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How to cite

SCHREYERS, L.j. et al. Revealing the role of land-use features on macrolitter distribution in Swiss freshwaters. In: Environmental pollution, 2024, vol. 362, p. 124911. doi: 10.1016/j.envpol.2024.124911

This publication URL: https://archive-ouverte.unige.ch/unige:180369
Publication DOI: 10.1016/j.envpol.2024.124911

Environmental Pollution 362 (2024) 124911

Contents lists available at ScienceDirect

Environmental Pollution

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

Revealing the role of land-use features on macrolitter distribution in Swiss freshwaters☆

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ARTICLE INFO

Keywords:
Macroplastic
Microplastic
Water quality
Plastic pollution
Rivers
Lakes
Contaminants
Marine debris
Transport
Accumulation

ABSTRACT

Macrolitter, especially macroplastics, (> 0.5 cm) negatively impact freshwater ecosystems, where they can be retained along lake shores, riverbanks, floodplains or bed sediments. Long-term and large-scale assessments of macrolitter on riverbanks and lake shores provide an understanding of litter abundance, composition, and origin in freshwater systems. Combining macrolitter quantification with hydrometeorological variables allows further study of leakage, transport, and accumulation characteristics. Several studies have explored the role of hydrometeorological factors in influencing macrolitter distribution and found that river discharge, runoff, and wind only partially explains its distribution. Other factors, such as land-use features, have not yet been thoroughly investigated. In this study, we provide a country-scale assessment of land-use influence on macrolitter abundance in freshwater systems. We analyzed the composition of the most commonly found macrolitter items (referred to as 'top items', n = 42,565) sampled across lake shores and riverbanks in Switzerland between April 2020 and May 2021. We explored the relationship between eleven land-use features and macrolitter abundance at survey locations (n = 143). The land-use features included buildings, city centers, public infrastructure, recreational areas, forests, marshlands, vineyards, orchards, other land, and rivers and canals. The majority of top items are significantly and positively correlated with land-use features related to urban coverage, notably roads and buildings. Over 60% of top items were found to be correlated with either roads or buildings. Notably, tobacco, food and beverage-related products, as well as packaging and sanitary products, showed strong associations with these urban land-use features. Other types of items, however, did not exhibit a relationship with land-use features, such as industry and construction-related items. Ultimately, this highlights the need to combine measures at the local and regional/national scales for effective litter reduction.

1. Introduction

Macrolitter is a ubiquitous environmental risk, affecting both aquatic and terrestrial ecosystems (van Emmerik and Schwarz, 2020). A growing amount of observational evidence shows high levels of exposure of freshwater ecosystems to macrolitter, with plastic found as the dominant material (van Emmerik et al., 2020). Macroplastics can threaten ecosystems, injure animals, cause economic damage by clogging hydraulic infrastructures, and lead to increased urban flood risks (van Emmerik and Schwarz, 2020; Azevedo-Santos et al., 2021). Despite these threats, the leakage processes and transport pathways of macrolitter in freshwater systems remain largely unknown. Large-scale quantification of macrolitter abundance in freshwater systems has only been undertaken recently (Barer and Kull, 2018; Hengstmann and Fischer, 2020; van Emmerik and Schwarz, 2020; González-Fernández et al., 2021). As a result, only a handful of studies have so far explored the drivers of macrolitter variability in freshwater systems (Cowger

☆ This paper has been recommended for acceptance by Michael Bank.

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https://doi.org/10.1016/j.envpol.2024.124911
Received 30 August 2023; Received in revised form 30 July 2024; Accepted 5 September 2024
Available online 10 September 2024

et al., 2019; Roebroek et al., 2021a; Cowger et al., 2022; Schuyler et al., 2022; Tasseron et al., 2023). Additional research on this would be essential for guiding effective litter reduction and mitigation strategies.

The most commonly used methods to quantify macrolitter involve sampling either the freshwater surface or lake shores and riverbanks (Castro-Jiménez et al., 2019; van Emmerik et al., 2019; Mason et al., 2020; van Emmerik and Schwarz, 2020; Tasseron et al., 2020). Floating macrolitter assessments typically use visual counting of macrolitter items from bridges or deploy nets to retrieve water samples from boats or bridges. These monitoring techniques require the presence of infrastructure or the availability of equipment. In addition, they only provide a 'snapshot' view of the quantity and composition of floating litter at a given time. By contrast, monitoring macrolitter abundance on river and lake banks allows one to cover larger geographical areas and to conduct more frequent observations (Vriend et al., 2020). As a result, some countries have deployed large-scale monitoring programs of macrolitter abundance along riverbanks and lake shores, often relying on the participation of trained volunteers. This is the case in the Netherlands with the *Schone Rivieren* (Clean Rivers) initiative (van Emmerik and Schwarz, 2020), the Swiss Litter Report in Switzerland (Barer and Kull, 2018), and the Great Canadian Shoreline Cleanup (Hengstmann and Fischer, 2020). These large-scale and long-term monitoring programs provide baseline estimates of macrolitter quantities and composition. They can also be used to explore fundamental transport and accumulation processes of macrolitter in freshwater systems.

Despite baseline assessments of macrolitter in freshwater ecosystems becoming more common, the factors determining its variability remain largely unresolved. Macrolitter found on riverbanks and lake shores comes either from terrestrial pathways (direct littering or dumping) or from transport from the aquatic systems (river flow and lake currents) (Mellink et al., 2022; Roebroek et al., 2021a). It is commonly assumed that hydrometeorological variables, such as precipitation, wind speed, water flow velocity, and river discharge play an important role in the transport and deposition of macrolitter items along the banks of freshwater bodies (Liro et al., 2020; Bruge et al., 2018; Haberstroh et al., 2021; Roebroek et al., 2021a). Other factors affecting macrolitter transport and accumulation processes pertain to the items characteristics, (e.g. buoyancy, level of biofouling, shape and size) and the aquatic system characteristics (e.g. meanders and channel width in the case of rivers) (Lechthaler et al., 2020; Lobelle et al., 2021; Newbould et al., 2021). Macrolitter abundance on riverbanks and lake shores can also come from mobilization through terrestrial pathways (Mellink et al., 2022). In this case, wind speed and surface runoff are also presumed to be major drivers of macrolitter transport (Lebreton et al., 2017; Meijer et al., 2021; Roebroek et al., 2021a). A study on macrolitter abundance on the Dutch riverbanks demonstrated the influence of hydrometeorological factors, but also highlighted that the studied variables (wind speed, flow velocity and precipitation) only accounted for 19% of macrolitter variability (Roebroek et al., 2021a). Similarly, Tasseron et al. (2023) investigated the relationship between environmental drivers, such as rainfall, sunlight, wind speed, tidal regimes, and macrolitter transport, revealing minimal and statistically insignificant correlations. Other potential driving factors have not yet been studied in relation to macrolitter abundance and composition in freshwater systems, but may play an important role. These include partially stochastic events such as direct littering and dumping of macrolitter close to freshwater systems (Cieplik, 2021). These actions can be driven by individual human behavior, which can vary significantly due to factors such as personal habits, convenience, awareness of proper waste disposal, and even mood or emotions at the time of disposal. Other factors driving direct littering and dumping of macrolitter include cultural, societal and economic factors, including the availability and effectiveness of municipal solid waste management services. A crucial open question is the role of local leakage processes in macrolitter presence along lake shores and riverbanks. In this study, we investigate the impact of differing land-use features on macrolitter quantities, considering item origins and composition. This could ultimately improve our understanding of leakage and (terrestrial and aquatic) transport mechanisms of macrolitter into freshwater systems. Additionally, it could provide an initial step to differentiate between locally and non-locally leaked items, as well as items transported for short distances and items traveling long distances before beaching.

Land-use features are an explaining factor for variability in macrolitter accumulation in coastal, marine and land environments (Aydin et al., 2016; Grelaud and Ziveri, 2021; Harris et al., 2021; Pietz et al., 2021). To date, only one study has investigated the role of land-use features in macrolitter accumulation in freshwater systems in the United States (Cowger et al., 2019). The proximity of land-based litter sources, such as recreational and urban areas, might be an indicator for high leakage rates (i.e. high littering rates and losses into the environment). Impervious surfaces also generate higher surface runoff volumes, which in turn can accelerate leakage and propagation of litter from land to the aquatic environment (Baldwin et al., 2016). Many regional and global scale studies model plastic waste inputs into lakes, rivers and oceans, as a function of nearshore population densities, generally using global population datasets (Jambeck et al., 2015; Hoffman and Hittinger, 2017; Lebreton et al., 2017; Schmidt et al., 2017). However, higher human densities do not necessarily translate into higher rates of leakage into the environment at a local scale (Schuyler et al., 2021). This highlights that population density should not be used as the sole proxy for litter inputs for accurate modeling of its distribution in the environment. Analyzing land-use features in relation to macrolitter accumulation could reveal specific point sources of macrolitter items, such as industries and commercial areas. Additionally, such analysis can provide insights into the impact of areas with high levels of human activity, such as recreational areas, potentially leading to higher leakage rates into the environment. The role of several land-use features should be considered, but has so far not been thoroughly quantified in relation to empirical data on macrolitter abundance. Such insights are relevant for several reasons. First, a better understanding of the leakage and transport processes of litter pollution is crucial in designing targeted intervention strategies and formulating policies to prevent and reduce their leakage into the environment. Second, they can be used for improving large-scale models on debris distribution and propagation into the environment.

In this study, we test the hypothesis that land-use features partially explain the variability in macrolitter abundance and composition in freshwater systems. We used an extensive observational dataset on macrolitter abundance, collected across Switzerland in 11 lakes and 17 rivers (Fig. A.1). 386 surveys were conducted over a 13-month period, during which 50,649 macrolitter items were sampled on Swiss riverbanks and lake shores. We analyzed the composition and likely origin of the most commonly found macrolitter items (n = 42,565) - herein referred to as 'top macrolitter items'. We then assessed the role of eleven land-use variables (buildings, city centers, recreational areas, public infrastructure, roads, forests, marshlands, vineyards, orchards, other land and rivers and canals) in macrolitter abundance among top items. Based on this analysis, we provide insights on the role of land-use features in macrolitter abundance in freshwater systems.

2. Data and methods

Hypotheses on land-use and macrolitter correlations

We formulate hypotheses for the possible correlation signs between the land-use features and macrolitter abundance (Table 1). A positive (and significant) correlation would indicate that macrolitter abundance increases with an increase in the coverage of land-use feature considered. The substantiation of the hypotheses is mainly derived from existing observational studies. Given that understanding the relationships between land-use features and macrolitter abundance is largely

Table 1
Hypotheses for correlations between macrolitter abundance and land-use features. '+/−' signs indicate that the correlation sign is expected to be either positive or negative. For some variables, two diverging hypotheses are formulated. The first one is considered the most likely one.

Variables	Hypotheses	Substantiation	References
Buildings City centers	+	Populated and/or frequently visited areas, high littering rates.	Ryan et al. (2018) Tasseron et al. (2020, 2023)
Public infrastructure	−	High clean-up rates. Impervious surfaces facilitate transport of macrolitter outside of the considered area.	Mellink et al. (2022)
Recreational areas	+	Areas of high number of visitors, thus prone to high littering rates. Previous studies show that recreational areas and parks can be pollution sources.	Carpenter and Wolverton (2017)
	−	High clean-up rates due to the aesthetical value of some recreational areas.	
Vineyards Orchards	+	Leakage of items used in the agricultural sector, such as agricultural sheeting. Touristic visits in the wine sector, high littering rates.	Steinmetz et al. (2022)
	−	Low population densities, low littering rates.	
Forests Marshlands	+	Areas of touristic frequentation, can be prone to high littering rates. Dense tree and vegetation cover might induce low transport of items and high retention capacity, especially if in contact with rivers and lakes that might deposit items on the shores.	Pietz et al. (2021) Delorme et al. (2021) Mellink et al. (2022)
	−	Low population densities, low littering rates. High clean-up rates due to the aesthetical value of some forested areas.	
Other land	+	Areas where macrolitter could be discarded informally.	Sakti et al. (2023)
	−	Low frequentation and low littering rates.	
Roads	+	Proxy for densely populated areas and direct littering along roads. Accumulation observed at roadside ditches.	Matos et al. (2012) Pietz et al. (2021)
Rivers and canals	+	Pathways of macrolitter pollution, potential entry points into the environment. Accumulation and deposition along rivers.	van Emmerik et al. (2022)
	−	Rivers could mobilize items previously accumulated on riverbanks, thus acting as a removal factor of accumulated macrolitter.	van Emmerik et al. (2023)

unresolved, for most variables, two opposite correlations could be hypothesized. For instance, it is yet unknown whether rivers act more as plastic reservoirs or pathways of plastics (van Emmerik et al., 2022) and thus whether rivers mainly deposit items on their banks or re-mobilize previously accumulated items and carry them further downstream. Both roles can coexist, as well as vary depending on space and time, river characteristics, hydrological conditions and item characteristics.

Macrolitter dataset

The macrolitter data used in this research were collected between 1 April 2020 and 31 May 2021 by the Non-Governmental Organization (NGO) Hammerdirt. Overall, 386 surveys were conducted at 143 locations, located in 98 different municipalities in Switzerland (Fig. A.1). A total of 50,649 macrolitter items were counted and categorized. Of the 386 surveys, 331 (85.8%) were undertaken along lake shores and the remaining 55 (14.2%) were undertaken along riverbanks. The surveys were conducted by Hammerdirt staff and trained volunteers (two surveyors on average per survey). Several criteria determined the selection of the survey locations. Firstly, the survey area had to be a bank of a lake or river, with direct contact with the water. The length of the sampling area was determined as the longest continuous stretch of lake shore or riverbank accessible. Despite international protocols such as OSPAR requiring to survey areas of 100 m of length (Wenneker et al., 2010), this was not possible in the Swiss context, given that the majority of beaches have smaller strips of land available (due to both legal and physical barriers), with a site median length for the surveys considered in this study of 45 m. The width of the survey area was defined as the distance from the waterline to the high-water line. The high-water line is intended as the mark left by the highest water level reached during a particular period, such as during a flood or a period of high waters. Overall, the survey locations had an area typically comprised between 50 and 200 m^2. Secondly, survey locations were required to be accessible (both physically and legally) throughout the year. Also, the site had to be within 30 min of the nearest public transport station to ensure that surveyors could easily reach it. Finally, survey locations that had already been selected for the national Swiss Litter Report (Barer and Kull, 2018) in 2018 were preferred to facilitate time-series analysis.

During each survey, participants collected all visible items > 5 mm in size (i.e. macrolitter). Items were subsequently categorized using the Marine Litter Beach item classification, which contains a total of 217 categories (Marine Strategy Framework Directive Technical Subgroup on Marine Litter, 2013). The measurement process itself introduces inherent uncertainty, which includes potential misclassification of items by observers and the possibility of missing some items. To minimize the uncertainty, we grouped the survey results by riverbank and lake shore locations, as the grouping helps to average out individual measurement errors. It is unclear how representative the survey locations are of the level of macrolitter pollution of all lake shores and riverbanks in Switzerland. To date, no comprehensive studies have quantified the uncertainty associated with macrolitter surveys, making it challenging to provide a precise estimate of the uncertainty in our measurements. Further research is needed to address this knowledge gap and enhance our understanding of the uncertainties inherent to macrolitter surveys.

All items collected and analyzed during each survey were also categorized by material types (plastic, glass, metal, textile and paper). In addition, we categorized all items by their functional characteristics, either morphological or related to their use: plastic fragments and

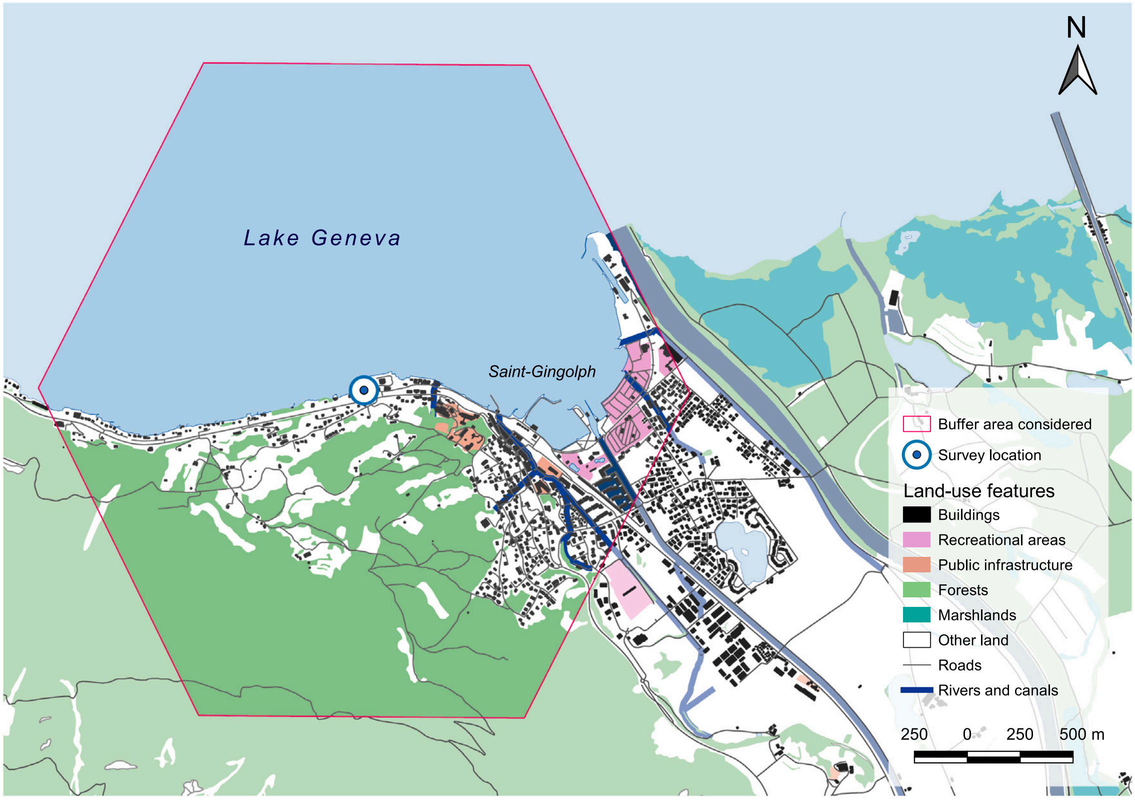

Fig. 1. Example of land-use features present in one buffer area around a survey location. The example is from the Saint-Gingolph survey location (46.387746, 6.843686) at Lake Geneva, Switzerland. Note that not all land-use features are present at this location and thus not all are displayed on the map.

pieces, industry and construction, tobacco, food and beverages, sanitary, non-food packaging, and others. This classification by functional type was done by using the description of each macrolitter category as an indicator for the use and morphological characteristics of items. Items for which no clear use or morphological characteristics could be inferred from the category description were categorized as 'others'. We considered expanded polystyrene (EPS) under the industry and construction type. In Europe, this plastic item is mainly used as insulation material in the construction sector (Kawecki and Nowack, 2019; Lobelle et al., 2023). Macrolitter abundance was ultimately reported in both total items count and number of items/100 m of shoreline, in line with the EU Marine Litter Baselines, which express marine macrolitter abundance in items/100 m of shoreline (Marine Strategy Framework Directive Technical Subgroup on Marine Litter, 2013).

Geospatial study design

At each survey location, we extracted land-use features within a buffer area. We defined an area of 5.8 km^2 (1500 m in radius) around each survey location and extracted land-use features of interest for each area (Fig. 1). The buffer area size was based on the average overland macrolitter transport distance (1500 m) found by Cowger et al. (2022). We chose a hexagonal shape for the area around the survey location as it offers several advantages for potential mapping of an entire territory (Birch et al., 2007). Firstly, the hexagonal shape provides a more uniform coverage of a territory compared to circles. This ensures that no gaps or overlaps occur between adjacent buffer areas, allowing for a comprehensive and accurate representation of the land-use features within the territory. Secondly, the hexagonal shape allows for efficient and systematic sampling or grid-based analysis. The regularity and symmetry of the hexagons facilitate consistent spatial arrangement and enable easier interpretation and comparison of the land-use data. Thirdly, the hexagonal shape minimizes edge effects and distortions, unlike squares or rectangles (Birch et al., 2007).

Land-use dataset

We used the Swiss Land Use Statistics (Federal office of topography Swisstopo, 2023) to extract land-use features at each survey location. This dataset is freely available and is updated every year. The land-use dataset is available in vector format and covers the entire country. The precision ranges from 0.2 m to 3 m, depending on the features. Among the land-use features extracted in this dataset, the following are identified: (1) Buildings (2) City centers (3) Recreational areas (4) Public infrastructure (5) Vineyards (6) Orchards (7) Marshlands (8) Forests (9) Rivers and canals, and (10) Roads. While these are the most prominent land-use features, other land-use types were present in the dataset, such as barren rocks, cliffs and glaciers. However, their presence in the survey locations is marginal compared to the ten extracted features and we did not include them in our analysis. The land-use dataset does not cover all the terrestrial land, and we thus generated an eleventh feature, called 'Other land', for all the areas not covered by the features listed above. A visual inspection using Google aerial imagery showed that these areas are mainly covered by fallows, pastures, and grasslands.

The feature 'Buildings' refers mainly to residential houses and buildings. Recreational areas include diverse public uses, from sport fields to camp sites, and capture all land surfaces dedicated to social activities. City centers identify the central areas of urban agglomerations. Public infrastructure includes schools, hospitals, prisons, cemeteries and administrative buildings. The feature 'Roads' refers to all roads intersecting the buffer area, from small paths to highways. Rivers and canals include all rivers and canals within the buffer area and that intersect the lake shores or riverbanks of the survey location. All land-use features except roads and rivers were expressed in km^2 and in percentage (%) of the total terrestrial surface of the buffer area around the survey location. To determine the total terrestrial surface, lake and river surfaces were subtracted from the total surface. Roads and rivers features were expressed in km. Table B.1 in Appendix B details the land-use characteristics for both lake and river survey locations. The dominant land-use class is buildings (49.1% and 41.5% for lake and river locations, respectively), followed by other land areas (21.1%–27.7%) and forested areas (17.6%–19.4%). The other land-use features represent much lower shares of the land-use (< 10%). The average length of the road network across survey locations is between 55.6 km and 10.0 km; and the average length of rivers and canals is between 1.0 km and 6.2 km (Table B.1).

Correlation analysis between land-use variables and macrolitter abundance

To determine the commonly found items, we considered those that were observed at least 20 times during the sampling period. For each of these commonly found items, we correlated their abundance (expressed as items per 100 m) with various land-use features. The correlations between land-use features and the top macrolitter items were calculated using the Spearman correlation analysis, which tests for statistically significant monotonic relationships between variables (Glasser and Winter, 1961). The null hypothesis tested was that there is no correlation between the land-use features and the top items. The test results provide information about the direction (R) of the correlation and whether the association is likely due to chance (p-value). We consider the correlation statistically significant if the p-value is less than 0.05. We only report correlations that are statistically significant, as correlations below this threshold are deemed too uncertain. It is important to note that the Spearman correlation analysis provides an indication of the relationship between land-use features and macrolitter abundance, but it does not establish causation, as other factors may also contribute to the observed association.

3. Results and discussion

A majority of consumption- and industry and construction-related items

A total of 50,649 macrolitter items were sampled in Switzerland between 1 April 2020 and 31 May 2021 (48,239 on lake shores and 2,410 on riverbanks). These items were classified into 199 distinct categories, reflecting the diverse range of sources and types of macrolitter encountered. Among the lake survey locations, 34 categories were identified with a minimum count of 20 items observed during at least one survey. For the riverbank survey locations, the most abundantly encountered items were distributed across ten distinct categories. These top categories accounted for 82.9% of the total items found, 84.1% (n = 40,566) for lake shores, and 58.0% (n = 1,399) for riverbanks. The most abundant items were mainly identified as plastic material (89.9%) while other materials include glass (6.1%), metal (2.8%) and paper (1.1%). Among the most commonly found items, the top ten categories (Fig. 2A) at lake locations consist of cigarette filters, fragmented plastics, expanded polystyrene, and food wrappers. The category of fragmented plastics includes various plastic types, such as foil, hard fragments, and foam. At riverbank locations (Fig. 2B), top ten items include diapers and wipes, cigarette filters, glass bottles and pieces, and industrial sheeting. Among the ten most frequently found item categories at riverbank locations, seven of them also appear among the 34 most commonly found categories at lake shores. This indicates a good agreement among the most commonly found items between lake shore and riverbank locations. Tables C.2 and C.3 in Appendix C present a complete overview of top items abundance, their type and dominant material for both lake shore and riverbank locations.

A considerable amount of items (n = 10,924, 26.6% of total) can be attributed to the industrial and construction sectors (Table C.4). Expanded polystyrene is often used as insulation material in the construction sector, and industrial sheeting is commonly used in the horticulture, industrial and construction sectors. These items are not typically linked to consumer littering behavior, implying that their leakage into the environment may occur differently. This could include accidental leakage near their manufacturing or construction sites, or during transportation. Alternatively, intentional dumping may also be a contributing factor. Items related to food and beverages (19.0%), as well as tobacco products (21.7%), contribute significantly to the top items. Together, these items make up for the highest share of items (40.7%). The presence of consumption-related items can be attributed to direct littering by consumers, with food wrappings, packaging, cigarette filters, and glass bottles being commonly discarded on land by visitors (Kelley and Ambikapathi, 2016; Kolenda et al., 2021; Ballatore et al., 2022; Youngblood et al., 2022; Vanapalli et al., 2023). Additionally, plastic fragments and pieces also contribute significantly, accounting for 17.4% of the top items. Hypothesizing pathways for plastic fragments is more difficult, because of their reduced size, fragmented state, and omnipresence. Fragmentation and degradation could be the result of long residence times on both land and water. Further investigation into the transport pathways and sources of these fragmented items is required. The remaining types of plastic contribute to a lower proportion of the top items, each accounting for less than 10% (Table C.4). Some sanitary products likely make their way into the environment at combined sewer overflows (CSOs), stormwater outlets and waste water treatment plants (WWTs) (Kawecki and Nowack, 2019). Sanitary products were found in higher proportion at riverbank locations than at lake shore locations (21.8% and 5.2%, respectively). This is within the range of the share of hygiene and sanitary products (6.3%) found on British beaches (British Marine Conservation Society, 2016). A modeling study found that 80% of macroplastic inputs into the water in Switzerland are attributable to sewer overflows (Kawecki and Nowack, 2020), a much higher proportion than what our analysis suggests.

Except from the higher share in items attributed to the industrial sector, the composition of the top macrolitter items found in Switzerland is similar to that found in other observational studies on macrolitter abundance across European waterways. Tramoy et al. (2019) found that plastic pellets, unidentified fragments and sticks (cotton buds and lollipop sticks) were the most abundant objects accumulated on the riverbanks of the Seine river, France. Other abundant items included expanded polystyrene, caps and industrial packaging films (Tramoy et al., 2019). Plastic fragments, food wrapping and packaging, caps and lids, cotton swabs and cigarette filters also feature among the top 20 items found on Dutch riverbanks (van Emmerik and Schwarz, 2020). These items were also among the top ten litter items collected on the riverbanks of the Adour river in France (Bruge et al., 2018). This consistency in macrolitter composition is likely the result of similar consumption patterns and waste management practices among European countries. Another explaining factor might be that transport and deposition affect specific litter items differently and that thus, the items commonly found on freshwater shores are those preferentially deposited, due to their characteristics and transport processes. Among the top macrolitter items found in the above-mentioned studies and in Switzerland, several categories indicates high amounts of caps and lids. In contrast, plastic bottles were rarely found. This could be due to the high recycling rate of plastic bottles and thus their removal from the environment. Another explanation could be that bottles in transport in the water would likely sinks into the lake or river, whereas the caps stay afloat and wash up on the shores due to the combined action of wind, current and discharge, as suggested by Bruge et al. (2018).

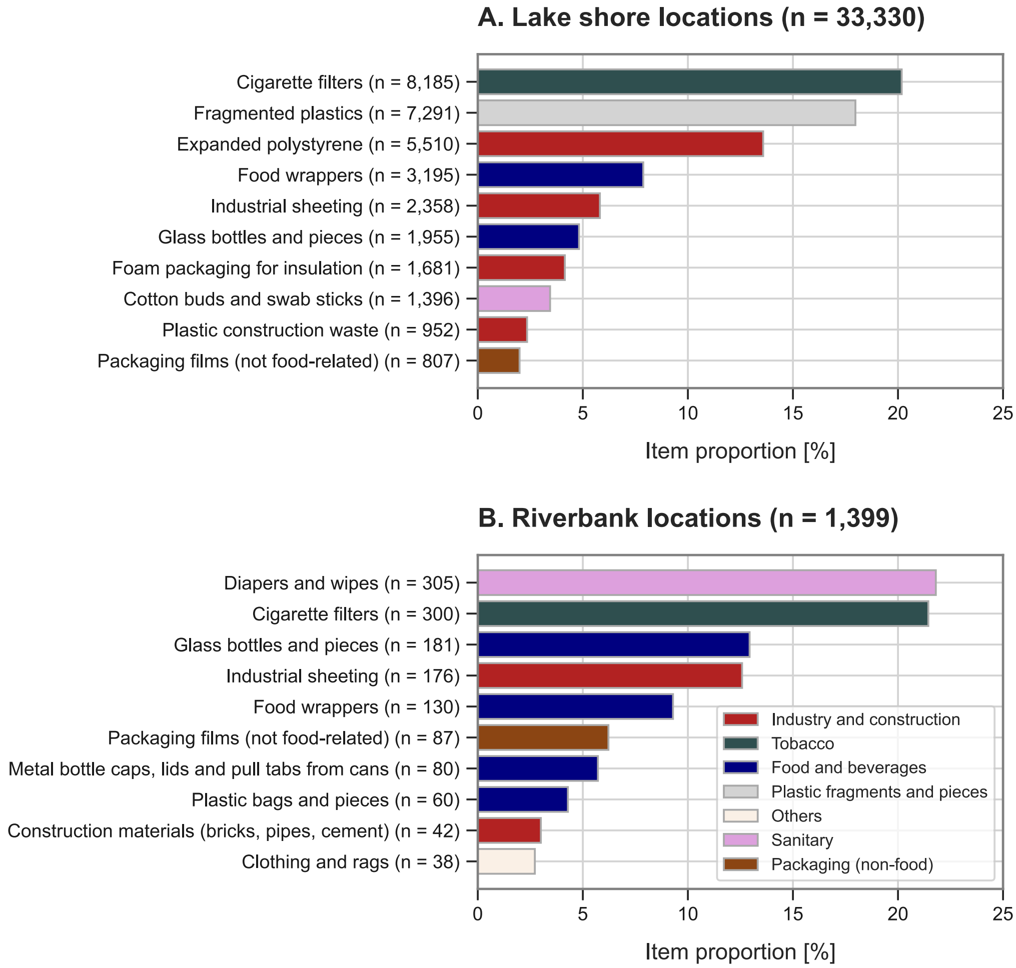

Fig. 2. Top ten macrolitter items found in Switzerland (n = 34,729–68.6% of total items sampled) and their likely origin for both lake shore survey locations (A) and riverbank locations (B). These top ten items correspond to 69.1% (n = 33,330) and 58.0% (n = 1,399) of all sampled items at lake shore and riverbank locations, respectively.

Roads and buildings are overall good predictors of macrolitter abundance

Overall, land-use features related to urban coverage emerged as the most influential predictors of macrolitter abundance. Indeed, roads and buildings resulted in the highest number of positive correlations (n = 18) with macrolitter items. Correlation coefficients varied significantly, ranging from 0.08 to 0.53. Out of these 18 correlations, 15 of them corresponded to both roads and buildings, indicating a strong relationship between these two factors. As much as 64.1% of top items were found positively correlated with roads, and 61.8% with buildings (Table D.5). Among land-use features, roads and buildings resulted in the highest number of positive associations (n = 18) with macrolitter items. These results are consistent with previous observation-based studies that have identified roadsides and built-up areas are macrolitter accumulation zones (Matos et al., 2012; Tasseron et al., 2020; Pietz et al., 2021; Tasseron et al., 2023; Winston et al., 2023). Public infrastructure buildings displayed a positive correlation with 58.5% of top items (Table D.5). Other land-use features related to urban coverage, such as city centers and recreational areas, also demonstrated significant and positive correlations with top macrolitter items, although to a lesser extent than buildings, roads and public infrastructure. One reason for this could be that city centers and recreational areas cover lower share of the total land-use area at survey locations (Table B.1). The presence of macrolitter items associated to direct consumption, such as tobacco, food and beverages and sanitary products was found to be strongly and positively correlated with urban coverage. All tobacco-related items (cigarette filters and plastic packaging for tobacco) and plastic fragments and pieces exhibit significant correlations with multiple land-use features associated with urban coverage. Cigarette filters, the most prevalent item found throughout the study (n = 8485), showed positive correlations with various land-use features related to urban coverage, supporting the hypothesis that these items tend to accumulate in areas where direct littering occurs (Vanapalli et al., 2023). Similarly, food and beverage-related items often demonstrate frequent correlations with urban coverage features. This is the case for food wrappers, metal bottle caps, lids and pull tabs from cans, as well as lids and cap rings from plastic bottles and aluminum foil (specifically for lake shores). However, other food and beverage-related items displayed limited associations with land-use features, resulting in 44.8% of food and beverage-related items with less than three positive and significant associations with land-use features.

Industry and construction-related items show no positive correlations with land-use features (Table D.6). Expanded polystyrene, industrial sheeting, foam packing for insulation, plastic construction waste, plastic sheeting, foamed EVA, and other construction materials have no or very few (less than three) positive significant correlations with land-use variables (Fig. 3). Three factors may explain the absence of positive associations between industry and construction-related items and land-use features. First, the spatial distribution of these items along riverbanks and lake shores may be diffuse and thus independent of

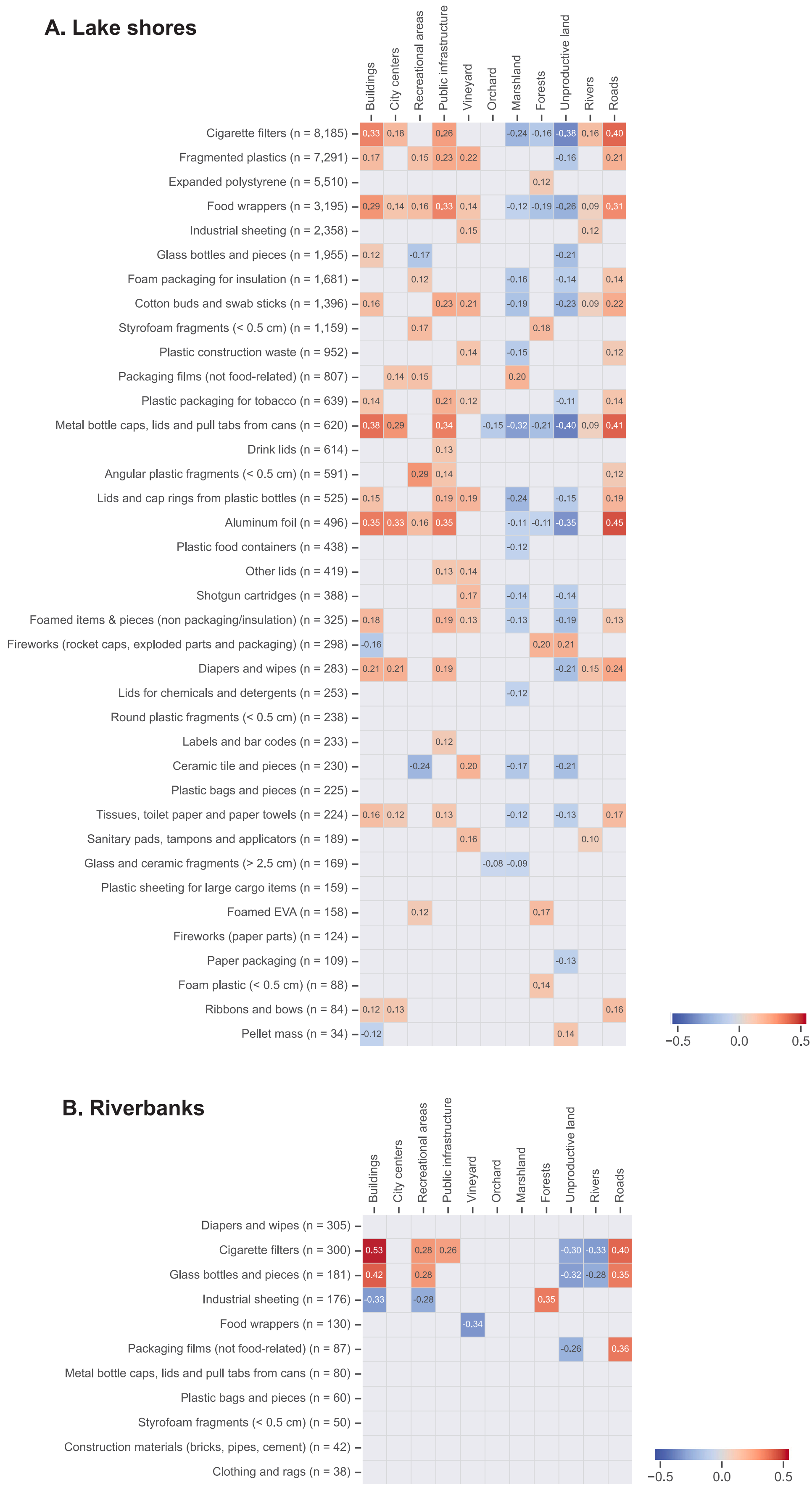

Fig. 3. Correlation matrix for the most commonly found items on lake shores (A) and riverbanks (B) in Switzerland. Each square details the Spearman correlation coefficient (R) for p-values below 0.05 for each item category and land-use variable combination. For combinations where the *p*-value is below 0.05, no R value is indicated, as the relationship is considered non-significant.

land characteristics. Previous research found that expanded polystyrene items are likely to be transported over longer distances in rivers than other items (Ryan, 2021). Because of their low densities and thus high buoyancy, these items are more likely to be mobile in the environment, notably through wind action. Thus, changes in land-use features may not significantly impact the accumulation of these items in the environment. Second, the leakage and supply of industry and construction-related items into the environment could also be spatially diffuse, resulting in limited or no discernible relationship with land-use features. Finally, it is worth noting that the available land-use dataset does not differentiate buildings and facilities specifically associated with the production and use of industry-related items. Buildings related to the industrial and construction sector are not distinguished from other types of buildings. As a result, establishing correlations between potential production and use areas, and areas of accumulation, becomes difficult.

Our research supports our initial hypothesis concerning forests, marshlands, and other land, indicating that areas with lower population densities and minimal human activity exhibit reduced littering rates and subsequent accumulation. In the case of these land-use features, a predominant proportion of significant negative correlations were observed, accounting for 28.3%, 46.1% and 65.6% of the top items for forests, marshlands and other land, respectively (Table D.5). This pattern indicates a reduced occurrence of macrolitter items in these environments. This was particularly evident for consumption-related items, such as cigarette filters, food wrappers, cotton buds and swab sticks, metal bottle caps, lids and pull tabs from cans (Fig. 3), all of which exhibited statistically significant negative correlations with forests, marshlands, and other land. It is important to note that 'Other land' primarily encompasses agricultural and unproductive land, where minimal direct littering of consumption-related items can be expected. Additionally, agricultural land could involve plastic film and sheet use and leakage, as documented by MacLeod et al. (2021). Our results also show notable positive links between expanded polystyrene (EPS) and foamed ethylene-vinyl acetate (EVA) with forests and other land. Interestingly, plastic bags and plastic pieces also exhibited a positive correlation with forested areas. However, the exact reasons behind this correlation remain unclear, and further investigation is needed to understand why such a relationship exists. Furthermore, the positive correlations observed for EPS, foamed EVA, and industrial sheeting (in river locations) may be attributed to their sources being primarily located outside of urban areas or their potential for longer-distance transport.

Among the land-use features related to agricultural use, only vineyards showed positive correlations with a significant portion of the top items, accounting for 42.3% of them (Table D.5). Among the items displaying a positive association with vineyards, some can be directly linked to their utilization in this agricultural sector, such as industrial sheeting, foamed items, and non-packaging/insulation pieces. Additionally, the presence of other items positively correlated with vineyards suggests that these areas are frequently frequented, resulting in observable littering of consumptions-related items. This is evident in items such as plastic fragments, food wrappers, plastic packaging for tobacco, as well as lids and cap rings from plastic bottles (Fig. 3). Orchards showed minimal significant correlations with the top macrolitter items, indicating that they are not a reliable indicator of macrolitter accumulation.

4. Synthesis and outlook

The results of this study have several implications, particularly concerning the design of clean-up and reduction strategies. We found that land-use features, in particular those related to urban coverage such as roads and buildings, are robust indicators for the abundance of the majority of macrolitter items on riverbanks and lake shores. Over 60% of the top items found on lake shores and riverbanks were positively and significantly correlated with roads and buildings (64.1% and 61.8%, respectively). For items strongly correlated with land-use features, such as tobacco-related products and items from take-out consumption, localized mitigation projects are likely to yield significant reductions in their abundance. These efforts can focus on targeted interventions at local (municipal) geographic scales to address littering hotspots effectively (Doolin and Zhang, 2015; Kelley and Ambikapathi, 2016). Such approaches acknowledge the need for behavioral changes and community engagement to effectively reduce macrolitter abundance and minimize its environmental impact. Therefore, it is crucial to address the local inputs and human component inherent in macrolitter pollution for the development of comprehensive and sustainable litter management strategies. Certain macrolitter items, particularly those associated with the industrial and construction sector, showed limited or no associations with land-use features. However, it is important to note that our study did not have data available to directly test the relationship between macrolitter abundance and manufacturing and construction sites. Therefore, it is possible that such an association exists, but we were unable to capture it with the current data. Assuming no relationship between industry-related items and land-use features, it would be advisable to implement strategies targeting these items at a regional scale, as they appear to be less influenced by specific land-use characteristics. By addressing the specific sources and practices within this sector, clean-up efforts can effectively minimize the occurrence of such items. Overall, both regional and local mitigation strategies are necessary for achieving substantial litter reduction, as our study identified a considerable proportion of macrolitter items associated with land-use features, as well as items that exhibited no such associations. By combining efforts at different geographic scales, stakeholders can create comprehensive reduction and clean-up strategies to tackle macrolitter pollution.

Furthermore, our study provides insights into the transport behavior of macrolitter. We highlight the spatial proximity of items to their potential leakage sources, as evidenced by the numerous significant correlations found between tobacco, food, and drink-related items and land-use features associated with urban coverage. This supports the findings of previous studies, highlighting that macrolitter items are not transported over long distances either in rivers (Tramoy et al., 2020; van Emmerik et al., 2022; Lotcheris et al., 2024) or over land Kelley and Ambikapathi (2016), Ballatore et al. (2022), Cowger et al. (2022). Macrolitter items tend to be found in the vicinity of their pollution sources (Kelley and Ambikapathi, 2016; Ballatore et al., 2022; Cowger et al., 2022; Schuyler et al., 2022). The high proportion (18%) of fragmented plastics found at lake shore locations may suggest that fragmentation and degradation of entire items occurred during transport in lakes. However, fragmentation processes could also take place through over land transport or when accumulated at lake shores. In addition, our results emphasize the stochastic nature of macrolitter pollution, with local factors and human behaviors contributing to the observed variability in spatial distribution (Cowger et al., 2022). In their investigation of macrolitter transport mechanisms at roadsides, Cowger et al. (2022) considered factors such as runoff, wind direction, and human travel. They found that human travel played a predominant role in macrolitter accumulation along roadsides. Understanding this stochastic component raises important considerations for incorporating it into predictive models. Most studies on macrolitter abundance have so far primarily investigated the role of environmental factors such as runoff, wind, river discharge, water levels, flood occurrence and magnitude (Mellink et al., 2022; Roebroek et al., 2021a,b; van Emmerik et al., 2023).

Our findings highlight the need to shift towards including urban coverage and human littering as key factors in predictive models (Tasseron et al., 2023). By integrating the stochastic element and the influence of human activities, we can improve the accuracy and effectiveness of predictive models for macrolitter abundance and develop more targeted strategies for its prevention and management. These efforts could include a greater focus on identifying source locations of macrolitter, such as restaurants, convenience stores, and supermarkets, as highlighted by Kelley and Ambikapathi (2016) and Ballatore et al. (2022).

Moreover, the geospatial analysis undertaken in this study employed an isotropic delineation of the area surrounding the survey locations. Consequently, our approach did not consider transport directionality, which could potentially influence both the accumulation and dispersion patterns of macrolitter. We found that road network was a significant predictor for the presence of over 60% of observed macrolitter, indicating a potential influence of connectivity factors on macrolitter pathways from sources to accumulation sites. However, roads may serve as indicators of human activity rather than direct conduits for macrolitter transport on land. Additionally, while our analysis did not directly account for directional transport, previous research (Stocker, 2020) has highlighted the role of wind as a significant driver in the movement of litter, irrespective of street directionality.

5. Conclusions

We investigated macrolitter composition at lake shores and riverbanks in Switzerland. Items that can be related to consumable products, such as tobacco and food and beverages products make up for the highest share of items (41%). Industry and construction-related items also constitute a significant proportion of macrolitter items, accounting for nearly 27% of the top items found on lake shores and riverbanks in Switzerland.

We found that urban coverage features, particularly roads and buildings, are robust indicators for the abundance of the majority of macrolitter items on riverbanks and lake shores (~ 60% of top items), notably items related to consumable products. However, industry and construction-related items show limited or no correlations with land-use features at the survey locations. Overall, urban land-use features are good predictors for the most commonly found macrolitter items, with the notable exception of industry-related items.

Our results show the need for targeted approaches in litter reduction strategies at different geographical scales to achieve effective impact. Local-scale efforts are likely to yield significant results for consumable products, while regional targeted strategies and actions may be more appropriate for other types of items, including those related to the industry. Furthermore, we emphasize the importance of further research to comprehend the dynamics of litter transport over land and within freshwater systems. Such knowledge is crucial for establishing more comprehensive and effective strategies to mitigate macrolitter pollution and safeguard our aquatic environments.

Data and code availability

The data and code used for this publication are available at: https://github.com/hammerdirt-analyst/landuse/tree/main. The entire dataset and scripts related to the Identification, quantification and analysis of Swiss litter (IQAASL) project are publicly available at: https://github.com/hammerdirt-analyst/IQAASL-End-0f-Sampling-2021. An online report is available at: https://hammerdirt-analyst.github.io/IQAASL-End-0f-Sampling-2021/intro.html.

CRediT authorship contribution statement

L.J. Schreyers: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **R. Erismann:** Writing – review & editing, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **S. Erismann:** Writing – review & editing, Investigation, Data curation. **C. Ludwig:** Writing – review & editing, Supervision. **B. Patel:** Writing – review & editing. **M. Filella:** Writing – review & editing, Supervision. **T.H.M. van Emmerik:** Writing – review & editing, Supervision, Methodology, 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.

Acknowledgments

We thank all the volunteers who counted, collected and categorized more than fifty thousand litter items. We thank Samuel Anrig, Rachel Aronoff, Rita Barros, Adrien Bonny, Martin Brenvasser, Gaetan Buser, Débora Camaro, Kurth Chanton, Jean Baptiste-Dussaussois, Thor Erismann, Amanda Finger, Andreas Gauer, Téo Gürsoy, Gary Hare, Hubert Heldner, Olivier Kressmann, Helen Kurukulasuriya, Taoufik Nouri, Lauren Thurnheer, Romain Tramoy, Marcel Regamey and students from the École Polytechnique Fédérale de Lausanne in the field of Solid Waste Engineering for valuable discussions and/or technical support. In addition, we would like to thank the reviewers and the editor for their constructive feedback. Support for this project was obtained from the following organizations: Association pour la Sauvegarde du Léman, Precious Plastic Léman, Geneva International School, the Summit Foundation, Hackuarium and the Swiss Federal Office for the Environment. We also thank the Swiss Federal Office for the Environment for funding Hammerdirt activities in 2020 and 2021. The work of TvE was supported by the Veni Research Program, the River Plastic Monitoring Project with project number 18 211, which was (partly) financed by the Dutch Research Council (NWO).

Appendix A. Macrolitter survey locations in Switzerland

See Fig. A.1.

Appendix B. Land-use characteristics

See Table B.1.

Appendix C. Top items characteristics

See Tables C.2–C.4.

Appendix D. Land-use features as predictors for macrolitter abundance

See Tables D.5 and D.6.

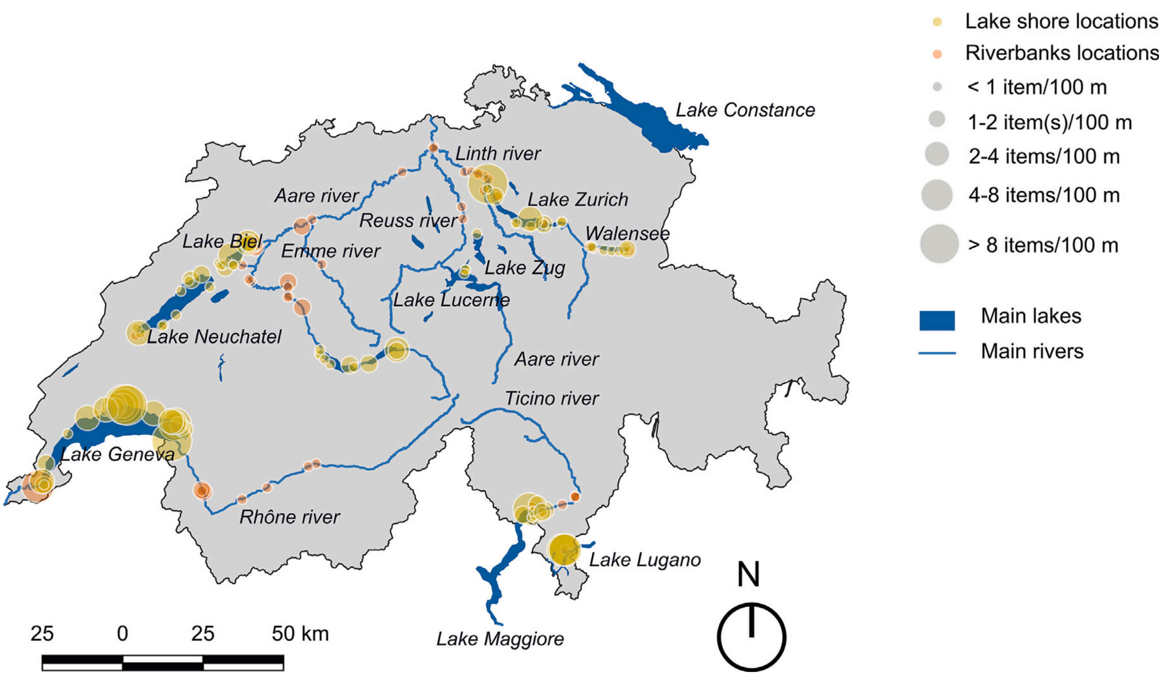

Fig. A.1. Map of survey locations for macrolitter sampling across Switzerland.

Table B.1
Land-use characteristics for all survey locations (n = 143).

	Area or length [km^2 or km]	Relative area [%]	Area or length [km^2 or km]	Relative area [%]
Buildings	1.7	49.1	2.5	41.5
City centers	0.0	0.7	0.0	0.5
Recreational areas	0.1	2.6	0.1	1.6
Public infrastructure	0.2	4.6	0.3	5.7
Vineyards	0.1	1.6	0.1	1.8
Orchards	0.0	1.1	0.0	0.7
Marshlands	0.1	1.6	0.1	1.1
Forests	0.6	17.6	1.2	19.4
Other land	0.7	21.1	1.6	27.7
Roads	55.6		10.6	
Rivers and canals	1.0		6.2	

Table C.2
Top items abundance, type and material characteristics for lake shore survey locations.

Description	Items count	roportion [%]	Abundance [items/100 m]	Main material	Type
Cigarette filters	8,185	20.2	60.4	Plastic	Tobacco
Fragmented plastics	7,291	18.0	68.2	Plastic	Plastic fragments and pieces
Expanded polystyrene	5,510	13.6	50.5	Plastic	Industry and construction
Food wrappers	3,195	7.9	26.2	Plastic	Food and beverages
Industrial sheeting	2,358	5.8	21.0	Plastic	Industry and construction
Glass bottles and pieces	1,955	4.8	17.2	Glass	Food and beverages
Foam packaging for insulation	1,681	4.1	15.2	Plastic	Industry and construction
Cotton buds and swab sticks	1,396	3.4	12.4	Plastic	Sanitary
Plastic construction waste	952	2.3	8.1	Plastic	Industry and construction
Packaging films (not food-related)	807	2.0	6.3	Plastic	Packaging (non-food)
Plastic packaging for tobacco	639	1.6	6.0	Plastic	Tobacco
Metal bottle caps, lids and pull tabs from cans	620	1.5	4.2	Metal	Food and beverages
Drink lids	614	1.5	5.3	Plastic	Food and beverages
Lids and cap rings from plastic bottles	525	1.3	4.4	Plastic	Others
Aluminum foil	496	1.2	3.6	Metal	Food and beverages
Plastic food containers	438	1.1	3.9	Plastic	Food and beverages
Other lids	419	1.0	3.6	Plastic	Others
Shotgun cartridges	388	1.0	3.4	Plastic	Others
Foamed items & pieces (non packaging/insulation)	325	0.8	2.6	Plastic	Others
Fireworks (rocket caps, exploded parts and packaging)	298	0.7	2.4	Plastic	Others
Diapers and wipes	283	0.7	2.0	Plastic	Sanitary
Lids for chemicals and detergents	253	0.6	2.3	Plastic	Others
Labels and bar codes	233	0.6	2.0	Plastic	Others
Ceramic tile and pieces	230	0.6	1.7	Glass	Industry and construction
Plastic bags and pieces	225	0.6	1.8	Plastic	Food and beverages
Tissues, toilet paper and paper towels	224	0.6	2.0	Paper	Sanitary
Sanitary pads, tampons and applicators	189	0.5	2.0	Plastic	Sanitary
Glass and ceramic fragments (> 2.5 cm)	169	0.4	0.6	Glass	Others
Plastic sheeting for large cargo items	159	0.4	1.4	Plastic	Industry and construction
Foamed EVA	158	0.4	1.2	Plastic	Others
Fireworks (paper parts)	124	0.3	1.2	Paper	Others
Paper packaging	109	0.3	0.8	Paper	Packaging (non-food)
Ribbons and bows	84	0.2	0.8	Plastic	Others
Pellet mass	34	0.1	0.2	Plastic	Industry and construction
Ribbons and bows	84	0.2	0.8	Plastic	Others
Pellet mass	34	0.1	0.2	Plastic	Industry and construction

Table C.3
Top items abundance, type and material characteristics for riverbank survey locations.

Description	Items count	Proportion [%]	Abundance [items/100 m]	Main material	Type
Diapers and wipes	305	21.8	12.8	Plastic	Sanitary
Cigarette filters	300	21.4	17.5	Plastic	Tobacco
Glass bottles and pieces	181	12.9	10.2	Glass	Food and beverages
Industrial sheeting	176	12.6	6.7	Plastic	Industry and construction
Food wrappers	130	9.3	8.0	Plastic	Food and beverages
Packaging films	87	6.2	6.2	Plastic	Packaging (non-food)
Metal bottle caps, lids and pull tabs from cans	80	5.7	5.6	Metal	Food and beverages
Plastic bags and pieces	60	4.3	3.3	Plastic	Food and beverages
Construction materials	42	3.0	1.3	Glass	Industry and construction
Clothing and rags	38	2.7	1.0	Cloth	Others

Table C.4
Top items characteristics (origin, item count, proportion and categories). The proportion, expressed in percentage, indicates the ratio of each type of items over the total count of top items.

Type	Locations	Quantity	Proportion by type [%]	Proportion of plastic items [%]	Items
Industry and construction	Lakes	10,924	26.9	97.9	Expanded polystyrene; Industrial sheeting;
	Rivers	218	15.6	80.7	Foam packaging for insulation; Plastic construction waste;
					Ceramic tile and pieces; Plastic sheeting for large cargo items;
					Construction material; bricks, pipes, cement; Pellet mass
	Total	11,142	26.6	97.6	
Tobacco	Lakes	8,824	21.8	100.0	Cigarette filters; Plastic packaging for tobacco
	Rivers	300	21.4	100.0	
	Total	9,124	21.7	100.0	
Food and beverages	Lakes	7,543	18.6	59.3	Food wrappers; Glass bottles and pieces; Metal bottle caps,
	Rivers	451	32.2	42.1	lids and pull tabs from cans; Drink lids;
					Aluminum foil; Plastic food containers; Plastic bags and pieces
	Total	7,994	19.0	58.3	
Plastic fragments and pieces	Lakes	7291	18.0	100.0	Fragmented plastics
	Rivers	0	0.0		
	Total	7,291	17.4	100.0	
Others	Lakes	2,976	7.3	90.2	Foamed items and pieces (non packaging/insulation);
	Rivers	38	2.7	0.0	Foamed EVA; Ribbons and bows; Clothing and rags
					Glass and ceramic fragments (> 2.5 cm); Labels and bar codes;
					Lids and caps rings from plastic bottles; Other lids;
					Lids for chemicals and detergents;
					Fireworks (rocket caps, exploded parts and packaging)
					Fireworks (paper parts); Shotgun cartridges
	Total	3,014	7.2	89.0	
Sanitary	Lakes	2,092	5.2	89.3	Sanitary pads, tampons and applicators; Diapers and wipes;
	Rivers	305	21.8	100.0	Tissues, toilet paper and paper towels; Cotton buds and swabs
	Total	2,397	5.7	90.7	
Packaging (non-food)	Lakes	916	2.3	88.1	Paper packaging, Packaging films (not food-related)
	Rivers	87	6.2	100.0	
	Total	1,003	2.4	89.1	

Table D.5
Proportion [%] of top items with significant correlations with land-use features.

	Items with significant positive correlation [%]	Items with significant negative correlation [%]
Roads	64.1	0.0
Buildings	61.8	0.8
Public infrastructure	58.5	0.0
Vineyards	42.7	0.0
Rivers and canals	38.7	0.0
City centers	37.8	0.0
Recreational areas	33.6	5.2
Forests	14.6	28.6
Marshlands	1.9	46.1
Other land	0.8	65.6
Orchards	0.0	1.9

Table D.6
Number of items with more than one significant and positive correlations with land-use features.

Type	Items with ≥ 1 positive and significant correlations	Total number of items	Proportion [%]
Industry and construction	0	11,142	0.0
Tobacco	9,124	9,124	100.0
Food and beverages	4,492	7,994	56.2
Plastic fragments and pieces	7,291	7,291	100.0
Others	1,353	3,014	44.9
Sanitary	1,903	2,397	79.4
Packaging (non-food)	807	1,003	80.5

References

Aydin, C., Güven, O., Salihoğlu, B., Kıdeyş, A., 2016. The influence of land use on coastal litter: An approach to identify abundance and sources in the coastal area of Cilician basin, Turkey. Turkish J. Fish. Aquatic Sci. 16:29.

Azevedo-Santos, V., Brito, M., Manoel, P., Perroca, J., Rodrigues-Filho, J., Paschoal, L., Gonçalves, G., Wolf, M., Blettler, M., Andrade, M., Nobile, A., Lima, F., Ruocco, A., Silva, C., Perbiche-Neves, G., Portinho, J., Giarrizzo, T., Arcifa, M., Pelicice, F., 2021. Plastic pollution: A focus on freshwater biodiversity. Ambio 1 (12).

Baldwin, A.K., Corsi, S., Mason, S., 2016. Plastic Debris in 29 Great Lakes tributaries: Relations to watershed attributes and hydrology. Environ. Sci. Technol. 50 (19).

Ballatore, A., Verhagen, T.J., Li, Z., Cucurachi, S., 2022. This city is not a bin: Crowdmapping the distribution of urban litter. J. Ind. Ecol. 26 (1), 197–212.

Barer, P., Kull, G., 2018. Swiss Litter Report. Technical Report, WWF Schweiz and Stop Plastic Pollution Switzerland, https://vsa.ch/wp-content/uploads/2020/06/Swiss-Litter-Report_2018.pdf.

Birch, C.P., Oom, S.P., Beecham, J.A., 2007. Rectangular and hexagonal grids used for observation, experiment and simulation in ecology. Ecol. Model. 206 (3), 347–359.

British Marine Conservation Society, 2016. Great British Beach Clean 2015 Report. https://www.mcsuk.org/downloads/gbbc/2016/487-2016. (Accessed 17 August 2022).

Bruge, A., Barreau, C., J., C., Collin, H., Moreno, C., P., M., 2018. Monitoring litter inputs from the Adour River (Southwest France) to the marine environment. J. Mar. Sci. Eng. 6 (24).

Carpenter, E., Wolverton, S., 2017. Plastic litter in streams: The behavioral archaeology of a pervasive environmental problem. Appl. Geogr. 84, 93–101.

Castro-Jiménez, J., González-Fernández, D., Fornier, M., Schmidt, N., Sempéré, R., 2019. Macro-litter in surface waters from the Rhone river: Plastic pollution and loading to the NW Mediterranean Sea. Mar. Pollut. Bull. 146, 60–66.

Cieplik, S., 2021. From land to sea: Model for the documentation of land-sourced plastic litter. In: Plastics in the Aquatic Environment-Part I: Current Status and Challenges. Springer, pp. 273–288.

Cowger, W., Gray, A., Hapich, H., Osei-Enin, J., Olguin, S., Huynh, B., Nogi, H., Singh, S., Brownlee, S., Fong, J., Lok, T., Singer, G., Ajami, H., 2022. Litter origins, accumulation rates, and hierarchical composition on urban roadsides of the Inland Empire, California. Environ. Res. Lett. 17 (1), 015007.

Cowger, W., Gray, A.B., Schultz, R.C., 2019. Anthropogenic litter cleanups in Iowa riparian areas reveal the importance of near-stream and watershed scale land use. Environ. Pollut. 250, 981–989.

Delorme, A.E., Koumba, G.B., Roussel, E., Delor-Jestin, F., Peiry, J.-L., Voldoire, O., Garreau, A., Askanian, H., Verney, V., 2021. The life of a plastic butter tub in riverine environments. Environ. Pollut. 287, 117656.

Doolin, H., Zhang, Q., 2015. Keep It Dirty Durham: A Social Marketing Strategy for Altering Public Littering Behavior Duke University, https://hdl.handle.net/10161/9618.

Federal office of topography Swisstopo, 2023. SwissTLM3D. https://www.swisstopo.admin.ch/en/geodata/landscape/tlm3d.html. (Accessed 15 August 2022).

Glasser, G.J., Winter, R.F., 1961. Critical values of the coefficient of rank correlation for testing the hypothesis of independence. Biometrika 48 (3/4), 444–448.

González-Fernández, D., Cózar, A., Hanke, G., Viejo, J., Morales-Caselles, C., Bakiu, R., Barceló, D., Bessa, F., Bruge, A., Cabrera, M., et al., 2021. Floating macrolitter leaked from Europe into the ocean. Nat. Sustain. 4 (6), 474–483.

Grelaud, M., Ziveri, P., 2021. The generation of marine litter in Mediterranean island beaches as an effect of tourism and its mitigation. Sci. Rep. 10.

Haberstroh, C.J., Arias, M.E., Yin, Z., Sok, T., Wang, M.C., 2021. Plastic transport in a complex confluence of the Mekong River in Cambodia. Environ. Res. Lett. 16 (9), 095009.

Harris, P., Westerveld, L., Nyberg, B., Maes, T., Macmillan-Lawler, M., Appelquist, L., 2021. Exposure of coastal environments to river-sourced plastic pollution. Sci. Total Environ. 769, 145222.

Hengstmann, E., Fischer, E., 2020. Anthropogenic litter in freshwater environments – Study on lake beaches evaluating marine guidelines and aerial imaging. Environ. Res. 189, 109945.

Hoffman, M., Hittinger, E., 2017. Inventory and transport of plastic debris in the Laurentian Great Lakes. Mar. Pollut. Bull. 115 (1–2), 273–281.

Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R., Law, K.L., 2015. Plastic waste inputs from land into the ocean. Science 347 (6223), 768–771.

Kawecki, D., Nowack, B., 2019. Polymer-specific modeling of the environmental emissions of seven commodity plastics as macro-and microplastics. Environ. Sci. Technol. 53 (16), 9664–9676.

Kawecki, D., Nowack, B., 2020. A proxy-based approach to predict spatially resolved emissions of macro- and microplastic to the environment. Sci. Total Environ. 748, 141137.

Kelley, C., Ambikapathi, R., 2016. Litter-Free Baltimore. The Abell Foundation, Baltimore, MD, USA.

Kolenda, K., Wiśniewski, K., Kujawa, K., Kuśmierek, N., Smolis, A., Kadej, M., 2021. Living in discarded containers: Spiders explore a new niche created by littering in urban woodlands. Biodivers. Conserv. 30 (6), 1637–1654.

Lebreton, L.C., Van Der Zwet, J., Damsteeg, J.-W., Slat, B., Andrady, A., Reisser, J., 2017. River plastic emissions to the world's oceans. Nat. Commun. 8 (1), 1–10.

Lechthaler, S., Waldschläger, K., Stauch, G., Schüttrumpf, H., 2020. The way of macroplastic through the environment. Environments 7 (10), 73.

Liro, M., van Emmerik, T., Wyżga, B., Liro, J., Mikuś, P., 2020. Macroplastic storage and remobilization in rivers. Water 12 (7), 2055.

Lobelle, D., Kooi, M., Koelmans, A., Laufkötter, C., Jongedijk, C., Kehl, C., Sebille, E.V., 2021. Global modeled sinking characteristics of biofouled microplastic. J. Geophys. Res.: Oceans 126, 2055.

Lobelle, D., Shen, L., van Huet, B., van Emmerik, T., Kaandorp, M., Iattoni, G., Baldé, C.P., Law, K.L., van Sebille, E., 2023. Knowns and unknowns of plastic waste flows in the Netherlands. Waste Manag. Res..

Lotcheris, R.A., Schreyers, L., Bui, T., Thi, K., Nguyen, H.-Q., Vermeulen, B., van Emmerik, T., 2024. Plastic does not simply flow into the sea: River transport dynamics affected by tides and floating plants. Environ. Pollut. 345, 123524.

MacLeod, M., Arp, H.P.H., Tekman, M.B., Jahnke, A., 2021. The global threat from plastic pollution. Science 373 (6550), 61–65.

Marine Strategy Framework Directive Technical Subgroup on Marine Litter, 2013. Guidance on Monitoring of Marine Litter in European Seas. Joint Research Center, European Commission.

Mason, S., Dialy, J., Aleid, G., Ricotta, R., Smith, M., Donnelly, K., Knauff, R., W., E., Hoffman, M., 2020. High levels of pelagic plastic pollution within the surface waters of Lakes Erie and Ontario. J. Gt. Lakes Res. 46 (2).

Matos, J., Oštir, K., Kranjc, J., 2012. Attractiveness of roads for illegal dumping with regard to regional differences in Slovenia. Acta Geographica Slovenica 52 (2), 431–451.

Meijer, L.J., van Emmerik, T., van der Ent, R., Schmidt, C., Lebreton, L., 2021. More than 1000 rivers account for 80% of global riverine plastic emissions into the ocean. Sci. Adv. 7 (18).

Mellink, Y., van Emmerik, T., Kooi, M., Laufkötter, C., Niemann, H., 2022. The plastic pathfinder: A macroplastic transport and fate model for terrestrial environments. Front. Environ. Sci. 10.

Newbould, R.A., Powell, D.M., Whelan, M.J., 2021. Macroplastic debris transfer in rivers: a travel distance approach. Frontiers in Water 3, 724596.

Pietz, O., Augenstein, M., Georgakakos, C., Singh, K., McDonald, M., Walter, M.T., 2021. Macroplastic accumulation in roadside ditches of New York State's Finger Lakes region (USA) across land uses and the COVID-19 pandemic. J. Environ. Manag. 298, 113524.

Roebroek, C.T., Harrigan, S., van Emmerik, T.H., Baugh, C., Eilander, D., Prudhomme, C., Pappenberger, F., 2021b. Plastic in global rivers: Are floods making it worse? Environ. Res. Lett. 16 (2), 025003.

Roebroek, C.T., Hut, R., Vriend, P., Winter, W.d., Boonstra, M., van Emmerik, T.H.M., 2021a. Disentangling variability in riverbank macrolitter observations. Environ. Sci. Technol. 55 (8), 4932–4942.

Ryan, P., 2021. Does size and buoyancy affect the long-distance transport of floating debris? Environ. Res. Lett. 10 (8), 107186.

Ryan, P.G., Perold, V., Osborne, A., Moloney, C.L., 2018. Consistent patterns of debris on South African beaches indicate that industrial pellets and other mesoplastic items mostly derive from local sources. Environ. Pollut. 238, 1008–1016.

Sakti, A.D., Sembiring, E., Rohayani, P., Fauzan, K.N., Anggraini, T.S., Santoso, C., Patricia, V.A., Ihsan, K.T.N., Ramadan, A.H., Arjasakusuma, S., Candra, D.S., 2023. Identification of illegally dumped plastic waste in a highly polluted river in Indonesia using Sentinel-2 satellite imagery. Sci. Rep. 13 (5039).

Schmidt, C., Krauth, T., Wagner, S., 2017. Export of plastic debris by rivers into the sea. Environ. Sci. Technol. 51 (21), 12246–12253.

Schuyler, Q., Hardesty, B.D., Lawson, T.J., Wilcox, C., 2022. Environmental context and socio-economic status drive plastic pollution in Australian cities. Environ. Res. Lett. 17 (4), 045013.

Schuyler, Q., Wilcox, C., Lawson, T., Ranatunga, R., Hu, C.-S., Partners, G.P.P., Hardesty, B.D., 2021. Human population density is a poor predictor of debris in the environment. Front. Environ. Sci. 9.

Steinmetz, Z., Löffler, P., Eichhöfer, S., David, J., Muñoz, K., Schaumann, G.E., 2022. Are agricultural plastic covers a source of plastic debris in soil? A first screening study. SOIL 8 (1), 31–47.

Stocker, S., 2020. Quantifying Litter Emissions into the Swiss Environment - A Bottom-Up Approach Focusing on Roads. Technical Report, École Polytechnique Fédérale de Lausanne (EPFL), Environmental Science and Engineering Section (SSIE), Solid Waste Treatment (EPFL - PSI).

Tasseron, P., Begemann, F., Joosse, N., van der Ploeg, M., van Driel, J., van Emmerik, T., 2023. Amsterdam urban water system as entry point of river plastic pollution. Environ. Sci. Pollut. Res..

Tasseron, P., Zinsmeister, H., Rambonnet, L., Hiemstra, A.-F., Siepman, D., van Emmerik, T., 2020. Plastic hotspot mapping in urban water systems. Geosciences 10 (9), 342.

Tramoy, R., Colasse, L., Gasperi, J., Tassin, B., 2019. Plastic debris dataset on the seine river banks: Plastic pellets, unidentified plastic fragments and plastic sticks are the Top 3 items in a historical accumulation of plastics. Data Brief 23, 103697.

Tramoy, R., Gasperi, J., Colasse, L., Silvestre, M., Dubois, P., Noûs, C., Tassin, B., 2020. Transfer dynamics of macroplastics in estuaries – New insights from the Seine estuary: Part 2. Short-term dynamics based on GPS-trackers. Mar. Pollut. Bull. 160, 111566.

van Emmerik, T.H.M., Frings, R.M., Schreyers, L.J., Hauk, R., de Lange, S.I., Mellink, Y.A., 2023. River plastic transport and deposition amplified by extreme flood. Nat. Water 1–9.

van Emmerik, T.H.M., Mellink, Y., Hauk, R., Waldschläger, K., Schreyers, L., 2022. Rivers as plastic reservoirs. Front. Water 212.

van Emmerik, T.H.M., Roebroek, C., Winter, W.D., Vriend, P., Boonstra, M., Hougee, M., 2020. Riverbank macrolitter in the Dutch Rhine-Meuse delta. Environ. Res. Lett. 15 (10), 104087.

van Emmerik, T.H.M., Schwarz, A., 2020. Plastic debris in rivers. Wiley Interdiscip. Rev.: Water 7 (1), e1398.

van Emmerik, T.H.M., Strady, E., Kieu-Le, T.-C., Nguyen, L., Gratiot, N., 2019. Seasonality of riverine macroplastic transport. Sci. Rep. 9 (1), 1–9.

Vanapalli, K.R., Sharma, H.B., Anand, S., Ranjan, V.P., Singh, H., Dubey, B.K., Mohanty, B., 2023. Cigarettes butt littering: The story of the world's most littered item from the perspective of pollution, remedial actions, and policy measures. J. Hazard. Mater. 453, 131387.

Vriend, P., Van Calcar, C., Kooi, M., Landman, H., Pikaar, R., van Emmerik, T.H.M., 2020. Rapid assessment of floating macroplastic transport in the Rhine. Front. Mar. Sci. 7, 10.

Wenneker, B., Oosterbaan, L., Intersessional Correspondence Group on Marine Litter (ICGML), 2010. Guideline for Monitoring Marine Litter on the Beaches in the OSPAR Maritime Area. Technical Report, Ospar Commission, http://dx.doi.org/10.25607/OBP-968.

Winston, R.J., Witter, J.D., Tirpak, R.A., Sester, L., Jenkins, H., Lillard, V., 2023. Abundance and composition of anthropogenic macrolitter and natural debris in road runoff in Ohio, USA. Water Res. 239, 120036.

Youngblood, K., Brooks, A., Das, N., Singh, A., Sultana, M., Verma, G., Zakir, T., Chowdhury, G.W., Duncan, E., Khatoon, H., et al., 2022. Rapid characterization of macroplastic input and leakage in the Ganges river basin. Environ. Sci. Technol. 56 (7), 4029–4038.