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OVERVIEW

Plastic debris in rivers

Tim van Emmerik¹  | Anna Schwarz²

¹Hydrology and Quantitative Water Management Group, Wageningen University, Wageningen, The Netherlands

²Netherlands Organisation for Applied Scientific Research (TNO), Utrecht, The Netherlands

Correspondence

Tim van Emmerik, Hydrology and Quantitative Water Management Group, Wageningen University, Wageningen, The Netherlands.

Email: tim.vanemmerik@wur.nl

Abstract

Plastic pollution in aquatic ecosystems is an emerging environmental risk, as it may negatively impacts ecology, endangers aquatic species, and causes economic damage. Rivers are known to play a crucial role in transporting land-based plastic waste to the world's oceans, but riverine ecosystems are also directly affected by plastic pollution. To better quantify global plastic pollution transport and to effectively reduce sources and risks, a thorough understanding of origin, transport, fate, and effects of riverine plastic debris is crucial. In this overview paper, we discuss the current scientific state on plastic debris in rivers and evaluate existing knowledge gaps. We present a brief background of plastics, polymer types typically found in rivers, and the risk posed to aquatic ecosystems. Additionally, we elaborate on the origin and fate of riverine plastics, including processes and factors influencing plastic debris transport and its spatio-temporal variation. We present an overview of monitoring and modeling efforts to characterize riverine plastic transport, and give examples of typical values from around the world. Finally, we present an outlook to riverine plastic research. With this paper, we aim to present an inclusive and comprehensive overview of riverine plastic debris research to date and suggest multiple ways forward for future research.

This article is categorized under:

Science of Water > Water Quality

Water and Life > Stresses and Pressures on Ecosystems

KEYWORDS

hydrology, macroplastic, marine plastic litter, microplastic, riverine plastic pollution

1 | INTRODUCTION

The discovery of plastics provided society with a material with almost limitless possibilities. Due to its beneficial characteristics (inexpensive, durable, lightweight, abundant, and can be produced in any desired shape), the popularity of plastics drastically increased during the 20th century and its production is still on the rise. Initially, plastics were mainly used for long-lasting items. Nowadays, a growing portion of plastic is used for single-use purposes (Andrady & McNeal, 2009; Geyer, Jambeck, & Law, 2017).

As more plastic waste started to accumulate in the natural environment, it became clear that plastic pollution can become an environmental hazard. As plastics are designed to last, inappropriately disposed plastic items remain in nature for a prolonged time (Andrady, 2003). Plastic pollution imposes threats on aquatic life, ecosystems, and human health (Derraik, 2002; Thompson et al., 2004; 2009a; 2009b; Rochman et al., 2015; Conchubhair et al., 2019). Plastic litter can result in entanglement and ingestion by aquatic life such as turtles, birds, and fish, causing severe injuries and death (Gall & Thompson, 2015; Wilcox, Van Sebille, &

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Hardesty, 2015). Plant species, such as mangrove forest trees and their associated fauna are reported to be negatively affected by plastic litter, as these ecosystems function as accumulation zones (Ivar do Sul et al., 2014; Martin, Almahasheer, & Duarte, 2019). Plastic pollution also negatively impacts human livelihood, as plastic waste clogs urban drainage infrastructure, increasing flood risk (Njeru, 2006; Windsor, Durance, et al., 2019). Furthermore, plastic litter causes severe economic losses through damage to vessels and fishing gear, negative effects on the tourism industry, and increased shoreline cleaning efforts (McIlgorm, Campbell, & Rule, 2011). Although collection and recycling rates have increased over time, yet approximately 79% of all plastics ever made have ended up into landfills or leaked into the natural environment (Geyer et al., 2017).

To date, most research efforts to quantify plastic pollution and its effects have focused on the marine environment (Blettler et al., 2018). Plastics in the ocean are transported by prevailing winds and surface currents (Eriksen et al., 2014). Although plastics have been found in all ocean regions, the highest plastic concentrations in surficial water have been reported in the subtropical gyres. These gyres are identified as the five main accumulation zones for surface plastics (Cózar et al., 2014; Eriksen et al., 2014; Lebreton et al., 2017). The North Pacific Ocean gyre, infamously known as the Great Pacific Garbage Patch, is predicted to carry at least 45–129 thousand tonnes of plastic waste and is still exponentially growing (Lebreton et al., 2018). Plastics can enter the marine environment through riverine and coastal sources or through direct disposal at sea (Horton & Dixon, 2018; Windsor, Tilley, Tyler, & Ormerod, 2019). For the latter, aquaculture equipment, and abandoned and lost fishing gear are a main source of plastic waste (Lebreton et al., 2018; Link, Segal, & Casarini, 2019; Wilcox et al., 2015). However, it is often suggested that a considerable share of total marine plastic litter originates from land, which is transported by rivers into the ocean (Jambeck et al., 2015; Jang et al., 2014). Nevertheless, riverine plastic transport remains relatively understudied in comparison to marine plastic litter, emphasizing the urgency to increase the global knowledge on plastic pollution in freshwater ecosystems (Blettler et al., 2018).

Research on riverine plastic debris transport is a relatively young science. The first efforts to quantify riverine plastic debris flow were done only in the early 2010s, and included sampling of waterways in Europe and North America, such as the Los Angeles area (Moore, Lattin, & Zellers, 2011), the river Thames (Morritt, Stefanoudis, Pearce, Crimmen, & Clark, 2014), the Danube (Lechner et al., 2014), the Seine (Gasperi, Dris, Bonin, Rocher, & Tassin, 2014), and Tamar estuary (Sadri & Thompson, 2014). These field-based studies provided valuable insights in plastic polymer composition, plastic debris concentrations, and variation over time and space. Complementary to river-specific case studies, modeling approaches provided the first global estimates of plastic emission into the oceans (Jambeck et al., 2015; Lebreton et al., 2017; Schmidt, Krauth, & Wagner, 2017). These assessments are extremely valuable as they present a first-order approximation of the expected magnitude and geographical distribution of riverine plastic transport. These insights can be used to further develop and harmonize plastic debris quantification methods and reveal geographical knowledge gaps.

With this review paper, we aim to (a) provide a comprehensive overview of riverine plastic debris research to date and (b) provide an outlook on future research directions. We start with discussing several typical plastic polymer types and items found in river systems. In the following section, we elaborate on the harmful effects of plastic debris on human and ecosystem health, demonstrating the urgency of riverine plastic debris research. Next, we present an overview of the origin and fate of riverine plastic debris. Using several examples, we illustrate the travel paths of unsoundly disposed plastics on route toward the ocean. In the subsequent section, we will discuss the available modeling and measurement approaches to quantify riverine plastic debris transport. We use data from studies conducted around the world to illustrate the current state of the science. We end with a future-oriented section to discuss the various ways forward.

2 | DEFINING PLASTICS

Plastic is a synthetic material made from hydrocarbons that can be molded in solid objects of almost all shapes and sizes. By cracking crude oil, a variety of petrochemicals are obtained that serve as a basis for plastics. Plastics including polyethylene and polypropylene (PP) are synthesized from olefins, while other plastics are synthesized from aromatic hydrocarbons, such as polystyrene (PS) and polyamide (PA) (nylon). Plastics are synthesized as spherical pellets or nurdles typically about 0.5–5 mm in size. These preproduction materials are transported to factories where they are heated, extruded, or blow molded in the shape of its purpose. Additionally, additives are added depending on the purpose, such as flame retardants for electronic plastics or flexibility enhancers for packaging. Nowadays, the sectors using plastics are roughly divided in; packaging, building, transportation, electronics, textiles, and safety and leisure. In 2017, an estimated 348 million tons of plastic was produced worldwide (PlasticsEurope, 2018). Due to its qualities, plastics have replaced heavier and more expensive materials such as glass, steel, and aluminum. In packaging, the use of plastic resulted in a high level of food preservation, decreasing food waste, and increasing the expiration date and transport possibilities. In the transport sector, the use of plastic packaging for transported goods resulted in a high decrease of CO₂ emissions per km (Palencia, Furubayashi, & Nakata, 2012).

Plastics come in a variety of configurations, depending on the used chemical building blocks. Main polymers produced nowadays are polypropylene (PP), high- and low-density polyethylene (HDPE and LDPE), polyethylene terephthalate (PET), polystyrene (PS), polyamide (PA), and polyvinyl chloride (PVC) (PlasticsEurope, 2018). The olefins, PP and PE, are used in all applications but mainly in packaging. PVC is mostly used in the building sector. Polyesters and PAs (nylon) are the main polymers found in textiles (PlasticsEurope, 2018). See Table 1 for an overview of the most commonly produced polymer types and their typical applications.

At the moment, only 9% of all plastics ever made are recycled (Geyer et al., 2017). This is mostly done through mechanical recycling. Mechanical recycling is an open loop recycling, meaning that the recycled plastics are used for different purposes than where they were recovered from (Ragaert et al., 2017). The mechanical recycling methods produces a lower quality end product compared to virgin plastics, due to degradation processes which results in a decrease of quality of the material (la Mantia, 2004). New recycling techniques are being developed that might improve recyclability which can result in potential closed loop recycling. These methods include chemical recycling (by dissolving the plastic in a solvent) and thermochemical recycling (pyrolysis) (Ragaert et al., 2017). Twelve percent of plastics in waste are incinerated (Geyer et al., 2017). In a few countries, energy is obtained from this burning process to heat houses and produce electricity (Scarlat, Fahl, & Dallemard, 2018). Most of the globally produced plastic is disposed in landfills. There are various levels of quality of landfills (Hoornweg & Bhada-Tata, 2012). In developed countries, these are often sanitary landfills, which can be considered “managed” (Jambeck et al., 2015). However, in developing countries, waste is being disposed in semicontrolled dumps. From these dumps, contaminants (which can include plastics) can be introduced in the environment (Hoornweg & Bhada-Tata, 2012). Additionally, there is a fraction of plastic lost to the environment directly through littering, often estimated at about 2% of the total plastic production (Jambeck et al., 2015).

Once in the environment, the fate of plastics varies by a plastic's properties. Travel distances, likelihood of accumulation, and degradation rate may vary considerable between plastic polymer and item types. Polymer identification is critical to develop expectations of a plastic's fate and effect due to its properties. For example, density affects the extend of transportation in aquatic environments (Schwarz et al., 2019). Additionally, also shape of plastics strongly affects exposed surface area, which can be important for transportation processes and chemical leakage (Schwarz et al., 2019). Shape groups observed in previous studies are the hard plastics (solid pieces), pellets (preproduction), films (thin layered), and fibers (elongated lines) (Eriksen et al., 2013; Free et al., 2014). Interestingly enough, the larger modeling studies focusing on river transport of plastics do not distinguish neither shape nor polymer type (Lebreton et al., 2017; Schmidt et al., 2017).

TABLE 1 Data on common plastic polymer types and their density. Densities higher than 1 are likely to sink in water. The percentages and most common products are assessed and calculated based on data from Schwarz et al. (2019), Textileworld (2019), and PlasticsEurope (2018)

Polymer	Abbreviation	Density (g/cm ³)		Main application
		Min	Max	
Polyethylene	PE	0.91	0.97	Packaging
Polypropylene	PP	0.9	0.91	Many applications, but mainly packaging
Polyester	PES	1.24	2.3	Textiles
Polyethylene terephthalate	PET	1.37	1.45	Packaging
Polystyrene	PS	1.01	1.04	Packaging
Expanded polystyrene	EPS	0.016	0.640	Food packaging, construction material
Ethylene vinyl acetate	EVA	0.92	0.94	Others
Alkyd	Al	1.67	2.1	Paints, fibers
Polyvinyl chloride	PVC	1.16	1.58	Building and construction
Polymethyl methacrylate	PMMA	1.17	1.2	Electronics (touch screens)
Polyamide (nylon)	PA	1.02	1.05	Automotive, textiles
Polyacrylonitrile	PAN	1.09	1.2	Textiles
Polyvinyl alcohol	PVOH	1.19	1.31	Textiles
Acrylonitrile butadiene styrene	ABS	1.06	1.08	Electronics
Polyurethane	PUR	0.03	0.1	Building and construction

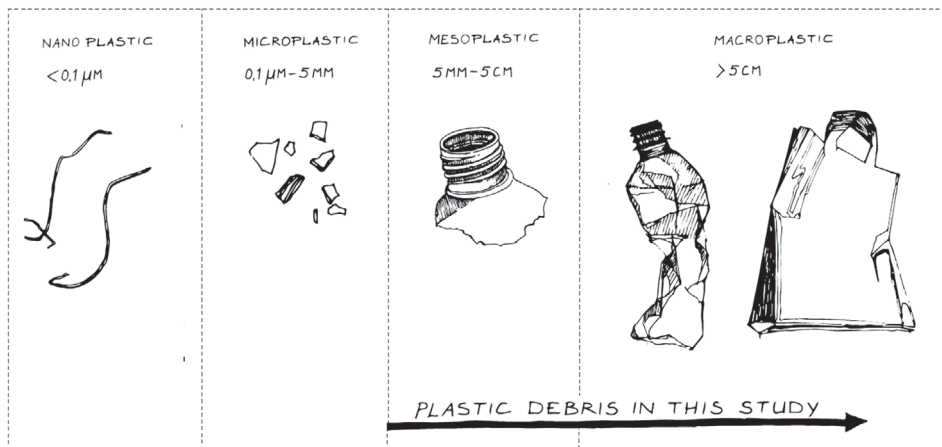


FIGURE 1 Plastic size classes (credit: Cher van der Eng)

For plastic sizes, consistent terminology and dimensions lack throughout plastic pollution studies. Most used terms are nanoplastics, microplastics, mesoplastics, macroplastics, and megaplastics (Blettler et al., 2017; Frias & Nash, 2019; Lebreton et al., 2018). Dividing plastics by size is still useful in terms of determining the source and to assess the final environmental impact. In this review paper, we focus on macroplastic debris in river systems, which are here defined as particles and items larger than 5 mm (see Figure 1). For microplastics and nanoplastics, more information is given in Box 1.

BOX 1 MICROPLASTICS IN FRESHWATER SYSTEMS

Microplastic pollution in aquatic ecosystems has been a more widely studied topic compared with macroplastic pollution (Blettler et al., 2018). Several river systems in Europe, North America, and China have been sampled extensively for microplastic research at the water surface and in the water column (Lechner et al., 2014; Mani, Hauk, Walter, & Burkhardt-Holm, 2015; Zhang, Gong, Lv, Xiong, & Wu, 2015), in sediments (Mani et al., 2019; Su et al., 2016; Wang et al., 2017; Zhang et al., 2016), or on the riverbanks (Imhof, Ivleva, Schmid, Niessner, & Laforsch, 2013; Klein, Worch, & Knepper, 2015). Most microplastic research focuses on quantity and composition of microplastics, but the complexity of microplastics and the lack of harmonization in sampling methodology make it difficult to compare different studies (Dris et al., 2015; Koelmans et al., 2019; Kooi & Koelmans, 2019). Several studies assessed the environmental effects of microplastics in freshwater ecosystems, such as ingestion by fish species (Biginagwa et al., 2016; de Souza Petersen, Krüger, Dezevieski, Petry, & Montone, 2016; Horton et al., 2018), invertebrates (Hurley, Woodward, & Rothwell, 2017; Redondo-Hasselerharm, Falahudin, Peeters, & Koelmans, 2018; Windsor, Tilley, et al., 2019), and vertebrates (Reynolds & Ryan, 2018). Despite the abundance of microplastics in biota and the natural environment, the actual environmental risks of microplastic pollution remain unknown (Koelmans et al., 2017).

3 | THE HARMS OF PLASTIC DEBRIS

Plastics are durable in the natural environment, leading to long-term pollution (Andrady, 2003). The harmful effects of plastics to the environment can be considered in roughly five categories, their severity depending on an item's size and shape:

- Ingestion of plastics;
- Entanglement in plastics;
- Leakage of toxic additives and accumulation of toxins;
- Breakdown in microplastics;
- Human livelihood.

3.1 | Ingestion

When plastic is ingested by animals, it can have various effects, varying in severity. These effects include starvation (due to gut obstruction), a false feeling of satiation, reduced fitness, changes in behavior, and affected reproduction and growth (Gall & Thompson, 2015). Furthermore, plastic, which can contain potential toxic contaminants, can travel up the food chain, especially when plastic ingestion is recorded in low trophic species such as jellyfish (Macali et al., 2018). An extensive review was published by Gall and Thompson (2015), which showed that 233 species of marine vertebrates were affected by ingestion. Main taxonomic groups studied are seabirds, mammals, fish, and turtles, and to a lesser extent also crustaceans, echinoderms, and other taxonomic groups. One of the conclusions from the Gall and Thompson (2015) study was that ingestion was widespread, the frequency of reporting increases over time, and that especially sea turtles have a high record of ingestion (Gall & Thompson, 2015). An effect on population level of plastic ingestion was not found. However, it was emphasized that a lack of evidence does not immediately imply a lack of effect (Gall & Thompson, 2015). The few available studies on ingestion in rivers indicate ingestion rates of up to 33% in the Goiana River, Brazil (Possatto, Barletta, Costa, do Sul & Dantas, 2011). Plastic has also been found in birds and fish in French and Swiss waters, with ingestion rates up to 12.5% (Faure et al., 2015). Although available studies (Andrade et al., 2019; Faure et al., 2015; Possatto et al., 2011; Windsor, Tilley, Tyler, & Ormerod et al., 2019) suggest that (macro)plastic ingestion by freshwater fauna is widespread, available data remain scarce in terms of spatial and taxonomic distribution.

3.2 | Entanglement

Entanglement in plastic material has been recorded often in marine environments, often because effects of entanglement are more obvious compared to, for example, ingestion (Gall & Thompson, 2015). Turtles, fish, sharks, and more vertebrates are observed lethally stuck in plastic waste; mainly in abandoned fishing gear, due to the size and the nature of the material. However, fishing activities take place in riverine systems as well, although not in such quantities compared to oceanic fishery. Gear losses are assumed less likely, as fishing gear has not yet been widely observed in river systems, and neither are entangled organisms.

3.3 | Chemical leaching and accumulation

There are toxic effects that are associated with (especially) microplastic uptake in organisms. These include additive leaching from plastics (Oehlmann et al., 2009; Teuten et al., 2009), persistent organic pollutant (POP) transfer from plastic to organisms (Besseling, Wegner, Foekema, Van Den Heuvel-Greve, & Koelmans, 2012; Rochman et al., 2013; Teuten et al., 2009) and even methane emissions to the atmosphere (Royer, 2018). These effects have been mainly observed in marine environments and marine species. However, leaching can also occur in lakes, rivers, and river shores, therefore risks are involved in freshwater systems as well.

3.4 | Breakdown into microplastics

Depending on the exposure rate of the plastic to ultraviolet (UV) and mechanical forces, plastics can either remain intact for decades, or break down into smaller fragments (Weinstein, Crocker, & Gray, 2016). Due to these degradation mechanisms, macroplastics tend to break down into smaller pieces until the size of micro and nanoplastics.

Microplastics are observed in various food products, such as beer, tap water, and sea salt (Kosuth, Mason, & Wattenberg, 2018). Also, preliminary results show microplastics to be widespread in human stools (Schwabe et al., 2018). The plastics may compromise human health, food security, and food safety (Barboza et al., 2018). Plastics that were found in human lung tissue may be correlated to the risk of lung cancer (Pauly et al., 1998). Due to the presence and potential hazards, Rochman et al. (2013) even proposed to label plastic waste as hazardous, rather than solid waste. However, uniformity on potential hazards is yet unclear, as much research still has to be done. Recently, a first global environmental risk assessment for microplastic in the environment was developed (Adam, Yang, & Nowack, 2019). This study found that the risk characterization ratio indicates no immediate risk of microplastics to the environment. However, a small risk could not be excluded, especially in Asia, where there is a certain overlap of the exposure and hazard probability distributions. As an important side note, the study mentioned that additional data would possibly change these conclusions, as data is still scarce on the topic.

3.5 | Human livelihood

Plastic debris in river systems directly impacts human livelihood, through economic losses and increased flood risk in urban areas. Like the marine environment, plastic pollution in riverine ecosystems can damage shipping and transport vessels (McIlgorm et al., 2011). Plastic debris accumulates on riverbanks, potentially affecting tourism or real estate value. In urban areas, plastic debris has been found to clog drains and other hydraulic infrastructure (Lebreton and Andrady, 2019), increasing flood risk in these areas. Recent work has demonstrated that plastic debris accumulating in urban drains leads to a faster increase in water level than organic debris (Honingh, 2018). It is often hypothesized that plastic waste transport rates increase with precipitation and river discharge. Blockage of urban drainage systems during such events can therefore have catastrophic effects. Unfortunately, there have only been few assessments to identify and quantify direct impacts of riverine plastic debris on this topic, and more studies are required to draw more solid conclusions.

4 | ORIGIN AND FATE OF RIVERINE PLASTIC DEBRIS

The sources of plastic waste in and around freshwater systems can be directly related to human activity, as river plastic quantities show high correlation with population density, urbanization, wastewater treatment, and waste management (Best, 2019). Plastic waste enters river systems through either natural transport processes or through direct dumping. Natural processes include wind (Bruge et al., 2018) and rainfall-induced surface runoff (Bruge et al., 2018; Moore et al., 2011; Tramoy, Gasperi, Dris, Colasse, Fisson, Sananes et al., 2019). In the Rhône, however, a peak in plastic transport was measured several days after rainfall events (Castro-Jiménez et al., 2019). This delayed response in the plastic transport peak suggests that these plastics were introduced more upstream, or took some time before entering the main river system. For many rivers, clear point sources were identified where plastics enter the river systems. In Chilean rivers, several illegal dumping sites were found along four rivers across the country (Rech et al., 2015). Mihai (2018) suggested that direct dumping of plastic waste in rivers is the main source of plastics found in rivers and lakes in the Romanian Carpathians. For the main German rivers such as the Rhine, Weber, and Elbe, Kiessling et al. (2019) revealed clear anthropogenic influence on mobilization of plastics, as people tend to bring plastics to river(bank)s and dispose it there intentionally or unintentionally.

Once entered a river (see Figures 2 and 3), plastic transport is influenced by hydrological factors such as water level, flow velocity, and discharge (van Emmerik et al., 2018). Several studies found a positive correlation between river discharge and plastic transport (Castro-Jiménez et al., 2019; Moore et al., 2011). Increased water levels can remobilize plastics that are temporarily accumulated on riverbanks or in vegetated riparian zones. On the other hand, during floods, plastics also accumulate in, for instance, vegetation (van Emmerik, Strady et al., 2019). Also, hydraulic infrastructure, such as dams and sluices, act as (temporary) sinks for riverine plastic debris (Honingh, 2018; Lebreton et al., 2017).

The fate of macroplastics that end up in freshwater systems is still one of the largest unknowns in river plastic transport research. It is usually assumed that all plastics in rivers are likely to end up in the ocean. However, still a large fraction of plastic pollution (99%) is not found back afloat in the ocean and is considered “lost” (ter Halle et al., 2016; van Sebille et al., 2012). There seems to be a missing fraction of especially micro and nanoplastics on the surface of the ocean (Cózar et al., 2014). Recent work suggested that these plastics reside below the surface (Choy et al., 2019). Also, the polymer types, shapes, and sizes of plastic are important. It has been found that the polymer composition varies strongly per aquatic environment studied, mainly because the properties of plastic strongly affect distribution of plastics in the environment (Schwarz et al., 2019).

The fate of plastics in freshwater systems is strongly dependent on three processes, being (1) the transport, (2) the accumulation, and (3) the degradation processes that all plastics are subjected to. From the degrading macroplastic, a secondary stream of micro and nanoplastics originates. For horizontal transport within freshwater systems, the flow velocity is the main environmental parameter affecting the speed and distance plastic moves. In rivers where the horizontal distribution was measured, a concentration peak can be observed along the river cross-section where flow velocity is highest; here most plastics seem to be afloat (van Emmerik et al., 2018; van Emmerik, Loozen, Van Oeveren, Buschman, & Prinsen, 2019). However, the effect of wind can be especially important for plastics that float higher up the water, such as low density expanded polystyrene (EPS), or air-filled containers, like PET bottles. Due to wind effects, these plastics are easily moved further and faster, or tend to beach sooner and, hence, cover riverbanks or lake beaches (Corcoran et al., 2015; Faure et al., 2015; Ivar do Sul et al., 2014). The other dimension of transport is vertical transport. Plastics can move from the surface to sediments or move back up to the surface. Turbulence, which can be created through storms or rough terrain, is a strong environmental variable that results in vertical mixing of plastics (Kukulka et al., 2012; Lebreton et al., 2018). However, the characteristics of the plastic play a key

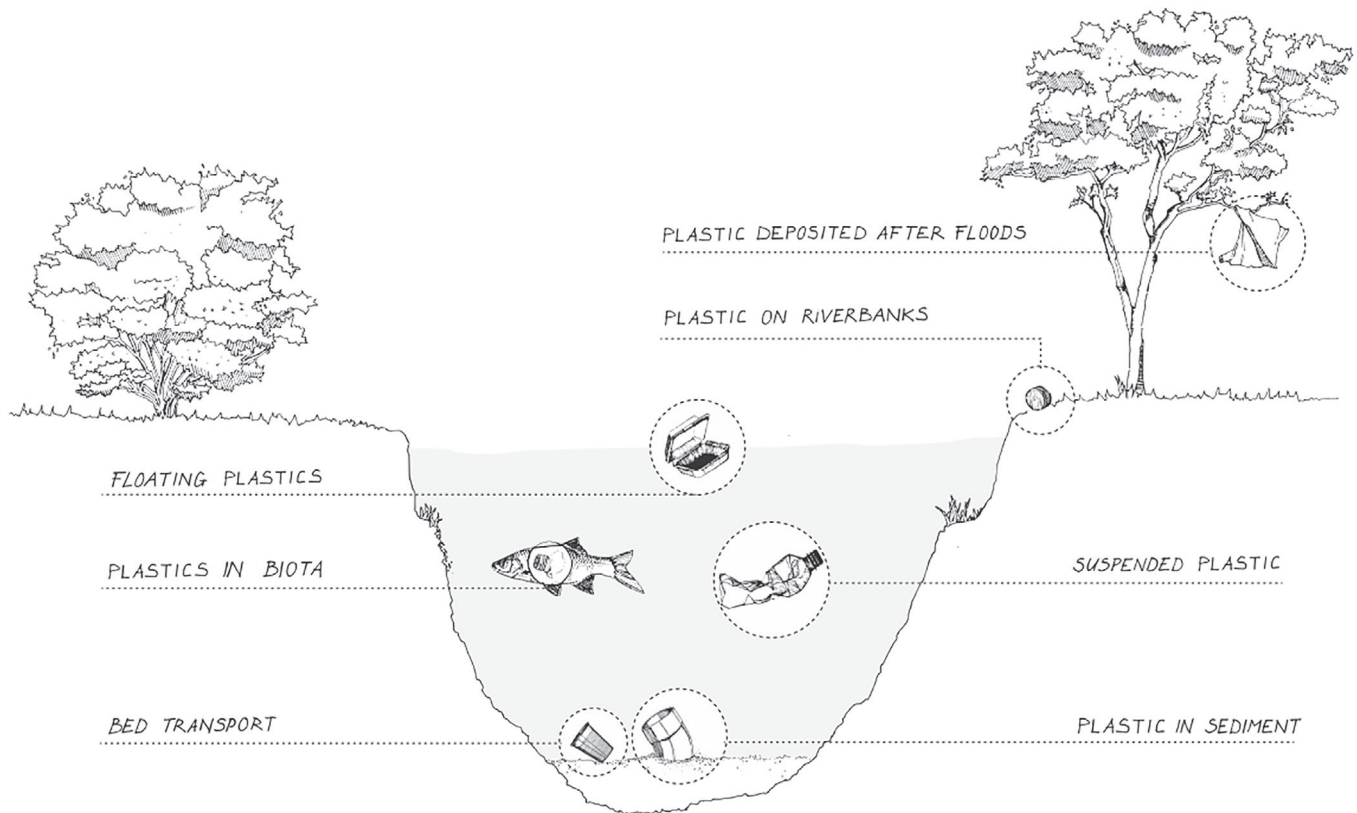


FIGURE 2 Overview of plastic abundance in river systems (credit: Cher van der Eng)

role in vertical transport. With higher density, plastics tend to sink more easily than low density plastics. Furthermore, foils and thin plastics, with a high surface area to mass ratio, tend to be affected more strongly by surface pollution, such as mud or biofouling, making the material heavier and more likely to sink or at least remain in the lower part of the water column (van Emmerik, Loozen et al., 2019). Smaller plastics, also having a large surface area to mass ratio, are more strongly affected by turbulence, hence, tend to be more affected by vertical transport. There seems to be a trade-off between vertical and horizontal transport of plastics. With low vertical transport, plastics remain more affected by horizontal transport. Lower in the water column, horizontal transport mechanisms are weaker and hence less pronounced (van Emmerik, Loozen et al., 2019).

In rivers where significant river vegetation is present, such as reeds, water lilies, or mangrove forests, there seems to be a significant retention factor for plastics. Mangrove forests tend to retain plastic debris for long periods (months–years) (Ivar do Sul et al., 2014). Results from the first long-term riverine plastics debris monitoring effort demonstrated that the magnitude of plastic transport was mainly related to the presence of aquatic vegetation, mainly consisting of water hyacinths (van Emmerik, Strady et al., 2019). Water hyacinths often accumulate and form large vegetation patches, which also retain plastic debris. In such rivers, plastic transport may be primarily driven by vegetation dynamics, and less directly by hydrometeorological processes, such as discharge, water level, flow velocity, or wind speed and direction.

A selection of plastic tends to accumulate in river sediments. These include the high-density plastics, but also the foil plastics and smaller plastics such as micro and nanoplastics (Mani et al., 2019; Schwarz et al., 2019). It has been suggested that through fragmentation and biofouling, the water column eventually hosts a uniform dispersion of nanoplastics particles (Kooi et al., 2017). Plastic transport through sediments may be compared to transport of other solid materials, such as rocks, gravel, and sand. Recent work demonstrated the decrease in riverbed microplastic concentrations as a result of floods (Hurley, Woodward, & Rothwell, 2018). However, for macroplastic debris, this remains an unstudied field.

Plastic debris in river systems is subjected to degradation. Degradation mechanisms include mechanical degradation, through physical contact with other plastics or with objects, but also thermal and UV degradation or photodegradation (Andrady, 2015). Especially on beaches and river banks, plastics are exposed to high temperatures and high levels of UV, increasing the degradation speed compared to plastics in surface waters and in sediments. Although occurring, biodegradation is not considered to contribute significantly to plastic degradation in aquatic environments due to its slow pace (Andrady,

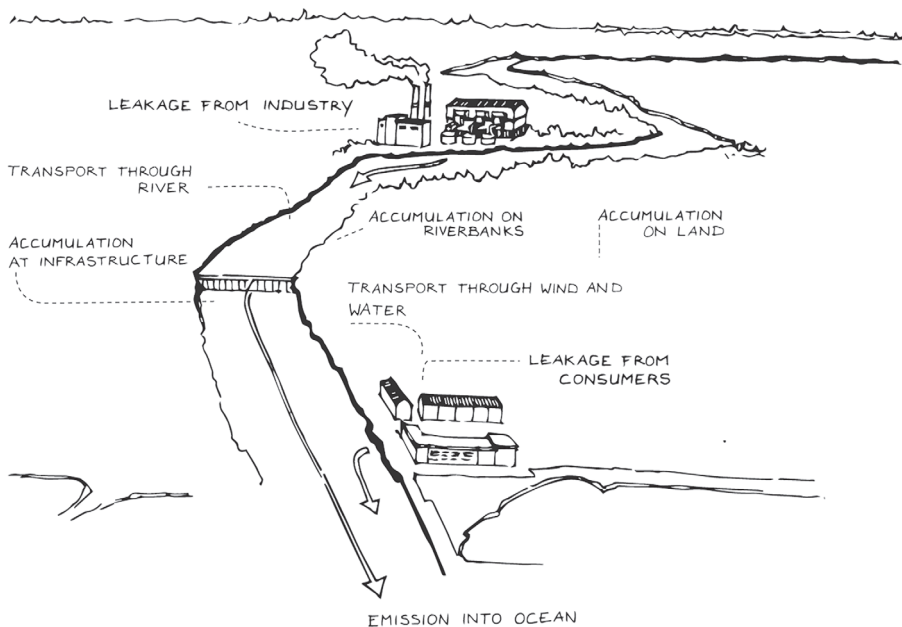


FIGURE 3 Sources, pathways, and sinks of riverine plastic debris (Credit: Cher van der Eng)

2015). Through degradation, macroplastics fragmentate to micro and even nanoparticles, increasing the amount of plastics that are smaller than 1 μm . Furthermore, additive leakage increases as plastics degrade. Several additives are toxic to environments in certain doses, such as bromide flame retardants used in electronic plastics.

As rivers interact with neighboring water bodies, plastic transport in lakes and estuaries provides additional insights in why some plastics never make it into the ocean. Plastic debris has been found to be abundant in several lakes in Europe and North America (Blettler et al., 2017; Flaure et al., 2015; Hoellein et al., 2014; Mihai, 2018). Due to the retention times in lakes, plastic debris may degrade into microplastics, settle, or accumulate on shores. Also, it may be removed through waste collection or sampling activities. It has been found that plastics in lakes can be dominated by household waste, which endangers ecosystems directly (Mihai, 2018). How lakes influence the travel paths of plastic debris from land into the ocean on catchment scale is yet to be explored.

Finally, estuaries play a crucial role in emission of plastic debris into the ocean as they are the actual outlet from rivers into the ocean. Estuaries are quite complex environments, and very little is known about transport processes of plastic debris in tidal zones. Due to bidirectional flow, plastic debris may accumulate in these regions. Available data showed increasing plastic transport and concentrations closer to the river mouth (Lechner et al., 2014; van Emmerik, Strady et al., 2019). However, to date only Sadri and Thompson (2014) measured macroplastics in estuaries. Microplastic studies around estuaries are scarce as well, with observations from Claessens et al. (2011) and Leslie et al. (2017). In order to understand the role of estuaries in the net transport of plastic debris from rivers into the ocean, future studies should focus on river deltas, estuaries, and near shore sediments.

5 | QUANTIFYING RIVER PLASTIC DEBRIS

In recent years many efforts have been made to quantify plastic debris in river systems. Here, we present an overview of several important studies that focused on (a) quantifying plastic waste sources, (b) quantifying river plastic transport through modeling approaches, and (c) quantifying river plastic transport through observations.

5.1 | Plastic waste sources

The major modeling studies, such as Jambeck et al. (2015), that tried to quantify plastic transport in rivers and into oceans used the world bank database on mismanaged waste (Hoornweg & Bhada-Tata, 2012). In this database, the fate of waste in a country is quantified in percentages, together with total mass of waste if available. Furthermore, the fraction of waste that is plastic is also given for several countries. Additionally, the open source “Waste Atlas” (2019) collects information from

different sources on global waste management. This database has been used in more recent studies of waste management and plastic, such as Lebreton and Andrady (2019). A database to quantify the fate of plastic waste (incineration/ recycling or land-fill), per product type (packaging/ non packaging), per country still has to be developed, but will be useful to more accurately estimate waste quantities which can be used for fate modeling.

5.2 | Modeling approaches

One of the first efforts to quantify land-based marine debris transport into the ocean was done by Jang et al. (2014) for South Korea. Here, the three main mechanisms of debris from land to sea were identified as (1) transport from rivers during nonflood season, (2) transport during flood season, and (3) shoreline activities. Transport from river was estimated by upscaling measurements done during normal and flood conditions on the Nakdong river over time and space, using flood occurrence and population data. For shoreline plastic emissions, it was estimated that an additional 30% waste was emitted, based on the same share of the population living along the coast. It was estimated that 35% of total marine debris emitted by South Korea originated from land, with 28% from rivers (Jang et al., 2014).

Jambeck et al. (2015) developed the first global framework to estimate the amount of plastic waste entering the ocean from 192 coastal countries. Based on the mass of waste generation per capita, the plastic to waste ratio, littered, and mismanaged waste, mean annual plastic emission per capita for each country was calculated. To estimate the total emission per country, the per capita emission was multiplied with the total population living within 50 km distance of the ocean. The high and low estimates were obtained by assuming an upper and lower rate (40 and 15%, respectively) in which mismanaged waste would end up in the ocean. These rates are based on one study of San Francisco water quality, where the plastics uncaptured by street sweepers and catchments were assumed to be able to reach the ocean. Additionally, littering fraction (not mismanaged waste) was set on 2% in all countries. Jambeck's study from 2015 revealed (Southeast) Asia as a main contributor to global land-based marine plastic pollution.

The results from Jambeck et al. (2015) have subsequently been used in other analysis to quantify the input from rivers and coastal populations. For example, Liubartseva et al. (2016) used the total input for the Adriatic Sea from Jambeck et al. (2015) to estimate the emission from individual rivers and urban areas. The total annual waste input into the Adriatic Sea was proportionally distributed over the rivers and urban populations, based on their discharge and population, respectively. Following this approach, the Po and Buna/Bojana rivers were identified as main regional sources of plastic emission. More recently, Tramoy, Gasperi, Dris, Colasse, Fisson, Sananes et al. (2019) adopted the Jambeck et al. (2015) model to assess emission for the Seine in France for comparison to an observation-based approach. Using local available hydrological and plastic data, an annual emission of 1,100–5,900 tonnes/year, of which 1.9–15.4% was estimated to be floating plastic litter.

Two global studies focused on quantifying the emission from rivers only, using a catchment-based approach. Lebreton et al., 2017 and Schmidt et al. (2017) formulated similar model approaches that estimated river-specific plastic emission based on river discharge and mismanaged plastic waste. The main differences between these studies were use of calibration parameters, the calibration datasets, and the conceptual treatment of dams. For the latter, Lebreton et al. (2017) assumed dams act as plastic sinks without letting through plastics, in contrast to Schmidt et al. (2017). The order of magnitude of total global riverine emission of plastics into the ocean is similar for both studies (Lebreton et al. (2017): 1.15–2.41 million tonnes/year; Schmidt et al. (2017): 0.41–4 million tonnes/year). However, the distribution over rivers globally differs. Where in Lebreton et al. (2017), the top 20 polluting rivers emit 67% of the global total (Lebreton et al., 2017), in Schmidt et al. (2017) the top 10 to emits 88–95%.

5.3 | Monitoring methods

Among plastic monitoring studies, there is not a uniform method identified to measure the amount of plastic waste in a river or freshwater system. However, the methods used to date can be roughly divided into five different methodologies: Plastic tracking, active sampling, passive sampling, visual observations, and citizen science.

5.3.1 | Plastic tracking

To study the travel paths and retention times of plastic debris in river systems, trackers are often used. There are two main approaches: actively track debris as it travels through the river system using global positioning system (GPS), release marked plastic items that can be registered once retrieved by either the public or professionals. Ivar do Sul et al. (2014), for example, used painted plastic items to study the retention time of plastic debris in mangrove forests. In two different seasons, plastic

items with different colors were released and tracked for several days, which demonstrated that plastic bags are more easily retained than items such as bottles. Ongoing work on the Seine uses GPS trackers to actively monitor the travel path of plastic items that are floating and submerged just below the water surface (Tramoy, Gasperi, Dris, Colasse, Fisson, Rocher et al., 2019). This can reveal preferential flow paths, temporary accumulation, and remobilization as a result of changing hydrometeorological conditions.

5.3.2 | Active sampling

Active sampling of plastic debris is one of the most straightforward approaches to study riverine plastic pollution. Typical examples of active sampling methods include the use of nets deployed from boats or bridges, collecting debris on riverbanks and beaches, or taking sediment samples. Riverine plastic debris samples can be used to study the typical composition, the mass and size distribution, degradation rate, and identification of items. Several studies have used small nets that can be deployed from bridges to collect (plastic) debris samples. Such nets are often around 1 m wide and 0.5 m tall and can easily be operated by one or two people. This allows frequent and flexible measurements at different locations across the river width. Depending on the plastic concentration and research focus, nets with varying mesh sizes can be used. Applications include sampling of the Mogami river in Japan (Onoi and Nihei, 2015), the Saigon river in Vietnam (van Emmerik et al., 2018; van Emmerik, Strady et al., 2019), the Cikapandung, Ciliwung, and Pesanggrahan rivers in Indonesia (Honingh, 2018; van Emmerik, Loozen et al., 2019), and the Seine in France (van Emmerik, Tramoy et al., 2019). Despite their practical advantages, they can often only be used effectively between certain flow velocities. For higher flow velocities (>1 m/s), the forces can become too high, and for low flow velocities, the forces are too low to keep the net horizontal and to collect plastic.

To allow for larger sample sizes and collecting debris during high discharge conditions, nets have also been deployed from bridges using cranes. Moore et al. (2011) deployed a manta trawl from a bridge to quantify plastic debris flows in the Los Angeles rivers during the dry and the wet season. Another study deployed a large three-layered sampling net using a crane to sample plastic debris flowing at three depths in the Donau (Hohenblum et al., 2015; Lechner et al., 2014; Liedermann et al., 2018). Although such setups allow for more robust sampling activities, they also require substantially more resources, labor, preparations, and infrastructure. Finally, methods from ocean debris sampling have been applied to river systems. For example, Sadri and Thompson (2014) used manta trawls deployed from a boat to study plastic pollution in the Tamar estuary in the United Kingdom.

Most of the measurement methods discussed above focus on quantifying mobile, mainly floating or superficially suspended, plastics in rivers. Recall from Section 4 that considerable amounts of plastics can also be found in sediment, riverbanks, and at deeper layers in the water column. Sediment samples were for example analyzed for the Ombrone river in Italy (Guerranti et al., 2017). Riverbank plastic samples were taken and analyzed for several rivers in Chile (Rech et al., 2015) and Germany (Kiessling et al., 2019). Morrill et al. (2014) deployed fish fykes close the riverbed to collect plastic debris samples at the bottom of the water column.

5.3.3 | Passive sampling

Rather than actively sample river plastic pollution, one can also collect and analyze debris that accumulates at existing infrastructure. In various rivers around the world, infrastructure is already in place to concentrate, retain, and extract (plastic) debris in rivers. For example, the river Seine in France is equipped with a network of 26 floating booms to collect and remove (plastic) debris. Gasperi et al. (2014) analyzed the collected waste to study the amount and composition of plastic in the Seine.

Another study by Lahens et al. (2018) examined riverine waste collected from urban canals in Ho Chi Minh City by municipal waste handlers. Similar work has been done on the Chao Phraya river in Thailand (DMCR, 2018) and the Rhine at Rotterdam, the Netherlands (Pikaar, 2018), where riverine debris, collected through floating barriers, has been collected and studied. In Baltimore, Maryland, focused river cleanup technology has been installed to reduce the plastic waste emission from the Jones Falls river into the city's harbor. Here, over 1,000 tonnes of waste has been collected and analyzed over 4 years, making it one of the longest riverine debris datasets available to date (Lindquist, 2016).

Compared to active sampling, these methods have the benefit of using existing infrastructure, allowing for debris analysis without additional investment in installing monitoring equipment. Disadvantages include that the samples may not always be tailored toward answering specific research questions. Existing infrastructure, such as the floating booms in the Seine, do not offer flexible deployment, restricting the possible sampling locations. Furthermore, temporal variations and factors such as wind and hydrology are harder to quantify using this methodology.

5.3.4 | Visual observations

In addition to methods focused on collecting plastic samples, several methods have also been developed to specifically quantify the riverine plastic flux or stock. One of the most applied methods is visual counting method from bridges (Castro-Jiménez et al., 2019; Crosti et al., 2018; González-Fernández et al., 2016; González-Fernández & Hanke, 2017; van Emmerik et al., 2018). For this method, observers are standing on bridges and count the amount of visible floating, and superficially submerged, plastics for a certain duration. The results can be used to quantify the plastic transport for the whole river at a given moment in time and its distribution over the river width. Although this simple method provides consistent data over time and space, several uncertainties are introduced through a possible observer bias and the minimum size of counted plastic as a result of bridge height and turbidity. If additional plastic mass statistics are available, such as mean mass per plastic item, the plastic item count observations can be converted to plastic mass transport (Castro-Jiménez et al., 2019; van Emmerik et al., 2018).

Long-term measurements on the Saigon river using visual counting revealed a strong seasonality of plastic transport and showed its distribution of the river width and length is strongly influenced by hydrometeorological factors such as wind, water level, and flow velocity (van Emmerik et al., 2018; van Emmerik, Strady et al., 2019). Other studies, such as the pan-European RIMMEL project collected visual counting observations for over 40 rivers (González-Fernández et al., 2019). In similar spirit, several other methods include the counting and identification of plastic litter along riverbanks (Kiessling et al., 2019; Rech et al., 2015). Measurements done at Chilean and German rivers, revealed clear spatial variation of plastics accumulated along riverbanks.

Parsimonious measurement methods provide a powerful tool to arrive at first-order estimations of floating plastic transport and accumulation of plastics along riverbanks. They are easy to apply, and data collection can be done by either professionals or through citizen science, all around the world. Although subjected to several sources of uncertainty, they do provide a consistent way of data collection, allowing for good comparison between rivers and over time. At the same time, many efforts focus on developing more high-tech approaches for flux and stock measurements. Recent work by Martin et al. (2018) presented a method to automatically identify plastic litter over an extended area using unmanned aerial vehicles (UAVs) and a machine learning algorithm. Geraeds, van Emmerik, de Vries, and bin Ab Razak (2019) used UAVs for the first time to monitor floating macroplastic transport in rivers. Image processing was done manually, but the study demonstrated the potential for further automation of plastic monitoring using UAVs. Camera-based solutions provide another way forward in automated plastic monitoring. Kylili et al. (2019) developed a deep learning algorithm to automatically detect marine plastic debris from images. Basurko et al. (2019) presented camera technology based on near-infrared imagery and particle tracking software to identify and track floating plastic debris in rivers. On an even larger spatial scale, a study by Biermann, Vincente, Saille, Mata, and Steele (2019) demonstrated how Sentinel-2 imagery can be used to detect floating macroplastic debris in coastal zones. Such new technological advances will allow for a rapid scale-up of observations across the globe. To date, plastic debris in rivers has only been monitored in a handful of rivers. Through affordable and accurate automated measurement methods, such as cameras, UAVs and spaceborne remote sensing, global coverage of riverine plastic debris monitoring is within reach in the coming years.

5.3.5 | Citizen science

Due to the simplicity of visual counting of floating plastic debris and plastic litter along riverbanks and beaches, riverine plastic data collection can also be done through the help of the public. As the plastic pollution problem is visual and well known to the broader public, several citizen science data collection efforts have been set up in the past years. Although the nature of citizen science-based may be different than conventional data (Buytaert et al., 2014), it has been proven to be of great value for riverine and marine plastic research.

Over 10 years of nationwide plastic litter collection on beaches provided valuable insights in the origin and faith of plastic pollution in coastal zones of the United Kingdom (Nelms et al., 2017). Beach plastic litter sampling was also done by Syakti et al. (2017), who organized a yearly sampling session in May to classify plastic items and polymer types. For rivers, several citizen science studies were done on Chilean and German rivers. In both studies, schoolchildren were motivated to participate in sampling and quantifying plastics along riverbanks (Rech et al., 2015; Kiessling et al., 2019). Barrows et al. (2018) organized collection of water samples by 120 volunteers for microplastic analysis, and showed that such an approach allows for (micro)plastic characterization at watershed scale.

New citizen science data collection tools and technology are being developed continuously. Simple smartphone-based apps allow for data collection of for example rainfall (Davids et al., 2019) and stream water level (Seibert et al., 2019). Recently, the Litterati app (www.litterati.org) was launched that allows for identifying and tagging waste anywhere around the globe. To date, more than 3 million litter items are geotagged, providing crucial new insights in the spread and transport of litter in

the natural environment. To collect more specific data on floating plastic in rivers and plastic on riverbanks, the CrowdWater app (Seibert et al., 2019) has recently been extended with a plastic measurement module. Such data is easier to collect by the larger public, stimulating large-scale data collection over time and space. Similar data for floating river plastic pollution and plastic litter on riverbanks are therefore expected to be of great importance to better understand and monitoring riverine plastic debris (Rambonnet et al., 2019).

6 | EXAMPLES OF OBSERVED RIVERINE PLASTIC DEBRIS AROUND THE GLOBE

Despite the global acknowledgement of plastic pollution in aquatic ecosystems as an emerging threat, useful data on plastic debris are scarce. Since there are no standardized protocols yet, available data is often collected inconsistently and is reported in different units. One of the first studies to quantify plastic pollution in river systems was done by Williams and Simmons (1997), who counted the number of plastic items along the Cynon river (UK). Several other studies only reported the amount of collected samples, as the main interested was often to analyze the polymer type of item class (Morritt et al., 2014; Tramoy, Colasse, Gasperi, & Tassin, 2019). Most studies focusing on riverbank plastics reported their results in items or mass per unit of surface area, with a maximum density of 400 items/m² measured in the Adour river, France (Bruge et al., 2018). Unfortunately, no data has been collected along rivers in South East Asia or Africa. Studies that sampled floating or suspended plastics generally report results in concentrations, both in items/m³ or kg/m³. Values range from 0.03 to 0.05 items/m³ (0.004–0.079 g/m³) in European rivers (Danube, Po, Rhine) (van der Wal et al., 2015) to 0.24 items/m³ in Chilean rivers (Rech et al., 2014; 2015). A peak value of 3.4·10³ items/m³ was measured after heavy rainfall in the Los Angeles river basin (Moore et al., 2011). Suspended plastic concentrations were measured between 0.08 and 0.24 items/m³ (0.0002–0.0054 g/m³) in European rivers. The ratio of floating to suspended plastic concentration ranged from almost 1 (Po) to over 300 (Rhine) (van der Wal et al., 2015). Besides these studies, no data on suspended plastics is available to date. Most plastic debris studies focused on estimating plastic transport or emission into the ocean. This is either expressed in items or mass per unit of time. Also, here most data are available for European rivers, estimating plastic transport between 10 and 1,000 items per hour, depending on the river and location (Castro-Jiménez et al., 2019; Crosti et al., 2018). For the Saigon river however, monthly mean plastic transport of 20·10³ items/hr was measured, 1–3 orders of magnitude larger than any measured European river. Similar variations can be found in available estimations of plastic mass emission into the ocean. For European rivers several estimates showed annual emissions between 0.71 (Rhône) (Castro-Jiménez et al., 2019) and 1,533 tonnes/year (Danube) (Lechner et al., 2014). However, most estimates range between 16 and 119 tonnes/year (Seine, Rhine, Po) (Gasperi et al., 2014; van der Wal et al., 2015). In Southeast Asia, estimates range between 2.1·10³ tonnes/year for the Jakarta waterways (van Emmerik, Loozen et al., 2019) to 1.3·10³ tonnes/year for the Saigon river (van Emmerik et al., 2018; van Emmerik, Strady et al., 2019). This shows that river plastic emission may be a more distributed problem than previously assumed (Schmidt et al., 2017) as also urban drainage systems and smaller rivers emit several orders of magnitude more plastic than large rivers. What becomes clear from this overview is that there are several knowledge gaps, both in methodology as coverage over time and space. No data is available for Central America or Africa, and only few rivers in Southeast Asia have been monitored. Most studies focus on either floating plastic or riverbank sampling. Only few efforts measured suspended plastics, bed transport or plastic in sediment or biota. Three studies analyzed stomach content of species in rivers and estuaries, and showed varying ingestion rates of 7.5–33% (Faure et al., 2015; Holland et al., 2016; Possatto et al., 2011). Unfortunately, only few holistic monitoring efforts, focusing on more than three components of riverine plastic transport, have been done to date.

7 | FUTURE RESEARCH DIRECTIONS

In the previous sections we provided an overview of the current state of research to macroplastic litter. There are many open questions and remaining challenges to be tackled before establishing a comprehensive understanding of plastic debris in river systems. In this section, an outlook is provided for future research directions crucial to improve our understanding of riverine plastic debris transport, which is crucial to minimize global plastic waste in terrestrial and aquatic ecosystems.

7.1 | Future of plastic pollution

Predictions on the development of plastic pollution in rivers are highly uncertain. Plastic production is foreseen to continue growing, and with that the pollution to the environment (Lebreton and Andrady, 2019). In case of business as usual, there will be an estimated three times more mismanaged plastic waste in 2060 which is likely to leak into the environment at the same rate (Lebreton and Andrady, 2019). With the effects of climate change increasing in the future, more frequent floods from rainfall or sea level rise will likely increase the flux of waste, including plastics, to aquatic environments (Gündoğdu, Çevik, Ayat, Aydoğan, & Karaca, 2018).

However, the risen attention to the plastic pollution problem has resulted in global initiatives to clean up or even reduce plastic pollution to the environment directly. This includes the ban on single use plastics in the European Union, or the plastic bag ban in Kenya (NEMA, 2017). However, these bans will create problems of their own as alternative, bio-based materials with an often higher environmental impact are used instead (Khuo, Tan, & Chng, 2010). Furthermore, the quantity and quality of plastic recycling will likely increase as technology develops. With that, waste management becomes more efficient and widely implemented over time as well, decreasing the leakage of plastics to the environment. Unfortunately, recycling of plastics will remain problematic as its cheap production will not result in an economic advantage, and pollution problems will remain if this does not change in the future.

In conclusion, plastic pollution demands increasing technology development, waste management and awareness to decrease plastic leakage levels close to zero. Even after that, the environmental impact of previously released plastics will remain for decades.

7.2 | Degradation mechanisms and legacy

Through several degradation processes, macroplastics are broken down into smaller fragments. The degradation rate of plastic is low, including bioplastics and even the biodegradable plastics (Napper and Thompson, 2019). This degradation to micro- and nanoplastics comes with all impacts mentioned earlier, however most impacts are still unknown. The rate of degradation depends on the environment; degradation rate is highest on beaches and for floating plastics, due to UV, degradation of plastics in sediments will likely be very low. Among floating plastics, plastic degrading microorganisms might accelerate the degradation of plastics, for example when cracks appear (Carson, Nerheim, Carroll, & Eriksen, 2013).

For oceanic environments, Brandon, Goldstein, and Ohman (2016) has evaluated the degradation of oceanic polyethylene, where it was found that most particles were at least 18 months afloat (Brandon et al., 2016). However, other polymer types are not yet assessed, however studies found polyethylene to be more vulnerable than PP (Cooper & Corcoran, 2010). Furthermore, variations in degradation in environments, such as sediments and in rivers, has not yet been covered well either. Therefore, for the degradation process, there are still many uncertainties and robust data on degradation rates in various environments for different polymers is a spot on the horizon for understanding the ultimate fate of plastic waste.

Due to the higher number of microplastic studies and the degradation processes, the relationship between macro and microplastics is more interesting than ever. So far, no relation found between macro and microplastics in Nakdong riverbanks (Lee et al., 2013). However, larger scale studies are required to explore such potential relationship.

7.3 | Monitoring

Most observation-based studies rely on existing infrastructure. Net sampling and visual observations of floating plastic debris strongly depend on bridges as observation locations. Consequently, it remains challenging to monitor plastic debris at any given river cross-section, especially for wide rivers. Therefore, larger rivers and estuaries remain understudied. Potential ways forward include using UAVs or spaceborne remote sensing to monitor riverine plastic transport. Martin et al. (2018) presented an approach to automatically monitor plastic litter on beaches. In similar spirit, Geraeds et al. (2019) developed an approach for riverine plastic litter monitoring. Additional possibilities of using UAVs for plastic monitoring in river systems are yet to be explored. An additional challenge is the dynamic nature of rivers compared to beaches, which calls for a different monitoring protocol. Another promising way forward includes the use of optical imagery from Sentinel-2 to detect plastic in the aquatic environment. Early results demonstrated that increased plastic concentrations in coastal waters lead to observable changes in image color statistics (Biermann et al., 2019).

Table 2 illustrates that most studies focused on floating plastic debris, as suspended plastic debris has only been measured at a handful of rivers. Available data suggests that subsurface plastic may make up a considerable share of total plastic transport (Hohenblum et al., 2015; Morritt et al., 2014). Several methods to quantify suspended plastic transport are identified,

TABLE 2 Overview of plastic debris measurements

Study	River	Country	Measured component				Monitoring period	Result	
			Floating	Suspended	Bed	Flood		Variable	Unit
Morritt et al. (2014)	Thames	United Kingdom	N				3 months	Amount	8,490 items
Williams and Simmons (1997)	Cynon	United Kingdom			S		3 months	Amount	150–400 items
Tramoy, Colasse et al. (2019)	Seine	France			S		45 years	Amount	20,259 items
Baldwin et al. (2016)	Great Lakes tributaries	United States	N				1 year	Density	0.001–0.62 items/m ²
Hoellein et al. (2014)	Chicago	United States		S	S		3 days	Density	0.02–0.04 items/m ²
Lee et al. (2013)	Nakdong	South Korea			V		6 months	Density	0.97–1.03 items/m ²
Ivar do Sul et al. (2014)	Goiana	Brazil			T		6 days	Density	1–6 items/20m ²
Kiessling et al. (2019)	German rivers	Germany			S		6 months	Density	0.54 items/m ²
Bruge et al. (2018)	Adour	France			S	S	3 years	Density	1–400 items/m ²
Cannas et al. (2017)	Tuscan rivers	Italy			S			Density	<20 items/kg
Guerranti et al. (2017)	Tuscan rivers	Italy			S		1 year	Density	57–1,069 items/kg
Rech et al. (2014; 2015)	Chilean rivers	Chile	N		S		1 time	Density Concentration	1–2 items/m ² 0–0.24 items/m ³
Sadri and Thompson (2014)	Tamar	United Kingdom	N				3 months	Concentration	0.028 items/m ³
Hohenblum et al. (2015)	Donau	Austria	N	N	N		6 months	Concentration Transport rate	20–320 mg/m ³ 100–2,400 mg/m ² /hr
Moore et al. (2011)	Los Angeles	United States	N	N	N		5 months	Concentration Concentration	0.16–3,437.94 items/m ³ 0.01–40.34 g/m ³
van der Wal et al. (2015)	Rhine	Netherlands	N	S			1 time	Concentration Concentration Concentration Concentration Emission	0.05 items/m ³ (floating) 0.079 g/m ³ (floating) 0.008 items/m ³ (suspended) 0.00024 g/m ³ (suspended) 20.4–30.9 tonnes/year

(Continues)

TABLE 2 (Continued)

Study	River	Measured component					Result		
		Country	Floating	Suspended transport	Bed	Flood	Monitoring	Variable	Unit
van der Wal et al. (2015)	Po	Italy	N	S			1 time	Concentration Concentration Concentration Concentration Emission	0.032 items/m ³ (floating) 0.0038 g/m ³ (floating) 0.031 items/m ³ (suspended) 0.0025 g/m ³ (suspended) 119 tonnes/year
Van der Wal et al. (2015)	Danube	Romania	N	S			1 time	Concentration Concentration Concentration Concentration Emission	0.372 items/m ³ (floating) 0.038 g/m ³ (floating) 0.24 items/m ³ (suspended) 0.0053 g/m ³ (suspended) 16.88 tonnes/year
Castro-Jiménez et al. (2019)	Rhône	France	V				1 year	Transport Emission	37 items/hr 0.71 tonnes/year
Gasperi et al. (2014)	Seine	France	P				6 years	Emission Emission	22–36 tonnes/year 2.3 g/cap/year
Carson, Lamson et al. (2013)	Hilo (Hawaii) rivers	United States	P				205 days	Emission	0.32 kg/day
van Emmerik et al. (2018)	Saigon	Vietnam	V, N				2 weeks	Emission	7.5–13.7 × 10 ³ tonnes/year
van Emmerik, Loozen et al. (2019)	Jakarta waterways	Indonesia	V, N	N			2 weeks	Emission	2.1 × 10 ³ tonnes/year
Lechner et al. (2014)	Danube	Austria	N	N			2 years	Emission	1,533 tonnes/year
Lindquist (2016)	Jones falls	United States	P				5 years	Emission	12.8 million plastic items
Lahens et al. (2018)	Nheu Loc—Thi Nghe canal	Vietnam	N				1 month	Transport	350–7,270 g/cap/year

(Continues)

TABLE 2 (Continued)

Study	River	Country	Measured component				Result		
			Floating	Suspended	Bed	Flood	Monitoring period	Variable	Unit
Crosti et al. (2019)	Tiber	Italy	V				1 year	Transport	10–130 items/hr
van Emmerik, Strady et al. (2019)	Saigon	Vietnam	V, N				10 months	Transport	9×10^3 items/hr
Geraeds et al. (2019)	Klang	Malaysia	V, N				1 week	Transport	1,500 items/hr
van Emmerik, Tramoy et al. (2019)	Seine	France	V				2 weeks	Transport	100–1,000 items/hr
Faure et al. (2015)	Swiss rivers	Switzerland	N			I		Transport	0–7.7 items/hr
								Transport	0–430 mg/hr
								Density	0–0.095 items/m ³
								Density	0–2.9 mg/m ³
								Ingestion rate	7.5–12%
Possatto et al. (2011)	Goiana	Brazil				I	20 months	Amount	0.3–1 items/fish
								Ingestion rate	17–33%
Holland et al. (2016)		Canada				I		Ingestion rate	11.10%

Note: Note that this table is not exhaustive.

*V, visual counting; N, net sampling; P, passive sampling; S, sampling; T, trackers; I, ingested debris sampling.

including physical sampling, remote sensing, and establishing empirical relationships between floating and suspended plastic transport. Physical sampling of plastic debris has been done using multilayered trawls deployed from ships on the open ocean (Kooi et al., 2016; Kulkula et al., 2012). Similar efforts may result in an initial estimation of the ratio between floating and suspended plastic debris transport in rivers. In the Scheldt (Belgium), fish population measurement methods are used to also study plastic concentrations and abundance. Existing fyke nets (like used by Morritt et al. (2014)) and anchor netting deployed from ships are used to capture plastic during single or double tidal cycles (Teunkens et al., 2018). As sampling methods are labor intensive, remote sensing techniques are also worth exploring. These may include using underwater cameras or acoustic sensing to detect plastic at deeper layers. Once more observational data is available, research should focus on understanding what factors determine the distribution of suspended plastic items. Preliminary findings in Jakarta demonstrated that the distribution of predominantly plastic bags was influenced by flow velocity. An empirical relation was established to estimate suspended plastics based on surface measurements. Additional observation in other rivers is required to establish more generic relations between the vertical distribution of plastic debris and river characteristics.

7.4 | Transport mechanisms

A thorough understanding of what factors determine plastic transport from land to aquatic systems is still lacking. Observations (Bruge et al., 2018; Castro-Jiménez et al., 2019; Crosti et al., 2019; Moore et al., 2011) support the hypothesis that wind and surface runoff are the main drivers of plastic transport from land to rivers. More fundamental research is needed to investigate the role of land use, surface friction and slope, and other factors on plastic transport. Available large datasets on anthropogenic litter collection can be explored in more detail (Cowger, Gray, & Schultz, 2019) to determine what factors influence the distribution of plastic items in the natural environment.

Similarly, for transport within rivers, fundamental research can shed additional light on what determines the transport rates, likelihood of entrapment or degradation rates of plastic debris. Available analyses show contradicting relations between river discharge and plastic concentrations (van Emmerik et al., 2018; Wagner et al., 2019). In some cases, increased discharge does not mobilize additional plastic (van Emmerik et al., 2018). In other cases, additional discharge comes with increased water levels and flow velocity, which can remobilize settled or accumulated plastics on riverbanks or hydraulic infrastructure. To further explore factors influencing plastic transport in rivers, additional hydrometeorological and hydraulic data are crucial.

7.5 | Extreme events

One of the open questions regarding plastic debris transport is what determines the temporal distribution. For other materials, it has been found that the majority of the annual river transport is caused by a single event (Chen et al., 2014). For plastic debris, such data are lacking. However, available observations demonstrate that plastic transport can fluctuate with a factor 10 between months (Castro-Jiménez et al., 2019; van Emmerik et al., 2019). In the Rhône, the maximum observed plastic transport was six times higher than the mean. Also, in other rivers, such as the Seine and Saigon, an order of magnitude difference was observed within a year (van Emmerik, Strady et al., 2019; van Emmerik, Tramoy et al., 2019). A study on lakes in the Bistrita river catchment in Romania demonstrated that plastic transport from rural areas into rivers and lakes was also mainly driven by floods. The importance of floods for plastic transport is supported by Hurley et al. (2018) who found a 70% decrease in microplastics in river sediments across the United Kingdom after heavy floods. With the available global flood risk models (Ward et al., 2015), assessments should be made on where to expect additional plastic debris transport as a result of riverine, marine, or compound flood events.

Additional plastic debris may also be transported toward the ocean as a result of other extreme events, such as landslides, storms, or tsunamis. Several studies have been done on the effect of the tsunami as a result of the 2011 Great East Japan Earthquake. It was found that 10–20% of the plastic input in the Great Pacific Garbage Patch could be traced to this event (Lebreton & Borrero, 2013; Lebreton et al., 2018). This was supported by Murray, Maximenko, and Lippiatt (2018) who demonstrated that the 10-fold increase of beach plastics on North American beaches was related to the same tsunami. The recorded number of natural disasters has more than doubled since 1980 (Cutter et al., 2015). Different natural disasters often occur together, leading to additional significant impact (Zscheischler et al., 2018). For example, extreme storms often coincide with floods. Unfortunately, natural disasters often cascade into additional catastrophes, such as additional plastic debris transport. This is caused by (Adam et al., 2019) increased initial mobilization of plastic waste, (AghaKouchak et al., 2018) remobilization of accumulated plastic debris, and (Andrade et al., 2019) the introduction of nonwaste plastic items into rivers and oceans. To date, most models only take into account mismanaged plastic waste to estimate plastic transport and emission

into the ocean (Lebreton et al., 2017; Schmidt et al., 2017; Tramoy, Gasperi, Dris, Colasse, Fisson, Sananes et al., 2019). Future work should also consider the additional nonwaste plastic transport.

7.6 | Data analysis and sharing

As visible in Table 2, plastic debris data is collected using many different methods. In turn, results are often also reported in different units. Recent efforts have presented a way forward to harmonize plastic debris measurements (Gonzalez and Hanke, 2017). As a direct consequence, observations at different rivers are now better comparable in time and space (Castro-Jimenez et al., 2019; Crosti et al., 2019; van Emmerik et al., 2018). Global riverine plastic research would benefit from similar harmonization efforts for other parts of the data pipeline, such as data analysis protocols, units, and data storage. A considerable portion of the collected data is only published in gray literature, making it inaccessible and hard to access. Many data are also collected during cleanup activities (Tramoy et al., 2019). However, their nonscientific nature makes reproducibility low and the data uncertain. A way forward to overcome these issues is to further develop harmonized data collection, analysis, and reporting tools. Furthermore, a global river plastic database would benefit the scientific community and beyond (Box 2).

BOX 2 BUSTING THE PLASTIC MYTHS

Recent media stories claim that 80% of marine plastic pollution comes from land (based on Jambeck et al. (2015)), and that 90% of the total riverine plastic export into the ocean comes from just 10 rivers (based on Schmidt et al. (2017)). Actually, the current state of the science is too limited to verify such claims. Most of such numbers reported in the media are based on assumption-driven modeling assessments and not extensively validated with field data. Although these numbers have contributed to an increase in the global plastic pollution challenge among the public, policymakers, and scientists, we have to remain cautious and critical on how to use and distribute them

8 | CONCLUDING REMARKS

Plastic debris transport by rivers is a crucial, but complex component of the global plastic pollution challenge. In this review, we provide an overview of the current state of the science, discussing the effects of plastic pollution, transport mechanisms, measurement methods and modeling approaches, and providing an outlook for future research. Riverine plastic debris transport is an emerging science and important knowledge has been developed in recent years. However, what becomes clear from our overview that there are still many scientific questions to answer and methodological challenges to overcome. Besides contributing to a better general understanding of plastic debris transport in rivers, we hope that this paper also provides directions for future research. Plastic pollution is a global environmental hazard and urgent action is required to tackle it.

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CONFLICT OF INTEREST

The authors declare no conflict of interests.

AUTHOR CONTRIBUTIONS

Tim van Emmerik: Conceptualization; visualization; writing-original draft, review, and editing. **Anna Schwarz:** Conceptualization; writing-original draft, review, and editing.

ORCID

Tim van Emmerik  <https://orcid.org/0000-0002-4773-9107>

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