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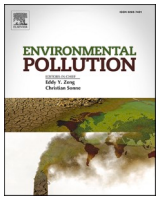

Spatial accumulation of flood-driven riverside litter in two Northern Atlantic Rivers☆

G. Pace [a,b,c,*], J. Lourenço [a,b,c], C.A. Ribeiro [c], C. Rodrigues [c], C. Pascoal [a,b], F. Cássio [a,b]

[a] Centre of Molecular and Environmental Biology (CBMA) / Aquatic Research Network (ARNET) Associate Laboratory, Department of Biology, University of Minho, Braga, Portugal
[b] Institute of Science and Innovation for Bio-Sustainability (IB-S), University of Minho, Braga, Portugal
[c] Landscape Laboratory (LL), Rua da Ponte Romana, Creixomil, 4835-095, Guimarães, Portugal

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ABSTRACT

The escalation of litter accumulation in aquatic environments is recognized as an emerging global concern. Although rivers represent the main conduits for land-based waste into the oceans, the spatial dynamics of litter accumulation in these systems remain poorly investigated, especially after hydro-climatic extreme events. Floods have been identified as major drivers of litter mobilization, including macroplastics, within rivers. However, predicting flood-induced litter accumulation along riverbanks is complex due to the cumulative interplay of multiple environmental (geomorphological and riparian) and anthropogenic factors.

Using empirical data collected from 14 stream reaches in two Northern Atlantic rivers in Portugal, our study evaluates which factors, among geomorphological, riparian, and anthropogenic descriptors, best drive riverside litter accumulation after floods. Taking into account the longitudinal gradient and the spatial heterogeneity of the studied reaches, our study enhances how the accumulation and characteristics (type, size) of riverside litter vary across a rural-urban continuum.

Our model reveals that the combination of the human population density and the stream slope at river reach showed the highest explanatory power for the accumulation of riverside litter. Our findings indicate that litter tends to be retained close to the source, even under flood conditions. We also found that the structure of riparian vegetation showed low explanatory power for litter accumulation. However, riparian trapping could be influenced by litter input (density and type) which varies with anthropogenic activities.

This work highlights the importance of gathering field data to identify critical areas of riverside litter accumulation within river basins. Our findings can further support environmental managers in designing and implementing effective cleanup campaigns and implementing plastic recovery strategies at specific areas. Nevertheless, it is crucial to enhance coordinated efforts across the entire value chain to reduce plastic pollution, promote innovative approaches for plastic litter valorization, and establish effective prevention pathways.

1. Introduction

Litter accumulation in aquatic environments is an emerging global issue due to the continuous increase in the amount of land-based waste produced and inadequately discarded, and the slow degradation rate of most items (van Emmerik et al., 2023). Among litter types, macroplastic debris (i.e., plastic debris >5 mm) is considered the primary contributor to environmental contamination compared to other materials, such as glass and metal. This is attributed to their intrinsic features (e.g., specific weight, buoyancy), which facilitate their dispersion across different environmental compartments (Cesarini and Scalici, 2022; Palmas et al., 2022).

Particularly, global plastic production has increased twenty-fold since the 1960s, reaching 322 million tonnes in 2015 (UNEP, 2021), with half of this being designed for single-use purposes (Geyer et al., 2017). Out of that, less than 10% is recycled, while 22% is mismanaged (OECD, 2022). According to the United Nations Environment Programme (UNEP), it is currently estimated that 19 to 23 million tonnes of

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* Corresponding author. Centre of Molecular and Environmental Biology (CBMA) / Aquatic Research Network (ARNET) Associate Laboratory, Department of Biology, University of Minho, Braga, Portugal.
E-mail address: giorgio.pace@bio.uminho.pt (G. Pace).

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plastic will end up in lakes, rivers and seas annually (https://www.un.org/en/observances/environment-day). Furthermore, plastic production is foreseen to continue growing and, under a business-as-usual scenario, mismanaged plastic waste in the environment might triple by 2060 (Lebreton and Andrady, 2019).

In the last few decades, research on plastic litter accumulation has been focused on the marine environment (Galgani et al., 2015; Schwarz et al., 2019). Although rivers represent the main conduits for land-based waste into the oceans (Palmas et al., 2022), they remain poorly investigated. Recent findings suggest that approximately 1000 rivers, in highly populated areas, are responsible for 80% of global annual plastic emissions, contributing between 0.8 and 2.7 million metric tonnes of macroplastics into the oceans each year (Meijer et al., 2021). However, the scarce observations of plastic pollution within and across river catchments suggest that most of the plastics produced and mismanaged in the environment may be retained in and around rivers, without ever reaching the open sea (Harris et al., 2021; van Emmerik et al., 2022a). In particular, recent studies enhance that rivers not only connect the terrestrial and the marine environment, but also transport and retain plastic in different environmental compartments, from riverbeds and riverbanks to riparian vegetation (van Emmerik et al., 2022a; Cesarini and Scalici, 2022; Hauk et al., 2023). However, the accurate quantification of sources and transport dynamics (e.g., total plastic transported from land to seas and total plastic accumulated in and around rivers) still presents considerable uncertainty (Roebroek et al., 2022). This uncertainty can be related to operational challenges in obtaining comparable in situ measurements and the lack of adequate standard monitoring methods (Broere et al., 2021; Edelson et al., 2021; van Emmerik and Schwarz, 2020; Weiss et al., 2021). Moreover, most research in freshwater environments has focused on microplastics rather than macroplastics (Bletter et al., 2018; Blettler and Wantzen, 2019). Given the scarcity of field-data in rivers, there is an urgent need for large-scale in situ studies considering that: (i) macroplastics represent a significantly greater input in terms of plastics mass compared to microplastics (Schmidt et al., 2017), (ii) macroplastics are the main source of microplastics, which originate from macroplastic breakdown and degradation (Singh and Sharma, 2008), (iii) macroplastics (e.g., bags, bottles, food wrappers) are the most frequently reported items entangling animals in the ocean (Witteveen et al., 2017), and iv) improving the interception and removal of macroplastics in rivers can effectively prevent plastics from reaching the ocean (Blettler and Wantzen, 2019). For these reasons, advancing our current understanding of plastic pathways from land into aquatic ecosystems can be crucial for designing effective prevention and reduction strategies (Borrelle et al., 2020; van Emmerik et al., 2023). In particular, predicting the spatial distribution of riverside litter in rivers is challenging, as it is influenced by multiple and cumulative effects of geomorphological (e.g., surface runoff, river curvature, slope) and anthropogenic (e.g., population density, land use types, presence of hydraulic infrastructure) factors (Palmas et al., 2022). For example, while surface runoff (e.g., floods) and wind have been identified as major drivers of plastic mobilization in rivers (van Emmerik et al., 2022b), the curvature and shape of the river influence the cross-sectional distribution (van Calcar and van Emmerik, 2019). Additionally, macroplastics are usually more easily deposited on the riverbanks along areas with low channel slopes (Bruge et al., 2018).

While plastic content in rivers has shown a significant correlation with human population density (Chen et al., 2022), land use type (e.g., roads, highways, wastewater treatment plants) has been identified as potential point sources for plastic pollution (Margenat et al., 2021; Schuyler et al., 2022). Furthermore, the presence of artificial infrastructures (e.g., weirs, dams and bridges) along the rivers, acting as barriers, can influence plastic deposition and accumulation (Calcar and van Emmerik, 2019; Schirinzi et al., 2020). Lastly, recent studies suggest that the riparian and riverine vegetation characteristics also play an important, yet unknown, role in trapping litter, affecting its accumulation on riverbanks and in floodplains (Kiessling et al., 2019; Lechthaler et al., 2020; Cesarini and Scalici, 2022; Gallitelli and Scalici, 2023).

Nevertheless, the retention mechanisms and patterns of plastic trapping and deposition remain largely unexplored (van Emmerik et al., 2022a), especially after hydro-climatic extreme events, such as flood. During a fluvial flood, large areas around the river become inundated, leading to increased mobilization of plastic litter from these submerged areas (Hauk et al., 2023). It is estimated that the mobilization potential increases tenfold due to floods during a 10-year return period compared to non-flood conditions (Roebroek et al., 2021). However, there is still limited knowledge about how far litter is flushed away by floods and where it accumulates after these hydro-climatic extreme events.

This study aims to improve our capacity to predict the spatial distribution of riverside litter, evaluating which factors, among geomorphological, riparian and anthropogenic descriptors, best drive its accumulation. Specifically, we address two main questions: i) how do the accumulation and characteristics (type, size) of riverside litter vary across a rural-urban continuum after floods, which corresponds to the highest litter mobilization phase? and ii) what are the main factors influencing the accumulation and deposition of riverside litter?

We expect that riverside litter accumulation will increase longitudinally (from upstream to downstream) and along a rural-urban continuum from less to more densely populated areas. In other words, the higher the population density, the higher the potential of mismanaged plastic waste entering the system (i.e. litter accumulation close to its source). We also expect that riparian and riverine vegetation types will affect litter accumulation on riverbanks and in floodplains. Specifically, the higher the presence of trees and shrubs on the riversides, the greater the trapping and accumulation of litter. Lastly, we expect detectable changes in litter size along the upstream-downstream gradient. Smaller particles will be flushed away by floods and travel further downstream, leaving larger particles trapped in the system.

2. Materials and methods

2.1. Study area

We selected 14 stream reaches in two Northern Atlantic rivers in Portugal, within the Guimarães municipality (Fig. 1): the Ave and the Selho rivers. The Ave River has its spring in the Cabreira mountain (spring altitude: 1286 m) and runs through ca. 94 km long, covering an area of ca. 1.39 km^2 (Araujo et al., 1998). The water is intensively used for agriculture and industry purposes. The Selho River has its spring in Santa Marinha, within the Fafe municipality (spring altitude: 580 m) and runs for ca. 21 km through agricultural, urbanized, and industrial areas before flowing into the Ave River (Ribeiro et al., 2022). The area of this basin (sub-basin of the Ave River) is 68 km^2 (Costa and Vieira, 2021).

The sampling sites were selected along a rural-urban continuum, covering the total number of Parish/Union of Parishes (UP), within the Guimarães municipality, which were close to the studied rivers (Table S6). A Parish/Union of Parishes (UP) represents the lower administrative subdivision of Portugal. Administratively, the municipality of Guimarães is divided into 48 civil parishes. Every time that a river reach crosses a different Parish, a new sampling site was selected. Selection criteria also included site accessibility, distances between sampling sites and differences in river type (Ave average river width = 33 ± 11 m; Selho average river width = 4.5 ± 1.4 m). Sampling sites were also selected as monitoring stations for the project REACTIVar Guimarães (https://labpaisagem.pt/en/projetos/corredor-verde-da-veiga-de-creixomil-en/). We therefore sampled 10 stream reaches in the Ave River (minimum distance between two consecutive reaches = 0.7 km, average distance between two consecutive reaches = 2.5 km), and 4 stream reaches in the Selho River (minimum distance between two consecutive reaches = 3.2 km, average distance between two consecutive reaches = 4.4 km).

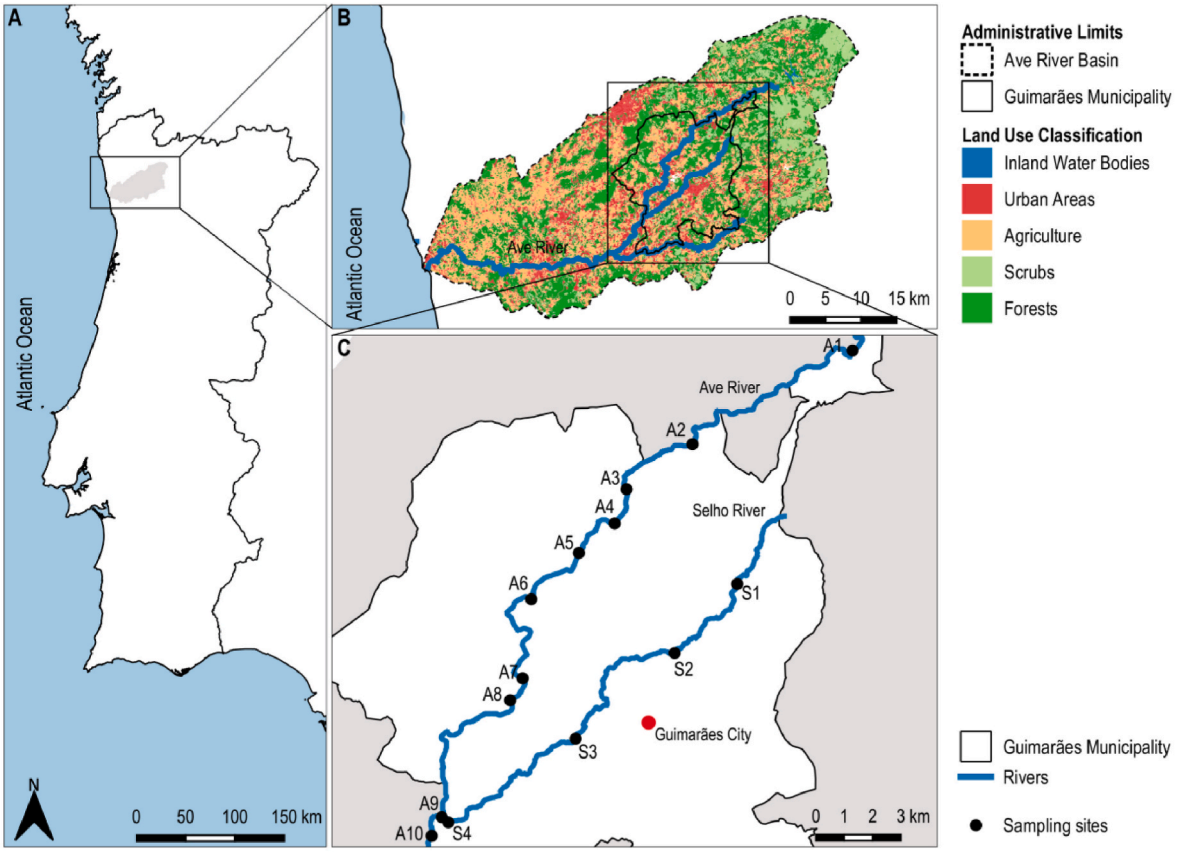

Fig. 1. Study locations: Portugal and the Ave River basin (A); Land Cover Map of the Ave River basin (B); The location of the sampling sites in the Ave River (A1-A10) and the Selho River (S1–S4) within the Guimarães Municipality (C). Representative pictures from the satellite (Google Earth satellite's high-resolution images and Land Use maps) and from the field of selected stream reaches are in Fig. S7 and Fig. S8. Representative pictures of different sampling sites before (November 2022) and after (February 2023) flood events are in Fig. S3 and Fig. S4.

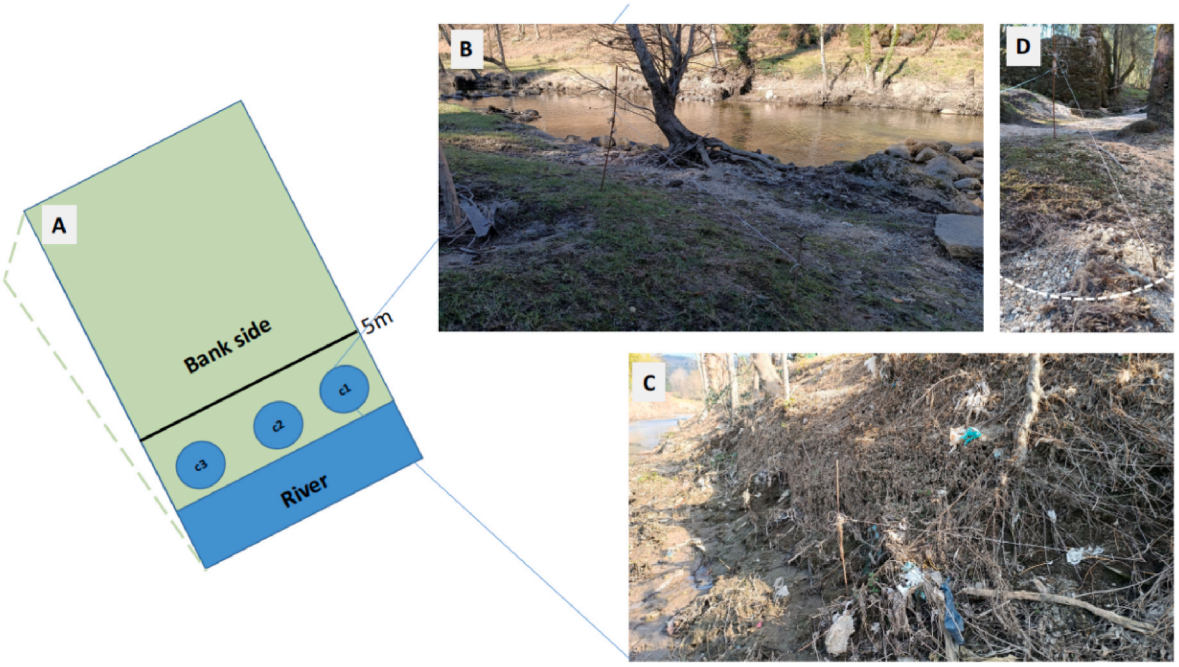

Fig. 2. Sampling design of riverside litter: three circles (c1-c3; circle area = 7.1 m^2) were sampled in each of the 14 stream reaches selected in the Ave and Selho rivers (A). Low litter accumulation at sampling site A1 (B). High litter accumulation at sampling site S4 (C). Hypothetic outer edge of a circle delimiting the sampling area (D). More info is in supplementary information (Figs. S7 and S8).

2.2. Sampling design

Given that floods play a crucial role in litter mobilization within rivers (van Emmerik et al., 2022b), we surveyed the 14 stream reaches from 27th February to March 3, 2023, during baseflow conditions after two flood events (December 20, 2022 and January 1, 2023) registered in the studied area (Fig. S1, Table S1, Fig. S2).

The assessment of riverside litter followed the sampling methodology used by Cesarini and Scalici (2022) and Kiessling et al. (2019) (Fig. 2). Briefly, three circle (c1-c3) with a radius of 1.5 m (circle area = 7.1 m^2) were established and sampled for each stream reach parallel to the river's edge, in a total of 42 samples (Fig. 2A). The first circle was randomly placed at an approximately 0–5 m distance to the river and from the water level. The following circles were placed at intervals of 15 m. An iron bar was used to fix the center of each circle to facilitate the sampling procedure.

According to Rech et al. (2015), we chose to sample in circles, because the sampling area is easily defined by fixing a line with the length of the radius in the center of each circle, and marking the outer edge of the circle along the tightened rope (Fig. 2D). Then, all visible litter items from a standing position within each circle were collected and transferred to labeled bags for further characterization in the laboratory (Fig. 2B and C).

2.3. Characterization and counting of riverside litter

Each litter item was identified in the laboratory and classified based on six characteristics: shape, size, colour, material, usage and mass, according to Bruge et al. (2018) and Gallitelli and Scalici (2022) (Table 1). Specifically, in relation to plastic and following the classification outlined by Gallitelli and Scalici (2022), this study focuses on the litter categories mega- (⩾20 cm), macro- (⩾ 2.5 cm) and mesoplastic (0.5–2.5 cm). For simplicity, these categories will collectively be referred to as macroplastic throughout the text.

2.4. Environmental (geomorphological and riparian) and anthropogenic characterization

To ascertain the primary factors influencing the occurrence and distribution of riverside litter, we tested a set of nine potential variables grouped into three categories (geomorphological, riparian, and anthropogenic descriptors; Table 2), according to the criteria outlined by Palmas et al. (2022) and Cesarini and Scalici (2022).

Among geomorphological factors, we calculated the altitude and slope for each stream reach using EU-DEM v1.1 (https://land.copernicus.eu/). To depict the longitudinal distribution, we determined the Euclidean distance of each stream reach from the first sampling site for both the Ave and Selho rivers (A1 for Ave and S1 for Selho, Table S6). River width was measured in situ for each of the stream reaches. However, when river width was impossible to measure in situ, due to the high-water depth (e.g., A6 - A10), the width was derived using Google Earth satellite's high-resolution images, loaded in QGIS via the QuickMapServices plugin.

To evaluate litter trapping by the riparian zone, we considered two observation scales: the riparian structure at the reach scale (ca. 100 m) and the riparian types within each sampled circle (within 7.1 m^2). The riparian structure at reach scale was evaluated based on the riparian quality index (QBR; Munné et al., 2003). QBR focuses on four aspects of the riparian zone: total riparian cover, cover structure, cover quality, and anthropogenic alteration (Zaimes and Lakovoglou, 2021; Pace et al., 2022).

The riparian types within each sampled circle were identified at a macroscopic level (e.g., arboreal, shrubby, grass, herbaceous, bare soil, and artificial soil). Subsequently, the percentage cover of all macroscopic riparian type within a circle was visually estimated. A Capacity Retention Index (CRI) was then calculated for each circle (as in Eq. (1)) using a weighted mean, considering riparian vegetation categories and their occupancy percentages. This weighted scoring system relies on different storage capacities for each vegetation type, as outlined in existing literature (Cesarini and Scalici, 2022; Liro et al., 2020).

$$CRI = 1\ (\%\ arboreal) + 0.8\ (\%\ shrubby) + 0.6\ (\%\ grass) + 0.4\ (\%\ herbaceous) + 0.2\ (\%\ bare\ soil) + 0\ (\%\ artificial\ soil) \quad (1)$$

To characterize human pressures at each stream reach, we considered human population density and land cover. Human population density (n° individuals/km^2) within each parish of the Guimarães municipality was obtained from CENSOS 2021 (https://censos.ine.pt). Subsequently, we calculated the human population density for each sampling site as the averaged values of the parishes (MPD) closest to each sampling site (Table S2, Table S6).

To characterize land use intensification and potential waste sources at the local scale, we used the Portuguese Land Use and Land Cover map (Level 4) also known as COS (https://www.dgterritorio.pt). For each site, we extracted land cover information within a circular buffer of 500 m surrounding each sampling site.

A Land Use Intensification index (LUI) was then calculated (as in Eq. (2)) using a weighted mean based on land-use categories and their percentage of occupancy, applying the scoring system outlined by Feld (2004) and applied by Pace et al. (2022).

$$LUI = 5\ (\%\ urban) + 3\ (\%\ agricultural) + (\%\ pasture) \quad (2)$$

All spatial analyses were performed in QGIS 3.10.12 (Quantum GIS

Table 1
Plastic classification according to six characteristics (adapted from Bruge et al., 2018; Gallitelli and Scalici, 2022).

Characteristics	Category	Explanation
Shape	Fragment	Three-dimensional Item
	Film	Flat Item
	Fiber	Linear Item
Size	Measurement	Maximum Length (cm)
Colour	Visual	Main Object Colour
Material	Plastic	Plastic Polymer Material
	Metal	Metal Material
	Textile	Cloth/Textile Material
	Glass	Glass Material
	Paper	Paper/Cardboard Material
	Wood	Processed/Worked Wood Material
	Other	Undefined Material
Usage	ATP	Agricultural Tarpaulin and Packaging
	FBP	Food and Beverages Packaging
	SI	Smoking-related Item
	SD	Sewage-related Debris
	FHT	Recreational Fishing and Hunting Tackle
	IPCD	Industrial Packaging and Construction Debris
	CHI	Common Household Items
	CI	Clothing-related Item
	UNK	Undefined
Mass	Measurement	Mass Unit (g)

Table 2
Candidate predictor variables influencing the accumulation and the distribution of riverside litter tested in this study. Mean values and the range of each variable are provided in Table S2.

Type	Variable	Code
Geomorphological	Altitude	ALT
	Slope	SLO
	Distance from upstream point	DIS
	River width	WID
Riparian	Coefficient of Retention Index within the field circle	CRI
	Riparian quality index at reach scale	QBR
Anthropogenic	Human population density	MPD
	% Urban land use	URB
	Land Use Index at 500 m circular buffer	LUI

Development Team, 2009).

2.5. Data analysis

First, we used Pearson's correlation coefficient to assess the capacity of geomorphological, riparian, and anthropogenic factors (candidate predictor variables) to depict changes in riverside litter characteristics (Table S3). This allowed us to identify predictors with the highest coefficients (ALT, SLO, CRI, QBR, MPD, and URB). Variables such as distance from the previous sampling sites (DIS), Land Use Index (LUI) and river width (WID) were excluded due to high collinearity (Variance Inflation Factor, VIF >2; Zuur et al., 2009).

Subsequently, to understand which combinations of predictors best capture variations in riverside litter density and size, we used a multimodel inference approach (Burnham and Anderson, 2002; Tredennick et al., 2021), based on linear mixed-effect models (LME). Linear mixed-effect models are particularly useful in dealing with pseudo replications of measurements (e.g., circle samples, CRI) and are fundamental tools for analyzing longitudinal data (Peng and Lu, 2012). For each response variable, we evaluated the explanatory capacity of 64 linear mixed-effect models, representing the total number of models with all possible predictor combinations. Site was included as a random factor to account for multiple measures (i.e., circle samples, CRI) taken at the same stream reach.

Then, the dredge function from the MuMIn R package (Barton, 2020) was used to rank all 64 models based on the Akaike Information Criterion for small sample sizes (AICc). Models with ΔAICc ≤2 relative to the top-ranked model were retained (Zuur et al., 2010). For each model, the explained variance (R^2) and Akaike weights were calculated to inform the explanatory power and the relative likelihood of each model of being the best. We used the MuMIn R package to calculate AICc, rank models and estimate explained variance and Akaike weights (Barton, 2020). For the retained models (best models), mean-weighted partitioned variance for each predictor was obtained based on model's Akaike weights (Hoffman and Schadt, 2016).

For all models, plots with the residuals were visually checked to verify model assumptions (i.e. normality, homoscedasticity and potential outlier). Before analysis, predictors were z-standardized (mean = 0; SD = 1) to facilitate comparisons among model coefficients. All statistical analyses were done in R 3.5.1 (R Core Team, 2021).

3. Results

3.1. Spatial accumulation and composition of riverside litter

A total of 1335 litter items (687 in the Ave, and 648 in the Selho) were collected at the riversides corresponding to an overall average (± standard deviation) of 4.5 ± 1 litter items/m^2. Litter density per sampled circle in the field ranged from 0 items (A1-c3; A4-c2; A6-c3; A7-c1 and S1-c3; S2-c3) to a maximum of 126 items found in the Selho River (S3-c3). Riverside litter mainly comprised plastics (86.14% of all litter), followed by textile materials (11.01%), glass (1.2%), metal (1.05%), paper (0.15%), wood (0.07%), and other materials (0.37%) (Fig. 3A).

Regarding the possible original usage of identified items along the Selho River, the majority were unknown (UNK = 406 items), followed by sewage-related debris items (SD = 92 items), food and beverages packaging items (FBP = 49 items), common household Items (CHI = 46), agricultural tarpaulin and packaging items (ATP = 26 items), industrial packaging and construction debris items (IPCD = 22 items), and clothing-related items (CI = 7 items) (Fig. 3B). In the Ave River, the possible original usage of identified items was primarily of sewage-related debris items (SD = 306 items), followed by unknown items (UNK = 200 items), common household items (CHI = 57 items), food and beverages packaging items (FBP = 55 items), agricultural tarpaulin and packaging items (ATP = 27 items), clothing-related items (CI = 26 items), industrial packaging and construction debris items (IPCD = 9 items), smoking-related Items (SI = 6 items), and recreational fishing and hunting tackle items (FHT = 1 items) (Fig. 3B). Higher litter density was found in the middle (S3) and lower (S4) courses of the Selho River, compared to the Ave River (Fig. 3C).

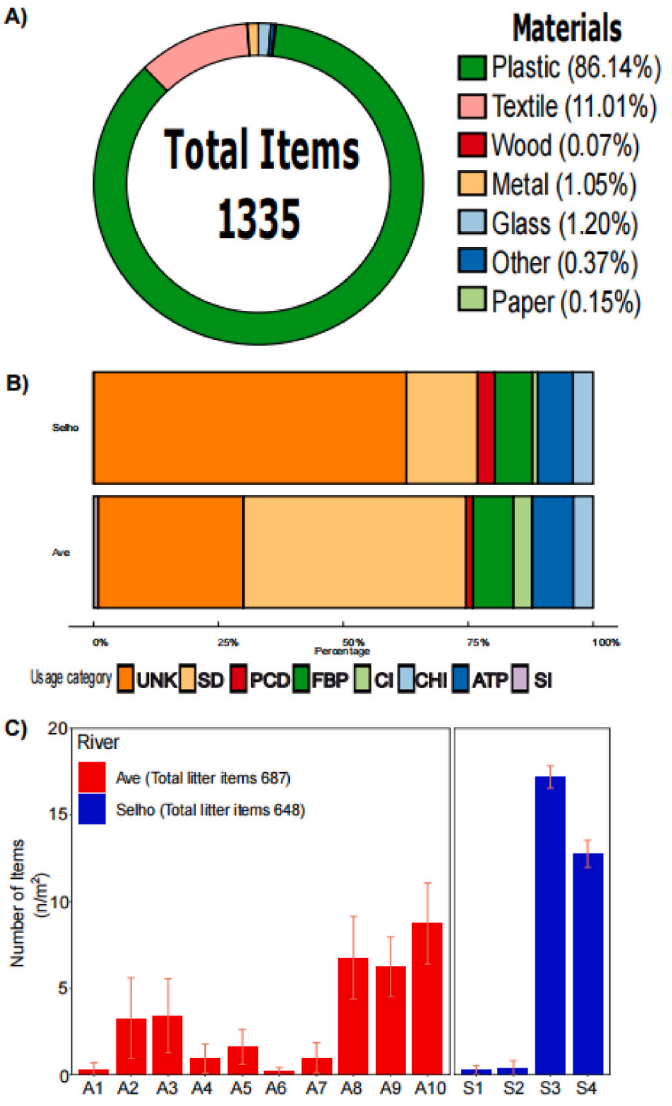

Fig. 3. (A) Proportion of total litter materials found in Ave and Selho rivers. (B) Percentage of possible original usage of each litter items identified (ATP = Agricultural Tarpaulin and Packaging items; FBP = Food and Beverages Packaging items; SI = Smoking-related Items; SD = Sewage-related Debris items; FHT = Recreational Fishing and Hunting Tackle items; IPCD = Industrial Packaging and Construction Debris items; CHI = Common Household Items; CI = Clothing-related Items; UNK = Unknown items. (C) Bar plot representation of the average litter accumulation (items/m^2) in the 14 river reaches under study. Error bars represent standard deviations among replicates (circles).

3.2. Potential predictors of accumulation and size of riverside litter

The human population density (MDP) was positively associated with the number of items (standardized coefficient ± SE: 2.8 ± 0.2). Conversely, stream slope (SLO) was negatively related to the number of items (standardized coefficient ± SE: −1.5 ± 0.5; Fig. 4A), along with the altitude (ALT; standardized coefficient ± SE: −1.4 ± 0.2), urbanization (URB; standardized coefficient ± SE: −1.4 ± 0.4), and weakly with the riparian quality index (QBR; standardized coefficient ± SE: −0.4 ± 0.5). The best predictors (Fig. 4A) for the number of items were the population density (MDP; explained variance: 26.1), followed by the

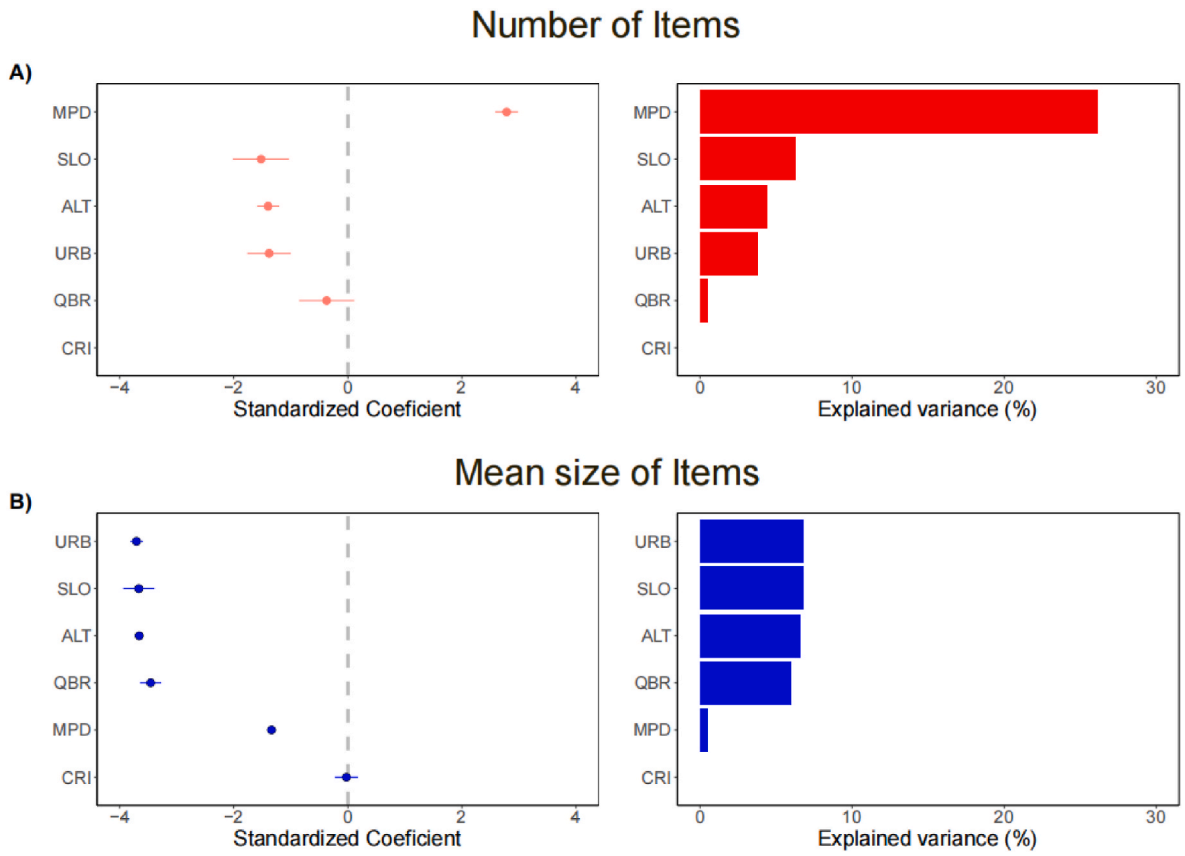

Fig. 4. (A) Effects (Standardized Coefficient) and explanatory power (explained variance) of geomorphological, riparian and anthropogenic factors influencing the riverside litter accumulation (number of items/m^2). Dots represent average standardized coefficient, and lines depict standard deviations among the best models. Ranking of linear models relating geomorphological, riparian and anthropogenic factors with the number of items is provided in Table S4. Relationships between each selected predictor variable and the number of items found in the riverside are illustrated in Figure S5 (B) Effects (Standardized Coefficient) and explanatory power (explained variance) of geomorphological, riparian and anthropogenic factors influencing the riverside litter size (mean size of items). Dots represent average standardized coefficient, and lines depict standard deviations among the best models. Ranking of linear models relating geomorphological, riparian and anthropogenic factors with the mean size of riverside litter items is provided in Table S5. Relationships between each selected predictor variable and the riverside litter size are shown in Fig. S6. ALT = Altitude; SLO = Slope; MDP = Mean population density; QBR = Riparian quality index at reach scale; CRI = Coefficient of Retention Index within the sampled field circle; URB = % artificial land use.

slope (SLO; explained variance: 6.3%), altitude (ALT; explained variance: 4.4%), and urbanization (URB; explained variance: 3.8 %).

The mean size of items was negatively associated with urbanization (URB) (standardized coefficient ± SE: −3.7 ± 0.1; Fig. 4B), along with stream slope (SLO; standardized coefficient ± SE: −3.7 ± 0.3), altitude (ALT; standardized coefficient ± SE: −3.7. ± 0.06), riparian quality index (QBR; standardized coefficient ± SE: −3.5 ± 0.2), and human population density (MDP; standardized coefficient ± SE: −1.3 ± 0.04). The best predictors (Fig. 4B) for the size of items were the urbanization (URB; explained variance: 6.8%) and the stream slope (SLO; explained variance: 6.8%) followed by altitude (ALT; explained variance: 6.6%) and riparian quality index (QBR; explained variance: 6.0%).

Based on our statistical models (Table S3 and Table S4), we obtain on average a higher explanatory power for the number of litter items (r^2 = 0.80), compared to the average litter size (r^2 = 0.35).

4. Discussion

4.1. Spatial accumulation of riverside litter after floods

The novelty of this study relies on the analysis of the riverside litter accumulation, considering both the longitudinal gradient and the spatial heterogeneity in reaches influenced by natural and anthropogenic factors. Our results clearly showed that riverside litter accumulation increases longitudinally (upstream-downstream gradient) and across a rural to urban continuum. This consistent pattern was observed in the two studied rivers within the same geographic area (Guimarães municipality), subjected to similar anthropogenic pressures (Ribeiro et al., 2022; Lourenço et al., 2023). Results remain consistent regardless of the differences in stream typology (e.g., river width, see Table S2 for details) within the studied rivers. This contrasts with previous studies (Kiessling et al., 2019) where larger rivers (>10 m wide) exhibited higher litter accumulation than smaller streams, due to better accessibility and recreational use of larger rivers. In our study, the Selho River accumulated a number of litter items (648 total items; item density = 7.6 ± 7.8 items/m^2; average river width = 4.5 ± 1.4 m) comparable to the Ave River (687 total items; item density = 3.2 ± 3.2 items/m^2; average river width = 33 ± 11 m), albeit the different number of sampled sites per river (4 in the Selho River vs. 10 in the Ave River).

In comparison with other litter deposition assessments, even in base flow conditions (Cesarini and Scalici, 2022), our results indicate higher item density than observed in Mediterranean rivers with agricultural land use (item density = 2.7 ± 0.4 items/m^2 in River Sacco; item density = 2.5 ± 1.6 items/m^2 in River Arrone) and are similar to those observed in rivers with urban land use (item density = 5.59 ± 1.04 items/m^2 in River Tiber; item density = 5.82 ± 6.82 items/m^2 in River Aniene). However, the higher deposition found in our study can be attributed to the higher mobilization during floods (Roebroek et al., 2021). This also agrees with the concept that riverbanks act as macroplastic storage zones, influenced by river flow (Liro et al., 2020).

In line with our first hypothesis, we argue that riverside litter, mobilized by floods, is unlikely to be transported over long distances, corroborating the findings of Roebroek et al. (2021). This suggests that a substantial amount of riverside litter can be deposited on floodplains and retained within river systems. In our study, the higher accumulation of riverside litter was found in the Selho River (S3 and S4, Fig. 1C) close to the parish of Creixomil, which is one of the parishes with the highest human population density in our study area (3225 n°/km^2, Table S6). This underscores a crucial finding of our study: litter deposition is closely associated with population density, and litter is potentially retained in close proximity to its source, even under flood conditions. In our study, the human population density can be considered a proxy for the anthropogenic input of litter in natural systems (mismanaged waste). This aligns with the findings in coastal environments, establishing a correlation between human population density and the influx of mismanaged plastic waste entering the sea (Jambeck et al., 2015). However, caution is needed when interpreting these results, as our study did not effectively trace the origins and the movement of the litter in our rivers.

According to our statistical models, the combination of human population density and stream slope showed the highest explanatory power for the accumulation of riverside litter. This contrasts with previous observations (Schuyler et al., 2021) suggesting that factors, such as land use, infrastructure and socioeconomics, and local site-level variables (e.g., visible humans, vegetation height, site type) were more strongly correlated with plastic accumulation than human population density. However, those studies compared the total number of items found in seven highly populated urban areas (Shanghai, Mombasa, Cape Town, Yeongsan, Negombo/Colombo, Kaohsiung, and Haiphong). Conversely, in our study, human population density was the primary driver of riverside litter accumulation, reflecting significant changes along longitudinal gradients, from sparsely populated to densely populated areas, and representing the main anthropogenic input of mismanaged waste. Our findings strongly support that rivers within urban contexts exhibit higher litter accumulation compared to rivers within agricultural or natural landscapes (Cesarini and Scalici, 2022; Battulga et al., 2019; Kiessling et al., 2019).

Additionally, our results suggest that geomorphological factors (stream slope and altitude) play a key role in riverside litter accumulation. Considering that most litter transport occurs during peak flood events (van Emmerik et al., 2022b), we argue that areas with steep slope generate more velocity, facilitating downstream transport of litter, whereas the areas with flatter slope will facilitate its accumulation. This aligns with the understanding that areas with low elevation generally have a gentle slope and are considered more prone to floods (Tariq et al., 2022). Moreover, the middle and lower course of the Selho River, under normal hydrological conditions, have low discharge that favors silting and river system obstruction (Costa and Vieira, 2021), leading to higher accumulation of litter and to more severe floods. This result is important considering the increasing probability of extreme climate events in the near future. More frequent floods from rainfall will likely increase the flux of waste, including litter and plastics, into aquatic environments (Gündogdu et al., 2018).

Surprisingly, in contrast to that predicted, we found that the presence and integrity (QBR) as well as the structure (CRI) of riparian vegetation exhibited low explanatory power for litter accumulation. This finding contrasts with the common understanding that trees have higher plastic trapping efficiency compared to grasses, shrubs, and reeds (Cesarini and Scalici, 2022). However, such results can be explained considering that the presence of riparian trees or shrubs in the bankside could be related not only to the higher potential retention mechanisms (Liro et al., 2020; Liro et al., 2022), but also to higher natural condition and higher riparian integrity at the reach scale where the input of waste could be lower. In other words, rural areas have a greater prevalence of trees and shrubs on the bankside, but lower potential of litter input (Fig. S6A). Moreover, when the population density is very high, the input of waste and plastics could be so high that the role of trapping mechanisms and of riparian types could be masked (Fig. S6B).

Finally, and contrary to our last prediction, our results showed no clear trends in the spatial variability of litter size across the study sites. The interaction of fragmentation, degradation, and transport of plastics through different river compartments remains largely unknown (Ford et al., 2022). Although plastics in river systems are commonly fragments of soft and hard plastics (Tramoy et al., 2019), their degradation depends on the original polymers, and their distribution can be largely aleatoric and difficult to predict.

4.2. Limitations and recommendations

When interpreting our results, several shortcomings need to be considered. Firstly, due to the inability to effectively trace the origin of the riverside litter analyzed in this study, our results cannot account for how far these items have traveled within the river systems. Therefore, we strongly recommend establishing a long-term tracking programme, based on new technologies to advance our understanding of litter distribution and sources. One approach could be placing GPS trackers on the riverbanks before a flood event to track their transport during the flood (Hauk et al., 2023). We also recommend the use of GSM bottle tags since recent research has enhanced their ability to significantly increase understanding of the location of accumulation areas and the timing of large inputs of plastic pollution into the aquatic system (Duncan et al., 2020). Moreover, electronic devices are constantly evolving, becoming increasingly miniaturized (Hussey et al., 2015). With smaller devices, it will be possible to track even smaller litter items.

Secondly, focusing specifically on post-flood events, our study does not address non-flood periods before the extreme events. Therefore, it still remains unresolved how long historically deposited litter items remain on riverbanks. However, this was the first time that riverbanks were sampled, and based on field information (Figs. S3 and S4), we can assume that the litter has been deposited after floods. Nevertheless, for future research, we strongly recommend sampling before and after an extreme event to avoid these uncertainties.

Finally, to fully understand the trapping function of riparian vegetation in rivers, future research must acknowledge that the deposition of riverside litter is spatially heterogeneous, depending on vegetation, floodplain, and river channel characteristics, but it is still mostly related to the anthropogenic inputs (e.g., human population density).

5. Conclusion

With this study, we highlight the importance of gathering field data to better understand the influence of geomorphological, riparian, and anthropogenic factors on the dynamics of accumulation and spatial distribution of riverside litter.

A major finding of our study lies in demonstrating that, even post-flood events, the highest spatial accumulation remains strongly linked to human population density. Given the likely increase in frequency and severity of extreme floods due to climate change, it is urgent to gain a better understanding of their impact on the fate of plastic litter in the environment.

Our results can be particularly important for environmental managers who need to quickly detect or predict 'hotspots' of riverside litter accumulation across a river basin. While our study represents an initial step towards developing robust predictions, it provides relevant insights into how a readily collectible set of environmental and anthropogenic indicators can be valuable in identifying critical areas of riverside litter accumulation within river basins. However, future efforts should validate the predictive capacity of our indicators over larger spatiotemporal scales to strengthen the empirical support of our conclusions.

Our findings can further help in distinguishing critical areas with the potential for riverside litter accumulation. This can assist managers in designing effective monitoring strategies, and implementing effective

prevention/cleanup campaigns at specific riverside sites to optimize plastic recovery strategies in river ecosystems. Moreover, new and innovative approaches, promoting the co-creation of participatory processes, are necessary to reduce plastic pollution, recover litter from ecosystems, and enhance the circularity of plastic products. A coordinated effort across the entire value chain including local governments, environmental organizations, industry, academia and the public is mandatory to co-create new solutions for the future of our freshwater and marine ecosystems.

CRediT authorship contribution statement

G. Pace: Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Data curation, Conceptualization. **J. Lourenço:** Writing – review & editing, Methodology, Formal analysis, Data curation, Conceptualization. **C.A. Ribeiro:** Writing – review & editing, Validation, Supervision, Funding acquisition, Conceptualization. **C. Rodrigues:** Writing – review & editing, Validation, Conceptualization. **C. Pascoal:** Writing – review & editing, Validation, Supervision, Conceptualization. **F. Cássio:** Writing – review & editing, Validation, Supervision, Conceptualization.

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

Data will be made available on request.

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Appendix A. Supplementary data

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