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Key Points:

- Plastic pollution is a global environmental challenge, but poorly understood and quantified due to a lack of reliable observations
- River plastic transport increases significantly during discharge during peak events
- Hydrology plays a crucial role in the transport and retention dynamics, and the spatiotemporal variation of floating plastic transport

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Hydrology as a Driver of Floating River Plastic Transport

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Abstract Plastic pollution in aquatic ecosystems is a growing threat to ecosystem health and human livelihood. Recent studies show that the majority of environmental plastics accumulate within river systems for years, decades and potentially even longer. Long-term and system-scale observations are key to improve the understanding of transport and retention dynamics, to identify sources and sinks, and to assess potential risks. The goal of this study was to quantify and explain the variation in floating plastic transport in the Rhine-Meuse delta, using a novel 1-year observational data set. We found a strong positive correlations between floating plastic transport and discharge. During peak discharge events, plastic transport was found up to six times higher than under normal conditions. Plastic transport varied up to a factor four along the Rhine and Meuse rivers, which is hypothesized to be related to the complex river network, locations of urban areas, and tidal dynamics. Altogether, our findings demonstrate the important role of hydrology as driving force of plastic transport dynamics. Our study emphasizes the need for exploring other factors that may explain the spatiotemporal variation in floating plastic transport. The world's most polluted rivers are connected to the ocean through complex deltas. Providing reliable observations and data-driven insights in the transport and dynamics are key to optimize plastic pollution prevention and reduction strategies. With our paper we aim to contribute to both advancing the fundamental understanding of plastic transport dynamics, and the establishment of long-term and harmonized data collection at the river basin scale.

Plain Language Summary Plastic pollution in rivers and oceans harms ecosystems and human livelihoods. Especially large plastic items (>0.5 cm) can be mistaken for food by animals, damage ships, and block waterways. Knowing how much plastic is floating through rivers is important for policy-makers to reduce plastic pollution in the environment. In our study, we measured floating plastic pollution in the Rhine and the Meuse, two large European rivers that flow into the ocean in the Netherlands. From January to December 2021, a team of students and volunteers counted plastic items floating in the rivers from bridges. We found that more plastic was counted when the river flow was higher. The highest amount of plastic was measured during two flood events, when parts of the land next to the rivers were flooded. We think that more plastic leaks into the river when streets, riverbanks, and floodplains are under water. We hope that our study can help to better predict how much plastic flows through other big rivers around the world. Only when we know how big the plastic problem is, we can successfully solve it.

1. Introduction

Plastic debris and other anthropogenic litter has negative impacts on ecosystem health and human livelihood (van Emmerik & Schwarz, 2020). Despite several global initiatives to tackle this emerging environmental challenge, plastic production and leakage into the environment is expected to further grow in the coming decades (Borrelle et al., 2020). Rivers have been assumed to be the main conveyors of land-based plastic waste into the ocean (Meijer et al., 2021; Schmidt et al., 2017). However, recent work has suggested that plastic pollution can be retained within river systems for years to decades, and potentially even longer (van Emmerik et al., 2022). Plastics accumulate on riverbanks, in vegetation, around hydraulic structures, and within estuaries, where they are exposed to environmental weathering leading to degradation and fragmentation (Delorme et al., 2021). The secondary micro- and nanoplastics that arise from this may lead to additional environmental risks, and may eventually be exported into the ocean (Koelmans et al., 2022). Understanding transport and retention dynamics

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is therefore crucial for optimizing monitoring strategies, risk assessments, and interventions to reduce plastic pollution.

Reliable observational data are imperative for improving fundamental understanding of plastic transport processes in rivers. However, plastic and anthropogenic litter monitoring efforts have been limited to date, as the scientific field is still emerging. Several measurement techniques have been developed in recent years, including visual counting from bridges, the use of drones, and net sampling (van Emmerik & Schwarz, 2020). Yet, direct comparison of available data remains complicated due to the lack of harmonized measurement methods and protocols (González-Fernández & Hanke, 2017; Wendt-Potthoff et al., 2020). As a consequence, thorough comparative analyses of driving processes of river plastic transport are limited to date. Several case studies have revealed that plastic transport can vary both seasonally, and spatially along the course of a river (Castro-Jiménez et al., 2019). For individual rivers, the observed variation was explained by, for example, the response to river flow, the abundance of plastic accumulating floating vegetation, or wind and rainfall (C. T. Roebroek, Hut, et al., 2021; Schirinzi et al., 2020; Schreyers et al., 2021). Due to the limited spatial and temporal extent of these studies, the challenge of arriving at a general understanding of the role of hydrology, wind dynamics, human factors, and other factors on variability in floating plastic transport remains largely unresolved. Many of the world's assumed most polluted rivers flow into the ocean through complex delta systems (Best, 2019). For such rivers, the transport and retention dynamics are further complicated by the tidal dynamics and river network architecture (Duncan et al., 2020; Haberstroh et al., 2021).

Our paper focuses on the Rhine-Meuse delta, which is one of the major European river networks (van Emmerik et al., 2020). Here, we present the results of an extensive year-long monitoring effort of floating plastic in the Dutch Rhine, IJssel, and Meuse rivers. The main goal of this paper is to explore the role of hydrology on the spatial and temporal variation of floating plastic transport. Field data on floating plastic were collected at a total of 26 locations along the studied rivers from January to December 2021. Seven locations were measured each month, and two additional measurements were done during peak discharge events. The data at these locations were used to assess the seasonal dynamics, quantify the difference between upstream and downstream, and explore correlations with measured river discharge. The 19 remaining locations were measured three times between June and December 2021, and were used to investigate the spatial variation of floating plastic along the rivers. We combine observations of floating plastic with an openly available data set on mass statistics of over 16,000 items sampled on riverbanks in the same period (van Emmerik & de Lange, 2022) to estimate the mass transport at the seven key locations. Our paper presents three key findings. First, we demonstrate the strong response of floating plastic transport to peak discharge events (Sections 3.1 and 3.2). Second, we show that floating plastic transport is higher around urban areas, and in the most downstream sections of all three rivers (Section 3.3). Finally, our results emphasize that estimates of floating plastic mass transport and export into the ocean are still highly uncertain due to limited data, and insufficient understanding of the driving processes (Sections 3.4, 3.5, and 3.6).

With this paper reveal the non-trivial variation of floating plastic in time and space in the Rhine-Meuse delta using novel field monitoring data. Both have societal and scientific implications, for example, for designing long-term monitoring programs, or planning prevention and reduction strategies (Wendt-Potthoff et al., 2020). Most importantly, we identified several urgent knowledge gaps related to the role of hydrology, tidal dynamics, and factors determining spatial variations. Future work should address these open challenges to advance the fundamental understanding of plastic transport dynamics. The results from this paper are of direct relevance for other river deltas around the world, as they emphasize the urgent need for investing in data collection to unraveling the complicated transport and retention dynamics in such rivers. Finally, our paper shows that river plastic pollution is a transboundary challenge, which calls for further harmonization of methods for data collection and planning of interventions.

2. Methods

2.1. Study Area

We measured floating plastic and other anthropogenic litter at 26 measurement locations distributed across the Dutch reaches of the Rhine (IJssel, Waal, Nederrijn) and Meuse rivers (see Figure 1) between 28 January and 7 December 2021. The Rhine enters the Netherlands from Germany at Spijk, and splits into the main Waal, IJssel and Nederrijn. The Waal is the main branch, and joins the Nederrijn-Lek branch at Rotterdam before flowing into

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Figure 1. Measurement locations along the Rhine, IJssel, and Meuse rivers. The large symbols represent the locations where measurements were done monthly and during the peak discharge events. The small symbols represent the locations where three measurements were done between June and December 2021. The thickness of the rivers represent the share of annual discharge in the Rhine-Meuse delta based on data from the Netherlands Directorate-General for Public Works and Water Management (Ministerie van Infrastructuur en Waterstaat, 2019; Reeze et al., 2017).

the North Sea. The IJssel flows into Lake IJssel at Kampen. The Meuse enters the Netherlands from Belgium at Eijsden, and discharging into the tidal Hollands Diep estuary. Here, the Meuse is joined by a Rhine distributary before reaching the North Sea.

2.2. Floating Plastic Measurements

Floating macroplastic and macrolitter (>0.5 cm) were measured using the visual counting method developed by González-Fernández and Hanke (2017) and van Emmerik et al. (2018), for which all items floating at the surface are counted from bridges. This quantitative method was developed as part of the RIverine and Marine floating macro litter Monitoring and Modeling of Environmental Loading (RIMMEL) project to quantify plastic litter flow from rivers into the ocean across Europe (González-Fernández et al., 2021). For large-scale and long-term monitoring, visual counting is often preferred as it is cost-efficient and no other equipment or infrastructure is required (such as nets, boats, cranes on bridges) (Aisyah et al., 2022; Schöneich-Argent et al., 2020). Only bridges that are safe and legally accessible, for example, presence of pedestrian or bicycle paths, were selected. At each location, three to 12 observation points were selected, depending on the river width. The majority of the locations had five or six points (23 out of 26), two locations had three points, and only the downstream Meuse location had 12 points. For a measurement, all visible floating items were counted within a predefined observation track. The minimum observable item size depends on the bridge height (8–20 m), but was estimated to be at least 2.5 cm for all locations. Note that the width of the observation tracks depends on the field of view and the height above the water, and there varied between bridges and between points on the same bridge (12–34 m). The observation track width was quantified by selecting a reference object (e.g., bridge column, buoy, orange peels) and measuring the distance to the observation point. The sum of the observation track widths per bridge covered between 25% and 85% of the total river width. On each measurement day each point was measured four times for a five-minute period. The total floating plastic flux F [items h^{-1}] was calculated using:

$$F = \sum_{i=1}^{S} \frac{\overline{f_i}}{w_i} \frac{1}{S} \cdot W \cdot T \tag{1}$$

With mean or median plastic flux observation $\overline{f}$ [items h^{-1}] for observation point i, total number of observation points S, observation track width w_i [m], total river width W [m], and extrapolation period T (e.g., hour, day, year). Since observations were done across the river width, the cross-sectional distribution may also be explored in future studies. This aspect is however outside the scope of this work.

Plastic flux can be both positive (toward downstream) and negative (toward upstream) in areas influenced by tidal dynamics. We aimed to only measure plastic flux during low tide, with discharge and plastic flux in downstream direction. Only at Rotterdam (Rhine) and Moerdijk (Meuse) negative plastic fluxes were occasionally observed. In this study we only focus on transport in downstream direction, and therefore use the absolute values of the measured plastic fluxes for the downstream locations to calculate the mean and median. More in-depth analysis of the effect of the tide is outside the scope of this work.

We measured floating plastic to quantify seasonality and the spatial variation along the river. All 26 locations (for details, see Appendix A) were measured three times (Table A1). For the measurement locations, we selected (a) the most upstream and downstream bridge for all rivers, and (b) each safely accessible bridge for the main Rhine and Meuse branches. The locations along the Rhine were measured in July, October and December, and the locations along the Meuse in June, September, and December. The seasonality was assessed using monthly measurements at the seven core locations from January to December 2021; the Rhine at Nijmegen and Rotterdam, the IJssel at Arnhem and Kampen, and the Meuse at Maastricht (starting late February), Ravenstein, and Moerdijk. Each month, all locations were measured within a 3-day period. Additional measurements were done during the peak discharge in early February for all core locations except for Maastricht. A second set of additional measurements were done for the Meuse locations in July during the floods. At Maastricht, measurements were done on 3 days, and at Ravenstein and Moerdijk on 1 day. At Ravenstein and Moerdijk, three to four observations were done for each point. For Maastricht each observation point was measured once per day, and therefore we used all observations during the 3 days to calculate the mean and median values for transport during the flood peak. All measurements were done by trained students and staff from Wageningen University, Open University, University of Applied Science Zuyd and Rijkswaterstaat.

The floating plastic data sets were tested for normality using the Anderson–Darling test. To test whether the mean and median plastic flux was significantly different between locations we used the Kruskal–Wallis (mean) and Wilcoxon rank sum (median) tests for non-normally distributed populations. We also used these tests to investigate whether the spring/summer (March–September) observations were higher or lower than the fall/winter (October–February) observations.

2.3. Plastic and Other Litter Composition

We adapted the visual counting method to determine the composition of the floating plastic. Plastic items were classified into 16 categories, based on material and use (see full list in Appendix B). As most litter items found in aquatic environments are plastic (González-Fernández et al., 2021; Morales-Caselles et al., 2021), we included seven more detailed plastic categories. The classification is a combination of the plastic categories, and the material and usage categories from the River-OSPAR protocol (van Emmerik et al., 2020). For the 110 most common plastic items in the Dutch rivers, we assigned one of the 16 categories used for the visual counting. The specific item list including categories can be found Appendix B (Table B1). When the floating plastic flux is relatively low (approximately 50 items per 5 min, per segment), the categorization can be done by a single surveyor. For increased plastic flux it is recommended to work in pairs (observer and scribe). In some cases the plastic flux becomes too high to categorize the individual items (van Lieshout et al., 2020). The latter was the case during the additional July measurements in Maastricht. In some cases the plastic flux becomes too high to categorize the individual items. The latter was the case during the additional July flood measurements in Maastricht. Here, only plastic items were counted and no further categorization was done. Also note that the categorization was added to the protocol after January. For all measurements, the categorization was done by a single surveyor.

2.4. Mass Transport Estimates

We estimated the floating plastic mass transport M at each location by combining the observed floating plastic flux F, and the average mass per item $\overline{m}$ (Vriend et al., 2020). We estimated the mass transport using the following two equations:

$$M = F \cdot \overline{m} \tag{2}$$

$$M = \sum_{j=1}^{16} F_j \cdot \overline{m_j} \tag{3}$$

Equation 2 can be used when only general statistics on the average mass per item were available. Equation 3 can be used in case more detailed mass statistics for the different litter categories j were available. We applied both equations to investigate the effect of increased data availability. We calculated the mass transport using both the mean and median values for the litter flux and mass statistics. In total, this yielded eight values of total yearly mass transport for each location. For the mass statistics we used a detailed data set of over 16,000 sampled and analyzed macrolitter items, collected from riverbanks at the same time as the visual counting measurements (van Emmerik & de Lange, 2022). We use this data set to calculate the mean and median mass per item for (a) all items, (b) all plastic and non-plastic items, and (c) all 16 item categories.

2.5. Correlation With Hydrology

We explore the correlation with hydrology by comparing the observed floating plastic flux with discharge time series at some of the measurement locations. Discharge data was only available for locations outside the tidal influence: Nijmegen (Rhine), Arnhem and Kampen (IJssel), and Maastricht and Ravenstein (Meuse). Note that for Kampen, we used the nearest station of Olst, located 35 km upstream. All data are publicly available from the Directorate-General for Public Works and Water Management (Rijkswaterstaat, https://waterinfo.rws.nl/). For the five locations we calculated the Spearman and Pearson correlations between the observed daily mean plastic flux, and the mean discharge during the observation period of the matching floating plastic observation.

3. Results and Discussion

3.1. Seasonality of Floating Plastic Transport

Floating plastic flux showed several clear peaks during the year, especially for the locations along the Meuse and the downstream location on the Rhine (Figure 2). The strongest increase was observed for the Meuse river. In July, the plastic flux increased with a factor 4 for Maastricht (Upstream; 1,374 vs. 306 items/hour) and Moerdijk (downstream; 1,571 vs. 436 items/hour), and 6 for Ravenstein (midstream; 857 vs. 153 items/hour), compared to the yearly mean transport. In February, the plastic flux increased with a factor 1.5 in Ravenstein and Moerdijk.

Both increases are associated to the discharge peak in February and the flood event in the upstream regions of the Meuse in July. Between 13 and 20 July, severe floods occurred in the Meuse basin, leading to broken discharge records in the Dutch part of the river (Strijker et al., 2021). The return period of the measured discharge at Maastricht and Ravenstein were 200 and 50 years, respectively.

At Rotterdam, close to the river mouth, two peaks were observed in February and June. The February peak (1,284 items/hour) was 2.8 times higher than the yearly mean (459 items/hour) and the June peak (1,625 items/hour) 3.5 times higher than average. The February peak was a response to the annual discharge peak, which will be further discussed in Section 3.2. The June peak did not correspond to any hydrometeorological events, but may be explained by increased outdoor activity after suspension of several COVID-19 pandemic related measures. Note that the measurement location is in the middle of Rotterdam, the second largest city in the Netherlands, and home to Europe's largest port. Floating plastic may be introduced along the riverbanks of the city, but can also flow toward the city from the port areas (downstream of the measurement location) during flood tide. No evident peak or seasonal variation was observed at the upstream location at Nijmegen.

Floating plastic transport at the IJssel showed an increase of 60% during the February peak discharge (414–666 items/hour). During the remainder of the measurement period the plastic flux at both the upstream and downstream locations remained relatively constant. After July the plastic flux downstream decreased (33–113 items/hour), compared to the period before July (120–666 items/hour). The decrease may be explained by the flushing effect of the discharge peak in July (Hurley et al., 2018).

The floating litter transport showed a significant seasonal variation, with higher values during the spring/summer than during the fall/winter at Kampen ($p < 0.01$), Rotterdam ($p < 0.01$), Ravenstein ($p = 0.03$), and Moerdijk ($p = 0.02$). The upstream locations did not show a significant difference. As we omitted the observations done during the February and July peaks for this specific analysis, these results suggest that other factors may influence the seasonal variation in litter flux. The role of river discharge will be further explored in the next section. Future work should focus on investigating the influence of other seasonal effects, such as human activities, shipping, tidal dynamics, and other hydrometeorological variables (Schirinzi et al., 2020).

3.2. Correlation Between Floating Plastic Transport and Hydrology

At four of the five tested locations (Meuse: Maastricht, Ravenstein; Rhine: Nijmegen; IJssel: Arnhem and Kampen) the floating plastic flux is strongly positively correlated to discharge (Spearman $\rho = 0.59$–0.66, $p = 0.02$–0.05; Pearson $\rho = 0.74$–0.90, $p = 0.01$). The observed discharge peaks in February and July therefore explain the increased floating plastic flux at those locations (Figure 3). The found correlations in the Meuse and IJssel confirm the hypotheses posed by previous work on the link between discharge and plastic flux (Castro-Jiménez et al., 2019; C. T. Roebroek, Harrigan, et al., 2021; Schirinzi et al., 2020). Only at Nijmegen a negative, non-significant correlation was found. There is no clear explanation for the deviating results here, and it is most likely a combination of the timing of the measurements (peaks were missed), and actual absence of a strong relation between discharge and plastic flux at Nijmegen. The absence of a correlation here emphasizes that although plastic flux and discharge may be correlated at some locations, an actual more generalized relation is most likely more complicated and non-trivial (C. T. Roebroek, Hut, et al., 2021). As can be seen in Figures 3f and 3g, the slope of any linear approximation of the relation between discharge and plastic flux would yield varying degrees of steepness. For IJssel, Kampen and Maastricht, Meuse, the slope seems steeper than for IJssel, Arnhem and Meuse, Ravenstein. A simple linear model may be a suitable approach to reconstruct a higher resolution time series for a limited historical period at a specific location. Due to the variation in (cor)relation between discharge and plastic transport, transferability to other locations within and across river systems remains rather limited.

3.3. Spatial Variation Along the Rhine and Meuse

For both the Rhine and Meuse the highest floating plastic flux was observed at the most upstream locations (200–400 items/hour), and closest to the river mouth (100–250 items/hour). These observations suggest that a substantial amount of plastic is already transported in the river from across the border, and floating plastic may in fact accumulate in the tidal zone.

Emmerich am Rhein (upstream, Figure 4a) is located before the rivers splits, and the drop from 330 items/hour to 150 items/hour (Nijmegen) may be explained by the distribution of plastic over the different branches. Downstream of Nijmegen there is again an increase, especially in July (at Ewijk, 400 items/hour). Around the measurement locations there are various recreational areas, and river ports along the river, which may be considered as a source of plastic. During October and December, the plastic flux remains low until it reaches Rotterdam. In July a peak was observed around Gorinchem (70 km from the river mouth), which may be related to the urban, recreational and industrial areas, and shipping activities. The variation along the Meuse is lower than for the Rhine. Except for a peak in Roermond (230 km from the river mouth) in December (206 items/hour), the floating plastic flux is relatively stable between Maaseik and Peerenboom (20–50 items/hour). At Moerdijk another peak was observed (50–240 items/hour). Between Peerenboom and Moerdijk, the Meuse is joined by a side branch of the Rhine, which may transport some plastic from the Rhine system into the Meuse estuary.

All three rivers have significantly higher mean and median floating plastic fluxes in the most downstream location compared to the upstream location (see Figure 5). The multiplication factors between the upstream and downstream locations are 1.4 (Meuse), 2.8 (IJssel), and 2.1 (Rhine). The difference in the upstream and downstream mean and medians is not significant for all rivers. For the IJssel, both the mean ($p = 0.0196$) and median ($p = 0.021$) downstream flux is significantly higher than the upstream flux. In the Meuse, both the median and mean of the upstream (mean $p = 0.0141$, median $p = 0.0088$) and downstream locations (mean $p = 0.0117$, median $p = 0.0059$) are larger than the midway values. The difference between Maastricht and Moerdijk is less significant (mean $p = 0.2801$, median $p = 0.2917$). For the Rhine, the difference in the mean is not very significant ($p = 0.1740$), and the median is not different at all (hypothesis not rejected, $p = 0.1823$). Note that during specific months, such as during the flood peak in July, plastic transport can be much larger upstream than downstream.

A logical reason for the increase is the additional plastic that may be introduced in the rivers. However, the results from the Meuse show that this may not always be the case, as the intermediate locations almost all show lower values compared to the upstream and river mouth. A second explanation could be related to the urban and industrial areas around the downstream locations. The Rhine and IJssel transverse Rotterdam and Kampen, respectively, and the downstream Meuse location is neighbored by heavy industry and shipping infrastructure.

Another likely reason for the increased downstream values is the (temporary) accumulation in the river mouth. Due to the tidal dynamics, the river flow alternates direction diurnally (Blondel & Buschman, 2022; López et al., 2021; Okuku et al., 2022). The floating plastic within the tidal zone therefore also flows back and forth, increasing the likelihood of accumulation on riverbanks, or deposition on the riverbed (Acha et al., 2003; Tramoy et al., 2020). Note that for both the Rhine and Meuse, the most downstream location was still 30–50 km upstream from the river mouth. The lack of suitable measurement locations (i.e., safe bridges), and the complex tidal dynamics make it challenging to accurately estimate the actual emission of floating plastic into the sea.

3.4. Plastic and Litter Composition

The majority of the 3,293 categorized items (44% of the total counted items) were plastic (86.7%). Only wood (3.5%) and paper (3.8%) items contributed more than 1%. In total 4,244 items were not categorized, which was mainly due to the high transport fluxes during the July flood. Counting per individual categories was not possible. Note that with our categorization, cigarette butts were counted as paper, in contrast to some other studies which label them as plastic. Most plastic items were soft (56.6%), with PO_{soft} (39.5%) and Multilayer (17.1%) as the most abundant categories. These categories include items such as food packaging, soft fragments, bags, and foils. Hard plastic items made up 30.3% (15.6% PO_{hard}, 7.7% EPS, 6.0% PS, 1.1% PET), and 13.1% were non-identified items. On average, the floating plastic composition is similar to the plastic found on the Dutch riverbanks (85.1% plastic, 33.4% PO_{soft}, 16.1% PO_{hard}) (van Emmerik et al., 2020). The plastic composition in the Dutch rivers is similar to the European average (82%), which was based on one year of measurements in 42 rivers across the continent (González-Fernández et al., 2021). A clear difference was found for the plastic bottles, which was much lower in the Dutch rivers (1.1%) than the European mean (almost 10%). The composition is also in line with global statistics, with an average of 50%–55% soft items, and relatively low abundance of PET (<5%) (van Calcar & van Emmerik, 2019).

Plastic composition can change considerably over time. We do find that when more items were observed, the plastic composition is more distributed, and closer to the mean statistics. Strongly deviating composition is often related to the low number of observed items. During periods with high observed plastic, the percentage of non-identified items is often higher. These results emphasize one of the major limitations of the visual counting method. For high plastic fluxes, especially during discharge peaks, not all items can be categorized by a single surveyor. The uncertainty may be reduced by working in teams of two surveyors, one observer and one scribe. However, previous studies have emphasized that for extremely high plastic fluxes the categorization cannot be done by visual observations anymore (van Lieshout et al., 2020). Cameras may provide a solution, as recorded videos allow for counting by multiple people and at slower speeds. Future developments may even include further automation of plastic observations. Preliminary results from rivers in Jakarta show that during floating plastic flux peaks, the camera-based estimates were structurally higher than the visual counting-based estimates (van Lieshout et al., 2020). Plastic composition is important to identify sources, understand transport processes, and improve risk assessments. Most plastic is mobilized during peak discharge, which underscores the importance of composition analysis during those events.

Floating plastic composition is relatively constant between measurement locations. For almost all locations, at least 79% of the items were plastic. Only in Maastricht, the most upstream Meuse location, the plastic content was lower (21%). During the July flood event, the plastic flux was however too large (1,374 items/hour on average) to categorize individual items. When these items are excluded, also here the plastic content increases to 92%. When comparing the seven locations where monthly measurements were done, the composition statistics remains similar. In Nijmegen, the upstream location Rhine, PO_{soft} was higher (48%) than at the other locations (28%–35%). Previous studies have suggested that soft plastics may be found less in downstream regions of rivers, as they are more likely to entangle in riparian vegetation or accumulate on riverbanks (van Emmerik et al., 2022). For the Rhine the percentage of soft plastics decreased from 68% to 46% from upstream to downstream locations, but for the IJssel (54%–50%) and Meuse (50%–45%) it remained within limited range.

3.5. Floating Plastic Mass Transport

The estimated annual item transport of the Rhine, IJssel and Meuse were consistently larger at the most downstream locations, and varied between 2.4 and 4.0 million items/y (2.1–3.5 million plastic items/year), see Table 1. The Rhine transported the most items (2.7–3.5 million items/year), followed by the IJssel (2.4–2.6 million items/year) and the Meuse (2.3–3.8 million items/year). All three rivers are among the European top polluted rivers measured to date, with similar values to the Danube (~1.8–3.0 million items/year), Tiber (~2 million items/year), and Drini (~1.2 million items/year) (González-Fernández et al., 2021).

The plastic mass transport closest to the river mouth was largest for the Rhine (mean: 16.0–58.8 t/y; median: 1.3–6.3 t/y), followed by the Meuse (mean: 15.3–45.5 t/y; median: 1.2–6.4 t/y), and the IJssel (mean: 9.7–24.8 t/y; median: 0.8–5.0 t/y), see Table 1. The downstream mass transport was higher for all three rivers. Similar to the item transport, the Meuse had the lowest mass transport midway at Ravenstein. The mass transport estimates vary almost by an order of magnitude, depending on whether the mean or median item statistics are used. A similar range was found during an assessment of mass transport of three German rivers (Schöneich-Argent et al., 2020). Plastic has the highest share when the median item transport F is used, and the lowest when the aggregated item mass statistics are used. Our calculations show that because of the large discrepancies in the mean and median for both item transport and item-mass statistics, the estimates of total yearly mass transport come with substantial uncertainty.

The distribution of the mass transport in Rhine, Meuse, and IJssel branches do not follow the distribution of total annual discharge. The Rhine at Rotterdam accounts for 54% of the yearly discharge into the ocean from the Rhine-Meuse delta, but only conveys 25% of the annual item transport and 41% of the mass transport. At Moerdijk 40% of the item transport and 36% of the mass transport was estimated, against 32% of the river discharge. The IJssel at Kampen accounts for 14% of the discharge, but 35% of item transport and 24% of the mass transport. The contribution of the item and mass transport at Moerdijk seems to be most in line with the river discharge, the Rhine distributes relatively low, and the IJssel relatively high amounts of plastic. These results again emphasize the non-trivial relation between discharge and plastic transport, especially when comparing river branches or different river systems.

Table 1
Estimated Yearly Floating Plastic Flux Transport in Items/Hour and Tonnes/Year

		Floating transport									
		Item transport F [million items/year]		Mass transport M [tonnes/year]							
				Mean mass/item				Median mass/item			
				Specific categories		Aggregated		Specific categories		Aggregated	
Location		Mean	Median	Mean F	Median F	Mean F	Median F	Mean F	Median F	Mean F	Median F
Rhine											
Nijmegen	Litter	1.9	1.6	32.4	24.9	25.5	19.6	5.7	4.4	1.1	0.8
	Plastic	1.7	1.4	28.1	24.4	8.9	7.8	5.0	4.3	0.7	0.6
Rotterdam	Litter	4.0	3.1	65.5	50.2	52.7	40.4	8.2	6.3	2.2	1.7
	Plastic	3.5	2.7	56.8	49.2	18.5	16.0	7.1	6.2	1.5	1.3
IJssel											
Arnhem	Litter	0.9	0.8	10.5	8.1	11.6	8.9	1.7	1.3	0.5	0.4
	Plastic	0.8	0.7	9.1	7.9	4.1	3.5	1.5	1.3	0.3	0.3
Kampen	Litter	2.4	2.6	28.6	22.0	32.0	24.5	5.8	4.4	1.3	1.0
	Plastic	2.1	2.3	24.8	21.5	11.2	9.7	5.0	4.3	0.9	0.8
Meuse											
Maastricht	Litter	2.7	1.8	38.9	29.8	35.2	27.0	5.9	4.5	1.5	1.1
	Plastic	2.3	1.5	33.7	29.2	12.3	10.7	5.1	4.5	1.0	0.8
Ravenstein	Litter	1.3	0.8	20.1	15.4	17.5	13.4	3.8	2.9	0.7	0.6
	Plastic	1.2	0.7	17.4	15.1	6.1	5.3	3.3	2.8	0.5	0.4
Moerdijk	Litter	3.8	2.4	52.5	40.3	50.1	38.4	7.3	5.6	2.1	1.6
	Plastic	3.3	2.1	45.5	39.5	17.6	15.3	6.4	5.5	1.4	1.2

Note. The mass calculations were calculated using three combinations of input. First, we estimated the yearly floating item transport based on the mean and median observed item flux. Second, the calculations were done using both mean and median mass per item. Third, we used the aggregated item statistics, and the category specific item statistics. Note that the range of values refer to the estimates based on the mean (first value) and median (second value) item flux. The mass statistics were taken from (van Emmerik & de Lange, 2022).

The mean mass transport values are close to recent model estimates by Meijer et al. (2021). The model estimates for the Rhine (56.2 t/y) and IJssel (23.7 t/y) are well within our calculated range. The highest agreement between the model estimates and our observation based values was found when using the mean item statistics of the specific item categories. For the Meuse, most of our transport estimates are higher than the modeled values (22.7 t/y). The observation based approach included measurements during two peak discharge events, with substantially higher floating plastic fluxes. The model based estimates only use average yearly input data, and therefore does not capture the seasonal dynamics or extreme values. Our findings emphasize the further development of modeling approaches that better represent the temporal dynamics of driving forces and retention dynamics (C. Roebroek et al., 2022).

Previous assessments estimated the mass transport downstream of the Rhine between 0.5 and 3.5 t/y (Vriend et al., 2020) and 5.8–58.4 t/y (van der Wal et al., 2015). Vriend et al. (2020) based their estimates on observations during low discharge, and are closer to our lowest estimates based on the mean. The values presented by van der Wal et al. (2015) are closer to our higher estimates. When plastic flux is low, it is more likely that the few observed items statistics are close to the median item statistics. During periods of high plastic flux, especially during extreme hydrological conditions, the likelihood of larger and heavier items being transported increases (Liro et al., 2020). There is no consensus yet on whether using mean or median statistics results in more realistic estimates of mass transport. However, our results suggest that a hybrid approach may be the way forward. During

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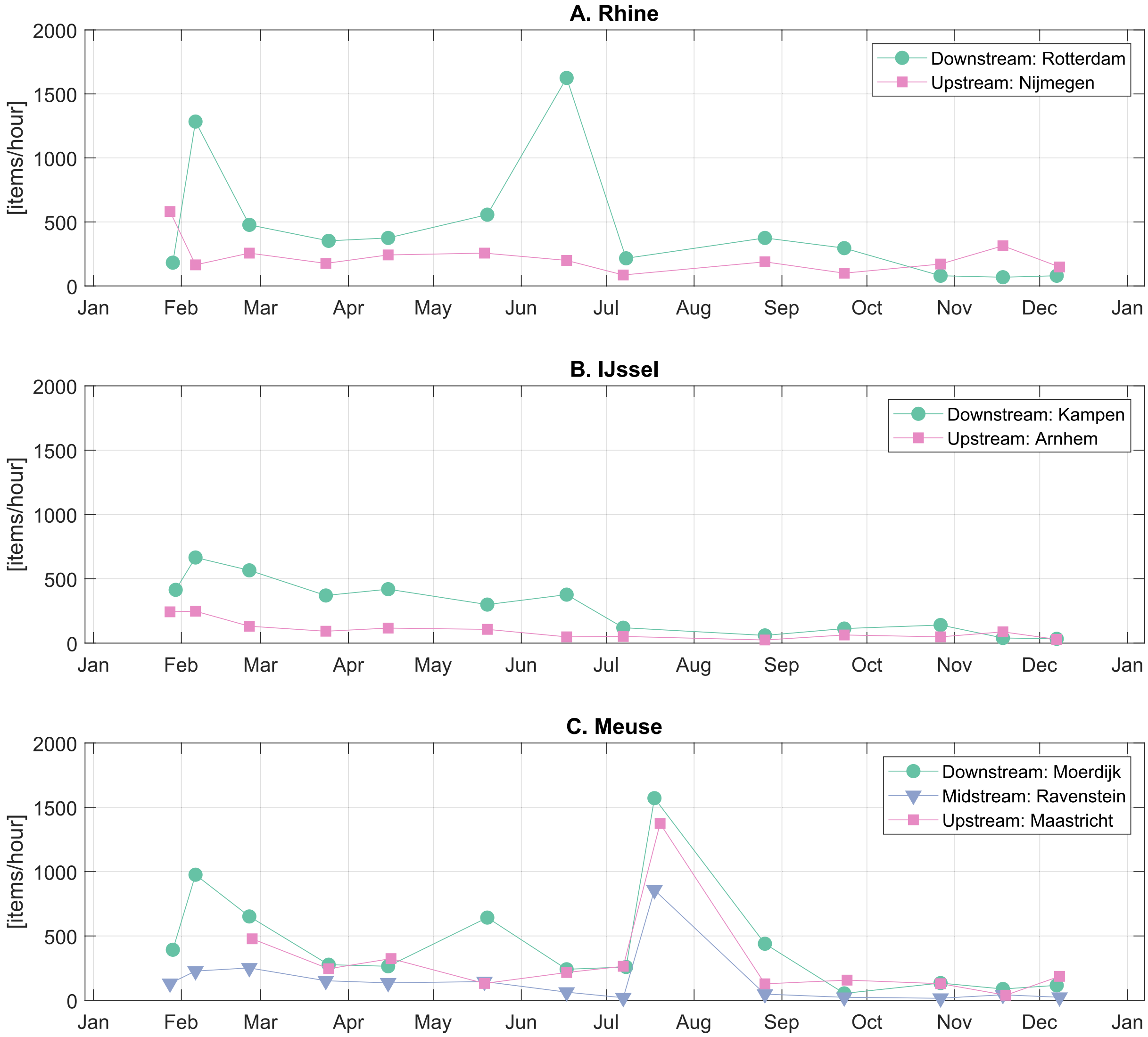

Figure 2. Observed mean daily floating plastic flux for (a) the Rhine at the upstream (Nijmegen) and downstream (Rotterdam) locations, (b) the IJssel at the upstream (Arnhem) and downstream (Kampen) locations, and (c) the Meuse at the upstream (Maastricht), midstream (Ravenstein), and downstream location (Moerdijk). In February, the annual peak discharge occurred in the Rhine, IJssel, and Meuse, and in July an extreme flood event occurred in the upstream regions of the Meuse.

periods of low plastic flux, median items statistics can be used, whereas during periods of high plastic flux the mean statistics may be more realistic.

The estimates that used the aggregation item-mass statistics are lower, and plastics make up a smaller share of the total mass transport. Other studies that analyzed the mass of sampled litter generally find that plastics constitute a share larger than 80% (Schöneich-Argent et al., 2020; Treilles et al., 2022; van Calcar & van Emmerik, 2019). We therefore recommend using the item-mass statistics of the specific categories for future estimates. Openly available databases (van Emmerik & de Lange, 2022) can be used for more accurate estimates in case limited resources are available for detailed data collection.

3.6. Synthesis and Outlook

Hydrology plays an important but complex role in floating plastic transport in rivers. For five out of six locations we found significant correlations between discharge and plastic transport. However, the response to changing discharge varies substantially between rivers. Most global river plastic transport models assume a general relation between discharge (or surface runoff) and river plastic transport (Lebreton et al., 2017; Meijer et al., 2021). A

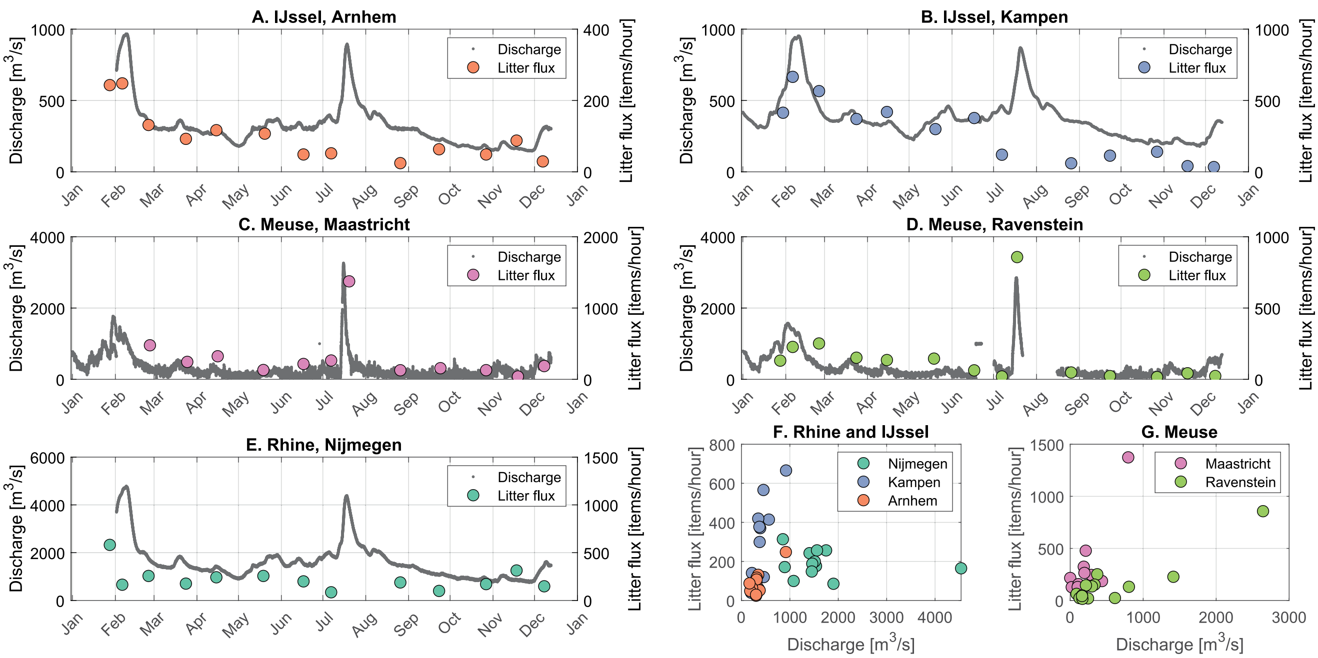

Figure 3. The observed mean daily floating plastic flux and discharge for the measurement locations without tidal influence. (a) IJssel at the upstream location Arnhem (Spearman $\rho = 0.59$, $p = 0.05$; Pearson $\rho = 0.81$, $p < 0.01$). (b) IJssel at the downstream location Kampen (Spearman $\rho = 0.66$, $p = 0.02$; Pearson $\rho = 0.74$, $p < 0.01$). (c) Meuse at the upstream location Maastricht (Spearman $\rho = 0.60$, $p = 0.03$; Pearson $\rho = 0.90$, $p < 0.01$). (d) Meuse at the midstream location Ravenstein (Spearman $\rho = 0.60$, $p = 0.02$; Pearson $\rho = 0.76$, $p < 0.01$). Note that the discharge time series is interrupted as a result of the July flood, probably due to failure of the gauge. (e) Rhine at the upstream location Nijmegen (Spearman $\rho = -0.16$, $p = 0.61$; Pearson $\rho = -0.19$, $p = 0.55$). (f) Discharge versus floating plastic for the Rhine and IJssel location. (g) Discharge floating plastic versus floating plastic for the Meuse locations.

recent study already revealed that the correlations between floating plastic flux, discharge and wind varies greatly between different rivers (C. Roebroek et al., 2022). With our work we highlight that such (cor)relations also clearly vary within river systems. Increased discharge is often associated with increased preceding rainfall, higher water levels, and higher flow velocity. Rainfall, especially with high intensity and in urban areas, can be a driver of plastic transport from land into rivers. Plastic can be transported over land, although the main mechanisms are assumed to be through direct littering, combined sewer overflow, or discharge of urban drainage on surface water systems (Treilles et al., 2021, 2022). When water levels and flow velocity increases, parts of the riverbanks and floodplains may become inundated. If the mobilizing forces are large enough this may (re)mobilize accumulated plastic (Liro et al., 2020). All the factors above vary greatly per location, and depend on mismanaged plastic waste rates, urban water system characteristics, and river characteristics. Future work should focus on identifying the governing transport and retention principles, that can be used to better explain and forecast plastic flux dynamics and link it to their sources. One way forward is to include plastic concentration-discharge analyses, as the hysteresis patterns reveal whether increased discharge leads to dilution or enrichment of plastic pollution at specific locations (Hashemi et al., 2020). In turn, describing the concentration-discharge dynamics helps to identify the sources of the observed additional river plastic transport.

Discharge peaks, and floods in particular, are one of the main drivers of floating plastic transport. During the Meuse floods of July 2021, the transport increased with a factor 4–6 compared to the yearly means. Compared to the lowest observed values, the transport during extreme discharge was ∼30–50 times higher. The large spread of plastic transport emphasizes the skewed distribution over time. Similar to sediment and woody debris transport, it seems that also most plastic transport occurs in a relatively short amount of time (Hooke, 2019; Ruiz-Villanueva et al., 2019). Our findings are in line with previous studies on the role of floods on mobilizing and transporting plastics during flood events regionally and globally (Hurley et al., 2018; C. T. Roebroek, Harrigan, et al., 2021). The strong response to high discharge values may have important implications for the transport and fate dynamics, and for development of monitoring and intervention strategies. For reliable estimates of floating plastic transport, it may not be necessary to increase the measurement frequency.

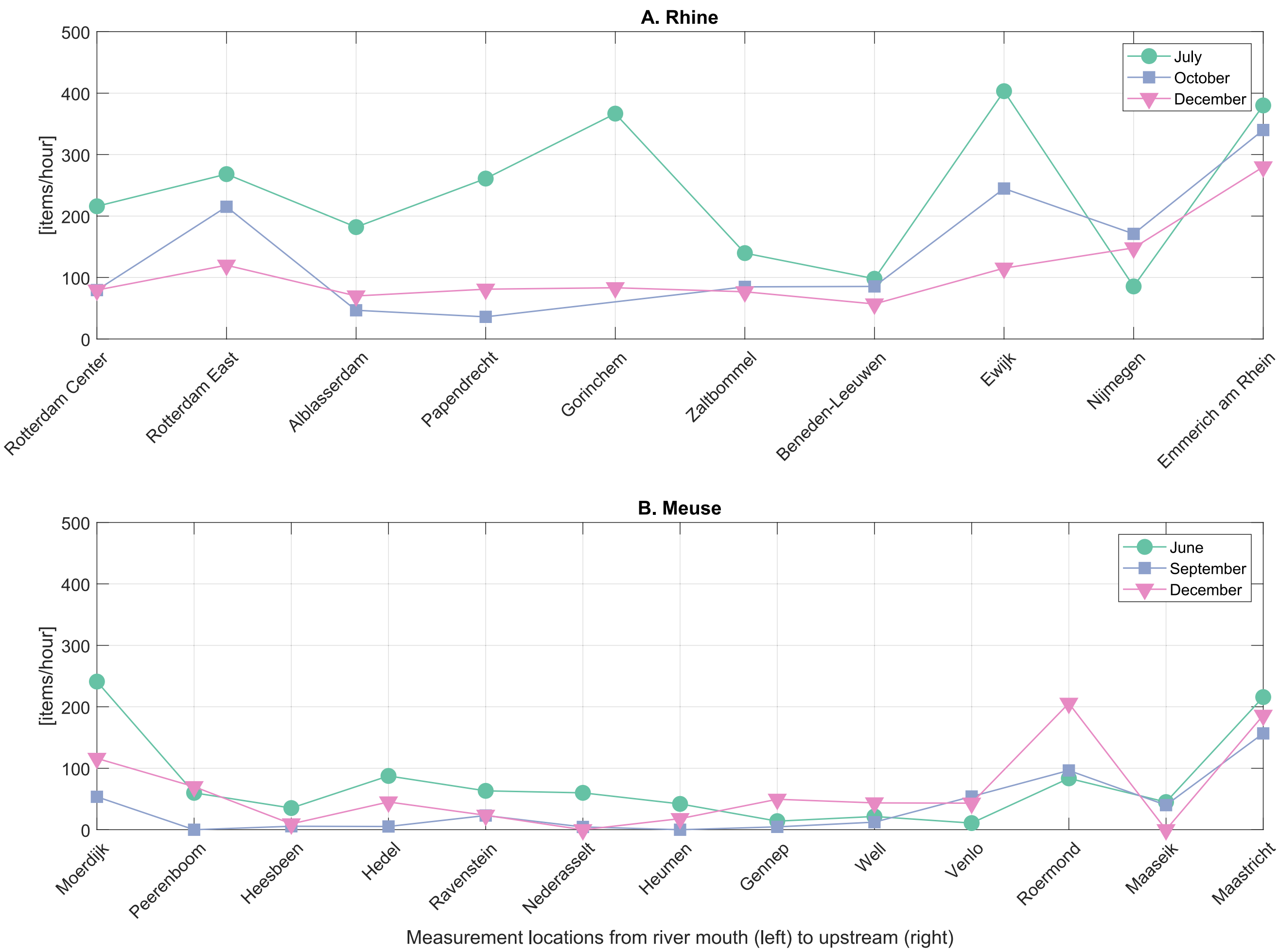

Figure 4. Longitudinal profiles of floating plastic flux for (a) the Rhine in July, October, and December 2021, and (b) the Meuse in June, September, and December 2021.

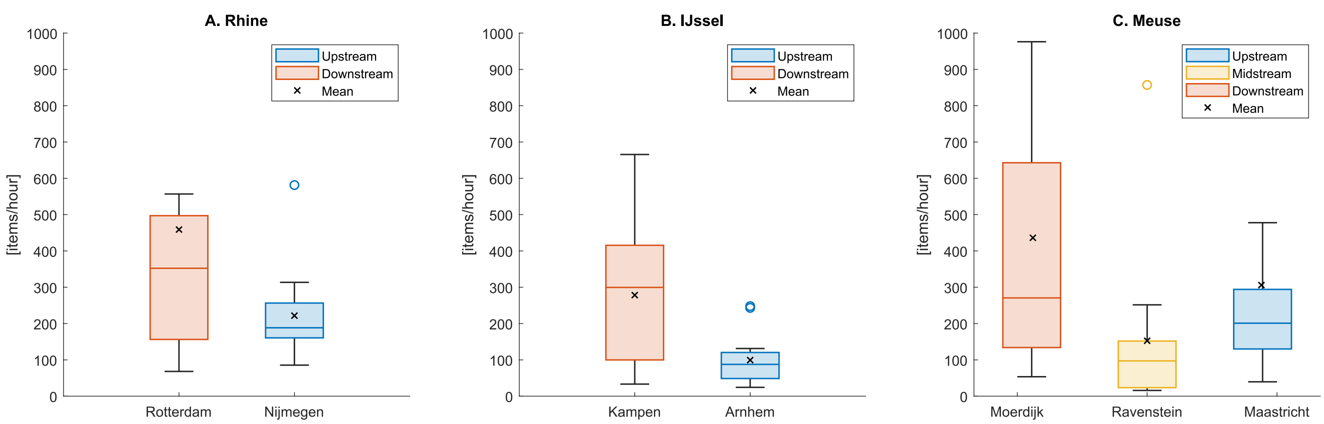

Figure 5. The difference between the upstream, downstream and midstream plastic flux observations at the (a) Rhine, (b) IJssel, and (c) Meuse rivers.

During regular discharge conditions, the plastic transport shows relatively low variation. It is imperative however to monitor during peak events, as most transport may occur during those times. The fate of plastic during peaks events remains unclear. Previous work found increased plastic concentrations on riverbanks in the most downstream reaches of the Rhine-Meuse delta after floods (van Emmerik et al., 2020), suggesting that the high values for floating plastic do not necessary result in export into the ocean. A growing amount of evidence suggests that the majority of mobile plastics may be entrapped on floodplains, on riverbanks or in riparian vegetation (Cesarini & Scalici, 2022).

This study excluded any plastics below the surface, either suspended in the water column or sunk to the river bed. To date it remains unclear what share of floating plastics is to the total plastic transport. In some cases, the highest plastic concentrations were measured both at the surface and close to the river bed (Blondel & Buschman, 2022). Other studies reported a rather uniform distributed of plastics over the water column Broere et al., 2021, Haberstroh et al., 2021, or a clear peak concentration at the surface (Haberstroh et al., 2021). The few available studies demonstrate that the vertical distribution is far from trivial, and may depend on flow conditions, and plastic item characteristics (e.g., size, shape, effective buoyancy) (Kuizenga et al., 2022). The main challenge remains data collection below the surface, as it involves heavy equipment such as nets, boats, and cranes (Blondel & Buschman, 2022; Liedermann et al., 2018), or relies on novel technology that is still under development, including sonar (Broere et al., 2021). Future work should focus on improving estimating plastic transport below the surface by combining new measurement methods, a better understanding of settling velocities, and empirical models to relate surface observations to the total transport.

Our paper demonstrates the importance of basin scale quantitative assessments, especially in complex river deltas. To date, most river plastic assessments, also in large rivers, have focused on single locations within river basins (González-Fernández et al., 2021; Vriend et al., 2020). Although this has resulted in new insights regarding the local driving mechanisms that determine the temporal variation, many challenges regarding the transport and retention dynamics across large river deltas remain unresolved. One of the main challenges in plastic research focuses on closing the mass balance of plastics in the open ocean (Weiss et al., 2021). As it is assumed that a considerable share comes from land-based sources, and is conveyed to the ocean through river systems, it is imperative that the transport dynamics between rivers and the sea are better quantified and understood. Several works have investigated the travel paths of macroplastics along river systems, demonstrating that the majority of items are removed, or retained on riverbanks, in vegetation, at infrastructure, or otherwise (Duncan et al., 2020; Schreyers et al., 2021; Tramoy et al., 2020; van Emmerik et al., 2022). Also our results show that these dynamics are not trivial, and we emphasize the need for additional monitoring efforts in other large river deltas that are expected to emit large amounts of plastics into the ocean.

Our study emphasized the importance of understanding plastic transport in tidal areas. Despite the largest values found in the downstream regions, it is not at all certain to say how much of these are emitted into the ocean. In rivers around the world, high concentrations of plastics are found around the estuary (Acha et al., 2003; Núñez et al., 2021; Ryan & Perold, 2021; Tramoy et al., 2020). At the same time, observational evidence of floating plastics actually flowing into the ocean remain limited. Partly this is caused by the lack of observations, as river mouths are often difficult to monitor. The available data do suggest that the majority of plastics do not leave the estuary (López et al., 2021). Future work may focus on collecting more observations within the complex tidal areas with bidirectional flow dynamics. High temporal resolution measurements during full tidal cycles may shed additional light on the factors that determine net emission or accumulation across temporal time scales.

Estimates of mass transport and emission into the ocean have become important figures for policymakers, stakeholders, and initiatives focused on environmental plastic reduction. Studies such as Jambeck et al. (2015) and Schmidt et al. (2017) presented straightforward numbers on global plastic input into the ocean, and the contribution of rivers. Our work shows that mass transport estimates of specific rivers remain highly uncertain, even when relatively large and detailed data sets are available. For the floating plastic item transport estimates, using the mean and median yielded very similar results (38% difference at most). The mass transport estimates however varied more than an order of magnitude for all locations. A potential source of uncertainty is the use of mass statistics of riverbank plastics, rather than floating plastics. Future work should further investigate to what extent plastic characteristics vary between river compartments. As established by C. Roebroek et al. (2022), the largest uncertainty in mass transport estimates lies within the highly variable mass statistics of (plastic) litter items. The variation in our mass transport estimates for each of the three rivers confirm this uncertainty. Future efforts may therefore explore the use of more probabilistic descriptions of item characteristics (Kooi & Koelmans, 2019) and transport modeling approaches (C. Roebroek et al., 2022). Rather than selecting a fixed value for assessments, a probabilistic description can result in an ensemble of possible outcomes with various degrees of certainty.

Finally, we would like to emphasize the importance of international and transboundary harmonization of monitoring strategies. The current data collection only focused on the Dutch reaches of the Rhine and Meuse rivers. We demonstrated that the longitudinal profiles are non-trivial, and similar measurements along the full course of the river may give additional insights in points of entry and retention. Also for policy and management practices it is key that data are collected and reported consistently (Wendt-Potthoff et al., 2020). For example, to establish material flow analyses (Lobelle et al., 2022), or to assess the efficacy of interventions (Helinski et al., 2021). Riverbank monitoring in the Netherlands (van Emmerik et al., 2020) and Germany (Kiessling et al., 2019) is both done through citizen science approaches, but the used protocols are quite different in terms of spatiotemporal coverage and level of detail (Wendt-Potthoff et al., 2020). The recent RIMMEL project (González-Fernández et al., 2021) showcased how the straightforward visual counting method can be applied in a pan-European effort to harmonize floating plastic monitoring. The missing link that can connect the point scale to the European or global scale is the river basin scale, the natural system boundary of plastic mobilization, transport, and retention dynamics. We therefore stress the necessity for further development of basin-wide approaches and monitoring strategies.

4. Conclusions

Hydrology is an important driver of floating plastic mobilization, transport and retention dynamics. Especially during peak discharge events, a strong response in plastic flux was observed. The highest plastic flux was observed during the Meuse floods of July 2021. The exact relations between hydrology and plastic transport are however non-trivial, and vary strongly between and along rivers. Fundamental work is necessary to arrive at a more general understanding of plastic transport mechanisms.

Plastic mass transport estimates remain highly uncertain, in most cases larger than an order of magnitude. The uncertainty is largely due to the skewed distribution in item-mass statistics, with large differences in the means and medians. The high estimates of mass transport were in good agreement with previous model results. The remaining discrepancy was related to the inclusion of peak discharge events in our approach. Future work should explore the development of probabilistic approaches to describe item-mass statistics, and model river plastic transport.

The largest uncertainty is found in the transport estimates in the areas under tidal influence. Current data do not allow for estimating the net emission or accumulation of plastic. It remains therefore unknown whether the observed floating plastic at the most downstream locations flow into the ocean, or remain within the river systems. Estuaries are assumed to be a major sink for plastic pollution. Additional measurements are required to further explore the transport dynamics in the Dutch Rhine-Meuse estuaries and beyond.

Plastic pollution is a global challenge that requires international and transboundary harmonization of monitoring approaches. We demonstrated how relatively simple measurements can be done across a complex river delta at the national scale, yet revealing crucial new insights on the seasonality and spatial variation. As hydrology is an important driver of river plastic transport, river basin wide approaches for monitoring and intervening are required to address this environmental stressor within its natural system boundaries.

With this paper we highlight the importance of consistent field data to understand the role of hydrology on the transport dynamics, temporal variation, and spatial distribution of floating plastics. The presented insights are crucial for planning further fundamental research, optimize long-term monitoring strategy, and develop international collaboration for river plastic monitoring.

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Appendix A: Overview of Measurement Locations

Table A1 presents the overview of the measurement locations along the Rhine, IJssel and Meuse Rivers.

Table A1
Overview of the Measurement Locations Along the Rhine, IJssel, and Meuse Rivers

								Measurements 2021 x* = additional measurements during discharge peak											
Location	Dist. to mouth [km]	Coordinates [lon, lat]	River width [m]	Obs points	Obs	Total items	Total hours	J	F	M	A	M	J	J	A	S	O	N	D
Rhine - Waal																			
Emmerich am Rhein (DE)	171	51.828926, 6.226301	420	5	60	100	5							x			x		x
Nijmegen	141	51.852691, 5.857029	380	6	239	236	20	x	x*	x	x	x	x	x	x	x	x	x	x
Ewijk	131	51.885791, 5.737637	500	5	55	51	5							x			x		x
Beneden-Leeuwen	115	51.889436, 5.497387	200	5	60	34	5							x			x		x
Zaltbommel	93	51.818882, 5.260073	200	5	59	42	5							x			x		x
Gorinchem	70	51.827146, 4.942190	500	5	40	27	3							x					x
Papendrecht	53	51.823282, 4.705814	300	5	60	42	5							x			x		x
Alblasserdam	46	51.856393, 4.654418	400	5	58	32	5							x			x		x
Rotterdam East	36	51.904052, 4.654418	500	5	61	31	5							x			x		x
Rotterdam Center	31	51.909284, 4.486466	500	6	298	412	25	x	x*	x	x	x	x	x	x	x	x	x	x
Rhine - Nederrijn																			
Arnhem	141	51.958200, 5.937085	112	5	24	27	2	x											x
Rhine - IJssel																			
Arnhem	113	51.969409, 5.959129	71	3	141	238	12	x	x	x	x	x	x	x	x	x	x	x	x
Kampen	6	52.559602, 5.918914	213	6	315	550	26	x	x	x	x	x	x	x	x	x	x	x	x
Meuse																			
Maastricht	291	50.846234, 5.697250	110	6	294	4441	26			x	x	x	x	x*	x	x	x	x	x
Maaseik (BE)	254	51.092855, 5.798352	80	3	32	17	3						x			x			x
Roermond	227	51.198261, 5.980660	150	5	55	52	5						x			x			x
Venlo	202	51.368746, 6.161304	150	5	55	18	5						x			x			x
Well	179	51.548057, 6.099343	150	5	54	16	5						x			x			x
Gennep	158	51.693214, 5.959068	120	5	55	12	5						x			x			x
Heumen	145	51.758523, 5.838436	150	5	60	10	5						x			x			x

Table A1
Continued

Location	Dist. to mouth [km]	Coordinates [lon, lat]	River width [m]	Obs points	Obs	Total items	Total hours	Measurements 2021 x* = additional measurements during discharge peak											
								J	F	M	A	M	J	J	A	S	O	N	D
Nederasselt	137	51.794507, 5.663464	140	5	52	9	4						x			x			x
Ravenstein	131	51.769005, 5.735756	120	5	266	541	22	x	x*	x	x	x	x	x*	x	x	x	x	x
Hedel	95	51.739671, 5.268502	140	5	60	22	5						x			x			x
Heesbeen	84	51.736041, 5.118175	150	5	60	8	5						x			x			x
Peerenboom	67	51.719815, 4.890445	300	5	60	13	5						x			x			x
Moerdijk	49	51.718369, 4.636068	1000	12	617	556	52	x	x*	x	x	x	x	x*	x	x	x	x	x
Total					3190	7537	268												

Appendix B: Item Category List

Table B1 presents the used item category list, with the Item ID, the original Dutch description, the translation in English, and the material category.

Table B1
Item Categories With Their Original Item ID, the Original Description in Dutch, the Description in English, and the Material Category (PO_{Soft}: Soft Polyolyfins; PO_{Hard}: Hard Polyolefins; PET: Polyethylene Terephthalate; PS: Polystyrene; EPS: Expanded Polystyrene)

Item ID	Description (Dutch)	Description (English)	Material category
1	plastic_6_packringen	Six pack ring	PO soft
2	plastic_tassen	Bag	PO soft
3	plastic_kleine_plastic_tasjes	Small bag	PO soft
4.1	plastic_drankflessen_groterdan_halveliter	Bottle (>= 0.5 L)	PET
4.2	plastic_drankflessen_kleinerdan_halveliter	Bottle (<0.5 L)	PET
4.3	plastic_wikkels_van_drankflessen	Bottle label	PO soft
5	plastic_verpakking_van_schoonmaakmiddelen	Cleaning product packaging	PO hard
6	plastic_voedselverpakkingen_frietbakjes_etc	Food packaging	PS
7	plastic_cosmeticaverpakkingen	Cosmetics packaging	PO hard
9	plastic_motorolieverpakking_groterdan50cm	Motor oil packaging (>= 50 cm)	PO hard
10	plastic_jerrycans	Jerrycan	PO hard
13	plastic_kratten	Crate	PO hard
14	plastic_auto_onderdelen	Car parts	PO hard
15	plastic_doppen_en_deksels	Caps and lids	PS
16	plastic_aanstekers	Lighter	PO hard
20	plastic_speelgoed	Toy	PS
21	plastic_plastic_bekers_of_delen_daarvan	Cup	PS
24	plastic_netzakken	Net bag	PO soft
25	plastic_handschoenen_huishoudelijk	Cleaning glove	PO soft
113	plastic_handschoenen_professioneel	Glove	PO soft
31	plastic_touw_diameter_groterdan_1cm	Rope	PO soft

Table B1
Continued

Item ID	Description (Dutch)	Description (English)	Material category
32	plastic_touw_diameter_kleinerdan_1cm	Rope	PO soft
35	plastic_sportvisspullen	Fish gear	PO soft
36	plastic_breekstaafjes	Glowstick	PO hard
38	plastic_emmers	Bucket	PO hard
40	plastic_industrieel_verpakkingsmateriaal	Industrial packaging	PO soft
42	plastic_helmen	Helmet	PO hard
43	plastic_geweerpatronen	Gun rounds	PO hard
57	plastic_schoenen	Shoe	PO hard
117.1	plastic_plastic_stukjes_0_2_5cm_hard_plastic	Hard fragment (<5 cm)	PO hard
46.1	plastic_plastic_stukjes_2_5_50cm_hard_plastic	Hard fragment (>= 5 cm)	PO hard
117.2	plastic_plastic_stukjes_0_2_5cm_zacht_plastic	Soft fragment (<5 cm)	PO soft
46.2	plastic_plastic_stukjes_2_5_50cm_zacht_plastic	Soft fragment (>= 5 cm)	PO soft
48	plastic_overig_plastic	Other plastic	Other plastic
1172	plastic_piepschuim_0_2_5cm	Foam fragment (<5 cm)	EPS
462	plastic_piepschuim_2_5_50cm	Foam fragment (>= 5 cm)	EPS
6.1	plastic_piepschuim_voedselverpakkingen	Foam food packaging	EPS
47.1	plastic_plastic_folies_groterdan_50cm	Foil (>= 50 cm)	PO soft
47.2	plastic_hard_plastic_groterdan_50cm	Hard other (>= 50 cm)	PO hard
22.1	plastic_rietjes	Straw	PS
19	plastic_snoep_snack_chipsverpakking	Food wrapping	Multilayer
472	plastic_piepschuim_groterdan_50cm	Foam (>50 cm)	EPS
212	plastic_piepschuim_bekers	Foam cup	EPS
22	plastic_bestek	Cutlery	PS
481	plastic_biofilm_waterfiltertjes	Water filter	PO hard
11	plastic_kitspuiten	Caulking gun	PO hard
39	plastic_kunststof_band_tiewraps	Cable tie	PO hard
19.1	plastic_lolliestokjes	Stick	PO hard
8	plastic_motorolieverpakking_kleinerdan50cm	Motor oil packaging (<50 cm)	PO hard
2.1	plastic_vuilniszakken	Garbage bag	PO soft
17	plastic_schrijfwaren	Pen	PO hard
35.1	plastic_visdraad	Fishing wire	PO soft
43.1	plastic_vuurwerk	Firework	PO hard
22.1	plastic_borden_new	Plate	PS
22.2	plastic_roerstaafjes_new	Mixing stick	PS
38.1	plastic_bloempotten_new	Plant pot	PO hard
39.1	plastic_plakband_new	Tape	PO soft
49	rubber_ballonnen	Balloon	Rubber
52	rubber_banden	Tire	Rubber
53	rubber_overig_rubber	Other rubber	Rubber
54	textiel_kleding	Clothing	Textile
55	textiel_vloerbedekking	Carpet	Textile
44	textiel_schoeisel	Shoeware	Textile
59	textiel_overig_textiel	Other textile	Textile

Table B1
Continued

Item ID	Description (Dutch)	Description (English)	Material category
60	papier_tassen	Paper bag	Paper
61	papier_karton	Carton	Paper
63	papier_sigarettenverpakking	Cigarette pack	Paper
64	papier_sigarettenfilters	Cigarette filter	Paper
65	papier_kartonnen_bekers	Carton cup	Paper
66	papier_kranten	Newspaper	Paper
67	papier_papier_overig	Other paper	Paper
62.1	papier_drankkarton	Drink carton	Paper
67.1	papier_ondefinieerbaar	Other paper	Paper
68	hout_kurk	Cork	Wood
69	hout_pellets	Pellet	Wood
72	hout_ijsstokjes	Stick	Wood
73	hout_kwasten	Paintbrush	Wood
74	hout_overig_hout_keinderdan_50cm	Other wood (<50 cm)	Wood
75	hout_overig_hout_groterdan_50cm	Other wood (>= 50 cm)	Wood
81	metaal_aluminiumfolie	Aluminium foil	Metal
81.1	metaal_capsules	Metal capsule	Metal
78	metaal_drankblikjes	Drink can	Metal
79	metaal_elektriciteitsdraad	Electrical wire	Metal
83	metaal_oud_ijzer	Iron part	Metal
77	metaal_kroonkurken	Metal bottle cap	Metal
84	metaal_oliedrum	Oil drum	Metal
88	metaal_omheinigsdraad_prikkeldraad	Barbed wire	Metal
76	metaal_spuitbussen	Spray can	Metal
86	metaal_verfblik	Paint can	Metal
80	metaal_vislood	Fish lead	Metal
82	metaal_voedselblikken	Food can	Metal
120	metaal_wegwerpbarbecues	Single use grill	Metal
89	metaal_overig_metaal_kleinerdan_50cm	Other metal (<50 cm)	Metal
90	metaal_overig_metaal_groterdan_50cm	Other metal (>= 50 cm)	Metal
91	glas_flessen_pottten	Pot	Glass
92	glas_lampen_tl_lampen	Tube lamp	Glass
93	glas_overig_glas	Other glass	Glass
7	sanitair_cosmetica	Cosmetics	Sanitary
98	sanitair_plastic_wattenstaafjes	Cotton swab	PO hard
982	sanitair_kartonnen_wattenstaafjes	Carton cotton swab	Sanitary
102.2	sanitair_vochtige_doekjes	Wet tissue	Sanitary
97	sanitair_condooms	Condom	Sanitary
99	sanitair_maandverband_en_verpakkingen_ervan	Sanitary towel	Sanitary
18	sanitair_plastic_kam_borstel	Hair brush	PO hard
100	sanitair_tampons_en_tamponapplicators	Tampon (applicator)	Sanitary
102.3	sanitair_tissues_wc_papier	Toilet paper	Sanitary
101	sanitair_toiletverfrissers	Toilet refresher	PO hard

Table B1
Continued

Item ID	Description (Dutch)	Description (English)	Material category
102	sanitair_overig_sanitair	Other sanitary	Sanitary
103	medisch_verpakkingen	Medical packaging	Multilayer
104	medisch_spuiten	Syringe	Medical
105	medisch_overig_medisch	Other medical	Medical

Data Availability Statement

All data are openly available through http://doi.org/10.4121/19447199.

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