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River plastic transport and storage budget

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ABSTRACT

Rivers are one of the main conduits that deliver plastic from land into the sea, and also act as reservoirs for plastic retention. Yet, our understanding of the extent of river exposure to plastic pollution remains limited. In particular, there has been no comprehensive quantification of the contributions from different river compartments, such as the water surface, water column, riverbank and floodplain to the overall river plastic transport and storage. This study aims to provide an initial quantification of these contributions. We first identified the main relevant transport processes for each river compartment considered. We then estimated the transport and storage terms, by harmonizing available observations on surface, suspended and floodplain plastic. We applied our approach to two river sections in The Netherlands, with a focus on macroplastics (≥2.5 cm). Our analysis revealed that for the studied river sections, suspended plastics account for over 96% of item transport within the river channel, while their relative contribution to mass transport is only 30%–37% (depending on the river section considered). Surface plastics predominantly consisted of heavier items (mean mass: 7.1 g/#), whereas suspended plastics were dominated by lighter fragments (mean mass: 0.1 g/#). Additionally, the majority (98%) of plastic mass was stored within the floodplains, with the river channel accounting for only 2% of the total storage. Our study developed a harmonized approach for quantifying plastic transport and storage across different river compartments, providing a replicable methodology applicable to different regions. Our findings emphasize the importance of systematic monitoring programs across river compartments for comprehensive insights into riverine plastic pollution.

1. Introduction

Rivers are one of the main conduits for the delivery of land-based plastic into the sea (0.8–2.7 MT/y), and also function as plastic reservoirs (Meijer et al., 2021; van Emmerik et al., 2022a). Plastics can be retained in river systems for years to decades (Tramoy et al., 2020a). But the current understanding of the extent to which different river compartments are exposed to plastic pollution is still limited. Understanding the river plastic transport and retention capability requires a system-based approach that identifies the main transport processes and the relevant storage compartments. Until recently, most observation-based studies have focused on surface plastic transport (Lebreton et al., 2022), and consequently our understanding of the magnitude of other transport processes is limited. In particular, there is growing evidence that lateral exchanges between the river channel and the riverbanks and floodplains are key processes in river plastic transport (Grosfeld, 2022; Lotcheris et al., 2024). Similarly, plastic transport suspended within the water column is increasingly recognized as a significant component of river plastic transport (Oswald et al., 2023; Valero et al., 2022; Vriend et al., 2023). Taking into account both lateral exchanges between river channel and riverbank, and suspended transport in river plastic transport is crucial for a comprehensive understanding of river plastic pollution.

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Recent Lagrangian-based studies show that surface plastics are transported for only about 10%–50% of their time within the river, depending on the system considered (Mani et al., 2023; Lotcheris et al., 2024; Ledieu et al., 2022; Tramoy et al., 2020b). During the remaining time, plastics are mainly retained within floodplains or in riparian vegetation (Delorme et al., 2021; Roebroek et al., 2021). The magnitude of observed deposition and remobilization processes (Lotcheris et al., 2024) highlights the need to consider lateral exchanges between floodplains and the river channel itself. During an episode of increased water levels and high discharge (5205 m^3/s) in the river Waal in January 2022, Grosfeld (2022) found a maximum mobilization rate of 13 #/h/km length (from one side of the floodplain) into the river channel. Considering a river reach of 25 km in length, this corresponds to 650 additional #/h in the river channel. For comparison, the mean surface plastic transport observed in that area reached 526 #/h/km of river width (yearly average for 2021) (van Emmerik et al., 2022b). These findings underscore the significance of lateral exchanges between the main river channel and floodplains and the need to include those to understand river plastic transport and retention capability.

Furthermore, growing evidence suggests that suspended plastic transport may also play a substantial role in river transport. Valero et al. (2022), for example, estimated that monitoring only surface plastics can lead to an underestimation of up to 90% of the total river transport. Haberstroh et al. (2021), who monitored both surface and suspended plastics at the Mekong confluence in Phnom Penh, Cambodia, found that an average of approximately 61% of items were transported below the surface. Thus, neglecting both suspended plastic transport and the exchanges between river channel and floodplains may result in a significant underestimation of the true magnitude of plastic transport in rivers. Despite the growing recognition of the importance of floodplain exchanges and suspended transport of plastic, a comprehensive quantitative assessment that integrates factors is still lacking. For instance, Schöneich-Argent et al. (2020) provided a thorough estimation of macroplastic pollution levels in various river compartments, reporting transport rates and concentrations. However, they did not harmonize data for comparing the plastic distribution among compartments nor quantified the storage capability of these compartments.

The primary objective of this study was to apply a river plastic budget. To achieve this, we developed a conceptual model that identifies key plastic transport processes within, and between, the various river compartments, including the surface, water column, floodplain, riverbed and sediments. Subsequently, we estimated as many plastic transport and storage terms as we could. For this, we harmonized available data on surface, suspended, and floodplain plastic in two river sections, both located on the Dutch Rhine. The primary objective of this study was to apply a river plastic budget to collected data on plastic transport and deposition.

Our study focuses on macroplastic (≥ 2.5 cm) (Blettler et al., 2018), although the methodology could be adapted to other plastic size ranges. Our plastic budget approach allows us to compare the plastic transport and storage at the surface, in the water column, and on the floodplain. Consequently, this research can help to better inform future strategies for both plastic monitoring and the prevention or reduction of plastic pollution in rivers. Importantly, the river plastic budget approach proposed in this paper could be adapted to other rivers to quantify and understand river plastic transport and storage.

2. Methods

In the Methods section, we introduce a conceptual model that identifies key processes related to riverine plastic transport and retention, necessary for formulating the river plastic budget (Section 2.1). Subsequently, we align the river plastic budget with commonly available plastic observations (Section 2.2). The relevant equations required for estimating plastic transport and storage terms are then presented (Section 2.3). Lastly, we provide details on the application of this approach to the two considered river sections (Section 2.4). Note that in our application, transport and storage values correspond to yearly averaged values as simultaneous plastic measurements across river compartments were not available. We therefore did not differentiate between transport rates at specific flow conditions or other possible intra-annual variations. The plastic budget approach we introduce could be applied at a range of timescales, depending on the scope of its application and the availability of observational data.

2.1. Conceptual model for river plastic budget

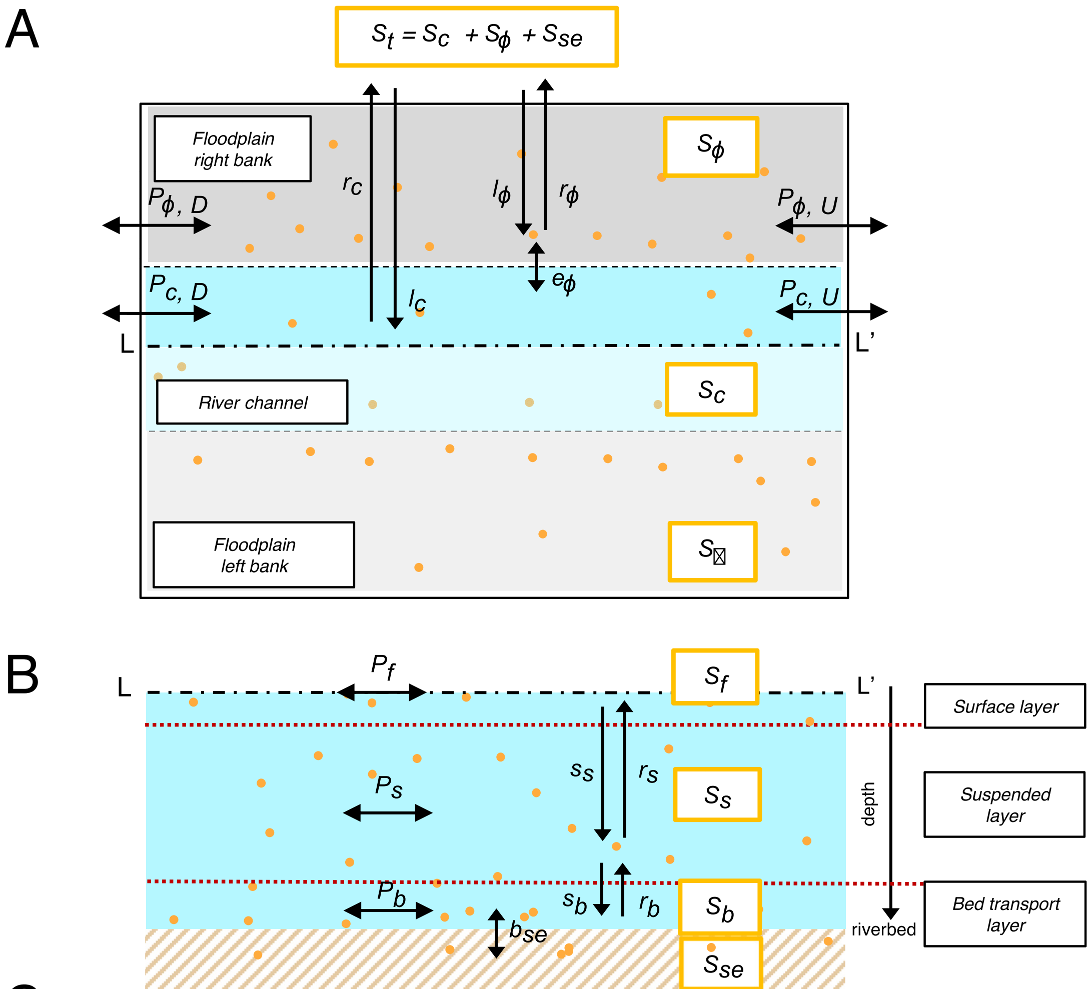
2.1.1. Plastic transport and retention processes

We present a conceptual model (Fig. 1) for establishing a plastic budget in and around rivers. This model considers a river section, delineated by upstream and downstream boundaries, for which plastic transport and storage are quantified. While specifically tailored to macroplastic items measuring 2.5 cm or larger, the model can easily be adapted to other size ranges, including microplastics.

In this model, the river channel is defined as the region of the river which contains and transports the flow the majority of the time and is bounded by the riverbed and the banks. The floodplain is defined as the area beyond the main channel, which is periodically inundated during high waters (Leopold et al., 1964). Floodplains are subdivided here into 'left' and 'right', using the standard convention that orientation is based upon viewing the river in the downstream direction. The distinction between left and right floodplain is preferred in view of the application of the plastic budget approach, as the two sides of the river channel might exhibit different, and contrasting morphological, floodplain, and anthropogenic characteristics that may impact plastic source, transport and retention. Note that the model can be applied to tidal rivers, and therefore may have bi-directional flow. In our definition, we include riverbanks as a component of the floodplains. Within the river channel, we distinguish three compartments: the surface layer, the suspended layer, and the bed transport layer. We define the river surface as the upper layer (10–20 cm) of the water column, since surface measurements typically focus on this layer. The suspended layer is the vertical extent of water between the river surface and the riverbed where material is in suspension. Finally, the bed transport layer is defined as the layer in which transport of material takes place that has (occasional) contact with the riverbed.

Considering a river section of interest, we can distinguish between longitudinal transport at the upstream ($P_{c,U}$) and at the downstream section boundaries ($P_{c,D}$) [M/T or #/T]. The longitudinal transport at both section boundaries can be either positive (downstream direction) or negative (upstream direction) (Fig. 1). Longitudinal transport includes three components: (1) surface transport (P_f), (2) suspended transport (P_s) and (3) bed transport (P_b) [M/T or #/T]. Surface plastic transport has been observed across several studies in multiple rivers around the globe (van Calcar and van Emmerik, 2019; van Emmerik et al., 2022b). This mode of transport predominates among positively buoyant plastics (Schwarz et al., 2019). Its dynamics have been found to be affected by flow velocity, discharge, wind shear stress, and surface tension (Schirinzi et al., 2020; Valero et al., 2022; van Emmerik et al., 2022b, 2023) (Table 1). Plastics can also be transported in suspension within the water column (Haberstroh et al., 2021; Oswald et al., 2023), where turbulent mixing affects transport (Valero et al., 2022).

The influence of vertical mixing, as well as changes in water density and turbulent fronts within the water column are known to potentially affect plastic buoyancy, especially in tidal reaches (Acha et al., 2003). In estuarine areas, increased salinity could lead to increased buoyancy, potentially leading to the resurfacing of items that were previously submerged beneath the water surface (Kooi et al., 2017; Ye and Andrady, 1991). Suspended plastics can thus be converted into surface plastics (r_s) and surface plastics can sink into the water column



C

Longitudinal transport terms [M/T or #/T]

$P_{c,U}$: longitudinal transport in the river channel at the upstream boundary
$P_{c,D}$: longitudinal transport in the river channel at the downstream boundary
$P_{\phi,U}$: longitudinal transport in the floodplains at the upstream boundary
$P_{\phi,D}$: longitudinal transport in the floodplains at the downstream boundary
P_f : longitudinal surface transport
P_s : longitudinal suspended transport
P_b : longitudinal bedload transport

Lateral transport terms [M/T or #/T]

l_ϕ : land-based transport to the floodplain
r_ϕ : removal rate from the floodplain
e_ϕ : mobilization/deposition between river channel and floodplain
l_c : land-based transport to the river channel
r_c : removal rate from the river channel

Vertical exchanges terms [M/T or #/T]

s_s : settling from surface layer to suspended layer
r_s : rising from suspended layer to surface layer
s_b : settling from suspended layer to bed transport layer
r_b : rising from bed transport layer to suspended layer
b_{se} : burial/mobilization in/from sediments (riverbed and floodplain)

Storage terms [M or #]

S_t : Entire river storage
S_c : River channel storage
S_ϕ : Floodplain storage
S_f : River surface storage
S_s : Suspended storage
S_b : Bedload storage
S_{se} : Storage in sediments (riverbed and floodplain)

Fig. 1. Conceptual model for plastic budget at a river section. A. Planform view. B. Vertical cross-sectional profile. C. Nomenclature.

(s_s) [M/T or #/T]. Bed load transport (P_b) [M/T or #/T] can occur through saltation and traction processes (Russell et al., 2023), similar to bed load transport of sediments. Bed load transport has rarely been observed for macroplastics (McGoran et al., 2023; Schöneich-Argent et al., 2020), a likely consequence of the difficulties in sampling the bed transport layer.

Other aspects of river channel transport dynamics include direct input from terrestrial systems into the river channel (and bypassing the floodplain), which we conceptualize as land-based transport into the river channel (l_c) [M/T or #/T]. Such phenomena have been observed from bridges and boats (Oswald et al., 2023), through littering or mobilization by wind (Table 1). Conversely, removal processes in

Table 1
River plastic transport and exchange terms and main associated drivers.

Symbols	Description	Main drivers
P_f	Longitudinal surface transport	Flow velocity, tidal amplitude, salinity, surface tension, wind
P_s	Longitudinal suspended transport	Flow velocity, tidal amplitude, turbulence, salinity
P_b	Longitudinal bed load transport	Bed shear velocity, bottom slope, bed roughness
e_ϕ	Lateral exchanges between floodplain and river channel (mobilization/deposition)	Direction and velocity of flow on the floodplains, waves in the river channel
l_c	Land-based inputs into the river channel	Surface runoff, wind and littering
l_ϕ	Land-based inputs into the floodplain	Surface runoff, wind and littering, terrain slope
r_c	Removal rate from the river channel	Anthropogenic cleaning actions
r_ϕ	Removal rate from the floodplain	Wind and anthropogenic cleaning actions
P_ϕ	Floodplain longitudinal transport	Wind, flow velocity on the floodplain, surface runoff, terrain slope
r_s	Rising of suspended plastics towards the surface	Turbulence, buoyancy
s_s	Settling of suspended plastics from the surface	Biofouling, buoyancy, turbulence
r_b	Rising of bed load plastics towards the water column	Turbulence, buoyancy
s_b	Settling of bed load plastics from the water column	Biofouling, turbulence, buoyancy
b_{se}	Burial rate in sediments (riverbed and floodplains)	Biofouling, turbulence, buoyancy, bioturbation, sedimentation/deposition

the river channel could also induce changes in plastic amounts in the river channel (r_c) [M/T or #/T]. Removal processes include the use of floating booms and dedicated vessels, as for instance reported for the Seine river in France (Gasperi et al., 2014; Tramoy et al., 2019).

Lateral exchanges between the river channel and the floodplains occur mainly through deposition from the river channel onto the floodplains and mobilization from the floodplains into the river channel (e_ϕ) [M/T or #/T]. Both deposition and mobilization of plastics on floodplains have been observed in rivers (Grosfeld, 2022; Tramoy et al., 2020a,b). Deposition and mobilization dynamics are hypothesized to be mainly driven by changes in water levels and flow velocity, direction and magnitude in the floodplains (Grosfeld, 2022). In addition, waves induced by riverine navigation were also demonstrated to be a significant factor in the mobilization of floodplain plastics into the river channel (Climo et al., 2022). It should be noted that transport processes do not act uniformly amongst the compartments. In the case of wave-inducted mobilization of floodplain plastics, this phenomenon primarily affects riverbanks. Within the floodplain, plastics can be transported along the floodplain (P_ϕ) [M/T or #/T], in both upstream and downstream directions, although there are no direct observations of such phenomena recorded in the academic literature to date. Wind and flow during inundation may be considered the key governing mechanisms of transport along the floodplains (Roebroek et al., 2021). Plastic exchanges between the floodplains and terrestrial ecosystems mainly occur through direct littering and land-based transport to the floodplains (l_ϕ) and through removal (r_ϕ) [M/T or #/T]. Land-based transport results from the combined action of runoff and wind (Mellink et al., 2024; Weideman et al., 2020). Direct littering is also considered to be a main factor for additional inputs of plastics into floodplains (Roebroek et al., 2022). Burial into sediments, or mobilization of plastics previously buried in sediments (b_{se}) [M/T or #/T], situated either on floodplains or the riverbed, likely occurs through similar processes to those identified in deposition on the floodplain and settling of bed load plastics from the water column. Despite the initial quantification of plastic concentrations buried in riverbed sediments (Constant et al., 2021), the governing mechanisms are yet unknown.

2.1.2. River plastic budget formulation

The total storage of plastics [M or #] within the river section considered (S_t) corresponds to the sum of storage within the river channel (S_c), the floodplains (S_ϕ) and the sediments (S_{se}):

$$S_t = S_c + S_\phi + S_{se} = \underbrace{S_f + S_s + S_b}_{S_c} + S_\phi + S_{se} \tag{1}$$

The variation of plastic storage over time can be expressed as the difference between incoming and outgoing plastic transport terms. Certain transport processes can be bidirectional (Fig. 1), as influenced by flow and wind direction. In such cases, we consider that negative transport values indicate transport in the upstream direction, and positive values in the downstream direction. Considering all incoming and outgoing transport terms, we can express the variation of river plastic storage over time as follows:

$$\frac{\Delta S_t}{\Delta t} = \frac{\Delta S_c}{\Delta t} + \frac{\Delta S_\phi}{\Delta t} + \frac{\Delta S_{se}}{\Delta t}$$

$$= \underbrace{P_{c,U} + l_c}_{\substack{\text{Incoming transport} \\ \text{through the channel}}} - \underbrace{P_{c,D} - r_c}_{\substack{\text{Outgoing transport} \\ \text{through the channel}}} + e_\phi + \underbrace{P_{\phi,U} + l_\phi}_{\substack{\text{Incoming transport} \\ \text{through the floodplains}}} - \underbrace{P_{\phi,D} - r_\phi}_{\substack{\text{Outgoing transport} \\ \text{through the floodplains}}} - e_\phi + \underbrace{b_{se}}_{\substack{\text{Burial rate} \\ \text{in sediments}}} \tag{2}$$

e_ϕ represents the lateral exchanges between floodplain and river channel and is thus an internal transport term. These exchanges cancel each other out in the equation. Note that we here consider that $e_\phi > 0$ corresponds to net mobilization and $e_\phi < 0$ to net deposition. Similarly, we consider that $b_{se} < 0$ corresponds to net burial of plastics in sediments and $b_{se} > 0$ to net mobilization of plastics previously buried in sediments.

2.2. Aligning river plastic budget to observational data

In this section, we simplify our initial river plastic budget equation (Eq. (2)) to match available macroplastic observations. Most field measurements have so far focused on surface and floodplain data (González-Fernández and Hanke, 2017; Kiessling et al., 2019; Roebroek et al., 2021). Only recently, large-scale measurements have been conducted on suspended macroplastic (Oswald et al., 2023; Schöneich-Argent et al., 2020). No data are available to quantify land-based transport into the river channel or the floodplain as well as removal rates. In addition, commonly-used measurement protocols for floodplain plastics (Kiessling et al., 2019; van Emmerik et al., 2020) do not enable one to distinguish between the various exchange terms involved. We simplified the model to make most use of the available plastic observations.

The net floodplain transport rate ($P_{\phi,N}$) [#/T or M/T] can be defined as the change in plastic item count or mass (N_ϕ) between two successive measurements, divided by the time (Δt) [T] between those measurements.

$$P_{\phi,N} = \frac{N_{\phi,i+1} - N_{\phi,i}}{\Delta t} \cdot \frac{A_\phi}{A_s} \quad (3)$$

Here, A_ϕ is the total floodplain area considered and A_s the observed floodplain area. Alternatively, the net floodplain transport rate $P_{\phi,N}$ can also be expressed as the difference between incoming and outgoing floodplain related transport terms:

$$P_{\phi,N} = \frac{\Delta S_\phi}{\Delta t} = (P_{\phi,U} + l_\phi) - (P_{\phi,D} + r_\phi) - e_\phi \quad (4)$$

We here consider that bed load transport is included in suspended plastic transport estimates. When measuring suspended plastics, nets are typically deployed at various depths (as described in Section 2.3.2), and nets placed in the lower section of the water column are likely to capture plastic items that have been mobilized from the riverbed (McGoran et al., 2023; Schöneich-Argent et al., 2020). We simplify our initial river plastic budget equation (Eq. (2)) by using Eq. (4):

$$\frac{\Delta S_t}{\Delta t} = P_{f,U} + P_{s,U} + l_c + e_\phi - P_{f,D} - P_{s,D} - r_c + P_{\phi,N} \quad (5)$$

In addition, all transport terms that cannot be linked to current observations, e.g.: l_c, r_c and e_ϕ were lumped together in a residual transport term ω ($\omega = -e_\phi - l_c + r_c$). Ultimately, the total residual term (R) is the sum of the change of storage over time and ω:

$$R = \frac{\Delta S_t}{\Delta t} + \omega = \underbrace{P_{f,U} + P_{s,U} - P_{f,D} - P_{s,D} + P_{\phi,N}}_{\text{Terms linked to observations}} \quad (6)$$

2.3. Plastic transport and storage equations

2.3.1. Plastic transport equations

Surface plastic transport (P_f) can be calculated as follows:

$$P_f = \frac{N_f}{\Delta t} \quad (7)$$

Here, N_f is the sampled amount of surface plastic in transport at the river surface [M or #] and Δt is the time between two measurements [T]. Note that surface measurements are typically conducted at the river cross-section, including the first 10–20 cm below the water surface. The sampled depth depends on the sampling method used, discharge and visibility conditions and thus a precise estimate of sampled depth cannot be provided. Surface plastic transport is expressed over the entire width of the river channel cross-section considered. Normalization by river width [M/T/L of river width or #/T/L of river width] is also possible.

To estimate suspended plastic transport (P_s), two equations can be formulated:

$$P_{s,1} = c_s \cdot Q \quad (8)$$

$$P_{s,2} = \frac{N_s}{\Delta t} \quad (9)$$

In Eq. (8), c_s is the suspended plastic concentrations in either mass or item count per water volume considered [M/L^3 or #/L^3, respectively], Q is the river discharge [L^3/T]. In Eq. (9), N_s is the suspended plastic count or mass [M or #] and Δt is the time between measurements [T]. Note that suspended plastic transport is here expressed for the entire depth area considered.

The net floodplain plastic transport ($P_{\phi,N}$) can be estimated using Eq. (3).

2.3.2. Plastic storage equations

Plastic storage in the floodplains (S_ϕ) can be calculated as follows:

$$S_\phi = (N_{\phi,i+1} - N_{\phi,i}) \cdot \frac{A_\phi}{A_s} \quad (10)$$

We estimated the plastic storage at the surface (S_f) by multiplying the longitudinal plastic amount [M/L or #/L] by the river section length [L]. The first is calculated by dividing the plastic transport [M/T or #/T] by the surface flow velocity ($\overline{u_f}$) [L/T]. We then extend our estimate of surface plastic storage from the cross-section to the full length of the river section through the multiplication by the river section length (L_c) [L] in the equation.

$$S_f = \frac{P_f}{\overline{u_f}} \cdot L_c \quad (11)$$

Suspended plastic storage (S_s) can be calculated as follows:

$$S_s = \frac{P_s}{\overline{u}} \cdot L_c \quad (12)$$

Here, $\overline{u}$ is the depth-averaged flow velocity [L/T].

2.3.3. Retention time-scale

The retention time-scale provides an estimate of the time required for a given quantity of plastics to be completely flushed out of a specific river section, given certain storage and transport values. The retention time-scale provides a rough estimate, as it assumes a constant outflow of plastics regardless of their specific characteristics such as size, buoyancy, mass; as well as perfect mixing. The retention time-scale can be specified for each river compartment considered (e.g.: surface, suspended or floodplain). It should be noted that the net floodplain transport rate, denoted as $P_{\phi,N}$ and defined in Eq. (4), represents an aggregate of various transport terms within the floodplain. Therefore, when we estimate the time-scales associated with the floodplain, we are essentially dealing with this combined, aggregated term. As a result, it is not possible to separately estimate the time-scales for the individual transport terms considered within the floodplains.

To estimate the retention time-scale T [T], the storage term (S) [M or #] can be divided by the transport term (P) [M/T or #/T]:

$$T = \frac{S}{P} \quad (13)$$

2.4. Application to two river sections in the Netherlands

We applied our river plastic budgeting approach in two selected river sections in the Netherlands. These sections were chosen due to the availability of plastic data, allowing us to maximize input data and minimize uncertainties in our budgeting approach.

2.4.1. River sections descriptions

We estimated the plastic budget for two river sections in the Netherlands located along the IJssel and the Waal (Fig. 2). The Waal section is located between the municipalities of Nijmegen and Tiel and is approximately 26 km long. This section of the river Waal has only mild meanders, compared to its upstream and downstream reaches. Section 2 includes the entire IJssel, which is approximately 118 km long, between Westervoort (near Arnhem) and the river outlet at Lake IJssel. A system of weirs controls the distribution of the discharge from the Upper Rhine to the IJssel and ensures a minimum flow of 30 m^3/s in the Nederrijn. This minimum flow is necessary to ensure adequate navigation depths along the Waal and to facilitate the inflow of freshwater to Lake IJssel (Schielen et al., 2008). The section lengths were determined as the distance along the river network between the most upstream and the most downstream plastic measurement location, which effectively constitute the upstream and downstream section boundaries.

Both sections form part of the Rhine: the Upper Rhine bifurcates at Millingen into the Pannerden Canal and the Waal. A few kilometers

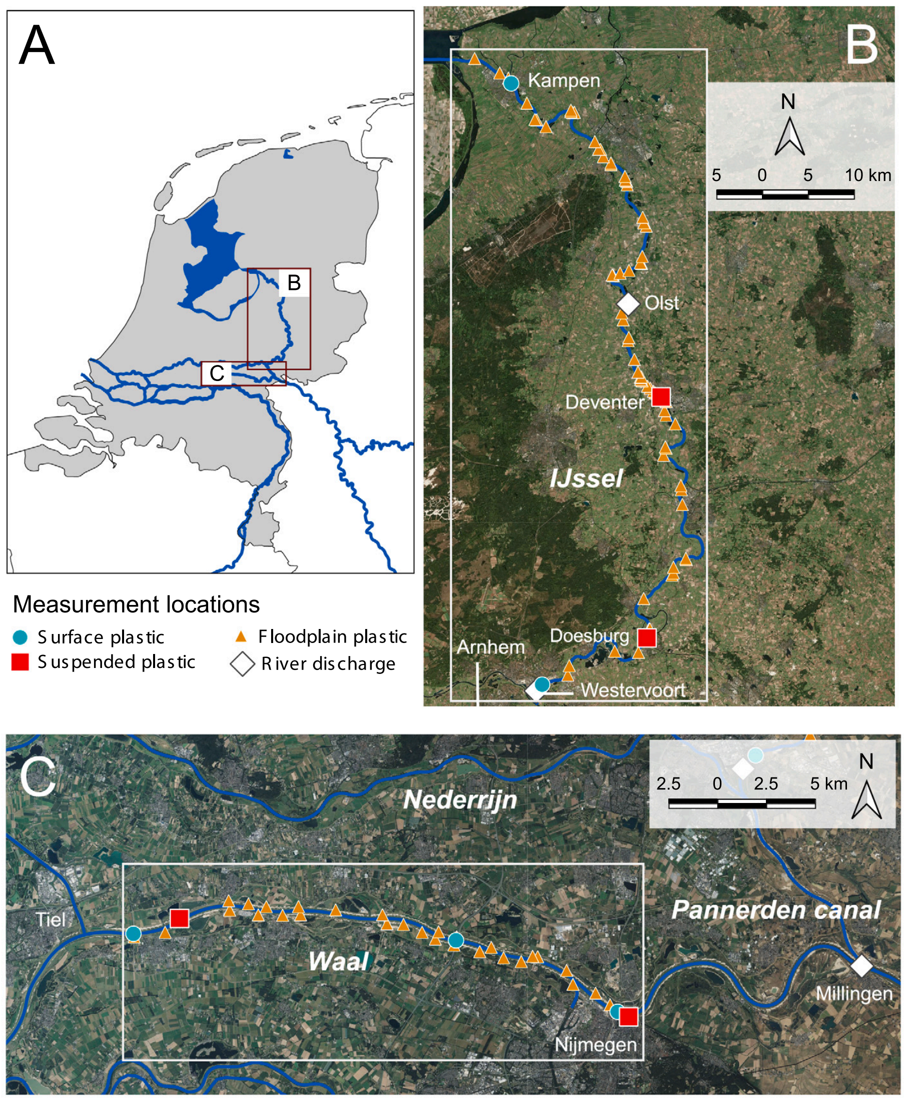


Fig. 2. Overview of the river sections. A. Overview of Dutch main rivers. B. IJssel section. C. Waal section. Note the different scales for each panel. For the Waal section, the closest discharge station was located outside of the section boundaries.

downstream, the Pannerden Canal branches into the river IJssel and the Nederrijn. Slightly over two-thirds (68%–70%) of the Rhine annual discharge at Lobith flows into the Waal and 13%–14% into the IJssel (Chowdhury et al., 2023). The sediment partitioning is similar, with the Waal receiving 65% to 95% of sediment fluxes, depending on grain sizes and the IJssel between 5% and 15% (Chowdhury et al., 2023). Both selected sections are located within the Eastern part of the country and are unaffected by tidal dynamics. During the measurement period, discharge ranged between 108 m^3/s and 967 m^3/s; and between 546 m^3/s and 4790 m^3/s at the Waal.

2.4.2. River plastic measurements

We used data from floodplain, suspended, and surface plastic measurements obtained at the considered river sections (Fig. 3). We estimated mass and item transport and storage for each compartment. Further information on plastic measurements and flow velocity estimates can be found in Appendix B (Extended Methods), as well as calculations to convert item estimates to mass estimates.

2.4.3. Model inputs

We calculated transport and storage per river section and compartment for the measurement duration (Tables C5 and C6, in Appendix C). The transport and storage values correspond to long-time averages and we did not differentiate between transports at specific flow conditions or other possible short-term variations.

We estimated the net floodplain plastic transport [M/T or #/T] using Eq. (3). Plastic measurements on floodplains also involved the removal of items, thus the term $N_{\phi,i}$ was by definition always zero. We averaged all available data for the river sections over space and time.

In addition to net floodplain transport, we also estimated the removal rate from floodplains (r_ϕ) [M/T or #/T]. The removal rate is a measure of how much plastics is taken out from the floodplains over time and is one of the outgoing terms included in the net floodplain transport rate (Eq. (3)). The removal rate r_ϕ was estimated as follows:

$$r_\phi = \frac{N_R}{\Delta t} \tag{14}$$

The rationale for this equation lies in the fact that the floodplain plastic measurements carried out by the *Schone Rivieren* program (Section 2.3.2) also involved cleaning the surveyed areas. To the best of our knowledge, no other large-scale cleanup operations have been documented in the two river sections considered. However, there may be other cleanup initiatives that have not been factored in, including individual voluntary cleanups.

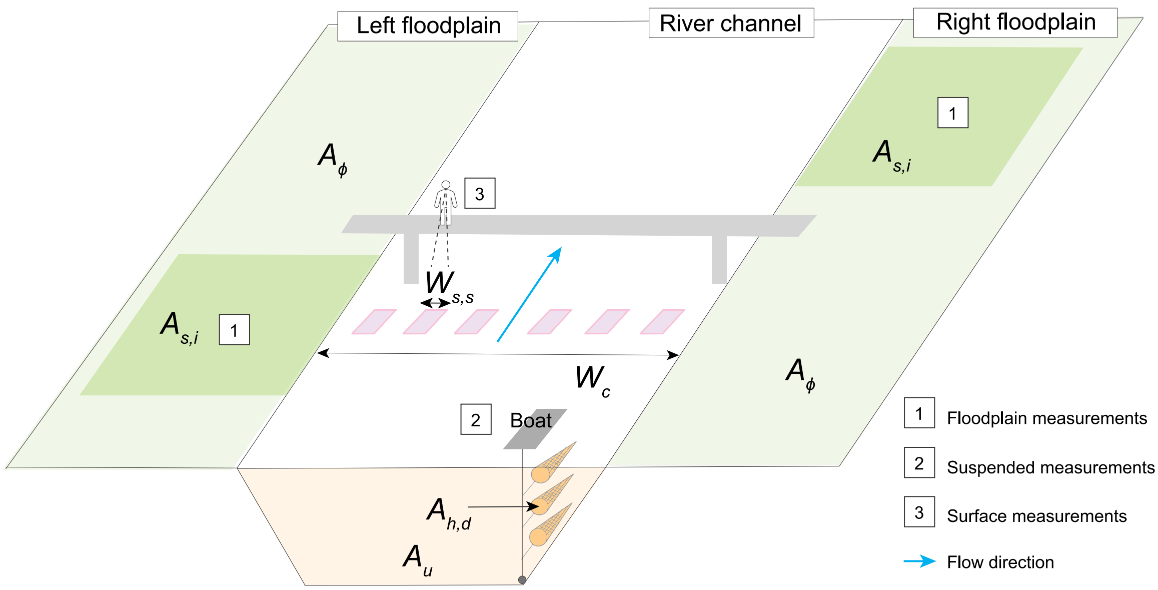


Fig. 3. Schematic representation of measurements conducted at the river section. On the floodplains, $A_{s,i}$ is the sampled area per measurement i and A_ϕ the total floodplain area considered. At the river surface, $W_{s,s}$ is the measurement track width per measurement s and W_c is the total river channel width. Below the river surface, $A_{h,d}$ is the sampled area per depth h and A_u is the total underwater surface area considered.

We estimated surface plastic transport as follows, using Eq. (7):

$$P_f = \frac{\overline{N_f}}{\Delta t} \cdot \frac{W_c}{W_s} \tag{15}$$

Here, $\overline{N_f}$ is the average surface plastic mass or count [M or #] per segment s. We averaged all available data for the segments over space and time. W_c is the total river width considered [L] and W_s is the segment observation width [L] covered by all segments.

We calculated suspended transport using Eq. (9), as the variables used were directly measured during the suspended plastic samplings. Using the river discharge method instead (Eq. (8)) would require us to use discharge data collected at different times and locations (Fig. 2).

3. Results

3.1. Vertical distribution of river plastics depends on mass or item based estimates

Suspended plastics account for 96% of item transport within the river channel (Fig. 4A and B) for the two river sections considered. Floating plastic account for 63%–70% of the total mass transport. This discrepancy can be attributed to the different characteristics of suspended and surface plastics. Surface plastics consist of heavier items, whereas lighter dominate among suspended plastics, with average masses of 7.1 g/# and 0.1 g/#, respectively. A logical implication is that surface items are larger in size compared to suspended plastics.

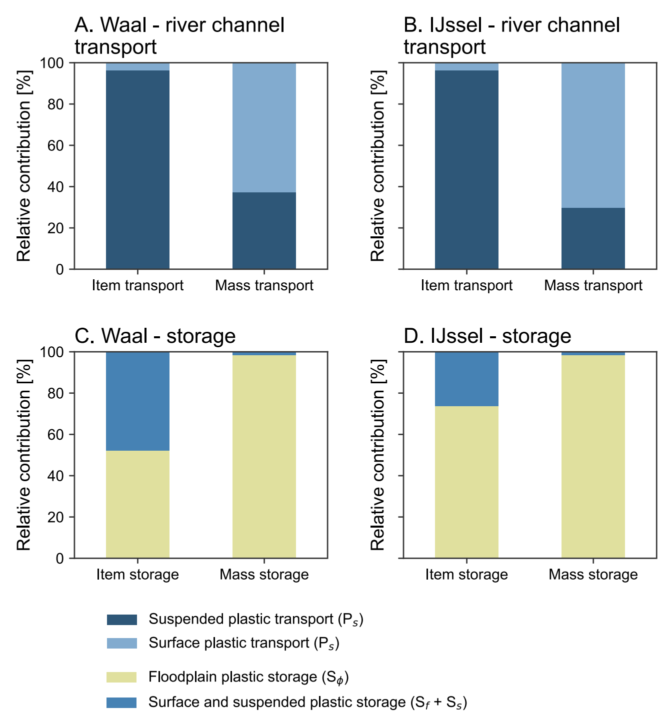


Fig. 4. Distribution of mass and item transport over river compartments for the Waal and IJssel sections.

3.2. Floodplains: a relevant compartment for both plastic storage and transport

The majority of plastics are stored within the floodplains, constituting 98% of the total mass storage and between 52% (Waal) to 74% (IJssel) of the item storage (Fig. 4C and D). We estimate that the Waal floodplains hold approximately 679 ± 423 kg of plastics; while the IJssel floodplains store around 1976 ± 2018 kg. This substantial difference in absolute mass storage can be explained by the differences in floodplain areas of the two river sections considered, with the floodplain areas amounting to 1.3 km^2 and 5.9 km^2 for the Waal and the IJssel, respectively. Normalized to the length of the river reach, these quantities translate to 13.1 ± 8.1 kg/km for the Waal and 8.4 ± 8.6 kg/km for the IJssel.

We quantified the net exchanges occurring within the floodplains. We found positive net floodplain transport rates, indicating a net accumulation of plastic over time onto the floodplains. In the Waal section, the net floodplain transport was estimated at 0.2 ± 0.1 kg/h (16 ± 13 #/h), while in the IJssel section, it amounted to 0.6 ± 1.0 kg/h

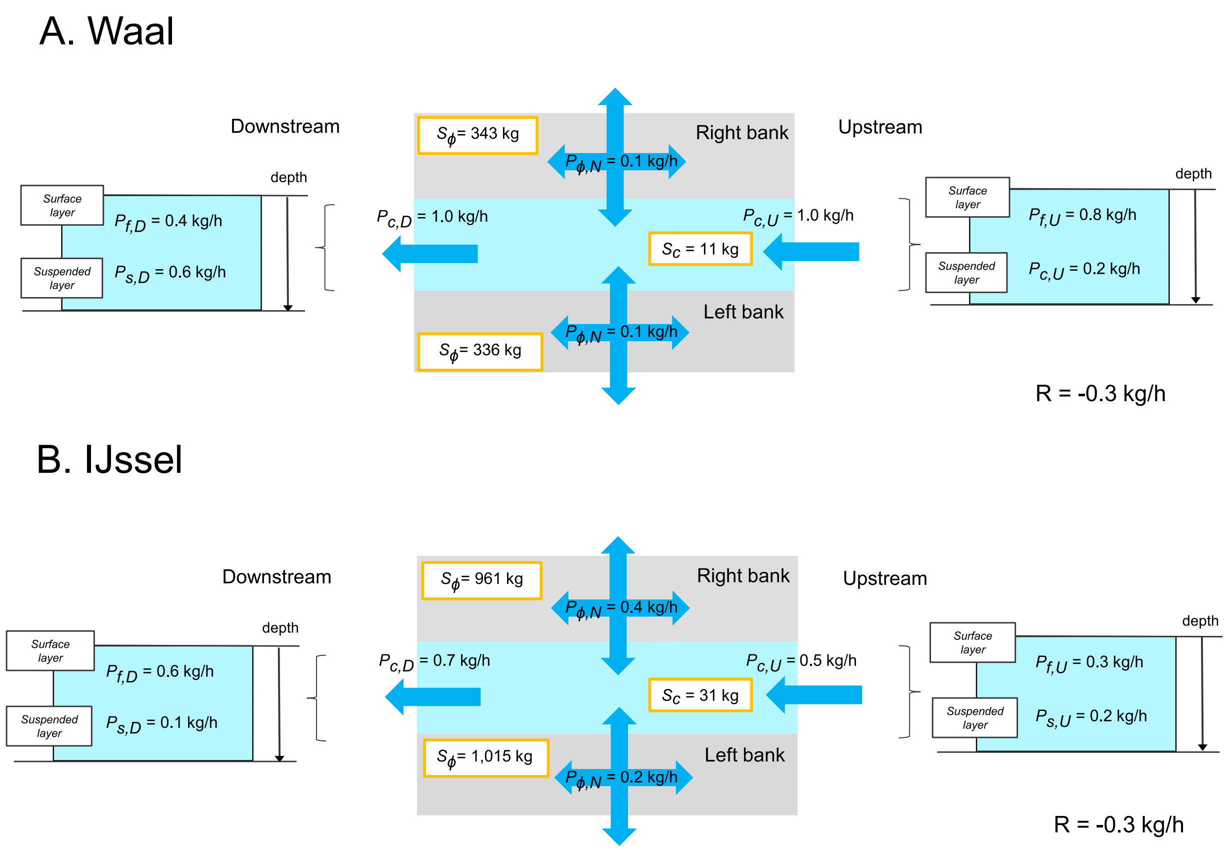


Fig. 5. Plastic mass transport and storage for two river sections: A. Waal and B. IJssel.

(62 ± 163 #/hour). Normalized to the floodplain length considered, the net floodplain transport rates were found to be similar between the two river reaches considered. The rates were estimated at 3.8 ± 1.9 g/h/km of floodplain (0.3 ± 0.3 #/h/km) for the Waal and 2.5 ± 4.2 g/h/km of floodplain (0.3 ± 0.7 #/h/km for the IJssel).

Among the various transport components comprising the net floodplain transport, the removal rate was the only term that could be quantified. We found that these removal rates were negligible in comparison to the overall net floodplain transport (less than 1%). In the case of the Waal section, both item and mass removal rates accounted for only about 0.3% of the net floodplain transport rate, while for the IJssel section, this proportion was even lower, at 0.1%.

3.3. River channel transport in the IJssel and Waal sections

Comparing the two sections, the Waal shows nearly double the mass and item transport of the IJssel (Waal: 1.1 ± 0.8 kg/h and 4480 ± 1521 #/h; IJssel 0.6 ± 0.7 kg/h and 1974 ± 1145 #/h) (Tables C7 and C8, Appendix C). Normalized to the river sections widths however, transport rates are higher in the IJssel than in the Waal River channel. Indeed, we found a plastic transport rate of 5.2 ± 4.9 g/h/km of river width for the IJssel and of 3.3 ± 2.4 g/h/km for the Waal.

In the Waal, we found that the upstream and downstream mean plastic transport rates in the river channel are equal, at 1.0 kg/h (Fig. 5A). In the IJssel section, a difference was observed between upstream and downstream river channel transport, with rates of 0.5 ± 0.4 kg/h and 0.7 ± 0.9 kg/h, respectively (Fig. 5B and Table C8, Appendix C). Overall, the plastic mass transport rates at the various section boundaries were found to be relatively comparable between the two river sections, ranging from 0.5 kg/h to 1.0 kg/h on average.

3.4. Closing the plastic budget

We found large total residuals, with average total transport residuals of −0.3 kg/h for both the IJssel and the Waal sections (Table 2A). These residual terms collectively contribute to 30% to 50% of the plastic mass transport within the river channel (averaged between upstream and downstream river channel transport), depending on the river section considered. Item transport residuals were even larger, accounting for as much as 80% and 40% river channel transport for the Waal and IJssel, respectively. The negative sign of the mass transport residuals indicates a loss of plastic in storage over time and/or the presence of missing input terms. These could be land-based inputs into the river channel (I_c) and/or lateral exchanges between river channel and floodplains (e_ϕ), as both were not quantified.

3.5. Long-term retention of plastics in floodplains vs. short-term presence in the river channel

The retention time-scales for the river channel and floodplain are shown in Table 2A. For the floodplains, the estimated retention time-scales range from 97 to 170 d, depending on the specific river section and the metrics used (mass or item transport and storage values). In contrast, the retention time-scales for river channel plastic are considerably shorter, ranging from 20 to 86 h. These findings highlight the longer-term storage of plastics within floodplain environments compared to the relatively rapid turnover of plastics within the river channel.

4. Discussion

4.1. Most macroplastics are stored within the floodplains

Our findings confirm the significance of floodplains as storage sites for plastic, particularly when considering plastic mass (Roebroek et al.,

Table 2
A. Total transport residuals (R) and B. Retention time-scales (T).

A. Total residual transport rates (R)

	Mass transport		Item transport	
	Transport rate	**Fraction of channel transport**	**Transport rate**	**Fraction of channel transport**
	[kg/h]	[–]	[#/h]	[–]
Waal	-0.3	0.3	3,463	0.8
IJssel	-0.3	0.5	-881	0.4

B. Retention time-scale (T)

	Floodplains		River channel	
	Mass [d]	**Item [d]**	**Mass [h]**	**Item [h]**
Waal	170	148	20	20
IJssel	145	97	84	86

2021; van Emmerik et al., 2022a). We estimated that 98% of the total stored plastic mass was located in the floodplains, and only 2% in the river channel. This highlights the importance of targeting floodplains and riverbanks in reduction strategies. Our results also emphasize the importance of plastic exchanges between the river channel and the floodplains. Despite being lower than longitudinal plastic transport, the net floodplain transport remains substantial, ranging from 0.1 kg/h to 0.4 kg/h for the two river reaches considered (compared to 1.3 and 0.6 kg/h of longitudinal transport in the river channel). The individual floodplain transport rates might be much larger than the net floodplain transport rate. Also, the floodplain areas we considered for both sections are very narrow, with a constant width of 25 m and our floodplain storage and transport estimates are therefore likely highly conservative. The actual floodplain widths average 550 m along the Waal and 500 m along the IJssel (Reeze et al., 2017). Current data limit the estimation of individual floodplain transport rates. We could not provide specific estimates for deposition, mobilization and land-based transport. Bankfull stages were exceeded twice for the Waal between floodplain plastic measurements and once for the IJssel (Fig. C6, Appendix C). This suggests that lateral exchanges between river channel and floodplains, involving processes such as deposition and mobilization, likely played a substantial role on the overall net floodplain transport rate. Removal rate was estimated to be negligible (less than 1% of the net floodplain transport rates). To gain a more comprehensive understanding of plastic transport processes within floodplains and riverbanks, we need to rethink plastic monitoring, in order to characterize individual transport terms. Physical sampling, as well as alternative monitoring techniques such as item tagging and camera-based referencing could provide insights on the transport rates of plastic from and onto floodplains. For example, Grosfeld (2022) conducted frequent (sub-weekly/weekly) surveys to count macroplastics at a groyne site along the river Waal. This enabled them to provide high-frequency snapshots of floodplain plastic counts and estimate deposition and re-mobilization rates over the study period. The temporal scale at which floodplain transport processes are most relevant remains uncertain, due to our limited understanding of lateral exchange processes. However, preliminary evidence suggests that re-mobilization rates are influenced by changes in water level, but such a relation was not found for deposition processes (Grosfeld, 2022). To bridge this knowledge gap, it is crucial to monitor floodplain plastics during periods of high variation in discharge and water level, as this approach allows for a more accurate assessment of deposition and mobilization dynamics. Overall, our study underscores the necessity of considering floodplains in both reduction efforts and monitoring initiatives.

4.2. The contribution of suspended plastics to river channel transport

Our study highlights the necessity to monitor suspended plastics. Suspended plastics accounted for 96% of total transported items in the river channel. Haberstroh et al. (2021) found that approximately 61% of items were transported below the water surface in the Mekong. In terms of mass transport, suspended plastics constitutes a lower proportion (30%–37%) of longitudinal river transport but their contribution is far from negligible. Haberstroh et al. (2021) found that 99.6% of the total plastic mass was transported at the surface. This large disparity in the contributions of surface and suspended plastic transport between two major rivers underscores the natural variability between systems. It also indicates the necessity for field calibration when attempting to convert findings from surface to entire river channel transport. This is particularly relevant for the validation of global plastic emission models, as these models frequently rely on surface plastic observations and convert them into total river transport rates using such conversion factors (Meijer et al., 2021). We found that 63%–70% of river plastic mass transport occurs at the river surface and only 4% of the item transport. This highlights the importance of distinguishing between item and mass transport; and provides some nuance to the claims by Valero et al. (2022) that neglecting suspended plastics could result in gross underestimation (up to 90%) of total river transport. We found suspended plastics to be much lighter on average than surface plastics (0.1 g/# vs 7.1 g/# on average). This difference in mass is hypothesized to be caused by their smaller size compared to surface plastics. The limited sampling area for suspended plastic net measurements may not effectively capture larger and heavier items. However, Collas et al. (2021) compared the composition and concentrations of suspended plastics collected through larvae nets and larger nets (stow nets). Their study did not find significant differences in plastic composition nor item concentrations. Oswald et al. (2023) found that suspended plastics in the Waal predominantly consisted of soft fragments, accounting for approximately 57% of the total suspended plastic count. Vriend et al. (2020) observed that hard polyolefins comprised a larger proportion of surface plastics in terms of mass. These findings support the hypothesis proposed by Valero et al. (2022) that longitudinal plastic transport occurs at two distinct regimes: (1) surface transport for positively buoyant and large items; (2) suspension within the water column for neutrally and negatively buoyant plastics. Currently, there is a lack of precise quantification and characterization of suspended plastics in terms of item composition, mass and density to reliably compare surface and suspended plastic transport regimes. Furthermore, the uncertainty associated with suspended plastic measurements is greater compared to floodplain and surface measurements. Extrapolation factors, which represent the scaling between the sampled areas or width and the entire area or width being studied, are substantially higher for suspended measurements (ranging between 231 and 866) than for floodplains (28–39) and surface (2–4) measurements (Table C9). It is unknown whether suspended plastic transport rates vary considerably across the cross-sectional area. To address this limitation, the use of larger nets such as stow net vessels (Oswald et al., 2023) would significantly increase the coverage of suspended sampled area. Finally, suspended plastic measurements were mainly done under low discharge conditions (Fig. C6). To fully characterize the distribution between surface and suspended plastic transport within the river channel, it is essential to extend these measurements to encompass a larger range of discharge flows as well. Vriend et al. (2023) found that suspended plastic concentrations increased significantly with increased discharge, further highlighting the need of including suspended plastic data collected during high-flow conditions.

4.3. Plastic routing differs from sediment and water

Longitudinal transport rates at the Waal was found to be approximately a factor of two higher than our estimates for the IJssel, both for item and mass transport rates (Waal: 1.1 kg/h and 4480 #/h; IJssel 0.6 kg/h and 1974 #/h). In comparison, sediment loads are between 18 and 4 times higher at the Waal compared to the IJssel; and 5 times higher for water flow (see Section 2.4.1). This discrepancy suggests that local factors, including river morphology, floodplain characteristics, and proximity to potential pollution sources, play a dominant role in driving plastic transport dynamics. Two hypotheses can explain this smaller difference in plastic transport rates compared to sediment loads and discharge between these two connected sections of the Rhine. The first hypothesis suggests that the plastic inputs are occurring very close to the monitored areas, and therefore the transport rates found in the IJssel and Waal do not reflect the routing of plastics already present in the Upper Rhine before the bifurcation (Fig. 2A). This hypothesis is consistent with previous studies that have found limited travel distances by plastic, due to frequent deposition on the riverbanks and floodplains (Ledieu et al., 2022; Lotcheris et al., 2024; Tramoy et al., 2020a), even under high discharge conditions (van Emmerik et al., 2023). A second hypothesis suggests that plastic transport dynamics in the IJssel may be more responsive to increased discharge conditions than in the Waal. Surface plastic transport showed strong positive correlations with discharge in the IJssel but not in the Waal (see Appendix B "Filtering based on river discharge conditions"). Possibly, inundation of floodplains and subsequent mobilization of plastics into the river channel primarily influence transport dynamics within the IJssel. To investigate this further, a detailed analysis of bankfull discharge events and floodplain spatial distribution within the Rhine is necessary.

4.4. Where does the remaining plastic go?

We found total residuals for the plastic mass budget of −0.3 kg/h for both river sections studied, indicating a net loss in plastic mass. Our total residual term includes all unaccounted transport terms (ω). This includes lateral exchanges between the floodplain and the river channel (e_ϕ), removal rate from the river channel (r_c), and land-based inputs into the river channel (l_r). We hypothesize that the removal rate from the river channel would not be significantly higher than the removal rate from the floodplains. There is no infrastructure targeted at plastic removal installed in either of the two river sections. We estimated the removal rate from the floodplains (r_ϕ) to be negligible, representing less than 1% of net floodplain transport. Given these considerations, it appears unlikely that the negative mass residuals found in the plastic mass budget are the result of removal rates from the river channels. An explanation for the observed negative mass residuals could be that plastics are lost through other outgoing transport processes, such as deposition and burial in riverbed sediments. Although our current application of the river plastic budget does not incorporate a burial term, this possibility was acknowledged in our conceptual model. An alternative explanation for the residuals relates to the uncertainties of the transport estimates. The residual term can serve as an indicator of overall uncertainty rather than signifying a loss in the mass budget. The standard deviations often fall within the same range as our mean transport values Tables C7 and C8). In the case of the Waal, the standard deviation for net floodplain is ± 0.1 kg/h, and ± 0.8 kg/h for river channel transport. For the IJssel, the standard deviation for net floodplain transport is ± 1.0 kg/h, and for river channel transport, ± 0.7 kg/h. This relatively large range in the transport estimates is related to the seasonality and temporal variability in plastic transport processes (van Emmerik et al., 2022b; Vriend et al., 2023). To reduce the large uncertainties in our river plastic budget, simultaneous measurements in multiple compartments within the river section are essential, rather than employing long-term averaged values. However, conducting simultaneous measurements across various river compartments is practically challenging. Another strategy for reducing uncertainties could involve either shortening or extending the period over which the budgeting approach is established. Nonetheless, the appropriate time-scale for establishing the plastic budget remains currently unknown.

4.5. Next steps in river plastic budget approaches

Model-based estimates indicate that less than 2% of the total mismanaged plastic waste generated on land makes it to the ocean (Meijer et al., 2021). Field-based studies often corroborate these findings by identifying comparable export rates within plastic river transport (Lotcheris et al., 2024). For instance, Lotcheris et al. (2024) reported that approximately 3% of plastic transported in rivers left the system boundaries. These findings confirm the need to extend the scope of plastic studies, moving beyond the quantification of river emission rates into the ocean and longitudinal river channel transport, as commonly done in plastic research studies (González-Fernández et al., 2021; Meijer et al., 2021; Lebreton et al., 2017; van Calcar and van Emmerik, 2019). Therefore, the use of river plastic budget approaches is valuable, as they promote a systemic approach to comprehensively understand river plastic dynamics, by extending beyond the traditional focus on the river channel. Moreover, plastic budget approaches are useful in creating order in the apparent chaos of observational and modeling data available. In similarity to sediment budget approaches (Frings and Ten Brinke, 2017), integrating all available river plastic data can enable us to obtain a unified and coherent view of plastic pollution in rivers. Finally, plastic budget approaches are crucial in setting priorities for plastic reduction interventions. By identifying the river compartments that predominantly store and transport plastics, these approaches offer guidance for targeted reduction efforts. Our study illustrated that floodplains are major sinks for plastics, emphasizing the necessity to focus on reduction and monitoring efforts in these areas. The next steps in advancing river plastic budgets involve three key aspects. First, we need to better understand floodplain transport dynamics, notably by quantifying plastic deposition and mobilization and the relevant time-scales of these processes. The current focus on floodplains primarily provides snapshots of plastic quantities, and thus the various transport mechanisms are not understood. In addition, the long time intervals between floodplain observations (in our application, spanning several months) do not enable us to understand the relevant time-scales governing the exchanges between the floodplain and river channel. Also, the floodplain transport terms are not spatially uniformly distributed, highlighting the need to further understand how they affect different areas within the floodplain. Second, future steps may further refine our plastic budget model by explicitly incorporating channel and floodplain characteristics. Several field-based studies have highlighted the influence of river characteristics on plastic transport and retention. Integrating these elements would represent a crucial step towards extending the applicability of our budget approach to river sections lacking direct observations. Below we provide some examples of the potential influence of river and floodplain characteristics on river plastic transport and storage. Channel sinuosity, the presence of riparian vegetation and riverbank roughness have all been identified as factors increasing retention of plastics at riverbanks (Cesarini and Scalici, 2022; Newbould et al., 2021), compared to non-vegetated banks and straight channels. Sinuosity, presence of riparian vegetation and higher riverbank roughness would thus lead to increased plastic storage on floodplains, all other variables remaining unchanged. Additionally, the presence of groyne fields within river channels has been shown to result in plastic routing through recirculation zones. This can potentially prolong residence time of plastics within specified river sections (Przyborowski et al., 2024). Therefore, the presence of groyne field would result in increased plastic storage at the water surface, all other variables remaining unchanged. It is essential to consider other river discontinuities, such as dams, bridges and weirs (Mennekes et al., 2024), which may play a significant role in influencing the plastic budget between various river sections, as is the case for sediment transport along, for example, the Rhine (Frings et al., 2019). The presence of river discontinuities would also result in increased plastic storage at the water surface, all variables remaining unchanged. Lastly, bi-directional flows generated by tidal dynamics increase plastic transport distances and thus the retention probability of plastics, for instance through deposition on riverbanks or accumulation at river structures such as mooring piers (Lotcheris et al., 2024; Schreyers et al., 2024). Tidal influence would likely result in both increased plastic storage at the water surface and increased plastic storage in floodplains.

Third, accounting for floods might be key in determining the budget between flood driven mobilization and deposition (van Emmerik, 2024). Indeed, it is yet unclear whether floods act mainly a factor for plastic mobilization e.g.: flushing out of a given system) or as a factor of deposition. So far, there is only scattered evidence of the impact of floods on plastic transport and storage, with very contrasted findings depending on the phase of the flood event during which observations were collected (van Emmerik et al., 2023), as well as their locations (Hauk et al., 2023).

5. Conclusions

We present an approach to quantify the river plastic budget. Our results highlight the dominant role of floodplains in plastic storage, accounting for 98% of the total mass of plastics observed in the two river sections considered. Estimates of the retention time-scales showed that plastics tend to remain in floodplains for several months, in contrast to the shorter retention times in the river channel. However, further research is necessary to gain a more comprehensive understanding of floodplain-river channel exchanges. Specifically, the quantification of floodplains exchanges and the underlying processes involved in deposition, re-mobilization and land-based inputs could not be independently assessed using floodplain measurements alone. The contribution of suspended plastic transport within the river channel is found to vary considerably depending on whether mass or item transport is considered (96% and 30%–37%, respectively). These results support the hypothesis of two distinct plastic transport regimes, with surface transport for positively buoyant and large items, and transport in suspension within the water column for neutrally and negatively buoyant plastics. Large-scale suspended plastic monitoring is in its early stages, and further measurements are needed to improve spatial coverage and reduce uncertainties associated with extrapolating results to suspended cross-sectional areas. Measurements during different discharge conditions are also crucial to better understand the distribution between surface and suspended transport under varying hydrological conditions. Our study offers a practical example for harmonizing observational data and estimating plastic transport and storage based on measurements conducted across various river compartments. Our methodology can be replicated in other regions and with different datasets, enabling the application of similar approaches and the quantification of plastic transport and storage elsewhere. In conclusion, our study advances our understanding of plastic transport and storage within rivers and provides practical guidance for future research in this field. We encourage to take a systematic approach in quantifying plastic dynamics by developing comprehensive monitoring programs that simultaneously measure plastic pollution across various river compartments. These programs have the potential to reveal transport dynamics that may not have been fully captured and understood to date.

CRediT authorship contribution statement

Louise J. Schreyers: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. **Tim H.M. van Emmerik:** Conceptualization, Methodology, Writing – review & editing. **Fredrik Huthoff:** Conceptualization, Investigation, Writing – review & editing. **Frank P.L. Collas:** Data curation, Methodology, Writing – review & editing. **Carolien Wegman:** Conceptualization, Writing – review & editing. **Paul Vriend:** Data curation, Methodology, Writing – review & editing. **Anouk Boon:** Data curation, Writing – review & editing. **Winnie de Winter:** Data curation, Writing – review & editing. **Stephanie B. Oswald:** Writing – review & editing. **Margriet M. Schoor:** Writing – review & editing. **Nicholas Wallerstein:** Conceptualization, Supervision, Writing – review & editing. **Martine van der Ploeg:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Remko Uijlenhoet:** Conceptualization, Methodology, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data used in this study can be accessed at: https://doi.org/10.1016/j.watres.2024.121786.

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Appendices A, B and C. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.watres.2024.121786.

References

Acha, E., Mianzan, H., Iribarne, O., Gagliardini, D., Lasta, C., Daleo, P., 2003. The role of the Rio de la Plata bottom salinity front in accumulating debris. Mar. Pollut. Bull. 46 (2), 197–202.

Blettler, M.C., Abrial, E., Khan, F.R., Sivri, N., Espinola, L.A., 2018. Freshwater plastic pollution: Recognizing research biases and identifying knowledge gaps. Water Res. (ISSN: 0043-1354) 143, 416–424. http://dx.doi.org/10.1016/j.watres.2018.06.015.

Cesarini, G., Scalici, M., 2022. Riparian vegetation as a trap for plastic litter. Environ. Pollut. 292, 118410.

Chowdhury, M.K., Blom, A., Ylla Arbós, C., Verbeek, M.C., Schropp, M.H., Schielen, R.M., 2023. Semicentennial response of a bifurcation region in an engineered river to peak flows and human interventions. Water Resour. Res. 59 (4), e2022WR032741.

Climo, J.D., Oswald, S.B., Buschman, F.A., Hendriks, A.J., Collas, F.P.L., 2022. Inland navigation contributes to the remobilization of land-based plastics into riverine systems. Front. Water (ISSN: 2624-9375) 4, http://dx.doi.org/10.3389/frwa.2022.888091.

Collas, F., Oswald, S., Verberk, W., 2021. Plastic in de waterkolom van de Boven-Rijn, Waal en IJssel. Technical Report, Radboud University.

Constant, M., Alary, C., De Waele, I., Dumoulin, D., Breton, N., Billon, G., 2021. To what extent can micro-and macroplastics be trapped in sedimentary particles? A case study investigating dredged sediments. Environ. Sci. Technol. 55 (9), 5898–5905.

Delorme, A., Koumba, G., Roussel, E., Delor-Jestin, F., Peiry, J.L., Voldoire, O., et al., 2021. The life of a plastic butter tub in riverine environments. Environ. Pollut. 287, 117656.

Frings, R., Hillebrand, G., Gehres, N., Banhold, K., Schriever, S., Hoffmann, T., 2019. From source to mouth: Basin-scale morphodynamics of the Rhine river. Earth-Sci. Rev. 196, 102830.

Frings, R.M., Ten Brinke, W.B., 2017. Ten reasons to set up sediment budgets for river management. Int. J. River Basin Manag. 16 (1), 35–40.

Gasperi, J., Dris, R., Bonin, T., Rocher, V., Tassin, B., 2014. Assessment of floating plastic debris in surface water along the Seine river. Environ. Pollut. (ISSN: 0269-7491) 195, 163–166. http://dx.doi.org/10.1016/j.envpol.2014.09.001.
González-Fernández, D., Cózar, A., Hanke, G., Viejo, J., Morales-Caselles, C., Bakiu, R., Barceló, D., Bessa, F., Bruge, A., Cabrera, M., et al., 2021. Floating macrolitter leaked from Europe into the ocean. Nat. Sustain. 4 (6), 474–483.
González-Fernández, D., Hanke, G., 2017. Toward a harmonized approach for monitoring of riverine floating macro litter inputs to the marine environment. Front. Mar. Sci. 4, 86.
Grosfeld, J., 2022. Macrolitter in Groyne Fields: short Term Variability & the Influence of Natural Processes (Master's thesis). Delft University of Technology.
Haberstroh, C.J., Arias, M.E., Yin, Z., Sok, T., Wang, M.C., 2021. Plastic transport in a complex confluence of the Mekong River in Cambodia. Environ. Res. Lett. 16 (9), 095009.
Hauk, R., van Emmerik, T.H., van der Ploeg, M., de Winter, W., Boonstra, M., Löhr, A.J., Teuling, A.J., 2023. Macroplastic deposition and flushing in the Meuse river following the July 2021 European floods. Environ. Res. Lett. 18 (12), 124025.
Kiessling, T., Knickmeier, K., Kruse, K., Brennecke, D., Nauendorf, A., Thiel, M., 2019. Plastic pirates sample litter at rivers in Germany – riverside litter and litter sources estimated by schoolchildren. Environ. Pollut. (ISSN: 0269-7491) 245, 545–557. http://dx.doi.org/10.1016/j.envpol.2018.11.025.
Kooi, M., Nes, E.H.v., Scheffer, M., Koelmans, A.A., 2017. Ups and downs in the ocean: effects of biofouling on vertical transport of microplastics. Environ. Sci. Technol. 51 (14), 7963–7971.
Lebreton, L., Kooi, M., Mani, T., Mintenig, S.M., Tekman, M.B., van Emmerik, T., Wolter, H., 2022. Plastics in freshwater bodies. In: Plastics and the Ocean. ISBN: 9781119768432, pp. 199–225. http://dx.doi.org/10.1002/9781119768432.ch7.
Lebreton, L.C., Van Der Zwet, J., Damsteeg, J.W., Slat, B., Andrady, A., Reisser, J., 2017. River plastic emissions to the world's oceans. Nat. commun. 8 (1), 1–10.
Ledieu, L., Tramoy, R., Mabilais, D., Ricordel, S., Verdier, L., Tassin, B., Gasperi, J., 2022. Macroplastic transfer dynamics in the Loire estuary: Similarities and specificities with macrotidal estuaries. Mar. Pollut. Bull. 182.
Leopold, L.B., Wolman, M.G., Miller, J.P., Wohl, E.E., 1964. Fluvial Processes in Geomorphology. Courier Dover Publications.
Lotcheris, R., Schreyers, L., Bui, T., Thi, K., Nguyen, H.Q., Vermeulen, B., van Emmerik, T., 2024. Plastic does not simply flow into the sea: River transport dynamics affected by tides and floating plants. Environ. Pollut. (ISSN: 0269-7491) 345, 123524. http://dx.doi.org/10.1016/j.envpol.2024.123524.
Mani, T., Hawangchu, Y., Khamdahsag, P., Lohwacharin, J., Phihusut, D., Arsiranant, I., Junchompoo, C., Piemjaiswang, R., 2023. Gaining new insights into macroplastic transport 'hotlines' and fine-scale retention-remobilisation using small floating high-resolution satellite drifters in the Chao Phraya River estuary of Bangkok. Environ. Pollut. 320, 121124. http://dx.doi.org/10.1016/j.envpol.2023.121124.
McGoran, A.R., Clark, P.F., Smith, B.D., Morritt, D., 2023. Macrolitter and mesolitter in the Thames Estuary: A temporal litter assessment and brand audit of submerged and riverbed debris. Environ. Pollut. (ISSN: 0269-7491) 337, 122484. http://dx.doi.org/10.1016/j.envpol.2023.122484.
Meijer, L.J., van Emmerik, T., van der Ent, R., Schmidt, C., Lebreton, L., 2021. More than 1000 rivers account for 80% of global riverine plastic emissions into the ocean. Sci. Adv. 7 (18), eaaz5803.
Mellink, Y.A., van Emmerik, T.H., Mani, T., 2024. Wind-and rain-driven macroplastic mobilization and transport on land. Sci. Rep. 14 (1), 3898.
Mennekes, D., Mellink, Y., Schreyers, L.J., van Emmerik, T.H.M., Novack, B., 2024. Macroplastic fate and transport modeling: freshwaters act as main reservoirs (submitted for publication).
Newbould, R., Powell, D.M., Whelan, M., 2021. Understanding river plastic transport with tracers and GPS. Nat. Rev. Earth Environ. 2, 591.
Oswald, S.B., Ragas, A.M., Schoor, M.M., Collas, F.P., 2023. Quantification and characterization of macro- and mesoplastic items in the water column of the river Waal. Sci. Total Environ. (ISSN: 0048-9697) 877, 162827. http://dx.doi.org/10.1016/j.scitotenv.2023.162827.
Przyborowski, L., Cuban, Z., Łoboda, A., Robakiewicz, M., Biegowski, S., Kolerski, T., 2024. The effect of groyne field on trapping macroplastic. Preliminary results from laboratory experiments. Sci. Total Environ. (ISSN: 0048-9697) 921, 171184. http://dx.doi.org/10.1016/j.scitotenv.2024.171184.
Reeze, B., van Winden, A., Postma, J., Pot, R., Hop, J., Liefveld, W., 2017. Watersysteemrapportage Rijntakken 1990–2015: ontwikkelingen waterkwaliteit en ecologie. Harderwijk: Bart Reeze Water Ecologie.
Roebroek, C.T.J., Hut, R., Vriend, P., de Winter, W., Boonstra, M., van Emmerik, T.H.M., 2021. Disentangling variability in riverbank macrolitter observations. Environ. Sci. Technol. 55 (8), 4932–4942. http://dx.doi.org/10.1021/acs.est.0c08094.
Roebroek, C.T.J., Laufkötter, C., González-Fernández, D., van Emmerik, T., 2022. The quest for the missing plastics: Large uncertainties in river plastic export into the sea. Environ. Pollut. 312, 119948. http://dx.doi.org/10.1016/j.envpol.2022.119948.
Russell, C.E., Fernández, R., Parsons, D.R., Gabbott, S.E., 2023. Plastic pollution in riverbeds fundamentally affects natural sand transport processes. Commun. Earth Environ. 4 (1), 255.
Schielen, R.M.J., Havinga, H., Lemans, M., 2008. Dynamic control of the discharge distributions of the Rhine River in the Netherlands. In: Altinakar, M., Kokpinar, M., Aydin, I., Cokgor, S., Kirkgoz, S. (Eds.), Proceedings of River Flow 2008- Fourth International Conference on Fluvial Hydraulics, 3-5 September 2008, Izmir, Turkey. In: River Flow 2008: 4th International Conference on Fluvial Hydraulics - Izmir, Turkey, Kubaba Congress Department and Travel Services, Izmir, Turkey, pp. 395–404.
Schirinzi, G.F., Köck-Schulmeyer, M., Cabrera, M., González-Fernández, D., Hanke, G., Farré, M., Barceló, D., 2020. Riverine anthropogenic litter load to the Mediterranean Sea near the metropolitan area of Barcelona, Spain. Sci. Total Environ. (ISSN: 0048-9697) 714, 136807. http://dx.doi.org/10.1016/j.scitotenv.2020.136807.
Schöneich-Argent, R.I., Dau, K., Freund, H., 2020. Wasting the North Sea? – a field-based assessment of anthropogenic macrolitter loads and emission rates of three German tributaries. Environ. Pollut. (ISSN: 0269-7491) 263, 114367. http://dx.doi.org/10.1016/j.envpol.2020.114367.
Schreyers, L.J., Van Emmerik, T.H., Bui, T.K.L., van Thi, K.L., Vermeulen, B., Nguyen, H.-Q., Wallerstein, N., Uijlenhoet, R., van der Ploeg, M., 2024. River plastic transport affected by tidal dynamics. Hydrol. Earth Syst. Sci. 28 (3), 589–610.
Schwarz, A., Ligthart, T., Boukris, E., van Harmelen, T., 2019. Sources, transport, and accumulation of different types of plastic litter in aquatic environments: A review study. Mar. Pollut. Bull. (ISSN: 0025-326X) 143, 92–100. http://dx.doi.org/10.1016/j.marpolbul.2019.04.029.
Tramoy, R., Gasperi, J., Colasse, L., Silvestre, M., Dubois, P., Noûs, C., Tassin, B., 2020b. Transfer dynamics of macroplastics in estuaries – new insights from the Seine estuary: Part 2. short-term dynamics based on GPS-trackers. Mar. Pollut. Bull. 160, 111566. http://dx.doi.org/10.1016/j.marpolbul.2020.111566, Publisher: Elsevier BV.
Tramoy, R., Gasperi, J., Colasse, L., Tassin, B., 2020a. Transfer dynamic of macroplastics in estuaries — New insights from the Seine estuary: Part 1. long-term dynamic based on date-prints on stranded debris. Mar. Pollut. Bull. 152, 110894. http://dx.doi.org/10.1016/j.marpolbul.2020.110894, Publisher: Elsevier BV.
Tramoy, R., Gasperi, J., Dris, R., Colasse, L., Fisson, C., Sananes, S., Rocher, V., Tassin, B., 2019. Assessment of the plastic inputs from the Seine basin to the sea using statistical and field approaches. Front. Mar. Sci. (ISSN: 2296-7745) 6, http://dx.doi.org/10.3389/fmars.2019.00151.
Valero, D., Belay, B.S., Moreno-Rodenas, A., Kramer, M., Franca, M.J., 2022. The key role of surface tension in the transport and quantification of plastic pollution in rivers. Water Res. (ISSN: 0043-1354) 226, 119078. http://dx.doi.org/10.1016/j.watres.2022.119078.
van Calcar, C.J., van Emmerik, T.H., 2019. Abundance of plastic debris across European and Asian rivers. Environ. Res. Lett. 14 (12), 124051.
van Emmerik, T.H., 2024. The impact of floods on plastic pollution. Glob. Sustain. 1–13.
van Emmerik, T., de Lange, S., Frings, R., Schreyers, L., Aalderink, H., Leusink, J., Begemann, F., Hamers, E., Hauk, R., Janssens, N., et al., 2022b. Hydrology as a driver of floating river plastic transport. Earth's Future 10 (8), e2022EF002811.
van Emmerik, T.H., Frings, R.M., Schreyers, L.J., Hauk, R., de Lange, S.I., Mellink, Y.A., 2023. River plastic transport and deposition amplified by extreme flood. Nat. Water (6), 1–9.
van Emmerik, T., Mellink, Y., Hauk, R., Waldschläger, K., Schreyers, L., 2022a. Rivers as plastic reservoirs. Front. Water 3, 212.
van Emmerik, T., Roebroek, C., de Winter, W., Vriend, P., Boonstra, M., Hougee, M., 2020. Riverbank macrolitter in the Dutch Rhine–Meuse delta. Environ. Res. Lett. 15 (10), 104087. http://dx.doi.org/10.1088/1748-9326/abb2c6.
Vriend, P., Schoor, M., Rus, M., Oswald, S.B., Collas, F.P.L., 2023. Macroplastic concentrations in the water column of the river Rhine increase with higher discharge. Sci. Total Environ. (ISSN: 0048-9697) 900, 165716. http://dx.doi.org/10.1016/j.scitotenv.2023.165716.
Vriend, P., Van Calcar, C., Kooi, M., Landman, H., Pikaar, R., Van Emmerik, T., 2020. Rapid assessment of floating macroplastic transport in the Rhine. Front. Mar. Sci. 7, 10.
Weideman, E.A., Perold, V., Arnold, G., Ryan, P.G., 2020. Quantifying changes in litter loads in urban stormwater run-off from cape town, South Africa, over the last two decades. Sci. Total Environ. 724, 138310.
Ye, S., Andrady, A.L., 1991. Fouling of floating plastic debris under biscayne bay exposure conditions. Mar. Pollut. Bull. 22 (12), 608–613.