From source to sea: Floating macroplastic transport along the Rhine river

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ABSTRACT

Rivers are pathways and storage zones for plastic pollution. Land-based plastic waste enters river systems through anthropogenic and hydrometeorological processes, after which they are transported and retained. Only a fraction is assumed to make it into the ocean. Understanding and quantifying river plastic transport is important to optimize prevention and reduction strategies, and to evaluate the efficacy of any new regulations and interventions. To achieve this, consistent and reliable data are crucial. River plastic pollution monitoring is still an emerging field, especially river-scale plastic pollution assessments are limited to date. Here, we present an estimate of floating plastic transport and polymer characterization along the Rhine, from Switzerland to the river mouth in the Netherlands. We show that plastic transport is highly variable along the river, but with a significant increase towards the river mouth. High plastic transport was observed close to urban areas, and confluences with tributaries, suggesting both are likely to be entry points of plastic pollution. The largest plastic transport was measured in the estuary, which is explained by the tidal dynamics, limiting transport of plastic into the sea. Our results can be used as a baseline to compare with future assessments. Furthermore, the plastic transport and composition estimates can be directly compared to other rivers that applied the same approach, which may reduce the uncertainty in global river plastic emission simulations. With our study we aim to contribute to the development of a simple harmonized plastic monitoring approach to quantify plastic pollution at the river basin scale.

Keywords: Plastic pollution, harmonization, monitoring, marine litter, debris, hydrology, water quality

1 INTRODUCTION

Over the past decades, the use of plastic has increased. Because plastics are easy to produce, relatively cheap, and highly durable, they are now omnipresent (Andrady and Neal, 2009). As plastic is designed to last, it may take decades or longer before they are degraded (Delorme et al., 2021). This results in an accumulation of plastic in terrestrial and aquatic ecosystems (Barnes et al., 2009; Lebreton et al., 2018; van Emmerik et al., 2022b). Rivers have an important role in transporting land-based plastic waste towards and into the sea (Meijer et al., 2021). Furthermore, plastic pollution also has direct negative effects on river systems (van Emmerik and Schwarz, 2020; Meijer et al., 2021). To better understand plastic transport and accumulation dynamics in rivers, and to identify source and sink locations, catchment-scale monitoring efforts are needed (Windsor et al., 2019). In this paper, we present results from a first effort to quantify floating macroplastic (larger than 0.5 cm) along the Rhine, one of Europe's largest rivers.

One of the main challenges in understanding and reducing plastic pollution is the harmonization of monitoring strategies (González-Fernández et al., 2021). In recent years, several efforts have been made to provide guidelines for harmonization of specific methods (González-Fernández and Hanke, 2017), and development of monitoring strategies (Wendt-Potthoff et al., 2020). However, applications of those guidelines for river-scale assessments are limited. In this study, we demonstrate how the cost-effective visual counting method can be used to quantify floating macroplastic along the Rhine, from Switzerland to the river mouth in the Netherlands. For this method, the observer stands on the bridge and counts the floating plastics and other litter (González-Fernández and Hanke, 2017; van Emmerik et al., 2018). Visual counting measurements have been performed all over the world, and have proven to give an accurate estimate of the floating plastic transport in rivers (González-Fernández et al., 2021; Castro-Jiménez et al., 2019; van Calcar and van Emmerik, 2019). Using statistics on mean and median mass per plastic item, or using hydrological data, the plastic mass transport and emissions into the ocean can be estimated at daily, monthly or annual time scales. (Castro-Jiménez et al., 2019; van Emmerik et al., 2022a; de Lange et al., 2023). To date, such assessments have mainly been done for single locations within rivers. Estimating plastic transport along a river may however provide insights in potential sources and accumulation zones, which is in turn crucial for harmonized monitoring, prevention and reduction strategies.

This study focuses on quantifying the river plastic transport and composition along the Rhine. The Rhine is the largest river of Northwestern Europe, and flows through six countries. The Rhine basin is densely populated and industrialized and may therefore be regarded a 'blueprint' for other large rivers with considerable anthropogenic influence around the world. Previous work demonstrated the persistent abundance of microplastics along the Rhine (Mani et al., 2015, 2019), but similar assessments have not been made for macroplastics to date. Only around the Dutch part of the Rhine plastic transport has been estimated. Close to the river mouth around Rotterdam previous studies estimated the floating and total plastic transport between 1.3-156 kg/d (Vriend et al., 2020; van Emmerik et al., 2022a) and 55-85 kg/d (Blondel and Buschman, 2022), respectively. Around the Dutch-German border, floating mass transport was estimated at 1.6-77 kg/d. Here, we present an assessment of floating plastic pollution along the complete Rhine. Within a time frame of six days, we measured floating plastic transport and composition at 20 locations over a stretch of over 1100 km between Rotterdam (the Netherlands) and Tamins (Switzerland). Longitudinal profiles of river plastic pollution provides insights in the distribution along the river, and may identify source and sink locations. Furthermore it sheds light on the influence of urban areas as potential points of entry of plastic pollution, and the effect of river confluences and tributaries.

With this paper, we aim to contribute to a better understanding of the spatial distribution of plastic in large rivers. Our estimates can be used as a baseline for future comparison and assessing the efficacy of plastic pollution prevention and reduction measures. Finally, our approach can be used as a blueprint for developing similar monitoring strategies for other large and small rivers around the world.

2 METHODS

2.1 Study area

In this study, floating plastic was counted from twenty bridges between Rotterdam (the Netherlands) and Tamins (Switzerland), covering nearly the entire length of the Rhine river from source to mouth. This river belongs to the largest river systems in Europe, crosses four countries, and is characterised by a diverse land use ranging from dense industrial areas to nature reserves. The twenty bridges used as observation points were selected at equidistant intervals, as shown in 1 and Table 2.

2.2 Data collection and analysis

Data collection at the measurement locations was pursued through the visual counting method developed by (González-Fernández and Hanke, 2017), which has been used for floating plastic assessments in rivers worldwide (González-Fernández et al., 2021; Castro-Jiménez et al., 2019; van Calcar and van Emmerik, 2019). Two observers count floating plastic items in seven different plastic categories for a predetermined time interval and observation width. Based on the polymer composition of plastics, these categories are: PET, PO_{soft}, PO_{hard}, PS, Multilayer, PS-E (expanded polystyrene) and Other plastic. Each bridge was divided in four to six segments, which were strategically chosen using satellite imagery. The total number of segments per bridge is dependent on the length of the bridge, ensuring each segment covers a part of the river within the field of view of the observer. By default, each segment was measured four times for a period of five minutes, resulting in a total observation time of 80 - 120 minutes per bridge.

The floating plastic transport per polymer type F_{cat} for each bridge was subsequently calculated using equation 1. In this equation, I_{cat} the total observed items per segment per five minutes for each polymer type, R the river width at the measurement location [m], and O the observation width [m], which was estimated based on the bridge height and field-of-view of the observer. Taking the sum of all F_{cat} values results in the total plastic transport per measurement location [items/hr]. In addition, an estimate of the floating plastic mass transport M [kg/day] was made using plastic transport per polymer category F_{cat} [items/hr] and the mean/median mass statistics per category m_{cat} [g], summarized in Table 1 (equation 2). These mass statistics are based on 16,000 weighed macrolitter items collected from Dutch riverbanks (de Lange et al., 2023).

$$F_{cat} = \frac{I_{cat} \cdot 12 \cdot R}{O} \tag{1}$$

$$M = \sum_{cat=1}^{7} F_{cat} * \frac{m_{cat}}{1000} * 24 \tag{2}$$

Furthermore, we assessed whether there is a relation between the abundance of floating plastics and the presence of upstream cities. Using satellite imagery, a categorical classification was made for each measurement location, describing the presence of cities: city present on both banks (B), city present on one bank (O), no city present (N). This classification was then used in a pairwise Wilcoxon signed-rank test to assess any significant differences between the classes. In addition, a rapid comparison between item counts for B, O, and N was made by averaging the counts for each group and comparing the difference in plastic transport for B and O compared to N.

Item statistics	PET	PO_{soft}	PO_{hard}	PS	ML	EPS	Other plastic
Mean	34.9	11.1	6.4	2.7	16.4	3.2	0.2
Median	21.0	0.5	0.7	0.2	8.7	0.6	0.1

Table 1. Mean/Median statistics of the weight per item category in grams (de Lange et al., 2023).

Additional analyses were performed to assess a potential relationship between discharge [m^3/s] and observed item transport values [items/hr], using Spearman's rank correlation coefficient and Pearson's correlation coefficient. Historical daily discharge data of the Rhine was downloaded from the Global Runoff Data Centre (Bundesanstalt für Gewässerkunde, available online at https://grdc.bafg.de). An average discharge value for March was calculated using daily discharge data between 2008-2018 for sixteen different stations close to the measurement locations. Lastly, we tested whether an observer bias might be present and lead to skewed results. An observer bias might strongly influence the results when the measurements are done by inexperienced or a small number of people (van Emmerik et al., 2018; González-Fernández and Hanke, 2017). The bias was calculated for each measurement location by dividing the total counted items of one observer by the total counted items of the other observer.

3 RESULTS AND DISCUSSION

3.1 Increased floating plastic transport towards the Rhine mouth

A large range in plastic transport (3-988 items/hour) was found between the measured locations (table 2). The plastic transport close to the river mouth at Spijkenisse was more than three times as much than the plastic transport close to the source at Tamins. The mean plastic transport in the Netherlands (593 items/hour) is 11.2 times larger than the plastic transport in Switzerland (53 items/hour). The plastic transport in Germany (239 items/hour) is 4.5 times as large compared to the Switzerland. Figure 2 shows the plastic transport at the measured locations. In total, 84% of the counted items were plastic. Furthermore, of all the counted plastic, 76% was PO_{soft}. The category PO_{soft} consists of both PP and PE, and is mainly plastic foils and bags. Also in other studies on river debris, it is found that the large majority of found items is plastic: 94% (on riverbanks), 82%, and 84%, found by Bruge et al. (2018); González-Fernández et al. (2021); van Emmerik et al. (2022a), respectively.

Multiple explanations for these spatial differences exist. For example, urban areas and industrial sites could be important (point-source) contributors to river plastic pollution (LI et al., 2016), of which the presence increases with increasing river length. Although a general increase in plastic river transport is observed towards the river mouth, local differences exist between neighbouring measurement locations. For example, the plastic transport measured at Mainz is at least two times higher than the nearby locations up- and downstream (Koblenz (D), and Mannheim, respectively). This difference can have many different explanations, for example the dilution or input of plastic plastic by nearby tributaries, a temporary peak in plastic transport, or local wind effects. Another explanation could include (temporary) sinks of plastics on riverbanks, which is corroborated in van Emmerik et al. (2022b).

When considering the transport along the entire Rhine profile, a general trend can be derived. An exponential relation was fit ($R^2 = 0.54$) between the distance to the river mouth and the plastic transport expressed in kg/day (figure 2a). A study in the Adour river in the south of France by Bruge et al. (2018) derived an exponential function of similar nature to describe the increase in plastic item density on riverbanks as a function of distance towards the river mouth. It remains unclear to what extent an exponential function realistically describes the spatial variation in plastic transport or riverbank plastic density. However,

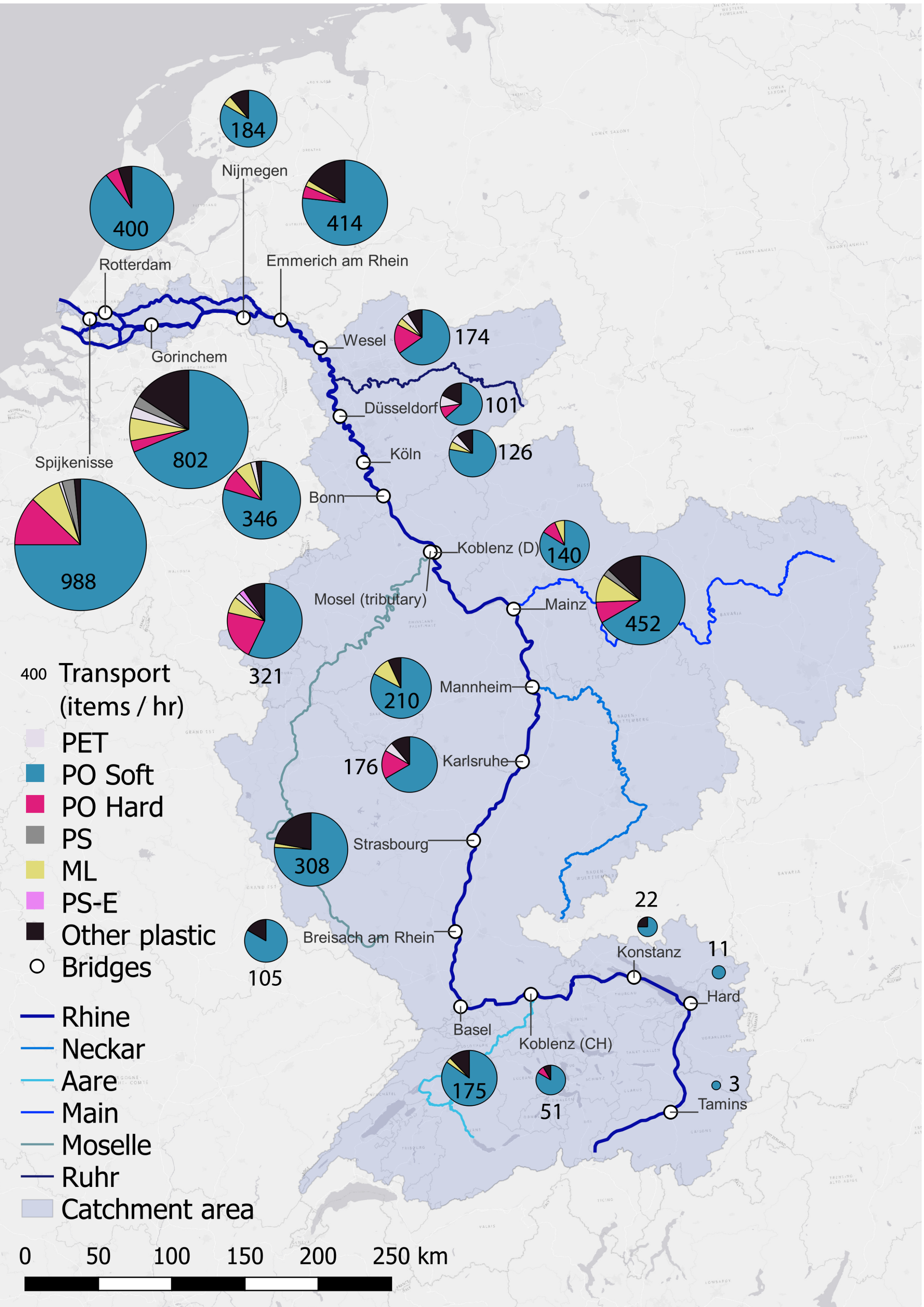

Figure 1. Measurement locations with associated plastic transport per hour, divided in seven categories. The Rhine catchment is the area in blue.

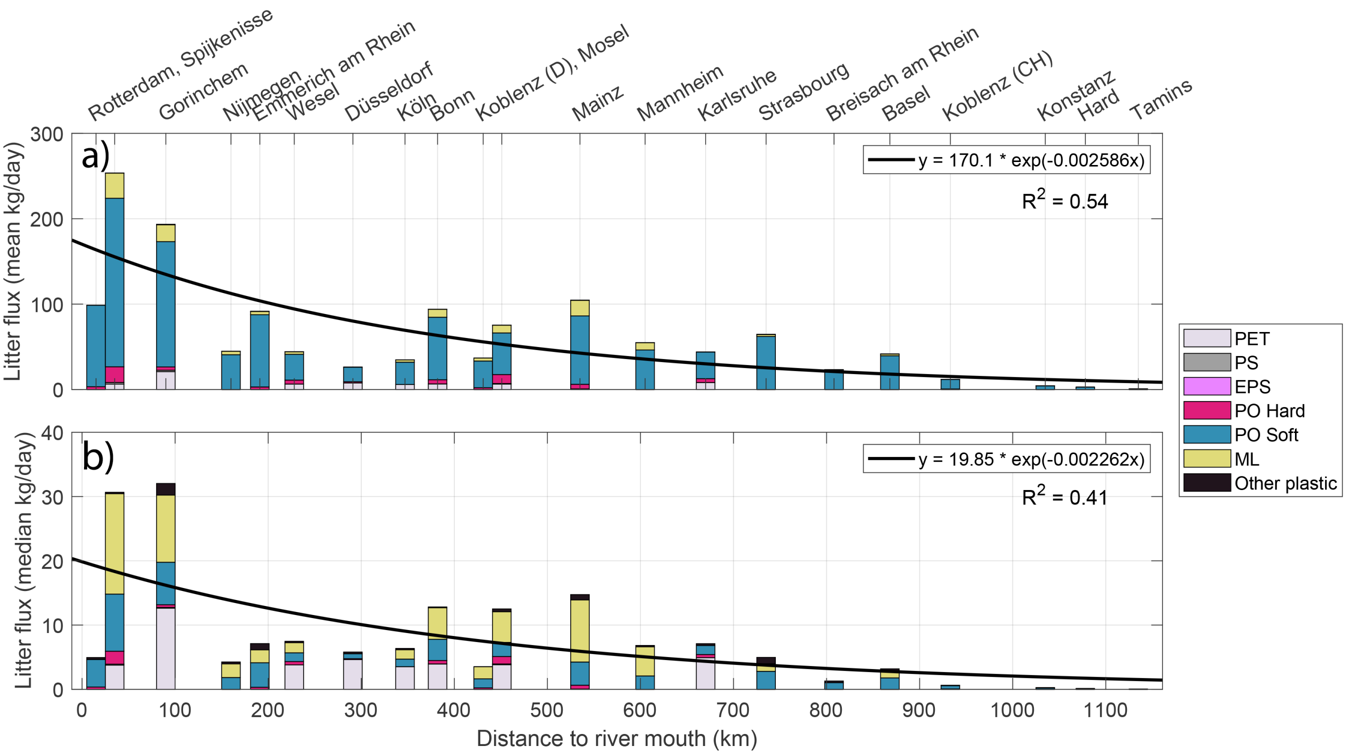

Figure 2. Litter transport (kg/day) along the profile of the Rhine river based on a) mean weight statistics, b) median weight statistics. Estimates of the transport can be an order of magnitude higher when using mean weight statistics compared to median weight statistics.The increasing plastic transport downstream is explained with an exponential function, similar to (Bruge et al., 2018).

such equations may be used for comparative analysis or to account for spatial variability in large-scale modeling efforts (such as (Meijer et al., 2021)).

Another study in the Rhine-Meuse delta shows plastic transport to be higher in downstream locations, compared to upstream locations within the borders of the Netherlands (van Emmerik et al., 2022a). Part of the explanation for this can be the tidal influence close by the sea. The river at Spijkenisse and Rotterdam in the Netherlands is influenced by the tide, with a bi-directional flow regime. In such cases, the net transport from tidal zone has been found to be relatively low Schreyers et al. (2022); Mani et al. (2023). According to Tramoy et al. (2020), tidal influence combined with wind direction are important factors for plastic accumulation and remobilization in estuaries. This effect can have an influence on the observed plastic transport in Rotterdam, Spijkenisse, and - to a lesser extent - Gorinchem. The estuarine region has been hypothesized to accumulate considerable amounts of plastic from rivers Harris et al. (2021), which is supported by our findings. Note that therefore the increased values of plastic transport in the tidal zone are not representative for the actual export into the ocean.

3.2 The role of urban areas and tributaries floating plastic transport

Plastic transport in the Rhine is 2.3 times higher for highly urbanized areas (urbanized riverbanks on both sides), than areas that were considered by non-urbanized land use. In case only one riverbank is urbanized, 1.5 times more plastic is found for non-urbanized riverbanks. This is in line with results found by van Emmerik et al. (2022a), who identified an increase of floating plastic downstream of urban areas. The increased abundance of floating plastic in the vicinity of urban areas suggests that urban areas are a source of river plastic pollution, or that plastics are more easily retained around urban infrastructure Tasseron

Location	Sampling date	Longitude	Latitude	Distance to mouth [km]	River width [m]	# segments	Urban riverbank	Plastic transport [#/h]
Rotterdam	23-03	51.90914	4.48656	25	500	6	Both	400
Spijkenisse	23-03	51.87132	4.33123	25	325	6	Both	988
Gorinchem	23-03	51.82754	4.9423	90	530	5	Right	801
Nijmegen	24-03	51.8526	5.85689	160	340	4	Left	184
Emmerich am Rhein	25-03	51.82916	6.22641	191	450	6	Right	414
Wesel	25-03	51.64557	6.60486	228	300	6	Right	174
Düsseldorf	25-03	51.22126	6.76341	291	350	5	Right	101
Köln	26-03	50.9309	6.96794	347	350	6	Both	126
Bonn	26-03	50.71777	7.1436	382	350	6	None	346
Koblenz (D)	26-03	50.35309	7.60458	441	200	6	Left	140
Mosel tributary	26-03	50.35908	7.56306	441	290	5	Right	320
Mainz	27-03	49.97444	8.32149	535	480	6	None	451
Mannheim	27-03	49.48948	8.44545	605	250	5	Right	210
Karlsruhe	27-03	49.03701	8.30319	670	255	4	None	176
Strasbourg	27-03	48.57432	7.80157	735	240	6	Left	307
Breisach am Rhein	28-03	48.02265	7.58179	808	301	7	None	105
Basel	28-03	47.56013	7.5897	868	230	6	Both	175
Koblenz (CH)	28-03	47.60858	8.23319	933	120	5	None	50
Konstanz	29-03	47.66623	9.17885	1035	145	5	Left	22
Hard	29-03	47.47781	9.66973	1078	70	4	None	11
Tamins	29-03	46.82378	9.40972	1135	75	4	None	3

Table 2. Overview of the bridges. Location is the name of the closest city to the measurement location. Breisach am Rhein consists of three separate canals of which the larger two were measured. These data were combined into the data shown. In Rotterdam, all segments were measured twice instead of four times due to time constraints and changing tide.

et al. (2022). For example, Willis et al. (2017) identified stormwater drains as a substantial outflow point of urban litter. In addition, dams and sluices could be clogged and act as temporary sinks of plastic litter (Lechthaler et al., 2020; van Emmerik et al., 2022b). Understanding the role of urban areas and its relation to river plastic pollution is key for optimizing cleanup strategies in various compartments (Helinski et al., 2021; Hohn et al., 2020). The influence of tributaries and their relative contribution to observed floating plastic transport should be studied in more detail. Quantitative data of plastics in river tributaries and their relation to pollution in downstream freshwater environments is limited and poorly understood (Guerranti et al., 2020). In this research, only one out of five tributaries (Mosel) was measured. Yet, the observed plastic transport at the Mosel tributary was more than twice as high as the plastic transport in the main river branch at Koblenz (D). Tributaries contribute to the total discharge in the main river, which can dilute or increase the plastic concentration in the water depending on the concentration of plastic in the tributary Wagner et al. (2019). A moderate relationship between discharge and observed item transport for sixteen out of twenty measurement locations (main river) was present (Pearson r = 0.55, p = 0.04, Spearman r = 0.55, p = 0.04). This implies some (unambiguous) factors other than discharge influence the magnitude of plastic transport. Changes in discharge and flow velocity at points where tributaries merge with the main can influence the plastic transport dynamics Haberstroh et al. (2021). Understanding and quantifying the contribution of individual tributaries may lead to more focused efforts to prevent and reduce plastic pollution in large river basins.

3.3 Observer bias

An observer bias was present, in which observer one structurally counted more items than a observer two. In total, the observer one observed 21.3% more items than observer two, which could possibly be explained by surface glint and water bubbles being misclassified as floating items. An overview of the observer bias calculation and statistics is summarized in 3 in the Supplemental Data section.

3.4 Recommendations for catchment-scale monitoring

Visual counting measurements from bridges are cost-effective compared to other measurement methods such as the use of cameras. However, there are various drawbacks to the method. Differences in bridge height, water turbidity, sun glare and other weather conditions might result in uncertainties of the total floating item counts(van Emmerik and Schwarz, 2020). In this research, a combination of these factors and a difference in experience resulted in an observer one to count 21.3% more items than an observer two. Since both observers measured every location twice, they have both measured each location for a similar time, resulting in a systematic bias. Elaboration on these results can be found in the supplementary materials. It is not clear what percentage of plastic transport can be observed by a researcher on a bridge, and how accurate the observations are. If the observer is not trained accurately to distinguish different types of plastic, not paying attention, or more sensitive to identify certain types of plastic, the accuracy of the counted items can be affected. Therefore, actual plastic transport in rivers might be different than reported. It will be beneficial to the method to research the percentage of plastic that can be seen by an observer, and relating it to turbidity, bridge height and measurement time. Further research should indicate whether these assumptions need to be changed for an improved measuring method. Systematical research on the method can be a first step: for example, visual observations should be combined with passive or active sampling to see if the observations correspond with the actual transport (for example combining bridge counting measurements with net sampling to be able to see the total plastic transport).

Contrary to the plastic transport found in this research, microplastic transport does not necessarily increase towards the river mouth. In this research, more plastic is found downstream than upstream. Mani et al. (2015) measured floating microplastic concentrations in the Rhine river at eleven locations and found a higher microplastic concentration in densely populated areas, especially the Ruhr area. In a study on the Danube, microplastic concentrations were also found to be higher around wastewater treatment plants and industrial areas (Kittner et al., 2022), with PE (PO$_{soft}$) dominating the polymer composition. However, in this research, the macroplastic transport is increasing towards the mouth of the river. That means that microplastics and macroplastics may behave differently in a river system and that for both, different estimation and removal strategies have to be developed.

The research was done in the last week of March 2022. During this week, the discharge at Lobith (where the Rhine enters the Netherlands) the recorded discharge was average 1547 m^3/s, which is considered normal discharge according to the Department of Waterways and Public Works of The Netherlands. Thus, the measurements were not done during a high discharge event. It has been shown that during high discharge, the plastic transport can increase as well (van Emmerik et al., 2022a; Cowger et al., 2022), as the plastic that is retained in the river is partly released. Therefore, the influence of high discharge peaks on the plastic transport in the Rhine river should be researched to get insight in the distribution of plastic at high discharge events and the amount of plastic retained in the river system.

Elements included in this research can form a blueprint for future catchment-scale monitoring of river plastic pollution. Here, a cost-effective approach was applied using a standardized method for quantifying floating plastic, allowing consistent comparisons of plastic pollution along an entire river profile. Future efforts could include repeated measurements at specific intervals to provide insights in temporal patterns, in addition to the spatial pattern studied here. Understanding different polymer types and their transport characteristics can provide further insights into the sources, pathways and sinks of riverine plastic pollution.

4 CONCLUSION

In this study we present the first longitudinal profile of floating macroplastic pollution along the Rhine, from Switzerland to the Netherlands. We found a significant increase in floating plastic transport from the source to the river mouth. The composition of the plastic items remains relatively similar along the Rhine, with soft plastics (PO_{soft}) as the most abundant plastic type. The high values measured at the river mouth do not necessarily equal export into the ocean, but rather reflect the potential retention capacity of the river estuary due to tidal dynamics (e.g. bidirectional flow). In addition, we observed an alternating pattern of increased and decreased plastic transport between the measurement locations along the profile. This can be explained by (1) an additional entry of plastic at point sources (e.g. tributaries and urban areas), (2) gradual accumulation of plastics in the water column, and (3) retention on riverbanks and at infrastructures. Lastly, we demonstrate that floating transport along the full extent of one of Europe's largest rivers can be assessed with cost-effective methods in a relatively short amount of time. This provides (1) a first baseline for macroplastic transport along the Rhine river, and (2) a framework for future assessments of other river systems. With this paper, we aim to contribute to further harmonization of river plastic monitoring, and shed new light on the spatial variation of floating macroplastic transport in large river basins.

CONFLICT OF INTEREST STATEMENT

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.

AUTHOR CONTRIBUTIONS

Conceptualization: BK, TvE; Methodology: BK, PT, TvE; Formal Analysis: BK, PT, TvE; Investigation - Data collection: BK; Visualization: BK, PT; Data curation: TvE; Writing–original draft: BK, PT, TvE; Writing–reviewing and editing: all authors; Supervision: TvE; Project administration: TvE, KWP; Funding acquisition: TvE, SK, CS, KWP.

FUNDING

This research was partly funded by the World Water Quality Alliance (WWQA) a programme supported by the UN Environment Programme (UNEP) and the Joint Research Centre (JRC) of the European Commission. The work of PT was supported by the project Solving the Urban Plastic Soup, which is (partly) funded by the the SESA programme (Subsidie Economische Structuur en Arbeidsmarktversterking) of the City of Amsterdam, the directie Stadswerken (Programma Plastic Smart City) of the City of Amsterdam, the Netherlands Ministry of Infrastructure and Water Management, Directorate-General for Public Works and Water Management (Rijkswaterstaat), and Waternet. The work of TvE was supported by the Veni research program The River Plastic Monitoring Project with project number 18211, which is (partly) funded by the Dutch Research Council (NWO).

ACKNOWLEDGMENTS

We thank Daan Aarts for joining the data collection along the Rhine. We thank Christian Schmidt and Sabrina Kirschke for their input during the project and their feedback on an earlier version of the manuscript.

SUPPLEMENTAL DATA

DATA AVAILABILITY STATEMENT

The dataset for this study can be found at the 4TU Repository `http://doi.org/10.4121/21763220`.

	Observer one					Observer two				
Location	Mean	Std	St. Error	Rel. Error	Item count	Mean	Std	St. Error	Rel. Error	Item count
Rotterdam	3.33	1.75	0.71	0.21	20	1.67	1.37	0.56	0.33	10
Gorinchem	4.30	3.10	0.98	0.23	43	1.70	1.34	0.42	0.25	17
Spijkenisse	6.08	3.22	0.93	0.15	73	5.92	4.25	1.23	0.21	71
Nijmegen	1.25	1.04	0.37	0.29	10	1.00	1.07	0.38	0.38	8
Emmerich am Rhein	1.83	1.64	0.47	0.26	22	2.00	1.60	0.46	0.23	24
Wesel	1.33	1.42	0.41	0.31	16	1.17	1.27	0.37	0.31	14
Düsseldorf	0.50	0.85	0.27	0.54	5	0.70	0.82	0.26	0.37	7
Köln	0.67	1.08	0.31	0.47	8	0.58	0.51	0.15	0.25	7
Bonn	2.33	1.27	0.37	0.16	28	1.83	1.19	0.34	0.19	22
Koblenz (D)	1.75	1.86	0.54	0.31	21	1.17	1.27	0.37	0.31	14
Mosel tributary	2.60	2.98	0.94	0.36	26	1.90	3.03	0.96	0.51	19
Mainz	1.92	0.94	0.27	0.14	23	2.08	2.43	0.70	0.34	25
Mannheim	1.70	1.60	0.50	0.30	17	1.40	1.35	0.43	0.30	14
Karlsruhe	2.00	0.92	0.32	0.16	16	1.25	0.89	0.31	0.25	10
Strassbourg	3.00	1.16	0.34	0.11	36	2.25	1.36	0.39	0.17	27
Breisach am Rhein	1.00	0.71	0.25	0.25	8	1.00	1.07	0.38	0.38	8
Basel	1.50	1.00	0.29	0.19	18	1.67	0.89	0.26	0.15	20
Koblenz (CH)	0.90	0.79	0.25	0.28	9	0.60	0.97	0.31	0.51	6
Konstanz	0.40	0.48	0.15	0.38	4	0.20	0.42	0.13	0.67	2
Hard	0.25	0.46	0.16	0.65	2	0.25	0.46	0.16	0.65	2
Tamins	0.00	0.35	0.13	0.00	0	0.00	0.00	0.00	0.00	0
Mean	1.84	1.36	0.43	0.27	19.29	1.44	1.31	0.41	0.32	15.57
Total					421					340

Table 3. Overview of the observed items per measurement location, with statistics to compare an observer one with observer two. The difference in the total item count between both observers is 21.3%

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