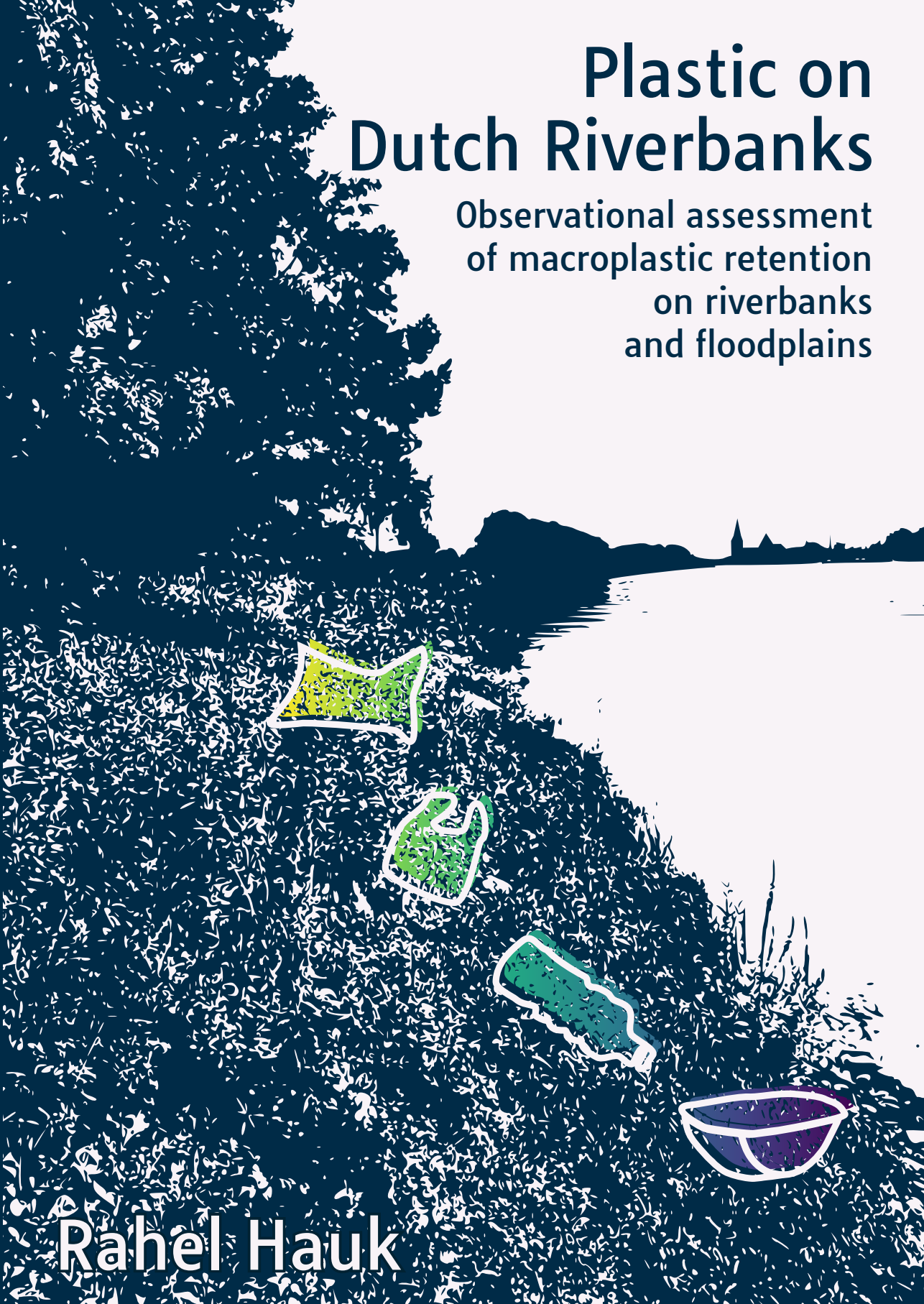
Plastic on Dutch Riverbanks

Observational assessment of macroplastic retention on riverbanks and floodplains



Rahel Hauk

Plastic on Dutch Riverbanks

Observational assessment of macroplastic retention on riverbanks and floodplains

Rahel Hauk

Thesis committee

Promotors
Dr *ir.* A.J. Teuling
Associate Professor in Hydrology and Environmental Hydraulics
Wageningen University & Research

Prof. Dr *ir.* M. J. van der Ploeg
Professor of Hydrology and Environmental Hydraulics
Wageningen University & Research

Co-promotor
Dr *ir.* T.H.M. van Emmerik
Associate Professor in Hydrology and Environmental Hydraulics
Wageningen University & Research

Other members
Prof. Dr A. A. Koelmans, Wageningen University & Research
Dr A. Praetorius, University of Amsterdam
Dr D. Wüthrich, Delft University of Technology
Dr S. R. Lutz, Utrecht University

This research was conducted under the auspices of the Graduate School for Socio-Economic and Natural Sciences of the Environment (SENSE).

Plastic on Dutch Riverbanks

Observational assessment of macroplastic retention on riverbanks and floodplains

Rahel Hauk

Thesis
submitted in fulfilment of the requirements for the degree of doctor
at Wageningen University
by the authority of the Rector Magnificus,
Prof. Dr C. Kroeze,
in the presence of the
Thesis Committee appointed by the Academic Board
to be defended in public
on 18 November 2026
at 3.30 p.m. in the Omnia Auditorium.

Rahel Hauk
Plastic on Dutch Riverbanks - Observational assessment of macroplastic retention on riverbanks and floodplains,
ix+164 pages.

PhD thesis, Wageningen University, Wageningen, the Netherlands (2026)
With references, with summaries in English and Dutch

DOI 10.18174/681629
© 2026 Rahel Hauk

Summary

Plastic is an essential part of everyday human life, and even though plastic mass production started less than 100 years ago, plastic pollution is now a global problem. In this thesis the focus is on one small facet of macroplastic (> 2.5 cm) pollution, macroplastic on riverbanks in the Netherlands. Macroplastic can enter the riverine environment via multiple pathways such as surface run-off, sewer overflow, or littering. Rivers transport and store a variety of natural and anthropogenic materials, nowadays including (macro-)plastic. Macroplastic in rivers can be transported and emitted to the sea, or (intermittently) stored in the river bed, in riparian vegetation, or in and on riverbanks and floodplains. In this thesis I investigated different aspects of riverbank macroplastic pollution along Dutch rivers. In particular the research in this thesis followed four questions:

1. How stable is macroplastic deposition on riverbanks over time and space?
2. How does macroplastic concentration and composition on riverbanks and floodplains differ following a flood event vs. non-flood conditions?
3. How far are macroplastic items transported during a flood event and over the following years, and how does their condition develop in terms of mass and fragmentation?
4. Following flood events, how do macroplastic concentrations and characteristics differ between landcover elements on riverbanks and floodplains, and how is plastic distributed in the lateral direction?

Chapter 1 is the introduction to the thesis topic. I introduce the history of plastic production and plastic pollution as well as its consequences. I then introduce the role of rivers in plastic pollution (transport), and plastic transport and deposition during flood and non-flood conditions. And finally, macroplastic deposition on Dutch riverbanks which is the main focus of this thesis.

Chapter 2 assesses and quantifies the temporal stability of macroplastic concentrations across riverbanks and rivers over time. The results show that macroplastic pollution across riverbanks is not evenly distributed and does not appear random over time. Hotspot and coldspot locations which are consistently above/below the macroplastic concentration average are identified.

Chapter 3 compares plastic deposition along the Meuse river following a flood event to plastic deposition along the Meuse during non-flood conditions. This is done by fieldwork following the July 2021 flood event and comparing this fieldwork to multi-year monitoring data on the same riverbanks.

Chapter 4 focuses on a case study of plastic spilled into the Meuse river during the July 2021 flood. The study followed the transport and fate of spilled buttertubs over the two years after the flood event. Their transport path and velocity was tracked, as well as their fragmentation and mass development.

Chapter 5 investigates flood induced deposition of macroplastic on riverbanks and floodplains. Where exactly plastic is deposited, spatially on riverbanks, and in relation to riverbank and floodplain elements such as different vegetation and debris piles. In this chapter also the characteristics of macroplastic deposited off the ground, in trees and other riparian vegetation, vs. macroplastic deposited on the ground and in groundcovering vegetation, are investigated.

Chapter 6 is the synthesis of this thesis, I discuss the main findings and how the results from the individual chapters connect and fit into a broader context. I also discuss what these results reveal about plastic pollution and what we can learn from this for plastic pollution research. Especially implications of the thesis results in view of modeling plastic transport and deposition along rivers, as well as sampling and monitoring strategies. I will discuss emerging and open questions in the research field, and potential future research directions.

Samenvatting

Plastic is een onmisbaar onderdeel van het dagelijks leven van de mens, en hoewel de massaproductie van plastic nog geen 100 jaar geleden begon, is plasticvervuiling inmiddels een wereldwijd probleem. In dit proefschrift ligt de focus op één klein aspect van de vervuiling door macroplastic (> 2,5 cm), namelijk macroplastic op rivieroevers in Nederland. Macroplastic kan via verschillende routes in het riviermilieu terechtkomen, zoals afvloeiing van het oppervlak, riooloverstorten of zwerfafval. Rivieren vervoeren en slaan een verscheidenheid aan natuurlijke en antropogene materialen op, waaronder tegenwoordig ook (macro-)plastic. Macroplastic in rivieren kan worden getransporteerd en in zee terechtkomen, of (met tussenpozen) worden opgeslagen in de rivierbedding, in oevervegetatie, of in en op rivieroevers en uiterwaarden. In dit proefschrift hebben we verschillende aspecten van macroplasticvervuiling langs Nederlandse rivieroevers onderzocht. Het onderzoek in dit proefschrift richtte zich met name op vier vragen:

1. Hoe stabiel is de afzetting van macroplastic op rivieroevers in tijd en ruimte?
2. Hoe verschillen de concentratie en samenstelling van macroplastic op rivieroevers en uiterwaarden na een overstroming ten opzichte van normale waterniveaus?
3. Hoe ver worden macroplasticdeeltjes getransporteerd tijdens een overstroming en in de daaropvolgende jaren, en hoe ontwikkelt hun toestand zich in termen van massa en fragmentatie?
4. Hoe verschillen de concentraties en eigenschappen van macroplastic na overstromingen tussen de verschillende landbedekkingselementen op rivieroevers en in uiterwaarden, en hoe is het plastic in de zijdelingse richting verdeeld?

Hoofdstuk 1 vormt de inleiding van het proefschrift. Ik zal de geschiedenis van de plasticproductie en de plasticvervuiling bespreken, evenals de gevolgen daarvan. Vervolgens ga ik in op de rol van rivieren bij plasticvervuiling (transport), en op het transport en de afzetting van plastic tijdens zowel hoogwater- als normale afvoer. En tot slot de afzetting van macroplastic op Nederlandse rivieroevers, het belangrijkste onderwerp van dit proefschrift.

In **hoofdstuk 2** beoordeelt en kwantificeert de stabiliteit in de tijd van de macroplasticconcentraties langs rivieroevers en in rivieren. De resultaten tonen aan dat de macroplasticvervuiling langs rivieroevers niet gelijkmatig is verdeeld en in de tijd geen willekeurig patroon vertoont. De hotspots en coldspots, die consequent boven of onder het gemiddelde van de macroplasticconcentraties liggen, worden in kaart gebracht.

Hoofdstuk 3 vergelijkt de afzetting van plastic langs de Maas na een overstroming met de afzetting van plastic langs de Maas tijdens normale waterniveaus. Dit gebeurt door middel van veldwerk na de overstroming van juli 2021 en door dit veldwerk te vergelijken met meerjarige monitoringgegevens over dezelfde rivieroevers.

Hoofdstuk 4 richt zich op een studie van plastic dat tijdens de overstroming van juli 2021 in de Maas terechtkwam. Het transport en het lot van de gemorste boterkuipjes gedurende de twee jaar na de overstroming, is in deze studie gevolgd. Hun transportroute en snelheid zijn bijgehouden, evenals hun fragmentatie en massavorming.

Hoofdstuk 5 onderzoekt de door overstromingen veroorzaakte afzetting van macroplastic op rivieroevers en uiterwaarden. Waar precies wordt het plastic afgezet, in relatie tot de waterlijn vs. hoogwaterlijn, en in relatie tot elementen van de oever en de uiterwaarden, zoals verschillende soorten vegetatie en drijfvuilophopingen. In dit hoofdstuk worden ook de kenmerken onderzocht van macroplastic dat niet op de grond ligt, maar in bomen en andere oevervegetatie, in vergelijking met macroplastic dat op de grond ligt en in bodembedekkende vegetatie.

Hoofdstuk 6 vormt de synthese van dit proefschrift; ik bespreek de belangrijkste bevindingen en hoe de resultaten uit de afzonderlijke hoofdstukken met elkaar in verband staan en in een bredere context passen. Ook bespreek ik wat deze resultaten ons leren over plasticvervuiling en welke lessen we hieruit kunnen trekken voor het onderzoek naar plasticvervuiling. Met name de implicaties van de resultaten van het proefschrift voor het modelleren van het transport en de afzetting van plastic langs rivieren, evenals voor bemonsterings- en monitoringstrategieën. Ik ga hier ook in op opkomende en open vragen in het onderzoeksveld, en mogelijke toekomstige onderzoeksrichtingen.

Contents

Summary v

Samenvatting vii

1 | Introduction 1

2 | Temporal stability of macroplastic distribution 17

3 | Riverbank macroplastic following the July 2021 European floods 39

4 | Buttertubs as tracers for freshwater macroplastic transport 59

5 | Preferential deposition of macroplastic on floodplains 81

6 | Synthesis 109

7 | Appendices 125
Supplementary materials 127
Bibliography 133
Nomenclature 149
Acknowledgements 153
Statement of authorship contribution 157
List of publications 159
About the author 161
Graduate school certificate 162



Introduction



1.1 | The ubiquitous case of plastic (pollution)

Plastic is an umbrella term for a variety of materials, mainly natural, synthetic and semi-synthetic polymers. Within less than 100 years we invited it into every aspect of human life. Plastic applications include (single-use) packaging, textiles, construction, medical, household items and consumer goods, fishery, transportation, and technology. Plastic items have an average useful life between less than a year for packaging, and a few decades for building and construction (Geyer et al., 2017). However, plastic does not simply disappear once its' useful life has ended. Global plastic production in 2024 was 430.9 million metric tonnes (Mt), with the most common polymers as high and low density polyethylene 26.0% (PE), polypropylene 19.0% (PP), polyvinylchloride 12.8% (PVC), polyethylene terephthalate 6.2% (PET), (expanded) polystyrene 5.1% ((E)PS), and polyurethane 5.3% (PUR) (Plastics Europe, 2025). Of the 430.9 Mt, 89.8% were fossil based, 9.5% post-consumer mechanically recycled, 0.6% bio-based, 0.1% chemically recycled, and <0.1% carbon-captured (Plastics Europe, 2025). Geyer et al. (2017) estimated that between 1950 - 2015, 8300 Mt of plastic had been produced cumulative, combined with estimated global plastic production (excl. recycled plastic) between 2016 - 2024 (Plastics Europe, 2021, 2024, 2025) this amounts to an estimated total of 11514 Mt of produced plastic by 2024.

Global plastic production steadily increased over the last decades. Under the conservative assumption that in 2025 and 2026, production stays the same as 2024 with 386.9 Mt (excl. recycling), that would amount to about 12288 Mt of plastic produced globally between 1950 - 2026. While this is only an estimation, it can give an idea of the order of magnitude. A large fraction of the produced plastic ends up in landfill or the environment as mismanaged plastic waste (MPW). Pottinger et al. (2024) estimate that in 2020 about 425 Mt plastic waste was generated globally, with 39% (166 Mt) going to landfill, 24% (102 Mt) were formally incinerated, 22% (94 Mt) recycled, and the remaining 15% (64 Mt) were MPW. These estimates indicate the increase of recycling and formal incineration over time. Geyer et al. (2017) estimated that approximately 6300 Mt of plastic waste had been generated by 2015, thereof approximately 9% (567 Mt) recycled, 12% (756 Mt) incinerated, and 79% (4977 Mt) in landfills or emitted to the environment. Given business as usual, future estimations are in the range of 55 Mt recycling, 140 Mt disposal, and 240 Mt MPW per year in 2040 (Lau et al., 2020). This is in the same order of magnitude as the estimation by Pottinger et al. (2024) who estimated 121 Mt MPW and

271 Mt going to landfill per year by 2050 and Lebreton & Andrady (2019) who estimated 155–265 Mt of MPW per year by 2060.

Plastics are lightweight, sturdy, and cheap, which makes them a great material for a whole range of uses and applications. However, over the last around 75 years, plastic got out of control and we trashed our planet. As a consequence, human life but also flora and fauna are affected by plastic in unintended ways. The word 'ubiquitous' is used ubiquitously across literature to describe the state of global plastic pollution. In short, it is everywhere. Wherever the environment is sampled for plastic, the 'success rate' of detection is very high. Whether in the deep sea (Galgani et al., 1996; Song et al., 2021; Zhu et al., 2024), in the arctic (Bergmann et al., 2022), or on Mount Everest (Napper et al., 2020), not to mention urban areas (Schuyler et al., 2022) and human bodies (Li & Liu, 2024). The physical presence of plastic with its mechanical properties and risk of entanglement, ingestion or inhaling, is just one side of the coin. Plastic is also never 'just plastic'. It is produced with a huge range of additives, most common are plasticizers, antioxidants, heat stabilizers, and slip agents, but also colorants, processing aids, flame retardants, or fillers (Hahladakis et al., 2018; Monclús et al., 2025). There are more than 16.000 known plastic chemicals, of which at least 4.200 are chemicals of concern, since they are either persistent and or bioaccumulative, and or toxic (Monclús et al., 2025).

Currently the annual plastic production rate is around 430 Mt and rising (Plastics Europe, 2025), which means roughly 50 kg for each person on this planet (Symeonides et al., 2021). Seewoo et al. (2023) analyzed over 3500 peer-reviewed publications on human exposure to plastic and plastic related chemicals, and impacts on human health. They found that there are quite a few gaps in studies on impacts of plastic on human health, e.g. 26 out of 1202 known hazardous additives, actively used in plastic production were not included in the reviewed studies. Further, there are very few studies on recent substitutive chemicals. They call for a paradigm shift where plastic additives have to be rigorously tested before and while being introduced in consumer products. However, they also found that the concern over how plastic impacts human health is increasing, >45% of reviewed publications had been published in the five years previous to the study. The issues of plastic additives has been known for decades (Deanin, 1975). Yet, it is still on authorities and policymakers to identify and regulate toxic additives. The burden of proof should be reversed to where plastic producers have to disclose additives and ensure that their products are not causing any short- or long-term harm to

workers, consumers, or at any step post use (Castillo et al., 2023). In the process of the global plastic treaty, researchers pointed out that the preparatory documents focused mainly on downstream waste, when plastic additives should be negotiated more prominent (Dey et al., 2022; Brander et al., 2024). Plastic additives have been linked to a large range of human health impacts, including miscarriage, decreased birth weight, ADHD, cognitive development, hay fever, asthma, breast cancer, endometriose, polycystic ovarian syndrome, decrease in sperm concentration and quality, non-hodgkin lymphoma, melanoma, thyriod function, lung cancer, obesity, insulin resistance/type 2 diabetes, liver cancer, and total cancer deaths (Symeonides et al., 2021; Kahn et al., 2020).

Humans are not the only ones impacted by plastic use and pollution. We might not yet oversee all impacts and consequences of plastic production, usage, and pollution, but there is already a wide range of known effects. Entanglement and ingestion of plastic, fishing gear, and other anthropogenic debris has been recorded for decades, especially for marine birds and mammals (Shaughnessy, 1980; Ryan, 1987; Fowler, 1987; Jones, 1994). Plastic debris can also serve as 'rafts' for invasive species (Gregory, 1991; García-Gómez et al., 2021). Peng et al. (2024) estimate that through plastic floating at the ocean surface already up to 50 tons of plastic additives have been released. Species in the freshwater environment are also affected by plastic pollution, Azevedo-Santos et al. (2021) found evidence of plastic ingestion in over 200 freshwater species. The ubiquity of plastic pollution, the increasing plastic production rates, the large range of additives, and its persistency in the environment are concerning. And as of today we are not overseeing the entirety of short- and long-term impacts and consequences of plastic pollution.

1.1.1 | Macroplastic in rivers

At a zoomed out level, our environment consists of four spheres, atmosphere (air), lithosphere (sediment), hydrosphere (water), and biosphere (everything living). In plastic research, these spheres are commonly broken down further into environmental (sub-)compartments. Plastic research focuses often on either terrestrial, freshwater, marine, or atmospheric. Within each of these compartments studies often target a specific country or geographic region, a certain aspect of plastic pollution, e.g. a size range of plastic particles or a specific source. Research methods and measurement approaches differ between plastic particle size, environmental compartments, and also measurement protocols changed over the last few decades (Aliani et al., 2026; Hurley et al., 2023; Stock et al., 2019). Therefore it can be chal-

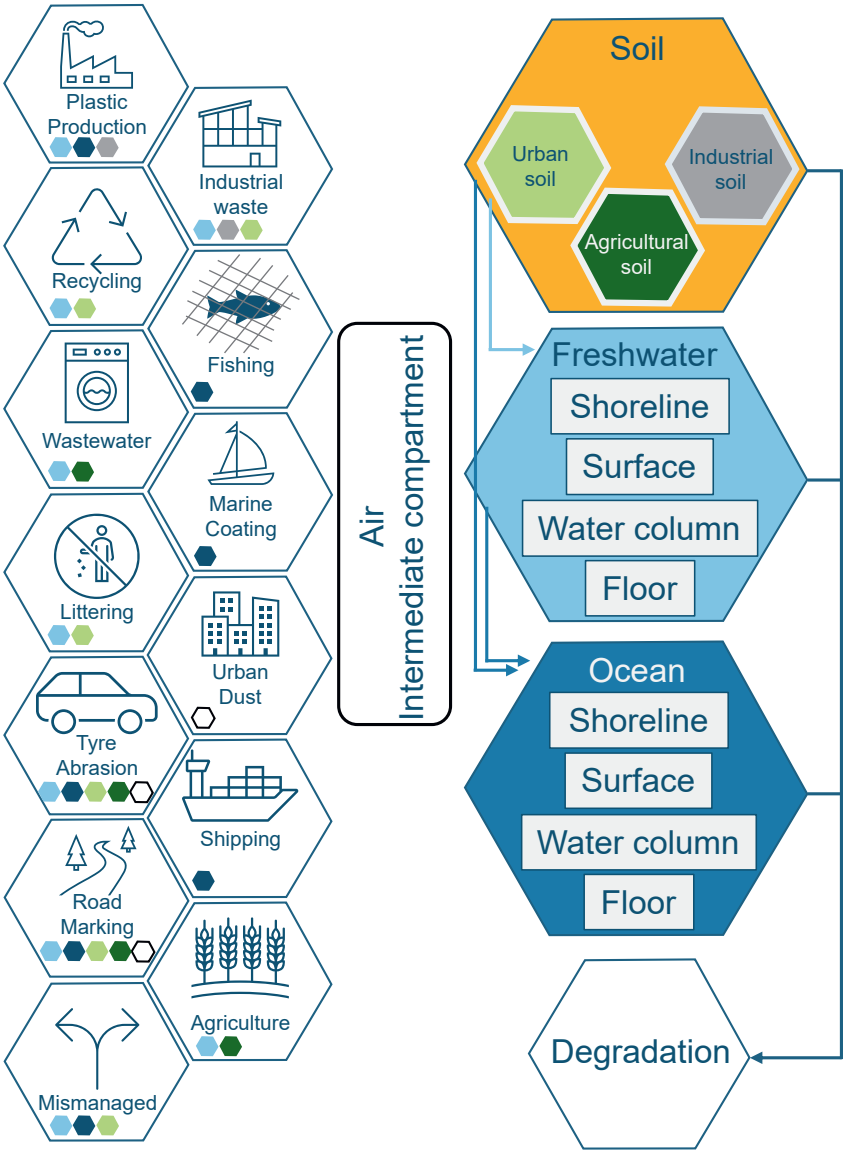


Figure 1.1 | Overview of potential sources and sinks of plastic. The colored hexagons at the sources on the left indicate the compartment the plastic first enters from that particular source. Figure adapted from Hoseini & Bond (2022).

lenging to compare results, and draw zoomed out, large scale conclusions. This thesis focuses on meso- (0.5 - 2.5 cm) and macro- (>2.5 cm) (based on Hanke et al., 2013) plastic pollution (hereafter macroplastic) in the freshwater environment, specifically in and along rivers on riverbanks and floodplains. For an overview of plastic sources and sinks in the environment see Figure 1.1.

As we are reminded of in every study involving them, rivers connect the terrestrial with the marine environment. In a way, they are 'natures conveyor belts' (Ferguson, 1981). Transporting natural and anthropogenic materials, such as sediment, wood, small organic debris, plankton, and also plastic and other litter. But that is only one aspect of rivers role in plastic pollution (transport). It seems the vast majority of plastic emitted on land stays either in the terrestrial or the freshwater environment (Mennekes et al., 2024; van Emmerik et al., 2022b; Nyberg et al., 2023).

Liro et al. (2020) identified five phases of macroplastic transport through a river, 1. input, 2. transport, 3. storage, 4. re-mobilization, 5. output (export to sea or removal via clean-up). They described that 1. is mainly controlled by humans, 2.-4. by fluvial processes, and 5. by both. Input of plastic into the river corridor can occur via multiple pathways. Plastic can be littered directly, via surface runoff, via mobilization during a riverine flood, via transport by wind, emission from a landfill close by the river, or via sewer- or stormwater overflow (Lechthaler et al., 2020; Wang et al., 2024). 'Output' i.e. when plastic is leaving a river either means it is emitted from the river to the sea, or it is removed from the river during a clean-up of a riverbank, or by a plastic/litter removal device (Helinski et al., 2021). Plastic in a river can be stored in the river bed (Hurley et al., 2018), entangled in vegetation (Cesarini & Scalici, 2022; Liro et al., 2022), and on or incorporated in riverbanks and floodplains (Hidayat et al., 2022; Dalu et al., 2025; Uogintė et al., 2024), also see Figure 1.2. Plastic can be stored in and around rivers for decades (McGoran et al., 2023; Tramoy et al., 2020b). Presumably macroplastic items repeat the phases 2. - 4., as studies with trackers or tracers indicate that plastic in rivers goes through a repeated cycle of transport, deposition, and re-mobilization (Tramoy et al., 2020a; Lotcheris et al., 2024).

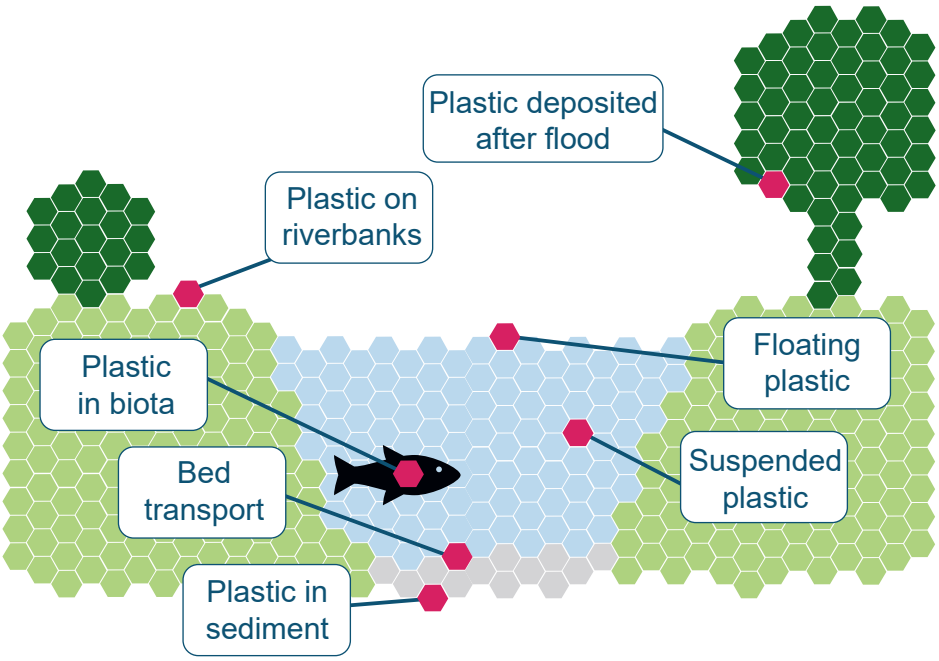


Figure 1.2 | Macroplastic transport and deposition in rivers. Figure adapted from van Emmerik & Schwarz (2020).

Ideally as plastic researchers we would like to somehow track the precise movement of a million pieces of different macroplastic litter and follow their transport path through the environment. Identify precisely where they came from, where they take a break, and where they eventually end up at. Track them over the course of decades or longer. Will they even 'end up' anywhere? Or will they just keep moving, break down into smaller and smaller fragments, release additives, and the journey of one piece of macroplastic litter turns into many. I specifically would like to apply this to macroplastic litter items in Dutch rivers. As of March 2026, unfortunately this is not possible. For most macroplastic items the location of 'input' is unclear. While for some litter categories their source can be estimated, e.g. fishing line or food containers, usually a large proportion are fragments of soft or hard plastic or foam (Pinto et al., 2024a; Nguyen & Bui, 2023; van Emmerik et al., 2020c) that can not be further identified. There are multiple approaches to monitoring plastic in and along rivers, observational fieldwork, experimental fieldwork, use of cameras or unmanned aerial vehicles (UAVs or 'drones') or remote

sensing (via satellite imagery) (Hurley et al., 2023; van Emmerik & Schwarz, 2020). Observational fieldwork means manual sampling or observation of macrolitter on the riverbank, floating at the surface e.g. by observing from a bridge or deploying a boom, or in the watercolumn by deploying nets. Experimental fieldwork utilizes released (GPS-) trackers or other tracers.

However, all approaches come with limitations. Some are very time and labor intensive, such as monitoring floating and near-surface plastic from bridges, and also this method neglects any plastic transported lower in the water column or right above/in the riverbed. Remote sensing options such as cameras on bridges, drones, or satellite imagery can also only monitor whats on or close to the surface (Marye et al., 2025). Monitoring or sampling via nets at different depths in the river can include plastic at almost all depths (Oswald et al., 2025), but sample collection and analysis is once again very labor intensive. Further, the nets do not cover the entire river cross-section. In contrast to observational fieldwork with monitoring and sampling 'what is there', experimental fieldwork makes use of of (GPS-)trackers or tracers (Newbould, 2021). For trackers and tracers, the point and time of release is precisely known, and their transport path can be tracked relatively detailed, at least for a certain time span. However, trackers and tracers come with their own limitations. Depending on the selected method, the ones allowing for precise tracking such as GPS trackers can be quite costly, have limited battery life, and have characteristics such as mass and buoyancy that differ from the common macroplastic litter pieces, and they need to stay near to the water surface in order to not loose signal (Tramoy et al., 2020a; Semcesen et al., 2025). Other tracers such as marked macroplastic items can be labor intensive to track and might have a relatively low retrieval rate (Tramoy et al., 2021; Liro et al., 2025). In any case, trackers and tracers are retrieved after a limited time span and or retrieved within set spatial boundaries. Studies involving trackers and tracers can give very valuable insights into macroplastic transport and storage in rivers, however, they do not depict reality.

Monitoring and sampling of deposited plastic in the 'storage' phase comes with similar constraints and limitations. Manual monitoring of plastic on riverbanks implies 'going to each riverbank' to manually identify and count macroplastic items in the sampling area. However, remote sensing of plastic on riverbanks, especially with the plastic sizes and concentrations common in the Netherlands is also not completely feasible yet (Tasseron et al., 2024b; Maathuis et al., 2026). As of the time of this thesis, the most promising approach seems to be to 'go out and count'. Of

course that is not sustainable and very labor and cost intensive, and also limited to when and where you decide to monitor or sample. That being said, there have been numerous studies giving insights on macroplastic transport and deposition in rivers, especially in the last decade.

1.1.2 | Plastic transport and riverine floods

Floods in general and riverine floods in particular can occur due to various causes (e.g. Rosenzweig et al. (2018); Kreibich & Dimitrova (2010); Mohor et al. (2020); Leal et al. (2018)). Depending on the cause, there are in general four types of floods; fluvial (from latin 'fluvialis', 'of the river'), pluvial (from latin 'pluvialis', 'of the rain'), flash floods, and coastal floods. Coastal floods (or storm surge) as indicated by their name occur along the coast, when seawater is pushed onto the coast, typically during a severe storm or a tsunami. Pluvial floods, also called surface water floods occur outside a body of water, when rainfall exceeds the infiltration or drainage capacity and leads to pooling. Coastal and pluvial floods are not subject of this thesis. Fluvial floods occur when the waterlevel of a river, stream, or lake increases to a point where it exceeds its bank and overflows onto surrounding land. Fluvial floods are usually caused by excessive rainfall or snowmelt. Flash floods are severe floods (fluvial or pluvial) that occur very fast, within minutes or up to six hours, either due to excessive rainfall, or e.g. breaking of a dam. When multiple types of floods occur simultaneously or in close succession it is called a compound flood.

Plastic in rivers can be transported anywhere in the water column (Oswald et al., 2025). It can also be transported in biota (Azevedo-Santos et al., 2021; Collard et al., 2019), but as that is not in the focus of this thesis it will not be further discussed (Fig.1.2). Most commonly plastic transport in rivers has been observed by researchers standing on bridges and counting macroplastic that is floating and transported near the river surface (Vriend et al., 2025). However, recent studies also investigated plastic transported in the water column. Blondel & Buschman (2022) sampled plastic and other litter in the surface and water column (surface, 2.5 m and 5 m depth) of a river bend in the Rhine-Meuse delta. They found that overall the plastic concentration in the middle net was the lowest, and there was an overall higher plastic concentration at the downwind side compared to the upwind side. The most common items they found were soft plastics, with a relatively higher concentration of hard plastic in the lower net compared to the other two nets. Overall they found around 0.5 mg of plastic per m^3 of water. Oswald et al. (2025)

however found hard plastics more frequently at the river surface and soft plastics near the river bed. They sampled the rivers Waal and IJssel, two branches of the Rhine in the Netherlands, during two fieldwork campaigns. One event during normal conditions, one during a high discharge peak. During normal conditions, the plastic concentration was greatest at the bottom, while during the discharge peak, the plastic concentration was more uniform in the water column. This is likely due to increase in vertical mixing related to higher discharge and turbulent flow (Oswald et al., 2025; Vriend et al., 2023).

Plastic transport in rivers is not uniform over time, it seems there is a strong relationship between floods and macroplastic transport (van Emmerik, 2024). One source of plastic pollution to rivers can be urban flooding, and it seems plastic pollution and urban flooding influence one another (MacAfee & Löhr, 2024). Urban floods are predicted to increase in frequency and severity due to climate change. Urban flooding can be intensified by plastic pollution clogging drains and sewers (Breukelman et al., 2019), or other urban structures (Honingh et al., 2020). Downstream in rivers, floods and plastic transport seem also related. Wagner et al. (2019) found a positive relationship between discharge and floating/near-surface plastic concentration downstream of an urban catchment for the Parthe river in Germany. They think this could be to due to additional plastic from sewer overflow. Based on the relationship between plastic and discharge, they estimated that 90% of plastic is transported during only 20% of the time. A study on micro- and mesoplastics came to very similar results, with 90% of mesoplastic transported in only 11.8% of the year in a Japanese river Tanaka & Nihei (2025). Another study at the Seine river in France also came to similar conclusions (van Emmerik et al., 2019). Close to the river mouth van Emmerik et al. (2019) measured ten times more floating plastic during high flow than during low flow. With the high flow having two to three times the discharge of the low flow measurements. They also estimated that large amounts of plastic can be transported during relatively short periods of time, similar to transport of other materials like sediment. Roebroek et al. (2021a) investigated the potential of plastic mobilization at a global level in relation to floods with various return periods. They estimate that floods with a 10 year return period have the strongest impact on plastic mobilization compared to non-flood conditions. van Emmerik et al. (2023) observed plastic transport in the Dutch Meuse river during the July 2021 flood event and compared the observed floating plastic to modeled annual transport. They estimate that over one-third of the annual plastic transport occurred during just six days of extreme discharge.

Schreyers et al. (2025) and van Emmerik et al. (2023) found that floods also increase macroplastic concentrations on riverbanks and floodplains. Overall it seems that even during extreme discharge a large proportion of plastic in rivers is deposited and stored along the river corridor, and not emitted to the sea. Schreyers et al. (2024c) introduced a budget for plastic transport and storage in rivers. For two sections along the Dutch IJssel and Waal rivers they estimate that 98% of stored plastic mass is stored in riverbanks and floodplains and only 2% in the river channel.

1.1.3 | Macroplastic on riverbanks and floodplains

Macroplastic pollution has been reported on riverbanks and floodplains globally. The most commonly found plastic litter categories can vary by country, and region, but ultimately they appear quite similar. Some examples, along the Odaw river in Ghana soft plastic fragments are the predominant plastic items on the riverbanks (27%), whereas the top three identifiable plastic categories are water sachets (11%), caps and lids (9%), and small bags (8%) (Pinto et al., 2024a). On riverbanks along the Saigon river in Vietnam the most common plastic litter category are unidentifiable pieces of foam (18%). Here the top three identifiable plastic categories are bags (12%), plastic cups (9%), and foam food packaging (8%) (Nguyen & Bui, 2023). In the Netherlands, the focus of this thesis, the most common riverbank macroplastic categories are soft and foam fragments (56% in total), the most common identifiable categories are food wrappers, caps and lids, and food packaging (van Emmerik et al., 2020c). Not just plastic composition, but also plastic concentrations on riverbanks and floodplains vary between rivers, locations, and landcover elements.

On riverbanks and floodplains, plastic can get deposited in riparian vegetation (Cesarini & Scalici, 2022; Martuscelli et al., 2025), but also on the ground (Fortibuoni et al., 2025), and even incorporated into the riverbank sediment (Hidayat et al., 2022). This thesis focuses on the Netherlands with multiple lowland rivers and the Rhine-Meuse delta. In the Netherlands, waste disposal in general is well organized, however, Lobelle et al. (2024) estimate the recycling quota of plastic in the Netherlands is only about 33%. Over the whole Netherlands, the average macroplastic litter concentration is roughly two items per meter of riverbank (van Emmerik et al., 2020c). Estimated sources of macroplastic on Dutch riverbanks include sewer overflow, recreation, angling, agriculture, and industry (Roebroek et al., 2021b). However, the most common plastic litter categories are soft plastic and foam fragments, which cannot be linked to a specific source (van Emmerik

et al., 2020c). Of course, estimations of linking plastic litter categories to one or multiple sources can usually only be an estimate by litter category. A individual piece of plastic litter can usually not be linked to a source or time and place of emission (Fig. 1.3).



Figure 1.3 | Examples of macroplastic litter on Dutch riverbanks. Pictures by Rahel Hauk

As discussed earlier, observational fieldwork is time and labor intensive. Monitoring thousands of kilometers of riverbank for deposited macroplastic seems unfeasible, there are already ~7000 km of just waterways in the Netherlands (CBS, 2026), not included smaller non-navigable canals and streams. In order to better understand macroplastic deposition on riverbanks, it is therefore essential to identify its' drivers, i.e. riverbank characteristics and other factors related to it. Identifying what leads to plastic deposition in a certain location can ultimately allow to predict its' spatial and temporal variability. Some studies identified drivers and factors that could be linked to plastic concentrations. Palmas et al. (2022) found that lightweight (plastic) litter can be partly explained by levels of urban or agricultural land use along rivers in Sardinia. Heavyweight macrolitter was more determined by proximity of the sampling point to bridges, and the local population density. Guimarães et al. (2024) found higher plastic concentrations during the dry season compared to the rainy season in the Amazon river in Brazil. Further, they found a moderate positive correlation between plastic and the macrophyte biomass at the sampling location, and overall higher plastic retention on upstream banks vs. downstream. Valyrakis et al. (2024) also investigated the impact of the riparian zone, but in a flume experiment. They found that riparian vegetation can slow down transport velocity, and given a vegetation density $1 m^{-1}$ potentially cap-

ture all macroplastic litter. Pace et al. (2024) investigated macrolitter deposition on riverbanks in Portugal following two flood events. They found that the factor with the highest explanatory power was human population density, and litter transported during floods seems to be deposited rather quickly and not transported over long distances. However, these insights do not yet allow to predict plastic concentrations and deposition on riverbanks, which can be investigated in two dimensions, spatial and temporal.

1.1.4 | Thesis outline and research questions

Based on the above, it appears there is a lack of understanding in the spatial and temporal variability of macroplastic on riverbanks. Many previous studies quantified plastic but without investigating spatial and temporal variability. Here we aim to find structure in observations of plastic distribution. In order to address this I will address the following questions.

- How stable is macroplastic deposition on riverbanks over time and space?
- How does macroplastic concentration and composition on riverbanks and floodplains differ following a flood event vs. non-flood conditions?
- How far are macroplastic items transported during a flood event and over the following years, and how does their condition develop in terms of mass and fragmentation?
- Following flood events, how do macroplastic concentrations and characteristics differ between landcover elements on riverbanks and floodplains, and how is plastic distributed in the lateral direction?

Chapter 2 shows that macroplastic is not dispersed uniformly along rivers, some rivers show overall higher concentrations of plastic on their riverbanks, compared to other rivers. Also when investigating a single river, plastic is not distributed evenly. It seems there are morphological characteristics and riverbank features which would favor plastic deposition. However, since plastic emission and (riverine) transport are quite complex, it is currently unclear which factors lead to plastic deposition in a specific location. Taking a step back, to investigate whether local factors play a role in plastic deposition, I investigate the relative spatial and

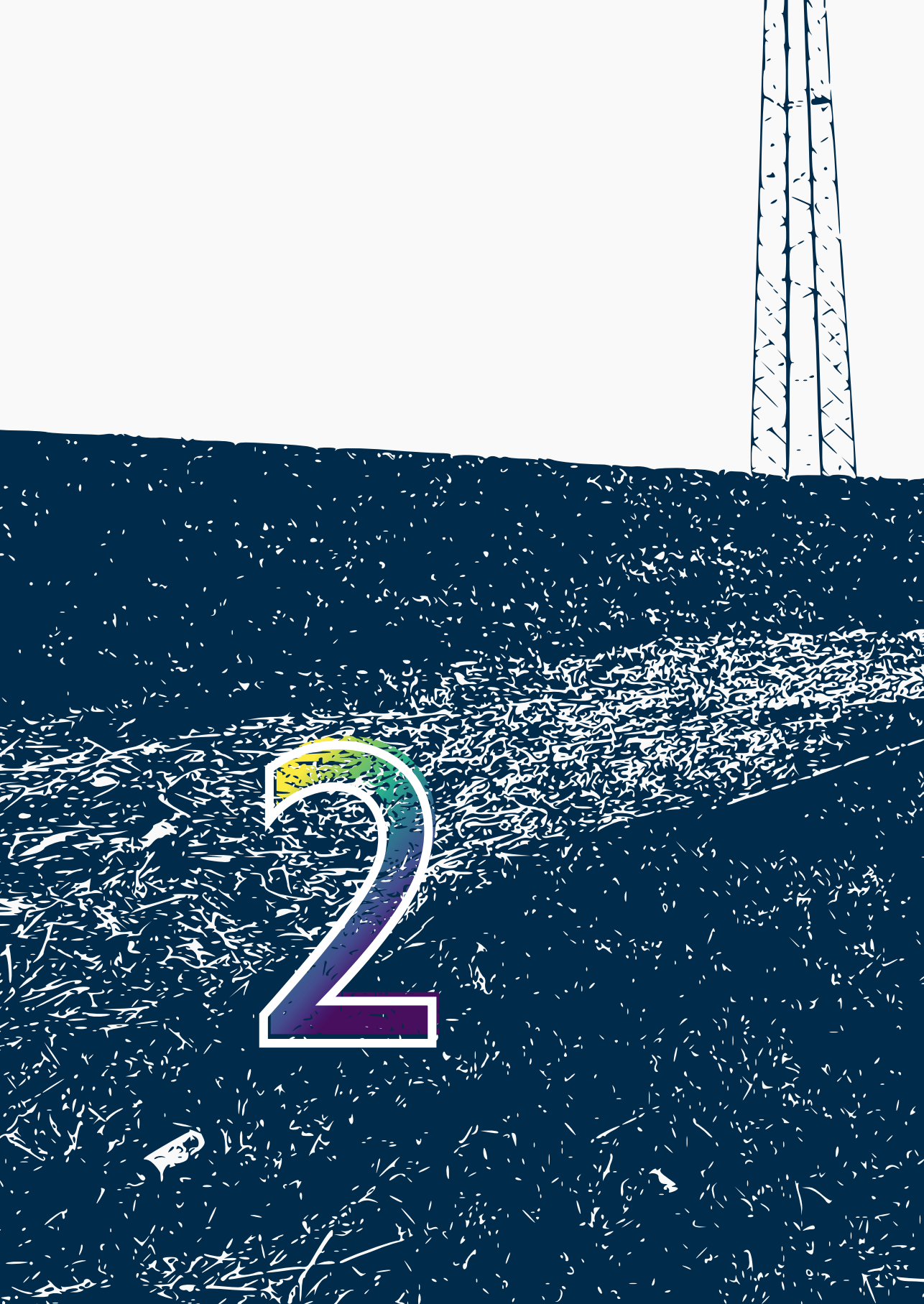
temporal stability of plastic pollution on Dutch riverbanks. Utilizing a large dataset spanning seven years of bi-annual measurements, and around 800 riverbanks along all major Dutch rivers. If there are indeed riverbanks with consistently high and low plastic concentrations, relative to other riverbanks, it emphasizes the impact of local factors on plastic deposition.

Chapter 3 compares plastic deposition along the Meuse river following a flood event to plastic deposition along the Meuse during non-flood conditions. This is done by fieldwork following the July 2021 flood event and comparing this fieldwork to multi-year monitoring data on the same riverbanks.

Chapter 4 a case study of plastic spilled into the Meuse river during the July 2021 flood. We followed the transport and fate of spilled buttertubs over the two years after the flood event. Tracked their transport path and velocity, as well as their fragmentation and mass development.

Chapter 5 investigates flood induced deposition of macroplastic on riverbanks and floodplains. Where exactly is plastic deposited, spatially on riverbanks, and in relation to riverbank and floodplain elements such as different vegetation and debris piles. In this chapter is also investigated the characteristics of macroplastic deposited off the ground, in trees and other riparian vegetation, vs. macroplastic deposited on the ground and in groundcovering vegetation.

Chapter 6 is the synthesis of this thesis, what are the main findings and how do the results from the individual chapters connect and fit into a broader context. What do these results reveal about plastic pollution and what can we learn from this for plastic pollution research? What are potential future research directions?


2

Temporal stability of macroplastic distribution



Under review
Preprint published as

Hauk, R., van der Ploeg, M.,
van Emmerik, T.H., & Teuling, A.J. (2026),
Temporal stability of riverbank macroplastic.
DOI: 10.21203/rs.3.rs-8901463/v1
Research Square

Abstract

Macroplastic pollution is prevalent on riverbanks and floodplains globally. Macroplastic can reach riverbanks via various pathways. These pathways include direct littering, overland transport by wind or surface runoff, or transport and deposition by the river. Local factors such as the type of riparian vegetation can influence macroplastic deposition on riverbanks. However, the combination of physical processes and anthropogenic influences that control macroplastic transport and deposition remain largely unclear. While macroplastic transport and deposition processes are not thoroughly understood, there is growing evidence that there are preferential deposition locations for macroplastic on riverbanks. To understand why plastics accumulate at certain locations, we first need to investigate if the spatial distribution is consistent over time. We quantified the temporal stability of macroplastic on 229 riverbanks along eight Dutch rivers, measured six to eight times between 2020 and 2024. Applying a method originally developed to investigate the temporal stability of soil moisture, we found that plastic distribution on Dutch riverbanks indeed exhibits temporal stability. We classified riverbanks into hotspots, coldspots, and above and below average, based on the count of macroplastic per 100 m riverbank for each measurement round. Per river between 10 – 42% of riverbanks were coldspots, with measurements always below average, and 0 – 8% of riverbanks were hotspots with all measurements above average. The ratios of riverbanks classified as hotspots, coldspots, and above and below average, and their temporal stability, are similar between all eight rivers we investigated. Our proposed method can streamline macroplastic pollution monitoring, as well as clean-up efforts, and be applied to any macroplastic dataset where locations were measured repeatedly over time. Among other uses, the method allows to identify riverbanks representative of the average plastic concentration in the monitoring area and also hotspots and coldspots. Spatial and temporal stability in macroplastic distribution indicates underlying factors and mechanisms which can be investigated as a next step.

2.1 | Introduction

Rivers play an important role in the global material transport as they connect the terrestrial and the marine environment. Natural materials such as wood (Wohl, 2013) and sediment (Barneveld et al., 2025), and nowadays also anthropogenic plastic litter (Schmidt et al., 2017; van Emmerik et al., 2022a). Global plastic mass production steadily increased since its start in 1950, and in 2022 it surpassed 400 million metric tonnes (Mt) per year (Plastics Europe, 2024). In 2020, the annual estimated emission into the environment was $>$ 50 Mt (Cottom et al., 2024). In this study we focus on macroplastic larger than 0.5 cm, hereafter called 'plastic'. Plastic emission is the point in time and space where plastic moves from a managed (under anthropogenic control) to an unmanaged state (determined by physical processes) (Cottom et al., 2024). Plastic can be emitted via littering (Chaudhary et al., 2021), sewer overflow (Treilles et al., 2020), agricultural practices (Ren et al., 2024) or by wind or surface runoff from urban areas (Funes et al., 2025; Mellink et al., 2022). Of the plastic emitted into the environment, Nyberg et al. (2023) estimated that about 0.8 Mt of plastic entered rivers in 2015, which is expected to triple by 2060. It is estimated that less than 2% of mismanaged plastic waste is emitted to the seas (Meijer et al., 2021). Rivers therefore not only transport plastic, but also retain and store it (Tramoy et al., 2020b; Windsor et al., 2019; van Emmerik et al., 2020c). Plastic can be (temporarily) stored in different compartments of the river corridor, e.g. in the riverbed (Hurley et al., 2018), or at weirs and other obstacles (Rocamora et al., 2021). However, it seems most plastic in rivers is (temporarily) stored on riverbanks and floodplains (hereafter compiled under 'riverbanks') (Schreyers et al., 2024c).

Riverbanks retain and store plastic. The plastic can be deposited and remain on the surface or become integrated in the bank sediment (Hidayat et al., 2022), but can also be entangled in riparian vegetation (Cesarini & Scalici, 2022; Valyrakis et al., 2024; Schreyers et al., 2025). There is a large number of studies that measured plastic on riverbanks, along different types of rivers, and with various levels of detail e.g. Kiessling et al. (2019); Dalu et al. (2025); Pinto et al. (2024a); Grigera et al. (2025). Usually these studies find that the plastic is not distributed evenly across riverbanks along a river (Chowdhury et al., 2023; Ballerini et al., 2022; Hauk et al., 2023c). Different riverbank characteristics and factors have been linked to plastic retention. Anthropogenic factors such as population density/proximity to populated/urban areas (Pace et al., 2024), or the presence of land use features

such as roads and buildings (Schreyers et al., 2024a). Also different types of riparian vegetation (Gallitelli et al., 2025), whereas Blettler et al. (2026) found the highest macroplastic concentrations on non-vegetated riverbanks along an urban waterway, which might be related to human activity, and accessibility of the riverbank. Schreyers et al. (2025) linked macroplastic deposition to slope of the riverbank and river morphology, especially during flood conditions. However, so far making a predictive model for riverbank plastic based on riverbank characteristics has remained an elusive goal.

Some studies also identified plastic concentration hotspots in different study areas and based on various definitions. Definitions such as percentile (Franceschini et al., 2021) or above average (Fok & Cheung, 2015). Tasseron et al. (2024a) applied multiple ways of hotspot definition to different plastic litter datasets. They found, depending on the definition, that $< 1\%$ to 50.3% of locations are classified as hotspots, containing 0.8% to 93.3% of plastic. However, regardless of the tested dataset about 25% of locations with the highest plastic concentration contain $\geq$57.0% of plastic. This indicates that in these systems, plastic is not distributed evenly, but there usually are locations with (very) high and low plastic concentrations. One dataset they included, is an earlier version of the *Schone Rivieren* dataset also used in this study. However, all eight datasets they investigated between an urban and global level, followed a similar pattern of plastic distribution. Riverbanks are part of the plastic pathway in the environment and serve as short- and long-term plastic storage. Yet, it is unclear how stable plastic distribution is between riverbanks over time.

Temporal stability, often defined as the temporal persistence in the relative rank of locations in space, is of interest in many research fields and has been investigated for decades. Examples include temporal stability in psychology (Gronnerod, 2003), or ecology (Grimm et al., 1992). For this study we applied a simple method originally developed to assess the temporal stability of soil moisture (Vachaud et al., 1985) to determine the temporal stability of plastic on riverbanks. If riverbanks have consistently relatively high or low amounts of plastic compared to other riverbanks, it seems more likely that there are local variables related to plastic deposition. Therefore this can serve as a base to further investigate potential explanatory factors. In this study we use a plastic monitoring dataset, which spans seven years (2018 – 2024) of bi-annual measurements. The monitoring covers around 800 riverbanks along all major Dutch rivers and the Rhine-Meuse-delta. Identifying temporal stability of the spatial plastic distribution on riverbanks can

serve as a first step to understand factors and variables that drive plastic retention in rivers. On one hand, this can contribute to improve and streamline monitoring protocols. The method we applied in this study was originally used to limit the number of monitoring locations for soil moisture. If plastic on riverbanks is stable over time, this can contribute to selecting plastic monitoring locations representative of a river or region. On the other hand, unraveling the likelihood of plastic retention can lead to forecasting plastic deposition, and therefore serve as a base for mitigation measures.

We quantified how many times each riverbank is above or below the average of all riverbanks per river, to identify hotspots and coldspots of plastic. Further, we analyzed what percentage of riverbanks, and plastic is covered by hotspots and coldspots, and riverbanks above and below average. Finally we investigated the prevalence of plastic litter categories for riverbanks with consistently relatively high and low amounts of plastic. We do this to test whether hotspots and coldspots have a similar plastic composition, or if hotspots can be explained by a prevalence of specific litter categories.

2.2 | Data and Methods

2.2.1 | Dataset

The macrolitter dataset we used in this study is from the *Clean Rivers Project* (Dutch: *Schone Rivieren*) by the *North Sea Foundation* (Dutch: *Stichting De Noordzee*). In this project citizen scientists collect, count and categorize all macrolitter on riverbanks along all major Dutch rivers. The measurements are done twice a year, in spring and in fall, in some locations already since 2017. The number of measurement locations in the *Clean Rivers Project* was increased over time and some locations were moved for various reasons, such as inaccessibility of the site. From this dataset we selected data from eight river sections in the Netherlands. The Waal, Nederrijn, IJssel and Oude Maas (all branches of the Rhine), the Meuse, Vechte, the Scheldt and Haringvliet (the latter two part of the Rhine-Meuse Delta).

Even though the Scheldt and Haringvliet are part of the Rhine-Meuse delta, all eight waterbodies/river sections are referred to as 'rivers', and all measurement locations are referred to as 'riverbanks' throughout the chapter. To get the largest possible sample size, we selected riverbanks that had been sampled at least six out of eight times between fall 2020 and spring 2024. This resulted in a total of 229

riverbanks and 1580 measurements across those eight rivers (Fig. 2.1). The citizen scientists sample the riverbanks in spring and fall following the River-OSPAR method (van Emmerik et al., 2020b), this method involves removal of all sampled litter. The measurements in spring are during a four week period in February and March, and the measurements in fall during a four week period in October and November. The sampling area is 100 m along the river, and the width equals the distance from the water line to the highest visible floodline, with a maximum of 25 m. Occasionally the citizen scientists deviate from the measurement protocol, e.g. due to very high plastic concentrations or over-enthusiasm. All litter in the sampling area is collected and classified into 111 litter categories. The 111 litter categories are divided into nine subgroups; plastic, rubber, textile, paper, wood, metal, glass, sanitary, medical. In this chapter we included the subgroups plastic, categories from sanitary and medical where the items are made from plastic, and cigarette filters from the subgroup paper. For each measurement at each location we normalized the plastic concentration to 100 m of riverbank [#/100 m]. We decided on #/100 m because the River-OSPAR method calls for a measurement area including the highest visible floodline, and as described sampling width therefore varies. Normalizing the data to #/m^2 could be misleading, in case riverbanks have a similar amount of items but the floodlines are located at different distances to the waterline. We assume that plastic with similar physical properties (e.g. density, rigidity) is subject to similar physical transport processes. Based on this, we also aggregated and analyzed the plastic by seven polymer groups. The polymer groups we considered were based on van Emmerik et al. (2020a). They include 'polyolefins soft', especially polyethylene and polypropylene (PO Soft), 'polyolefins hard' (PO Hard), polystyrene (PS), expanded polystyrene (EPS), polyethylene terephthalate (PET), 'multilayer items' (Multilayer), and 'other plastic' (Other).

2.2.2 | Assessing the temporal stability of riverbank plastic concentration

Vachaud et al. (1985) developed a method to quantify the temporal stability of soil moisture across locations. We propose an application of this method in order to characterize the temporal stability of plastic deposition across riverbanks. We investigated the plastic item concentration on riverbanks along eight Dutch rivers, in plastic items per 100 m of riverbank [#/100 m]. Between 2020–2024, there were eight measurement rounds (m[-]). The riverbanks (r[-]) considered in this study were measured six to eight times during those eight measurement rounds. We

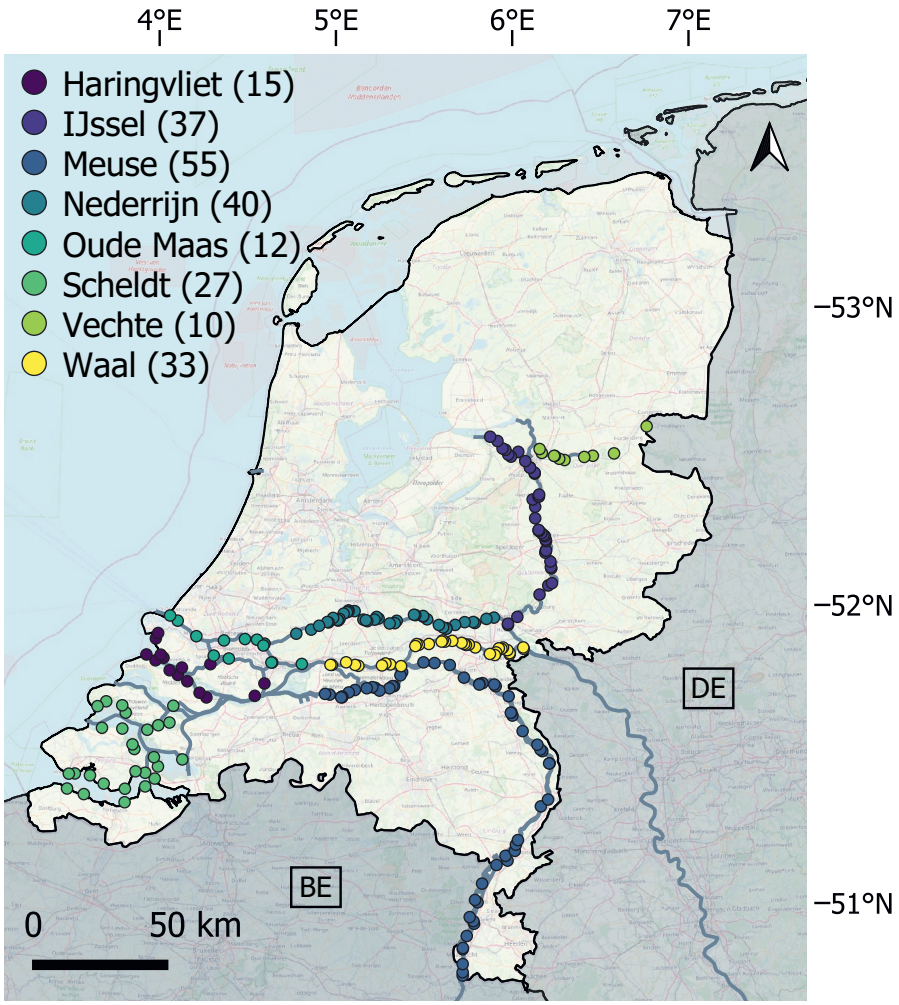


Figure 2.1 | Overview of the study area, the Netherlands and its neighboring countries Belgium (BE) and Germany (DE), and the eight river sections (blue lines) included in this study. The riverbank sampling locations per river are indicated by points, behind each river in parentheses indicated the number of included riverbanks (total riverbanks 229). Base map from OpenStreetMap and OpenStreetMap Foundation (CC-BY-SA). © https://www.openstreetmap.org and contributors.

investigated the temporal stability for each river individually, and for all riverbanks across all rivers combined. To compare plastic across riverbanks r during one specific measurement round m,

$$\overline{S}_m = (1/n) \sum_{r=1}^{r=n_r} S_{rm} \tag{2.1}$$

is obtained, where S_{rm} [#/100 m] is plastic at one specific riverbank during the specific measurement round. Therefore $\overline{S}_m$ [#/100 m] is plastic at the specific measurement round averaged across all riverbanks. To compare plastic at one riverbank to all riverbanks during a specific measurement round, we calculate

$$\Delta_{rm} = S_{rm} - \overline{S}_m \tag{2.2}$$

where Δ_{rm}[#/100 m] is the difference between plastic at one specific riverbank and plastic averaged across all riverbanks during one specific measurement round. Therefore, if Δ_{rm} equals 0, this means the plastic concentration [#/100 m] at that riverbank is exactly the average of all riverbanks. To obtain the relative difference between plastic at one specific riverbank and average plastic of all riverbanks, we calculate the relative difference

$$\delta_{rm} = \frac{\Delta_{rm}}{\overline{S}_m} \tag{2.3}$$

for each riverbank r at each measurement round m. This ultimately allows to calculate

$$\overline{\delta}_r = (1/n) \sum_{m=1}^{m=n_m} \delta_{rm} \tag{2.4}$$

which is the relative difference over time [-] for each individual riverbank.

Riverbank classes

Based on δ_{rm} we classified riverbanks into four classes 'hotspot', 'coldspot', 'over', and 'under'. Riverbanks were classified as hotspots if all $\delta_{rm} > 0$, and as coldspots

if all $\delta_{rm} < 0$. If not all $\delta_{rm} > 0$, but median $\delta_{rm} > 0$ a riverbank was classified as over, and if not all $\delta_{rm} < 0$, but median $\delta_{rm} < 0$ a riverbank was classified as under. 'Above average' includes hotspots and over, and 'below average' includes under and coldspots. We split the dataset two ways to further investigate stability over time. We split it between the first and second two years (fall 2020 - spring 2022 and fall 2022 - spring 2024), and by season. So we repeated the analysis for each river with the dataset split into first two and last two years, and split into spring and fall measurements. This allowed us to test if riverbanks retained their assigned classes. We also tested whether the classification is related to certain plastic categories or polymer types. Thus we calculated the contribution (%) of each aggregated polymer type for all four riverbank classes, based on the entire dataset. Further, we determined the ten most common River-OSPAR categories for each of the four riverbank classes. We then calculated the contribution (%) of those ten categories based on all plastic measured at all riverbanks per class. The dataset we used in this study included measurements of zero plastic items detected at riverbanks during at least one measurement round, consequently δ_{rm} has a minimum boundary of -1.

2.3 | Results and Discussion

2.3.1 | Temporal stability of plastic on riverbanks

For each of the eight rivers we ranked the riverbanks by their median relative difference (Fig.2.2) and we see a similar pattern of riverbanks below and above average for all eight rivers. The black line at $\delta_{rm} = 0$ indicates the river average, if the plastic concentration between riverbanks along each river was hypothetically completely uniform or completely randomly distributed, the expected mean difference for all locations would be zero. However, this is clearly not the case. Per river there are more coldspots (10.0 – 41.7% of riverbanks) (Table 2.1) than hotspots (0.0 – 8.3%), and more riverbanks under (33.3 – 60.0%) than over (16.2 – 30.3%). On average the interquartile range (IQR) of relative difference per riverbank increases from coldspots to under to over to hotspots. Coldspots have a mean IQR of 0.19 ± 0.12, riverbanks classified under 0.57 ± 0.32, riverbanks classified over 1.37 ± 0.87, and hotspots have an IQR of 2.28 ± 2.06. The high IQR of hotspots is due to individual measurements with a δ_{rm} up to 10, very far from the average macroplastic concentrations (Fig. 2). The riverbank classes not only differ in the range of relative difference they cover, but also in the proportion of plastic they

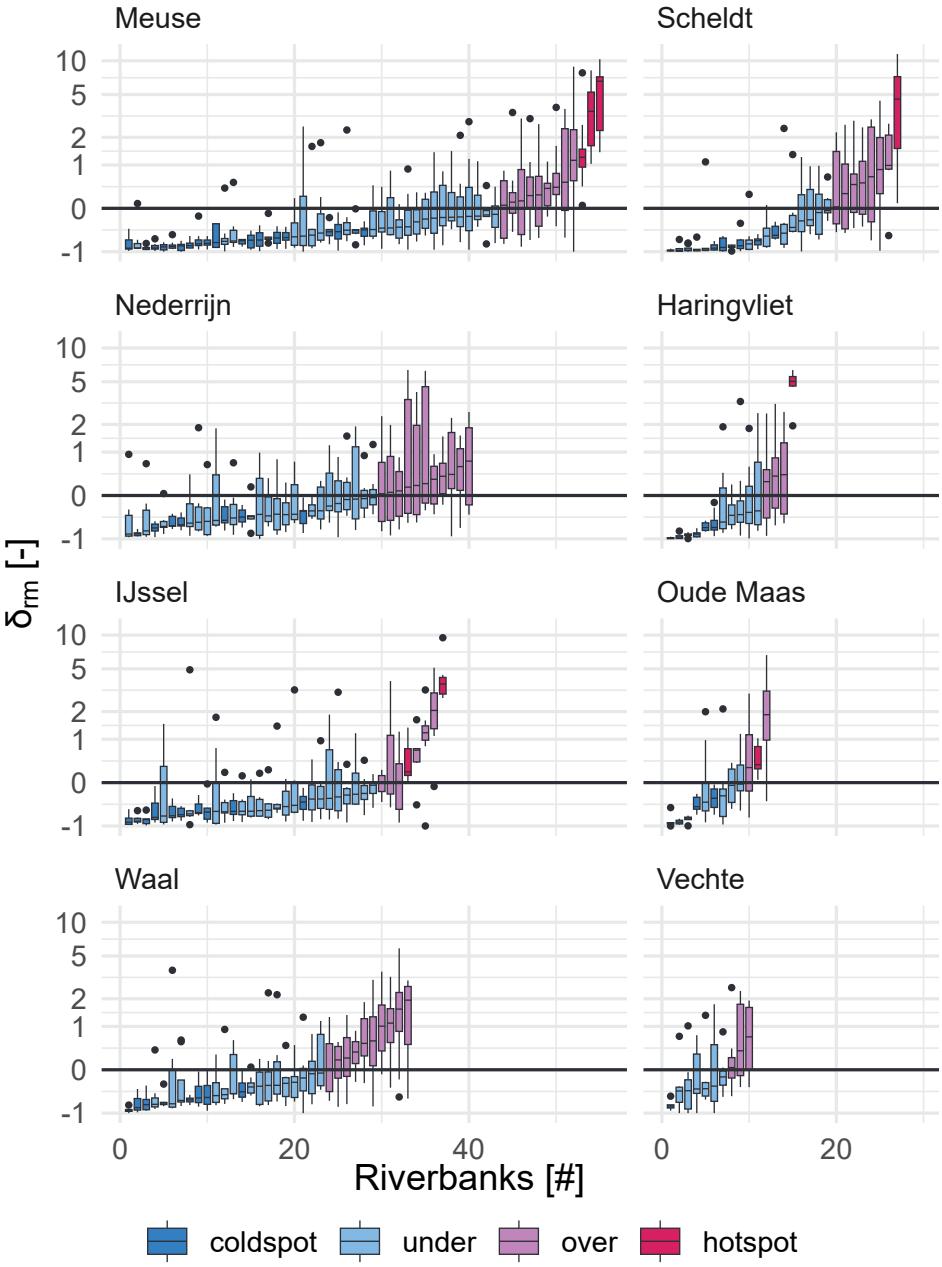


Figure 2.2 | Relative difference per location along all river, by items/100 m. The order of riverbanks per river is from lowest to highest median relative difference. Each boxplot represents one location and consists of the six to eight δ_{rm} from the different measurement rounds. Note that the y-axis is transformed for readability with an asinh transformation (inverse hyperbolic sine).

contain.

Across all eight rivers, only about one quarter of riverbanks are classified as over or as a hotspot (Fig. 2.2), but together they contain almost 60% of all sampled plastic items (Fig. 2.3). On average 22.9 ±6.2% of riverbanks per river (2–11 riverbanks per river) (Table 2.1) are classified as over, containing 39.9 ±11.1% of all sampled plastic items. Only 5.9 ±1.7% (0–3 riverbanks) are classified as hotspots, containing 23.9 ±8.4% of all sampled plastic items. On average 29.2 ±11.5 % (1–20 riverbanks) of riverbanks are classified as coldspots, containing 8.3 ±3.2% of all sampled plastic items. The majority of riverbanks are classified as under, on average 44.2 ±10.5% (4–23 riverbanks), containing 36.9 ±12.5% of all sampled plastic items.

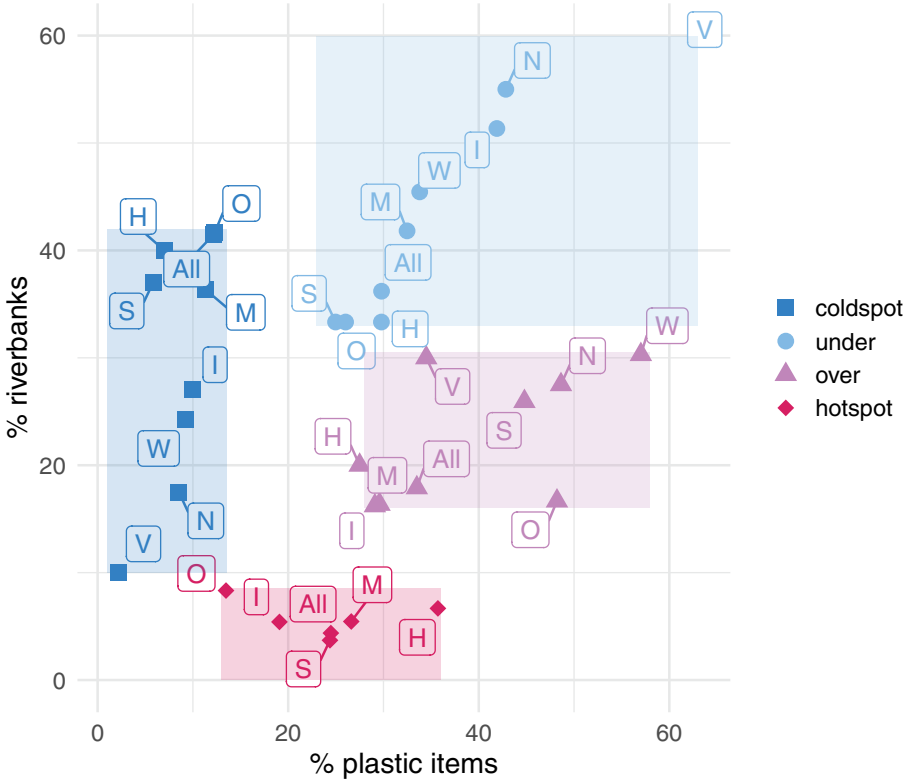


Figure 2.3 | This plot shows for each river and riverbank category, the proportion of riverbanks and the proportion of all sampled plastic. The extent of hotspots, coldspots, over, and under are indicated by shaded rectangles. The eight rivers are indicated by their first letter, Haringvliet (H), IJssel (I), Meuse (M), Nederrijn (N), Oude Maas (O), Scheldt (S), Vechte (V), and Waal (W). 'All' indicates the results from the analysis for all rivers combined. The rivers Nederrijn, Waal, and Vechte do not have riverbanks classified as hotspots, therefore hotspot is only displayed for five rivers.

It seems plastic deposition on riverbanks can be subject to seasonal variations. Riverbank plastic in the Netherlands showed higher concentrations in spring compared to fall, potentially due to increased discharge and deposition over winter (van Emmerik et al., 2020c). However, other studies found no significant differences in riverbank plastic concentration between wet and dry season (Pinto et al., 2024b), or influence of monsoon season (Sharma et al., 2025). Our method normalizes the data per measurement round, therefore absolute values and seasonal

variations across the whole system are not relevant for the analysis. Our method also does not have a pre-determined number of riverbanks for hotspots or per riverbank class. Some methods, e.g. defining hotspots by percentiles, have a pre-determined number of riverbanks that will be classified as hotspots. These methods could lead to miss-classification, in case there are either less or more hotspot riverbanks than the pre-determined number. Riverbank plastic monitoring can have different purposes. One purpose could be to have a baseline of the rivers' state of plastic pollution. Such a baseline can serve as a reference to investigate the impact of plastic related measures and policies. Another objective could be to identify hotspot riverbanks with high plastic concentration for targeted clean-up efforts. Our proposed method allows to identify whether there are riverbanks consistently above or below or around average in the investigated river(s)/area. Since this identification is solely based on riverbanks' relative plastic concentration, it ensures to capture all hotspots regardless of how many are present in the system.

For all rivers combined, 41.5% of riverbanks were classified as coldspots containing 12.2% of plastic (Fig. 2.3 and Table 2.1), and 36.2% of riverbanks classified as under containing 29.8% of items. Only about one fifth of riverbanks are above average but they contain over half the plastic. With 17.9% of riverbanks classified as over containing 33.5% of plastic, and 4.4% of riverbanks classified as hotspots containing 24.5% of plastic. The analysis of the dataset split into first two versus the second two years showed that overall riverbanks are very consistent in their above or below average classification over time. On average 83.7 $\pm$10.4% of riverbanks per river retained their classification above or below average between the two analysis. However, only 55.7 $\pm$11.6% of riverbanks retained their specific classification of hotspot, coldspot, over, or under. This is mainly due to some riverbanks having only one or two S_{rm} above or below average and are classified as hotspot or coldspot in one part of the dataset and over or under in the other. Only 17% of riverbanks did not retain their above or below average classification between the split dataset. Those riverbanks had a mean $\overline{\delta}_r$ of 0.16 $\pm$0.34, therefore very close to the overall average. The riverbanks that retained their above average classification had a mean $\overline{\delta}_r$ of 1.30 $\pm$1.32 and the riverbanks that retained their below average classification had a mean $\overline{\delta}_r$ of -0.47 $\pm$0.29. The high standard deviation for the riverbanks above average suggests a relatively high variability in the data. However, the mean of these riverbanks is still further from zero, i.e. the overall average, compared to the riverbanks that do not retain their above or below average classification.

Table 2.1 | Overview of the riverbanks and plastic items per riverbank class, per river, and for all eight rivers combined.

River	Variable	total #	coldspot	under	over	hotspot
All Rivers	Items % (#)	266484	12.2 (32510)	29.81 (79448)	33.5 (89284)	24.48 (65243)
	Riverbanks % (#)	229	41.48 (95)	36.24 (83)	17.9 (41)	4.37 (10)
Haringvliet	Items % (#)	20970	7.0 (1469)	29.79 (6246)	27.5 (5766)	35.71 (7489)
	Riverbanks % (#)	15	40 (6)	33.33 (5)	20 (3)	6.67 (1)
IJssel	Items % (#)	21924	9.92 (2175)	41.9 (9186)	29.1 (6379)	19.08 (4184)
	Riverbanks % (#)	37	27.03 (10)	51.35 (19)	16.22 (6)	5.41 (2)
Meuse	Items % (#)	81887	11.32 (9268)	32.48 (26593)	29.59 (24228)	26.62 (21798)
	Riverbanks % (#)	55	36.36 (20)	41.82 (23)	16.36 (9)	5.45 (3)
Nederrijn	Items % (#)	33093	8.53 (2822)	42.84 (14178)	48.63 (16093)	-
	Riverbanks % (#)	40	17.5 (7)	55 (22)	27.5 (11)	-
Oude Maas	Items % (#)	35199	12.29 (4327)	26.02 (9160)	48.21 (16969)	13.47 (4743)
	Riverbanks % (#)	12	41.67 (5)	33.33 (4)	16.67 (2)	8.33 (1)
Scheldt	Items % (#)	42876	5.85 (2508)	24.97 (10707)	44.79 (19206)	24.38 (10455)
	Riverbanks % (#)	27	37.04 (10)	33.33 (9)	25.93 (7)	3.7 (1)
Vechte	Items % (#)	2026	2.22 (45)	63.29 (1282)	34.49 (699)	-
	Riverbanks % (#)	10	10 (1)	60 (6)	30 (3)	-
Waal	Items % (#)	28510	9.18 (2618)	33.8 (9637)	57.01 (16255)	-
	Riverbanks % (#)	33	24.24 (8)	45.45 (15)	30.3 (10)	-

The temporal stability between seasons is slightly lower than between the first two and second two years. Between spring and fall measurements, we found that on average 73.2 $\pm$7.4% riverbanks per river retained their classification above or below average. For the specific classification, 47.3 $\pm$13.8% of riverbanks per river retained classification as hotspot, coldspot, over, or under. This could indicate that there is a slight difference in spatial plastic distribution between seasons. Yet, about three-quarter of riverbanks retain their above or below average classification between seasons. It seems therefore unlikely that the spatial distribution of relative plastic deposition varies severely between seasons.

Figure 2.4 shows the distribution of hotspots and coldspots along the eight rivers. As indicated by the point shape, the majority of riverbanks classified as a hotspot or coldspot for the analysis per river, are also hotspots and coldspots respectively across all rivers. For hotspots, only one riverbank along the IJssel was classified as hotspot for the IJssel, but not when all rivers were analyzed together. Overall, 67.2% of riverbanks keep their exact classification between the analysis of just one

river and all rivers together and 84.2% of riverbanks keep their classification of above or below average. Our study area is located in the Netherlands, a relatively small country with a high population density. All included rivers are lowland rivers, or part of the Rhine-Meuse delta, and also only the most downstream sections of the Rhine and Meuse, not their entire river length. Nevertheless, our study showed distinct patterns of riverbanks consistently above or below average plastic concentration. This signal might be even stronger when applying this method to the entire length of rivers, and consequently covering more diverse river morphology, population density, and discharge.

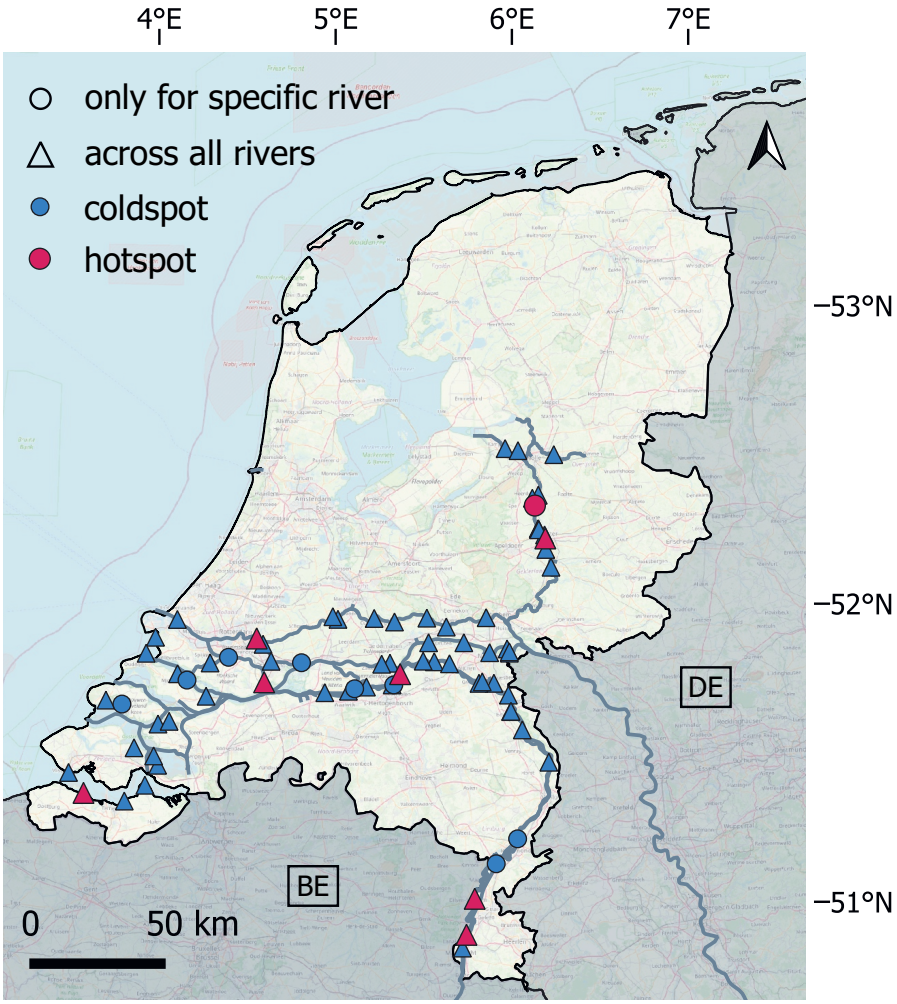


Figure 2.4 | Overview of riverbanks classified as coldspots and hotspots, the symbol shape indicates whether the riverbank is only considered a coldspot/hotspot in the analysis for the specific river (circle), or if the riverbank is also a coldspot/hotspot when all rivers are analyzed together (triangle). Base map from OpenStreetMap and OpenStreetMap Foundation (CC-BY-SA). © https://www.openstreetmap.org and contributors.

2.3.2 | Temporal stability of top litter categories

Table 2.2 | Overview of the ten most abundant plastic River-OSPAR categories, ranked by their prevalence per riverbank class.

rank	%	hotspot	%	over	%	under	%	coldspot
1	19,6	PO Soft 2.5 - 50 cm	14,4	PO Soft <2.5 cm	13,0	PO Soft 2.5 - 50 cm	14,1	PO Soft 2.5 - 50 cm
2	12,3	Fishing line	13,0	PO Soft 2.5 - 50 cm	10,9	PO Soft <2.5 cm	11,7	PO Soft <2.5 cm
3	8,6	PO Soft <2.5 cm	10,8	EPS <2.5 cm	7,9	EPS <2.5 cm	5,5	PO Hard <2.5 cm
4	6,9	EPS 2.5 - 50 cm	7,6	PO Hard <2.5 cm	5,8	PO Hard <2.5 cm	5,5	Food wrappers
5	6,4	PO Hard <2.5 cm	6,1	Food wrappers	5,6	PO Hard 2.5 - 50 cm	5,0	PO Hard 2.5 - 50 cm
6	5,9	Food wrappers	5,2	PO Hard 2.5 - 50 cm	5,2	Food wrappers	4,4	EPS <2.5 cm
7	5,7	EPS <2.5 cm	4,2	Caps and Lids	4,4	EPS 2.5 - 50 cm	4,4	Fishing line
8	5,2	PO Hard 2.5 - 50 cm	4,1	Fishing line	4,2	Fishing line	3,4	Caps and Lids
9	3,7	Caps and Lids	3,5	EPS 2.5 - 50 cm	3,9	Caps and Lids	3,2	EPS 2.5 - 50 cm
10	2,0	Fast food containers	2,8	Cigarette filters	2,2	Cigarette filters	2,0	Cigarette filters
sum	**76,4**		**71,9**		**63,1**		**59,1**	

The four riverbank classes based on the analysis for all rivers combined share nine out of ten top OSPAR-River plastic litter categories (Table 2.2). However, the categories rank, and amount of plastic covered by the top ten categories varies between riverbank class. For the ten hotspot riverbanks, the top ten litter categories cover 76.4% of all plastic items, for the 95 coldspot riverbanks, the top ten categories cover only 59.1%. The coldspot class includes 9.5 times the number of riverbanks compared to the hotspots. Yet, the hotspots include about twice the number of plastic items compared to the coldspots, with 65243 vs. 32510 plastic items respectively. Out of all four riverbank classes, hotspots have the highest percentage of PO Soft 2.5 - 50 cm. PO Soft <2.5 cm and 2.5–50 cm, and PO Hard <2.5 cm are in the top five categories across all four riverbank classes, and together contain 30–35% of plastic items per class. Overall, nine out of the ten most common plastic categories are consistent across the four riverbank classes. Only the fast food items (hotspots) and cigarette filters (over, under and coldspots) are not in the top ten of each riverbank class. The dataset used in this study was collected by citizen scientists and, as with any other data, it is possible that there are measurement errors, or observer bias. Roebroek et al. (2021b) investigated observer bias in an earlier stage of the dataset used in this study, and they found that citizen scientists find around 10% less PO Soft <2.5 cm, plastic cotton buds, wet tissues, and sanitary pads and packaging. In case of the PO Soft, this is probably due to detectability and in case of the sanitary categories to aversion. They could not detect an

observer bias for any other commonly found litter items. However, in the top ten litter categories it is possible that PO Soft <2.5 cm is slightly underrepresented.

One litter category that stands out in Figure 2.2 is fishing line. At hotspot riverbanks fishing line represents 12.3% of sampled plastic items, whereas at the other riverbank categories it represents 4.1 – 4.4%. As with all litter types, this prevalence of fishing line could be both supply and/or retention related. It could indicate that hotspot riverbanks are popular spots for recreational fishing. However, it could also indicate that these riverbanks have a high retention potential for fishing line and plastic in general, or a combination of the two. Recreational fishing might not only lead to littering of fishing line, but also plastic litter in general. O'Toole et al. (2009) investigated shorelines with high- and low-angling activity in Canada, and found significantly more litter (fishing related and general) at the sites with high angling activity. However, they investigated very small (6 m²) sections of shoreline, directly where angling activities had been observed regularly, and were able to relate the littering directly to angling activities. For the hotspots we identified in the Netherlands, a next step could be to assess the ease of access of the hotspot riverbanks, e.g. compared to close by coldspot riverbanks.

2.3.3 | Recommendations and limitations

In this study we investigated the application of a method from the temporal stability of soil moisture for the temporal stability of plastic on riverbanks. The application proved successful and we identified consistent spatial and temporal distribution of plastic concentration on Dutch riverbanks. However, what this study could not answer is what causes this distribution. Most likely it is due to interactions of multiple processes and variables. Other studies identified variables such as anthropogenic factors like population density/proximity to populated/urban areas (Pace et al., 2024), or the presence of land use features such as roads and buildings (Schreyers et al., 2024a). Also different types of riparian vegetation (Gallitelli et al., 2025). We tested some variables, e.g population density and river morphology, especially for the Meuse river, and had a closer look at the hotspot locations of the Meuse and Waal river. However, we could not find any clear relations between riverbank characteristics and plastic concentration (Hauk et al., 2025). Therefore, more insights on which processes are contributing and how they interact, is necessary. It is also possible that the sum of variables and processes at different times at different places contribute to the observed consistent distribution. Interactions we might not be able to disentangle. However, our proposed method follows a general

approach on investigating plastic distribution, regardless of present variables and processes.

Ultimately, plastic pollution is about individual litter items with specific physical properties (such as density, size, shape). These litter items are coming from a source (the moment they are emitted into the environment) at a specific location in space at a specific point in time. Once emitted, they are transported through the environment, and their physical properties can change (e.g. due to fragmentation). However, plastic transport is subject to the same physical influences as other materials. In this study we successfully applied a method from a different field for plastic pollution research, and it showed riverbanks' relative plastic concentration is stable over time. Plastic pollution as a comparatively new field of research can benefit from adapting approaches and methods from other fields of research. Whether that be sediment (Waldschläger et al., 2022; Armitage & Rohais, 2025) in rivers, species diversity in ecology (Battisti et al., 2018; Mashamba et al., 2024), or as in the case of this study temporal stability of soil moisture.

We expect this proposed method to be applicable to assess the temporal stability of plastic distribution in any system or region. All rivers included in this study are located in the Netherlands, i.e. lowland rivers, or part of the Rhine-Meuse delta in a densely populated country. Therefore our study area is relatively uniform, compared to other rivers and regions globally. However, even along the Dutch rivers we identified clear patterns of temporal stability of plastic concentration. Based on the results of this study, we recommend to sample riverbanks repeatedly, to get an idea of the temporal stability of relative plastic deposition between the riverbanks. After two years, 83.7% of riverbanks retained their classification of above or below average over the following two years. It would be interesting, if similar temporal stability can also be observed for other study areas and other spatial scales. The temporal stability analysis in soil moisture studies is used to minimize monitoring locations for time and cost effective reasons. Similarly, once hotspots and coldspots, as well as riverbanks above and below average are identified, monitoring location selection can be revised or optimized. Which riverbanks are selected would depend on the respective research question, e.g. riverbanks of each class, representative for the system, or hotspot riverbanks containing the majority of plastic.

2.4 | Conclusion

Dutch riverbanks have temporally consistent high or low concentrations of plastic litter. We found temporal stability in four dimensions; individual riverbanks as hotspots or coldspots always above or below average, the proportion of riverbanks per class between rivers, between the first and second two years of the dataset, and between seasons. First, 10 – 42% of riverbanks per river were coldspots, always below average, and 0 – 8.3% of riverbanks were hotspots, always above average. Second, the number of riverbanks per class was consistent between rivers, with 29.2±11.5% coldspots, 44.2±10.5% under, 22.9±6.2% over, and 5.9±1.7% hotspots (for rivers that contained hotspots). Third, riverbanks seem very stable over time, 83.7% of riverbanks retained their above or below average classification between the first and second two years of measurements. Fourth, 73.2 ±7.4% of riverbanks retained their above or below classification between spring and fall measurements. This was slightly lower than stability between the first and second two years of the dataset. However, we found no indication that plastic retention differs spatially between summer and winter. The different riverbank classes also contain disproportionally high or low percentages of plastic. For all eight rivers combined, the riverbank classes hotspot and over combined contain 58% of plastic at only 22% of riverbanks. Contrary, coldspots are the class with the most riverbanks (41%), but they contain only 12% of plastic.

The proportion of plastic items covered by the top then litter categories increases with relative $\overline{\delta}_r$ from 59.1% in coldspots to 76.4% in hotspots. One noteworthy litter category is fishing line, where hotspot riverbanks show a prevalence compared to other riverbank classes. Overall, nine out of the top ten plastic litter categories remain the same between the four riverbank classes. The only categories that differ are fast food containers and cigarette filters. Fast food containers are the tenth most common plastic category for hotspots, and cigarette filters are in tenth place for over, under, and coldspots.

Our study covered only (downstream) sections of the Meuse and Rhine river, yet the proposed methodology proved effective. The proposed method is also a simply way to investigate the temporal stability of plastic concentrations along the entire length of rivers, and larger regions. Temporal stability can be considered in planning for future monitoring, but also to investigate existing datasets from a new perspective. Identifying patterns of hotspots and coldspots can serve as a base to investigate factors and variables linked to plastic deposition and hotspot

formation. Further, understanding spatial distribution of plastic can contribute to and enhance monitoring protocols as well as targeted mitigation and clean-up measures. The proposed method allows for optimized location selection. Selecting riverbanks that represent the low- and high-end of plastic concentration for a specific river, or at country level can make monitoring strategies more effective. Further, understanding factors and variables linked to plastic retention could in the future contribute to forecasting plastic deposition, and therefore streamline targeted prevention, mitigation, and clean-up.



Riverbank macroplastic following the July 2021 European floods

This chapter was originally published as:

Hauk, R., van Emmerik, T.H.M., van der Ploeg, M., De Winter, W., Boonstra, M., Löhr, A.J., and Teuling, A.J. (2023). Macroplastic deposition and flushing in the Meuse river following the July 2021 European floods. Environmental Research Letters, 18(12), 124025. DOI: 10.1088/1748-9326/ad0768

Abstract

Rivers play an important role in the macroplastics transport and retention dynamics in the environment. Therefore, gaining an understanding of these processes is vital in order to help determine the fate of macroplastic in the environment. During flood events the transport of floating macroplastic is known to increase. We compared plastic accumulation and flushing on sixteen riverbanks along the Dutch Meuse river during the period that includes the July 2021 extreme flood to plastic accumulation on the same riverbanks as during normal discharge conditions between 2018 and 2021. Here we show that following the flood small macroplastic categories (< 2.5 cm) were flushed from the riverbanks, while larger soft plastic fragments (2.5–50 cm) and wet tissues were deposited. We found that for all plastic categories and for all riverbanks averaged, the plastic accumulation rate during the July 2021 flood was higher than that which would be expected for that time of year. However, the average accumulation rate for all locations during the period that included the flood was lower than the average accumulation rate over the Dutch winter (Oct/Nov–Feb/Mar). Our results show that litter category composition following the July 2021 flood differed from normal conditions. This indicates that plastic deposition and remobilization processes on riverbanks differ between extreme flood and annually average conditions. These observations contribute to a better understanding of the fate of macroplastic in the environment in terms of the drivers of both its transport and deposition.

3.1 | Introduction

Macroplastic pollution can be found almost everywhere on Earth. By 2015, approximately 8300 million metric tons (Mt) of plastic had been produced. Of these, about 4900 Mt have been mismanaged or otherwise been emitted into the environment (Geyer et al., 2017). Rivers not only connect the terrestrial and the marine environment, they also transport and retain plastic (van Emmerik et al., 2022b), in riverbeds (Constant et al., 2021), aquatic (Schreyers et al., 2021) and riparian vegetation (Cesarini & Scalici, 2022; Williams & Simmons, 1996), at anthropogenic structures (Honingh et al., 2020), and on riverbanks (e.g. Tramoy et al., 2021; Kundu et al., 2021; Hidayat et al., 2022). One river where plastic litter on the riverbanks has been studied is the Dutch Meuse river (van Emmerik et al., 2020c; Roebroek et al., 2021b). During a fluvial flood riverbanks, inactive parts of the river channel, and other areas around the river become inundated and plastic litter from these areas can become mobilized. It is estimated that mobilization potential increases tenfold due to floods with a 10-year return period as compared with non-flood conditions (Roebroek et al., 2021a). In the Seine river, for instance, a strong increase in floating plastic was observed with increasing discharge, potentially leading to a large fraction of the annually transported plastic to be transported in a relatively small fraction of time (van Emmerik et al., 2019). With extreme precipitation and flood risk increasing globally (Pörtner et al., 2022; Kundzewicz et al., 2014), a better understanding of macroplastic fate in the environment and the impact of flood events is needed.

In July 2021 heavy precipitation over large areas in Central-Western Europe led to severe flooding across the Rhine and Meuse river basins in Germany, Belgium, Luxembourg and the Netherlands. For the Meuse, flooding occurred mainly in the tributary catchments of the Ourthe, Amblève, and Vesdre in Belgium (Mohr et al., 2022). In this region almost 200 mm of rainfall was observed within 24 hours, which exceeds the statistical 200-year return period (Dewals et al., 2021). In the Netherlands, heavy rainfall mainly occurred over the catchments of the Meuse tributaries the Roer, the Geleenbeek, and the Geul. Combined with the discharge coming from the Belgian part of the Meuse, this lead to widespread flooding reaching 90 km downstream of the Belgian-Dutch border. This flood was exceptional as it occurred in the summer. Increased discharge in the Meuse river usually occurs in winter, due to extended periods of rainfall. The highest summer flood previously recorded on the Meuse occurred in July 1980 with 2016 $m^3\ s^{-1}$ mean daily

discharge at Eijsden. On 15 July 2021 the mean daily discharge at Eijsden was nearly 2800 m^3 s^{-1}, more than ten times the mean annual discharge of 255 m^3 s^{-1} and almost twice the mean annual maximum discharge of 1473 m^3 s^{-1}. The return period of the July 2021 flood was estimated to be around 400 years for the Ahr/Arft region and the Belgian Meuse catchment (Kreienkamp et al., 2021). The flood thus presents a unique opportunity to study flood impact on plastic in rivers.

In this study, we aim to quantify plastic accumulation on riverbanks and the composition of plastic litter categories after the July 2021 flood event in the Meuse, and compare these to non-flood conditions. We could study the impact of the July 2021 flood event by using a unique combination of data. Data were collected immediately after the flood, and combined with data from routine monitoring of litter accumulation carried out between 2017 and 2021 by citizen scientists within the framework of the *Clean Rivers Project (Dutch: Schone Rivieren)*. This study focuses on the litter categories macro- ($\geq$ 2.5 cm) and mesoplastic (0.5–2.5 cm), which hereafter will be referred to jointly as macroplastic for simplicity.

3.2 | Methods and Data

3.2.1 | Reference dataset

Over 150 riverbank locations along the Dutch Meuse river are being monitored for litter by citizen scientists (Fig. 3.1) within the *Clean Rivers project*, using the River-OSPAR protocol (van Emmerik et al., 2020c). The monitoring started in 2017 and is conducted biannually within four week periods in February/March, (hereafter named "Q1"), and October/November, (hereafter named "Q4"). The resulting dataset from the ongoing monitoring reflects plastic litter accumulation on riverbanks along the Dutch Meuse under normal conditions. Since the litter is removed from the monitoring area during each monitoring, we use the dataset from consecutive monitoring rounds to estimate the net accumulation rate between rounds.

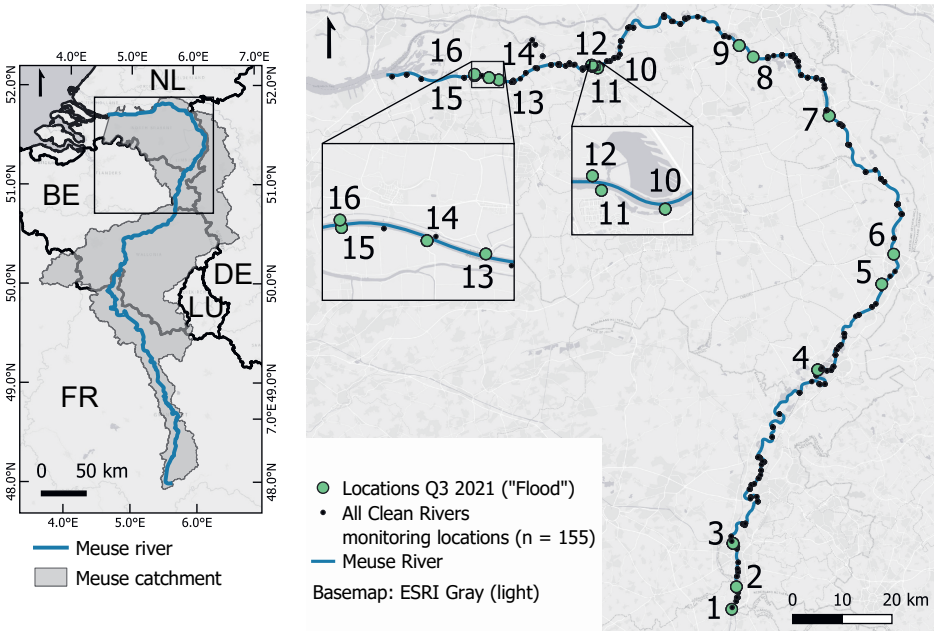


Figure 3.1 | Map of the study area. To the left the Meuse catchment that extents over France, Belgium, Luxembourg, and the Netherlands. To the right, the Dutch section of the Meuse river with all locations from the Clean Rivers monitoring and the sixteen locations that were sampled additionally in Jul/Aug "Q3" by the authors of the present study. (Credits Basemap: Esri, HERE, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community).

The data from the first monitoring at each location is not used here, as it represents the accumulation over an unknown period of time. Based on the baseline dataset we calculated the plastic accumulation rate per area R_{PA}:

$$R_{PA} = \frac{I}{A \times t} \tag{3.1}$$

which is the number of plastic items sampled on an individual riverbank during a monitoring round I, divided by the area of the sampled stretch of riverbank in hectare A, and the time interval in number of days since the last monitoring t.

We used the *Clean Rivers* dataset as a baseline to identify how plastic accumulation and composition on the riverbanks after the July 2021 flood differed from non-

flood conditions. Fig. 3.2c shows a conceptualized timeline of the routine monitoring and our own sampling in Q3 2021. In general, the River-OSPAR protocol calls for a sampling area 100 m along the river. However, during a few measurements the citizen scientists were overly enthusiastic and took a sample up to the highest visible floodline, even when it exceeded the maximum width of 25 meters. Also, when the riverbank was extremely polluted the length of the sampling area was shortened due to a lack of sampling time. On the sixteen riverbanks included in this study, the citizen scientists sampled between 100 and 5000 m^2 (average 1667 m^2) riverbank per monitoring round (2017–2021). For further explanation of the River-OSPAR protocol see van Emmerik et al. (2020c).

3.2.2 | Post-flood sampling campaign

From the monitored riverbanks we selected sixteen riverbanks for sampling. The selection was made to cover the entire length of the Dutch Meuse river ($\sim$ 200 km), from the Dutch-Belgian border, to the Biesbosch National Park (Fig. 3.1). The choice of the riverbanks was informed by their accessibility, as some areas were still inundated. The sampling took place within three weeks after the flood, between 22 July and 4 August 2021, before 14 August 2021 when the first large-scale riverbank clean-up campaign was planned (Hendrikx, 2021) (Fig. 3.2a). Due to time constraints we adapted the River-OSPAR sampling protocol (Sect. 3.2.1). On each riverbank, 2 m wide sections were measured, beginning at the waterline at the time of sampling (Fig. 3.2c). If not prevented by terrain or inundation conditions, measurements were done in triplicate at each location. One section in the center of the measurement location and then 40 m upstream and 40 m downstream, to stay within the 100 m that are monitored within the *Clean Rivers project*. However, we had to adjust the placement of one (locations 2, 14, and 15) or two (location 1) stripes, due to partial inaccessibility of the riverbanks. For further information on the measurements at each location see Supplementary Material, Table A.

A smartphone (Huawei WAS-LX1A, Shenzen, China) was used to geolocate the center of the measurement location. A tape measure was placed on the ground from the water-riverbank interface perpendicular to the waterline (Fig. 3.2c). Two researchers visually counted the litter items, with one researcher walking on either side of the measurement tape. All litter items within 1 m of the tape measure were counted and classified according to the River-OSPAR litter categories (River-OSPAR protocol developed by the *North Sea Foundation, Stichting de Noordzee in Dutch*). We did not count wooden items, as it was too difficult to distinguish

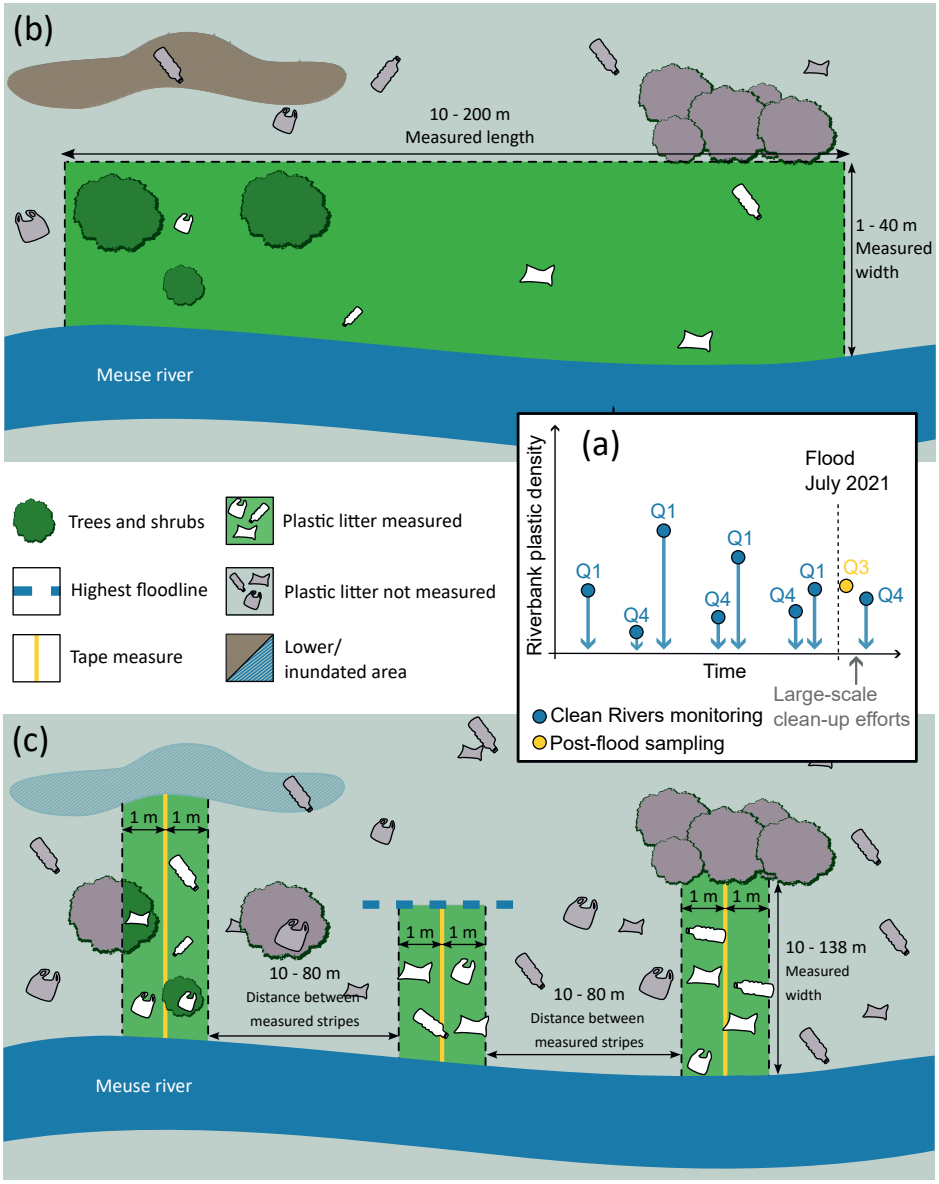


Figure 3.2 | (a) The concept of plastic deposition, monitoring and removing of litter on the riverbanks over time. (b) Schematic overview of measurement protocols in the *Clean Rivers Project* and (c) post-flood measurements in Q3, 2021, from top view.

natural wood from processed wooden items. This did not influence the results, as we only consider plastic items in this study. Sampling was done by walking slowly and looking carefully from a standing position, with vegetation being gently moved from side-to-side to ensure that no litter items were missed. For litter items that were not clearly (visual judgement) within or out of the measurement zone, their distance to the measurement tape was measured. If the centroid of the item was within 1 m it was counted, otherwise it was neglected since it was outside of the measurement zone. In case there was any doubt about the material of an item, the item was picked up and pulled apart to distinguish between plastic and plant material. The measurement sections were extended until either the highest visible floodline (e.g. at a levee) or a physical barrier (e.g. dense, impassable vegetation, fence, inundated area) was encountered. Distance between the center, upstream, and downstream sections was measured in steps by the same researcher at all locations. Note that in contrast to the regular monitoring described in Section 3.2.1 we did not remove the litter items during the post-flood measurements.

3.2.3 | Data analysis

As this study focuses on macroplastic, the analysis focused on the River-OSPAR categories under “plastic”, “sanitary”, “medical”, and the category “cigarette butts” (henceforth called “macroplastic"). Macroplastic represented 88.8% of sampled litter items in Q3 2021, the remaining 11.2% consisted of “rubber", “textile", “paper", “metal", and “glass" categories. In the regular monitoring dataset, macroplastic represented 96.2% in Q1, 91.0% in Q4, 2021, and 87.1% in Q4, 2018–2020 (all excluding wood categories, see Section 3.2.2). For each location, the number of days between sampling events was calculated by subtracting the date of the prior sampling event from the subsequent one. For each macroplastic category in each sampling round at each location, the number of measured items [items] was divided by the sampled area [ha] and the number of days since the last sampling [days], to calculate the accumulation rate per area of riverbank R_{PA} [items ha^{-1} day^{-1}]. This approach allowed us to compare accumulation between riverbanks that were sampled in Q1 2021 before the flood, and riverbanks that were last sampled and cleaned during earlier monitoring rounds (for further details on which location was monitored and when see *Supplementary Material, table 1*). To compare between plastic accumulation rates per riverbank area R_{PA} and length of riverbank along the Meuse, the plastic accumulation rate along the Meuse R_{PL} was also determined by dividing the number of measured items I by the length of the

sampled area along the river in km L and the time interval in number of days since the last monitoring t:

$$R_{\mathrm{PL}} = \frac{I}{L \times t} \tag{3.2}$$

We compared the plastic accumulation rate in Q3, 2021 with Q4 monitoring rounds of previous years averaged, additionally we were interested in the impact the flood event had on macroplastic accumulation and composition of plastic categories three to four months after the flood event. Therefore we also investigated the monitoring data from Q4, 2021. Not all sixteen locations were monitored in Q4, 2021, so for Q4, 2021, we included the closest monitoring location on the same side of the Meuse for location 1, 2, 12, and 13, with the assumption that river features in these locations are similar. Historical plastic accumulation rates are not significantly different ($p \geq 0.30$). For further information see *Supplementary Materials, Table B*.

We calculated the distance along the Meuse between the sixteen locations with the method from Vermeulen et al. (2014) and tested for a Spearman rank correlation between the distance and the plastic accumulation rate measured in Q3 2021 for each location. For the composition of macroplastic in the different seasons (Q4 2018–2020 mean, Q1 2018–2021 mean, Q4 2021, Q3 2021) the five macroplastic categories with the largest abundance were selected per season. The deposition factor D_{f} was used to quantify plastic accumulation:

$$D_{\mathrm{f}} = \frac{R_{\mathrm{P1}} - R_{\mathrm{P2}}}{R_{\mathrm{P1}} + R_{\mathrm{P2}}}. \tag{3.3}$$

D_{f} indicates how accumulation rates compare between different periods P1 and P2. Here, R_{P1} represents the accumulation period Q3 that includes the flood in July 2021, and R_{P2} represents the accumulation periods leading up to a measurement in Q4 in 2018–2020. D_{f} ranges between -1 and $+1$, where $D_{\mathrm{f}} > 0$ indicates the accumulation rate during the flood was increased ("deposition"), as $R_{\mathrm{P1}} > R_{\mathrm{P2}}$, whereas $D_{\mathrm{f}} < 0$ indicates the accumulation rate was decreased ("flushing"), as $R_{\mathrm{P1}} < R_{\mathrm{P2}}$. The time periods between measurements vary, as well as the areas of the measurement zones, which is why we use R_{PA} (section 3.2.1) rather than the density.

3.3 | Results

3.3.1 | Distribution of plastic accumulation rates

Figure 3.3a shows the distribution of R_{PA} measured in Q3 2021. Locations 1 to 5, the most upstream locations, show the highest R_{PA}, between 250.3 items ha^{-1} day^{-1} at location 1, to 11.5 items ha^{-1} day^{-1} at location 4, whereas locations 11, 13, 14, and 16 show a low R_{PA} between 2.4 items ha^{-1} day^{-1} at location 13 and 1.3 items ha^{-1} day^{-1} at location 16. Overall R_{PA} decreases from location 1 with 250.3 items ha^{-1} day^{-1} to 16 with 1.3 items ha^{-1} day^{-1} in Q3, 2021. There is a significant correlation between R_{PA} and the distance of the locations to the river mouth (with $p = 2.017 \times 10^{-6}$, $\rho = -0.85$). In Fig. 3.3b, which represents the average of Q4, the correlation between R_{PA} and the distance of the locations to the river mouth is still significant ($p = 0.045$) but less strong ($\rho = -0.51$). During Q3 2021, high plastic accumulation was found in locations 1 to 5, while in Q4 2018–2020, it extended 44 km further downstream (up to location 7). Figure 3.3a depicts the longitudinal distribution of the deposition factor, with 62.5% of riverbanks showing increased macroplastic deposition compared to the average monitoring data from Q4 2018–2020. Plastic was only flushed from one location (2) within the first 100 km from the Belgian border, whereas further downstream plastic was flushed from 3 locations (11,13,16 between 214 km and 239 km). This indicates that a large fraction of macroplastic was quickly deposited on riverbanks along the Meuse during the July 2021 flood event.

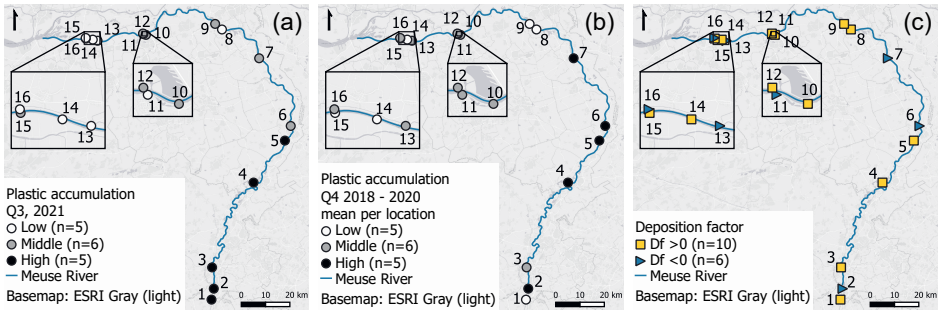


Figure 3.3 | (a) Spatial distribution of low, middle, and high plastic accumulation rates in Q3, 2021, and (b) the Q4 2018–2020 average. Low, middle, and high accumulation rates are not defined by absolute values, but relative between the sixteen locations. High accumulation rates shows the five locations with the highest R_{PA}, low accumulation rate shows the five locations with the lowest R_{PA}, and middle shows the locations between high and low. (c) Spatial distribution of the Deposition factor, >0 indicates deposition during Q3, 2021 in comparison to Q4, 2018–2020, and <0 indicates flushing.

3.3.2 | Differences between flood and normal conditions

For all plastic categories combined, ten out of sixteen locations show deposition and six show flushing (Fig. 3.3c). For all locations combined, eight plastic categories were deposited, while twelve were flushed out (Fig. 3.4). Location one shows deposition for thirteen out of the twenty most common plastic litter categories, which is the highest rate for all locations. Overall the number of values > 0 per litter category shows a decreasing trend from common to less common litter categories after the flood. There is also a decreasing trend visible from upstream towards downstream, but not as clear, as from common to less common litter categories. From the sixth common category (Foams 2.5—50 cm) and the second location downwards and downstream, the majority of values are -1 (with the exception of pieces of rope < 1 cm), which indicates that the item category has been found at the location in Q4, 2018–2020 measurements, but not in the Q3 measurement in 2021.

The two plastic categories that were found most commonly in Q3, 2021 are soft plastic fragments (2.5–50 cm) and wet tissues (Fig. 3.4), they show additional deposition at fourteen out of sixteen and six out of sixteen locations respectively. The six locations with increased deposition of wet tissues are within the seven locations farthest upstream. Overall it seems that foams were flushed out during the flood. Small foams (<2.5 cm) and larger foams (2.5–50 cm) were flushed from

eleven out of sixteen locations. Small foams do not show deposition at any location and larger foams show deposition at four out of sixteen locations.

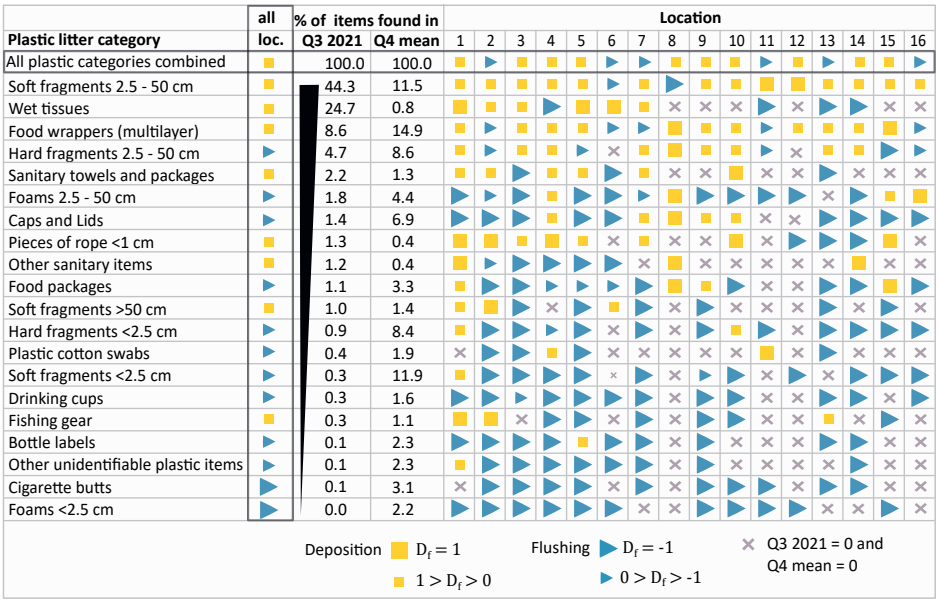


Figure 3.4 | D_f for all plastic litter categories combined and the plastic litter categories that are most common in Q3 (following the July 2021 flood) and Q4 (Oct/Nov monitoring). The most common categories are defined as categories that make up $\geq$ 1% of plastic litter in Q3 and or Q4 average (2018–2020). The litter categories are sorted from most to least common in Q3 and the locations 1 to 16 are sorted from upstream to downstream respectively. For each plastic litter category at each location, the figure depicts the deposition factor. Values >0 (indicated by yellow squares) indicate increased deposition in Q3, values <0 (indicated by blue triangles) indicate flushing in Q3, a grey cross indicates that this category of plastic was not present in Q3 and Q4 at this location.

3.3.3 | Litter composition

Soft plastic fragments (2.5–50 cm) are the most abundant macroplastic category and on average make up 13.9% of macroplastic items in Q4 and 13.4% in Q1, while in Q3 they made up 44.3% of the measured plastic. Wet tissues on average make up 0.9% of the plastic items in Q1 and Q4, in Q3 they made up 24.7%. The relative abundance of soft plastic fragments in Q3 is increased, compared to Q1 and Q4 where the values are much closer together (Fig. 3.5). Small litter items $<$ 2.5 cm are more abundant in Q1 than in Q4 and least abundant in Q3 2021. The main

five plastic categories across all measurements make up >85% of plastic items by number in Q3 2021, but <40% in the baseline.

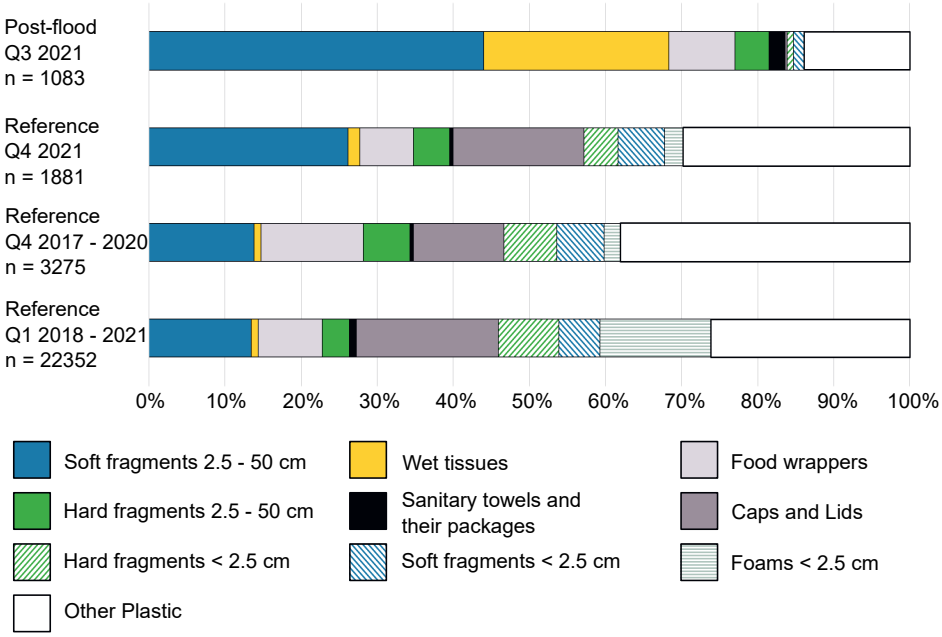


Figure 3.5 | Macroplastic item numbers and composition in the Q3 measurements after the flood event 2021, the Q4 monitoring in 2021, the Q4 average (2018–2020), and the Q1 average. The litter categories were chosen based on the five top frequent litter categories in Q3, Q4 2021, Q4 2018–2020 average, and Q1 2018–2021 average.

3.3.4 | Seasonal effects

Figure 3.6 shows a comparison between R_{PA} and R_{PL}. R_{PL} with an average of 54.8 items km^{-1} day^{-1} for Q3, 2021 is almost twelve times what would be expected for that time of year; the average rates in Q4, 2018–2020 with 4.7 items km^{-1} day^{-1}. The overall highest plastic accumulation rates are measured in Q1, with an average of 51.1 items ha^{-1} day^{-1}, which is almost double what was measured in Q3, 2021 with an average of 25.7 items km^{-1} day^{-1}, and almost six times the average of Q4, 2018–2020 with 8.7 items km^{-1} day^{-1}. Overall Fig.3.6 indicates that accumulation rates over the winter (measured in Q1) are the highest, followed by accumulation rates over the summer of 2021, and lastly accumulation over average summers (Q4 2018–2020). The measurement in Q4 2021 is lower than Q4 measurements in

previous years, this could be highly influenced by the extensive clean-up efforts that were undertaken all along the Dutch Meuse in August 2021 (Maas Cleanup, 2021).

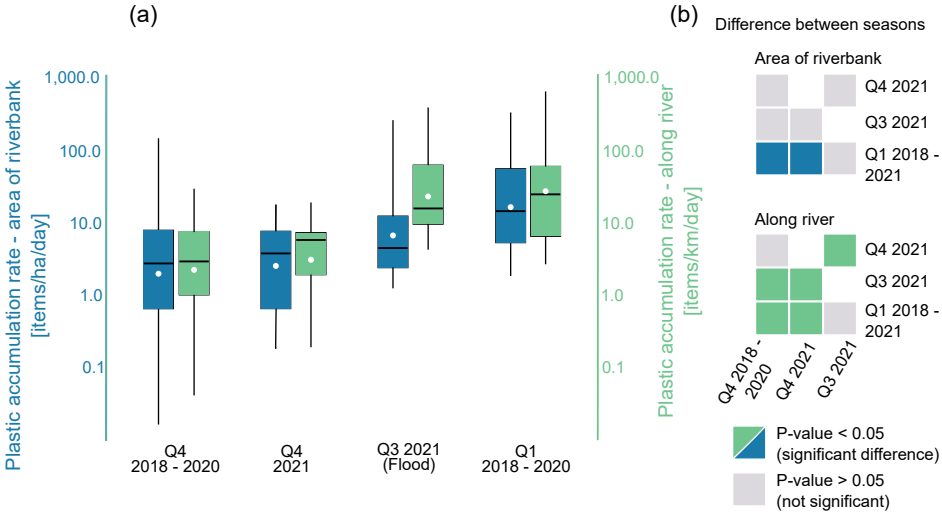


Figure 3.6 | (a) Macroplastic R_{PA} [items ha^{-1} day^{-1}] (blue) and R_{PL} [items km^{-1} day^{-1}] (green), during different "seasons" of measurement. The boxplots contain values for each year at each location, if applicable. The whiskers extend to the min and max values. The black line indicates the median value and the white point indicates the mean value. (b) To check if differences between the seasons for R_{PA} and R_{PL} are significant, we performed a pairwise Wilcoxon rank sum test with Bonferroni adjustment.

3.4 | Discussion

3.4.1 | Material transport in fluvial floods

This is the first study to capture the impact of a severe flood event on macroplastic accumulation on riverbanks. Rivers transport human-made materials such as macroplastic and other macrolitter items, and microplastic, as well as natural materials (such as wood and plant debris, and sediment). While the size, density and other characteristics of these materials are diverse and not necessarily comparable they do show parallels to transport and deposition of macroplastic. Wood recruitment, transport, and deposition are known to be related to the rising limb, the flood peak, and the recessional limb of a flood, respectively (Wohl et al., 2019). Although we did not include wood in the Q3 sampling the most upstream loca-

tions (1 to 3) showed high densities of wood and other plant material intermixed with the deposited macroplastic, while further downstream there were comparably lower densities of wood and plant debris (Fig. 3.7).

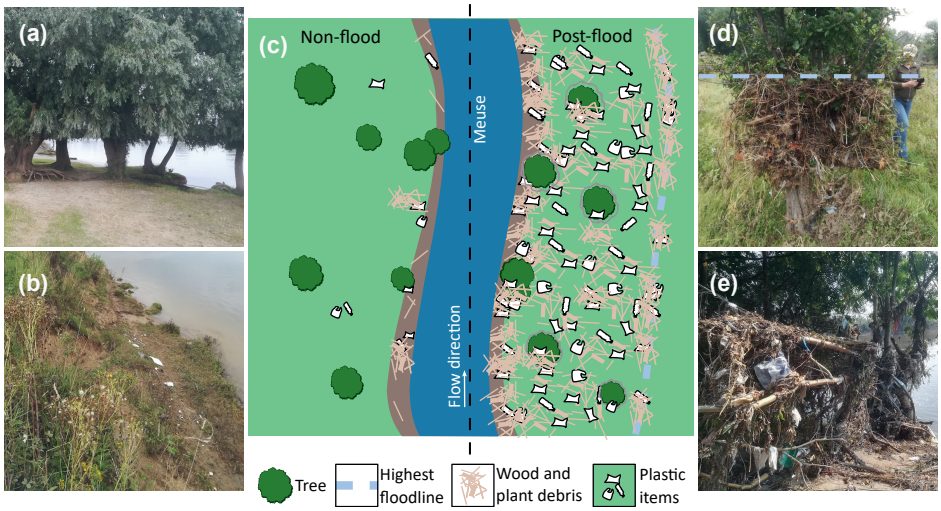


Figure 3.7 | Concept of flooded riverbanks and riverbanks that were not flooded, which showed different litter and natural debris densities and modes of litter deposition (c). Location 11 (a) showed no litter deposition, even though the tree roots provided potential for entanglement. Location 9 (b) showed very low litter deposition, close to the waterline at the time of Q3 measurements. Location 2 (d) and location 1 (e) showed high deposition, especially in higher vegetation. The flood peak water level is clearly depicted by litter and plant debris deposition and entanglement in higher vegetation.

The discharge peak in the July 2021 Meuse flood decreased from 3195 m^3 s^{-1} on July 15, 2021, 9.50 pm at Eijsden (location 1) to 2328 m^3 s^{-1} on July 19, 2021, 7.30 am between location 9 and 10 (van der Veen and Agtersloot, 2021). Floating macroplastic during the flood also showed a decrease from Maastricht (between location 2 and 3) to Ravenstein (ca. 3 km downstream from location 9), to Moerdijk (20 km downstream of location 16). At Maastricht during the discharge peak on July 15, 2021 the mean daily plastic transport was 32,760 items $hour^{-1}$ which is 141 times the non-flood average of 232 items $hour^{-1}$. At Ravenstein (ca. 3 km downstream from location 9), measurements of floating plastic on July 18, 2021, showed a mean daily plastic transport of 857 items $hour^{-1}$, which is 5.3 times the non-flood transport of 159 items $hour^{-1}$. At Moerdijk the transport during the flood was 4.5 times higher than non-flood with 1571 items $hour^{-1}$ compared to

346 items hour^{-1} (van Emmerik et al., 2023). This is in line with our findings for the plastic accumulation rates on the riverbanks and indicates that a fraction of the macroplastic transported by the July 2021 flood was deposited on riverbanks and not transported the whole length of the Dutch Meuse river. This agrees with the concept of macroplastic storage and remobilization in rivers discussed by Liro et al. (2020). The authors argue that riverbanks act as macroplastic storage zones, with river flow, including riverine floods as one of the main factors influencing macroplastic transport and transport distance. Further they argue that riparian vegetation and its associated surface roughness can favor plastic storage during floods.

At the most upstream locations 1–2 the high water levels led to the inundation of tall vegetation, while downstream the peak water level was less significant. At the two most upstream locations a large fraction of the deposited litter was entangled in trees and higher vegetation that served as obstructions to the flow with the majority of plastic being deposited on the upstream side of each obstruction (Fig. 3.7). At locations 1 and 2, 28.3% and 42.1% of plastic respectively was found entangled in trees, with $< 30\%$ of the measured riverbank area covered by trees/tree branches. Trees and shrubs have been identified to serve as “traps" for macroplastic (Cesarini & Scalici, 2022) and the term "Christmas tree effect" of entangled macroplastic in riparian vegetation was coined by Williams & Simmons (1996), to describe this phenomenon.

R_{PA} of soft plastic fragments (2.5–50 cm) for Q3 and Q1 are in the same order of magnitude with an average of 10.5 and 8.4 items ha^{-1} day^{-1} respectively. Average R_{PA} of wet tissues however is 7.8 items ha^{-1} day^{-1} in Q3 and 0.6 items ha^{-1} day^{-1} in Q1. Measurements at the Bergsche Maas (location 13 – 16) indicated emission of additional wastewater into the Meuse river (Rongen et al., 2021), which could explain the increase in wet tissues.

Similar to our study, Treilles et al. (2020) found the most common category of plastic with 40–60% were soft plastic bags and fragments in stormwater in Paris, France. This corresponds to the 44% of plastic fragments (2.5–50 cm) we found in Q3, 2021. Similar to macroplastic, microplastic transport and deposition is also impacted by flood events. In a 2018 flood event in the river Seine, Paris, France, 40% of the annual microplastic flux occurred during 14.5% of time of the year (Treilles et al., 2022). However, the similarities and differences in transport and deposition of macro- and microplastics in rivers are not conclusively clarified and

need further investigation.

3.4.2 | Limitations and Recommendations

The sampled sixteen locations in Q3 along ~200 km of Dutch Meuse river only represent 10.3% of the 155 riverbanks in the Clean Rivers monitoring dataset. Sampling a higher number of locations would potentially have given a better and more complete picture of the impact of the July 2021 flood on the plastic accumulation. In the Clean Rivers project an average of 1667 m^2 was sampled on each riverbank during each monitoring round. In Q3, 2021 we sampled 248 m^2 on average. The overall area we sampled is smaller but in most cases wider than the Clean Rivers monitoring area, since we tried to cover larger areas that had been inundated. For future research we recommend to sample the same area on each riverbank before and after an extreme event that is sampled in the monitoring, to avoid these uncertainties.

For monitoring and modelling of plastic pollution in rivers, we recommend to include flood events in the sampling and modelling respectively. One approach could be to place GPS trackers on the riverbanks before a flood event, to track their transport during the flood. We recommend to also capture the mass of the deposited plastic, since this might be more meaningful than the item count. Extreme floods are likely to increase in frequency and severity, due to climate change. Understanding their impact on the fate of plastic litter in the environment is therefore very important.

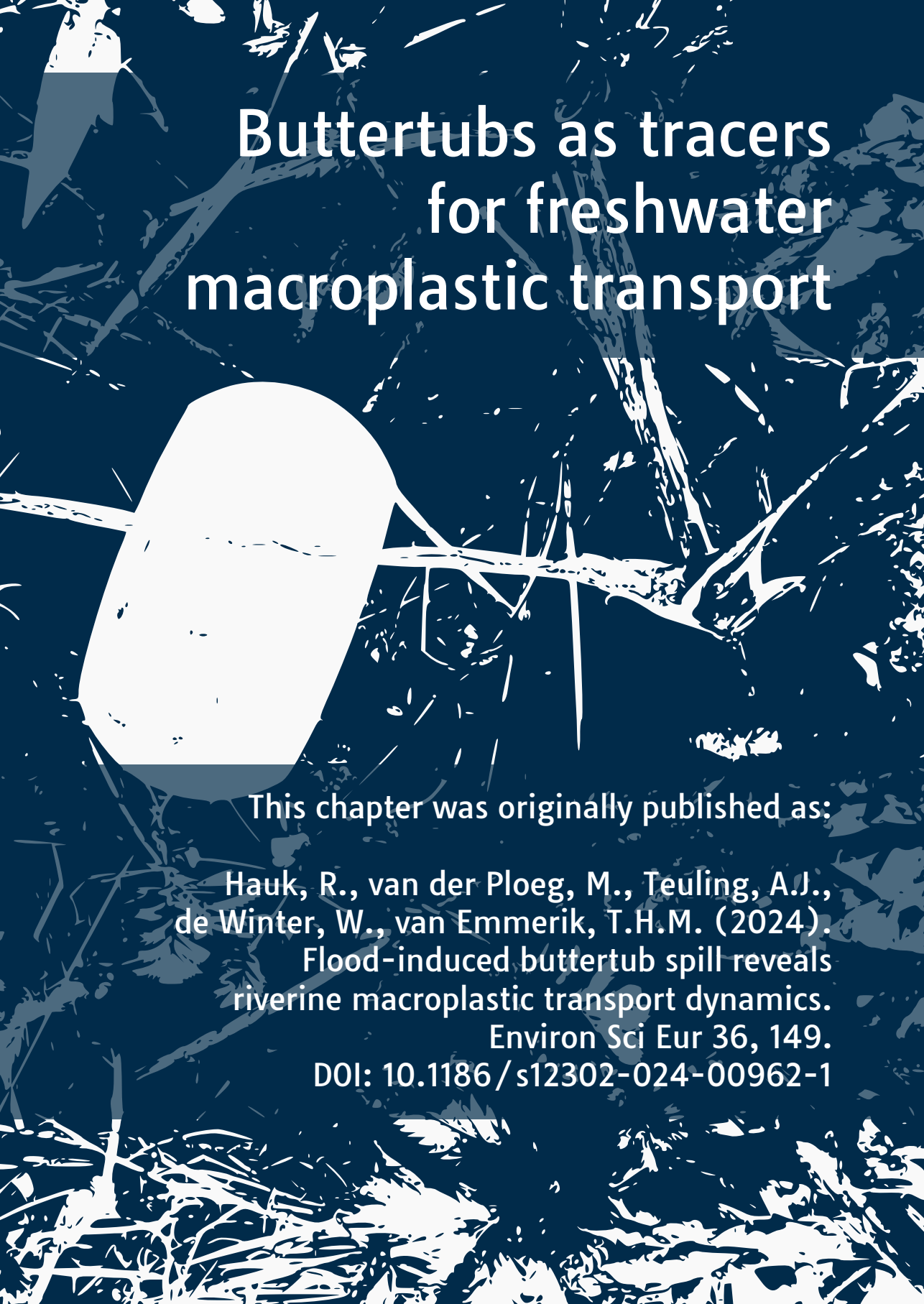
3.5 | Conclusion

In this study we compared the plastic accumulation rate and composition between the July 2021 flood event and normal conditions on sixteen riverbanks along the Dutch Meuse river. We found that post-flood in Q3, 2021 overall there was an increase in macroplastic deposition, compared to what would be expected for that time of year. However, the deposition and flushing varied considerably between locations and for different plastic categories. Overall eight out of the twenty main plastic categories showed deposition and twelve showed flushing. Plastic categories with the largest increase compared to normal conditions were soft plastic fragments (2.5–50 cm) and wet tissues, with an increase of ~3 times and ~24 times respectively. Small macroplastic categories were flushed out by the July 2021 flood,

combined, they only made up 2.5% of macroplastic items, whereas on average they make up 27.2% in Q4 and 46.6% in Q1. Our results emphasize the importance of including pre- and post-flood measurements in future monitoring efforts. The differences in plastic accumulation rates and plastic litter composition between flood and non-flood conditions demonstrate that an extreme event like the July 2021 flood indeed impacts macroplastic transport and deposition.


4

Buttertubs as tracers for freshwater macroplastic transport



This chapter was originally published as:

Hauk, R., van der Ploeg, M., Teuling, A.J., de Winter, W., van Emmerik, T.H.M. (2024). Flood-induced buttertub spill reveals riverine macroplastic transport dynamics. Environ Sci Eur 36, 149. DOI: 10.1186/s12302-024-00962-1

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 buttercups 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 two years following the flood. We also collected buttertubs at different points in time to investigate their fragmentation and mass loss. Within three 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 three weeks were deposited within less than 100 km of the point of emission. Over the following two 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 three weeks, to 0.2 km/d by July 2023. Based on the 89 buttertubs we collected and analyzed in detail over the two 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.

4.1 | Introduction

By 2019, the global annual plastic production reached 386 million metric tonnes (MT) (Plastics Europe, 2020). Of these, approximately 22 MT (6%) were dumped, discarded, or otherwise leaked into the environment (OECD, 2023). 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 (van Emmerik & Schwarz, 2020; Liro et al., 2020; Meijer et al., 2021). Fluvial floods impact plastic transport and can mobilize a large fraction of annually transported plastic in a river (Roebroek et al., 2021a; van Emmerik et al., 2019). 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 (van Emmerik et al., 2023). 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 clean-up 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 (Tramoy et al., 2020a; Teunkens, 2021; Newbould et al., 2021; Lotcheris et al., 2024; Maclean et al., 2021). 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 hours 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 (Saliba et al., 2022) and spilled macroplastic items that have been studied include inkjet cartridges (Turner et al., 2021), Lego (Williams, 2022), and plastic bath toys (Ebbesmeyer & Ingraham Jr, 1994; Ebbesmeyer et al., 2007). 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 (Tramoy et al., 2020a; Falk-Andersson et al., 2021). 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 (Barnes et al., 2009). Whereas chemical degradation includes photodegradation due to exposure to UV-light, thermal degradation, thermo-oxidative degradation, biodegradation, and hydrolysis (Andrady et al., 2011; Waldschläger et al., 2020). Degradation depends on the type of plastic polymer, but also on environmental conditions (Chamas et al., 2020). Delorme et al. (2021) 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 two 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 hours 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 (Dewals et al., 2021). 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 three 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 two years later along the Dutch Meuse and investigate their degradation. Over two 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.

4.2 | Methods

We used three different datasets in this study, and all datasets 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 (EC, 2004), 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. For reference, the River-OSPAR protocol utilized by the *Clean Rivers project* contains categories such as plastic helmets, even though

between Oct/Nov 2021 and Feb/Mar 2023 there were only 0 – 1 plastic helmet found along the entire Dutch Meuse.

The three datasets include the dataset presented in Hauk et al. (2023c) of post flood riverbank measurements (Hauk et al., 2023a), as well as ongoing riverbank litter monitoring by citizen scientists (Fig. 4.1). Further, during additional fieldwork two years after the flood event, we sampled 25 of the monitored riverbanks specifically for buttertubs. Investigating these datasets, where buttertubs were reported as a distinct item category allowed us to analyse their transport along the Dutch Meuse river over the course of two 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 4.2.4).

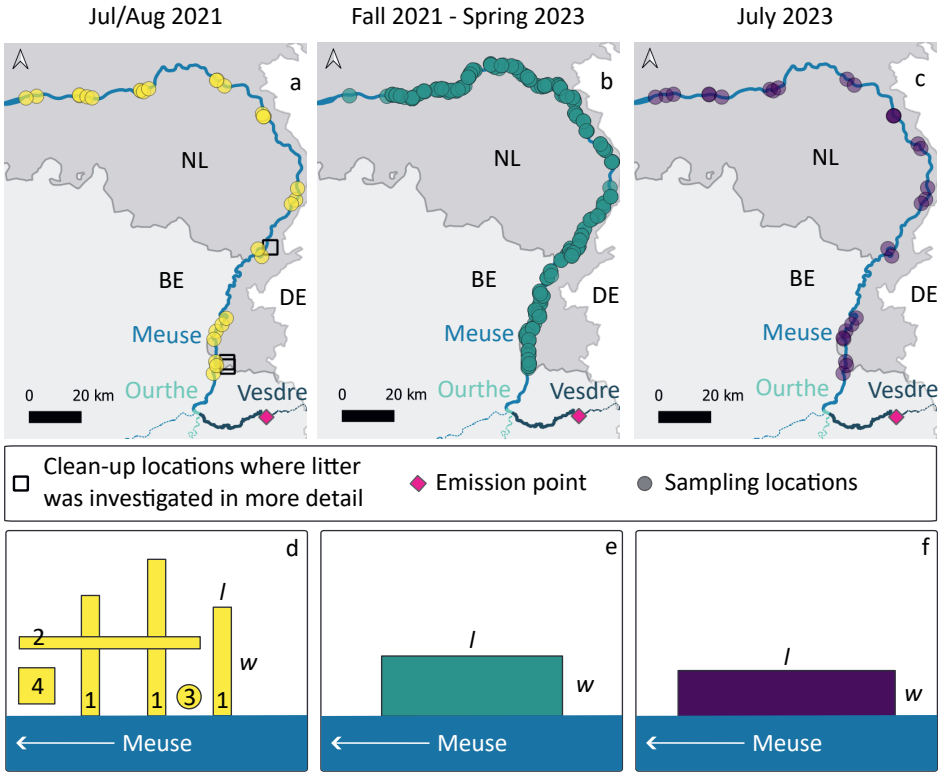


Figure 4.1 | Buttertub sampling strategy. Riverbank locations (a-c) and measurement areas (d-f) during the different measurement rounds (not to scale). (a-c) Overview maps that show the point of emission of the buttertubs (pink diamond shape), the path of the buttertubs through the Vesdre, Ourthe, and 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.

4.2.1 | Dataset 1: Riverbank sampling post-flood July/August 2021

We used the dataset from Hauk et al. (2023c) (Hauk et al., 2023a) that covers 25 riverbanks that were sampled along the Dutch Meuse river, between 22 July – 4 August, 2021 (Fig. 4.1a). 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 Hauk et al. (2024a). 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 (van Emmerik et al., 2020c), 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 (Maas Cleanup, 2021) and during that day we visited three locations that were cleaned, and collected three full garbage bags of litter from each location at random (Fig. 4.1a). 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.

4.2.2 | Dataset 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.4.1b) area of riverbank, according to the River-OSPAR protocol (van Emmerik et al., 2020c). 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. Figure 4.2b 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 also count any of the distinct lids.



Figure 4.2 | Illustration of buttertubs collected by the authors of this study (a) and by volunteers from the Clean Rivers Project (b and c). Pictures taken by authors of this study (a) and volunteers from the Clean Rivers Project (b and c)

4.2.3 | Dataset 3: Riverbank sampling July 2023

Between 26 July and 28 July 2023, we sampled 25 riverbank locations (Fig. 4.1c), 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 – 50 m, but at most locations the first 5 – 15 m of riverbank were sampled (Fig. 4.1f). We collected all six buttertubs we found on the sampled riverbanks. We only focused on buttertubs during this fieldwork and did not count and collect any other litter categories.

4.2.4 | Buttertubs mass/fragmentation analysis

We collected a total of 89 buttertubs, 70 in July 2021, 13 in February 2023, and six 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 six 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 (Turner et al., 2020). 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.

4.2.5 | 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.

4.3 | Results and Discussion

4.3.1 | 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. 4.2) 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.

4.3.2 | Buttertubs transport distance

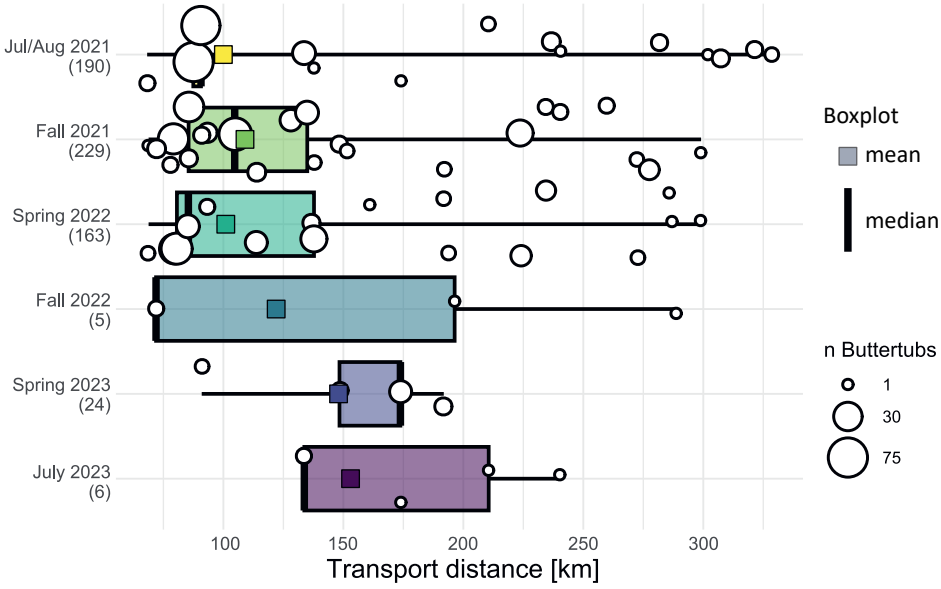


Figure 4.3 | Transport distance of buttertubs along the Dutch Meuse in different measurement rounds. All of these buttertubs were removed from the riverbanks, with the exception of Jul/Aug 2021, then most buttertubs were left in place and only 70 were collected from one location for further analysis. 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.

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. 4.3). Twelve buttertubs were transported over 300 km, up to 328 km in less than three weeks (∼50 km from the river mouth, but the Rhine-Meuse delta is complicated). The 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, two 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 (van Emmerik et al., 2023; Hauk et al., 2023c). The average transport distance per measurement almost continuously moves downstream, which suggests that the buttertubs are slowly transported downstream (Fig. 4.4a). However, the average transport distance by buttertub density per m riverbank is not quite as clear (Fig. 4.4b). Given the limited transport distance we expect only a small fraction may have potentially been emitted into the North Sea.

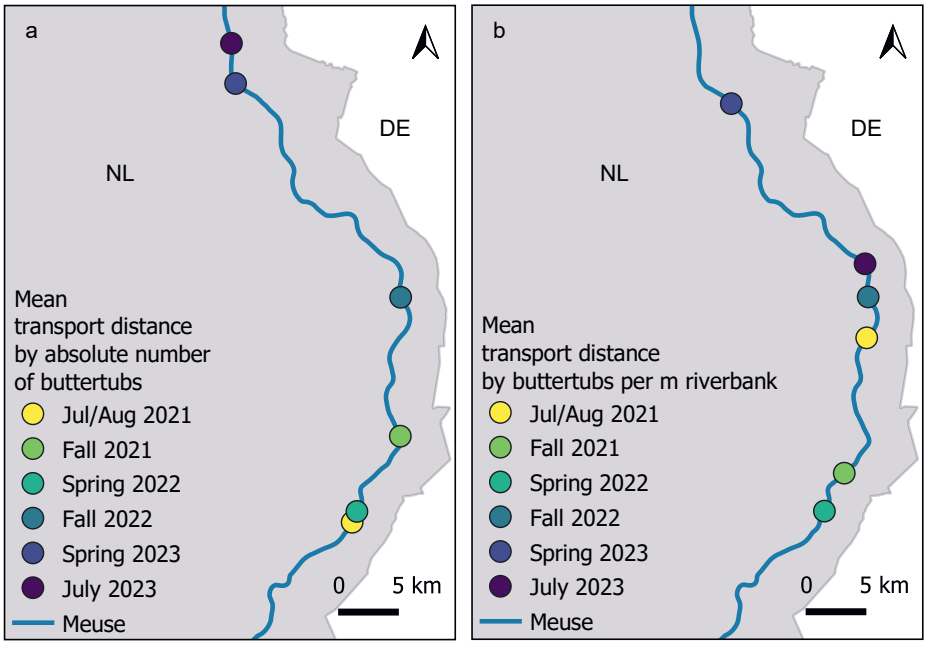


Figure 4.4 | Differences in mean transport distance between buttertubs (a) and buttertubs density in buttertubs per m riverbank (b)

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. 4.5). If quantified, the average transport distance by Fall 2021 would likely have been lower than 109 km.



Figure 4.5 | 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.

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. 4.1). 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/in ground

covering vegetation, and only six were found deposited higher up such as in trees/bushes/fences. 162 buttertubs were found within the debris line/debris accumulation "accumulation zone" and out of these at least 143 (at two locations) were found in debris along the highest floodline.

4.3.3 | 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. 4.6). Based on the riverbanks where buttercups were found within three weeks after the flood event, they were transported at a velocity between 9.8 – 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) (Meijer & Agtersloot, 2020) 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 – 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. Further, 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. 4.5).

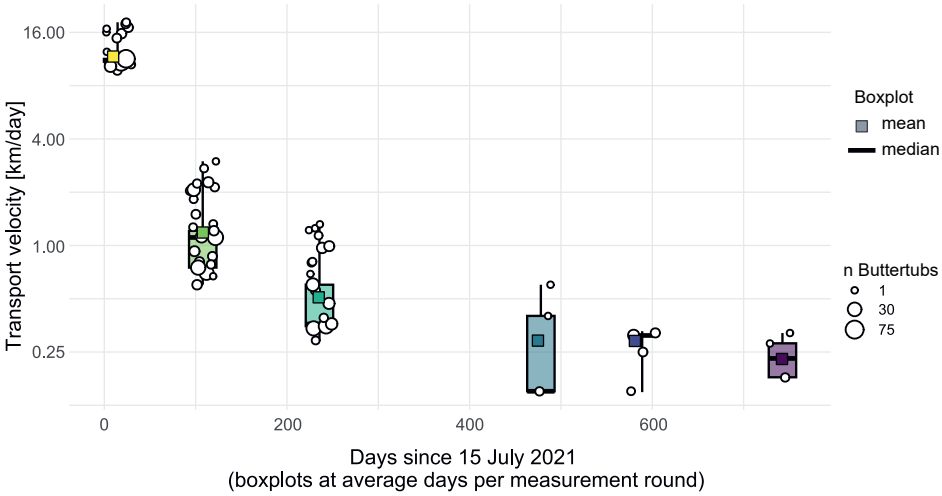


Figure 4.6 | Transport velocity of buttertubs in the Dutch Meuse for the different monitoring rounds. Transport velocity in logarithmic scale.

The strong decrease of the buttertubs transport velocity over the course of two 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 1.250m³/s (Rijkswaterstaat, 1985). 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 hours in January 2022 and ∼40 hours 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 two years is in about the same order of magnitude as short term transport in a study utilizing GPS trackers in PET bottles (Newbould et al., 2021) in the UK. Tramoy et al. (2020a) investigated transport distances and velocities of plastic bottles with GPS-trackers under various hydro-meteorological 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. Duncan et al. (2020) 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.

4.3.4 | Mass loss and fragmentation

Table 4.1 | Differences in mass for buttertubs we collected at different points in time. 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 Figure 4.7.

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

The standard deviation of $\pm$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 eight days after the flood event by 0.025 g (about 0.4%) over the course of 568 days in the environment (Table 4.1).

However, for all buttertubs combined mean mass increases over the two years. There is no significant difference between the buttertubs mass that were collected after eight 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 (Hoseini et al., 2023). 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 slightly overestimated. Of the buttertubs collected eight 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 two years after the spill appears completely intact with no signs of fragmentation or mass loss.

Figure 4.7 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. Delorme et al. (2021) 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 two years. Whereas buttertubs placed protected from solar radiation stayed mostly intact. The buttertubs we collected after two 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 Tramoy et al. (2021) 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 Delorme et al. (2021) and Tramoy et al. (2021) are in line with our results on mass loss and fragmentation. Our results indicate that relevant time scales for mass loss and fragmentation are likely much longer than two years.

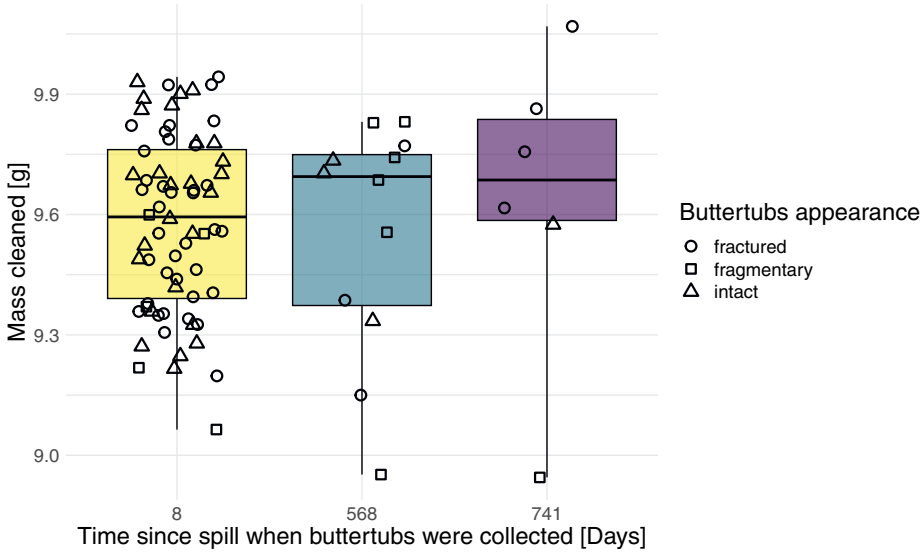


Figure 4.7 | Mass distribution of buttertubs after 8, 568, and 741 days of exposure in the environment. Aggregated mass available in Table 4.1.

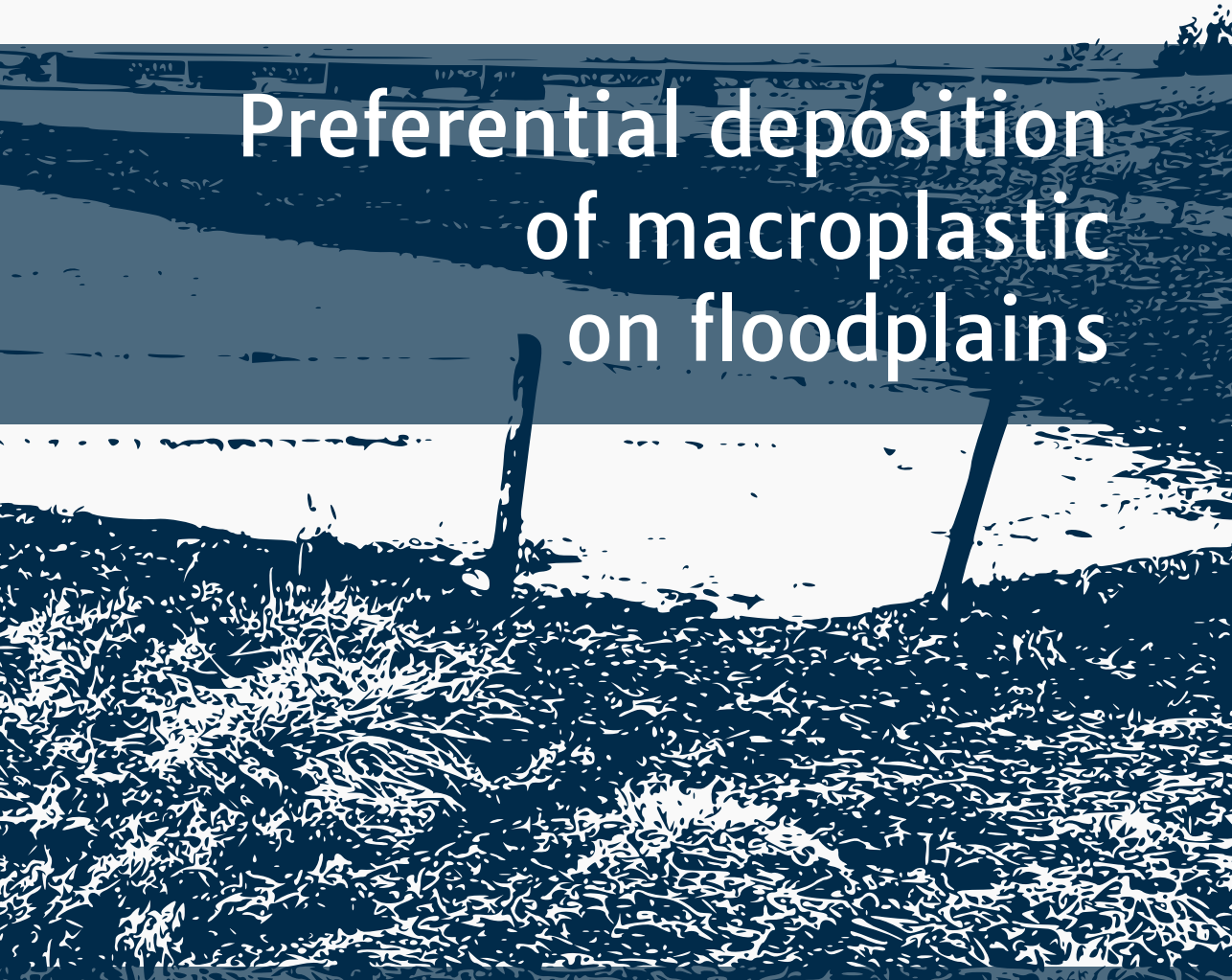
4.4 | Conclusion

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 two 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 three 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 (two years after the flood). We hypothesize this is because of a large number of buttertubs not being remobilized over the two 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 eight to 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.


5
I.V.M.
HOOG-
WATER

Preferential deposition of macroplastic on floodplains



This chapter was originally published as:

Hauk, R, Schreyers L, van der Ploeg M, Teuling AJ, Wallerstein N, van Emmerik T (2026). Preferential deposition of macroplastic on floodplains. Cambridge Prisms: Plastics, 1-12 DOI: 10.1017/plc.2026.10054

Abstract

Floods have a large impact on the mobilization, distribution, and retention of macroplastic in rivers. Some of the transported plastic is deposited on riverbanks and floodplains. However, the specific deposition patterns, i.e. where precisely macroplastics are deposited across the floodplains are poorly investigated. We sampled 25 floodplain sites along the Meuse following the 2021 summer flood (>100 year^{-1}), and 23 floodplain sites along the IJssel following the 2024 winter flood (4 year^{-1}). For each found item we recorded the landcover element (such as grass, herbaceous, bushes, tree, debris pile) it was deposited in. Along the IJssel, debris piles contained plastic concentrations of 12.7 #/m^2 and 58% of plastic by count, despite covering only 2% of the sampled area. We found that plastic concentrations vary between landcover elements, but also plastic characteristics. Out of the macroplastic deposited in riparian vegetation along the Meuse, 84% were soft plastics or textiles, compared to 53% of items deposited on the ground. This paper sheds additional light on the role of vegetation and debris piles on plastic retention caused by floods. Our results can be used to help improve the monitoring, mitigation and reduction of river scale plastic pollution.

5.1 | Introduction

Rivers connect the terrestrial and marine environment and have the ability to transport materials of both natural and anthropogenic origin. One such anthropogenic material is macroplastic and other human-made litter. Recent evidence has shown that rivers can retain plastic pollution for decades (Tramoy et al., 2020b; van Emmerik et al., 2022b; McGoran et al., 2023). Within rivers, the riverbanks and floodplains are estimated to contribute the most to total stored plastic pollution (Schreyers et al., 2024c). Riverbanks presumably go through a continuous cycle of material deposition and (re-)mobilization, due to waves and water-level changes, whereas floodplains are only activated during overbank discharge events. Floods mobilize high amounts of macroplastic (Pow et al., 2025; MacAfee & Löhr, 2024; Roebroek et al., 2021a), due to various factors such as surface runoff, increased water level, and combined sewer overflow (van Emmerik, 2024; Roebroek et al., 2021a). As a consequence, plastic transport is not temporally steady, but rather a large fraction of the annual transport occurs during a short fraction of time (van Emmerik et al., 2019; van Emmerik et al., 2023; Wagner et al., 2019).

Some proportion of the macroplastic is transported through the river system to estuaries and potentially into the sea (Pierdomenico et al., 2022; Korshenko et al., 2020). However, it seems that large amounts of macroplastic transported during flood events do not actually reach the sea, or even the estuary. Rather they are trapped and deposited on riverbanks and floodplains, often not very far from the source or entry point (Pace et al., 2024; Hauk et al., 2023c, 2024b). As floodplains are only activated during flood events, they provide increased potential of plastic deposition during flood events, compared to non-flood conditions.

Macroplastic deposition on riverbanks and floodplains has been linked to multiple variables, and it seems inundated trees and dense riparian vegetation show high trapping efficiency (Gallitelli et al., 2024; Valyrakis et al., 2024; Schreyers et al., 2025). However, macroplastic deposition has also been linked to proximity to highly populated areas, with a less clear relation to vegetation structure (Pace et al., 2024; Palmas et al., 2022). In some cases floodplains retain the majority of macroplastic along rivers, compared to riverbanks (Schreyers et al., 2024c; Huthoff et al., 2025). Woodjams can also be efficient in macroplastic retention, especially in mountainous rivers (Liro & Gallitelli, 2025; Rajwa-Kuligiewicz et al., 2025), but also in urban streams (Hoellein et al., 2024a). Macrophytes on riverbanks (Guimarães et al., 2024), as well as floating plants, such as water hyacinths can also be effi-

cient in trapping macroplastic, with, for example, significantly higher macroplastic densities in hyacinth patches compared to the surrounding water (Schreyers et al., 2024b). Similar to floating patches of water hyacinths, macroplastic transport has also been linked to floating organic debris 'rafts' in rivers (Hoellein et al., 2024b). Only a fraction of macroplastic that is transported by rivers is emitted into the sea. However, the majority of macroplastic is most likely retained in and along river corridors. There are numerous studies on macroplastic occurrence and accumulation on riverbanks and floodplains e.g. Uogintė et al. (2024); Hidayat et al. (2022); Dalu et al. (2025), however specific deposition dynamics are less clear. While it is not very clear where plastic is stored in rivers and why, rivers most likely act as long-term plastic storage areas.

The goals of this study are to investigate the effect of riverbank characteristics on the spatial distribution, surface concentration, and characteristics of deposited plastic items. We investigated at a detailed level, where macroplastic and other human-made litter (>5 mm, hereafter anthropogenic debris) was deposited on riverbanks and floodplains. More specifically, we sampled anthropogenic debris at 25 locations along the Dutch Meuse river after the summer 2021 flood, and 23 locations along the IJssel river after the winter 2024 flood. We did not do any sampling prior to the floods and therefore this study can not give a comparison of pre- and post-flood deposition, but only an insight on deposited anthropogenic debris following flood events. Our field observations included the systematic recording of the landcover elements in which each anthropogenic debris item was found (e.g. trees, shrubs, grass or debris piles), and its distance from the water line. We also recorded the category of anthropogenic debris, following the River-OSPAR categorization (van Emmerik et al., 2020b) with 110 macroplastic and other litter categories. This detailed sampling allowed us to compare anthropogenic debris count and mass densities between different landcover elements. As we sampled the riverbanks after the flood events, we have no information on when exactly each specific anthropogenic debris item was deposited. However, we are aware that the specific deposition location of each individual item is potentially related to a specific phase of the flood. One example of that is anthropogenic debris items entangled in trees which had been temporarily inundated. We compared the characteristics (size, mass, polymer type) of anthropogenic debris entangled in inundated trees to anthropogenic debris deposited on the ground, and anthropogenic debris deposited within organic debris to anthropogenic debris deposited independently of organic debris. We also investigated the lateral distribution and

clustering of anthropogenic debris between the waterline and the highest floodline. The aim of this study was to conduct a detailed assessment of deposited anthropogenic debris on riverbanks and floodplains, following two flood events. We assume that anthropogenic debris transport is not linear over time, but rather the majority of anthropogenic debris is in motion during floods and high discharge events. Therefore, investigating and understanding anthropogenic debris motion during floods will cover a large proportion of the annual/decadal anthropogenic debris transport in rivers. The detailed insights from this study could contribute to a better understanding of anthropogenic debris pathways through the freshwater environment, and consequently improve mitigation and monitoring.

5.2 | Methods and study area

5.2.1 | Study area and flood events

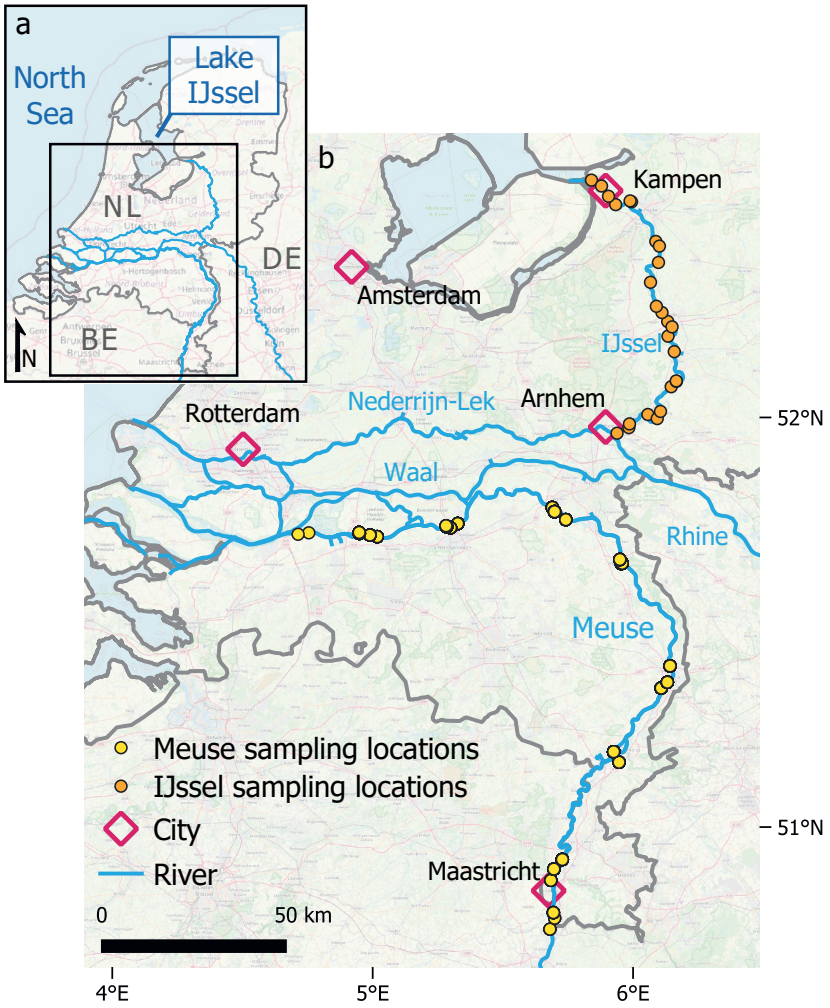


Figure 5.1 | Overview of the study area. a The Netherlands and its neighboring countries Belgium (BE) and Germany (DE), and the extent of b. b shows the Meuse and IJssel rivers with their respective measurement locations and an overview of the main Dutch rivers and relevant cities. Base map from OpenStreetMap and OpenStreetMap Foundation (CC-BY-SA). © https://www.openstreetmap.org and contributors.

We conducted observations along the Meuse and IJssel floodplains, two Dutch rivers (Fig. 5.1) that each flow through multiple cities and towns as potential plastic sources. The Meuse originates in France, crosses Belgium, and drains into the Rhine-Meuse Delta in the southwest of the Netherlands, and its catchment is ~35,000 km². The Meuse has an annual average discharge of 221 $m^3 s^{-1}$ (years 1911 - 2017) (Reeze et al., 2020), and bankful discharge is at approximately 1250 $m^3 s^{-1}$ (Rijkswaterstaat, 1985). Monthly average discharge over the summer, from June to October is usually below 100 $m^3 s^{-1}$. Due to high precipitation, the Meuse usually experiences flooding in winter with the highest average monthly discharge of approximately 500 $m^3 s^{-1}$ occurring in January (Reeze et al., 2020). However, in July 2021 extreme rainfall over Belgium, Luxembourg, and Germany caused severe flooding across multiple European rivers (Rongen et al., 2021; Lehmkuhl et al., 2022; Mohr et al., 2022; Kreienkamp et al., 2021), including the Meuse and some of its tributaries. The discharge peak at Eijsden (<10 km south of Maastricht), was estimated at 3179 $m^3 s^{-1}$ on 15 July 2021, with a return period of >100 years (Strijker et al., 2023; Lehmkuhl et al., 2022; Mohr et al., 2022; Kreienkamp et al., 2021).

The IJssel is a branch of the Rhine river which originates in Switzerland, transects or borders Liechtenstein, Austria, France, Germany, and the Netherlands, and drains into the Rhine-Meuse Delta, the Rhine catchment is ~185,000 km². In the east of the Netherlands the Rhine splits into the Waal (~2/3 of the Rhine discharge) and the Pannerdense Kanaal (~1/3). The Pannerdense Kanaal then splits into the Nederrijn (~1/9), and IJssel (~2/9) (Schielen et al., 2008; De Bruijn et al., 2022) with the last draining into Lake IJssel. The annual average discharge for the IJssel river is approximately 330 $m^3 s^{-1}$ (Reeze et al., 2017), and bankful discharge occurs at approximately 700 $m^3 s^{-1}$ (Gensen et al., 2020). High levels of precipitation in Germany and the Netherlands from October to December 2023 led to increased discharge in the Rhine and IJssel between December 2023 and January 2024. The IJssel reached a discharge peak of 1100 $m^3 s^{-1}$ equaling a discharge with a return period of four years (ENW, 2024).

5.2.2 | Field data collection

We selected sampling locations along the Meuse and IJssel rivers (Fig. 5.1) that are used in the *Clean Rivers Project (in Dutch Schone Rivieren)* which is run by the *North Sea Foundation (Stichting de Noordzee)*. The *Clean Rivers Project* covers around 150 riverbank locations (i.e. sampling locations) along the Dutch Meuse and and 100

along the IJssel, which are monitored on a routine basis twice per year. For both rivers, we selected locations distributed along the left and right bank, and between locations with high and low surrounding population density. In addition to the routine sampling, we sampled 25 riverbank sites along the Dutch Meuse river, following the 2021 summer flood. We completed the sampling within three weeks of the flood event, from 22 July to 4 August (Hauk et al., 2023c), before the start of any large-scale clean-up efforts by municipalities and volunteers (Hendrikx, 2021). The riverbank sites along the Meuse river were distributed along the entire length of the Dutch Meuse river (∼200 km), and were selected based on accessibility, as some floodplains were still inundated at the time of the sampling campaign. Along the IJssel, we sampled 23 riverbanks, following the 2024 winter flood, from 25 January to 14 February. We selected sampling locations up to a floodplain width of 100 m (three out of 23 locations between 100 – 400 m). It should be noted that some floodplains along the IJssel are very wide, up to a few hundred meters. In order to complete the fieldwork before large scale clean-up started on 15 February, we preferably selected locations with narrower floodplains.

At each location we started the measurements at the coordinates of the *Clean Rivers* monitoring location. Usually on each riverbank three transects of 2 m width were sampled with a distance of 40 m between them (Fig. 5.2a) (Hauk et al., 2023c). Each 2 m wide transect was sampled in 3 m long sections, to document the location of items between the waterline and highest floodline. This sampling approach allowed us to cover the entire depth of riverbanks and floodplains, from waterline to highest floodline, within the available time. For the sampling in 2021, we placed a measurement tape from the waterline towards the highest floodline. We walked along the measurement tape with two observers and documented all anthropogenic debris items, and in which 3 m long section of transect they were located. For each section we recorded the landcover elements ('grass/bare', 'herbaceous', 'shrubs', 'trees', 'debris pile' or 'mixed', if multiple landcover elements were present in one section) (Fig. 5.2 and 5.3). We identified 'shrubs' as plants with woody branches, but no tree trunk, and 'trees' as plants with a woody tree trunk and branches. We also recorded whether an item was deposited on the ground or in ground covering vegetation (d_g), or off the ground in an object such as a tree (d_o) (Fig. 5.2b).

For d_o items, the type of element was noted. For these d_o items we also checked if the tree or other object showed signs of previous inundation, such as sediment on leaves, and deposited organic debris, to avoid including anthropogenic debris

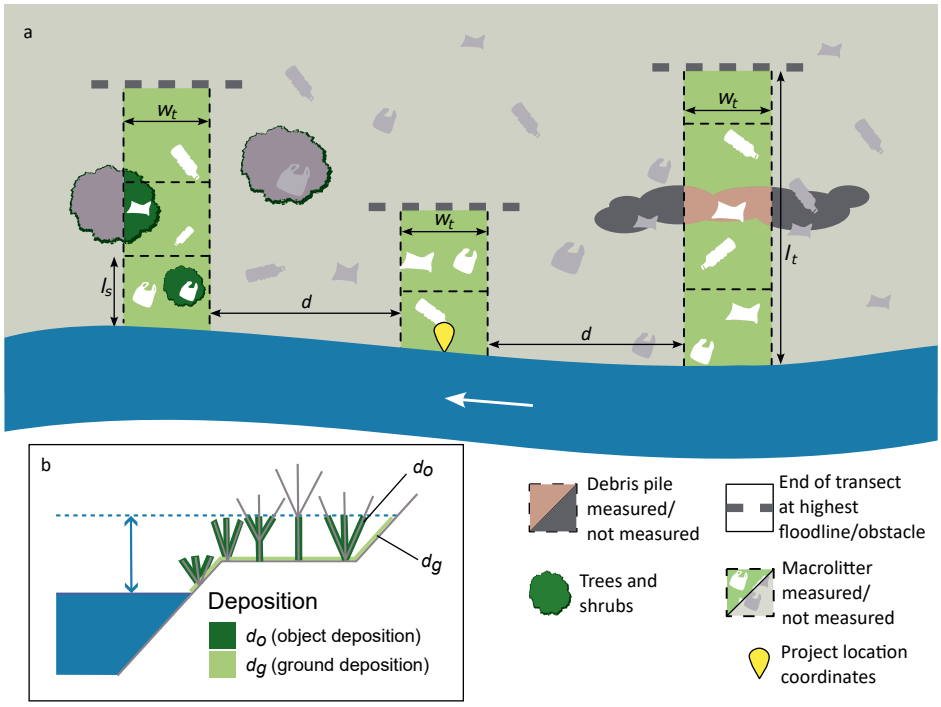


Figure 5.2 | Overview of the sampling approach, a) riverbanks were sampled in three transects from the waterline towards the highest floodline. Transect width w_t was 2 m, distance d between transects was 40 m where possible (30–300 m). Each transect was sampled in multiple sections with section length l_s, which add up to the transect length l_t. b) Anthropogenic debris items deposited in objects (d_o) and on the ground/in ground covering vegetation (d_g). The blue dashed line and double sided arrow indicate the changes of water-level. Figure a) adapted from Hauk et al. (2023c).

items deposited by wind. All items were categorized into the 110 River-OSPAR categories, based on the protocol developed by the *North Sea Foundation* (van Emmerik et al., 2020b), contrary to the protocol, we left all items in place and did not collect them. Along the Meuse we also sampled trees outside the 2 m transects which showed signs of inundation due to the presence of deposited organic debris and anthropogenic debris in the branches. These additional measurements were only taken into account to compare the characteristics of d_g (ground deposition) vs. d_o (object deposition) anthropogenic debris (Fig. 5.2b). For the Meuse, we sampled debris piles only based on what was visible at the surface, and did not disentangle the debris piles, this was due to time constraints and was improved for the IJssel

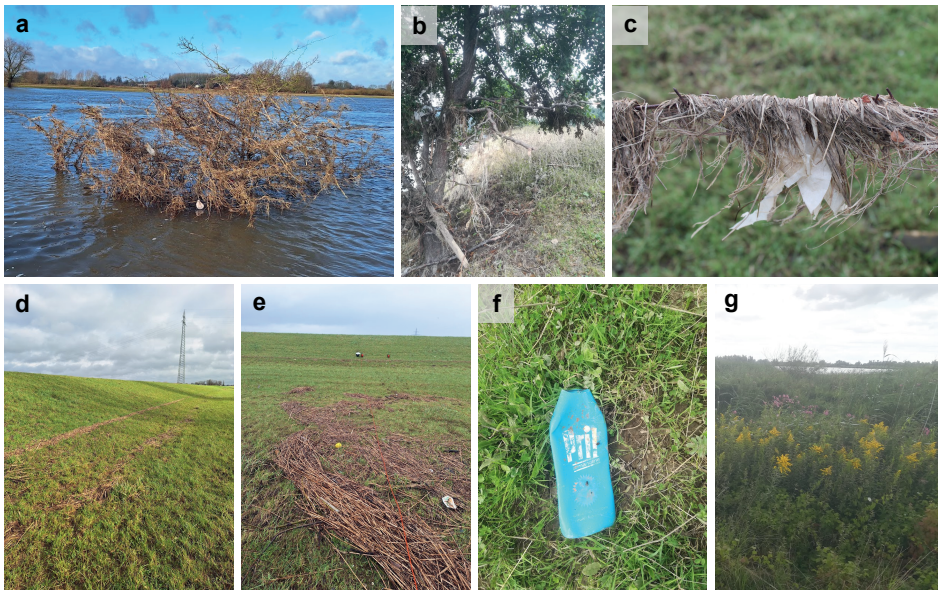


Figure 5.3 | Examples of the different elements and deposited anthropogenic debris in this study. (a) In a partially inundated shrub, (b) in a tree, (c) in a fence, (d) distinct debris lines along previous highest floodlines, (e) debris on a less steep section of riverbank, (f) anthropogenic debris on grass, (g) herbaceous vegetation. (Pictures by Rahel Hauk)

measurements. We made some adjustments for the sampling along the IJssel in 2024. A tape measure was used to identify 3 m sections and to subdivide the area by individual elements within each section, so this time it did not include 'mixed' sections. Each anthropogenic debris item was again recorded with the respective River-OSPAR ID and also according to which landcover element it was found in. Debris piles consisted mainly of plant debris such as pieces of reed, small branches, grass and leaves, but also included anthropogenic debris. If a debris pile was present in the transect, depending on the dimensions of the debris pile, either all debris in the transect was sampled, or only a randomly selected sub-section area. The debris pile was deconstructed and searched for anthropogenic debris items through its entire depth.

5.2.3 | Data analysis – Anthropogenic debris item and mass concentrations

We investigated the deposited anthropogenic debris for each landcover element individually. Per landcover element we calculated the anthropogenic debris density by item count [#/m²] and mass [g/m²]. Further, we wanted to know whether the characteristics of deposited anthropogenic debris differed between landcover elements. We estimated average item mass, length, and width per landcover element based on the dataset from de Lange et al. (2022). We linked this dataset to our own data based on the River-OSPAR litter categories. For the length-width-ratio we divided the length by width for each item, to assess the item shape (elongated vs. compact). To further analyze anthropogenic debris characteristics in different elements, we aggregated the macroplastic litter categories by polymer type, based on Vriend et al. (2020a). Polystyrene (PS), polyethylene terephthalate (PET), expanded polystyrene (EPS), hard polyolefins (PO Hard), soft polyolefins (PO Soft), and Other), and the non-plastic by River-OSPAR material group (Paper, Rubber, Glass, Metal). In this method, the polymer types are an estimation based on the River-OSPAR litter categories, and which polymer they are typically made from.

We analyzed the data on debris piles only for the IJssel, since at the Meuse, debris piles had only been sampled at the surface and not the entire depth. Characteristics of anthropogenic debris entangled in shrubs and trees was only analyzed for the Meuse, since along the IJssel only three anthropogenic debris items were found entangled in trees and shrubs. Regarding debris piles along the IJssel, we checked each transect for the presence of debris, those transects with debris were then checked for the presence of any vegetation other than grass between the waterline and the debris. Based on this, the debris data was grouped into debris behind only grass and debris behind higher vegetation (any vegetation higher than grass), since the IJssel sampling was conducted in European winter, the grass was very short ($<$ 5 cm). This was done to test whether vegetation acts as a filter on inundated floodplains. To test whether the the items in debris behind vegetation vs. behind only grass had different characteristics, we conducted Mann-Whitney U Tests (as the data was not normally distributed), to test for significant difference in item length, mass, and length-width-ratio.

For the Meuse, we investigated the item characteristics for d_0 items vs. d_g items, to test whether some items were more likely to be entangled in inundated riparian vegetation. Since the data was also not normally distributed, we again conducted

Mann-Whitney U Tests for item length, mass, and length-width-ratio.

5.2.4 | Data analysis – Clustering and lateral distribution

To investigate the anthropogenic debris deposition patterns on riverbanks and floodplains post-flood, we also examined the lateral item and mass distribution along each transect between the waterline and end of the transect (Fig. 5.4). For each transect we normalized the transect length from zero (waterline) to one (end of transect) and divided it into quartiles. We normalized the item count and mass per transect to one and summarized the share of item mass and count found per quartile. Based on this we deduced four modes of deposition which were test fitted by three mathematical functions, 'bounded increase function', 'exponential increase function', 'linear function', and 'other'. A bounded increase function means that >50% of items were deposited in the first quartile, closest to the waterline. An exponential increase function means that >50% of items were deposited in the last quartile, in or closest to the highest floodline. A linear function means that each quartile had <50% but >10% of items, and 'other' means the distribution does not follow any of the previous three functions. We did this analysis based on item count, and also based on mass distribution.

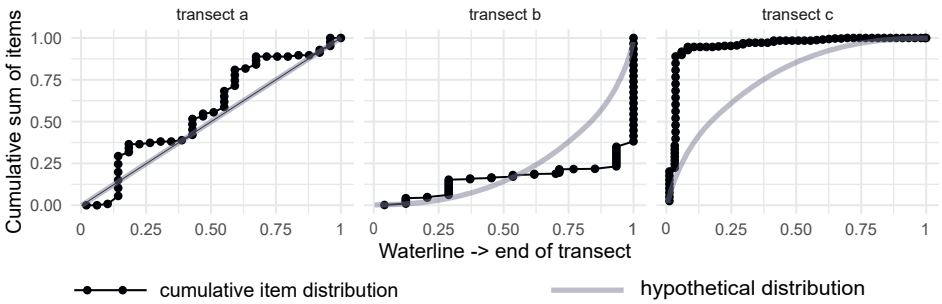


Figure 5.4 | Examples for the three defined modes of deposition 'linear' (transect a), 'exponential increase' (transect b), and 'bounded increase' (transect c). The gray functions are hypothetical, to illustrate the different distributions.

To quantify whether the anthropogenic debris items were linearly distributed between the waterline and the end of the transect, or concentrated in just one of the sections, we investigated the degree of clustering. For this we considered all transects that had at least two anthropogenic debris items, (64/70 transects for the Meuse, 49/51 transects for the IJssel). We calculated the percent of anthropogenic

debris items per section for each transect, and also the percent of transect area covered by each section. We then sorted the sections from highest anthropogenic debris percentage to lowest per transect, and calculated the cumulative sum of anthropogenic debris and section area. We then determined the absolute maximum difference between the cumulative item sum, and a linear distribution. The higher this absolute difference, the more clustered the items in the transect. If the maximum absolute difference was zero, it would mean all plastic items are uniformly distributed between waterline and highest floodline. If the maximum absolute difference was one, it would mean all anthropogenic debris items sampled in a transect are located in just one section.

5.3 | Results and discussion

5.3.1 | Overview – Sampled landcovers and anthropogenic debris concentrations

Along the IJssel in winter 2024, the 51 transects covered a total area of 5729 m^2 with 2785 anthropogenic debris items and a total related mass of 9.9 kg (Table 5.1). Of the 5729 m^2, 128 m^2 where covered by debris piles, representing 2.2% of the total sampled area, however, comprising 58.3% of items by count and 32.3% of items by mass (Fig. 5.5). This translates to an item density of 12.7 items m^{-2} and a mass density of 25.0 g m^{-2}, whereas grass showed densities of only 0.12 items m^{-2} and 1.22 g m^{-2}. The transects we measured along the Meuse in summer 2021 covered a total of 6477 m^2, with 1863 items and a total related mass of 22.6 kg. Of these transects 15 of 69 were covered by only grass, their average item and mass density was 0.40 items m^{-2} and 2.55 g m^{-2}, whereas in transects that contained vegetation other than grass this was 0.83 items m^{-2} and 10.44 g m^{-2}. Within the transects we sampled along the Meuse, there were 6 m^2 of distinct debris piles, but often debris piles only covered part of a section and were then recorded as part of the 'mixed category'.

Table 5.1 | Overview of the different vegetation elements and their corresponding item count and mass densities. *For the Meuse river, transect sections that contained multiple elements were recorded as 'mixed', for the IJssel river, the method was improved and the different elements were recorded as subsections. Therefore there are no mixed elements in the IJssel data. **Debris along the Meuse were sampled only at the surface (no digging through the debris), most likely this severely underestimates the number of items and mass, also, 'mixed' elements can include debris.

		Per element					
	All transects	Grass/ bare	Herbaceous	Shrubs	Mixed*	Trees	Debris pile**
Meuse							
Area [m²]	6477	3429	618	129	2134	92	6
Items [#]	1863	434	152	35	891	282	34
Mass [g]	22593	3202	1009	374	12840	4818	209
Item density [#/m²]	0.29	0.13	0.24	0.25	0.42	3.02	5.67
Mass density [g/m²]	3.49	3.40	6.23	3.36	13.92	53.53	34.83
IJssel							
Area [m²]	5729	4794	761	46	-	10	128
Items [#]	2785	575	566	16	-	3	1625
Mass [g]	9898	5841	786	63	-	7	3201
Item density [#/m²]	0.49	0.12	0.74	0.35	-	0.30	12.70
Mass density [g/m²]	1.72	1.22	1.03	1.40	-	0.70	25.01

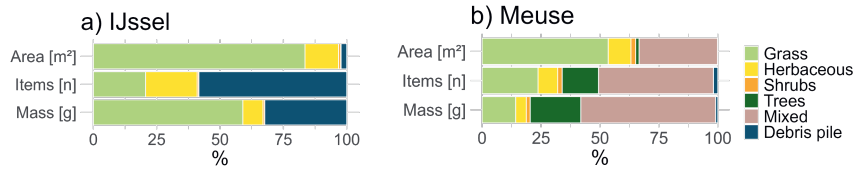
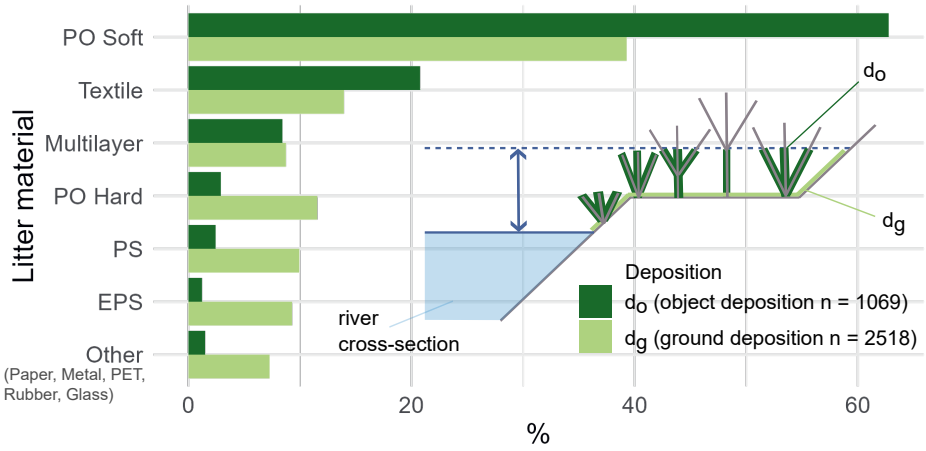


Figure 5.5 | Composition of sampled landcover elements and anthropogenic debris count and mass per landcover element for a) IJssel and b) Meuse river.

5.3.2 | Anthropogenic debris deposited in riparian vegetation



	d_o		d_g				
	mean	sd	mean	sd	t-value	df	p-value
Mass [g]	13.40	4.09	12.20	2.20	−7.83	1532.50	<0.05
Length [cm]	17.70	0.66	13.30	0.35	−183.67	1529.20	<0.05
Length-width-ratio [-]	8.07	1.31	6.89	0.72	−26.06	1591.40	<0.05

Figure 5.6 | Anthropogenic debris sampled following the 2021 summer flood along the Meuse river, showing a comparison between anthropogenic debris deposited in riparian vegetation off the ground d_o (dark green) and on the ground and in ground covering vegetation d_g (light green). The table shows the comparison between the mass, length, and length-width-ratio of anthropogenic debris items sampled in object deposition, and anthropogenic debris items sampled in ground deposition.

Of the 3587 anthropogenic debris items sampled along the Meuse, 70% were ground deposition d_g (on surface or grass), and 30% were object deposition d_o (in trees and shrubs) (Fig.5.6). Of d_o, 84% of items were soft anthropogenic debris items (PO Soft and Textile) vs. d_g, with 53% of soft anthropogenic debris items. This was reversed for rigid materials (PO Hard, PS, and EPS), with 31% of d_g items and 7% of d_o items. Items deposited in objects are 33% larger in size and 10% higher in mass (average 13.4 g and 17.7 cm), compared to items deposited on the ground (average 12.2 g and 13.3 cm). However, the data from de Lange et al. (2022) that we based our size and mass estimates on was recorded over the course of one year, not specifically after high discharge periods.

In the case of d_o, the deposition can occur as the waterlevel increases and inundates obstacles such as riparian vegetation. Anthropogenic debris items transported at the surface, or in the water column encounter the inundated objects and can become entangled, with riparian vegetation acting as a filter. Inundated dense riparian vegetation structures slow down the transport velocity of anthropogenic debris which increases the likelihood of retention (Valyrakis et al., 2024). Mutshekwa et al. (2025) found similar patterns along two South African rivers, with multilayer items and PO Soft mostly deposited in herbaceous vegetation and also wood jams. Soft elongated items are more likely to wrap around the vegetation, and become entangled, compared to rigid items having a more compact shape. This could explain the overall higher proportion of soft items (PO Soft and Textiles) with a higher length-width-ratio deposited d_o (Fig. 5.6), whereas rigid items (PO Hard, PS, EPS) have a higher tendency to be deposited as d_g (Fig. 5.6). Item deposition d_g occurs either due to settling of items, or at the intersection between water and ground surface where the 'floodline' or 'wrack line' forms.

PO Soft is commonly the predominant type of macroplastic found on riverbanks in the Netherlands (van Emmerik et al., 2020c), but is also very common along rivers globally (Talavera et al., 2024; Mutshekwa et al., 2025). The fraction of soft anthropogenic debris we found entangled in trees aligns with a study on macroplastic entanglement in trees on riverbanks in Italy (Gallitelli et al., 2025), where 63% of plastic entangled in trees were soft items. Entanglement of anthropogenic debris items during flood events, might have been amplified by an increase in anthropogenic debris transported as suspended load in the water column during increased discharge (Vriend et al., 2023). Another study on macroplastic entanglement on riverbanks also found trees showed higher trapping efficiency compared to grass, shrubs, and reeds (Gallitelli et al., 2024). However, contrary to our study, they did

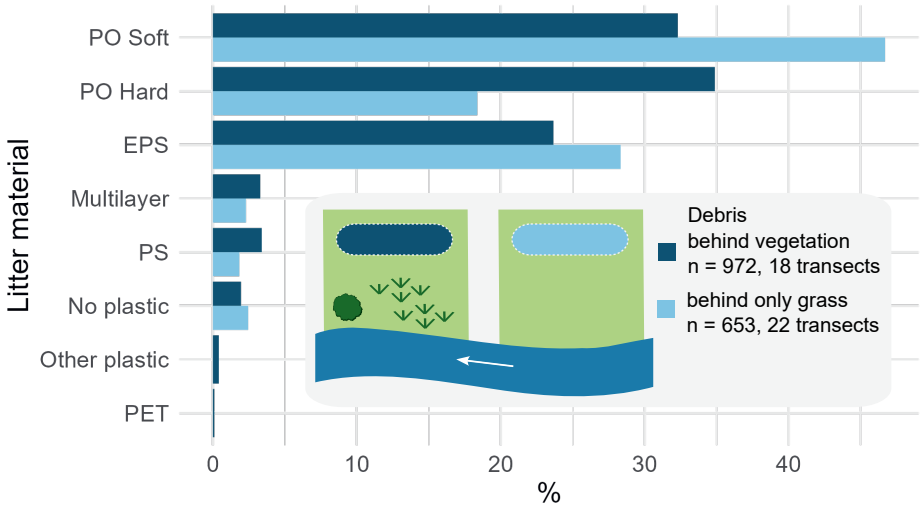
not find a significant difference in macroplastic shape and size between elements. A study on flood deposited macroplastic on Portugese riverbanks found riparian macroplastic trapping mainly related to litter input and population density, with low explanatory power for the structure of riparian vegetation (Pace et al., 2024). It seems deposition of PO Soft is related to the structure of riparian vegetation, however that seems to be not the only exploratory factor.

5.3.3 | Anthropogenic debris deposited within debris piles

Along the IJssel we sampled 51 transects, of which 37 transects contained one or multiple distinct organic debris piles (Fig.5.2c and f). The debris piles overall showed the highest anthropogenic debris density by item count and mass across all elements along the IJssel. On average debris piles had 12.7 #/m² and 25.0 g/m², compared to 0.5 #/m² and 1.7 g/m² average across all elements. The average item size and mass within debris piles however, was smaller than any other element, 4.9 cm and 4.4 g, compared to 7.3 cm and 12.6 g for items deposited in grass, and 9.8 cm and 14.2 g for items in herbaceous vegetation.

There are two main explanations for anthropogenic debris deposition within organic debris. Either plastic and debris follow the same transport dynamics, are possibly entangled during transport, and deposited jointly as aggregates, or plastic and debris are transported independently, but are still deposited at the same locations. Besides anthropogenic debris, river floods transport large amounts of various materials such as wood (Wohl, 2013; Dixon & Sear, 2014), sediment (Karimaee Tabarestani & Zarrati, 2015; Barneveld et al., 2025), and organic debris (Mazur et al., 2016). Hoellein et al. (2024b) detected floating macroplastic only in debris rafts, not in the surrounding open water in the Chicago River. Whereas in the Saigon river van Emmerik et al. (2025) found that water hyacinth patches transport 73% of floating macroplastic, while the patches only cover 1.3% of the total river surface. It seems likely that macroplastic and debris transported together would also be deposited together on the riverbanks. Another possibility is that on riverbanks and inundated floodplains, transported material is deposited primarily at the the land-water-interface i.e. the waterline or the highest floodline, also known as a 'wrack line', which also contains the highest concentration of organic debris. This is similar to organic debris 'wrack' and macroplastic deposited together at the waterline of sandy beaches, which contains higher densities of macroplastic than the surrounding bare sand (Battisti et al., 2020; von Thenen et al., 2025).

Anthropogenic debris in debris piles behind only grass were on average of 41% higher mass and 14% increased length with 4.20 $\pm$2.38 g and 5.38 $\pm$0.50 cm compared to items in debris piles behind higher vegetation with 2.98 $\pm$1.39 g and 4.73 $\pm$0.30 cm respectively (Fig. 5.7). The average item density in debris piles behind only grass and behind higher vegetation is almost the same, with 0.31 items dm^{-3} and 0.36 items dm^{-3} respectively, however, the median item density in debris behind grass is 0.22 items dm^{-3} whereas it is only 0.13 items dm^{-3} in debris piles behind higher vegetation. Debris piles located parallel to the waterline, behind only grass have a >15% higher proportion of PO Soft and a >15% lower proportion of PO Hard fragments, compared to debris piles located behind higher vegetation. This could be linked to soft fragments having a higher chance of being entangled in vegetation, i.e. being 'filtered out'.



	Debris behind only grass		Debris behind vegetation				
	mean	sd	mean	sd	t-value	df	p-value
Mass [g]	4.20	2.38	2.98	1.39	14.05	1612.40	<0.05
Length [cm]	5.38	0.50	4.73	0.30	35.01	1644.30	<0.05
Length-width-ratio [-]	7.25	1.61	6.46	0.98	13.231	1653.90	<0.05

Figure 5.7 | Difference in anthropogenic debris composition in debris lines along the IJssel river. On riverbanks with higher vegetation between the waterline and debris line (dark blue), and debris lines with only grass between debris line and waterline (light blue). The light blue and dark blue bars respectively add up to 100%. The table shows the comparison between the mass, length, and length-width-ratio of anthropogenic debris items behind only grass and behind vegetation.

5.3.4 | Lateral distribution and clustering of anthropogenic debris on riverbanks

For the Meuse and IJssel, we investigated the lateral distribution of anthropogenic debris items and mass between the waterline and end of sampling transect. Along the IJssel, we found that items were mainly deposited at or close to the highest floodline, whereas for the Meuse, items were found close to the waterline. For both rivers most transects ($\geq$68%) follow one of three distributions: bounded increase, exponential increase, or linear (Fig. 5.8). For the Meuse 49% of transects by item count and 52% of transects by mass follow a bounded increase function, with >50% of anthropogenic debris by count and mass deposited close to the waterline. However, the bounded increase transects only contained 28% of total items, and 22% of total mass. Transects following a linear distribution contained the highest share of anthropogenic debris by item count (31%) and mass (27%) along the Meuse. For the IJssel, for 49% of transects, the lateral distribution of anthropogenic debris mass between the waterline and the highest floodline followed an exponential increase function. This means that >50% of anthropogenic debris mass per transect are deposited in the fourth quartile of the transects, close to or in the floodline. However, these 49% of transects only contain 23% of the total mass we found. This is likely due to high densities of small anthropogenic debris items in debris lines, which were often located along the highest floodline. Along the IJssel, the first and fourth quartile each contain 30% of the total anthropogenic debris mass, but the first quartile contains only 24% of items by count, whereas the fourth quartile contains 43% of items by count. A further 23% of transects along the IJssel follow a bounded increase function, where >50% of mass is deposited in the first quartile, close to the waterline at the time of sampling. These 23% of transects contain 37% of total mass sampled along the IJssel.

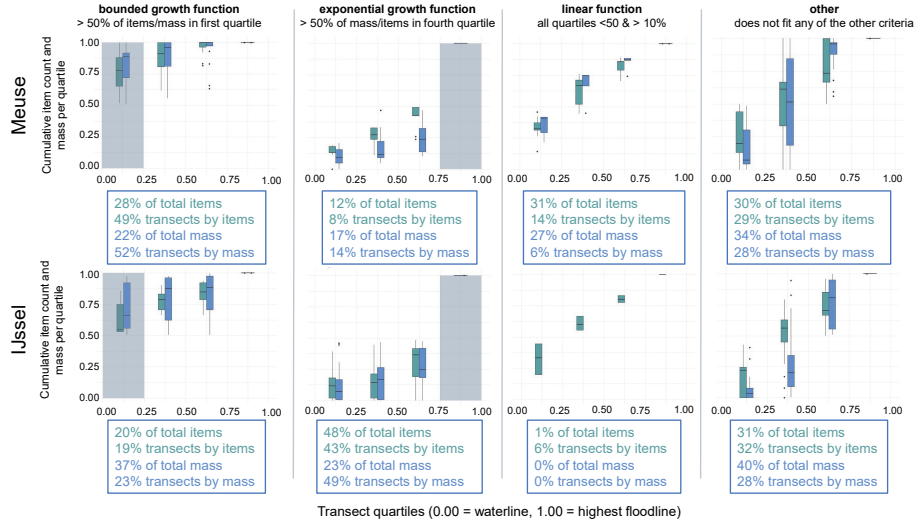


Figure 5.8 | Lateral distribution of anthropogenic debris items (green) and mass (blue) between the waterline and highest floodline/end of transects. For the Meuse we sampled a total of 69 transects with a total anthropogenic debris count of 1,863 items, and a total estimated anthropogenic debris mass of 22.6 kg. For the IJssel we sampled 51 transects with a total anthropogenic debris count of 2785, and a total estimated anthropogenic debris mass of 9.9 kg. As the barplots show a cumulative distribution, the fourth quartile (1.00) always shows 1.00.

Overall, the percentage of items by count and mass following each distribution are more aligned for the Meuse than for the IJssel. This could be due to the fact that debris was sampled differently, and most likely large counts of small, low mass anthropogenic debris items within debris were overlooked for the Meuse, but not for the IJssel. For the transects along the Meuse and IJssel, we investigated the clustering of items along each transect. Overall, along the Meuse more transects have a higher level of clustering, compared to the IJssel. This is also reflected in Figure 5.8, especially the bounded increase function, where the median of cumulative item count for the Meuse is above 0.75 in the first quartile, whereas for the IJssel the median is just above 0.50. It seems the transects with a maximum clustering value close to one, probably have a anthropogenic debris distribution pattern

of one distinct (flood-) line, parallel to the waterline (Tasseron et al., 2024b). Transects with lower values are located on riverbanks with a more random or uniform distribution.

5.3.5 | Anthropogenic debris deposition during a riverine flood event

Some observations on anthropogenic debris deposition during a riverine flood event are relatively obvious. In the case of anthropogenic debris deposition in trees, this occurred during a water level where that section of the tree was inundated. Along the Meuse in 2021, there was also a thin layer of sediment present on vegetation and anthropogenic debris, which was not present higher up in the vegetation, and relatively clearly indicated the maximum level of inundation. However, at which point in time each individual item of anthropogenic debris was deposited is less clear. It is possible that the majority of anthropogenic debris deposited high up in vegetation, and along the flood line at the edge of the inundated area, was pushed ahead of the flood wave. However, the water level stayed at the maximum level for some time, around four hours at Sint Pieter south of Maastricht, and around nine hours at Roermond, 69 km downstream of Sint Pieter (Strijker et al., 2023). As we did not undertake any measurements or observations during the flood event itself, we only observed the accumulated results within the following three weeks. It is therefore also possible that anthropogenic debris along the floodline and entangled in trees was deposited at any point in time during the required inundation level. The Meuse flood was quite severe with a return period of 100 years and large inundated areas, especially upstream of the Dutch Meuse, and along Meuse tributaries (Strijker et al., 2023). Most likely large amounts of plastic and other litter was mobilized from inundated areas and flushed into the Meuse, see Hauk et al. (2023c), where we also compared anthropogenic debris deposition following the July 2021 flood to non-flood conditions. Some riverbanks along the Meuse in the upstream section close to the Dutch-Belgian border have relatively steep riverbanks with dense riparian vegetation. We encountered quite high anthropogenic debris concentrations on these riverbanks, in trees and shrubs (2.6 – 45.8 items m^{-2}, mean 12.7) and on the ground (0.0 – 12.5 items m^{-2}, mean 1.0), and it seems a large fraction of anthropogenic debris transported by the flood was deposited there.

The IJssel flood differed from the Meuse flood in estimated return period (four years for the IJssel [ENW, 2024], and >100 years for the Meuse (Strijker et al., 2023; Lehmkuhl et al., 2022; Mohr et al., 2022; Kreienkamp et al., 2021)) and flood char-

acteristics, which appears to be reflected in the subsequent anthropogenic debris deposition. During the IJssel flood there were repeated elevated water levels with two distinct discharge peaks between 20 December 2023 and 12 January 2024, with the first peak higher than the second (measured at Olst, around 40 km upstream of Kampen) (WMCN, 2024). These two peaks are potentially reflected in the distinct double lines of debris we encountered along some floodplains (Fig. 5.2e). Schreyers et al. (2025) also investigated these two flood events, among others, and investigated in greater detail the link between flood return period and deposited macroplastic. For the IJssel we found that only a few trees showed signs of inundation due to plant debris deposited in lower branches, we only found three anthropogenic debris items deposited in trees, and overall it seemed that at most trees, the inundation level did not reach the branches. With a return period of four years, the flood event was less severe than the Meuse flood in 2021. It seems likely that the additional amount of plastic which was flushed into the IJssel during the flood was relatively low.

5.3.6 | Limitations

When selecting which riverbanks to include in the sampling along the IJssel, we prioritized narrower floodplains, in order to be able to sample the whole extent that had been inundated under tight time constraints. However, wider floodplains have been found to positively correlate with anthropogenic debris concentration (Schreyers et al., 2025), so there could be a sampling bias in our data, leading to an underestimation of anthropogenic debris concentration. For future sampling and monitoring we therefore recommend a combination of narrow and wide floodplains, to cover the potential variability of anthropogenic debris concentration in the river system.

For the Meuse river we did not select floodplains based on their potential inundation extent, it was however at some locations not possible to sample the entire extent that had been inundated. Therefore our findings could potentially under estimate the plastic amount, due to not sampling the highest floodline, and missing the proportion of anthropogenic debris deposited within the highest floodline. Whenever possible, we recommend to sample all the way to the highest floodline.

Debris piles were sampled differently between the Meuse and the IJssel sampling campaign. For the Meuse sampling, we only counted items that were visible on top of the debris from a standing position, without sampling the entire depth of

debris until the ground beneath. For the IJssel sampling on the other hand we sampled the entire depth of debris. Along the IJssel we found large quantities of small anthropogenic debris entangled within the debris, on average 12.7 items/m^2, compared to 5.7 items/m^2 along the Meuse. One of the findings for the Meuse was that there were less small anthropogenic debris items post-flood 2021 than under regular conditions (Hauk et al., 2023c). This difference may be an artifact of the different sampling protocols. We expect that the actual density of small anthropogenic debris items within the debris was higher for the Meuse. We therefore recommend to always sample the entire depth of debris and deposited organic matter, depending on time and other constraints, either the entire extent of debris in the sampling area, or a sub-section.

5.3.7 | Recommendations

For future anthropogenic debris sampling on riverbanks and floodplains following a flood event, we recommend that researchers sample the entire distance between the waterline and the highest extent of inundation. In the case of the Meuse flood in 2021, this was up to multiple kilometers (Rongen et al., 2021). Therefore, following this recommendation could lead to quite large sampling areas, however, we expect it would give a more accurate estimate of flood-driven deposition. Since deposition patterns on riverbanks follow different patterns of lateral deposition, sampling only part of the inundation extent could lead to missing the majority of deposited anthropogenic debris. However, we also found that in the majority of transects the majority of items were concentrated in just one quartile of the transect, either the first or last (Fig. 5.8). Further understanding the dynamics behind this could contribute to optimize post-flood clean-up strategies, by focusing on the part of riverbanks and floodplains that contain the majority of items, especially under tight constraints of time and other resources. We also recommend that researchers should measure the size and mass of anthropogenic debris following a flood event, to compare the item characteristics per River-OSPAR category to the measurements during normal conditions such as in the dataset of de Lange et al. (2022).

Extreme events potentially flush large amounts of anthropogenic debris into river systems, and are likely to be responsible for a large share of (multi-)annual anthropogenic debris transport (Roebroek et al., 2021a; van Emmerik et al., 2019). We therefore recommend that sampling be undertaken pre- and post- such events in anthropogenic debris monitoring campaigns. Sharma et al. (2025) investigated de-

posited anthropogenic debris along the Ganga river pre- and post-monsoon, while they did not find a significant difference in debris density, they found a significant difference in debris composition, indicating a displacement of debris. The recommended threshold for events depends on the specific river system and expected inundation extent per event. Since monitoring or research studies often cover only one or a few years, we recommend to include any event with a one year return period, and or any event where the bankfull discharge is exceeded and vegetation is inundated. Regular monitoring and event related sampling should also cover all landcover elements present in a system, since mass and count density of anthropogenic debris can vary significantly between elements. For representative monitoring of different landcover elements, we suggest the selection of monitoring area(s) so that each landcover element covers a similar share as in the region in general i.e. if 5% of the riverbanks and floodplains are covered by shrubs, about 5% of the monitoring area should be shrubs. Especially debris piles and inundated trees, which may not occur under non-flood conditions, can show a high item and mass density and should be included in event related anthropogenic debris sampling. Monitoring during regular conditions, as well as post-flood events, can give a baseline to evaluate the state of anthropogenic debris pollution in a certain river, as well as the impact of specific events, and mitigation/prevention measures.

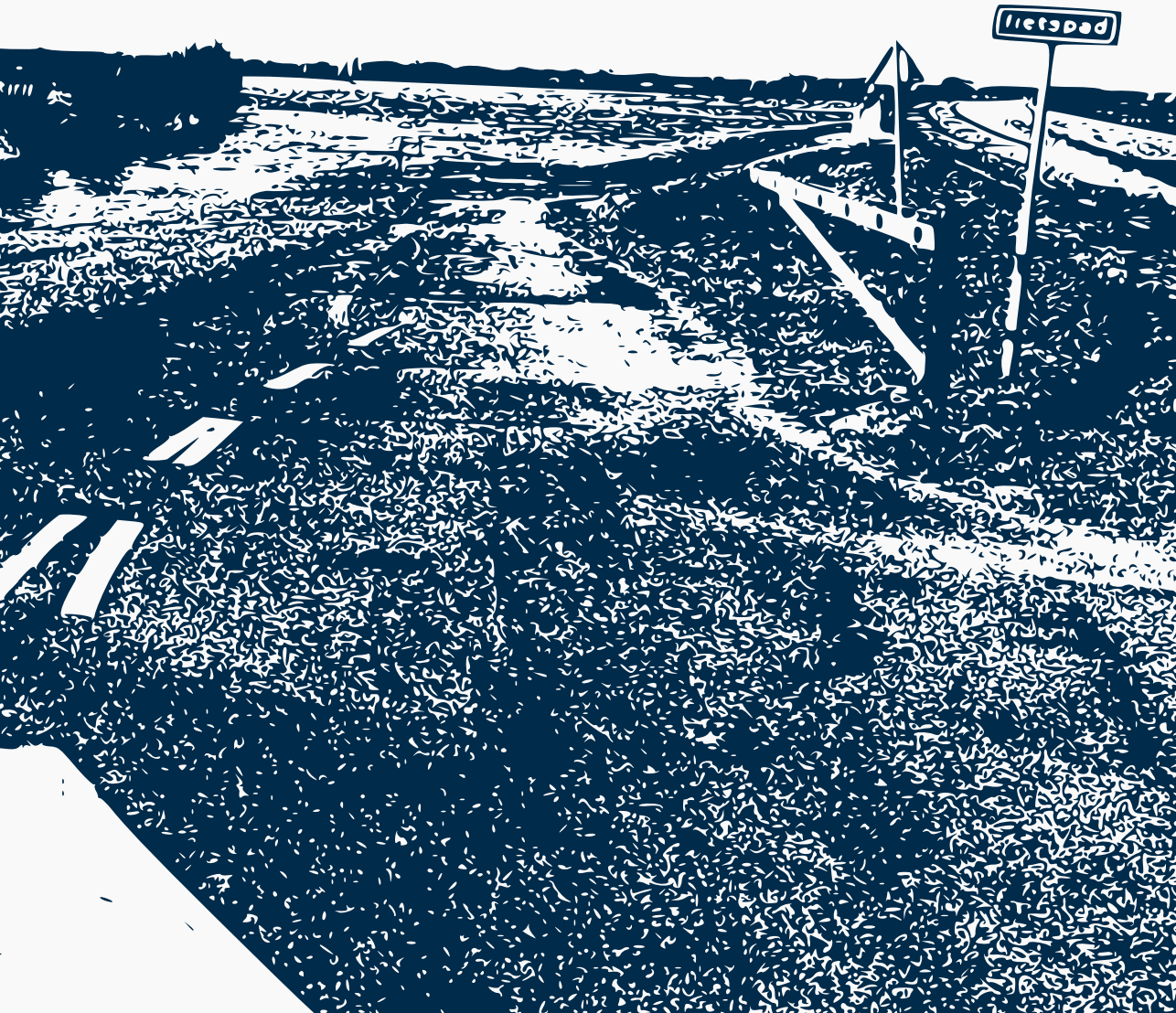
5.4 | Conclusion

Plastic is not deposited evenly along rivers, either by item and mass concentration, or by composition. Soft plastic items are more likely to be entangled in vegetation off the ground, whereas rigid items are more likely to be deposited on the ground. Debris piles only cover relatively small areas on riverbanks and floodplains, but tend to accumulate high concentrations of small plastic items. Also in the lateral direction normal to the river channel plastic is not distributed evenly between the waterline and highest floodline. In the majority of transects we measured along the IJssel and the Meuse, the majority of plastic items are deposited in either the first or last quartile of the transect cross-floodplain. Deposition along the highest floodline could indicate that plastic and other debris are picked up on the rising limb of the hydrograph, transported in this flow, and then deposited and then deposited at the high water margins of flood inundation, both in wrack-lines and in vegetation. It appears that the receding limb of the hydrograph carries less debris, although plastic mobilized on the floodplain may return to the river channel. Since floods potentially cause a large proportion of plastic mobilization, transport, and

deposition in rivers, including floods in plastic pollution prevention, monitoring, and clean-up is important. Especially debris piles and plastic deposited in riparian vegetation should be included, as we found especially high plastic concentrations in those riverbank and floodplain features.


6

Synthesis



6.1 | Main findings of the thesis

6.1.1 | Plastic deposition is not random

The first question this thesis was investigating was whether macroplastic deposition on riverbanks is stable over time and space. And indeed, it appears that plastic deposition is not random, but rather there are riverbanks with consistently high and low plastic concentrations, relative to other riverbanks as investigated in Chapter 2. On average three out of four (73%) riverbanks per river remain above or below average plastic concentration over time. A small number of riverbanks (4.4%) are considered hotspots and their plastic concentration is above average every time they are measured. Even though only ten out of 229 riverbanks along eight Dutch rivers are considered hotspots, these ten riverbanks contain one in four (24.5%) measured plastic items. While it is not fully clear what makes a riverbank a hotspot or a coldspot, the stability over time indicates there are local factors and dynamics influencing plastic deposition on riverbanks.

6.1.2 | Fluvial floods mobilize and deposit plastic

The other questions addressed in this thesis are related to macroplastic deposition and riverine floods. How do macroplastic concentrations and compositions on riverbanks and floodplains differ following a flood event vs. non-flood conditions? Riverine floods cause increased mobilization, transport, and deposition of plastic compared to non-flood conditions. And it appears there are patterns where the plastic is deposited along the river. During a fluvial flood large areas can be inundated due to excessive precipitation. Plastic can be mobilized from the inundated areas and ultimately flushed into the river. Inundation can also cause damage to buildings and lead to a spill of plastic or other materials, as described in Chapter 4 with the buttertubs. Another source of plastic during floods is combined sewer overflow (CSO), which can results in items such as the wet tissues flushed into the Meuse and deposited on the riverbanks and floodplains in Chapter 3. These spill events can contribute quite significantly to the plastic transported and deposited on riverbanks following a flood event. After the flood in July 2021 with a return period of 100 years we found 7.5% of plastic items where buttertubs coming from one distinct source. Even though we started measuring ~66 km downstream from the spill site and anecdotal evidence indicates that their concentration was much higher along their first kilometers of transport (Chapter 4). Wet tissues usually make up less than 1% of plastic items on Meuse riverbanks, but following the July

2021 flood we found that almost one in four items (24.7%) deposited on the Meuse riverbanks and floodplains was a wet tissue (Chapter 3).

6.1.3 | Even during floods, macroplastic is not transported very far

How far are macroplastic items transported during a flood event and over the following years? And how does the condition of these macroplastic items develop in terms of mass and fragmentation? Following the July 2021 flood, the plastic concentration decreased from upstream to downstream along the Meuse, from a deposition rate of 250 items ha^{-1} day^{-1} at the Dutch-Belgian border to 1.3 items ha^{-1} day^{-1} 239 km further downstream. It appears that even during very high discharge, the majority of plastic is not transported very far, but deposited rather close (tens of kilometers) within its point of emission. There were large-scale clean-up efforts along the Meuse and its tributaries, in Belgium and the Netherlands following the 2021 flood event. It seems those clean-up efforts reduced the buttertubs along the Belgian Meuse as a source for the Dutch Meuse and over the following two years, we observed the bulk of buttertubs slowly being transported downstream along the Dutch Meuse (Chapter 4).

6.1.4 | Riparian vegetation accumulates macroplastic during flood events

And finally, following flood events, how do macroplastic concentrations and characteristics differ between landcover elements on riverbanks and floodplains, and how is plastic distributed in the lateral direction? To this end we investigated where exactly plastic is deposited on riverbanks and floodplains, and in which landcover element, such as grass, debris piles, trees, and shrubs, see Chapter 5. We investigated riverbanks and floodplains along the Dutch Meuse following the July 2021 flood, and along the IJssel following winter high water levels, a flood event with a return period of four years. We found that vegetated riverbanks and floodplains have higher concentrations of plastic than riverbanks and floodplains covered only by grass. Further we found that debris piles can contain very high concentrations of plastic items.

6.1.5 | Emerging (research) questions

With this thesis I found answers to some research questions, but as Einstein may or may not have said 'The more I learn, the more I realize how much I don't know'.

And the same goes for investigating freshwater macroplastic pollution. One obvious question emerging from this thesis pertains to the temporal stability analysis in chapter 2; what drives macroplastic deposition on riverbanks? And consequently, can we identify riverbank characteristics related to macroplastic deposition, and predict (relative) macroplastic deposition along rivers?

Based on the results from chapter 2, I started to investigate. Exemplary for the Meuse river I did some explorative tests. The hypotheses to test were based on literature on freshwater plastic pollution, personal experience in the field, and literature on material transport and deposition in rivers in general.

1. Riparian vegetation - the area coverage of higher vegetation (shrubs, trees) positively correlates with the plastic concentration (Cesarini & Scalici, 2022; Delorme et al., 2021; Williams & Simmons, 1996; Speaker et al., 1988), and the results from chapter 5.
2. River curvature - higher plastic concentrations on riverbanks at the inner bend compared to outer bend or a straight section based on sediment erosion and deposition in river meanders (e.g. Bluck, 1971; Thomson, 1876).
3. Compass direction of riverbank relative to the river centerline - some compass directions have higher plastic concentrations than others, due to influence of dominant wind direction on transport of floating items (Roebroek et al., 2021b; Garello et al., 2021)
4. Population density - positive correlation between plastic concentration and population density in the area around the riverbank (Schuyler et al., 2021; Pace et al., 2024)

I tested based on the processed dataset for the Meuse used in Chapter 2, covering the years 2020-2024 for the total plastic concentration. I investigated whether the factors riparian vegetation, river curvature, compass direction, and population density are significantly different for riverbanks we classified as 'coldspots' and 'under' combined vs. riverbanks we classified as 'hotspot' and 'over' combined. Which they appear not to be (Hauk et al., 2025). The measurement locations from the Schone Rivieren dataset used in chapter 2 were available as point coordinates and as polygons covering the measurement area (also see Fig. 2.1). The coverage by 'grass', 'trees', 'shrubs', 'vegetation unclear', 'unvegetated', and 'water' was

calculated for the Schone Rivieren polygons from a dataset on riparian vegetation (RWS, 2018) in QGIS. The river centerline curvature was calculated with a MatLab script (Vermeulen et al., 2014), and the compass direction in QGIS based on the riverbank point coordinates and the direction in relation to the Meuse centerline (RWS, 2004). The compass direction indicates the position of the river centerline from the bank, e.g. 'South' means the river centerline is located south of the riverbank. Population density is based on (CBS, 2022) and the mean and maximum population density in a 1 km and 10 km circular buffer around the riverbank point coordinates, calculated in QGIS.

None of the local factors I tested were significant (Wilcoxon Rank-Sum Test, data non-normal distribution), see examples in Figure 6.1. For the four factors p values ranged between 0.17 and 0.45, and in most cases the variation in the data distribution is larger than variation between the medians. Due to sample size and the observed variation I did not further analyze the data. Contrary to our findings in Chapter 5, I could also not identify a significant influence of riparian vegetation. It appears riparian vegetation has a significant influence during floods and corresponding high water levels, but might have a much lower influence during non-flood conditions. However, the compass direction of 'over' appears to have a smaller range than of 'under'. The Meuse is located between 172 – 352 degrees, south, west, and north of those riverbanks, not to the east. This corresponds with the prevalent wind direction in the Netherlands and seems interesting to investigate in future research. Blondel & Buschman (2022) also found more plastic at the downwind side when investigating plastic transport in the water column in a river bend. Other studies before have investigated the drivers of macroplastic deposition on riverbanks, and whether local factors are related to it. Some studies identified significant factors, nevertheless, usually even significant factors can only explain a small percentage of the data. Pace et al. (2024) found that human population density can explain around 27% of variance in post-flood macroplastic concentration on riverbanks by item count. The geomorphological and riparian factors they tested all had less than 10% of explanatory power. Roebroek et al. (2021b) investigated an earlier version of the Schone Rivieren dataset along Dutch rivers and found a significant correlation between 72/111 litter categories and hydro-meteorology, with a maximum explanatory power of 20% (R^2 = -0.2 – 0.2). Schreyers et al. (2024a) investigated the relation between land-use in a 1.5 km proximity to riverbanks in Switzerland and found a significant relation between five litter categories and land-use (R = -0.34 – 0.53). Cigarette filter and glass bottles showed significant relations

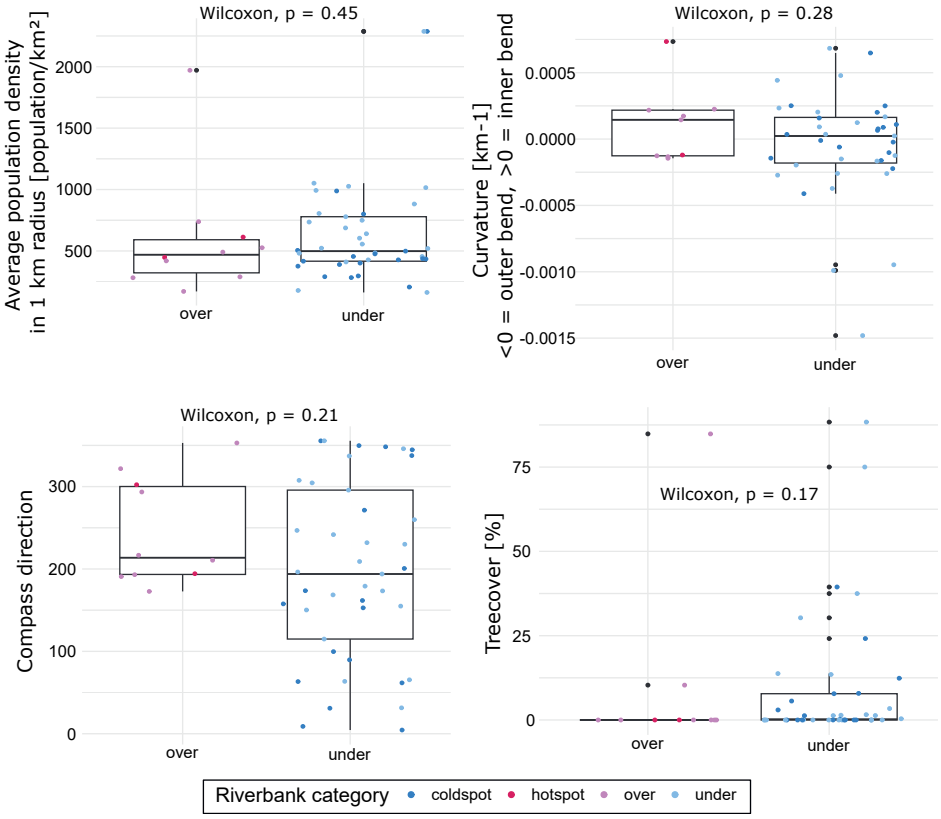


Figure 6.1 | Riparian vegetation, river curvature, compass direction of river in relation to bank, and population density tested for riverbank plastic concentrations (in [items/100 m]) with categories over and hotspot combined, and under and coldspot combined. For the compass direction, ≤45 & >315 correspond to North, >45-135 to East, >135-225 to South, and >225-315 to West. Riverbank categories correspond to the riverbank categories for the Meuse river, see Figure 2.2

with the most land-use categories, positive with buildings, recreational areas, and roads, and negative with unproductive land and rivers. So even when temporal patterns of plastic concentration seem relatively stable, the factors leading to macroplastic deposition on riverbanks (either deposition after transport in the river, or from land) appear less straight forward. It is well possible that a combination of factors contribute to the temporal stability. More research is needed in identifying explanatory (local) factors and the influence of interacting factors on macroplastic deposition over time.

6.2 | Implications and Recommendations

6.2.1 | Implications and recommendations for plastic research

As discussed in section 6.1 there are riverbanks with consistent high and low plastic concentrations. This indicates that there are local factors related to plastic deposition, whether that is deposition of plastic transported in the river, or deposition via e.g. littering in place. While I could not identify predictive factors of plastic deposition during non-flood conditions in this thesis, the patterns identified in Chapter 2 form a base for further research. Research (on macroplastic pollution) is subject to constant change, learning, and improvement. Most sampling protocols for macroplastic pollution on riverbanks were implemented within the last fifteen years (Vriend et al., 2020b). I would recommend to extent the temporal stability approach to a larger scale, across multiple countries, and entire rivers from source to sea. To test if the method is usable for larger scales and gives meaningful results, or if it should be adapted to be applied to larger areas and entire rivers.

It appears that a large proportion of plastic transport happens during (severe) flood events and relatively short intervals of time (section 6.1.2), and (at least in the Netherlands) a large proportion of plastic transported during a flood originates from just a few identifiable sources. I recommend to consider this in future plastic research and investigate whether a few specific (additional) sources of plastic provide a significant proportion of the annually transported and deposited plastic in rivers. Plastic pollution should be considered a flood hazard, and main sources of additional plastic (compared to non-flood conditions) should be identified. And how can plastic mobilization during floods be prevented? Where possible, priority should be given to prevent spilling events, but if they occur, make use of them. Monitoring strategies need room for additional measurements, pre-

and post-flood, and also in case of a spill during a flood, or spills during non-flood conditions. Perhaps research should focus more on plastic mobilization, transport, and deposition over time, as it appears not linear, but often linked to seasons or events. In the Netherlands there are generally higher plastic concentrations on riverbanks in spring compared to fall. This is most likely due to increased river discharge over the Dutch winter, preceding the spring measurements (van Emmerik et al., 2020c; Roebroek et al., 2021b). If indeed plastic input, transport, and deposition over time is very skewed, and a large part occurs in short periods of time, it might make sense to focus on those periods of time (section 6.1.2). Following the 2021 Meuse flood, a large fraction of the deposited plastic by count was wet tissues (24.7%), most likely due to combined sewer overflow, and the spilled buttertubs (7.5%). These two categories could be linked to a specific source, or in case of the wet tissues a specific process. I recommend to investigate whether similar processes can be detected for other flood events. Do the compositions of plastic litter categories after a flood event diverge from non-flood conditions? Can a large proportion of items be attributed to a specific source or process? If that is the case, this can provide guidance for mitigation measures.

Of course, the rivers included in the research of this thesis were all in the Netherlands, the Dutch sections of the Rhine and Meuse rivers, and the Rhine-Meuse delta. Lowland rivers in a country where only about 5% of plastic waste ends up as mismanaged (estimated at 4.3 – 21.2 kilotonnes [kt]) or unreported (445 – 801 kt) (Lobelle et al., 2024). While this is still a significant amount, of course the dynamics are expected to be different for different countries and (additional) mobilization during flood events highly varies. Roebroek et al. (2021a) estimate a relative factor increase for plastic mobilization during a flood with a ten year return period between $\sim$1 – 40 compared to non flood conditions for different countries.

6.2.2 | Implications and recommendations for plastic modeling

Large-scale (global) plastic models often focus on the transport or export of plastic from the terrestrial to the marine environment (e.g. Jambeck et al., 2015; Meijer et al., 2021; Strokal et al., 2023). They estimate plastic emission on land e.g. based on mismanaged plastic waste (MPW) per catchment (Jambeck et al., 2015) or human development index (Mai et al., 2020). Then they estimate the share of plastic that reaches the riverine environment, how much stays in the rivers, and the main result is usually the amount of plastic emitted to the marine environment, often

on an annual basis. So while rivers play an important role in these transport processes at a global scale, they are considered in but not the main focus of large-scale models. The ocean can be considered a final sink for the plastic items which are transported there. Once plastic items left the area influenced by the estuary, and are transported away from the coastal zones, they are highly unlikely to go back upstream. Removing macroplastic from the ocean involves much higher effort and costs compared to the riverine or terrestrial environment, or it is just impossible. Further, macroplastic items might stay intact for decades or millennia, but they also break down into microplastic (Chamas et al., 2020; Barnes et al., 2009). In **Chapter 4** we showed that the emitted buttertubs we encountered did not show a significant loss of mass over the course of two years (Hauk et al., 2023b). Spatially and temporally, there is a window where emitted plastic can still be removed again from the environment. However, once plastic reaches certain locations or a certain size, removal is basically impossible (MacLeod et al., 2021). On the one hand it makes sense to focus on plastic emitted to the seas, and how that can be prevented. However, on the other hand plastic in the terrestrial and freshwater environment is not an inert, harmless material. Plastic and plastic additives can cause harm to flora, fauna, and humans wherever they are.

If indeed a large fraction of macroplastic mobilization, transport, and deposition occurs during flood events and therefore relatively short periods of times, this should be considered in plastic modeling. Further, after a severe flood event, we found a large increase in concentration of wet tissues (Chapter 3), presumably from sewer overflow. Flood events can mobilize plastic into the river that is not considered plastic litter pre-flood, but plastic items used around urban areas and agriculture. Further, floods can also re-mobilize plastic which has been deposited by a previous flood event, e.g. from floodplains, at a large lateral distance from the main channel of the river. We know plastic items on riverbanks and floodplains can stay intact for at least decades (Tramoy et al., 2020b) (time will need to tell the possible extent of this). Also, it seems plastic during floods is limited by supply. So, perhaps not the flood duration, but the flood severity is crucial for the mobilized/transported amount of plastic. If a flood event has a longer duration, it seems possible that at some point all plastic in the affected area is mobilized, transport and deposited, and plastic transport decreases along with the falling limb of the hydrograph (van Emmerik et al., 2023). Anecdotal evidence from the 2021 flood along the Meuse shows that macroplastic is deposited on the upstream side at trees or other large vegetation, especially along riverbanks upstream the Dutch Meuse.

This could indicate it was pushed along with the flood wave, whereas along the IJssel in January 2024, we saw items entangled in vegetation deposited parallel to the waterline, which could be in line with rising and falling water levels over a longer period of time (Schreyers et al., 2025). Roebroek et al. (2026) argue that when river discharge crosses a certain threshold, plastic transport is no longer determined by discharge, but by plastic availability. Overall, modeling plastic transport in rivers is complex and it seems river floods play an important role and should receive added attention.

6.2.3 | Implications and recommendations for plastic monitoring

The results from this thesis lead to two main implications and following recommendations. First, for ongoing monitoring it seems promising to check the temporal stability of the relative plastic distribution, see **Chapter 2**. Test whether hotspots, coldspots, and above and below average locations can be identified and they appear steady over time. If this is the case, this can be considered for monitoring site selection. Of course this depends on the motivation and aim of the monitoring. Monitoring hotspots for example allows to sample the most litter items and could be interesting for a better insight on litter composition, and whether mitigation measurements which target specific plastic litter categories are successful. Including hotspots, coldspots, and above and below average riverbanks in the monitoring can potentially give a good overview of the state of pollution of the entire river. Second, given that floods play an important role in plastic transport and deposition, I recommend to leave room for (additional) monitoring pre- and post-flood, to investigate the flood specific impact.

One result in **Chapter 2** was that plastic items $<$2.5 cm were flushed out from along the Meuse river during the July 2021 flood. After additional fieldwork in 2024 along the IJssel for chapter 5 where we adjusted the sampling method, this conclusion from **Chapter 2** is most likely underestimating the plastic concentration, and solely due to the sampling method. In 2021 we sampled debris piles only for what was visible from the surface without 'digging' through the debris. This was done due to time constraints, and the assumption that it was more important to focus on sampling as much area as possible. In 2024 however, we adjusted the method and sampled (sub-sections) of debris piles in their entire depth, and there we found very high concentrations of plastic items $<$2.5 cm. I would therefore recommend to always sample debris in their entire depth, and as time is often limited, rather subsample small areas in their entire depth, than larger areas solely

at the surface.

6.3 | Reflections

6.3.1 | Reflections on working on this thesis

In hindsight, the different chapters of this thesis vary in how straightforward they felt to work on them. Chapter 2 originated from taking a step back and asking 'are there actually locations that have consistently high and low amounts of plastic?', which brought very clear results. There are indeed locations with relatively high and low amount of plastic. It seems plastic littering in place, but also transport and deposition of plastic by the river is not random. Plastic is not distributed evenly along rivers, which is not groundbreaking news, sampling different riverbanks along a river usually reveals different levels of plastic concentrations on different riverbanks (e.g. Pinto et al., 2024a; Uogintė et al., 2024; Palmas et al., 2022). In chapter 2 we found that there are hotspots and coldspots and most locations tend to stay above or below, or around average over time. This strengthens the hypothesis that there are local factors related to plastic deposition and accumulation. The other relatively straightforward and seemingly 'useful' chapter of this thesis was chapter 4 about the spilled buttertubs as tracers during a riverine flood. Usually with plastic pollution in rivers we do not know the point in time and space where a plastic item was emitted and no longer under human control. We might be able to estimate a potential source, e.g. a wet tissue probably was emitted due to sewer overflow, and narrow down the potential time, e.g. due to a printed 'use-by-date' on food packaging, however, we can never be completely sure. The buttertubs during the July 2021 flood presented a unique opportunity with interesting results. Even though the buttertubs are 'boat' shaped and of stiff plastic and probably not prone to entanglement, the vast majority of them was deposited along the first 100 km from their point of emission. Taking into account the anecdotal evidence from pictures taken during clean-ups along the first 66 km where we did not do any measurements, it seems the vast majority of buttertubs was deposited even closer to the point of emission, along the first few tens of kilometers. Over the course of the following two years we found buttertubs stayed mostly intact. While we cannot rule out that individual buttertubs were broken down beyond recognition, we found a few buttertubs two years after the event which appeared completely intact. In the case of the buttertubs, they were very uniform in size, shape, and material, and therefore not representative of the range of macroplastic

litter we find on riverbanks and floodplains. Of course plastic pollution is a flood risk and focus should be on prevention, however, if it happens, like in this case, where the place of emission was not even considered flood risk area, it presents a valuable opportunity for research.

Chapter 3 however, seems much less straightforward. I assume most researchers would be absolutely thrilled about a time machine allowing them to go back to their fieldwork during data analysis and manuscript writing. This chapter was no exception. One of the findings of this chapter was that it seems small plastic items are flushed out from the river during a flood. However, 2.5 years later doing measurements along the IJssel following the winter high water levels, we found large concentrations of small plastic items embedded in the wrack line and deposited organic debris in general. Along the Meuse in 2021 we had only sampled the surface of debris piles due to time constraints. While this seemed like a reasonable choice at the time, it is very likely we missed significant amounts of small plastic items which had been deposited within the debris along the Meuse. Further, is it really relevant and bringing new insights to measure where precisely plastic is deposited on riverbanks following a flood event? Maybe. Understanding macroplastic deposition and retention dynamics could eventually lead to 'predict' relative plastic concentrations between locations, i.e. where to prioritize clean-up or plastic mitigation measures for example (see also Schreyers et al., 2025).

6.3.2 | Reflection on the data used in this thesis and citizen science in plastic research

The data I used in this thesis has two main origins. I conducted fieldwork after two flood events, with the support of many colleagues, along the Meuse in July and August 2021, and along the IJssel (in collaboration with Louise Schreyers) in January and February 2024. And then additional fieldwork in 2023 for the 'buttertubs' study. The other main dataset I used in this thesis is the monitoring data from the Schone Rivieren Project, a citizen science project initiated in 2017 by the North Sea Foundation, Plastic Soup Foundation, and IVN Nature Education (now lead by IVN Nature Education). I got access to their monitoring data from biannual measurements over multiple years and hundreds of riverbanks along Dutch rivers. And they even very kindly kept an eye out for buttertubs specifically for my study. The resulting dataset was invaluable for my research and the completion of this thesis. The main focus of the Schone Rivieren project is 'river clean-ups',

'research on river litter', 'exploring the rivers', and 'finding solutions'. The data collection is set up according to these interests, and also ensuring feasibility for the citizen scientists. Complexity of data and measurement protocols can be a an issue between citizen science and academic research (Nelms et al., 2022). Based on the results of this thesis, it might be desirable to have measurements at high spatial and temporal intervals, and temporal intervals which are partly fixed, e.g. at a monthly level, and partly flexible, e.g. before and after a high discharge event. Further, it would be interesting to measure also the mass and size of items, to have data not only on item count, but also mass. However this might go beyond what can reasonably asked of citizen scientists who do this voluntarily in their free time. This does not make this dataset any less valuable, as it gives an extensive overview of macroplastic pollution on Dutch riverbanks over time and space.

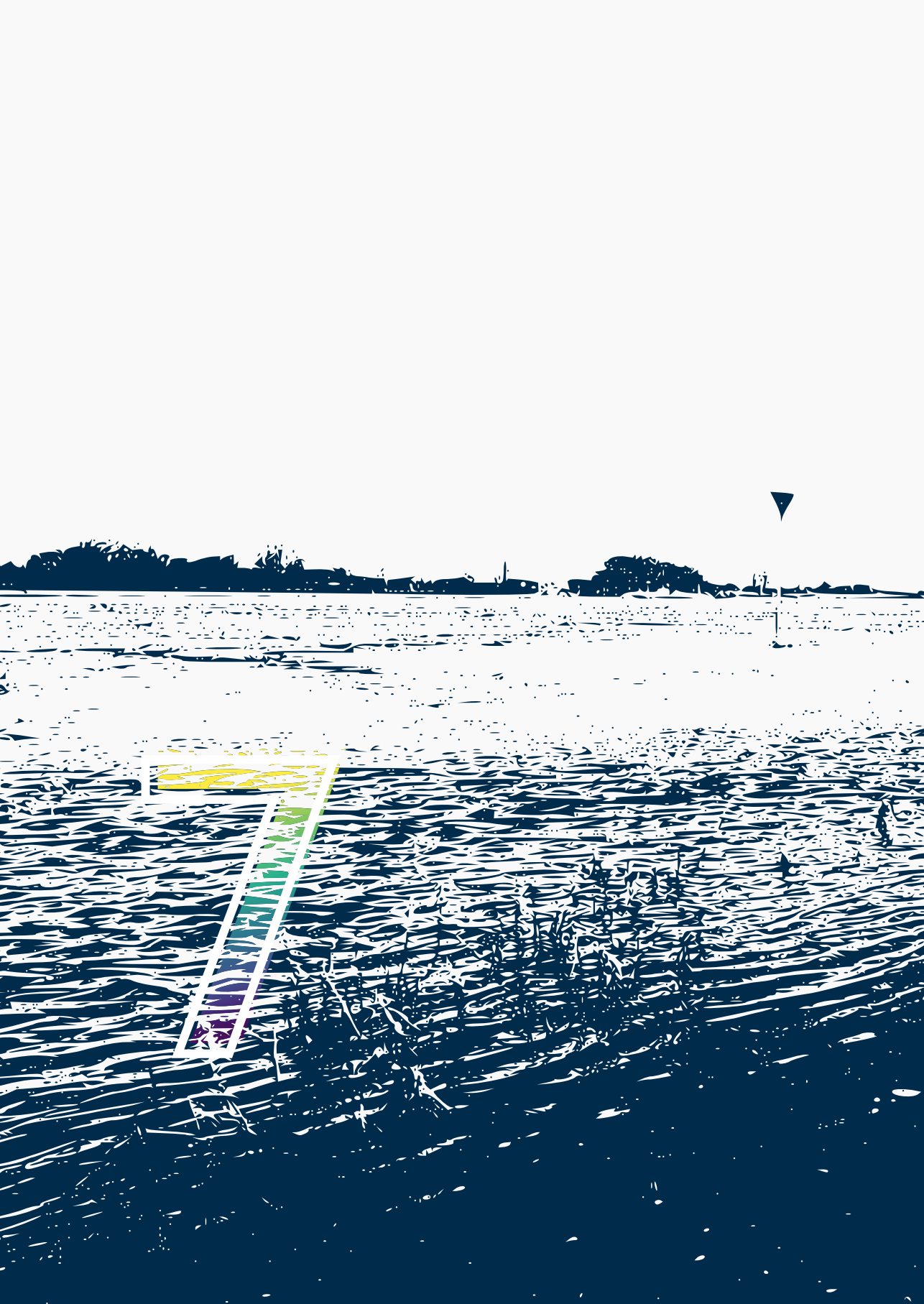
In plastic research there is this paradox, I can only speak for myself and anecdotal evidence from colleagues, but I think most plastic researchers feel the same. We don't like finding plastic, but if we go out and measure, we do want to measure plastic, because we know it is there and a 0 measurement can be frustrating. I heard the citizen scientists in the Schone Rivieren project feel similar, and occasionally ask for a different measurement location if they feel 'their' riverbank is 'too clean' and 'not worth it'. It is therefore possible that there is some bias in the data, occasionally citizen scientists stray from the 100 m riverbank the River-OSPAR protocol calls for, that can have various reasons. In case of high macroplastic concentrations they might measure a shorter area, as they are instructed to stop after two hours of measurement. They might also measure a larger area, due to enthusiasm, a relatively low plastic concentration and left over time, or because outside the original 100 m there is a higher plastic concentration which they feel should be included. As mentioned before, this is an invaluable dataset and due to the large number of measurements these effects (if present) most likely even out. The vast majority of measurements showed a length of exactly 100 m, out of 3684 measurements between 2017 and spring 2024 7.3% measured less than 100 m along the river and only 2.6% of measurements were above 100 m. The citizen scientists might also have a lower detection rate for some plastic litter categories, Roebroek et al. (2021b) investigated the influence of citizen scientists vs reference measurements for the Schone Rivieren dataset, and found that the citizen scientists detect significantly less soft mesoplastic (0.5 – 2.5 cm), probably due to low detectability, and on average 10% less of plastic cotton buds, wet tissues, and sanitary pads and packaging, probably due to aversion. Citizen science in plastic pollution research

can be very valuable, to get insights and knowledge, e.g. where hotspots and cold-spots might be on riverbanks in a region, or what seem to be the most dominant issues regarding plastic pollution at a local level.

6.3.3 | Reflections on 'solving' plastic pollution

Wherever we look on this planet, there is plastic. So the question is, how much resources, time, and energy should we invest in 'looking'? Is it not time to focus on prevention? Most likely it will not be possible to remove all plastic emitted into the environment. That might be me lacking vision and optimism in future development of technology and understanding how this planet works. However, it seems especially plastic at the microplastic (<5 mm) size range in water and soil is there to stay. We might not oversee all potential impacts of trashing our planet. But should we not follow the precautionary principle and focus on prevention of further plastic pollution? Focus on 'turning off the tap' (Fletcher et al., 2023)? Of course, in order to test whether new policies and plastic mitigation measures have an effect, we need a baseline. We need to know how much and what type of plastic is where in the environment, and how much and what is emitted, to test whether changes have an impact. Such as the introduction of the 'statiegeld' (bottle deposit) in the Netherlands in 2021 and its impact on plastic bottles along Dutch rivers (Schep et al., 2025). But "*when do we know enough*" (Horton, 2022)? Should researchers really fly to a different continent to manually count a few hundred pieces of plastic on some riverbanks, or floating below a few bridges?

My colleague Louise Schreyers argued in her thesis that there is not a single tap to turn off but rather plastic pollution as a complex problem requires complex solutions (Schreyers, 2025). I agree with her that 'turning off the tap' oversimplifies the problem. But what could then be a way to go forward? The United Nations 'Global Plastics Treaty' recently failed, mostly due to a few states with strong petrochemical interests (Dauvergne & Allan, 2025). 'No treaty rather than a weak treaty' in a way can be considered a win and perhaps the two year timeline was too ambitious (Dauvergne et al., 2025). But there are >400 Mt of plastic produced annually (Plastics Europe, 2025) and ~64 Mt of annual mismanaged plastic waste (not to mention ~166 Mt going to landfill) (Pottinger et al., 2024). There is no time to lose.



Appendices



Supplementary materials

Supplementary information for Chapter 2

The supplementary data file for chapter 2 will be published as supplementary material along the publication.

Supplementary information for Chapter 3

Table B Overview of locations 1 - 16, their distance from location 1 and when they have been monitored for litter (x), as well as the number of 2 m wide sections and the total sampled area in Q3 2021

Location	Latitude	Longitude	Distance from location 1 [km]	Q4 2017	Q1 2018	Q4 2018	Q1 2019	Q4 2019	Q1 2020	Q4 2020	Q1 2021	Q3 2021 number of sections and total sampled area [m²]	Q4 2021
1	50.7554	5.6817	0.0	-	-	-	x	x	-	x	-	2 [60.0]	-
1*	50.7767	5.6965	-	-	-	-		-	-	-	x	-	x
2	50.7959	5.6953	4.6	-	x	-	x	x	-	-	-	3 [71.4]	-
2*	50.8150	5.6967	-	-	-	-	-	-	-	-	x	-	x
3	50.8747	5.6860	13.3	x	-	x	x	x	x	-	x	3 [90.0]	x
4	51.1880	5.9321	75.2	-	-	x	x	x	x	x	x	3 [758.0]	x
5	51.3424	6.1192	100.6	-	-	-	x	x	x	x	x	3 [360.0]	x
6	51.3963	6.1547	108.1	-	-	-	-	-	x	x	x	3 [240.0]	x
7	51.6480	5.9710	144.7	-	x	x	x	x	x	x	x	3 [390.0]	x
8	51.7555	5.7507	169.1	-	-	-	-	-	x	x	-	3 [260.0]	-
9	51.7763	5.7100	173.1	-	x	x	x	x	x	x	x	3 [242.0]	x
10	51.7361	5.2972	212.9	-	x	-	-	x	x	x	x	3 [128.0]	x
11	51.7389	5.2817	214.0	-	x	-	-	x	x	-	x	3 [444.0]	-
12	51.7411	5.2795	214.2	-	x	-	x	x	-	-	-	1 [20.0]	-
12*	51.7424	5.2307	-	-	-	-	-	-	-	-	x	-	x
13	51.7139	5.0090	233.8	-	x	x	-	-	x	-	x	3 [226.0]	-
13*	51.7191	4.9847	-		-	-	-	-	-	-	x	-	x
14	51.7178	4.9804	236.5	-	x	x	x	x	x	x	x	3 [256.0]	-
15	51.7216	4.9388	239.5	-	x	x	x	x	x	x	x	3 [216.0]	x
16	51.7239	4.9380	239.5	-	-	-	x	x	x	-	-	2 [202.0]	x

Supplementary information for Chapter 4

The supplementary material for chapter 4 has been published under:

Hauk, Rahel; van der Ploeg, Martine; Teuling, Adriaan J.; de Winter, Winnie; van Emmerik, Tim (2024): Data underlying the publication: Flood induced buttertub spill reveals riverine plastic transport dynamics. Version 1. 4TU.ResearchData. dataset. https://doi.org/10.4121/05ba396b-90f7-460e-8f2e-b88752b1b51b.v1

Supplementary information for Chapter 5

Table C Overview of transects that include and do not include certain vegetation types.

			Transects that include (T) / do not include (F)											
		All transects	Only grass/ bare		Herbaceous		Shrubs		Mixed		Trees		Debris pile	
			T	F	T	F	T	F	T	F	T	F	T	F
Meuse	# transects	69	15	54	13	56	10	59	41	28	8	61	-	
	Items [#/m²]	0.74	0.40	0.83	0.73	0.74	0.60	0.76	0.88	0.53	2.27	0.53	-	
	Mass [g/m²]	8.73	2.55	10.44	5.12	9.56	4.27	9.48	12.52	3.17	44.05	4.09	-	
IJssel	# transects	51	20	31	26	25	8	43	-		3	48	37	14
	Item [#/m²]	0.49	0.49	0.49	0.59	0.36	0.23	0.64	-		2.50	0.43	0.68	0.14
	Mass [g/m²]	1.72	3.07	1.23	1.57	1.92	0.37	2.50	-		6.60	1.58	1.92	1.36



Figure C.1 Sampled riverbanks along the upstream section of the Dutch Meuse river. (Pictures by Rahel Hauk)



Figure C.2 Sampled riverbanks midstream and downstream along the Dutch Meuse river. (Pictures by Rahel Hauk)



Figure C.3 Sampled riverbanks along the IJssel river. (Pictures by Rahel Hauk)

Bibliography

Aliani, S., A. Lusher, G. Suaria, S. Primpke, L. Roscher, B. De Witte, D. Vanavermaete, K. Verlé, V. Nikiforov, D. Herzke et al. (2026). Toward harmonised monitoring of plastic pollution: description of a systematic review to evaluate and apply reproducible methods. *Microplastics and Nanoplastics*, 6(1), 25. doi: 10.1186/s43591-026-00184-7.

Andrady, A., H. Hamid & A. Torikai (2011). Effects of solar uv and climate change on materials. *Photochemical & Photobiological Sciences*, 10(2), 292–300. doi: 10.1039/c0pp90038a.

Armitage, J. & S. Rohais (2025). A numerical model of microplastic erosion, transport, and deposition for fluvial systems. *Earth Surface Dynamics*, 13(4), 771–789. doi: 10.5194/esurf-13-771-2025.

Azevedo-Santos, V. M., M. F. Brito, P. S. Manoel, J. F. Perroca, J. L. Rodrigues-Filho, L. R. Paschoal, G. R. Gonçalves, M. R. Wolf, M. C. Blettler, M. C. Andrade et al. (2021). Plastic pollution: A focus on freshwater biodiversity. *Ambio*, 50(7), 1313–1324. doi: 10.1007/s13280-020-01496-5.

Ballerini, T., N. Chaudon, M. Fournier, J. P. Coulomb, B. Dumontet, E. Matuszak & J. Poncet (2022). Plastic pollution on durance riverbank: First quantification and possible environmental measures to reduce it. *Frontiers in Sustainability*, 3, 866982. doi: 10.3389/frsus.2022.866982.

Barnes, D. K., F. Galgani, R. C. Thompson & M. Barlaz (2009). Accumulation and fragmentation of plastic debris in global environments. *Philosophical transactions of the royal society B: biological sciences*, 364(1526), 1985–1998. doi: 10.1098/rstb.2008.0205.

Barneveld, H., R. Frings, E. Mosselman, J. Venditti, M. Kleinhans, A. Blom, R. Schielen, W. Toonen, D. Meijer, A. Paarlberg et al. (2025). Extreme river flood exposes latent erosion risk. *Nature*, pages 1–3. doi: 10.1038/s41586-025-09305-3.

Battisti, C., G. Fanelli, A. Filpa & F. Cerfolli (2020). Giant reed (arundo donax) wrack as sink for plastic beach litter: First evidence and implication. *Marine Pollution Bulletin*, 155, 111179. doi: 10.1016/j.marpolbul.2020.111179.

Battisti, C., M. Malavasi & G. Poeta (2018). Applying diversity metrics to plastic litter 'communities': a first explorative and comparative analysis. *Rendiconti Lincei. Scienze Fisiche e Naturali*, 29(4), 811–815. doi: 10.1007/s12210-018-0737-0.

Bergmann, M., F. Collard, J. Fabres, G. W. Gabrielsen, J. F. Provencher, C. M. Rochman, E. Van Sebille & M. B. Tekman (2022). Plastic pollution in the arctic. *Nature Reviews Earth & Environment*, 3(5), 323–337. doi: 10.1038/s43017-022-00279-8.

Blettler, M., O. Shumilova, L. Gallitelli & A. Sukhodolov (2026). Macroplastic in urban waterways: assessing storage in berlin's spree river. *Environmental Research*, page 123990. doi: 10.1016/j.envres.2026.123990.

Blondel, E. & F. A. Buschman (2022). Vertical and horizontal plastic litter distribution in a bend of a tidal river. *Frontiers in environmental Science*, 10, 861457. doi: 10.3389/fenvs.2022.861457.

Bluck, B. J. (1971). Sedimentation in the meandering river endrick. *Scottish Journal of Geology*, 7(2), 93–138. doi: 10.1144/sjg07020093.

Brander, S. M., K. Senathirajah, M. O. Fernandez, J. S. Weis, E. Kumar, A. Jahnke, N. B. Hartmann, J. J. Alava, T. Farrelly, B. C. Almroth et al. (2024). The time for ambitious action is now: Science-based recommendations for plastic chemicals to inform an effective global plastic treaty. *Science of the Total Environment*, 949, 174881. doi: 10.1016/j.scitotenv.2024.174881.

Breukelman, H., H. Krikke & A. Löhr (2019). Failing services on urban waste management in developing countries: A review on symptoms, diagnoses, and interventions. *Sustainability*, 11(24), 6977. doi: 10.3390/su11246977.

Castillo, A., K. Brophy & I. van Holstein (2023). Addressing plastic additives. vol. briefing topic no. 10. *Institute for Molecular Science and Engineering*. doi: 10.25561/105699.

CBS (2022). Vierkantstatistieken 100m 2022. https://www.pdok.nl/ogc-webservices/-/article/cbs-vierkantstatistieken-100m. Accessed: 26 May 2024.

CBS (2026). Dataset length of waterways. https://opendata.cbs.nl//CBS/nl/dataset/85761NED/table?ts=1773740559804. Accessed: 10 March 2026.

Cesarini, G. & M. Scalici (2022). Riparian vegetation as a trap for plastic litter. *Environmental Pollution*, 292(April 2021), 118410. doi: 10.1016/j.envpol.2021.118410.

Chamas, A., H. Moon, J. Zheng, Y. Qiu, T. Tabassum, J. H. Jang, M. Abu-Omar, S. L. Scott & S. Suh (2020). Degradation rates of plastics in the environment. *ACS Sustainable Chemistry & Engineering*, 8(9), 3494–3511. doi: 10.1021/acssuschemeng.9b06635.

Chaudhary, A., M. Polonsky & N. McClaren (2021). Littering behaviour: A systematic review. *International Journal of Consumer Studies*, 45(4), 478–510. doi: 10.1111/ijcs.12638.

Chowdhury, Z., K. Yokota, M. N. Nguyen & T. Inoue (2023). Bank accumulation of macroplastic samples in a farmland river in japan. *Water, Air, & Soil Pollution*, 234(12), 787. doi: 10.1007/s11270-023-06799-3.

Collard, F., J. Gasperi, G. W. Gabrielsen & B. Tassin (2019). Plastic particle ingestion by wild freshwater fish: a critical review. *Environmental Science & Technology*, 53(22), 12974–12988. doi: 10.1021/acs.est.9b03083.

Constant, M., C. Alary, I. De Waele, D. Dumoulin, N. Breton & G. Billon (2021). To What Extent Can Micro- And Macroplastics Be Trapped in Sedimentary Particles? A Case Study Investigating Dredged Sediments. *Environmental Science and Technology*, 55(9), 5898–5905. doi: 10.1021/acs.est.0c08386.

Cottom, J. W., E. Cook & C. A. Velis (2024). A local-to-global emissions inventory of macroplastic pollution. *Nature*, 633(8028), 101–108. doi: 10.1038/s41586-024-07758-6.

Dalu, T., C. Oduro, R. M. Matsimela, L. F. Munyai, N. Wu, S. Moyo & R. N. Cuthbert (2025). Macroplastic distribution patterns and accumulation in an urbanised austral subtropical river system. *Scientific Reports*, 15(1), 9231. doi: 10.1038/s41598-025-94282-w.

Dauvergne, P. & J. I. Allan (2025). Un politics won't deliver an ambitious plastics treaty. doi: 10.1126/science.aec1353.

Dauvergne, P., J. I. Allan, S. Beaudoin, B. C. Almroth, J. Clapp, E. Cowan, B. de Groot, T. Farrelly, N. de Miranda Grilli, A. Mah et al. (2025). Competing axes of power in the global plastics treaty: Understanding the politics of progress and setbacks in negotiating a high-

ambition agreement. *Marine Policy*, 181, 106820. DOI: 10.1016/j.marpol.2025.106820.

De Bruijn, K. M., F. L. Diermanse, O. M. Weiler, J. S. De Jong & M. Haasnoot (2022). Protecting the rhine-meuse delta against sea level rise: What to do with the river's discharge? *Journal of Flood Risk Management*, 15(3), e12782. DOI: 10.1111/jfr3.12782.

Deanin, R. D. (1975). Additives in plastics. *Environmental health perspectives*, 11, 35–39.

Delorme, A. E., G. B. Koumba, E. Roussel, F. Delor-Jestin, J. L. Peiry, O. Voldoire, A. Garreau, H. Askanian & V. Verney (2021). The life of a plastic butter tub in riverine environments. *Environmental Pollution*, 287, 117656. DOI: 10.1016/j.envpol.2021.117656.

Dewals, B., S. Erpicum, M. Pirotton & P. Archambeau (2021). July 2021 extreme floods in the belgian part of the meuse basin.

Dey, T., L. Trasande, R. Altman, Z. Wang, A. Krieger, M. Bergmann, D. Allen, S. Allen, T. R. Walker, M. Wagner et al. (2022). Global plastic treaty should address chemicals. *Science*, 378(6622), 841–842.

Dixon, S. J. & D. A. Sear (2014). The influence of geomorphology on large wood dynamics in a low gradient headwater stream. *Water Resources Research*, 50(12), 9194–9210. DOI: 10.1002/2014WR015947.

Duncan, E. M., A. Davies, A. Brooks, G. W. Chowdhury, B. J. Godley, J. Jambeck, T. Maddalene, I. Napper, S. E. Nelms, C. Rackstraw et al. (2020). Message in a bottle: Open source technology to track the movement of plastic pollution. *PLoS One*, 15(12), e0242459. DOI: 10.1371/journal.pone.0242459.

Ebbesmeyer, C. C., W. J. Ingraham, T. C. Royer & C. E. Grosch (2007). Tub toys orbit the pacific subarctic gyre. *Eos, Transactions American Geophysical Union*, 88(1), 1–4. DOI: 10.1029/2007EO010001.

Ebbesmeyer, C. C. & W. J. Ingraham Jr (1994). Pacific toy spill fuels ocean current pathways research. *Eos, Transactions American Geophysical Union*, 75(37), 425–430. DOI: 10.1029/94EO01056.

EC (2004). Regulation (ec) no 853/2004 of the european parliament and of the council of 29 april 2004 laying down specific hygiene rules for food of animal origin. *Official Journal of the European Union*, 30(2004), 151.

van Emmerik, T. H. (2024). The impact of floods on plastic pollution. *Global Sustainability*, 7, e17. DOI: 10.1017/sus.2024.14.

van Emmerik, T. H., R. M. Frings, L. J. Schreyers, R. Hauk, S. I. de Lange & Y. A. Mellink (2023). River plastic transport and deposition amplified by extreme flood. *Nature Water*, pages 1–9. DOI: 10.1038/s44221-023-00092-7.

ENW (2024). *Water tegen de dijk - Het functioneren van waterkeringen tijdens het winterhoogwater 2023/2024*. Technical report, Expertise Netwerk Waterveiligheid p/a Rijkswaterstaat WVL, afdeling Waterkeringen, t.a.v. ir. N.R. van der Sleen, 3500 GE Utrecht.

Falk-Andersson, J., Z. Tairova, T. T. Drægni & M. L. Haarr (2021). Methods for determining the geographical origin and age of beach litter: Challenges and opportunities. *Marine Pollution Bulletin*, 172, 112901. DOI: 10.1016/j.marpolbul.2021.112901.

Ferguson, R. (1981). Channel form and channel changes. In *British rivers*, pages 90–125. Routledge.

Fletcher, S., A. L. A. March, K. Roberts, Y. Shirian, L. M. i Canals, A. Cairns, P. Lefort, A. Meso, A. D. Raine, A. Smagadi et al. (2023). *Turning off the Tap: How the world can end plastic pollution and create a circular economy*. United Nations Environment Programme.

Fok, L. & P. Cheung (2015). Hong kong at the pearl river estuary: A hotspot of microplastic pollution. *Marine pollution bulletin*, 99(1-2), 112–118. doi: 10.1016/j.marpolbul.2015.07.050.

Fortibuoni, T., S. Di Vito & E. Scocchera (2025). Preliminary assessment of waste accumulation along riverbanks in italy. *Environmental Science and Pollution Research*, 32(5), 2398–2410. doi: 10.1007/s11356-025-35899-2.

Fowler, C. W. (1987). Marine debris and northern fur seals: a case study. *Marine pollution bulletin*, 18(6), 326–335.

Franceschini, S., A. Cau, L. D'Andrea, M. Follesa & T. Russo (2021). Eating near the dump: identification of nearby plastic hotspot as a proxy for potential microplastic contamination in the norwegian lobster (nephrops norvegicus). *Frontiers in Marine Science*, 8, 682616. doi: 10.3389/fmars.2021.682616.

Funes, M. F., T. M. Reyna, C. M. García, M. Lábaque, S. López, I. Strusberg & S. Vanoni (2025). Estimating macroplastic mass transport from urban runoff in a data-scarce watershed: A case study from cordoba, argentina. *Sustainability*, 17(13), 6177. doi: 10.3390/su17136177.

Galgani, F., A. Souplet & Y. Cadiou (1996). Accumulation of debris on the deep sea floor off the french mediterranean coast. *Marine Ecology Progress Series*, 142, 225–234.

Gallitelli, L., M. Cutini, G. Cesarini & M. Scalici (2025). Plastic hotspot areas in riverine habitats: riparian vegetation diversity and structure entrap riverine plastics. *Current Plant Biology*, page 100450. doi: 10.1016/j.cpb.2025.100450.

Gallitelli, L., M. Cutini & M. Scalici (2024). Riparian vegetation plastic monitoring: A harmonized protocol for sampling macrolitter in vegetated riverine habitats. *Science of the Total Environment*, 912, 169570. doi: 10.1016/j.scitotenv.2023.169570.

García-Gómez, J. C., M. Garrigós & J. Garrigós (2021). Plastic as a vector of dispersion for marine species with invasive potential. a review. *Frontiers in Ecology and Evolution*, 9, 629756. doi: garcia2021plastic.

Garello, N., M. C. Blettler, L. A. Espínola, K. M. Wantzen, D. González-Fernández & S. Rodrigues (2021). The role of hydrodynamic fluctuations and wind intensity on the distribution of plastic debris on the sandy beaches of paraná river, argentina. *Environmental Pollution*, 291, 118168. doi: 10.1016/j.envpol.2021.118168.

Gensen, M. R., J. J. Warmink, F. Huthoff & S. J. Hulscher (2020). Feedback mechanism in bifurcating river systems: The effect on water-level sensitivity. *Water*, 12(7), 1915. doi: 10.3390/w12071915.

Geyer, R., J. R. Jambeck & K. L. Law (2017). Production, use, and fate of all plastics ever made. *Science Advances*, 3(7), 25–29. doi: 10.1126/sciadv.1700782.

Gregory, M. R. (1991). The hazards of persistent marine pollution: drift plastics and conservation islands. *Journal of the Royal Society of New Zealand*, 21(2), 83–100. doi: 10.1080/03036758.1991.10431398.

Grigera, A., S. Montecinos & S. Tognana (2025). Meso and macroplastics present on the surface and soil of a stream bank in the pampas region of argentina. *Environmental Monitoring and Assessment*, 197(5), 551. doi: 10.1007/s10661-025-14014-5.

Grimm, V., E. Schmidt & C. Wissel (1992). On the application of stability concepts in ecology. *Ecological modelling*, 63(1-4), 143–161. doi: 10.1016/0304-3800(92)90067-0.

Gronnerod, C. (2003). Temporal stability in the rorschach method: A meta-analytic review. *Journal of Personality Assessment*, 80(3), 272–293. doi: 10.1207/S15327752JPA8003_06.

Guimarães, G. d. A., S. A. Pereira, B. R. de Moraes, R. A. Ando, J. E. Martinelli Filho, G. F. Perotti, B. S. Sant'Anna & G. Y. Hattori (2024). The retention of plastic particles by macrophytes in the amazon river, brazil. *Environmental Science and Pollution Research*, 31(30), 42750–42765. doi: 10.1007/s11356-024-33961-z.

Hahladakis, J. N., C. A. Velis, R. Weber, E. Iacovidou & P. Purnell (2018). An overview of chemical additives present in plastics: Migration, release, fate and environmental impact during their use, disposal and recycling. *Journal of hazardous materials*, 344, 179–199. doi: 10.1016/j.jhazmat.2017.10.014.

Hanke, G., F. Galgani, S. Werner, L. Oosterbaan, P. Nilsson, D. Fleet, S. Kinsey, R. Thompson, A. Palatinus, J. Van Franeker et al. (2013). Guidance on monitoring of marine litter in european seas: a guidance document within the common implementation strategy for the marine strategy framework directive. doi: 10.2788/99475.

Hauk, R., T. H. van Emmerik, M. van der Ploeg, W. de Winter, M. Boonstra, A. J. Löhr & A. J. Teuling (2023a). Data underlying the publication: Macroplastic deposition and flushing in the meuse river following the july 2021 european floods. doi: 10.4121/21360531.v1.

Hauk, R., T. H. van Emmerik, M. van der Ploeg, W. de Winter, M. Boonstra, A. J. Löhr & A. J. Teuling (2023b). Data underlying the publication: Macroplastic deposition and flushing in the meuse river following the july 2021 european floods. doi: 10.4121/21360531.v1.

Hauk, R., T. H. van Emmerik, M. van der Ploeg, W. de Winter, M. Boonstra, A. J. Löhr & A. J. Teuling (2023c). Macroplastic deposition and flushing in the meuse river following the july 2021 european floods. *Environmental Research Letters*, 18(12), 124025. doi: 10.1088/1748-9326/ad0768.

Hauk, R., M. van der Ploeg, A. J. Teuling, W. de Winter & T. van Emmerik (2024a). Data underlying the publication: Flood induced buttertub spill reveals riverine plastic transport dynamics. doi: 10.4121/05ba396b-90f7-460e-8f2e-b88752b1b51b.v1.

Hauk, R., M. van der Ploeg, A. J. Teuling, W. de Winter & T. H. van Emmerik (2024b). Flood-induced buttertub spill reveals riverine macroplastic transport dynamics. *Environmental Sciences Europe*, 36(1), 149. doi: 10.1186/s12302-024-00962-1.

Hauk, R., A. J. Teuling, T. H. van Emmerik & M. van der Ploeg (2025). What river plastic hotspots do not have in common. In *EGU General Assembly Conference Abstracts*, pages EGU25–17676. doi: 10.5194/egusphere-egu25-17676.

Helinski, O. K., C. J. Poor & J. M. Wolfand (2021). Ridding our rivers of plastic: A framework for plastic pollution capture device selection. *Marine pollution bulletin*, 165, 112095. doi: 10.1016/j.marpolbul.2021.112095.

Hendrikx, A. (2021). Zelfs uit Groningen komt hulp voor de vervuilde Maasoevers in Eijsden.

Hidayat, H., S. Aisyah, A. Rahmadya, S. Husrin, I. S. Hermana, R. Hurley & M. Olsen (2022). Quantification of Riverbank Macroplastic Contamination in the Lower Citarum River. *IOP Conference Series: Earth and Environmental Science*, 950(1). doi: 10.1088/1755-1315/950/1/012010.

Hoellein, T. J., L. H. Kim, R. F. Lazcano & A. E. Vincent (2024a). Debris dams retain trash, mostly plastic, in urban streams. *Freshwater Science*, 43(1), 94–106. doi: 10.1086/729305.

Hoellein, T. J., B. A. Schwenk, E. M. Kazmierczak & F. Petersen (2024b). Plastic litter is a part of the carbon cycle in an urban river: Microplastic and macroplastic accumulate with organic matter in floating debris rafts. *Water Environment Research*, 96(9), e11116. doi: 10.1002/wer.11116.

Honingh, D., T. van Emmerik, W. Uijttewaal, H. Kardhana, O. Hoes & N. van de Giesen (2020). Urban River Water Level Increase Through Plastic Waste Accumulation at a Rack Structure. *Frontiers in Earth Science*, 8(February), 1–8. doi: 10.3389/feart.2020.00028.

Horton, A. A. (2022). Plastic pollution: When do we know enough? *Journal of Hazardous Materials*, 422, 126885. doi: 10.1016/j.jhazmat.2021.126885.

Hoseini, M. & T. Bond (2022). Predicting the global environmental distribution of plastic polymers. *Environmental Pollution*, 300, 118966. doi: 10.1016/j.envpol.2022.118966.

Hoseini, M., J. Stead & T. Bond (2023). Ranking the accelerated weathering of plastic polymers. *Environmental Science: Processes & Impacts*. doi: 10.1039/D3EM00295K.

Hurley, R., H. F. V. Braaten, L. Nizzetto, E. H. Steindal, Y. Lin, F. Clayer, T. van Emmerik, N. T. Buenaventura, D. P. Eidsvoll, A. Økelsrud et al. (2023). Measuring riverine macroplastic: Methods, harmonisation, and quality control. *Water Research*, 235, 119902. doi: 10.1016/j.watres.2023.119902.

Hurley, R., J. Woodward & J. J. Rothwell (2018). Microplastic contamination of river beds significantly reduced by catchment-wide flooding. *Nature Geoscience*, 11(4), 251–257. doi: 10.1038/s41561-018-0080-1.

Huthoff, F., C. Wegman, L. Schreyers, T. van Emmerik & J. V. da Silva (2025). A transport and accumulation model for macroplastics in rivers. In *River Flow 2024*, pages 683–689. CRC Press.

Jambeck, J. R., R. Geyer, C. Wilcox, T. R. Siegler, M. Perryman, A. Andrady, R. Narayan & K. L. Law (2015). Plastic waste inputs from land into the ocean. *science*, 347(6223), 768–771. doi: 10.1126/science.1260352.

Jones, M. M. (1994). Fishing debris in the australian marine environment. *AUSTRALIAN GOVERNMENT PUBLISHING SERVICE, CANBERRA, A. C. T.(AUSTRALIA). 1994.*

Kahn, L. G., C. Philippat, S. F. Nakayama, R. Slama & L. Trasande (2020). Endocrine-disrupting chemicals: implications for human health. *The lancet Diabetes & endocrinology*, 8(8), 703–718. doi: 10.1016/S2213-8587(20)30129-7ExternalLink.

Karimaee Tabarestani, M. & A. Zarrati (2015). Sediment transport during flood event: a review. *International Journal of Environmental Science and Technology*, 12(2), 775–788. doi: 10.1007/s13762-014-0689-6.

Kiessling, T., K. Knickmeier, K. Kruse, D. Brennecke, A. Nauendorf & M. Thiel (2019). Plastic

Pirates sample litter at rivers in Germany – Riverside litter and litter sources estimated by schoolchildren. *Environmental Pollution*, 245(February 2019), 545–557. DOI: 10.1016/j.envpol.2018.11.025.

Korshenko, E., V. Zhurbas, A. Osadchiev & P. Belyakova (2020). Fate of river-borne floating litter during the flooding event in the northeastern part of the Black Sea in October 2018. *Marine Pollution Bulletin*, 160(September). DOI: 10.1016/j.marpolbul.2020.111678.

Kreibich, H. & B. Dimitrova (2010). Assessment of damages caused by different flood types. *WIT Transactions on Ecology and the Environment*, 133, 3–11. DOI: 10.2495/FRIAR100011.

Kreienkamp, F., S. Y. Philip, J. S. Tradowsky, S. F. Kew, P. Lorenz, J. Arrighi, A. Belleflamme, T. Bettmann, S. Caluwaerts, S. C. Chan, A. Ciavarella, L. De Cruz, H. de Vries, N. Demuth, A. Ferrone, E. M. Fischer, H. J. Fowler, K. Goergen, D. Heinrich, Y. Henrichs, G. Lenderink, F. Kaspar, E. Nilson & F. E. L Otto (2021). *Rapid attribution of heavy rainfall events leading to the severe flooding in Western Europe during July 2021*. Technical report.

Kundu, M. N., H. C. Komakech & G. Lugomela (2021). Analysis of Macro- and Microplastics in Riverine, Riverbanks, and Irrigated Farms in Arusha, Tanzania. *Archives of Environmental Contamination and Toxicology*. DOI: 10.1007/s00244-021-00897-1.

Kundzewicz, Z. W., S. Kanae, S. I. Seneviratne, J. Handmer, N. Nicholls, P. Peduzzi, R. Mechler, L. M. Bouwer, N. Arnell, K. Mach, R. Muir-Wood, G. R. Brakenridge, W. Kron, G. Benito, Y. Honda, K. Takahashi & B. Sherstyukov (2014). Le risque d'inondation et les perspectives de changement climatique mondial et régional. *Hydrological Sciences Journal*, 59(1), 1–28. DOI: 10.1080/02626667.2013.857411.

de Lange, S., Y. Mellink, P. Vriend, P. Tasseron & T. van Emmerik (2022). Replication dataset for sample size requirements for riverbank macrolitter characterization. DOI: 10.4121/19188131.v1.

Lau, W. W., Y. Shiran, R. M. Bailey, E. Cook, M. R. Stuchtey, J. Koskella, C. A. Velis, L. Godfrey, J. Boucher, M. B. Murphy et al. (2020). Evaluating scenarios toward zero plastic pollution. *Science*, 369(6510), 1455–1461. DOI: 10.1126/science.aba947.

Leal, M., C. Ramos & S. Pereira (2018). Different types of flooding lead to different human and material damages: the case of the lisbon metropolitan area. *Natural Hazards*, 91(2), 735–758. DOI: 10.1007/s11069-017-3153-3.

Lebreton, L. & A. Andrady (2019). Future scenarios of global plastic waste generation and disposal. *Palgrave Communications*, 5(1), 1–11. DOI: 10.1057/s41599-018-0212-7.

Lechthaler, S., K. Waldschläger, G. Stauch & H. Schüttrumpf (2020). The way of macroplastic through the environment. *Environments*, 7(10), 73. DOI: 10.3390/environments7100073.

Lehmkuhl, F., H. Schüttrumpf, J. Schwarzbauer, C. Brüll, M. Dietze, P. Letmathe, C. Völker & H. Hollert (2022). Assessment of the 2021 summer flood in central europe. *Environmental Sciences Europe*, 34(1), 107. DOI: 10.1186/s12302-022-00685-1.

Li, P. & J. Liu (2024). Micro (nano) plastics in the human body: sources, occurrences, fates, and health risks. *Environmental Science & Technology*, 58(7), 3065–3078. DOI: 10.1021/acs.est.3c08902.

Liro, M. & L. Gallitelli (2025). Plastic-wood jams: macroplastic deposition on woody debris in a mediterranean mountain river and its similarities to temperate ecosystems. *Hydrobiologia*, pages

1–11. DOI: 10.1007/s10750-025-05875-5.

Liro, M., P. Mikuś & B. Wyżga (2022). First insight into the macroplastic storage in a mountain river: The role of in-river vegetation cover, wood jams and channel morphology. *Science of the Total environment*, 838, 156354. DOI: 10.1016/j.scitotenv.2022.156354.

Liro, M., P. Mikuś & A. Zielonka (2025). Field experiment confirms high macroplastic trapping efficiency of wood jams in a mountain river channel. *Scientific Reports*, 15(1), 2933. DOI: 10.1038/s41598-025-87147-9.

Liro, M., T. H. van Emmerik, B. Wyżga, J. Liro & P. Mikuś (2020). Macroplastic Storage and Remobilization in Rivers. *Water*, 12(7), 2055. DOI: 10.3390/w12072055.

Lobelle, D., L. Shen, B. van Huet, T. van Emmerik, M. Kaandorp, G. Iattoni, C. P. Baldé, K. Lavender Law & E. van Sebille (2024). Knowns and unknowns of plastic waste flows in the netherlands. *Waste Management & Research*, 42(1), 27–40. DOI: 10.1177/0734242X231180863.

Lotcheris, R. A., L. Schreyers, T. K. L. Bui, K. Thi, H. Q. Nguyen, B. Vermeulen & T. Van Emmerik (2024). Plastic does not simply flow into the sea: River transport dynamics affected by tides and floating plants. *Environmental Pollution*, 345, 123524. DOI: 10.1016/j.envpol.2024.123524.

Maas Cleanup (2021). Extra Maas Cleanup 14 augustus.

Maathuis, M. I., M. Russwurm, M. Bochow & T. H. van Emmerik (2026). Exploring plastic detectability on riverbanks using remote sensing. *Marine Pollution Bulletin*, 229, 119751. DOI: 10.1016/j.marpolbul.2026.119751.

MacAfee, E. A. & A. J. Löhr (2024). Multi-scalar interactions between mismanaged plastic waste and urban flooding in an era of climate change and rapid urbanization. *Wiley Interdisciplinary Reviews: Water*, 11(2), e1708. DOI: 10.1002/wat2.1708.

Maclean, K., E. A. Weideman, V. Perold & P. G. Ryan (2021). Buoyancy affects stranding rate and dispersal distance of floating litter entering the sea from river mouths. *Marine Pollution Bulletin*, 173, 113028. DOI: 10.1016/j.marpolbul.2021.113028.

MacLeod, M., H. P. H. Arp, M. B. Tekman & A. Jahnke (2021). The global threat from plastic pollution. *Science*, 373(6550), 61–65. DOI: 10.1126/science.abg5433.

Mai, L., X. F. Sun, L. L. Xia, L. J. Bao, L. Y. Liu & E. Y. Zeng (2020). Global riverine plastic outflows. *Environmental Science & Technology*, 54(16), 10049–10056. DOI: 10.1021/acs.est.0c02273.

Martuscelli, D., S. Francalanci, L. Innocenti & L. Solari (2025). Riparian vegetation as a natural barrier: experimental analysis of plastic particle retention in a vegetated reach. *Environmental Advances*, page 100645. DOI: 10.1016/j.envadv.2025.100645.

Marye, A. T., C. Caramiello, D. De Nardi, D. Miglino, G. Proietti, K. C. Saddi, C. Biscarini, S. Manfreda, M. Poggi & F. Tauro (2025). Remote sensing for monitoring macroplastics in rivers: A review. *Wiley Interdisciplinary Reviews: Water*, 12(2), e70020. DOI: 10.1002/wat2.70020.

Mashamba, R., R. Cuthbert, F. Dondofema, L. Munyai, N. Wu & T. Dalu (2024). Spatiotemporal variation in macroplastic abundances along a subtropical austral river system. *Environmental Monitoring and Assessment*, 196(3), 273. DOI: 10.1007/s10661-024-12409-4.

Mazur, R., T. Kałuża, J. Chmist, N. Walczak, I. Laks & P. Strzeliński (2016). Influence of

deposition of fine plant debris in river floodplain shrubs on flood flow conditions–the warta river case study. *Physics and Chemistry of the Earth, Parts A/B/C*, 94, 106–113. DOI: 10.1016/j.pce.2015.12.002.

McGoran, A. R., P. F. Clark, B. D. Smith & D. Morritt (2023). Macrolitter and mesolitter in the thames estuary: A temporal litter assessment and brand audit of submerged and riverbed debris. *Environmental Pollution*, 337, 122484. DOI: 10.1016/j.envpol.2023.122484.

Meijer, D. & R. Agtersloot (2020). Stroomsnelheden in de gemeenschappelijke maas - verslag hydraulisch modelonderzoek. *Agtersloot Hydraulisch Advies en RiQuest Rapport P0010.23 / 107.92*.

Meijer, L. J., T. van Emmerik, R. Van Der Ent, C. Schmidt & L. Lebreton (2021). More than 1000 rivers account for 80% of global riverine plastic emissions into the ocean. *Science Advances*, 7(18), eaaz5803. DOI: 10.1126/sciadv.aaz5803.

Mellink, Y., T. van Emmerik, M. Kooi, C. Laufkötter & H. Niemann (2022). The plastic pathfinder: A macroplastic transport and fate model for terrestrial environments. *Frontiers in Environmental Science*, 10, 979685. DOI: 10.3389/fenvs.2022.979685.

Mennekes, D., Y. A. Mellink, L. J. Schreyers, T. H. van Emmerik & B. Nowack (2024). Macroplastic fate and transport modeling: freshwaters act as main reservoirs. *ACS Es&t Water*, 4(6), 2470–2481. DOI: 10.1021/acsestwater.3c00817.

Mohor, G., P. Hudson & A. Thieken (2020). A comparison of factors driving flood losses in households affected by different flood types. *Water Resources Research*, 56(4), e2019WR025943. DOI: 10.1029/2019WR025943.

Mohr, S., U. Ehret, M. Kunz, P. Ludwig, A. Caldas-Alvarez, J. E. Daniell, F. Ehmele, H. Feldmann, M. J. Franca, C. Gattke et al. (2022). A multi-disciplinary analysis of the exceptional flood event of july 2021 in central europe. part 1: Event description and analysis. *Natural Hazards and Earth System Sciences Discussions*, 2022, 1–44. DOI: 10.5194/nhess-23-525-2023.

Monclús, L., H. Arp, K. Groh, A. Faltynkova, M. Løseth, J. Muncke, Z. Wang, R. Wolf, L. Zimmermann & M. Wagner (2025). Mapping the chemical complexity of plastics. *Nature*, 643(8071), 349–355. DOI: 10.1038/s41586-025-09184-8.

Mutshekwa, T., M. C. Mlambo, L. Mbadla, S. Mkhencele, L. Mofu, M. O. Osoh & S. N. Motitsoe (2025). Macroplastic accumulation across different surface covers, a case study of two south african rivers. *Scientific Reports*, 15(1), 42410. DOI: 10.1038/s41598-025-26494-z.

Napper, I. E., B. F. Davies, H. Clifford, S. Elvin, H. J. Koldewey, P. A. Mayewski, K. R. Miner, M. Potocki, A. C. Elmore, A. P. Gajurel et al. (2020). Reaching new heights in plastic pollution—preliminary findings of microplastics on mount everest. *One Earth*, 3(5), 621–630. DOI: 10.1016/j.oneear.2020.10.020.

Nelms, S. E., E. Easman, N. Anderson, M. Berg, S. Coates, A. Crosby, S. Eisfeld-Pierantonio, L. Eyles, T. Flux, E. Gilford et al. (2022). The role of citizen science in addressing plastic pollution: Challenges and opportunities. *Environmental Science & Policy*, 128, 14–23. DOI: 10.1016/j.envsci.2021.11.002.

Newbould, R. (2021). Understanding river plastic transport with tracers and gps. *Nature Reviews Earth & Environment*, 2(9), 591–591. DOI: 10.1038/s43017-021-00212-5.

Newbould, R. A., D. M. Powell & M. J. Whelan (2021). Macroplastic debris transfer in rivers: a

travel distance approach. *Frontiers in Water*, 3, 724596. DOI: 10.3389/frwa.2021.724596.

Nguyen, K. L. P. & T. K. L. Bui (2023). Riverbank macro-litters monitoring in downstream of saigon river, ho chi minh city. *Case Studies in Chemical and Environmental Engineering*, 7, 100306. DOI: 10.1016/j.cscee.2023.100306.

Nyberg, B., P. T. Harris, I. Kane & T. Maes (2023). Leaving a plastic legacy: Current and future scenarios for mismanaged plastic waste in rivers. *Science of the Total Environment*, 869, 161821. DOI: 10.1016/j.scitotenv.2023.161821.

Oswald, S. B., A. M. Ragas, M. M. Schoor & F. P. Collas (2025). Plastic transport in rivers: Bridging the gap between surface and water column. *Water research*, 269, 122768. DOI: 10.1016/j.watres.2024.122768.

O'Toole, A., K. Hanson & S. Cooke (2009). The effect of shoreline recreational angling activities on aquatic and riparian habitat within an urban environment: implications for conservation and management. *Environmental management*, 44(2), 324–334. DOI: 10.1007/s00267-009-9299-3.

Pace, G., J. Lourenço, C. Ribeiro, C. Rodrigues, C. Pascoal & F. Cássio (2024). Spatial accumulation of flood-driven riverside litter in two northern atlantic rivers. *Environmental Pollution*, 345, 123528. DOI: 10.1016/j.envpol.2024.123528.

Palmas, F., A. Cau, C. Podda, A. Musu, M. Serra, A. Pusceddu & A. Sabatini (2022). Rivers of waste: anthropogenic litter in intermittent sardinian rivers, italy (central mediterranean). *Environmental Pollution*, 302, 119073. DOI: 10.1016/j.envpol.2022.119073.

Peng, X., X. Li, J. Zhou, J. Tan, G. Chen, Z. Zhu & T. Yang (2024). Beyond plastic pollution: Unveiling chemical release from plastic debris in river water and seawater using non-target screening. *Water Research*, 267, 122515. DOI: 10.1016/j.watres.2024.122515.

Pierdomenico, M., D. Ridente, D. Casalbore, L. Di Bella, S. Milli & F. L. Chiocci (2022). Plastic burial by flash-flood deposits in a prodelta environment (Gulf of Patti, Southern Tyrrhenian Sea). *Marine Pollution Bulletin*, 181(February). DOI: 10.1016/j.marpolbul.2022.113819.

Pinto, R. B., L. Bogerd, M. van der Ploeg, K. Duah, R. Uijlenhoet & T. H. van Emmerik (2024a). Catchment scale assessment of macroplastic pollution in the odaw river, ghana. *Marine Pollution Bulletin*, 198, 115813. DOI: 10.1016/j.marpolbul.2023.115813.

Pinto, R. B., T. H. van Emmerik, K. Duah, M. van der Ploeg & R. Uijlenhoet (2024b). Mismanaged plastic waste as a predictor for river plastic pollution. *Science of the Total Environment*, 951, 175463. DOI: 10.1016/j.scitotenv.2024.175463.

Plastics Europe (2021). *Plastics - the Facts 2021*. Technical report, Plastics Europe AISBL.

Plastics Europe (2024). *Plastics - the fast Facts 2024*. Technical report, Conversio Market & Strategy GmbH and nova-Institute.

Plastics Europe (2025). *Plastics - the Fast Facts 2025*. Technical report, Plastics Europe AISBL.

Pörtner, H. O., D. C. Roberts, H. Adams, C. Adler, P. Aldunce, E. Ali, R. A. Begum, R. Betts, R. B. Kerr, R. Biesbroek et al. (2022). *Climate change 2022: Impacts, adaptation and vulnerability*. Cambride University Press. DOI: 10.1017/9781009325844.

Pottinger, A. S., R. Geyer, N. Biyani, C. C. Martinez, N. Nathan, M. R. Morse, C. Liu, S. Hu, M. de Bruyn, C. Boettiger et al. (2024). Pathways to reduce global plastic waste

mismanagement and greenhouse gas emissions by 2050. *Science*, 386(6726), 1168–1173. DOI: 10.1126/science.adr3837.

Pow, C. J., R. Fellows, H. L. White, L. Woodford & R. S. Quilliam (2025). Fluvial flooding and plastic pollution–the delivery of potential human pathogenic bacteria into agricultural fields. *Environmental Pollution*, 366, 125518. DOI: 10.1016/j.envpol.2024.125518.

Rajwa-Kuligiewicz, A., A. Bojarczuk, A. Lenart-Boroń, O. Kaflińska & W. Suwalska (2025). Journey of pathogen-loaded macroplastics in a gravel-bed mountain river: Hydrological and geomorphological controls in a probabilistic framework. *Science of the Total Environment*, 991, 179916. DOI: 10.1016/j.scitotenv.2025.179916.

Reeze, B., W. Liefveld, J. Postma, H. Barneveld, N. van Kessel, H. van der Jagt, T. Smit, H. Coops & D. Tjabbes-Van der Gaag (2020). Watersysteemrapportage maas. *Antea Group, sl projectnummer*, 434242(11).

Reeze, B., A. Van Winden, J. Postma, R. Pot, J. Hop & W. Liefveld (2017). Watersysteemrapportage rijntakken 1990-2015. *Ontwikkelingen waterkwaliteit en ecologie. Bart Reeze Water & Ecologie, Harderwijk*, page 136.

Ren, S., K. Wang, J. Zhang, J. Li, H. Zhang, R. Qi, W. Xu, C. Yan, X. Liu, F. Zhang et al. (2024). Potential sources and occurrence of macro-plastics and microplastics pollution in farmland soils: A typical case of china. *CritiCal reviews in environmental sCienCe and teChnology*, 54(7), 533–556. DOI: 10.1080/10643389.2023.2259275.

Rijkswaterstaat (1985). De maas is uit... *Directie Limburg - Report C11273*.

Rocamora, C., H. Puerto, R. Abadía, M. Brugarolas, L. Martínez-Carrasco & J. Cordero (2021). Floating debris in the low segura river basin (spain): avoiding litter through the irrigation network. *Water*, 13(8), 1074. DOI: 10.3390/w13081074.

Roebroek, C. T., S. Harrigan, T. H. van Emmerik, C. Baugh, D. Eilander, C. Prudhomme & F. Pappenberger (2021a). Plastic in global rivers: Are floods making it worse? *Environmental Research Letters*, 16(2). DOI: 10.1088/1748-9326/abd5df.

Roebroek, C. T., R. Hut, P. Vriend, W. De Winter, M. Boonstra & T. H. van Emmerik (2021b). Disentangling Variability in Riverbank Macrolitter Observations. *Environmental Science and Technology*, 55(8), 4932–4942. DOI: 10.1021/acs.est.0c08094.

Roebroek, C. T., A. J. Teuling, M. J. van der Ploeg, D. González-Fernández & T. H. van Emmerik (2026). Revising the role of discharge in global river plastic transport. *Cell Reports Sustainability*, 3(3). DOI: 10.1016/j.crsus.2025.100604.

Rongen, G., B. Strijker, J. Pol, M. Kok, B. Kolen, S. Rikkert, J. Schlumberger, M. van Haren & D. Wüthrich (2021). *Hoogwater 2021: Feiten en Duiding*. Technical report, Expertise Netwerk Waterveiligheid.

Rosenzweig, B. R., L. McPhillips, H. Chang, C. Cheng, C. Welty, M. Matsler, D. Iwaniec & C. I. Davidson (2018). Pluvial flood risk and opportunities for resilience. *Wiley Interdisciplinary Reviews: Water*, 5(6), e1302. DOI: 10.1002/wat2.1302.

RWS (2004). Kaderrichtlijn water oppervlaktewaterlichamen (lijnen). *Rijkswaterstaat Ministerie van Infrastructuur en Waterstaat*.

RWS (2018). Ecotopen cyclus five. *Rijkswaterstaat Ministerie van Infrastructuur en Waterstaat*.

Ryan, P. G. (1987). The effects of ingested plastic on seabirds: correlations between plastic load and body condition. *Environmental Pollution*, 46(2), 119–125. doi: 10.1016/0269-7491(87)90197-7.

Saliba, M., S. Frantzi & P. van Beukering (2022). Shipping spills and plastic pollution: A review of maritime governance in the north sea. *Marine Pollution Bulletin*, 181, 113939. doi: 10.1016/j.marpolbul.2022.113939.

Schep, E., G. Bergsma, P. Bouwman, W. {van Santen}, C. Backes & M. Boeve (2025). *Evaluatie statiegeld*. CE Delft.

Schielen, R. M. J., H. Havinga & M. Lemans (2008). Dynamic control of the discharge distributions of the rhine river in the netherlands. In *Proc. Int. Conf. on Fluvial Hydraulics, River Flow*, pages 3–5.

Schmidt, C., T. Krauth & S. Wagner (2017). Export of plastic debris by rivers into the sea. *Environmental science & technology*, 51(21), 12246–12253. doi: 10.1021/acs.est.7b02368.

Schreyers, L. (2025). *Lost in transportation macroplastic retention in rivers*. Ph.D. thesis, Wageningen University and Research. doi: 10.18174/681488.

Schreyers, L., R. Erismann, S. Erismann, C. Ludwig, B. Patel, M. Filella & T. van Emmerik (2024a). Revealing the role of land-use features on macrolitter distribution in swiss freshwaters. *Environmental Pollution*, 362, 124911. doi: 10.1016/j.envpol.2024.124911.

Schreyers, L., T. van Emmerik, T. L. Nguyen, E. Castrop, N. A. Phung, T. C. Kieu-Le, E. Strady, L. Biermann & M. van der Ploeg (2021). Plastic Plants: The Role of Water Hyacinths in Plastic Transport in Tropical Rivers. *Frontiers in Environmental Science*, 9. doi: 10.3389/fenvs.2021.686334.

Schreyers, L. J., T. H. van Emmerik, T. K. L. Bui, L. Biermann, R. Uijlenhoet, H. Q. Nguyen, N. Wallerstein & M. van der Ploeg (2024b). Water hyacinths retain river plastics. *Environmental Pollution*, 356, 124118. doi: 10.1016/j.envpol.2024.124118.

Schreyers, L. J., T. H. van Emmerik, F. Huthoff, F. P. Collas, C. Wegman, P. Vriend, A. Boon, W. de Winter, S. B. Oswald, M. M. Schoor et al. (2024c). River plastic transport and storage budget. *Water research*, 259, 121786. doi: 10.1016/j.watres.2024.121786.

Schreyers, L. J., R. Hauk, N. Wallerstein, A. J. Teuling, R. Uijlenhoet, M. van der Ploeg & T. H. van Emmerik (2025). Flood characteristics drive river-scale macroplastic deposition. *Environmental Science & Technology*, 59(36), 19414–19423. doi: 10.1021/acs.est.5c02969.

Schuyler, Q., B. D. Hardesty, T. Lawson & C. Wilcox (2022). Environmental context and socio-economic status drive plastic pollution in australian cities. *Environmental Research Letters*, 17(4), 045013. doi: 10.1088/1748-9326/ac5690.

Schuyler, Q., C. Wilcox, T. Lawson, R. Ranatunga, C. S. Hu & B. D. Hardesty (2021). Human population density is a poor predictor of debris in the environment. *Frontiers in Environmental Science*, 9, 583454. doi: 10.3389/fenvs.2021.583454.

Seewoo, B. J., L. M. Goodes, L. Mofflin, Y. R. Mulders, E. V. Wong, P. Toshniwal, M. Brunner, J. Alex, B. Johnston, A. Elagali et al. (2023). The plastic health map: A systematic evidence map of human health studies on plastic-associated chemicals. *Environment International*, 181,

108225. DOI: 10.1016/j.envint.2023.108225.

Semcesen, P. O., M. Wells, C. Sherlock, R. Gutierrez & C. Rochman (2025). Wind driven transport of macroplastic debris in a large urban harbour measured by gps-tracked drifters. *Marine Pollution Bulletin*, 217, 118034. DOI: 10.1016/j.marpolbul.2025.118034.

Sharma, E., A. Ramachandran, P. Dobriyal, S. Badola, H. Koldewey, S. A. Hussain & R. Badola (2025). Mapping the distribution and discharge of plastic pollution in the ganga river. *Sustainability*, 17(11), 4932. DOI: 10.3390/su17114932.

Shaughnessy, P. (1980). Entanglement of cape fur seals with man-made objects. *Marine Pollution Bulletin*, 11(11), 332–336. DOI: 10.1016/0025-326X(80)90052-1.

Song, X., M. Lyu, X. Zhang, B. Ruthensteiner, I. Y. Ahn, G. Pastorino, Y. Wang, Y. Gu, K. Ta, J. Sun et al. (2021). Large plastic debris dumps: new biodiversity hot spots emerging on the deep-sea floor. *Environmental Science & Technology Letters*, 8(2), 148–154. DOI: 10.1021/acs.estlett.0c00967.

Speaker, R. W., K. J. Luchessa, J. F. Franklin & S. V. Gregory (1988). The use of plastic strips to measure leaf retention by riparian vegetation in a coastal oregon stream. *American Midland Naturalist*, pages 22–31. DOI: 10.2307/2425883.

Stock, F., C. Kochleus, B. Bänsch-Baltruschat, N. Brennholt & G. Reifferscheid (2019). Sampling techniques and preparation methods for microplastic analyses in the aquatic environment–a review. *TrAC Trends in Analytical Chemistry*, 113, 84–92. DOI: 10.1016/j.trac.2019.01.014.

Strijker, B., N. Asselman, J. de Jong & H. Barneveld (2023). The 2021 flood event in the dutch meuse and tributaries from a hydraulic and morphological perspective. *Journal of Coastal and Riverine Flood Risk*, 2, 6.

Strokal, M., P. Vriend, M. P. Bak, C. Kroeze, J. van Wijnen & T. van Emmerik (2023). River export of macro-and microplastics to seas by sources worldwide. *Nature Communications*, 14(1), 4842. DOI: 10.1038/s41467-023-40501-9.

Symeonides, C., M. Brunner, Y. Mulders, P. Toshniwal, M. Cantrell, L. Mofflin & S. Dunlop (2021). Buy-now-pay-later: hazards to human and planetary health from plastics production, use and waste. *Journal of Paediatrics and Child Health*, 57(11), 1795–1804. DOI: 10.1111/jpc.15777.

Talavera, A. L., L. F. M. Dalida & M. B. L. D. Diola (2024). Riverine macroplastic survey along the segments of tullahan river in metro manila, philippines. *Frontiers in Environmental Science*, 12, 1396525. DOI: 10.3389/fenvs.2024.1396525.

Tanaka, M. & Y. Nihei (2025). How flooding rivers deliver plastic to the ocean: A case study of microplastic and mesoplastic load–discharge relationships. *Water Research*, page 125175. DOI: 10.1016/j.watres.2025.125175.

Tasseron, P., T. van Emmerik, P. Vriend, R. Hauk, F. Alberti, Y. Mellink & M. van der Ploeg (2024a). Defining plastic pollution hotspots. *Science of the Total Environment*, 934, 173294. DOI: 10.1016/j.scitotenv.2024.173294.

Tasseron, P. F., T. H. van Emmerik, W. de Winter, P. Vriend & M. van der Ploeg (2024b). Riverbank plastic distributions and how to sample them. *Microplastics and Nanoplastics*, 4(1), 22. DOI: 10.1186/s43591-024-00100-x.

Teunkens, B. (2021). Tracking marked plastic items on their journey through the scheldt estuary, using the permanent belgian acoustic receiver network (pbarn). final report: Brilliant marine research idea 2020.

von Thenen, M., M. von Loh, E. Robbe, L. B. Abdallah, G. Escobar-Sánchez, M. Haseler, F. M'hiri & G. Schernewski (2025). Beach wrack on baltic and mediterranean sea beaches: Litter pollution and management perspectives. *Estuaries and Coasts*, 48(3), 61. doi: 10.1007/s12237-025-01497-1.

Thomson, J. (1876). On the windings for rivers in alluvial plains, with remarks on the flow of water round bends in pipes. *Proc.Roy.Soc. London*, 25, 5–8.

Tramoy, R., J. Gasperi, L. Colasse, C. Noûs & B. Tassin (2021). Transfer dynamics of macroplastics in estuaries – New insights from the Seine estuary : Part 3 . What fate for macroplastics? *Marine Pollution Bulletin*, 169(May), 112513. doi: 10.1016/j.marpolbul.2021.112513.

Tramoy, R., J. Gasperi, L. Colasse, M. Silvestre, P. Dubois, C. Noûs & B. Tassin (2020a). Transfer dynamics of macroplastics in estuaries–new insights from the seine estuary: part 2. short-term dynamics based on gps-trackers. *Marine Pollution Bulletin*, 160, 111566. doi: 10.1016/j.marpolbul.2020.111566.

Tramoy, R., J. Gasperi, L. Colasse & B. Tassin (2020b). Transfer dynamic of macroplastics in estuaries—new insights from the seine estuary: Part 1. long term dynamic based on date-prints on stranded debris. *Marine pollution bulletin*, 152, 110894. doi: 10.1016/j.marpolbul.2020.110894.

Treilles, R., J. Gasperi, M. Saad, A. Rabier, J. Breton, V. Rocher, S. Guérin & B. Tassin (2020). Macro and Microplastics in Stormwater and Combined Sewer Overflows in Paris Megacity. pages 145–151. Springer, Cham. doi: 10.1007/978-3-030-45909-3{_}23.

Treilles, R., J. Gasperi, R. Tramoy, R. Dris, A. Gallard, C. Partibane & B. Tassin (2022). Microplastic and microfiber fluxes in the Seine River: Flood events versus dry periods. *Science of the Total Environment*, 805. doi: 10.1016/j.scitotenv.2021.150123.

Turner, A., R. Arnold & T. Williams (2020). Weathering and persistence of plastic in the marine environment: Lessons from lego. *Environmental Pollution*, 262, 114299. doi: 10.1016/j.envpol.2020.114299.

Turner, A., T. Williams & T. Pitchford (2021). Transport, weathering and pollution of plastic from container losses at sea: Observations from a spillage of inkjet cartridges in the north atlantic ocean. *Environmental Pollution*, 284, 117131. doi: 10.1016/j.envpol.2021.117131.

Uogintė, I., S. Byčenkienė, M. Davtalab & R. Markevičiūtė (2024). Exploring the abundance and characteristics of litter in lithuanian riversides: a citizen science approach. *Environmental Monitoring and Assessment*, 196(3), 324. doi: 10.1007/s10661-024-12503-7.

Vachaud, G., A. Passerat de Silans, P. Balabanis & M. Vauclin (1985). Temporal stability of spatially measured soil water probability density function. *Soil Science Society of America Journal*, 49(4), 822–828. doi: 10.2136/sssaj1985.03615995004900040006x.

Valyrakis, M., G. Gilja, D. Liu & G. Latessa (2024). Transport of floating plastics through the fluvial vector: the impact of riparian zones. *Water*, 16(8), 1098. doi: 10.3390/w16081098.

van Emmerik, T., S. De Lange, R. Frings, L. Schreyers, H. Aalderink, J. Leusink, F. Begemann,

E. Hamers, R. Hauk, N. Janssens et al. (2022a). Hydrology as a driver of floating river plastic transport. *Earth's Future*, 10(8), e2022EF002811. doi: 10.1029/2022EF002811.

van Emmerik, T., T. Janssen, T. Jia, T. K. L. Bui, R. Taormina, N. H. Quan & L. Schreyers (2025). Plastic pollution and water hyacinths consistently co-occur in the lower saigon river. *Environmental Research: Water*. doi: 10.1088/3033-4942/ae10d7.

van Emmerik, T. & A. Schwarz (2020). Plastic debris in rivers. *Wiley Interdisciplinary Reviews: Water*, 7(1), e1398. doi: 10.1002/wat2.1398.

van Emmerik, T., J. Seibert, B. Strobl, S. Etter, T. Den Oudendammer, M. Rutten, M. bin Ab Razak & I. van Meerveld (2020a). Crowd-based observations of riverine macroplastic pollution. *Frontiers in Earth Science*, 8, 298. doi: 10.3389/feart.2020.00298.

van Emmerik, T., P. Vriend & J. Roebroek (2020b). *An evaluation of the River-OSPAR method for quantifying macrolitter on Dutch riverbanks*. Technical Report May, Wageningen University. doi: 10.18174/519776.

van Emmerik, T. H., Y. Mellink, R. Hauk, K. Waldschläger & L. Schreyers (2022b). Rivers as Plastic Reservoirs. doi: 10.3389/frwa.2021.786936.

van Emmerik, T. H., C. T. Roebroek, W. De Winter, P. Vriend, M. Boonstra & M. Hougee (2020c). Riverbank macrolitter in the Dutch Rhine-Meuse delta. *Environmental Research Letters*, 15(10). doi: 10.1088/1748-9326/abb2c6.

van Emmerik, T. H., R. Tramoy, C. van Calcar, S. Alligant, R. Treilles, B. Tassin & J. Gasperi (2019). Seine Plastic Debris Transport Tenfolded During Increased River Discharge. *Frontiers in Marine Science*, 6(October), 1–7. doi: 10.3389/fmars.2019.00642.

Vermeulen, B., A. J. F. Hoitink, S. W. van Berkum & H. Hidayat (2014). Sharp bends associated with deep scours in a tropical river: The river Mahakam (East Kalimantan, Indonesia). *Journal of Geophysical Research: Earth Surface*, 119(7), 1441–1454. doi: 10.1002/2013JF002923.

Vriend, P., T. Bosker, Y. Mellink, F. Collas, F. Moscoso Cruz, N. Kamp, S. Drok, M. G. Vijver & T. H. van Emmerik (2025). Uncertainties in visual observations of floating riverine plastic. *ACS Es&t Water*, 5(7), 3920–3928. doi: 10.1021/acsestwater.5c00223.

Vriend, P., C. V. Calcar, M. Kooi, H. Landman, R. Pikaar & M. F. Costa (2020a). Rapid Assessment of Floating Macroplastic Transport in the Rhine. *Frontiers in Marine Science*, 7(January), 1–8. doi: 10.3389/fmars.2020.00010.

Vriend, P., C. T. Roebroek & T. Van Emmerik (2020b). Same but different: A framework to design and compare riverbank plastic monitoring strategies. *Frontiers in water*, 2, 563791. doi: 10.3389/frwa.2020.563791.

Vriend, P., M. Schoor, M. Rus, S. B. Oswald & F. P. Collas (2023). Macroplastic concentrations in the water column of the river rhine increase with higher discharge. *Science of The Total Environment*, 900, 165716. doi: 10.1016/j.scitotenv.2023.165716.

Wagner, S., P. Klo, B. Stier, M. Ro, B. Seiwert, T. Reemtsma & C. Schmidt (2019). Relationship between Discharge and River Plastic Concentrations in a Rural and an Urban Catchment. *Environ. Sci. Technol.*, 53(17), 10082–10091. doi: 10.1021/acs.est.9b03048.

Waldschläger, K., M. Brückner, B. Almroth, C. Hackney, T. Adyel, O. Alimi, S. Belontz,

W. Cowger, D. Doyle, A. Gray et al. (2022). Learning from natural sediments to tackle microplastics challenges: a multidisciplinary perspective. *Earth-Science Reviews*, 228, 104021. doi: 10.1016/j.earscirev.2022.104021.

Waldschläger, K., S. Lechthaler, G. Stauch & H. Schüttrumpf (2020). The way of microplastic through the environment–application of the source-pathway-receptor model. *Science of the Total Environment*, 713, 136584. doi: 10.1016/j.scitotenv.2020.136584.

Wang, T., B. Li, H. Shi, Y. Ding, H. Chen, F. Yuan, R. Liu & X. Zou (2024). The processes and transport fluxes of land-based macroplastics and microplastics entering the ocean via rivers. *Journal of hazardous materials*, 466, 133623. doi: 10.1016/j.jhazmat.2024.133623.

Williams, A. T. & S. L. Simmons (1996). The degradation of plastic litter in rivers: Implications for beaches. *Journal of Coastal Conservation*, 2(1), 63–72. doi: 10.1007/BF02743038.

Williams, T. (2022). *Adrift: The Curious Tale of the Lego Lost at Sea*. Unicorn Publishing Group.

Windsor, F. M., I. Durance, A. A. Horton, R. C. Thompson, C. R. Tyler & S. J. Ormerod (2019). A catchment-scale perspective of plastic pollution. *Global Change Biology*, 25(4), 1207–1221. doi: 10.1111/gcb.14572.

WMCN (2024). *Hoogwaterrapport IJsselmeergebied 2024-01*. Technical report, Watermanagementcentrum Nederland, Rijkswaterstaat.

Wohl, E. (2013). Floodplains and wood. *Earth-Science Reviews*, 123, 194–212. doi: 10.1016/j.earscirev.2013.04.009.

Wohl, E., N. Kramer, V. Ruiz-Villanueva, D. N. Scott, F. Comiti, A. M. Gurnell, H. Piegay, K. B. Lininger, K. L. Jaeger, D. M. Walters & K. D. Fausch (2019). The natural wood regime in rivers. *BioScience*, 69(4), 259–273. doi: 10.1093/biosci/biz013.

Zhu, X., C. M. Rochman, B. D. Hardesty & C. Wilcox (2024). Plastics in the deep sea–a global estimate of the ocean floor reservoir. *Deep Sea Research Part I: Oceanographic Research Papers*, 206, 104266. doi: 10.1016/j.dsr.2024.104266.

Nomenclature

List of abbreviations

ADHD	Attention-Deficit/Hyperactivity Disorder
EPS	expanded polystyrene
GPS	Global Positioning System
IQR	inter-quartile range
MPW	mismanaged plastic waste
Mt	million metric tonnes
OSPAR	Comission to protect the marine environment in the North-East Atlantic, named after the original Oslo and Paris conventions
PE	polyethylene
PET	polyethylene terephthalate
PO Hard	polyolefins hard
PO Soft	polyolefins soft
PP	polypropylene
PS	polystyrene
PUR	polyurethane
PVC	polyvinyl chloride
UAV	unmanned aerial vehicles
UV-light	ultraviolet radiation

List of symbols

δ_{rm}	relative difference between plastic at one specific riverbank and plastic averaged across all riverbanks during one specific measurement round (-)
$\overline{\delta}_r$	δ_{rm} averaged over time (-)
Δ_{rm}	difference between plastic at one specific riverbank and plastic averaged across all riverbanks during one specific measurement round (#/100 m)
A	area of the sampled stretch of riverbank (ha)
d	distance between transects (m)
D_f	indicates how accumulation rates compare between different period (-)
d_g	ground deposition
d_o	object deposition
I	number of plastic items sampled on an individual riverbank during a monitoring round (items)
L	length of the sampled area along the river in (km)
l_s	section length (m)
l_t	transect length (m)
m	measurement round (-)
Q1	Schone Rivieren spring sampling in February/March 'First quarter'
Q3	Sampling in July/August 2021 'Third quarter'
Q4	Schone Rivieren fall sampling in October/November 'Fourth quarter'

r	riverbank (-)
R_{P1}	represents the accumulation period Q3 that includes the flood in July 2021
R_{P2}	represents the accumulation periods leading up to a measurement in Q4 in 2018–2020
R_{PA}	Plastic accumulation rate per area (items ha^{-1} day^{-1})
R_{PL}	plastic accumulation rate per riverbank length (items km^{-1} day^{-1})
$\overline{S}_m$	is plastic at the specific measurement round averaged across all riverbanks (#/100 m)
S_{rm}	plastic at one specific riverbank during the specific measurement round (#/100 m)
t	time interval since the last monitoring (days)
w_t	Transect width (m)

Acknowledgements

Last but not least, I would like to say thank you. While I worked on this thesis I got to meet new people, visit new places, do new things, and learn so much, and I am very grateful for that! But now that it comes to putting that gratitude into words, I find it is not so easy. I will start by thanking you, whether you read my thesis from start to finish (let me know in case you actually did and why!) or jumped directly to this section, thank you for taking a look, I wish you all the best :)
And now I have some more people to thank.
Since this is my acknowledgement section, my sentences get to have as many commas and parentheses as I like, I blame the German language. As Mark Twain already noticed *"An average sentence, in a German newspaper, is a sublime and impressive curiosity, it occupies a quarter of a column; it contains all the ten parts of speech – not in the regular order, but mixed; it is built mainly of compound words constructed by the writer on the spot, [...] it treats of fourteen or fifteen different subjects, each inclosed[sic] in a parenthesis of its own, [...]."*[1] And I have to say, in English I miss the possibility of merging words till they fit. However, thank you to my (co-)promoters for regularly reminding me that a sentence spanning two lines is plenty, no need to permeate into the third or fourth. Jokes aside, Tim, Martine, and Ryan, thank you so much for hiring me for this project and giving me the opportunity to work on this thesis.
Tim, without you there would be no macroplastic team at HWM, and you and Martine came up with my thesis project in the first place. Thank you for all your support throughout my thesis, during my first fieldwork even helping me through phone calls from your holiday. Thank you for always bringing me back to 'what's the question' and for taking me to convene sessions at EGU. I appreciate the time and effort you always put into giving feedback on my work, and the celebratory mug you gave me for my first publication!
Martine, I really enjoyed all our meetings and chats, whether about statistics or cute animals. Thank you for reminding me that at some point I just have to 'throw it over the fence', and assuring me that what I have is good enough. Your confidence in me strengthened my confidence in myself. Thank you for many productive brainstorming meetings with you and Ryan, and both of you for taking me out for cake to celebrate my first publication!
Ryan, at first you were involved in my thesis mostly 'on paper', but even then our

[1] Twain, Mark. "The Awful German Language." Appendix D in A Tramp Abroad. Hartford, CT: American Publishing Company, 1880.

occasional meetings and walks helped me reflect on my work and my role as PhD candidate. Over time you became more involved and I am grateful you became part of the team. Thank you for convincing me that the Introduction section is an important part of a publication, and many occasions of practical advice when I got stuck in my writing (regularly on said introduction section).

Yvette, thank you for being my first Dutch friend, for all the chats and the laughs, the Disney movies, and the friesdays! Miranda, you have such a great energy and are just so fun to be around. I am really happy I got to meet both of you along the way of this thesis, and now being a part of my defence as paranymphs!

Thanks to the whole plastic team, I enjoyed our meetings, lunches, dinner, shared fieldwork, and very detailed sample analysis of trash piles. Tim, Rose, Louise, Paolo, Miranda, Paul, Naddi, Khoa, Elisa, and the many visitors we had over the years, Ámbar, Hanna, Gabi, Khim, Karolina, Olga, Eline, Mercedes, Francesca, Alice, and Gabi.

I greatly appreciate the people I got to share an office with during this thesis. First my 'PhD aunts' Femke, Linda, Sjoukje, Janneke, and Tessa. And then with Miranda, Jessica, Nazwa, Paolo, Hadeel, Elisa, and Douwe. Thank you all for the random chats and laughs, sharing celebrations and struggles, I loved working in the office with all of you!

I realize at this point the acknowledgements are turning more into a list of people and having a whole list of people to thank seems like a great problem in life! :) In no particular order, Ansje, Winnie, Margherita, Britt, Dennis, Jakub, Silke, Ulrike und Martine und Jonathan. Vivian and Koen, Silven, Yuna, Luca, Menno and Lian for welcoming me to the Thursday evening dinner and boardgames :) Anna-Luisa, Julia, Fransje, Jeroen, Anouk, Prajwal, and Jorge Johanna, Miriam, Sarah, Esther, Gabriela, Mirco, Lukas, Lena, Charlotte und Tom, Anna und Irma und Rita, Malte. Sina, Markus, Eva, Cornelius, Frederick und Mara.

Hartelijk dank aan de hele familie Okkersen, voor de warme ontvangst en voor een fijne vakantie in het Allgäu. Und vielen Dank an meine eigene Familie für eure Unterstützung und die vielen Briefe, Postkarten und Päckchen während meinen Abenteuern.

Dries, you are the best! ♡

Thank you


Femke
Ton
Potlucks
Tim
Douwe
Dragan
Victor
Silke
Judith
Hadeel
Boardgame nights
Martine
Mo
Gaël
Devi
Lieke
Ryan
Daan
Linda
Iceland
Roel
Sjoukje
Janneke
Iris
Evi
Jingwei
Ardennen
Tessa
Roeland
Harro
Niguse
Syed
Haftu
Nick
Tamara
Rose
Pim
many cakes
Marjanne
coffee breaks
Bích
Derk
Bert
Titus
Writing weeks
Jessica
Rachèl
Shiyu
Jelte
Nazwa
Yvette
MMM
Rick
Kryss
Anouk
Janien
Joris
Reinier
Naddi
Ruben
Hermjan
Henk
Paolo
Lunchwalks
Claudia
Ulrike
Awad
Elisa
JP
Khoa
Bart
Bob
Louise
sinterklaas
Marine
Miranda
Noortje
Svenja
Germano
Jasper
Bas

Statement of authorship contribution

The general research direction was proposed by my promotors and co-promoter. I wrote the Introduction (Chapter 1) and Synthesis (Chapter 6) with minor suggestions from my (co)promotors. Chapters 2-5 have been written in collaboration with co-authors, and an overview of their contribution is listed alphabetically below. Names have been abbreviated in the following way:

RH = Rahel Hauk (WUR)

AL = Ansje J. Löhr (Open Universiteit Heerleen)

AT = Adriaan J. Teuling (WUR)

LS = Louise J. Schreyers (WUR)

MB = Marijke Boonstra (Rijkswaterstaat)

MvdP = Martine J. van der Ploeg (WUR)

NW = Nicholas Wallerstein (WUR)

TvE = Tim H.M. van Emmerik (WUR)

WdW = Winnie de Winter

Chapter 2

Conceptualisation:	AT, MvdP, RH
Data collection/assembling:	RH
Data analysis:	RH
Data interpretation:	AT, RH, MvdP, TvE
Drafting of manuscript, visualisation:	RH
Revision of manuscript:	AT, MvdP, RH, TvE

Chapter 3

Conceptualisation:	AT, MvdP, RH, TvE
Data collection/assembling:	AL, MB, RH, WdW
Data analysis:	RH
Data interpretation:	AT, MvdP, RH, TvE
Drafting of manuscript, visualisation:	RH
Revision of manuscript:	AL, AT, MB, RH, TvE, MvdP, WdW

Chapter 4

Conceptualisation:	AT, MvdP, RH, TvE
Data collection/assembling:	MvdP, RH, WdW
Data analysis:	RH
Data interpretation:	AT, MvdP, RH, TvE
Drafting of manuscript, visualisation:	RH
Revision of manuscript:	AT, MvdP, RH, TvE, WdW

Chapter 5

Conceptualisation:	AT, LS, MvdP, NW, RH, TvE
Data collection/assembling:	LS, RH
Data analysis:	RH
Data interpretation:	AT, LS, MvdP, NW, RH, TvE
Drafting of manuscript, visualisation:	RH
Revision of manuscript:	AT, LS, MvdP, NW, RH, TvE

List of publications

Peer-reviewed journal papers | In this thesis

Hauk, R., van Emmerik, T.H.M., van der Ploeg, M., De Winter, W., Boonstra, M., Löhr, A.J. and Teuling, A.J. (2023). Macroplastic deposition and flushing in the Meuse river following the July 2021 European floods. *Environmental Research Letters, 18(12), 124025.* DOI: 10.1088/1748-9326/ad0768

Hauk, R., van der Ploeg, M., Teuling, A.J., de Winter, W., van Emmerik, T.H.M. (2024). Flood-induced buttertub spill reveals riverine macroplastic transport dynamics. *Environ Sci Eur 36, 149*. DOI: 10.1186/s12302-024-00962-1

Hauk, R., Schreyers, L., van der Ploeg, M., Teuling, A. J., Wallerstein, N., van Emmerik, T. (2026). Preferential deposition of macroplastic on floodplains. *Cambridge Prisms: Plastics, 1-12*. DOI: 10.1017/plc.2026.10054

Under review | In this thesis

Hauk, R., van der Ploeg, M., van Emmerik, T. H., and Teuling, A. J. (2026). Temporal stability of riverbank macroplastic. (Published as preprint at Research Square DOI: https://doi.org/10.21203/rs.3.rs-8901463/v1)

Peer-reviewed journal papers | Other

Schreyers, L.J., Hauk, R., Wallerstein, N., Teuling, A.J., Uijlenhoet, R., van der Ploeg, M., and van Emmerik, T.H.M. (2025). Flood Characteristics Drive River-Scale Macroplastic Deposition *Environmental Science & Technology 59 (36).* 19414-19423 DOI: 10.1021/acs.est.5c02969

Piehl, S., Hauk, R., Robbe, E., Richter, B., Kachholz, F., Schilling, J., Lenz, R., Fischer, D., Fischer, F., Labrenz, M. and Schernewski, G. (2021). Combined Approaches to Predict Microplastic Emissions Within an Urbanized Estuary (Warnow, Southwestern Baltic Sea). *Front. Environ. Sci. 9:616765.* DOI: 10.3389/fenvs.2021.616765

van Emmerik, T.H.M., Mellink, Y., Hauk, R., Waldschläger, K. and Schreyers, L.J. (2022). Rivers as Plastic Reservoirs. *Front. Water 3:786936.* DOI: 10.3389/frwa.2021.786936

Haseler, M., Balciunas, A., Hauk, R., Sabaliauskaite, V., Chubarenko, I., Ershova, A. and Schernewski, G. (2020). Marine Litter Pollution in Baltic Sea Beaches – Application of

the Sand Rake Method. *Front. Environ. Sci. 8:599978.* DOI: 10.3389/fenvs.2020.599978

Schernewski, G., Radtke, H., Hauk, R., Baresel, C., Olshammar, M., Osinski, R. and Oberbeckmann, S. (2020). Transport and Behavior of Microplastics Emissions From Urban Sources in the Baltic Sea. *Front. Environ. Sci. 8:579361.* DOI: 10.3389/fenvs.2020.579361

Schernewski, G., Radtke, H., Hauk, R., Baresel, C., Olshammar, M. and Oberbeckmann, S. (2021). Urban Microplastics Emissions: Effectiveness of Retention Measures and Consequences for the Baltic Sea. *Front. Mar. Sci. 8:594415*. DOI: 10.3389/fmars.2021.594415

Van Emmerik, T.H.M., Frings, R.M., Schreyers, L.J., Hauk, R., de Lange, S.I., Mellink, Y.A.M. (2023). River plastic transport and deposition amplified by extreme flood. *Nature Water 1, 514-522*. DOI: 10.1038/s44221-023-00092-7

Tasseron, P.F., van Emmerik, T.H., Vriend, P., Hauk, R., Alberti, F., Mellink, Y., and van der Ploeg, M. (2024). Defining plastic pollution hotspots. *Science of the Total Environment, 934*. DOI: 10.1016/j.scitotenv.2024.173294

Schernewski, G., Radtke, H., Robbe, E., Haseler, M., Hauk, R., Meyer, L., Piehl, S., Riedel, J. and Labrenz, M. Emission, Transport, and Deposition of visible Plastics in an Estuary and the Baltic Sea—-a Monitoring and Modeling Approach. *Environmental Management 68, 860–881* (2021). DOI: 10.1007/s00267-021-01534-2

de Lange, S.I., Mellink, Y., Vriend., P, Tasseron, P.F., Begemann, F., Hauk, R., Aalderink, H., Hamers, E., Jansson, P., Joosse, N., Löhr, A., Lotcheris, R., Schreyers, L., Vos, V., van Emmerik, T.H.M. (2023). Sample size requirements for macrolitter characterization. *Frontiers in Water 4*. DOI: 10.3389/frwa.2022.1085285.

Schernewski, G., Escobar Sánchez, G., Felsing, S., Gatel Rebours, M., Haseler, M., Hauk, R., Lange, X. and Piehl, S. (2024). Emission, Transport and Retention of Floating Marine Macro-Litter (Plastics): The Role of Baltic Harbor and Sailing Festivals. *Sustainability, 16(3), 1220*. DOI: 10.3390/su16031220

van Emmerik, T.H.M., de Lange, S.I., Frings, R., Schreyers, L., and H. Aalderink and J. Leusink, Begemann, F., Hamers E., Hauk, R., Janssens, N., Jansson, P., Joosse, N., Kelder, D., van der Kuijl, T., Lotcheris, R., Löhr, A., Mellink, Y., Pinto, R., Tasseron, P., Vos, V., Vriend, P. (2022). Hydrology as a Driver of Floating River Plastic Transport. *Earth's Future 10(8).* DOI: 10.1029/2022ef002811.

About the author

21 March 1990	**Born in Stuttgart, Germany**
2011 - 2015	**BEng Civil Engineering and Project Management** University of Applied Science Biberach an der Riss, Germany
2015 - 2018	**MSc Environmental Engineering Sciences** University of Rostock, Germany
2018 - 2019	**Research Associate** Leibniz Institute for Baltic Sea Research, Warnemünde, Germany
2021 - 2026	**PhD Candidate** Wageningen University, the Netherlands



Picture by Jakub Stepanovic

Netherlands Research School for the
Socio-Economic and Natural Sciences of the Environment

D I P L O M A

for specialised PhD training

The Netherlands research school for the
Socio-Economic and Natural Sciences of the Environment
(SENSE) declares that

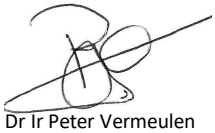
Rahel Hauk

born on 21 March 1990 in Stuttgart, Germany

has successfully fulfilled all requirements of the
educational PhD programme of SENSE.

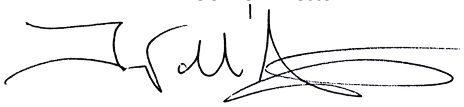
Wageningen, 18 November 2026

SENSE coordinator PhD education



Dr Ir Peter Vermeulen

The SENSE Director



Dr Jampel Dell'Angelo

The SENSE Research School declares that **Rahel Hauk** has successfully fulfilled all requirements of the educational PhD programme of SENSE with a workload of 51.4 EC, including the following activities:

SENSE PhD Courses

- A1: Environmental Research in Context (2021)
- A2 impact incubator: 'Organising the YHS-NL Symposium 2024' (2024)

In depth PhD courses

- Summer School on Exploring Frontiers in Natural Hazards Science: Drivers, Impacts, and Responses, Centre of Natural Hazards and Disaster Science; Uppsala University (2021)
- Summer School on Gender, Justice and Environmental Crises, University of Bergen (2022)
- NCR summer school, NCR/University of Twente (2023)

General Skill courses

- Scientific Writing, Wageningen Graduate Schools(2021)
- Scientific publishing, Wageningen Graduate Schools (2021)
- The Choice: Un-box your PhD process, Wageningen Graduate Schools (2022)
- Mindful productivity for scientists, Wageningen Graduate Schools (2022)
- FAIR Data Management, Wageningen University and Research (18.10.2022)
- Supervising BSc and MSc thesis students, Wageningen University and Research (2023)

Management and Organisational activities

- Co-convene a total of three sessions at EGU general assembly 2024 and 2025
- Board member (2023) and Chair (2024) of the Young Hydrologic Society of the Netherlands

Teaching and supervision

- Supervising 3 BSc students with thesis and one BSc student with internship (2021-2023)
- Assist teaching in the BSc course 'Field Practical, Hydrology, Water Quality and Meteorology' (2022), the MSc 'Catchment and Climate Hydrology' (2022-2024) and the BSc course 'Global Marine Cycles '(2024).

Oral Presentations

- *Plastic accumulation zone identification in river systems*. AGU Fall Meeting, 13 – 17 December 2021, online, United States
- P*lastic accumulation on Dutch Meuse riverbanks after the flood in July 2021*. Meuse Symposium, 17 October 2022, Liège, Belgium
- *Linking macroplastic deposition to riverbank characteristics*. EGU General Assembly, 23-28 April 2023, Vienna, Austria
- *The journey of buttertubs spilled during the July 2021 floods in the Meuse*. NAC conference, 07-08.03 2024, Utrecht, The Netherlands

Financial support from Wageningen University for printing this thesis is gratefully acknowledged.

Cover design: Photo & design Rahel Hauk, using inkscape
Bookmark design: Rahel Hauk
Layout design: Rahel Hauk, using LaTeX 2ε
Printed by: ProefschriftMaken on FSC-certified paper

