as compared to the less populated areas (Atawoge, 2023). These activities therefore influence the abundance of MPW in these areas. Therefore, stating population density as an indicator for plastic pollution levels as stated in some studies (Yonkos et al., 2014; De Carvalho et al., 2021) may be inaccurate. Instead, considering other factors like MPW is essential for a better understanding of plastic pollution dynamics. Future research could employ the use of multiple regression and spatial analysis to investigate the relative contributions of the various anthropogenic

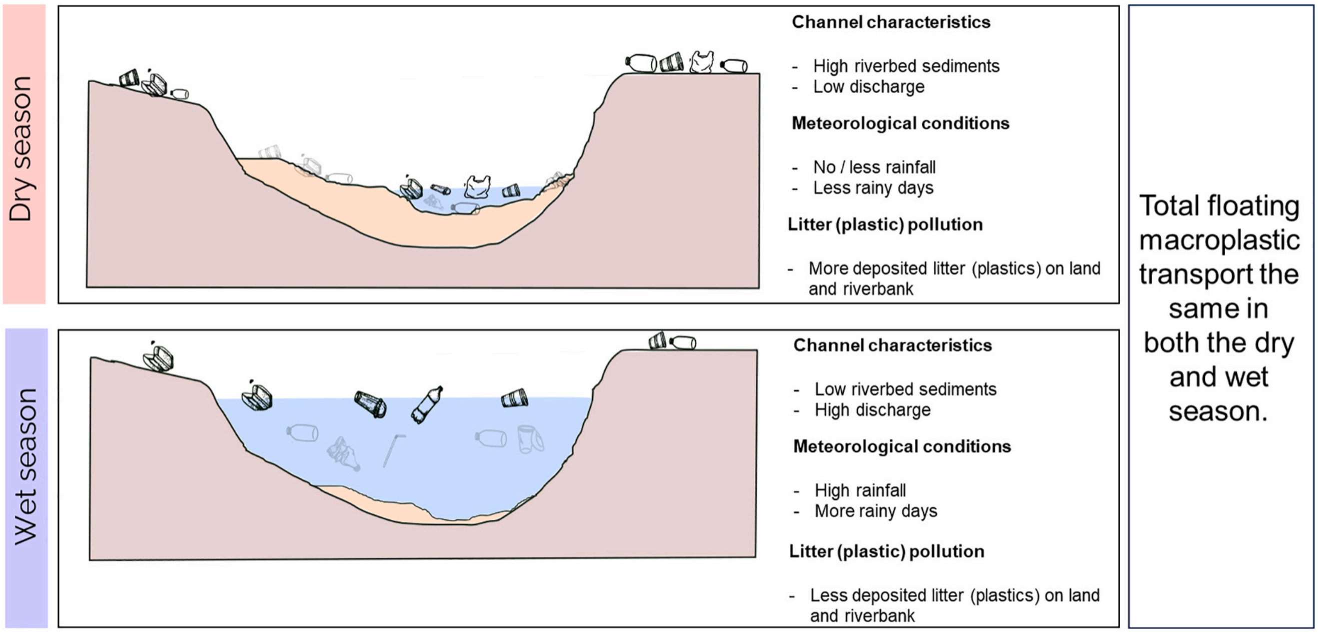

Fig. 9. Conceptual model of macroplastic transport in the Odaw river during dry and wet seasons. Transparent items in the figure were observed during field campaigns but not measured, supporting discussion of field work results.

factors, such as population density and MPW to the abundance of plastic pollution. This will provide insights into the prominent sources driving increased plastic pollution in urban areas.

The inconsistent correlations between the mean/median plastic density of the land/riverbank and MPW may result from the variable geometry of the land/riverbank at different sampling locations, influencing macroplastic transport and accumulation. The riverbanks at locations 1-3 and 9-10 are vegetated and rocky, unlike the bare riverbank at locations 5-8. Despite the intensive anthropogenic activities and inadequate waste management practices at these locations, the riverbank's bare condition experiences less litter accumulation due to wind erosion transport from the banks, compared to the vegetated/rocky riverbanks that retains litter (Cesarini and Scalici, 2022). This aligns with Cesarini and Scalici (2022), who showed lower plastic density at less vegetated areas due to increased exposure to environmental factors (wind, surface runoff), compared to vegetated areas. Vegetation can act as a barrier, trapping litter and limiting hydrometeorology's role in further transport. Additionally, litter removal rates, particularly for recyclables, in the commercial centres around locations 5-8 (Gugssa, 2012), though not entirely effective, reduces the presence of some plastics (water sachets and bottles) on land/riverbank. Future research could investigate the diversity of vegetation types along the Odaw river and assess their respective litter trapping mechanisms through field surveys and experimental setups, considering factors such as vegetation density and coverage. Additionally, studies could explore the impact of anthropogenic removal rates, such as cleanup exercises on plastic abundance across the different environmental compartments.

4.4. The prevalence of water sachets

The detailed characterisation of plastic items is important to help identify the most polluting item over time (seasonal) and across different spatial points. The consistent abundance of a particular plastic item across different compartments and seasons implies a common and consistent usage pattern for that specific item in the catchment. This relates to the large pollution due to water sachets, reflecting its widespread use within the catchment.

The demand for water sachets is due to its affordability as a source of drinking water in Ghana, where access to clean water is limited (Stoler et al., 2012). Its usage has increased over the years, driven by public perception that this water product is of higher quality than tap water (Moulds et al., 2022). Despite being a public good, the unresolved waste management issue leads to its extensive littering after use. This widespread littering contributes to high pollution loads in the catchment. Despite existing plastic recovery initiatives by informal recyclable waste pickers and recycling companies (Spaceplast, SESA Recycling) for this specific plastic item, the spatial coverage is not extensive, resulting in inefficient removal rates, thus its persistent presence in the environment.

Water sachet pollution was relatively higher upstream (rank 1) despite increased anthropogenic activities downstream (rank 1-6). This is because informal recyclable waste pickers in the downstream area are more actively involved in plastic (recyclable) removal efforts. Since this engagement is closely tied to financial incentives, acquiring larger quantities of recyclable plastics downstream is easier than upstream. Additionally, targeted cleanup campaigns in the highly polluted downstream locations influence water sachet quantity on land/riverbanks (Atawoge, 2023).

These results therefore provide insights into specific plastic items dynamics across the wet and dry seasons. The dominance of water sachets as the most prevalent plastic item in this catchment emphasizes the importance of addressing plastic waste through item-specific strategies in this catchment. Future research could engage stakeholders to investigate the factors driving the distribution and prevalence of these specific plastic items across the catchment. Investigating the sources and pathways, as well as the influence of human activities and hydrological processes provides a more comprehensive understanding on their dynamics.

4.5. Limitations

One of the main limitations of this study was the availability of discharge data, which were only available after July 2022. This could have introduced bias or inaccuracies in the correlation results, potentially impacting conclusions on the discharge-macroplastic transport relationship. We only sampled 2 to 5 rainy-days (4% to 9% of total), whereas the year had 52 to 87 rainy-days (14% to 24%). The missed rainy days for sampling may have impacted the conclusions on seasonal differences in macroplastic transport. Notably, most of these bridges are inaccessible during (heavy) rainfall events due to the high probability of flooding (Acheampong et al., 2023), limiting field campaigns. However, a time lag analysis showed minimal impact of missed rainy days on the results (see supplementary material), providing assurance regarding the credibility to the reported macroplastic transport. Nonetheless, future research could explore advanced monitoring technologies like cameras (Kataoka and Nihei, 2020) for rainy day monitoring, considering practical field constraints. Additionally, the study's focus on floating macroplastics, may have underestimated plastic pollution levels, limiting our understanding on the complete picture of plastic pollution in the Odaw river. Future studies should explore monitoring techniques like transect surveys for accumulated plastics and net sampling for suspended plastics (Schreyers et al., 2024) for a more comprehensive picture of riverine plastic pollution.

5. Conclusion

Our study found no significant difference in macroplastic pollution between the dry and wet seasons in the Odaw river. Weak correlations were observed between macroplastic transport/density and the hydrometeorological variables, indicating their limited role on macroplastic transport. Our findings highlight that rainfall, windspeed, or discharge are not the primary drivers of macroplastic temporal variability in the Odaw catchment. Only 14-18 % of the macroplastic transport peaks co-occurred with the hydrometeorological peaks, with peak rainfall events coinciding least (9%) with the largest macroplastic transport peaks. This emphasizes other driving factors behind the occurrence of the macroplastic transport peak events.

Spatial variability in macroplastic transport and density correlated strongly with anthropogenic factors, particularly mismanaged plastic waste, highlighting its significant role as the main macroplastic pollution source in this catchment. Water sachets were consistently prevalent throughout both seasons as the most common plastic item in the catchment, with higher rank upstream compared to downstream. Overall, the study highlights the limited role of hydrometeorology, showing the significant role of MPW in macroplastic transport. This result emphasizes the need for future research to explore the role of other driving factors of plastic pollution, particularly anthropogenic factors, and to assess the contribution level of each of these factors in driving plastic spatio-temporal variations. Also, the dominance of water sachets in our study area offers new insights, prompting further investigation into their littering points and potential mitigation strategies.

Funding

The work of Rose Pinto is funded by the African Talent Programme supported by Wageningen University. The work of TvE is supported by the Veni research program The River Plastic Monitoring Project with project number 18211, which is (partly) funded by the Dutch Research Council (NWO). The work of MvdP is supported by the 4TU.Federation Plantenna project.

CRediT authorship contribution statement

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

Declaration of competing interest

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Data availability

The datasets analyzed for this study can be found on the 4TU Research repository [doi:https://doi.org/10.4121/e73386f8-a10b-40a0-a91e-6be425ef8806.v1].

Acknowledgements

Special thanks to Joseph Acquah, Seth Toko, Jonathan, Rost Ohene, Rita, and Joel for their assistance in the field. We thank the reviewers for their constructive feedback during the review process.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.175463.

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