

River plastic transport and deposition amplified by extreme flood

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Plastic pollution in the world's rivers and ocean is increasingly threatening ecosystem health and human livelihood. In contrast to what is commonly assumed, most mismanaged plastic waste that enters the environment is not exported into the ocean. Rivers are therefore not only conduits but also reservoirs of plastic pollution. Plastic mobilization, transport and retention dynamics are influenced by hydrological processes and river catchment features (for example, land use, vegetation and river morphology). Increased river discharge has been associated with elevated plastic transport rates, although the exact relation between the two can vary over time and space. However, the precise role of an extreme discharge event on plastic transport is still unknown. Here we show that fluvial floods drive macroplastic (>2.5 cm) transport (items h^{-1}) and accumulation (items m^{-2}) in river systems. We collected unique observational evidence during the July 2021 flood along the whole Dutch part of the Meuse. Plastic transport multiplied by a factor of over 100 compared with non-flood conditions (3.3×10^4 versus 2.3×10^2 items h^{-1}). Over one-third of the modelled annual plastic item transport was estimated to occur within 6 days of extreme discharge. Between Maastricht and Ravenstein (291 km and 131 km from the river mouth), plastic transport during the flood period decreased by 90%, suggesting that the dispersal of plastic mobilized during the flood is limited due to the entrapment on riverbanks, in vegetation and on the floodplains. Plastic transport and accumulation on the riverbanks decreased significantly along the river, corroborating the river's function as a plastic reservoir. Using new observational evidence, we demonstrate the crucial role of floods as drivers of plastic transport and accumulation in river systems. Floods amplify the mobilization of plastics, but the effects are local, and the river-scale dispersal is limited. We anticipate that our findings will serve as a starting point for improving global estimates of river plastic transport, retention and export into the sea. Moreover, our results provide essential insights for future large-scale and long-term quantitative assessments of river plastic pollution. Reliable observations and a fundamental understanding of plastic transport are key to designing effective prevention and reduction strategies.

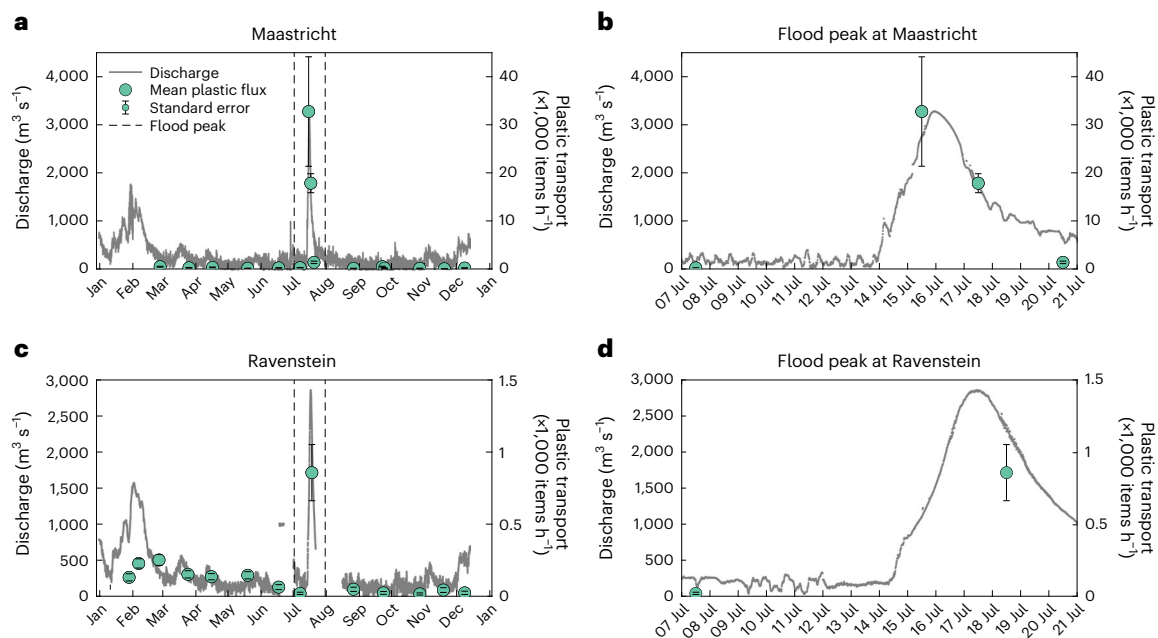


Fig. 1 Plastic transport along the Dutch Meuse river measured at during 2021, including the extreme flood event on 13–20 July 2021. **a–d**, River discharge and plastic transport at Maastricht (291 km from the river mouth) from January to December 2021 (**a**), at Maastricht during the July flood (**b**), at

Ravenstein (131 km from the river mouth) from January to December 2021 (**c**) and at Ravenstein during the July flood (**d**). Note that we refer to the mean plastic flux in the text.

Plastic pollution is an emerging environmental threat, negatively impacting oceans, lakes and rivers around the world^{1,2}. Rivers are assumed to act as main pathways for land-based plastic waste towards the ocean³. However, an increasing amount of observational evidence suggests that most mismanaged plastic waste accumulates on land, on riverbanks, in vegetation or within estuaries⁴. Here it can be retained for years, decades or even longer. River plastic transport and retention are mainly driven by hydrological factors and river characteristics. The seasonal variation of floating plastic transport is in many cases related to river discharge, where increased discharge generally leads to larger transport rates^{5,6}. In particular, river discharge peaks have been hypothesized to play an important role in the transport and retention dynamics of plastics in rivers^{7,8}. Understanding the response of plastic transport and retention to extreme discharge conditions, including floods, is crucial for optimizing prevention and reduction strategies.

Floods play a key role in the transport and retention dynamics of plastic pollution. Additional plastics are mobilized as a result of increased water level and flow velocity, and may either flow directly into the aquatic environment or be conveyed through urban drainage and sewer systems^{9,10}. Accumulated plastics in sediment, on riverbanks or in the floodplains may also be re-mobilized once the water level and flow velocity become high enough^{7,9,11}. At the global level, it has been estimated that floods with a return period of 10 years already result in a tenfold potential mobilization of plastic waste compared with non-flood conditions. The effect of floods on river plastic pollution is not unambiguous. Floods flush additional plastics into the river, but increased water levels may also lead to additional entrapment of plastics in riparian vegetation, and deposition on the floodplains^{4,12}. Floods therefore act as drivers of both transport and accumulation. As observations at the catchment scale are scarce, the role of floods on plastic transport and accumulation remains unresolved.

In this Article, we investigate the effect of extreme discharge during the July 2021 flood on macroplastic (>2.5 cm) transport and retention along the whole Dutch Meuse. Between 13 and 20 July, severe floods struck in Western Europe, leading to massive destruction and casualties in Belgium and Germany¹³. Although direct damage caused

by the floods in the Netherlands was limited, discharge records were broken. The observed discharge and water level of the Meuse at Maastricht were extremely rare, and had a return period of 200 years¹⁴. As part of a 1 year monitoring campaign⁵, we quantified floating plastic transport during the 6 day flood wave at three locations along the Dutch Meuse. Directly after the flood we sampled plastics on 25 riverbanks, from the Dutch–Belgian border to the downstream confluence of the Meuse and Rhine. So far, no river plastic transport and accumulation has been observed during such an extreme flood event. We use this unique dataset to (1) explore the role of extreme discharge as driving factor of plastic transport, (2) demonstrate the limited dispersal of plastics along the river during and after a flood, and (3) quantify the relative contribution of the flood to the modelled total annual plastic transport.

Floods amplify plastic transport

Plastic transport at Maastricht (291 km from the river mouth) responded strongly to the increase in river discharge (Fig. 1). During the flood peak on 15 July 2021, a mean daily plastic transport of 3.3×10^4 items h^{-1} was measured. The largest observed instantaneous plastic flux was 8.4×10^4 items h^{-1} at 15:00. Compared with the mean daily transport during non-flood conditions (2.3×10^2 items h^{-1}), this is an amplification by a factor 141 and 363, respectively. For the non-flood conditions, we averaged all measurements taken between January and December 2021. The relative error in the plastic transport at Maastricht was estimated at 7.3% for non-flood conditions, and 22.6% for flood conditions. Similar to the falling limb of the hydrograph, the mean daily plastic transport decreased in the days after the peak (1.8×10^4 items h^{-1} on 17 July and 1.4×10^3 items h^{-1} on 20 July). At Ravenstein (131 km from the river mouth), the discharge peak was similar in magnitude (around $3,000 \text{ m}^3 \text{ s}^{-1}$), but arrived 2 days later, on 17 July. Plastic transport was measured on 18 July (8.6×10^2 items h^{-1} , 22.7% relative error), and showed an increase by a factor of six compared with non-flood conditions (1.5×10^2 items h^{-1} , 8.0% relative error). At Moerdijk (49 km from the river mouth), the measured transport during the flood was 1.6×10^3 items h^{-1} (25.0% relative error), which is five times higher

than the average during non-flood conditions (3.5×10^2 items h^{-1} , 8.0% relative error). Moerdijk is located downstream of the confluence with a branch of the Rhine, and the observed plastic is therefore expected to be transported there by both rivers. This area is situated within the tidal zone of the Rhine–Meuse delta, and due to the bidirectional flow the net transport of plastics from this area is assumed to be low, as the area functions as a (temporary) sink of plastic pollution¹⁵. As no discharge data were available for Moerdijk, further analysis were not done for this location.

The peak daily mean plastic transport values of 3.3×10^4 items h^{-1} at Maastricht are among the highest measured so far globally. In Europe, the highest plastic transport values were between 1.0×10^2 and 1.0×10^3 items h^{-1} in rivers such as the Danube (Romania), Vistula (Poland) and Llobregat (Spain)¹⁶. Only in rivers such as the Saigon (Vietnam), Ciliwung (Indonesia) and Meycauyan (Philippines), daily mean transport values ranging between 1.0×10^4 and 1.0×10^5 have been measured so far¹⁷. Note that, for the rivers in Ciliwung and Meycauyan, data were collected only during low and medium flow conditions. Besides confirming the increasing effect of floods on plastic transport, this also emphasizes the urgent need for better coverage of extreme events during monitoring efforts. Some previous work collected plastic transport data around, or in the aftermath of, large rainfall or extreme discharge events^{18,19}. However, assessments of plastic transport during peak events are still scarce. Current global modelling approaches do not realistically take into account the effects of seasonality nor peak events^{1,3}, and mostly calculate plastic emission or leakage estimates using yearly averaged input data. Accounting for seasonality and peak events may result in more accurate model estimates, and in more realistic timing of plastic mobilization, transport and emissions.

Discharge as a driving factor of floating plastic

Although we found a significant correlation between discharge and plastic transport (Maastricht: $\rho = 0.53$, $p < 0.05$; Ravenstein: $\rho = 0.65$, $p < 0.02$), the exact relation remains unresolved. Recent work demonstrated that discharge alone is a poor generic predictor for plastic transport, as the correlation between the two can vary greatly between and within rivers^{5,20}. Our work feeds the hypothesis that plastic transport can occur in two different transport modes, depending on whether there are normal flow conditions or flood conditions (Fig. 2). During normal flow conditions, plastic transport may also be heavily impacted by wind speed and direction, retention dynamics, navigation and infrastructure, resulting in non-unique relations between discharge and plastic transport²¹. Flood conditions, and especially extreme events, lead to a second transport mode during which both discharge and increased plastic concentrations in the water are the governing drivers of mobilization and transport. When the water level exceeds the embankment level, the riverbanks and floodplains become inundated. The increased cross-sectional profile results in additional plastics being (re)mobilized, which locally leads to increased plastic concentrations. The inflection point may therefore mark the transition between transport modes during normal and flood conditions, which is probably the result of inundations of the floodplains, additional input from flooded tributaries, and higher plastic concentrations in the aquatic environment.

The modelled total annual transport is estimated (Methods) between 0.6×10^6 (model 2) and 0.8×10^6 (model 1) items per year in Ravenstein, and between 8.4×10^6 (model 1) and 10.0×10^6 (model 2) items per year in Maastricht. Note that the range comes from using the two different models (Methods). For Maastricht, the values are 3.1–5.6 times higher than previous estimates that used linear extrapolation of the observed mean and median plastic transport. For Ravenstein our values are within the same range, but up to 0.5 times lower than reported by Emmerik et al.⁵. This again shows that the effect of the flood at Ravenstein was relatively small, compared with the strong response in plastic transport at Maastricht. The decrease in transport suggests

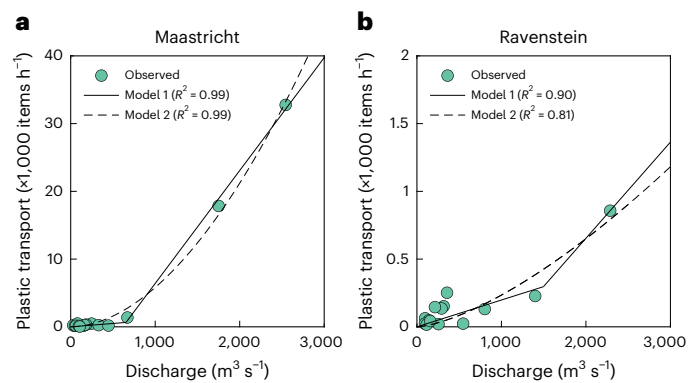


Fig. 2 | Modeled plastic transport. We fitted two models to describe the observations. The first model is a linear model with two transport modes to account for flood and non-flood conditions. The two modes are represented by a larger gradient in the linear relation between discharge and plastic transport. The second model is a power function. For more details on the model fitting, see Methods. **a, b**, Observed plastic flux and discharge at Maastricht (**a**) and Ravenstein (**b**).

that between 90% and 94% (using minimum and maximum differences between estimates at Maastricht and Ravenstein from models 1 and 2) of the plastic mobile in Maastricht is retained. For Maastricht, 29–33% of the annual transport occurred during the 6 day flood period (13–14% for Ravenstein). Similar to other types of debris or sediment transport, plastic transport is driven by hydrological peak events^{22–24}. The temporal distribution of plastic transport is therefore skewed, with most plastic transport occurring in limited time. The annual high discharge peak in February transported around 38–46% of the annual transport at Maastricht, and 2–3% at Ravenstein. However, the total plastic transported during the February discharge peak was distributed over a period of several weeks, rather than 6 days.

Roebroek et al.⁸ estimated that floods lead to ten times more plastic mobilization globally, with specific rivers and regions reaching multiplication factors of five orders of magnitude. Our results show that the local processes and proximity to sources are however important for the plastic mobilization and retention dynamics. Whereas Roebroek et al.⁸ estimated only river catchment-lumped multiplication factors, we show that the multiplication of plastic transport within the Meuse ranged from 141 (Maastricht) to 5 (Ravenstein). Also, Roebroek et al.⁸ only estimated the plastic mobilization, whereas our study sheds additional light on the retention of plastics after floods. An important factor that was not taken into account in the work of Roebroek et al.⁸ is the retention of plastics on riverbanks and floodplains. A comparison of the average plastic transport during the flood at Maastricht and Ravenstein suggests that 90–94% of the plastic transport upstream is retained on the 130 km river stretch between Maastricht and Ravenstein. Floods amplify the mobilization of plastics, but the downstream transport seems to be limited.

Limited transport towards the river mouth and sea

Plastic accumulation after the flood decreased significantly from upstream to downstream (Spearman $\rho = 0.76$, statistical P value < 0.01). The largest plastic density was found at the most upstream location north of Maastricht (5.8 items m^{-2}). The mean item density at the 10 upstream locations (1.3 items m^{-2}) was 15 times higher than at the 15 downstream locations (0.09 items m^{-2}). The mean upstream plastic density is 13 times larger than the mean plastic density along the Dutch Meuse as measured between 2017 and 2019 (0.1 items m^{-2}), but the mean downstream plastic density was similar¹⁵. The decrease of plastic density in the downstream direction is partly explained by the attenuation of the discharge peak as it propagates through the river. At Maastricht the measured discharge had a return period of 200 years, but around Gennep (27 km upstream of Ravenstein) the return period decreased

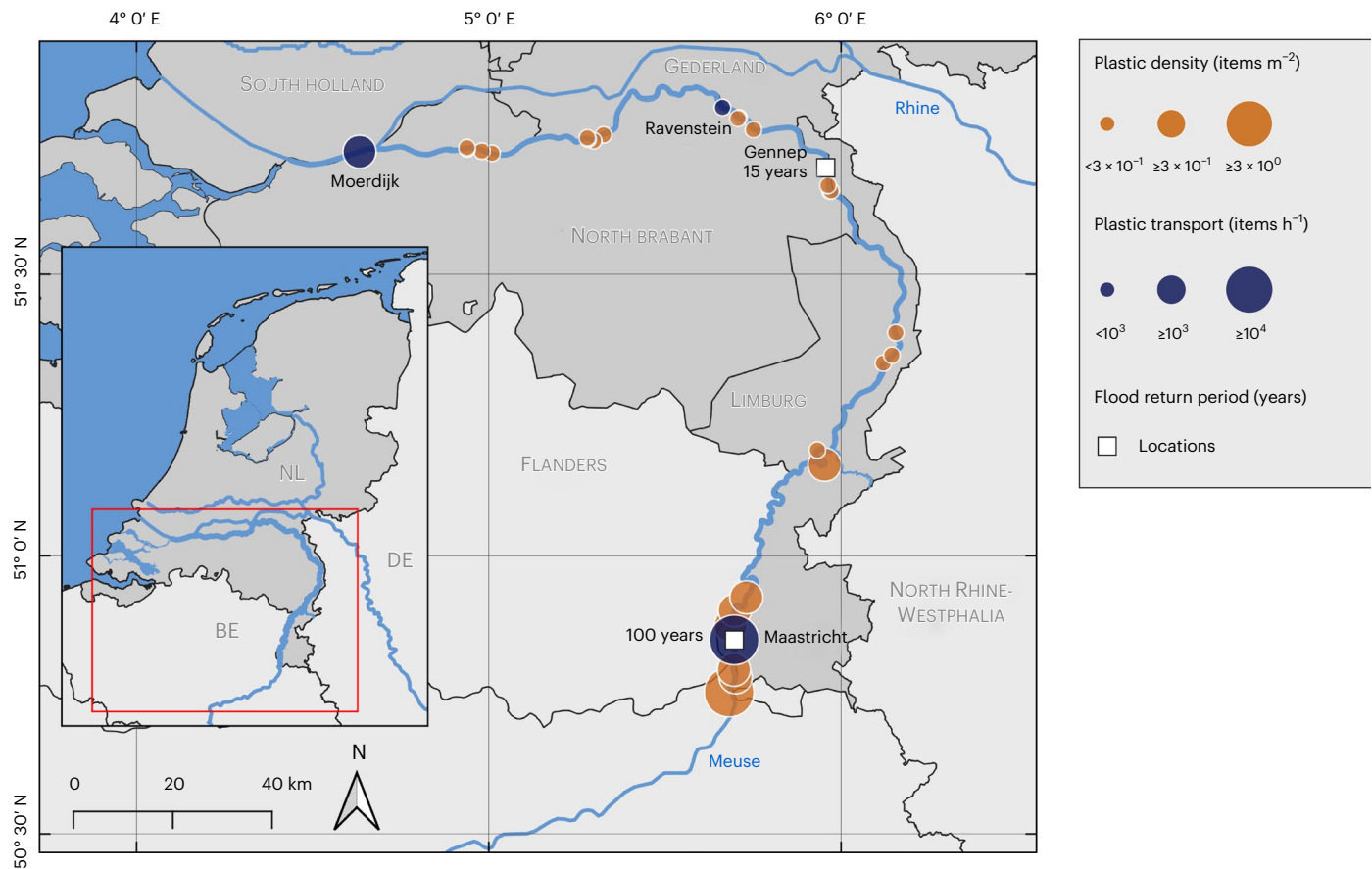


Fig. 3 | Mean floating plastic transport and riverbank plastic density along the Meuse. Mean floating plastic transport at Maastricht (15, 17 and 20 July), Ravenstein (18 July) and Moerdijk (18 July) during the July flood (15–20 July 2021), and riverbank plastic density at 25 locations measured after the flood (22 July to 4 August 2021).

to 15 years¹⁴. Dedicated retention zones and other areas with temporary storage capacity along the Meuse probably contributed to the attenuation of the flood wave. The attenuation effect of the discharge peak leads to lower flow velocity and water levels, which in turn results in deposition of mobile plastics. The net transport of plastics mobilized by the flood towards the sea is therefore expected to be limited.

The spatial distribution of the found plastics may also be explained by the proximity to likely sources. Several major cities, including Liège and Namur (20 km and 80 km upstream from Maastricht), are located not too far upstream along the Meuse. As the flood was most severe in the Belgian part of the Meuse, a share of the upstream plastic may also originate from there. Additional input from the Geul (58 km long, 121 km², mean discharge 4 m³ s⁻¹) and Rur (165 km long, 2,361 km², mean discharge 23 m³ s⁻¹) rivers is expected downstream of Maastricht, as both also experienced extreme discharge (return periods of 100 and 1,000 years, respectively)¹⁴. The Geul and Rur rivers had an estimated peak discharge of 100 and 270 m³ s⁻¹ during the flood, which jointly accounted for over 10% of the total Meuse discharge. The Geul, Rur and Meuse exceeded bankfull capacity during the flood. For the Meuse this mainly led to flooded floodplains. Towards Ravenstein, the additional plastic mobilized and transported by the flood wave was probably much lower. The limited extent of the high plastic concentrations on riverbanks is in line with the spatial variation in plastic transport (Fig. 3).

The variable observation duration at the three plastic transport measurement locations may have introduced some uncertainty. Both Ravenstein and Moerdijk were observed for a shorter time (18 July) than Maastricht (15, 17 and 20 July). The peak discharge occurred on 15 July in Maastricht, on 18 July in Ravenstein and on 19–20 July in Moerdijk. It is therefore uncertain if we observed the highest plastic transport value

in Ravenstein and Moerdijk. The spatial distribution of the post-flood riverbank plastic suggests that the majority of the mobilized plastic accumulates relatively close to the location it was (re)mobilized, corroborating the hypothesis of limited dispersal. Similar dynamics were observed by Weideman et al.²⁵ who found that macroplastics deposit close to their sources. Other work by Ryan and Perold²⁶ showed that plastic transport was linked to rainfall peaks, but the travel distance was limited.

Discussion

Floods have a clear effect on plastic transport and distribution in rivers. One of the main open challenges is the development of effective and harmonized monitoring strategies. So far, only few efforts have been made to structurally collect data on riverine plastic transport. A key step forward was the harmonization project RIVERine and Marine floating macro litter Monitoring and Modelling of Environmental Loading (RIMMEL), during which data were collected in over 40 rivers across Europe¹⁶. Unfortunately, most data collection was done right before or after peak rainfall or discharge events. For future monitoring efforts, we therefore suggest to complement fixed observation frequencies (for example, weekly or monthly) with flexible observations that can be scheduled on the basis of flood forecasts.

Closing the plastic mass balance for terrestrial, riverine and marine systems remains an open challenge^{27,28}. Our estimates show that a single 6 day flood event can transport 29–33% of the annual plastic item transport. Extreme events mobilize and disperse plastics very differently compared with normal conditions, as the driving forces are larger and the river water interacts with a larger surface area. Increased flow velocity, and therefore turbulence, may also affect the vertical

distribution of plastics^{29,30}. Especially neutrally buoyant items may have been transported below the surface. Furthermore, the types of plastic that are mobilized during such events can be very different compared with non-flood conditions. During flood conditions, much larger and heavier items are mobilized and transported, including waste bins, furniture and household items³¹. As such items have larger mass than plastics found during non-flood conditions (for example, soft fragments and food packaging), multiplication of plastic mass transport may be even larger than plastic item transport during flood conditions. We therefore consider our estimate of the contribution of floods to plastic mass transport as conservative. Future work should focus on providing more reliable conversion statistics to estimate the mass transport from item transport²⁰.

The temporal distribution of plastic transport also influences the optimization of prevention and solution strategies. Currently available plastic removal systems are often designed on the basis of estimates of annual or, at best, monthly plastic transport. In case large portions of the annual load are transported in short periods (for example, 30% of annual load in 6 days for the Meuse), removal technologies and strategies may need considerably different designs. Mitigating the effects of plastic pollution from floods or other extreme events may benefit from rapid response approaches (such as done after oil or chemical spills), rather than continuous extraction of relatively low plastic loads from the environment.

Recommendations

We recommend further fundamental work on plastic mobilization and retention dynamics, through both controlled and large-scale experiments, with a focus on quantifying (1) mobilization thresholds, (2) plastic transport velocities in response to varying driving forces, and (3) deposition thresholds. Controlled experiments may shed light on what stream flow velocities or water levels result in either mobilization or deposition, and how this is different under flood and non-flood conditions^{29,32,33}. Additional observations using Global Positioning System trackers allow for catchment-scale and long-term investigations of the mobilization and retention dynamics under natural conditions^{34,35}. We furthermore recommend to invest in more and better observations of plastic transport during flood conditions. Conventional methods, including net sampling or visual counting, are often not suitable due to dangerous conditions. Therefore we suggest to explore the use of image-based techniques for continuous observations, also during extreme events³⁶. The recent development of non-invasive methods based on sonar may be used to also quantify plastic transport below the surface, which will decrease the uncertainty in the vertical distribution of plastics during flood and non-flood conditions³⁷.

Finally, we emphasize that plastic pollution is very heterogeneous, with strongly varying characteristics (for example, size, shape and effective buoyancy)³⁸. As a consequence, any effort to estimate total plastic transport will come with uncertainty as long as its diversity is not accounted for. Sediment research offers several concepts that can be applied to plastic transport, including describing and accounting for diversity in particle characteristics³⁹. Recent work has proposed to characterize plastic more probabilistically to account for this diversity⁴⁰, although for macroplastic this has not been done so far. Further development of mechanistic transport models will benefit from accounting for particle variability of plastic pollution more realistically, for which additional and more detailed observational evidence is crucial.

Conclusions

The July 2021 Meuse flood amplified plastic transport up to 141 times during the discharge peak in the most upstream reach of the Dutch Meuse. The observed peak plastic transport was of similar magnitude as some of the most polluted rivers measured so far. Both the flood wave and plastic transport were dampened over the length of the river, as

further downstream only a multiplication factor of 5 in plastic transport values was found.

More than 29–33% of the modelled total annual plastic transport occurred during the 6 day flood events in the upstream reach of the Dutch Meuse. Our results suggest that the temporal distribution of plastic transport is heavily skewed, especially during years with extreme flood events. Better accounting for the temporal variation in plastic transport will contribute to decreasing uncertainties in global river plastic emission models, and further improvement of monitoring, prevention and reduction strategies.

Plastic transport decreased by 70–90% within a 131 km stretch of the Meuse, suggesting increased accumulation within the river. Riverbank plastic density was found to be nearly six times higher in the upstream sections compared with the downstream sections of the Meuse. For the areas most affected by the flood, the riverbank plastic density was ten times larger than under non-flood conditions. The observed damping effect is mainly caused by the retention of plastics on riverbanks. Our findings support the theory that most plastics are retained within rivers, and that emissions into the ocean are rather limited.

With our paper we demonstrate that floods are one of the main drivers of plastic mobilization, transport and retention in river systems. To better understand the role of extreme events on plastic pollution, further fundamental and observational work on the mobilization, transport and retention dynamics is needed.

Methods

Floating plastic observations

We measured macroplastic using the visual counting method first developed by González-Fernández and Hanke⁴¹. Floating plastic items are counted from bridges by trained observers for a specific duration of time. All observations were done facing the downstream direction of the river. This method allows for observations of surface and near-surface items larger than 2.5 cm (ref. 41). Note that we counted all litter items, but since the majority of the categorized items under non-flood conditions are plastic (~90%) (ref. 5) we indicate all items (that is, metal, paper, glass, sanitary, medical, rubber, textile and anthropogenic wooden) as such throughout this paper. Under non-flood conditions it is often possible to also categorize the observed litter items, but during the flood the transport was too high to accurately do so.

Work by van Lieshout et al.⁴² suggests that, compared with camera-based monitoring, visual counting may underestimate the total plastic transport above a certain threshold. Above certain plastic transport values, it becomes more difficult to count all items. On the basis of data from Jakarta rivers, it was estimated that above 10–15 items $\text{min}^{-1} \text{m}^{-1}$ width there is a structural underestimation by visual counting. At 35 items $\text{min}^{-1} \text{m}^{-1}$ width, this can reach up to 40% difference. During the flood measurements in the Meuse, the maximum value was 8.3 items $\text{min}^{-1} \text{m}^{-1}$ width. Therefore we assumed that the uncertainty during the flood measurements was not higher than during non-flood periods. Observations were done at three locations along the Dutch Meuse, that is, Maastricht, Ravenstein and Moerdijk. Maastricht is located 291 km from the river mouth and is characterized as an urbanized area (over 120,000 inhabitants). Ravenstein is located 131 km from the river mouth, has just over 3,000 inhabitants and is surrounded by a rural landscape. Moerdijk is located at the confluence of the Meuse and a branch of the Rhine, at 49 km from the river mouth. The municipality has over 37,000 inhabitants, and includes chemical industry plants and a seaport zone along the Rhine–Meuse. For each bridge, 5–12 cross-sectional observation points were defined, depending on the river width. At all observation points a fixed track width was determined, that is, the part of the river cross section in which all floating plastic items were counted. The track width varied between 11 and 33 m. During each measurement day, all observation points were measured two to four times, for a duration of 5 min each time. We then calculated the daily

Table 1 | Overview of the measurement locations for the floating plastic transport observations, including the distance to the river mouth, the coordinates, the sampling dates, the measurement location characteristics and total counted items.

Location	Distance to river mouth (km)	Coordinates		Dates	Floating/riverbank	Floating			
		Latitude	Longitude			River width (m)	Segments	Segment width (m)	Observed items
Maastricht	291	50.8462	5.6973	March to December 2021	Floating	110	6	11–33 m	4,441
Ravenstein	131	51.7690	5.7358	January to December 2021	Floating	120	5	20–22 m	541
Moerdijk	49	51.7184	4.6361	January to December 2021	Floating	1,000	12	28 m	556

Table 2 | Overview of the measurement locations for riverbank plastic density observations, including the distance to the river mouth, the coordinates, the sampling dates, the measurement location characteristics and total counted items.

Location	Distance to river mouth (km)	Coordinates		Dates	Floating/riverbank	Riverbank				
		Latitude	Longitude			Width (m)	Length (m)	Area (m ²)	Total observed items	Plastic items
L1	302	50.7554	5.6817	22 July 2021	Riverbank	4	15	60	349	167
L2	299	50.7823	5.7001	22 July 2021	Riverbank	4	10	40	72	41
L3	297	50.7959	5.6953	24 July 2021	Riverbank	6	12	71.4	176	92
L4	289	50.8747	5.6860	24 July 2021	Riverbank	6	15	90	55	34
L5	284	50.9022	5.6980	23 July 2021	Riverbank	6	73	438	186	165
L6	279	50.9255	0.7307	23 July 2021	Riverbank	6	38	228.6	118	102
L7	231	51.1622	5.9527	28 July 2021	Riverbank	6	26	155	100	95
L8	227	51.1880	5.9321	28 July 2021	Riverbank	6	126	758	129	119
L9	201	51.3424	6.1192	29 July 2021	Riverbank	6	60	360	83	77
L10	199	51.3565	6.1435	29 July 2021	Riverbank	6	57	340	76	72
L11	194	51.3963	6.1547	29 July 2021	Riverbank	6	40	240	11	8
L12	157	51.6475	5.9679	04 August 2021	Riverbank	6	39	232	11	8
L13	157	51.6480	5.9710	04 August 2021	Riverbank	6	66	396	54	24
L14	156	51.6574	5.9622	04 August 2021	Riverbank	6	25	150	28	26
L15	133	51.7555	5.7507	30 July 2021	Riverbank	6	43	260	18	14
L16	129	51.7763	5.7100	30 July 2021	Riverbank	6	40	242	14	14
L17	129	51.7752	5.7066	30 July 2021	Riverbank	6	90	540	15	12
L18	91	51.7464	5.3254	03 August 2021	Riverbank	4	43	172	4	3
L19	89	51.7361	5.2972	03 August 2021	Riverbank	4	32	128	20	18
L20	88	51.7389	5.2817	03 August 2021	Riverbank	6	74	444	15	14
L21	88	51.7411	5.2795	03 August 2021	Riverbank	2	10	20	7	7
L22	68	51.7139	5.0090	02 August 2021	Riverbank	6	38	226	10	8
L23	66	51.7178	4.9804	02 August 2021	Riverbank	6	43	256	6	5
L24	63	51.7216	4.9388	02 August 2021	Riverbank	6	36	216	7	7
L25	62	51.7239	4.9380	02 August 2021	Riverbank	4	45	178	11	11

mean and median plastic flux per observation point, normalized over the track width. The total plastic transport was calculated by extrapolating the normalized daily average plastic flux to the entire river width.

Data were collected monthly, with additional observations during the July flood peak, as part of the first 1 year monitoring effort in the Dutch rivers⁵. At Maastricht, monthly data were collected from March to December 2021, and during the flood peak on 15, 17 and 20 July 2021. At Ravenstein and Moerdijk, monthly data were collected from January to December 2021, and during the flood peak on 18 July 2021. Table 1 shows an overview of the measurement locations. The measurements were done by trained students and staff from the Wageningen

University, the Delft University of Technology, the Open University, the University of Applied Science Zuyd and the Netherlands Ministry of Infrastructure and Water Management. All data are openly available and can be accessed through van Emmerik and de Lange⁴³.

Riverbank plastics

Riverbank plastic was sampled between 22 July and 4 August 2021, at 25 locations between Maastricht and Moerdijk (Table 2). The riverbank locations were chosen to represent the entire length of the Dutch Meuse, and are based on accessibility, since after the flood some areas were still inundated or inaccessible due to very dense and high riparian

vegetation. Riverbanks were sampled in 2-m-wide segments from the waterline at the time of sampling towards the highest flood line, identified by deposition of debris. Note that at all locations the water level during sampling did not exceed bankfull conditions. The length of each segment was determined either by the highest visible flood line or until a natural barrier was encountered (for example, an area that was still flooded). The segment length varied between 10 and 126.3 m (mean 43.8 m). A measurement tape was placed on the ground from the current waterline at a right angle away, towards the highest flood line. The measurements were done by two researchers, one walking on either side of the measurement tape and each one observing a 1-m-wide stripe. All litter items on the ground or entangled in ground-covering vegetation were counted and classified in the OSPAR-River litter categories¹⁵. Items that could not be clearly identified as litter visually were picked up and gently pulled apart, to distinguish between litter and natural material, for example, plant parts. If it was unclear if an item was within or outside the 1 m width, the distance from the measurement tape to the item was measured. On each riverbank of the 25 riverbanks, one to three stripes were measured; in the case of multiple stripes, they were within a 100 m section of riverbank along the river, usually 40 m apart from each other. Litter items were left in place; due to the high litter densities and limited time, it was not possible to clean the riverbanks.

Discharge data and correlation analysis

We used openly available measured discharge data at Maastricht (station Sint Pieter noord) and Ravenstein (station Megen). Data are available with 10 min resolution, and accessible through <https://waterinfo.rws.nl/>. For the correlation analysis with plastic transport, we used instantaneous discharge values closest to the time of the plastic flux measurements. Both the discharge values and the plastic flux measurements were then averaged for a daily mean value, which was used for the following correlation analysis.

Plastic transport models

We developed two models to estimate plastic transport P (items h^{-1}) from discharge Q ($\text{m}^3 \text{s}^{-1}$). Model 1 accounts for two modes of plastic transport:

$$P = \begin{cases} \alpha \cdot Q, & \text{if } Q < Q_t \\ \beta \cdot Q + P_t, & \text{if } Q \geq Q_t \end{cases}$$

Depending on whether the discharge exceeds the threshold value Q_t (with threshold plastic transport P_t), plastic transport is either in the mode of normal flow conditions or the mode of flood conditions. The parameters of the equations vary per location, and cannot directly be transferred to other locations. For Maastricht we used (with 95% confidence bounds): $\alpha = 0.99$ (0.72 to 1.26), $\beta = 16.67$ (4.08 to 29.26) and $Q_t = 650 \text{ m}^3 \text{ s}^{-1}$. For Ravenstein we used: $\alpha = 0.25$ (0.16 to 0.24), $\beta = 0.51$ (-1.41 to 2.42) and $Q_t = 1,150 \text{ m}^3 \text{ s}^{-1}$. We applied the model to estimate the annual plastic transport for both locations.

Model 2 uses a power function similar to account for the amplification effect at higher discharges. Such equations are generally also used to describe sediment transport^{44,45}.

$$P = a \cdot Q^b \quad (1)$$

with model parameters a and b . Both models were fitted using a least squares approach. We used the available discharge time series with 1 h temporal resolution to calculate the yearly total plastic transport by taking the integral. We found the following parameters values (with 95% confidence bounds) for Maastricht: $a = 1.45 \times 10^{-5}$ (95% confidence bounds -0.78×10^{-5} to 3.68×10^{-5}), $b = 1.87$ (95% confidence bounds 1.67 to 2.01), and Ravenstein: $a = 0.90 \times 10^{-5}$ (95% confidence bounds -3.73×10^{-5} to 5.52×10^{-5}), $b = 1.47$ (95% confidence bounds 0.7921 to 2.153).

Statistical analysis

We calculated the correlations between river plastic transport and discharge, and between riverbank plastic density measured after the flood and distance to the ocean. In either case we used the non-parametric Spearman rank test, as the distribution of the data is unknown. We tested the normality of the riverbank plastic density ($N = 25$), daily mean plastic transport (Maastricht: $N = 15$; Ravenstein: $N = 14$) and daily mean discharge data (Maastricht: $N = 15$; Ravenstein: $N = 14$) using the Shapiro–Wilk test⁴⁶, and all were non-normally distributed (statistical P value < 0.01 for all three). As a measure of uncertainty, we calculated the relative error RE, for the mean for the measurements during flood and the measurements during non-flood.

$$\text{RE} = \frac{\sigma}{\frac{\sigma}{\sqrt{n}} \cdot \bar{x}} \cdot 100\% \quad (2)$$

With mean x , standard deviation σ , sample size n and confidence level value z (from t -distribution).

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

All data are openly available in this publication and at the 4.TU Repository through <https://doi.org/10.4121/19447199>.

Code availability

All code is openly available at the 4.TU Repository through <https://doi.org/10.4121/19447199>.

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Author contributions

Conceptualization: T.v.E. and R.M.F.; Methodology: T.v.E., S.I.d.L. and R.M.F.; formal analysis: T.v.E. and L.J.S.; investigation—data collection: R.M.F., Y.A.M.M., L.J.S., R.H. and S.I.d.L.; visualization: T.v.E. and L.J.S.; data curation: T.v.E.; writing—original draft: T.v.E.; writing—reviewing and editing: all authors; supervision: T.v.E.; project administration: T.v.E.; funding acquisition: T.v.E. and S.I.d.L.

Competing interest

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

Additional information

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Study description

We quantified macroplastic transport and riverbank macroplastic density along the Dutch Meuse during and after the July 2021 flood.

Research sample

Visual observations of floating and riverbank macroplastic debris.

Sampling strategy

We used the same sampling strategy as during conventional monitoring, e.g. 5-minute observation rounds at five points for each measurement locations, with 3-4 repetitions for each sampling day. Riverbank sampling was done on a reduced surface area compared to conventional monitoring due to extremely high plastic densities.

Data collection

Visual observations from bridges for floating plastics, and visual observations on riverbanks for riverbank plastic density. All items above 2.5 cm were recorded manually.

Timing and spatial scale

Flood-specific sampling was done from 15 to 20 July 2021, and after the flood from 22 July to 4 August 2021.

Data exclusions

N/A

Reproducibility

Due to the unique nature of the measured event (extreme flood), no attempt for reproducibility was made.

Randomization

N/A

Blinding

We blinded the data on a daily time scale, and express most results in daily mean plastic transport.

Did the study involve field work?

Yes

No

Field work, collection and transport

Field conditions

Cloudy, warm days with day-time max temperatures between 20-30 C.

Location

Moerdijk, Ravenstein, Maastricht (NL) for floating; 25 locations between Moerdijk en Maastricht for riverbank.

Access & import/export

Access was granted by Rijkswaterstaat, the responsible agency for the main rivers.

Disturbance

No physical sampling was done.

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