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Flood-induced buttertub spill reveals riverine macroplastic transport dynamics

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Abstract

During the July 2021 European floods approximately eight million empty dairy packaging (buttertubs) were flushed from a dairy processing facility in Belgium into the Vesdre river. Some were transported further downstream, into the Ourthe river and eventually the Meuse river. There are many unknowns when it comes to plastic transport in rivers, especially in response to floods. We therefore used this incident as an unique opportunity to study these buttertubs as a tracer for plastic transport dynamics in a riverine environment in response to an extreme flood event. Normally, it is unknown when and where individual plastic items found on riverbanks entered the environment. In this case, however, the ID stamps on the buttertups allowed for them to be traced back to the flooding of the factory. We studied the transport and deposition of these buttertubs in the Dutch Meuse over 2 years following the flood. We also collected buttertubs at different points in time to investigate their fragmentation and mass loss. Within 3 weeks of the flood, the buttertubs were transported up to 328 km from the spilling location. Overall, the majority (78%) of buttertubs we found within the first 3 weeks were deposited within less than 100 km of the point of emission. Over the following 2 years, the mean transport distance of the found buttertubs moved downstream from 100 km in July/August 2021, to 153 km in July 2023. The buttertubs average transport velocity decreased from 11.7 km/d within the first 3 weeks, to 0.2 km/d by July 2023. Based on the 89 buttertubs we collected and analyzed in detail over the 2 years, we did not find a significant mass loss. Of all 89 buttertubs found, 47 showed cracks and only 12 appeared to have pieces missing. This study shows that even during extreme flood events, the majority of spilled plastic litter is retained within a limited distance after being emitted into the river. The findings of this study can be utilized to improve plastic transport modelling, and overall better understand plastic transport in the freshwater environment.

Keywords Plastic pollution, Tracers, Freshwater, Extreme events, Meuse, Vesdre

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Introduction

By 2019, the global annual plastic production reached 386 million metric tonnes (MT) [1]. Of these, approximately 22 MT (6%) were dumped, discarded, or otherwise leaked into the environment [2]. Understanding the plastic sources, fate, and transport in rivers is a crucial step towards understanding and reducing the wider issue of plastic pollution. Rivers play a key role in the storage and land-to-sea transport of plastics in the environment [3–5]. Fluvial floods impact plastic transport and can mobilize a large fraction of annually transported plastic in a river [6, 7]. During fluvial floods, areas around the main river channel are inundated, stored macroplastic items can be remobilized and additional macroplastic from surrounding areas can be flushed into the river. In this study we include macroplastic (> 2.5 cm) and mesoplastic (0.5 – 2.5 cm) items, for ease of reading we refer to both as macroplastic throughout the article. Even though floods are likely to increase plastic emission into the sea, most macroplastic is retained along the river [8]. Investigating macroplastic transport pathways under different conditions is an important part of understanding the dynamics of plastic pollution, and crucial towards its mitigation. Understanding the transport dynamics can contribute to mitigation efforts such as targeted cleanup efforts, e.g., shortly after a flood event, to prevent the plastic litter from spreading further.

Macroplastic items found on riverbanks and in the environment in general can usually not be linked to their exact time and location of entry into the environment. There are, however, two exceptions: (1) experiments with intentional release of trackers and (2) items released from specific spilling incidents. Some studies utilize GPS-trackers, plastic items equipped with acoustic telemetry tags, or items marked to be recognizable [9–13]. These studies can provide valuable insights in plastic transport. However, they are usually limited to a relatively small number of tracers and short time frame, due to factors including costs and battery life. For GPS-trackers this means roughly ~24 h to 1 month of deployment time and up to ~100 trackers. Studies utilizing marked (e.g., painted) items can have higher numbers of items due to lower costs, items equipped with acoustic telemetry tags can be tracked for longer time frames. Spill incidents on the one hand can be detrimental for the environment, on the other hand they also present a unique opportunity for plastic pollution research. Incidents of plastic spills regularly occur at sea [14] and spilled macroplastic items that have been studied include inkjet cartridges [15], Lego [16], and plastic bath toys [17, 18]. Analyzing the pathways of these items contributes to the understanding of ocean drift patterns, material transport pathways, and also plastic degradation rates.

Most plastics are extremely durable, and can remain intact in the environment for decades [13, 19]. However, plastic is also subject to fragmentation and degradation. Plastic degradation is estimated to be in the range of hundreds to thousands of years, since it has only been mass-produced since the 1950s plastic degradation rates in the environment cannot yet conclusively be determined. Mechanical factors such as waves and abrasion through sediment can cause physical fragmentation of plastic [20]. Whereas chemical degradation includes photodegradation due to exposure to UV-light, thermal degradation, thermo-oxidative degradation, biodegradation, and hydrolysis [21, 22]. Degradation depends on the type of plastic polymer, but also on environmental conditions [23]. [24] placed polypropylene (PP) buttertubs at different locations on a riverbank and monitored their degradation over almost 4.5 years. One of the buttertubs placed with low exposure to solar radiation stayed mostly intact over the duration of the experiment. Another buttertub with high solar radiation exposure became extremely brittle and was considered lost due to fragmentation after 2 years in the environment. Plastic transport pathways also determine how and how fast plastic fragmentation happens. Therefore, spill incidents can be a way to learn about the fragmentation/mass change of plastic items after known times of exposure to environmental conditions.

In July 2021 heavy rainfall over large areas led to extreme fluvial floods in multiple European countries. One river that was particularly affected was the river Vesdre, a tributary to the Meuse river with a catchment of 700 km^2 in Belgium and bordering Germany. Precipitation in parts of the Vesdre catchment cumulated over 48 h reached almost 300 mm and contributed to a devastating flood on 14–15 July 2021. None of the four Vesdre gauging stations recorded during the flood, since they were either washed away or otherwise failed, e.g., due to loss of power supply. However, based on the partially available time series the peak discharge was estimated to be three times higher than the 100 year return period discharge at some locations along the Vesdre [25]. The Vesdre converges with the Ourthe and ultimately flows into the Meuse river. About 45 km upstream of the Ourthe–Meuse confluence, a dairy processing factory located right next to the river was severely affected by the flood, with most of their facilities damaged and inventory washed away. The factory's spokesperson confirmed that they lost approximately eight million pieces of empty dairy packaging (buttertubs). Previously to the July 2021 flood, buttertubs were not a commonly found plastic item on the riverbanks of the Dutch Meuse, further the buttertubs in this study are recognizable by a legally mandatory code, that links to the factory. It is, therefore, most likely that the buttertubs in this study originate from the spill caused by the July 2021 flood. These buttertubs provided an unique opportunity for an impromptu study on transport pathways of macroplastics in rivers.

In this study we followed an opportunistic approach using the buttertubs spilled at a specific point and time to study macroplastic transport dynamics. We collected data on 617 buttertubs between July 2021 (within 3 weeks after the flood) and July 2023. Over that same period we also collected and analyzed the mass and degree of fragmentation of 89 buttertubs. Therefore, we could compare the buttertubs condition immediately after the flood event to ones we found 2 years later along the Dutch

Meuse and investigate their degradation. Over 2 years we investigated the transport distance and velocity of the spilled buttertubs along the Dutch Meuse, between ∼ 66 km to 328 km downstream of their point of entry. We evaluated the transport distance and velocity development over time, in order to analyze their transport pathway and fate in a riverine environment.

Methods

We used three different data sets in this study, and all data sets contain the location, density, and quantity of buttertubs on riverbanks along the Dutch section of the Meuse river between July 2021 and July 2023. The found buttertubs have an ID code which is unique to the flooded dairy company in Belgium. This ID code ("identification mark") is mandatory for dairy and other animal products in the European Union [26], to clearly identify their processing facility. Previous to July 2021 no noticeable amounts of buttertubs were found along the Dutch Meuse, we, therefore, expect that the found buttertubs trace back to the spilling event during the flood in July 2021.

The three data sets include the data set presented in [27] of post flood riverbank measurements [28], as well as ongoing riverbank litter monitoring by citizen scientists. Furthermore, during additional fieldwork 2 years after the flood event, we sampled 25 of the monitored riverbanks specifically for buttertubs. Investigating these data sets, where buttertubs were reported as a distinct item category allowed us to analyse their transport along the Dutch Meuse river over the course of 2 years. In order to also investigate the buttertubs' mass loss and fragmentation, we collected a total of 89 buttertubs in July 2021, February 2023, and July 2023 and recorded their mass, as well as damage and fragmentation (section Buttertubs mass/fragmentation analysis).

Data set 1: Riverbank sampling post-flood July/August 2021

We used the data set from [27, 28] that covers 25 riverbanks that were sampled along the Dutch Meuse river, between 22 July and 4 August, 2021 (Fig. 1a). The riverbanks from that sampling campaing were chosen from riverbanks monitored within the *Clean Rivers project* by the *North Sea Foundation* and *Institute for Nature Education*. The riverbanks were chosen based on accessibility at the time of the sampling campaign, and also to cover the entire length and the left and right bank of the Dutch Meuse. Exact locations with coordinates are available in [29]. The sampling campaign quantified the impact of the flood event on plastic deposition and re-mobilization on riverbanks. One item that was noticeable during the campaign was the buttertubs, which is usually not a very common plastic litter item on Dutch riverbanks. There is no category for buttertubs in the River-OSPAR protocol [30], however, due to their large number and distinct appearance, they were recorded as a separate category during this sampling campaign. There were overall more buttertubs than distinct lids; however, there were also a few lid shapes and designs that we found repeatedly. From the second location upstream we counted the buttertubs and lids as a separate category. On one location, along the highest floodline we collected 70 buttertubs (no lids) along 100 m for future analysis. At this specific location we did not measure the other litter items. Except the buttertubs we collected from that location, all other litter items during that sampling campaign were left in place. Due to high densities of litter at some locations, sub-areas were sampled as 2 m wide stripes within the 100 m that are usually monitored within the *Clean Rivers project*. If present, also areas of high litter density ("accumulation zones") and trees with entangled litter were sampled on the riverbanks.

Large scale clean-up efforts started on 14 August, 2021 [31] during that day we visited three locations that were cleaned, and collected three full garbage bags of litter from each location at random (Fig. 1a). The purpose of this was to further investigate the composition of the litter that had been deposited on the riverbanks by the flood. We counted and classified all litter items in these nine garbage bags, according to the River-OSPAR categories, with the buttertubs as an additional category, to get a better understanding of the plastic litter composition following the flood event.

Data set 2: Monitoring clean rivers project fall 2021–spring 2023

In the *Clean Rivers project (Dutch: Schone Rivieren)* by the *North Sea Foundation* and *Institute for Nature Education* over 150 riverbanks along the Dutch Meuse were monitored for litter twice a year by citizen scientists between Oct/Nov 2017 and Feb/Mar 2023. The citizen scientists collect, classify and count all litter on a 100 m long and 25 m wide (Fig. 1b) area of riverbank, according to the River-OSPAR protocol [30]. However, sometimes they deviate from the protocol, due to inaccessibility of riverbanks, very high litter densities, or high enthusiasm. We instructed the citizen scientists to separately record buttertubs during their measurements in preparation for the Oct/Nov 2021 and the following measurement rounds in 2022 and spring 2023. The citizen scientists were provided with pictures of the buttertubs including their distinct ID stamp, and were asked to only count the buttertubs themselves and not the lids, as the lids do not have the ID stamp.

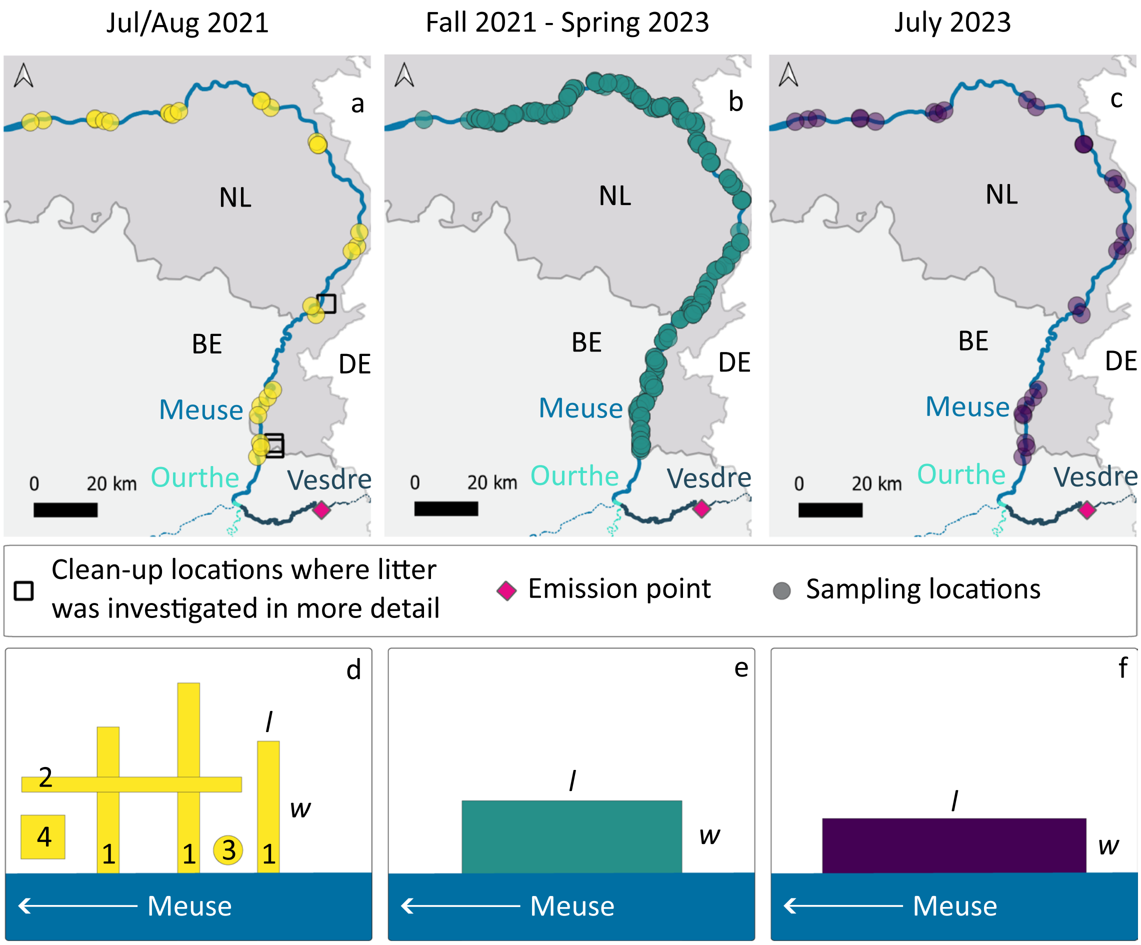


Fig. 1 Buttertub sampling strategy. Riverbank locations (**a**–**c**) and measurement areas (**d**–**f**) during the different measurement rounds (not to scale). **a**–**c** Overview maps that show the point of emission of the buttertubs (pink diamond shape), the path of the buttertubs through the Vesdre, Ourthe, and Meuse river (thick river lines). **a** Riverbanks sampled in Jul/Aug 2021 as well as the three locations we sampled three garbage bags each from the clean up on 14 August, 2021. The colored dots show which riverbank was monitored during which measurement round, Fall 2021–Spring 2023 means the location was sampled at least once in that time frame. For each area length (*l*) is measured in the direction along the Meuse river and width (*w*) is measured in the direction perpendicular away from the Meuse river. **d** In Jul/Aug 2021 with (1) stripes *l* = 2 m, *w* = 10–138 m, (2) measuring along a debris/flood line, (3) trees with entangled items, (4) accumulation zones with very high litter density. **e** Fall 2021–Spring 2023, *l* = 20–50 m, *w* = 1–100 m. **f** July 2023, *l* = 10–312 m, *w* = 1–50 m

Fig. 2 Illustration of buttertubs collected by the authors of this study (**a**) and by volunteers from the Clean Rivers Project (**b**, **c**). Pictures taken by authors of this study (**a**) and volunteers from the Clean Rivers Project (**b** and **c**)

Figure 2b and c shows pictures taken by Clean Rivers citizen scientists which indicate that indeed the correct type of buttertubs was counted during the monitoring rounds. However, it cannot be ruled out that some citizen scientists did not count any of the distinct lids.

Data set 3: Riverbank sampling July 2023

Between 26 July and 28 July 2023, we sampled 25 riverbank locations (Fig. 1c), 21 of which had also been sampled in July/August 2021. We adjusted the sampling area compared to the previous measurement rounds, to increase the likelihood of finding buttertubs. At most locations litter has been removed at least once since the flood event. We, therefore, decided to cover longer stretches of riverbank, to capture buttertubs that were recently deposited, as well as buttertubs that might have been in place since July 2021. The sampled lengths of riverbank varied between 10 m to 312 m, due to accessibility of riverbanks. The three most upstream riverbanks had very high and dense vegetation; therefore, only a few spots could be examined for buttertubs. The sampled width varied between 1 and 50 m, but at most locations the first 5–15 m of riverbank were sampled (Fig. 1f). We only focused on buttertubs during this fieldwork and did not count and collect any other litter categories.

Buttertubs mass/fragmentation analysis

We collected a total of 89 buttertubs, 70 in July 2021, 13 in February 2023, and 6 in July 2023. The 70 buttertubs collected in July 2021 were stored dry and protected from light in a non-climate controlled room. The 13 buttertubs collected in February 2023 were stored dry at room temperature, and the 6 collected in July 2023 were stored dry and protected from light in a non-climate controlled room. The mass of all collected buttertubs was measured in October 2023 before and after cleaning them of debris/sediment. First individual pictures were taken to capture their state and sediment/debris attachment. Then their dry uncleaned mass was measured with a balance [PM480, Mettler Toledo, Columbus, Ohio, USA] with an accuracy of 0.001 g. After this, the buttertubs were cleaned for mass analysis of only the plastic without sediment and debris. We soaked them in tap water for about half an hour, to soften sediment and debris, and then cleaned them under running water with a soft sponge, based on [32]. No visible pieces of plastic were removed or broke off during the cleaning process. To not damage the plastic, the buttertubs were cleaned very gently and some discoloration could not be removed in the process. After cleaning, the buttertubs were dried in a drying cabinet [Heraeus, Hanau, Germany] at 40° C for one day, 16 buttertubs were left in the drying cabinet for an additional day, since they appeared not completely dry upon visual inspection. After drying and visual inspection to confirm they were completely dry, the cleaned mass was determined. Furthermore, buttertubs were visually inspected for cracks and missing pieces. Difference in mass between the two shapes of buttertubs was tested for significance. Since the difference was not significant (unpaired t test, $p = 0.189$), the mass data of both shapes was analyzed together.

Transport distance and velocity analysis

The transport distance of the buttertubs along the rivers Vesdre, Ourthe, and Meuse was measured in QGIS, utilizing river shapefiles obtained from Atlas of Belgium (atlas-belgique.be), as well as a shapefile with kilometer markings along the Dutch Meuse river by Rijkswaterstaat. Transport velocity was calculated for all buttertubs in kilometer per day [km/d], with the number of days between 15 July 2021 as the day of emission and the sampling date. To investigate the density of buttertubs along the Dutch Meuse river the number of buttertubs that were found at each riverbank location was normalized by buttertubs per sampled meter [m] of riverbank.

Results and discussion

Buttertubs share of deposited litter

Between July 2021 and July 2023, buttertubs constituted a considerable share of plastic and other litter deposited on riverbanks along the Dutch Meuse. In Jul/Aug 2021 we counted 1565 plastic items deposited on 25 riverbanks thereof 118 buttertubs, (7.5%). This excludes the 70 buttertubs we found along the highest floodline where no other litter was counted. In the bags we collected from three flood clean-up sites, we counted a total of 1478 plastic litter items, thereof 34 buttertubs (2.3%). Over the following 1.5 years, the share of buttertubs of all counted plastic litter decreased. From 2.7% in Oct/Nov 2021 to 0.1% in Feb/Mar 2023. The Pictures provided by the citizen scientists from *Clean Rivers Project* (Fig. 2) indicate that they indeed sampled the correct buttertubs; however, this could not be verified in detail for every single measurement. Furthermore, it is possible that some of the sampled buttertubs had the same ID stamp, but were emitted outside of the spilling event, e.g., by littering; however, this is unlikely.

Buttertubs transport distance

Between July 2021 and July 2023 a total of 617 buttertubs were found along the Dutch part of the Meuse river. Within the first 7–20 days after the buttertubs were spilled, the mean travel distance was 100 km (Fig. 3). Twelve buttertubs were transported over 300 km, up to 328 km in less than 3 weeks (~50 km from the river mouth, but the Rhine-Meuse delta is complicated). The

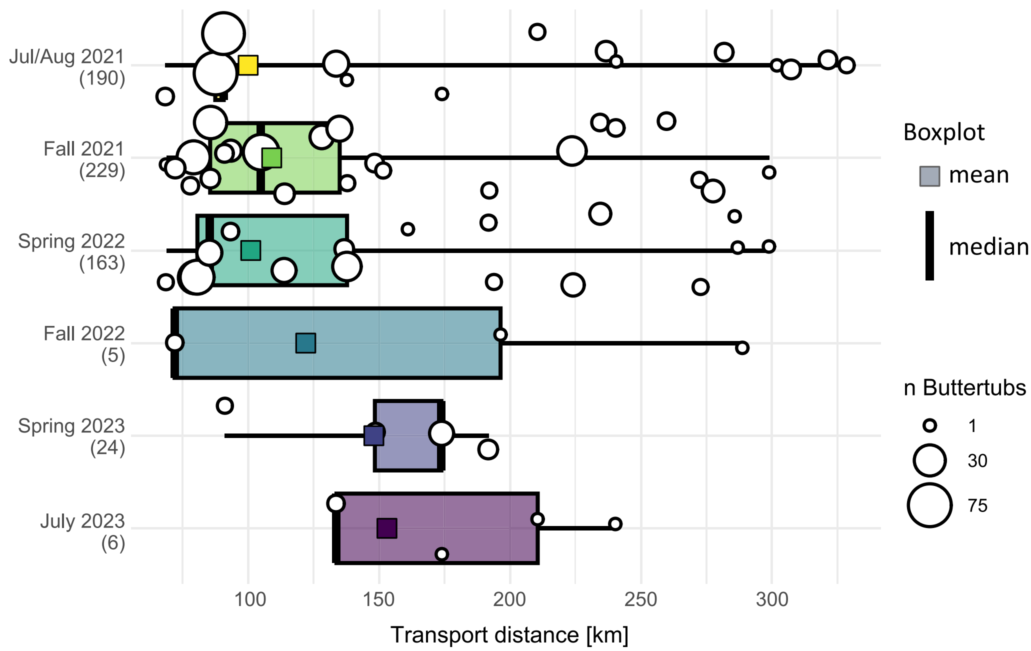


Fig. 3 Transport distance of buttertubs along the Dutch Meuse in different measurement rounds. All of these buttertubs were removed from the riverbanks, with the exception of Jul/Aug 2021, then most buttertubs were left in place and only 70 were collected from one location for further analysis. The x-axis starts at 66 km to match the extent of this study. The whiskers extent to the least and furthest transported buttertubs, with no regard for the interquartile range (no outliers were defined). Placement of circles indicates the number of buttertubs according to transport distance but random on y-axis

two locations with the largest number of buttertubs were at 87 and 91 km with 75 and 70 buttertubs respectively. While we found buttertubs along the entire length of the Dutch Meuse, the majority (78%) was transported less than 100 km. In Fall 2021 and Spring 2022, buttertubs again were found along the entire length of the Dutch Meuse, up until around 300 km of transport. The average transport distance from the sampled item to the point of emission was 109 km in Fall 2021 and 101 km in Spring 2022 on average after 108 and 236 days respectively. In Fall 2022 and Spring 2023, on average 478 and 589 days after the flood event, smaller numbers of buttertubs were reported. In July 2023 only six buttertubs were found at the 25 riverbanks visited. In Spring 2023 and Summer 2023, buttertubs were only found between 90 km and 240 km from the spill site, compared to between 68 km and 328 km in Jul/Aug 2021. Overall the average transport distance increased by 53 km over the measurement rounds, from 100 km within 3 week, to 153 km in July 2023, 2 years after the flood. On the contrary, the maximum reported travel distance decreased from 328 km to 240 km.

The mean transport distance suggests that the majority of buttertubs was only transported around 100 km within the first three weeks, and remained in the river. Limited downstream transport would align with transport and deposition of plastic litter during the July 2021 flood in general [8, 27]. The average transport distance per measurement almost continuously moves downstream, which suggests that the buttertubs are slowly transported downstream (Fig. 5a). However, the average transport distance by buttertub density per m riverbank is not quite as clear (Fig. 5b). Given the limited transport distance we expect only a small fraction may have potentially been emitted into the North Sea.

The increase in minimum transport distance could be due to extensive clean-up efforts following the July 2021 flood. If large numbers of buttertubs were cleaned up along their first 100 km of transport, there are less buttertubs left to be transported and feed into the Dutch Meuse. Therefore, the "bulk" of the remaining buttertubs traveled downstream.

Buttertubs transported and deposited by the flood were not quantified along the Vesdre, Ourthe, and Belgian part of the Meuse river (first 66 km of transport). However, pictures taken by *River Clean Up Belgium* during large scale clean up efforts along the Vesdre river, within the first 25 km downstream of the dairy company show very large numbers of buttertubs (Fig. 4). If quantified, the average transport distance by Fall 2021 would likely have been lower than 109 km.

Fig. 4 Pictures taken during clean-ups in September and November 2021 after the July 2021 flood event along the Vesdre river, within the first 25 km of transport. Buttertubs along the Vesdre river were not quantified, but found in large quantities during clean-ups following the July 2021 flood event. Pictures courtesy of River Cleanup

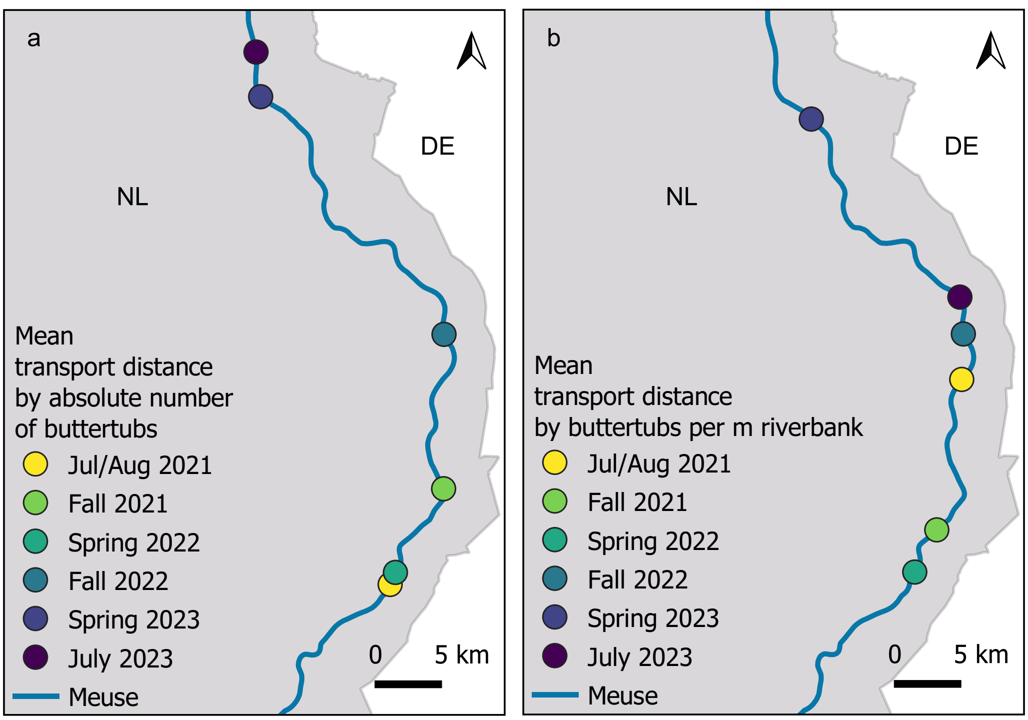


Fig. 5 Differences in mean transport distance between buttertubs (**a**) and buttertubs density in buttertubs per m riverbank (**b**)

The sampled riverbank lengths differed between sampling rounds, since only the measurements in July 2023 targeted the buttertubs specifically. In Jul/Aug 2021 on a number of riverbanks only 6 m length were measured in total. The sampling strategy was not developed for specific items, but rather to sub-sample the riverbank monitoring area within a tight time frame. Therefore, the different measurement rounds have different resolutions (Fig. 1). The minimum number of buttertubs that could be detected on a riverbank is one. Given that between 6 m to 100 m (and in a few cases even 500 m) were sampled in this study, the minimum positive measurement resolution differs between 0.2 and 16.7 buttertubs per 100 m riverbank.

In Jul/Aug 2021 potentially less buttertubs were sampled, since smaller areas of riverbank were covered. However, if a buttertub was located in one of the stripes, it had a higher influence on the item density than a buttertub located in a debris line or an area with high debris density, since the buttertub density was calculated per meter riverbank. During the fieldwork in July 2023, the three most upstream sampled riverbanks and the riverbank at 133 km of transport showed very dense vegetation and the sampled stretch of riverbank was, therefore, much smaller than at the riverbanks further downstream. At 133 km of transport three buttertubs were found along 30 m of riverbank sampled, which heavily influenced the mean transport in July 2023 where only six buttertubs were found in total.

For Jul/Aug 2021 the exact location of each buttertub on the riverbank was recorded, this was not recorded for the following measurement rounds. In Jul/Aug 2021, 184 out of the 190 buttertubs were found on the ground or in ground covering vegetation, and only six were found deposited higher up such as in trees/bushes/fences. Within the debris line 162 buttertubs were found and out of these at least 143 (at two locations) were found in debris along the highest floodline.

Buttertubs transport velocity

The mean transport velocity shows a non-linear decay from 11.7 km/d after the flood to 0.2 km/d in July 2023 (Fig. 6). Based on the riverbanks where buttercups were found within 3 weeks after the flood event, they were transported at a velocity between 9.8 and 18.3 km/d. The flow velocity of the Dutch Meuse is typically about 1–3 m/s (86–259 km/d) and can increase up to 4.3 m/s (372 km/d) [33] during floods. So the transport velocities we found are realistic, but likely much lower than the velocity of buttertubs in motion. Until Fall 2021, on average 108 days after the flood event, the average transport velocity decreases by a factor ten to 1.2 km/d. Yet, it still has a range between 0.6 and 3.0 km/d. The average transport velocity continues to decrease, to 0.5 km/d in Spring 2022, 0.3 km/d in Fall 2022 and Spring 2023. In July 2023 the found buttertubs on average had been transported with a velocity of 0.2 km/d. All transport velocities represent the minimum transport velocity, since we did not measure buttertubs in motion, therefore, the transport velocity of buttertubs when mobile is likely much higher. Furthermore, we only studied the buttertubs that were transported into the Dutch Meuse, which is only a subsample of all spilled buttertubs. Large numbers of them were cleaned up along the Vesdre river following the flood event (Fig. 4).

The strong decrease of the buttertubs transport velocity over the course of 2 years is probably connected to multiple factors. Buttertubs being transported quite far distances over short period of times during the flood, and a large amount of buttertubs remaining in place, once deposited on a riverbank. Bankfull discharge for the Dutch Meuse river is about 1.250 m^3/s [34]. Between the end of the flood event in July 2021 and July 2023 the Meuse river exceeded this discharge level a total of two times, with a duration of ~29 h in January 2022 and ~40 h in January 2023 at Eijsden, close to the Dutch–Belgian border. During these flood peaks, buttertubs could potentially have been re-mobilized from the floodplains. The 0.2 km/d of transport velocity after 2 years is in about the same order of magnitude as short term transport in a study utilizing GPS trackers in PET bottles [11] in the UK. [13]Investigated transport distances and velocities

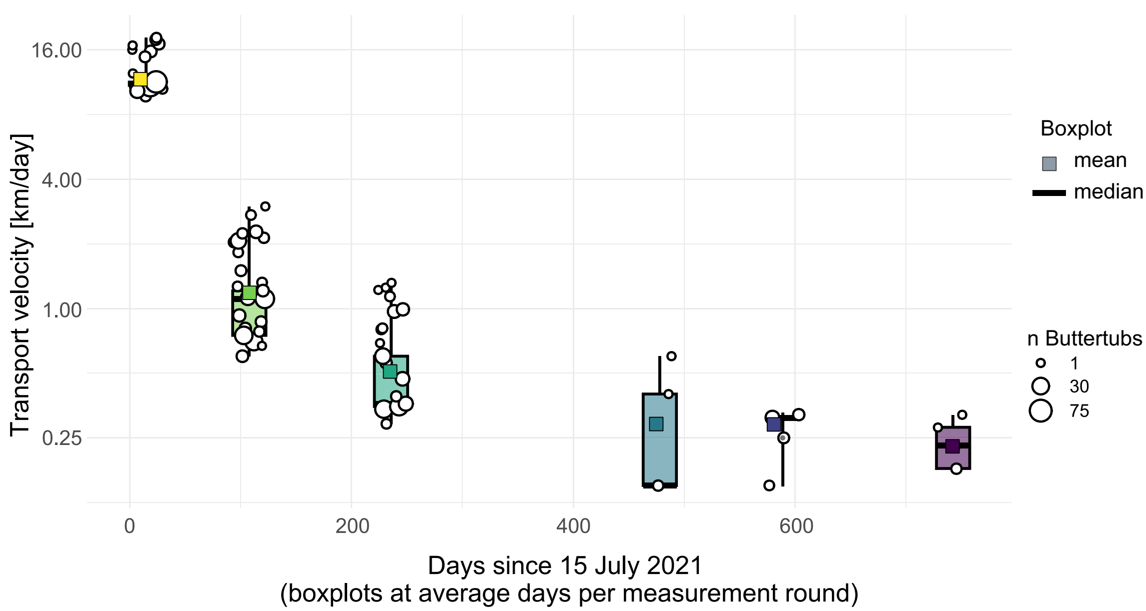


Fig. 6 Transport velocity of buttertubs in the Dutch Meuse for the different monitoring rounds. Transport velocity in logarithmic scale

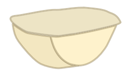
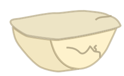
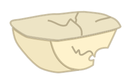
of plastic bottles with GPS-trackers under various hydrometeorological conditions in the Seine river, France. During flood conditions they measured transport velocities up to 110.2 km/d, whereas during non-flood conditions they found a median net speed of 2.3 km/d. Which is ten times higher than the average velocity in our study. In our study the transport velocity is influenced by the fact that we did not track the movement of buttertubs itself, but calculated the transport velocity based on the transport distance and time between the spilling event and sampling. It is, therefore, not linked to the transport velocity while the buttertubs were in motion, and an underestimation compared to the transport velocity during the flood event. [35] conducted another study to track macroplastic movement via GPS-tracker equipped plastic bottles in the Ganges river, India. Trackers deployed during pre-monsoon season which were tracked for an average of 20 days showed an average transport velocity of 1.0 km/d. Trackers deployed post-monsoon for 23 days on average had a mean velocity of 25.4 km/d. Which is in the same order of magnitude as the values from the buttertubs in July/Aug 2021 and Fall 2021. Since we did not measure buttertubs along their first ~66 km, the mean velocity is most likely overestimated. The results of our study suggests that short term tracking of macroplastic transport can give an indication on transport velocity under different conditions; however, long-term estimations and modeling should take the decrease of transport velocity into account.

Mass loss and fragmentation

The standard deviation of 0.23 g for intact buttertubs suggests that the buttertubs have a range of mass by production. Overall the mean mass for buttertubs we found that appeared intact decreases from 9.616 g 8 days after the flood event by 0.025 g (about 0.4%) over the course of 568 days in the environment (Table 1). However, for all buttertubs combined mean mass increases over the 2 years. There is no significant difference between the buttertubs mass that were collected after 8 days in the environment and the buttertubs that were collected after 741/743 days (p value = 0.73).

PP without any additives is inherently unstable, and therefore, all PP contains a large number of antioxidants to prevent degradation [36]. Which in the case of the buttertubs could play a large role, since the packaging is designed to keep its contents protected and hygienic. Discoloration remained on some buttertubs after the cleaning, due to a gentle cleaning protocol to ensure no pieces of the buttertubs were removed. It is, therefore, possible that the gentle cleaning protocol did not remove all attached material and the mass of the buttertubs was

Table 1 Differences in mass for cleaned buttertubs we collected at different points in time

Collected on		23 Jul 2021	3 Feb 2023	26/28 Jul 2023
Time in environment [days]		8	568	741/743
	*intact n*	26	3	1
	Mean mass [g]	**9.616**	**9.591**	**9.575**
	standard deviation	0.229	0.222	NA
	*fractured n*	39	4	4
	Mean mass [g]	**9.582**	**9.607**	**9.826**
	standard deviation	0.199	0.427	0.191
	*fragmentary n*	5	6	1
	Mean mass [g]	**9.361**	**9.599**	**8.945**
	standard deviation	0.225	0.333	NA

Mass data was grouped by intact buttertubs, i.e., that show no damage, fractured buttertubs, i.e., that appear cracked but complete, and fragmentary buttertubs, i.e., that appear cracked and with parts missing. Mass distribution of buttertubs displayed in Fig. 7

slightly overestimated. Of the buttertubs collected 8 days after the flood, the mean mass of the five buttertubs that appear fragmentary is 0.26 g lower than the mean mass of the buttertubs that appeared intact. One of the buttertubs collected 2 years after the spill appears completely intact with no signs of fragmentation or mass loss.

Figure 7 shows the range of mass of buttertubs for each time period. While the item with the lowest mass at each point in time is a buttertub that is fragmentary, there is no conclusive pattern that links mass, buttertubs appearance, and their respective exposure time. [24] placed buttertubs very similar to the ones of this study (both PP, similar in shape and size) on riverbanks and observed their degradation over the course of multiple years. The buttertub they had placed with high exposure to sunlight became so brittle, that is was considered lost to fragmentation after 2 years. Whereas buttertubs placed protected from solar radiation stayed mostly intact. The buttertubs we collected after 2 years were found partly buried, or covered by vegetation, which could (partly) protect them from sunlight exposure and slow down their degradation. However, it is possible that some buttertubs with high exposure to sunlight completely fragmented and were, therefore, not recognised as buttertubs anymore. PP items can be very durable and remain intact in the environment for decades [37] found PP packaging that (based on use by dates) was retained on riverbanks for up to around 40 years and did not show any signs of weathering and fragmentation. The results from the studies by [24] and [37] are in line with our results on mass loss and

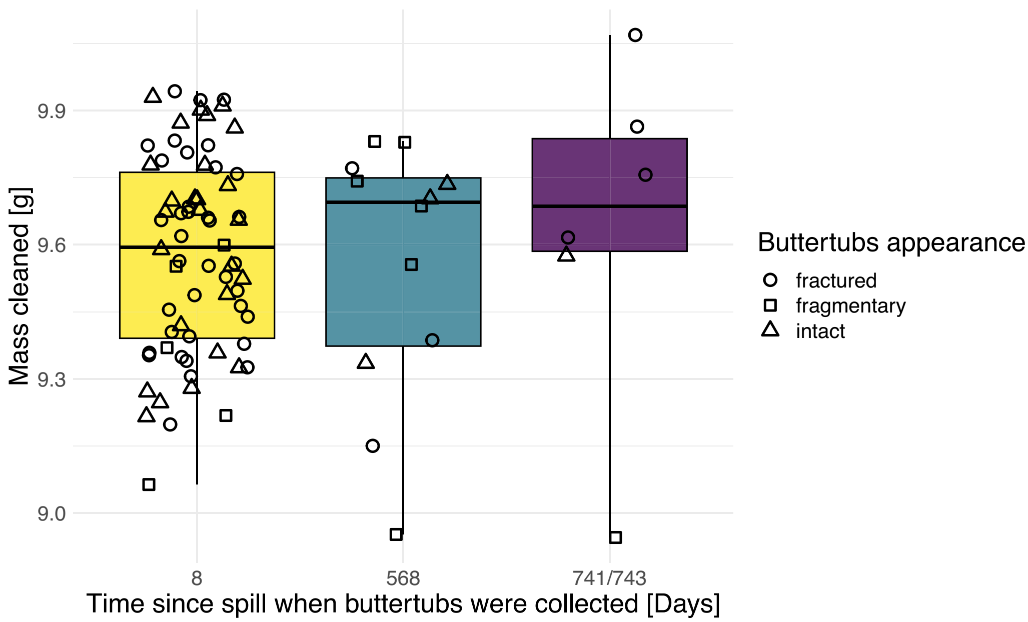


Fig. 7 Mass distribution of buttertubs after 8, 568, and 741 days of exposure in the environment. Aggregated mass available in Table 1

fragmentation. Our results indicate that relevant time scales for mass loss and fragmentation are likely much longer than 2 years.

Conclusion

We sampled litter on riverbanks following an extreme event and noticed a large amount of distinct buttertubs among the deposited litter, i.e., 7.5% of plastic litter items. For this unique study we combined sampling after an extreme event with monitoring by citizen scientists and a targeted sampling campaign 2 years after the spill. In total we sampled 617 buttertubs along the Dutch Meuse between 2021 and 2023. In Jul/Aug 2021 the mean transport distance was 100 km (since there is no data on the first ~66 km of transport, this is likely largely overestimated), which suggests that a large fraction of buttertubs was retained relatively close to the source. This emphasizes the importance of retention in macroplastic transport dynamics. The mean transport distance increased from 100 km in 2021 to 153 km in 2023. The increasing distance suggests that the buttertubs were still transported, albeit at a lower velocity. We hypothesize that the increase in transport distance is mainly caused by a depleted supply of buttertubs from upstream (across the Belgian border) after cleanup efforts following the July 2021 flood. Some of the buttertubs were transported between 300 to 328 km within 3 weeks of the flood event. The mean transport velocity of the found buttertubs decreased from 11.7 km/d (directly after the flood) to 0.2 km/d (2 years after the flood). We hypothesize this is because of a large number of buttertubs not being remobilized over the 2 years and staying in place, and some buttertubs being transported shorter distances than compared to during the flood event. We also collected 89 buttertubs after 8–743 days of exposure in the environment to determine their mass and fragmentation. There were no robust conclusions on mass loss or fragmentation rate. Given that plastic litter is very heterogeneous, similar studies should be done in the future, in case of spilling events of specific plastic items in rivers. This could improve the understanding of similarities and differences in transport dynamics of plastic items with varying characteristics such as polymer, density, shape, and size. With this study we showed that it is possible to use spilled plastic items as tracers for plastic transport in rivers.

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Author contributions

Conceptualization: RH, TvE, MvdP, RT. Methodology: RH, TvE, MvdP, RT . Data acquisition: RH, WdW, MvdP. Data analysis: RH, MvdP, TvE, RT. Writing—original draft: RH. Writing—reviewing and editing: all authors.

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Data availability
Data used in this study is published on 4TU. Research Data Repository at https://doi.org/10.4121/05ba396b-90f7-460e-8f2e-b88752b1b51b.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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