Urban water systems as entry points for river plastic pollution

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Urban water systems as entry points for river plastic pollution

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Abstract

Accumulation of plastic in aquatic environments negatively impacts ecosystems and human livelihood. Urban areas are assumed to the main source of plastic pollution in these environments, because of high anthropogenic activity. Yet, the drivers of plastic emissions, abundance and retention within these systems and subsequent transport to river systems is poorly understood. In this study, we demonstrate that urban water systems function as major contributors to river plastic pollution, and explore the potential driving factors contributing to the transport dynamics. Monthly visual counting of floating litter at six outlets of the Amsterdam water system results in an estimated 2.7 million items to enter the closely connected IJ river annually, ranking it among the most polluting systems measured in the Netherlands and Europe. Subsequent analyses of environmental drivers (including rainfall, sunlight, wind speed and tidal regimes) and litter flux showed no strong correlations ($\boldsymbol{r}$ = -0.19 - 0.16), implying additional investigation of potential drivers is required. High frequency observations at various locations within the urban water system and advanced monitoring using novel technologies could be explored to harmonize and automate monitoring. Once litter type and abundance are well-defined with a clear origin, communication of the results with local communities and stakeholders could help co-develop solutions and stimulate behavioural change geared to reduce plastic pollution in urban environments.

Keywords: Macrolitter, Plastic Soup, Hydrology, Floating Litter, Macroplastic

1 Introduction

Plastic pollution in aquatic environments is of increasing concern, because of its negative impacts on freshwater ecosystems, marine fauna, and local economies. Accumulation of plastic in urban and riverine water systems could lead to direct damage to essential infrastructure, limit water supply, and cause increased flood risks [4, 20, 44]. It is estimated that 19-23 million metric tonnes of macroplastic enter aquatic ecosystems annually [8, 27]. Urban water systems are assumed to be one of the largest sources of this macroplastic pollution [40, 45], yet the relation to river plastic pollution, and the connection between urban and natural water systems are poorly understood. High anthropogenic activity including recreation, open air markets, and tourism [11, 26] are assumed to be the main causes for macrolitter leakage in urban water systems. Subsequent transport to riverine and marine environments is facilitated by (extreme) rainfall events and stormwater overflow [1], hydrologic conditions [42], and other environmental factors [33]. However, a lack of observational data prevents further exploration of the abundance, transport and retention dynamics in urban water systems.

Recent studies of plastic pollution in urban water systems aim to quantify its abundance and identify accumulation zones or hotspots. For instance, Tramoy et al. [39] used GPS trackers in the Seine River, identifying several hotspots of plastic accumulation and observing increased floating plastic item discharges. Tramoy et al. [40] explore the use of screened materials collected by grey infrastructures in a small urban river to characterise the macroplastic composition and mass flow. Naidoo et al. [29] showed urban harbours to have high input and retention of macroplastics, as well as an attenuating plastic abundance further away from urban city centers. Another study by Treilles et al. [41] examined micro- and macrolitter concentrations of suburban stormwater runoff, aiming to estimate plastic mass fluxes per hectare of urban impervious surfaces and per capita. Even though accurate estimates of urban macroplastic abundance and its spatial distribution are made, the drivers of transport and the relation to river plastic pollution are poorly understood. Improving this understanding is critical, since many rivers are directly connected to urban water systems, which are often seen as main input locations for plastic litter (e.g. Rotterdam (Rhine) [42] , Ho Chi Minh City (Saigon) [23], Paris (Seine) [40, 41], Barcelona (LLobregat & Besòs) [34], Jakarta (Ciliwung) [30], Kuala Lumpur (Klang) [49]) [24, 27].

This paper studies the emissions of floating litter from urban water systems and its relation to riverine plastic pollution for the water system of Amsterdam. This system is characterised by a dense network of urban canals directly connected to the IJ river, from which 42 metric tonnes of floating plastic is removed annually [48]. The IJ river is in turn flowing into the North sea, which makes the urban water system of Amsterdam relevant to study urban-natural water system connections. By conducting monthly visual counting measurements from bridges close to outlets into the IJ river, we estimated the litter outflow for Amsterdam. Subsequent comparisons with litter abundance in larger river systems were made to show urban water systems as entry points for river plastic pollution. Furthermore, correlations between potential environmental drivers of litter transport and observed litter fluxes were determined to understand their influence on emissions to the IJ river. The goal of this study is to assess and quantify the role of urban water systems as a source of river plastic pollution.

2 Methods

2.1 Study Area

In this study, floating litter items were counted from bridges in Amsterdam, the Netherlands (52° 22´ 52” N 4° 53´ 50” E). Home to 820,000 inhabitants, it is the largest city in the Netherlands, welcoming approximately eighteen million tourists every year [13]. The urban water system in Amsterdam is characterised by extensive canals exceeding 100 km in length, consisting of multiple rings surrounding the historic and touristic city centre [32]. Northwest of the city center, the IJ river splits the urban area of Amsterdam and flows through the Noordzeekanaal to the North Sea.

The bridges used as observation locations were selected at the outlets of the six main canals in the inner city area of Amsterdam (Fig. 1). From downstream to upstream in relation to the flow direction of the IJ river, these are: Westerkanaal (L1), Westerdok (L2), Westertoegang (L3), Geldersekade (L4), Oudezijdskolkbrug (L5), and Piet Heinkade (L6). Each bridge is divided into 1 to 3 segments, depending on the length of the bridge. Consequently, each segment covers a part of the canal within the field of view of the observer, enabling the identification of all floating items within a given segment.

Some bridges contain unique properties that might influence the accuracy of the results. Downstream of the Westerdok (L2), a bubble barrier (https://thegreatbubblebarrier.com/) infrastructure is installed, aiming to prevent (plastic) litter being discharged into the IJ river. It generates a screen of bubbles, directing suspended and floating litter to a catchment system. In addition, both Geldersekade (L4) and Oudezijdskolkbrug (L5) are both not situated directly at the outlet of the canal into the IJ river. Yet, since the bridge at Oostertoegang (Fig. 1) was under construction at the time of measurements, the combination of these two bridges approach the closest estimate for litter emitted into the IJ river.

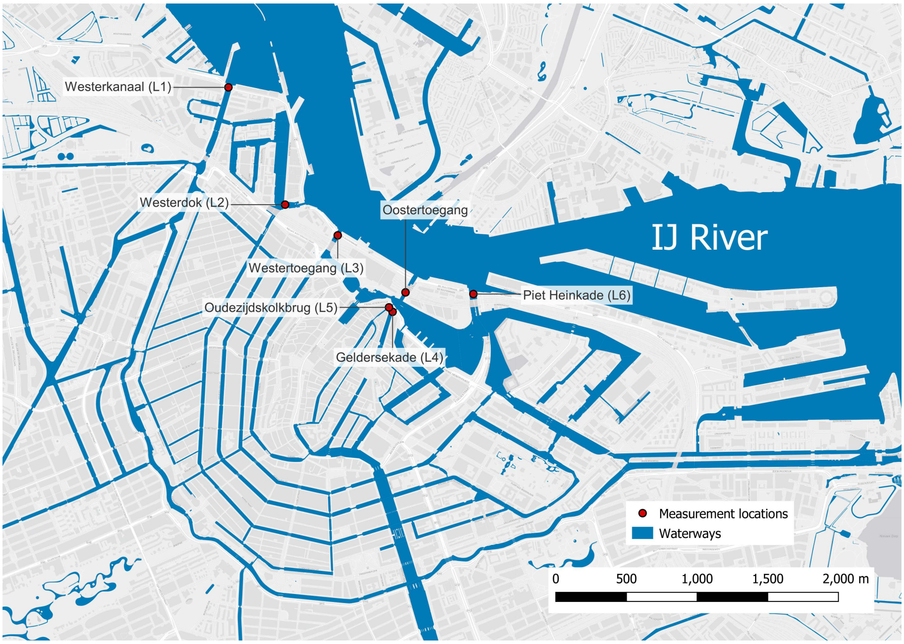

Fig. 1 IJ River, innercity waterways and measurement locations (bridges)

2.2 Data collection and processing

Data collection was pursued through the visual counting method developed by González-Fernández and Hanke [17]. This method allows for accurate and reliable quantitative data collection of floating litter fluxes. The observer counts litter items in seven categories for a predetermined time interval and observation width on top of a bridge [46]. Based on different polymer configurations, these categories are: PET (polyethylene terephthalate), PS (polystyrene), EPS (expanded polystyrene), PO Hard (polyolefins), PO Soft (polyolefins), Multilayer (multilayer plastics), and one category containing all other anthropogenic litter items (Other). Several examples of each category are summarised in Fig. 2, adopted from Tasseron et al. [37].

Fig. 2 Categories used for visual counting in this research, with examples of characteristic items for these classes. The 'Other' category cointains all anthropogenic litter outside of the six polymer-based classes. Adopted from Tasseron et al. [37].

Measurements were done bi-weekly from February 2021 until February 2022, spread over all days of the week (except Saturdays) between 7:00 AM and 7:00 PM. All observed items were logged with timestamps, location (latitude and longitude) and measurement interval duration. In total, 28 measurement days took place, with a total observed time of 37 hours and 5 minutes. Depending on the flow velocity of the water and the level of pollution in the water system, measurements were done with a time span ranging from 5 to 20 minutes per segment. Stationary floating items close to the bridge were not counted as discharged items and noted in the comments of the data sheet.

The floating litter flux F_{outlet} for each outlet was calculated using the following formula, adapted from van Emmerik et al. [42]:

$$F_{outlet} = \sum_{i=1}^{S} \frac{\bar{f}_i}{w_i} \frac{1}{S} * W * T \tag{1}$$

in which $\bar{f}$ is the mean litter flux [items h^{-1}] for bridge segment i, with total segments S, segment observation width w_i [m], total waterway width W [m], and extrapolation period T (e.g. day, month, year). To compute the total emission fluxes in the IJ river, the F_{outlet} values of all six outlets were summed and extrapolated to a time period of one year. In addition, an estimate of the floating litter mass transport M_{outlet} was made using the F_{outlet} flux, and the mean/median mass statistics of a detailed dataset containing over 16,000 weighed macrolitter items collected from Dutch riverbanks [43]. The following equation was used to calculate the litter mass transport per outlet:

$$M_{outlet} = \sum_{c=1}^{7} F_c * \bar{m_c} \tag{2}$$

in which $\bar{m_c}$ is the mean/median mass of litter category c [kg] (Figure 2), and $\bar{F_c}$ the mean litter flux of the associated category [items h^{-1}].

To analyse local drivers impacting litter abundance, retention and transport, litter fluxes were correlated to meteorological data. The meteorological variables were obtained from the Royal Netherlands Meteorological Institute (KNMI) data platform (https://dataplatform.knmi.nl/). Variables obtained from this data platform are: daily sun hours, accumulated daily rainfall, rainfall duration (hours), average wind speed, maximum wind speed, and wind direction. These are derived using the Schiphol Airport weather station, located approximately 10 km outside the Amsterdam city center. Information about tidal regimes (at IJmuiden, 20 kilometers downstream of Amsterdam) were obtained from Rijkswaterstaat (Dutch Directorate-General for Public Works and Water Management, https://getij.rws.nl/). The MATLAB software was used to derive Pearson correlations between meteorological variables, tidal regimes and observed floating litter fluxes. All data and scripts are included as supplementary material, as summarised in the data availability statement.

3 Results and Discussion

3.1 Outlet emissions

A total of 1,006 items were counted at six outlets over a period of 13 months. Of these items, 735 (73%) were categorised as plastic according to the six different polymer categories. This percentage is comparable to Tramoy et al. [40], in which 83% of anthropogenic items in urban water systems were characterised as plastics. Aditionally, Luo et al. [25] found plastic made up 70.3% of the total items found in littered mangroves close to Hongkong, which is also comparable to the 73% in our study. The largest amount of items observed were plastics in the '$\mathrm{PO_{Soft}}$' category (35%), followed by 'Other' (27%) and 'Multilayer' (23%). These high observations can be related to consumer products, such as shopping and grocery bags ($\mathrm{PO_{Soft}}$), Cigarette butts (Other) and single use food wrappers and packaging (Multilayer). The emissions of the other plastic categories 'EPS' (6%), '$\mathrm{PO_{Hard}}$', (5%), 'PS' (2%), and 'PET' (2%) are significantly smaller. van Emmerik et al. [42] observed comparable shares of floating $\mathrm{PO_{Soft}}$ (39.5%), Multilayer (17.1%), EPS (7.7%), and PET (1.1%) in Dutch rivers, implying that these categories are possibly linked to emissions from urban water systems.

The item fluxes of the individual outlets are shown in Fig. 3. The total flux of all outlets combined was 302 items/hr (221 plastic items/hr), approximately 2.7 million items/year (1.9 million plastic items/year). These flux values rank the Amsterdam canal system among the highest in comparison with 42 rivers in eleven European countries, of which the Danube river is most polluting (3.0 million items/year) [18]. Interestingly, the estimated yearly flux of the Amsterdam system into the IJ river is similar to estimates of the Dutch Rhine (2.7-3.5 million items/year), IJssel (2.4-2.6 million items/year) and Meuse (2.3-3.8 million items/year) rivers [42], implying that urban water systems are major contributors to river plastic pollution. Converted to mass estimates based on mean category mass, approximately 39.5 metric tons of litter (19.5 metric tons of plastic) flows in the IJ river annually. The mass estimates based on median category mass are 2.7 metric tons of litter (2.6 metric tons of plastic). These mean and median estimates are well within the range of estimates for Dutch rivers by van Emmerik et al. [42], further corroborating the major role of urban water systems in river plastic pollution.

3.2 Spatiotemporal variation

Variations in litter type and abundance were observed between the different measurement locations (Fig. 4a), at hours of the day (Fig. 4b), and monthly variation (Fig. 4c). Highest litter emissions were observed at the Westertoegang bridge (L3, 77 items/hr), at 13:00 (48.4 items/hr) and in May 2021 (588 items/hr). Possible causes for the variations in litter type and abundance include a range of explanations. Amongst others, these are (1) presence of people and the intensity of human activity [26], (2) new policy measures to reduce litter

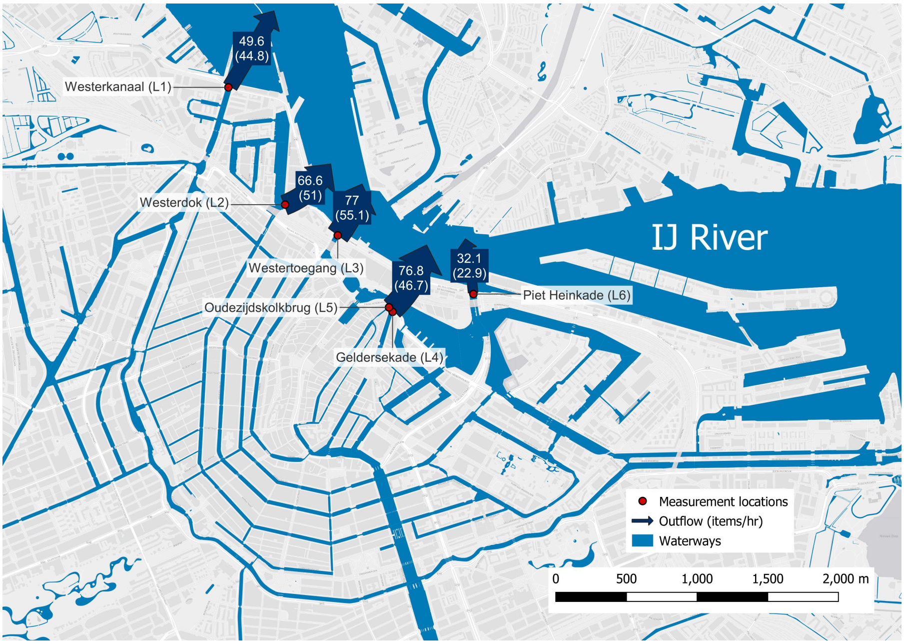

Fig. 3 Litter fluxes for each outlet, expressed in items per hour. Geldersekade (L4) and Oudezijdskolkbrug (L5) are combined. Numbers in parentheses indicate plastic fluxes.

emissions [28] , (3) presence of traditional open air markets [11], (4) COVID-19 regulations and impacts [12], and (5) environmental drivers [33], which is discussed in the next subsection.

Several variations in litter abundance depicted in Fig. 4 could be linked to these explanations. For instance, the number of people present and the intensity of human activities might cause immediate higher litter emissions to the channels [2]. People can use areas in vicinity of the canals as recreational areas [21], or dispose of waste illegally [16, 22]. Bridges discharging canals from the touristic city center discharge relatively more (66.6, 7, and 76.8 items/hr) compared to bridges discharging areas with less human activity (49.6 and 32.1 items/hr) (Fig. 3). Another factor that seemed to influence litter abundance is the behaviour of street workers and maintenance personnel. For multiple measurements at various locations, it was observed that street workers used leaf blowers to purposely mobilise litter items from the sidewalks and streets into the canals. As depicted in Fig. 4b, low litter fluxes were observed early in the mornings (7:00-10:00), whereas this increased to peak around lunchtime (13:00). An increase in ’PO_{Soft}’ and ’Other’ items throughout the day could be attributed to increased disposal of single use consumer products. No measurements were done between 18:00-07:00, so fluxes during the night remain unknown. An example of new measures to reduce litter emissions is the introduction of a € 0.15 deposit on small PET bottles in the Netherlands in July 2021 [19]. Yet, this does not result in a clear decrease of PET litter fluxes after

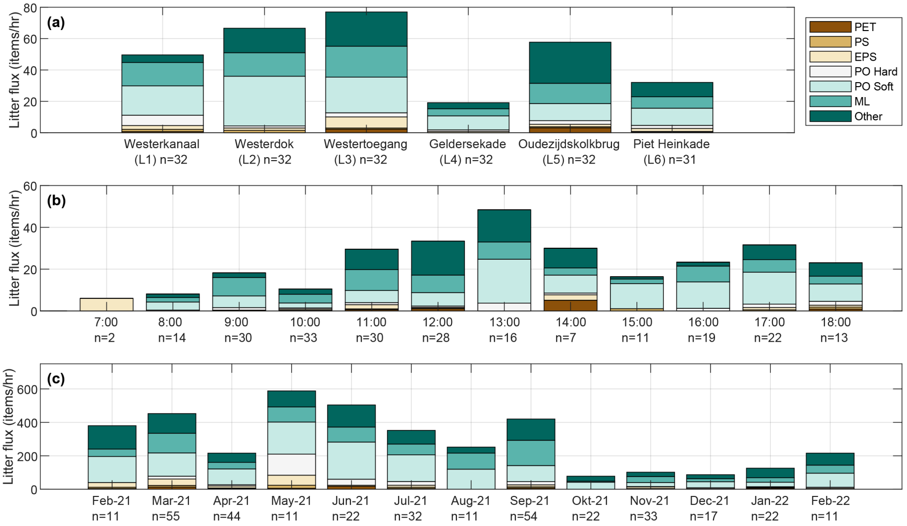

Fig. 4 Overview of categorised litter fluxes, with: (a) mean item fluxes per measurement location, (b) mean item fluxes per time of day, (c) mean item fluxes per month. For each flux, the number of individual measurements (n) is given.

this introduction (Fig. 4c). Even though these explanations could potentially lead to variation in litter abundance, additional monitoring close to actual sources, rather than at the outlets in the IJ river is necessary.

3.3 Environmental factors

Pearson correlations between environmental drivers and the observed litter fluxes are low, ranging from -0.19 to 0.16 (Fig. 5). During the measurements, wind gusts were observed to influence mobilisation and transport of floating litter at outlets, yet the correlation between highest daily wind gusts (Windspeed max (m/s)) and outflow of all item categories combined is low (0.13). Even though correlations between wind speed, rainfall and observed item fluxes are low, the sign of the correlation is positive for most categories and comparable to the explanatory power and sign of environmental drivers found by Roebroek et al. [33], who used multi-linear regression models to link various environmental factors with riverbank litter observations.

The other environmental factors (sunlight and tide) showed no strong or significant correlations with observed item fluxes, with two exceptions (Tide-PS, and Sunlight-Other). It is possible that a non-trivial combination of factors determine the spatiotemporal variability of observed fluxes. In combination with the low correlation values of windspeed and rainfall, it is evident that transport of floating litter in urban water systems is complex.The latter is corroborated by Roebroek et al. [34], stating that multi-linear regression models only using environmental factors to explain plastic litter fluxes in rivers are

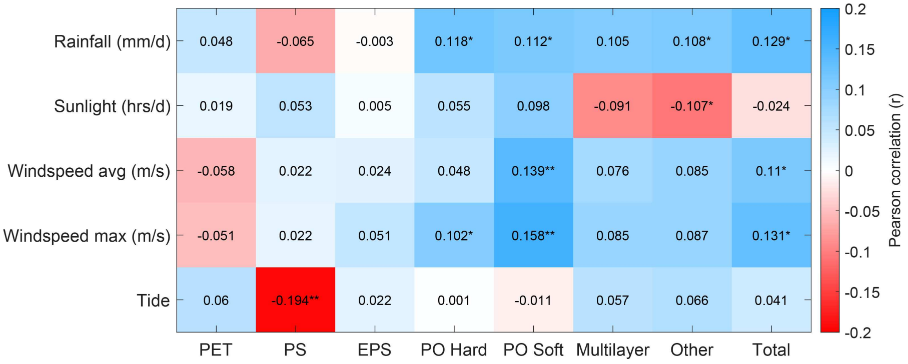

Fig. 5 Pearson correlations between the litter categories used for visual counting and environmental factors. Stars indicate the level of significance: p $\leq 0.05(*), p \leq 0.01(**)$.

unlikely to perform well. Anthropogenic activity, littering and transport mechanisms should be included in such models, especially in urban areas where litter generation is concentrated [40, 41].

4 Synthesis and outlook

4.1 Complexity and drivers of litter transport

Anthropogenic litter pollution in urban water systems and subsequent transport to river systems is complex and dynamic. In this study, monthly visual counting measurements at six outlets of the Amsterdam urban water system resulted in an estimate of approximately 2.7 million items/year to enter the IJ river. Even though this estimate is based on reliable observations, the current impacts of potential drivers on transport and retention of litter is poorly understood. While environmental factors, such as (high intensity) rainfall events in urban areas could be drivers of litter transport to rivers [42], it is argued that these factors on its own cannot fully explain observed litter fluxes [34]. The low correlation values between precipitation, sunlight, wind speed, tidal regimes and observed item fluxes in our study confirm the latter. Therefore, understanding other drivers such as direct littering and stormwater overflow [41], and intensity of anthropogenic activities [11, 26] is key for future efforts. These efforts could focus on high-frequency monitoring at locations with a variety of indicators for anthropogenic activity: e.g. open air markets, restaurants, city parks, public transport nodes, and other potential sources of emission.

4.2 Local factors and mitigating measures

In addition, local factors and indirect drivers can influence litter abundance, retention, and transport. For instance, regulatory instruments to mitigate or prevent direct littering could promote sudden changes in anthropogenic behaviour [5]. Other local factors include systems to collect litter, such as

The Great Bubble Barrier structure in Amsterdam, or larger initiatives focusing on reducing outflow to marine ecosystems (e.g. Plastic Smart Cities https://plasticsmartcities.org/). Another factor includes targeted cleanups, such as the 'Plastic Whale' initiative (https://plasticwhale.com/). This initiative collects floating litter from canals in Amsterdam, which is subsequently recycled to make furniture and fishing boats. While these instruments contribute to reducing litter abundance, they also influence estimations of litter transport from urban water systems to rivers and oceans. The latter is increasingly important for policymakers [42], which emphasises the need of including local factors in future estimations of litter transport. These efforts should also relate the abundance of (floating) litter with the presence of waste bins, open air markets, restaurants and other potential sources of emission. To these ends, it would be beneficial to expand the polymer-based categorisation with waste sectors (i.e. 'food', 'industry','housekeeping', etc.). In summary, it is relevant to include both contributing factors (emissions) and mitigating factors (local cleanups and regulatory measures) of litter transport and couple these to waste sectors.

4.3 Future research directions for advanced monitoring

Future research should explore additional monitoring techniques to quantify litter outflow. Since the relation between floating plastics and total plastics in the water column is unclear [42], the estimation of total outflow quantities based on just floating plastics could be inaccurate. Current technologies are either labour intensive and require heavy equipment [7, 31] or are based on rudimentary techniques, such as acoustic sonar [9, 15]. The Great Bubble Barrier could form the interface between these techniques, as it mobilises litter suspended in the water column to the surface, where it is captured. Additional monitoring techniques involve camera systems on bridges or drones, either RGB [47], multispectral [6, 14] or hyperspectral systems [3, 10, 38]. Using these systems in Amsterdam could greatly improve the temporal resolution of data sets and reduce the labour intensive visual counting from bridges. In addition, strategic application of these systems contributes to the understanding of direct and indirect drivers, including tidal regimes and dynamic environmental conditions.

4.4 Practical applications integration in communities

Finally, it is important to consider the practical applications of detailed monitoring techniques. At some point, well-defined types of litter with a clear origin, their abundance and transport mechanisms are determined. Communicating these results with local communities and municipalities could help to raise awareness and stimulate creative solutions to mitigate litter abundance and prevent emissions to urban water systems [35]. Various stakeholders in polluted areas such as restaurants, waste managers and/or citizen/community-based initiatives could be involved in experiments to reduce litter emissions.

Subsequent integration of the monitoring results, creative ideas and experiments in urban living labs would provide an innovative inclusive environment for solutions to be smoothly and swiftly implemented [36].

5 Conclusion

Urban water systems are estimated to the main source of plastic pollution in rivers, seas and oceans. The goal of this paper is to provide fundamental evidence for the latter, linking emission quantities and item categories to river plastic pollution. In this study, novel insights in assessing and quantifying the role of urban water systems as a source of river plastic pollution were delivered. Based on visual counting floating of litter from bridges, it is estimated that 2.7 million items enter the IJ river annually. This emission ranks the Amsterdam water system among Europe's most polluted rivers observed to date.

Variations in litter type and abundance at various spatiotemporal scales include a range of possible explanations. Environmental drivers including wind, precipitation, sunlight and tidal regimes lack strong correlations with observed item fluxes (r = -0.19 - 0.16). These results call for other factors such as the intensity of human activity, the influence of point sources (street markets, restaurants) to be included in future correlation analyses.

Aditionally, the largest amount of items were plastics in the '$\mathrm{PO}_{\mathrm{Soft}}$' category (35%), can be related to consumer products such as shopping and grocery bags. Yet, the categorisation of litter items in future efforts should include more detailed item categories, and include their waste sectors (i.e. 'food', 'industry', etc.). Communicating and integrating these results with local stakeholders in polluted areas could eventually provide an innovative environment for solutions to be efficiently implemented.

With this paper we present a first one-year assessment of floating plastic emissions from the Amsterdam water system into the IJ river. We aimed to shed new light on plastic transport dynamics within urban water systems, and its contribution to river plastic pollution. Future research is needed to further disentangle the driving factors of the observed spatiotemporal variability.

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Data Availability Statement. Data sheets and associated MATLAB files are available online at
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Declarations

Ethical approval. Not applicable.

Consent to participate. Not applicable.

Consent for publication. Not applicable.

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

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