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Rivers as microplastic factories

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Abstract

Even in an ideal future where macroplastic emissions into rivers are entirely eliminated, plastic stored in river channels and floodplains, will be remobilized, and fragment into microplastics through its interaction with natural fluvial processes, such that riverine plastic emissions will continue for centuries As more time passes, rivers may cut new routes through plastic deposits, such as landfill sites, whilst deposits of plastic in the oceans will eventually become rocks, perhaps becoming uplifted as plastic mountain ranges, ready to start the cycle again. These processes can generate ongoing lulls and fluxes of secondary microplastics, prolonging threats to ecosystems and human health for millennia. In this perspective, we explore how understanding the way todays rivers move and deposit sediment—based on fluvial geomorphological knowledge—can help explain where and how plastic debris breaks down into microplastics, and how this insight can be used to better manage and reduce long-term plastic pollution in rivers.

Plastic polymers have been an integral part of daily life for over 70 years (Stubbins *et al* 2021), but they have also become a new, synthetic component of sedimentary environments, including riverine sediments (e.g. Liro *et al* 2020, Tramoy *et al* 2020, Russell *et al* 2023, 2025). Over the past decade, riverine plastic pollution has gained increasing attention, initially as a critical pathway transporting plastic waste from land to the ocean, and more recently as a long-term sink for plastic pollution (e.g. van Emmerik *et al* 2022). Williams and Simmons (1996) published the first study demonstrating, through field experiments, that rivers can also generate microplastics by fragmenting larger plastic items. Subsequent studies have only rarely confirmed this phenomenon through field evidence (e.g. Liro *et al* 2024) or numerical modeling (e.g. Drummond *et al* 2022). As a result, significant gaps remain in our understanding of riverine macroplastic fragmentation (Liro *et al* 2023a) and the fate of secondary microplastics produced during this process, particularly in relation to sediment erosion, transport, and accumulation across the fluvial system.

We argue that integrating hydrological and geomorphological knowledge of fluvial processes across river systems (see Schumm 1977, Church, 2015), and applying them to riverine plastic, can guide future research in identifying potential hotspots for macroplastic fragmentation and long-term storage sites for secondary microplastics produced. For example, insights into sediment transport dynamics, river flow energy, and channel and bed characteristics can help identify the key controls and spatial patterns of these processes, similarly to how they have previously contributed to understanding the dynamics of organic debris in rivers (see e.g. Liro *et al* 2020 and literature cited therein). This integration is essential for predicting and mitigating the release of secondary microplastics (Kvale *et al* 2024) and the toxic additives they carry (Rilling *et al* 2021) throughout fluvial systems and into the oceans. It offers a process-based understanding of how plastics interact with sediment transport, storage, and remobilization—an often overlooked aspect (see Liro *et al* 2020). By capturing these dynamics, it enables more effective and spatially targeted monitoring and management of plastic pollution.

1. Fluvial processes as drivers of secondary microplastic generation and storage

A classic fluvial system is traditionally divided into three primary zones along its reach, based on the dominant process—erosion, transport, or accumulation (i.e. deposition)—which shapes fluvial morphology (see Schumm 1977, Church 2015). This zonation reflects spatial variations in mass and energy transport within river systems, providing a framework—used by fluvial geomorphologists, engineers, and ecologists—for understanding fluvial landscapes and dynamics (Wohl 2010). This framework is most apparent in large river systems encompassing both tributaries and main channels but is also observable in individual rivers. However, nowadays it is increasingly disturbed by hydrotechnical structures (e.g. dams), which alter natural flow regimes and sediment dynamics (see e.g. Petts and Gurnell 2005, Grill *et al* 2019). Despite their global prevalence—and the fact that their peak installation coincided with the onset of plastic pollution in the 1960s—the influence of these structures on secondary microplastic formation (Moore *et al* 2024) and storage (Dhivert *et al* 2022) remains poorly understood. We examine how this fluvial framework (figures 1(A)–(C)) can inform future studies of plastic sediment dynamics (figures 1(D)–(F)).

1.1. Erosion dominated zone

This zone encompasses the headwaters of river systems, often situated at higher altitudes, characterized by steep gradients, high-energy conditions, and a dominance of erosion processes. These factors result in intense sediment production, typically consisting of coarse materials such as boulders or gravel (see Church 2015). Channels in this zone lack developed floodplains and are highly sensitive to weather and climate fluctuations. Periodic high-flow events trigger sediment pulses downstream, altering channel morphology, which is subsequently re-established as flows subside (see Church 2015). These minor tributaries (1st–2nd order streams) constituting the erosion zone of the fluvial system are the most numerous in the global river networks, accounting for approximately 77% of the total stream length and 11% of their area (Downing *et al* 2012) (figure 1(C)). Although upper river sections contribute less to total discharge and generally have lower mismanaged plastic waste emissions due to sparse population in their catchments (Gallitelli and Scalici 2022), their channel conditions promote frequent collisions with coarse bed materials and obstacles like log jams, enhancing mechanical fragmentation of macroplastics into smaller particles (Liro *et al* 2023b). Coarse bed sediments here can also promote storage of produced secondary microplastics in low-flow conditions (Ockelford *et al* 2020). In these erosion-dominated zones, steep valley sides and high gradients limit floodplain development (Church 2015) that would provide a surface for plastic storage. Therefore, the river channel became the primary compartment for macroplastic fragmentation and transport of produced microplastic under both low- and high-flow conditions. It can be suggested that, without new plastic inputs, these upper sections of the fluvial system may exhibit a self-cleaning tendency through efficient fluvial removal processes (Ockelford *et al* 2020).

Check-dams and boulder ramps in mountain streams (Wohl 2010; figure 1(E)) can increase macroplastic fragmentation within and downstream of the structures (Moore *et al* 2024), while upstream flow reduction promotes sedimentation and vegetation growth that may trap macroplastics and their fragments (Gallitelli and Scalici 2022, 2024). Although reduced flow limits mechanical fragmentation, surface-stored plastics face prolonged UV exposure and biodegradation, which may accelerate the rate of its fragmentation during later flood events (Liro *et al* 2023a).

1.2. Sediment transfer zone

In the sediment transfer zone, sediment caliber, channel gradient, and sediment supply reduce, such that the channel exhibits moderate gradients and flow energy, therefore erosion and deposition processes are balanced (Church 2015) (figures 1(A) and (B)). Consequently, channel stability is higher, allowing sediment—and, by extension, plastic—to be stored more persistently along the banks (Church 2015). This zone (typically 3rd- to 5th-order streams) represents approximately 21% of total river length and 23% of the area (see supplementary material), significantly contributes to overall discharge (Downing *et al* 2012), and acts as a connection between headwaters and larger rivers (Church 2015). Here, plastic transported from upstream catchments, along with newly introduced material, undergoes further mechanical fragmentation during transport, abrasion by sediment, and intermittent interactions with the channel bed and banks. Plastics can be deposited and temporarily stored in bars, islands, wood jams, etc., (Liro *et al* 2022) (figure 1(A)) or more locally in sheltered zones created by coarse-bed sediments or bedforms (e.g. Ockelford *et al* 2020, Russell *et al* 2023). As sand or gravel bars erode and accrete, incrementally shifting the channel's position (e.g. Durkin *et al* 2017), plastic materials can become embedded within these deposits, remobilize during erosive flood events, and may locally enhance the erosion of natural sediments (Russell *et al* 2023). Vegetation stabilizes deposited sediment and trapped plastics, delaying their remobilization and fragmentation (Liro *et al* 2023a), while also serving as an additional trap for

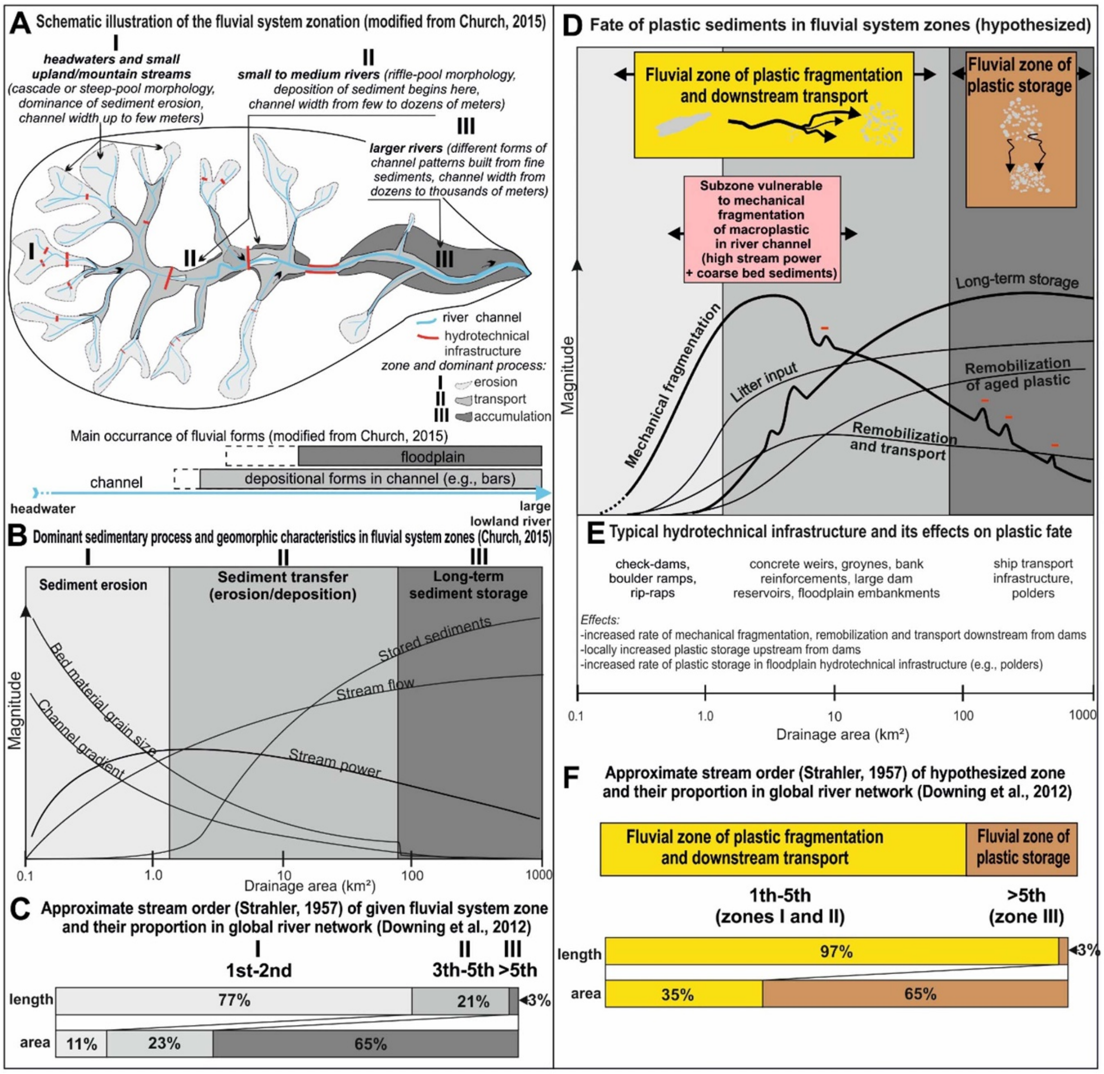

Figure 1. A schematic diagram illustrating the existing zonation of the fluvial system (A)–(C), and the proposed implications of this zonation for the occurrence and pathways of plastic fragmentation and the long-term storage of secondary microplastics (D)–(F). For details on stream proportion calculations from Downing database see the Supplementary Material.

plastics during floods (Gallitelli and Scalici 2024). Even if macroplastic emissions cease in the future, floodplains that are susceptible to erosion will continue to provide stored plastics into river channels, driving pulses of varyingly embrittled and fragmented plastic downstream, particularly during floods. Weirs in this zone can accelerate macroplastic fragmentation (Moore *et al* 2024), while dam reservoirs act as sinks for plastic (e.g. Watkins *et al* 2019), potentially enhancing fragmentation along shorelines due to wave action. Furthermore, changes in sediment load and hydromorphological alterations downstream of dams can potentially enhance mechanical fragmentation through increased energy of sediment-starved flows and the high surface roughness of riverbeds shaped by erosion processes (e.g. Petts and Gurnell 2005).

1.3. The accumulation zone of the fluvial system

This zone is characterized by low channel gradients and reduced flow velocities, promoting sediment accumulation and extensive floodplain development (Church 2015). Rivers in this zone (>5th-order) comprise only ∼3% of total stream length but cover ∼65% of the area and carry most of global water and sediment discharge (Downing *et al* 2012). Floodplains in the accumulation zone are extensive, acting as long-term sediment sinks over decades to centuries (Liro *et al* 2020, Tramoy *et al* 2020, van Emmerik *et al* 2022). They also provide conditions for prolonged UV-related plastic degradation and fragmentation, with sediment reworking during floods (Tramoy *et al* 2020) or sea level fluctuations.

In the accumulation zone, large dams form reservoirs where reduced flow promotes sediment and macroplastic accumulation. Floodplain embankments disrupt natural flooding, limiting floodplain extent and local plastic storage (Liro *et al* 2020), while tidal dynamics can modulate plastic retention in river estuaries (Tramoy *et al* 2020, van Emmerik *et al* 2022) (figure 1(E)). Frequently inundated floodplains are often densely vegetated, stabilizing sediment and enhancing macroplastic trapping and burial. Once submerged, overgrown, or buried, macroplastics degrade slowly due to limited UV exposure and low mechanical stress (Liro *et al* 2020, 2023a). These extensive floodplains, with their long-term storage and remobilization capacity, remain potential sources of plastic pollution, as buried macroplastics can be eroded and re-enter rivers, fragmenting further (see term *microplastic factory* introduced by Tramoy *et al* 2020, to describe plastic fragmentation in a river estuary). Looking to the deep future, sediment reworking—including plastic—in the lowermost sections of rivers may be triggered by sea-level fall, which would lead to rivers producing pulses of remobilised plastic. Managing current floodplain plastic accumulation and limiting its future remobilization are key to mitigating this risk.

1.4. River hyporheic zone as missing microplastic sink

The hyporheic zone beneath the riverbed, shaped by pressure-driven exchange between surface water and groundwater (Boano *et al* 2012), remains largely overlooked in microplastic research—despite its potential to significantly influence deposition, retention, and long-term accumulation (Frei *et al* 2019). While small microplastics ($<100\ \mu$m) are preferentially retained here, retention is variable and often temporary due to complex dynamics (Drummond *et al* 2020). River sediments may store 3%–8% of microplastics per kilometer, with additional short-term deposition depending on local conditions (Drummond *et al* 2022). However, the impact of hyporheic retention on microplastic fate remains poorly understood and requires further research. This zone may act as a distinct fourth compartment of the fluvial system.

2. Outlook

We suggest that the erosion and transfer zones, covering 97% of the river network (35% of its area), are more prone to secondary microplastic production and downstream transport than the remaining 3% (65% of its area) where long-term sediment accumulation dominates (figure 1(C)). However, this estimate does not fully account for extensive floodplains in lower river sections, which may further enhance long-term plastic accumulation beyond what river length and area comparisons suggest (see Downing *et al* 2012). Mechanical fragmentation likely dominates across all fluvial zones in inundated channels, especially for plastics transported as bed load or in suspension. UV-driven degradation occurs where plastic is exposed to UV light via limited or partial burial or submergence (Liro *et al* 2023a). These degraded plastics and resulting microplastics can later be remobilized and further fragmented during floods, producing episodic pulses of microplastics and associated absorbed pollutants. While mechanical fragmentation is shaped by local channel conditions, UV degradation patterns depend on broader regional factors such as latitude, altitude, climate (e.g. cloud cover, snow), and vegetation, which collectively modulate UV exposure and degradation rates (Andrady 2015). Since mechanical fragmentation is strongly influenced by physical channel characteristics—such as flow energy, sediment type, bedforms, and channel morphology—it is expected to vary significantly across different zones of the river system. Therefore, fluvial system zonation may serve as a spatial gradient for mechanical fragmentation, offering a useful framework for disentangling its dominant controls and spatial variability in the future. These findings highlight the need for tailored policies to reduce plastic fragmentation across different zones of the fluvial system (figure 1(D)). We recommend particular focus on river reaches where physical features (e.g. mountain rivers) (Liro *et al* 2023a) and artificial modifications (e.g. check dams) (Moore *et al* 2024) support high stream power and bed roughness (figure 1(D)) facilitating mechanical fragmentation. Hotspots of such fragmentation are likely to form between the lower erosion zone and the middle sediment transfer zone, where stream power peaks and coarse bed sediments are prevalent (figure 1(D)). In long-term accumulation zones, special attention should focus on managing floodplain zones by preventing dumping, conducting clean-up operations, and reducing bank erosion of sediments containing aged plastics—especially in the absence of clear international policy guidelines that currently hinder coordinated mitigation efforts.

Kvale *et al* (2024) noted that ocean plastic fragmentation is largely absent from UN policy. We highlight a similar gap in understanding how river processes shape plastic pollution and contribute to ocean contamination. Even in the absence of new macroplastic inputs, fluvial processes may sustain microplastic generation over timescales spanning millennia—effectively making it important from the perspective of a human lifespan. Urgent field studies are needed to identify spatial and temporal drivers of this process and inform targeted mitigation. Our perspective highlights that fluvial system zonation can govern where secondary microplastics form and persist—identifying priority areas for future action.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Author contributions

M L, conceived the idea, M L, A Z, H H, A C, wrote the initial manuscript, P M, J D, reviewed literature and contributed to manuscript revision and figure edits, C R, provided extensive feedback on revision of initial manuscript and figure. All authors approved the final version of the manuscript.

Conflict of interest

The authors declare no competing interests.

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