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Leaving a plastic legacy: Current and future scenarios for mismanaged plastic waste in rivers

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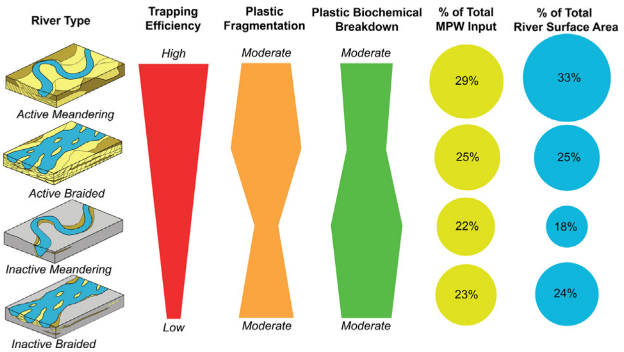
HIGHLIGHTS

- Plastic waste in different river systems and future scenarios are analyzed.
- Rivers received ~0.8MT of plastic waste in 2015 increasing 3-fold by 2060.
- 23 % of rivers are human impacted yet receive 49 % of total plastic waste input.
- Actively migrating meandering and braided rivers are large sinks of MPW (31 %).
- Targeted mitigation strategies are required for different river systems.

GRAPHICAL ABSTRACT



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ABSTRACT

Mismanaged plastic waste (MPW) entering the riverine environment is concerning, given that most plastic pollution never reaches the oceans, and it has a severe negative impact on terrestrial ecosystems. However, significant knowledge gaps on the storage and remobilization of MPW within different rivers over varying timescales remain. Here we analyze the exposure of river systems to MPW to better understand the sedimentary processes that control the legacy of plastic waste. Using a conservative approach, we estimate 0.8 million tonnes of MPW enter rivers annually in 2015, affecting an estimated 84 % of rivers by surface area, globally. By 2060, the amount of MPW input to rivers is expected to increase nearly 3-fold, however improved plastic waste strategies through better governance can decrease plastic pollution by up to 72 %. Currently, most plastic input occurs along anthropogenically modified rivers (49 %) yet these represent only 23 % of rivers by surface area. Another 17 % of MPW occur in free-flowing actively migrating meandering rivers that likely retain most plastic waste within sedimentary deposits, increasing retention times and likelihood of biochemical weathering. Active braided rivers receive less MPW (14 %), but higher water discharge will also increase fragmentation to form microplastics. Only 20 % of plastic pollution is found in non-migrating and free-flowing rivers; these have the highest probability of plastics remaining within the water column and being transferred downstream. This study demonstrates the spatial variability in MPW affecting different global river systems with different retention, fragmentation, and biochemical weathering rates of plastics. Targeted mitigation strategies and environmental risk assessments are needed at both international and national levels that consider river system dynamics.

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1. Introduction

Plastic pollution in our environment has received considerable attention in recent years given its potentially hazardous impact on ecosystems, human livelihoods and economies. However, the majority of existing plastic research has focused on the marine environment (Galgani et al., 2015; Harris et al., 2021b; Kane et al., 2020; Lebreton and Andrady, 2019; Thompson et al., 2004). A significant knowledge gap remains in understanding the entire source-to-sink perspective, including the atmospheric, terrestrial and hydrological cycles (Harris et al., 2021a; Hoellein and Rochman, 2021; van Emmerik and Schwarz, 2020; Waldschläger et al., 2022; Windsor et al., 2019) An important conclusion is that an overwhelming majority of mismanaged plastic waste (MPW) (>90 %) is retained in rivers and does not reach the sea (van Emmerik et al., 2022). At the same time, rivers are likely the single biggest contributor of plastic waste to our oceans (Jambeck et al., 2015; Meijer et al., 2022). It is therefore imperative to understand plastic transport in rivers to improve the much-needed mitigation and governance of plastic waste within both the terrestrial and marine environments (Vince and Hardesty, 2018).

Plastic debris has been found throughout the river environment including in sedimentary deposits within river channels (e.g., bars, levees) (Mani et al., 2019), on riverbanks (Dris et al., 2015; Klein et al., 2015) and on floodplains (Weber and Opp, 2020). Our knowledge on the behavior of plastic transport within rivers has also vastly improved over the last decade including the role of water discharge (Drummond et al., 2022; van Emmerik et al., 2018), and extreme flood events (Daniel et al., 2022; Hurley et al., 2018; Roebroek et al., 2021) on the remobilization of plastic waste. Simulations indicate that the longest microplastic residence times occur in headwaters averaging up to 7 years/km during low-flow conditions (Drummond et al., 2022). Global based studies on plastic generation and transport currently estimate the annual river-sourced contribution of MPW to our oceans range between 0.41 to >8 million tonnes/year (Lebreton et al., 2017; Lebreton and Andrady, 2019; Meijer et al., 2022; Schmidt et al., 2017; Chen et al., 2020). However, there remains uncertainty on the legacy of plastic waste within rivers due to our limited understanding of retention, remobilization, and transport of plastics that occur on different timescales and by different mechanisms (van Emmerik et al., 2022). The accumulation of plastics will depend on a wide range of factors that are either not well-understood, or included, in current models such as plastic size, river hydrodynamics, dams, degree of water regulation, water extraction and ecological and sedimentological processes to name a few (Tibbetts et al., 2018; van Emmerik et al., 2022; Waldschläger et al., 2022).

While our understanding on the accumulation of MPW is relatively young, we have better constraints on the consumption and generation of plastic waste (Lebreton and Andrady, 2019). Furthermore, planetary scale analysis of the Earth based on four decades satellite imagery has allowed for the historical analysis of river systems (Feng et al., 2022; Pekel et al., 2016). Knowledge of fluvial sedimentary processes can thus provide valuable insight into the expected behavior of plastic debris within our natural environment in the past and future (Waldschläger et al., 2022). Here we estimate a first global based analysis on the exposure of different types of river systems to MPW to better predict the legacy of plastic waste in our river systems. In addition, we compare our results to a worse-case scenario of potential accumulation of plastic waste in 2015 and 2060 to discuss considerations of river morphology and anthropogenic influence on rivers for targeting and achieving mitigation and remediation strategies.

2. Methods

2.1. River morphology and state

One of the main motivations of the current study is to highlight the legacy of MPW in different river systems. To achieve this goal, we classified each river system according to morphology, the historical river migration of the system (1984–2020), and the anthropogenic impact. To do this we utilized three datasets that define eight river morphology and state classifications combining the properties of: 1) Meandering or Braided; 2) Non-Migrating or Migrating and 3) Impacted or Free-Flowing.

Nyberg et al. (2022) describes global river systems based on a simplified geomorphological classification of either braided (multi-threaded) or meandering (single-threaded) river systems on a scale between a 0 to 100 % confidence at a 30 m resolution. The machine learning algorithm reports a 94 % accuracy to the training dataset and an 84 % accuracy compared to previous river channel morphology definitions. While different river morphologies are recognized, the two categories represent the main alluvial river geomorphic types according to literature (Schumm, 1985), and their delineations provide a foundation for further classification. This dataset was combined with historical water surface change maps (Pekel et al., 2016) based on the same 30 m Landsat imagery to define inactive versus actively migrating river channels. Here we define an inactive river channel as any location where 90 % of pixels in the Landsat image archive at a given locality were classified as water over the 36 years of available imagery. Any location where a given pixel changes from water to land (or vice versa) with at least 2 years of observation defines an area of an actively migrating river system. This map receives a reported commission accuracy over 98.3 % for waterbody extent (Pekel et al., 2016). Lastly, we consider the impact of humans on river systems by using the free-flowing river (FFR) dataset (Grill et al., 2019) define rivers that are either impacted or free-flowing. Here we consider the region of the entire sub-catchment in the HydroSHEDS river drainage dataset (Lehner et al., 2008) as impacted if a reach within its extent is defined as impacted.

2.2. MPW input and future scenarios

Lebreton and Andrady (2019) calculated total plastic waste in 2015 at a 30-arc *sec* resolution (~1 km) based on a compilation and correlation between reported municipal solid waste generation, GDP and population. The fraction of MPW (K) is based on country level reported values or by an empirical relationship for missing values using Eq. (1):

$$K = eXc + f \tag{1}$$

where e is equal to $-3.13\ 10^{-3}$, Xc is the per capita GDP and f is equal to 104. Future scenarios for the year 2060 were estimated based on changes in population, long-term economic growth rate, plastic generation and fraction of MPW (K) by country. This created three best-case scenarios for 2060 of a 'business-as-usual' (Scenario A), 'improved waste management' (Scenario B) and 'reduced plastic waste and improved waste management' (Scenario C) prediction (c.f. Lebreton and Andrady, 2019). To compare the spatial variability in MPW for the different future scenarios to the river classifications, we apply the country-level change predictions for each scenario to the gridded MPW data for 2015. It is important to note that more recent studies suggest that population density may be an unreliable variable in predicting MPW (e.g., Schuyler et al., 2021) and that this is a potential source of error in current global based predictions.

To relate the input of MPW to each river system, we first calculate the total volume of MPW per square kilometer for each of the 1,261,407 sub-catchments available in the HydroSHEDS river drainage delineations (Lehner et al., 2008). The concentration of MPW input is then compared to the area of each river classification to define the annual volume of MPW input to rivers for 2015 and for the three scenarios in 2060. This approach assumes most MPW within a sub-catchment for a given year will not enter the river environment which supports studies showing the longer residence time of microplastic in headwaters (Drummond et al., 2022). These results thus show the initial input of MPW exposure to the different river systems for a given year but not the potential downstream accumulation.

2.3. Calculating accumulation of MPW

Based on the current limited knowledge and observations (historical and present) of plastic transport and mechanisms along rivers (van Emmerik et al., 2022), we chose to examine a worst-case scenario on the accumulation of MPW. We assume that all MPW within each watershed is eventually transported downstream on different timescales (annual, decadal to centennial), thus showing the potential legacy of MPW impact from any given year. We include the impact of human interference along the river system given its known interference on plastic transport downstream (Lebreton et al., 2017; van Emmerik et al., 2022). This is achieved by combining the free-flowing river (FFR) dataset (Grill et al., 2019) with MPW estimates (Lebreton and Andrady, 2019). The FFR dataset maps the connectivity, from 0 to 100 %, of 8,477,883 river reaches based on the surrounding anthropogenic pressure impacting the vertical and lateral flow regime of rivers.

We apply the connectivity concept, used to analyze the natural flow state of river systems (Grill et al., 2019) to describe the potential impact of MPW along river reaches for 2015 and the 2060 scenarios (Lebreton and Andrady, 2019). To define the fraction of MPW input impacting each river reach, the total MPW within each sub-catchment of the HydroSHEDS dataset (Grill et al., 2019) is proportionally divided based on the length of each river reach. The connectivity of each river reach (Fig. 1A) is then combined with the MPW input (Fig. 1B) to define the potential accumulation of MPW in each reach (Fig. 1C). Only river reaches with an annual long-term discharge >0.01 $m^3 s^{-1}$ (Grill et al., 2019) were considered hydrologically connected downstream. In total, 4,367,073 river pathways were analyzed from source to its exorheic or endorheic river network termination.

To analyze the potential legacy of MPW in rivers and future scenarios, we compare the new river classification to the potential accumulation of MPW. This approach has limitations in that it does not consider the distance of the plastic source to a river, variations in emission input from wind and water discharge, or influence of land use that have been shown to impact plastic input to rivers (Meijer et al., 2022). However, given uncertainties that remain regarding the different timescales of plastic input (Drummond et al., 2022), as well as the different timescales of plastic transport along rivers (van Emmerik et al., 2022), this approach provides a worst-case scenario on the relative exposure of rivers to plastic waste. Furthermore, based on this uncertainty, we chose to express the plastic exposure for each sub-catchment into five categories of potential MPW accumulation rather than absolute values. These categories are defined as none (0 t/yr), low (0–1 t/yr), medium (1–10 t/yr), high (10–100 t/yr) and very high (>100 t/yr) plastic impact. Thus, this approach demonstrates the potential pathways of plastic waste accumulation to discuss the relative risks of plastic waste exposure in different river types.

3. Results

3.1. Global river morphology and state

We classify river systems based on eight categories that define: 1) the morphology of either meandering or braided rivers, 2) an actively migrating river system, and 3) whether the river system is naturally flowing. The results of the global river morphology and state analyses (Fig. 2) show that Asia has the largest proportion of rivers by surface area at 46 %. This is followed by South America (18 %), North America (17 %), Africa (8 %), Europe (8 %), and Oceania (3 %). The results show that approximately 77 % of the surface area of rivers is free-flowing, 58 % have a meandering morphology and 50 % have been actively migrating over the past four decades. Specifically, free-flowing, migrating, and meandering rivers represent nearly 27 % of the dataset while another 20 % are free-flowing non-migrating meandering rivers. Free-flowing non-migrating and migrating braided rivers represent 18 % and 13 %, respectively. For rivers with an impacted flow, we find that 7 % are non-migrating braided, 6 % are migrating meandering, 5 % are migrating braided and another 5 % are non-migrating meandering rivers.

3.2. MPW input to river systems

The new river classification was compared to the reported volume of MPW for 2015 and three scenarios in 2060 (Lebreton and Andrady, 2019) based on a: 1) ‘business-as-usual’ (Scenario A), 2) ‘improved waste management’ (Scenario B) and 3) ‘improved waste management and reduce plastic usage’ (Scenario C; see Methods and Materials). We estimate that the direct input of MPW to rivers in 2015 amounted to 0.8 MT (Fig. 3). Here we see that 77 % of MPW input is found in Asia, followed by 14 % in Africa and 6 % in South America. Europe, North America, and Oceania together amount to <4 % of the total MPW input. Based on a ‘business-as-usual’ projection, the volume of plastic input to rivers will significantly increase from 0.8MT/year to 2.2MT/year by 2060. Asia will contribute the most at 74 % of the total volume, while Africa will increase from 14 to 20 % (Fig. 3A). However, the implementation of improved recycling (scenario B) or an improved recycling and reduced plastic use scenario (Scenario C) is expected to significantly reduce MPW input to 0.47MT/yr (42 % decrease) and 0.22MT/yr (72 % decrease), respectively (Fig. 3B). Furthermore, the total proportion of MPW input by continent is predicted to be similar between Africa and Asia (Fig. 3A).

The type of river systems exposed to MPW in 2015, and projections for 2060 are shown in Fig. 4. Nearly half of all MPW input in 2015 (49 %) occurs along rivers with an impacted flow, which is proportionally higher than their distribution by river surface area at 23 % (Fig. 2). However, Asia, South America and Africa also have a high amount of MPW in river systems that are currently free-flowing, allowing for the downstream transport of the plastic waste. In total, free-flowing meandering and free-flowing braided rivers received approximately 17 % and 14 % of MPW input, respectively. Based on a business-as-usual projection, most river system types will see an increased MPW input by at least 2.5times. However, the data suggest that due to the current distribution of river systems, migrating

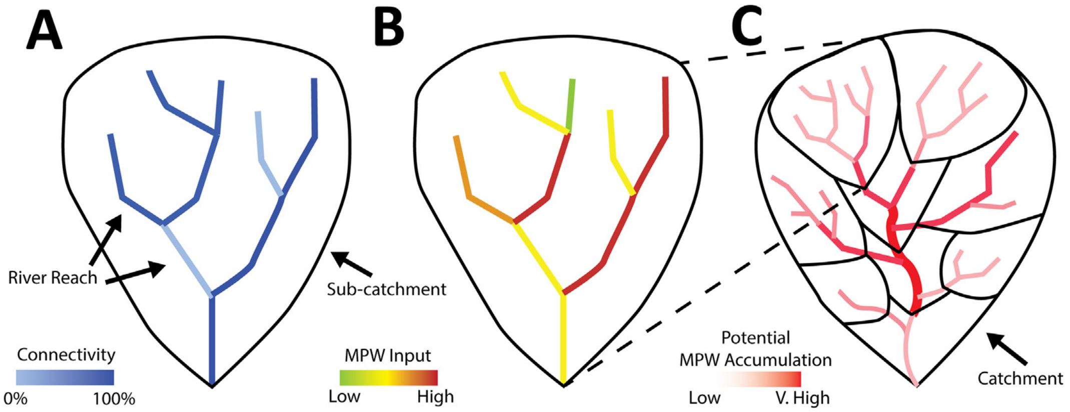

Fig. 1. Methodology used to classify the exposure of plastic to each river reach. (A) Each sub-catchment is defined by a series of river reaches and a connectivity value ranging from 0 to 100 % based on Grill et al. (2019). (B) The MPW input to each river reach is calculated proportionally to its length and the total MPW within each sub-catchment. (C) Based on the connectivity (A) and MPW input (B) to each river reach, the accumulative plastic volume is calculated.

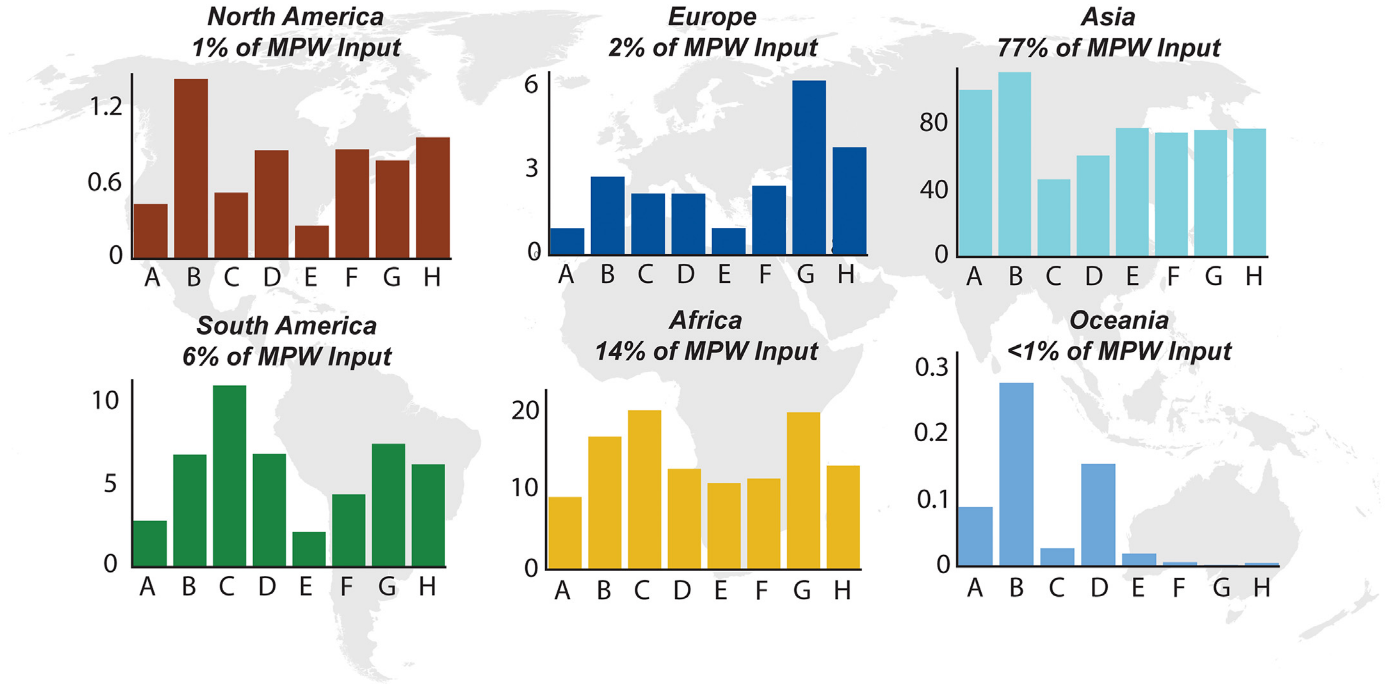

Fig. 2. Global River Morphology and State. Shows the surface area of river system types as a percentage of the total by continent. A – free-flowing migrating braided rivers, B – free-flowing migrating meandering rivers, C – free-flowing non-migrating braided rivers, D – free-flowing non-migrating meandering rivers, E – impacted flow migrating braided rivers, F – impacted flow migrating meandering rivers, G – impacted flow non-migrating braided rivers, H – impacted flow non-migrating meandering rivers. See Data availability section for interactive map.

braided river systems will be the most impacted increasing by nearly 3-fold. Based on an improved recycling and reduced plastic use scenario (Scenario C), river systems with an impacted flow (with an exception to migrating braided rivers), will see a MPW input decrease of between 5- and 6-fold. In comparison, free-flowing river systems will see an important but significantly lower 2- to 3-fold decrease under Scenario C (Fig. 4).

3.3. Accumulation of MPW in Rivers

A worst-case predicted accumulation of MPW (see methods) based on the volume in 2015, and the three different scenarios for 2060 is presented. A large proportion of the potential medium and higher (>10 T/km^2) plastic exposure risk exists currently in Asia and Africa (Fig. 5). Based on a ‘business-as-usual’ model, MPW in Asia will remain significant but the African continent will become an increasingly problematic region (see supplementary figures). However, an improved waste management scenario shows significant improvements in Asia, the Americas and Europe reflecting the reported MPW calculations of Lebreton and Andrady (2019). Improved waste management and reduced plastic use policies will further reduce the overall number of regions impacted by a high degree of MPW, although a significant proportion of river systems on the African continent will continue to be at greater risk (see figures in supplementary data).

3.4. Impact of MPW accumulation on river systems

The potential accumulation of MPW as of 2015 has impacted 84 % of rivers by surface area. In summary, we estimate that 47 % of the surface area of rivers is exposed to a low risk of MPW, 17 % to medium, 13 % to

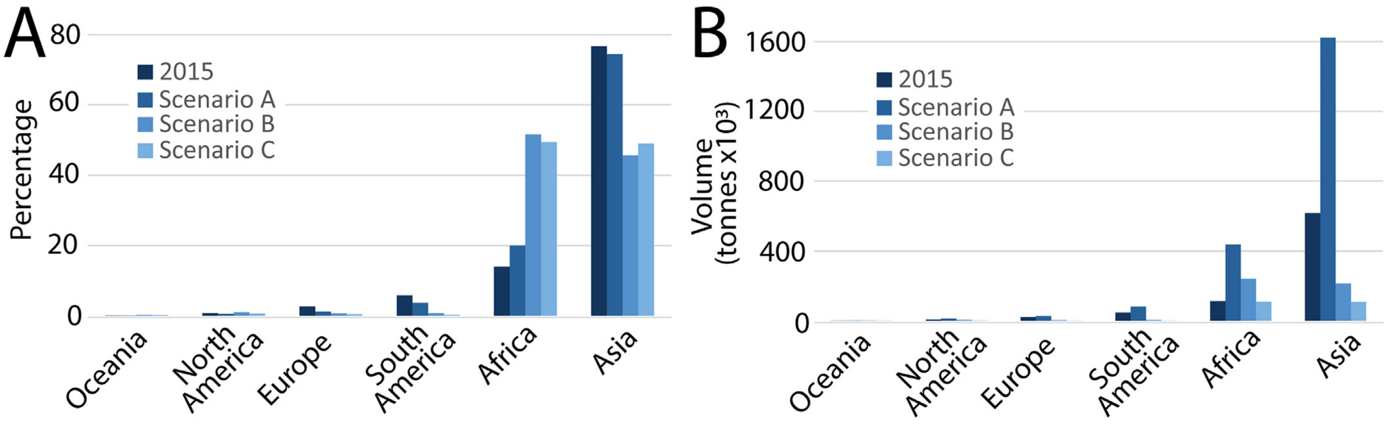

Fig. 3. Input of MPW to Rivers by Continent. (A) shows the percentage of MPW input to rivers by continent for 2015 and future projections. (B) shows the volume of MPW input to rivers by continent for 2015 and future projections. The three different scenarios of MPW in 2060 based on Lebreton and Andrady (2019) are: Scenario A, a business-as-usual trend, Scenario B, an improved waste management scenario trend and Scenario C, an improved waste management and reduced plastic usage trend.

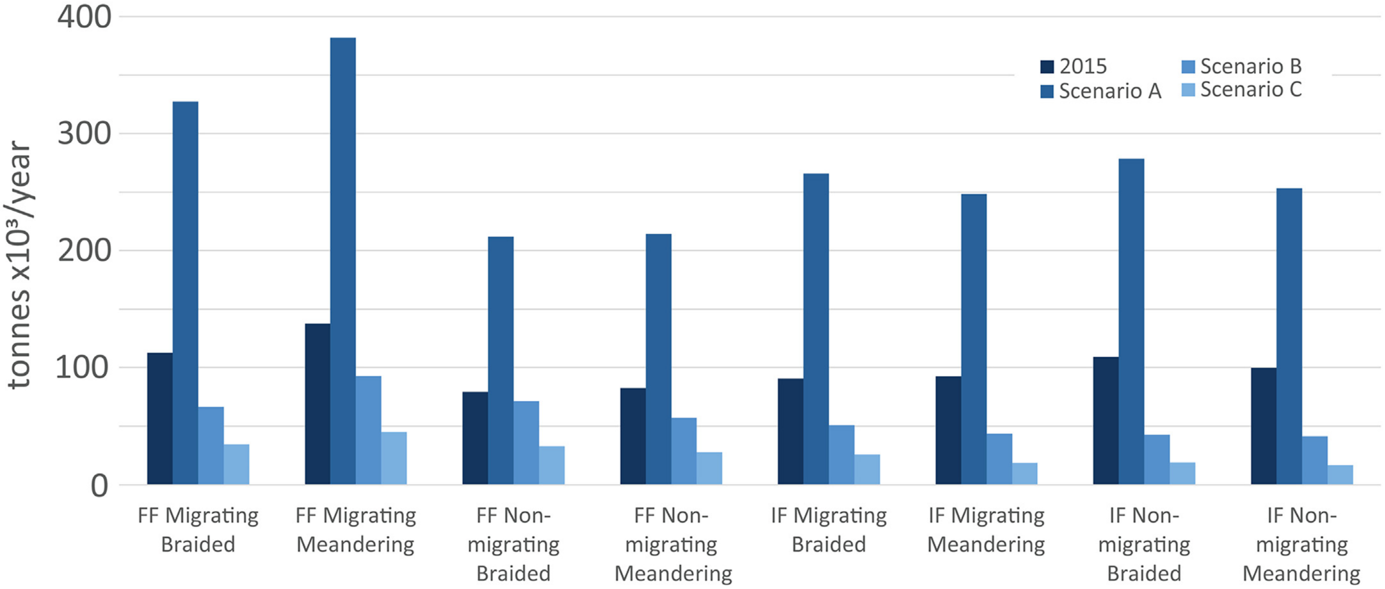

Fig. 4. Input of MPW by River Morphology and State. Shows the volume of MPW input in thousands of tonnes per year by river morphology and state. IF - Impacted flow, FF - Free flowing.

high and another 7 % to very high risk (Fig. 6A). By 2060, a business-as-usual projection will mean very high MPW impacted rivers will increase to 11 % (Fig. 6). In addition, medium and high MPW impacted rivers will continue to remain significant covering roughly 14 % each of the total river surface area. In total, no less than one third of all rivers will be exposed to a medium or higher amount of MPW by 2060 given the current trends in plastic waste.

If plastic waste management is improved by a global effort (scenario 2060B), the number of very high MPW impacted rivers will decrease significantly to 4.8 % and high MPW impacted rivers will reduce to 7 % (Fig. 6A). Lastly, improved waste management and recycling strategy (scenario 2060C), will result in more than a 50 % decrease in medium or higher levels of MPW exposure in river systems. Very high MPW exposure will decrease 2.2 times and high MPW exposure will decrease nearly 3-fold compared to the present-day, Fig. 6A.

In contrast to the input of MPW (Fig. 3), the accumulation of MPW will impact a larger area of river systems globally. In 2015, 35 % of the total area of rivers exposed to a medium or higher amount of MPW are found in North America, Europe and in South America (Fig. 6B). Asia, however, remains the most affected with 47 % of all impacted river systems whereas Africa

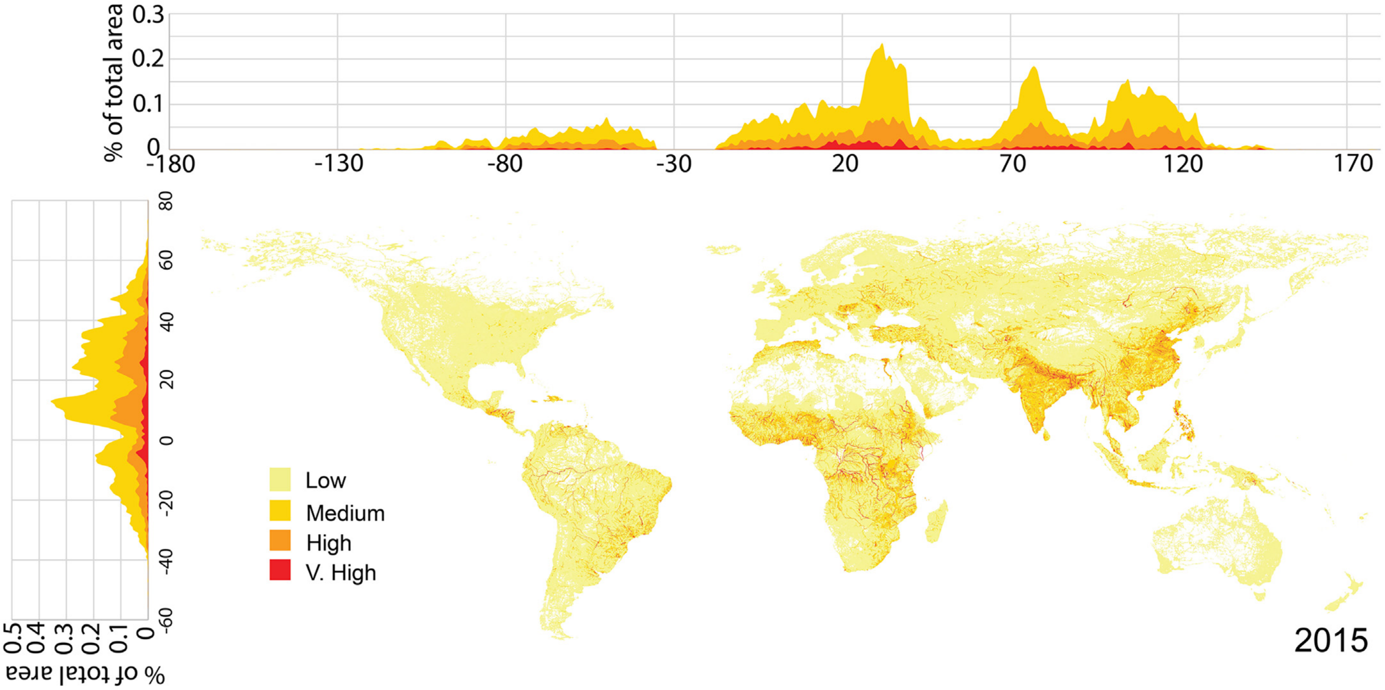

Fig. 5. Accumulation of MPW. The global exposure of rivers to MPW in 2015 based on the reported values by Lebreton and Andrady, 2019. Line graphs show the percentage of MPW by river surface area in 1 degree latitude and longitude bins for medium or higher exposure levels. Low MPW (0–1) Medium (1–10), High (10–100) and V. High (>100) t/km^2. See supplementary material for scenarios in 2060 or Data availability section for interactive map.

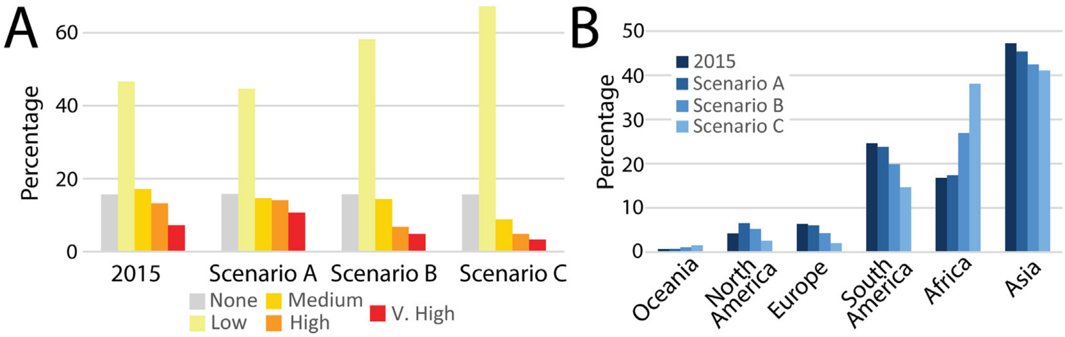

Fig. 6. Future Scenarios of MPW by River Extent. (A) For each year the bar graphs show the proportion of MPW in river systems as either None (0), Low MPW (0–1) Medium (1–10), High (10–100) and V. High (>100) t/km^2. (B) Shows the proportion of rivers by surface area with a medium or higher MPW risk for the different continents.

represents 16 % by river surface area. By 2060, Scenarios B and C will have the most positive change in North America, Europe and South America, whereas Africa will increasingly become the most impacted region by river surface area at 38 %.

Proportionally, the type of rivers most exposed to the 2015 distribution of MPW are free-flowing migrating meandering rivers representing 34 % of the total surface area of rivers (Fig. 7A). Within those meandering rivers, 4.9 % are exposed to a medium volume of MPW plastic risk, another 4.3 % are high and nearly 1.8 % are very high. In total, 25 % of the total river surface area of free-flowing meandering or braided rivers is exposed to at least a medium amount of MPW risk. While impacted rivers represent a smaller 22 % of the total river surface area (Fig. 4), 43 % of those river systems are exposed to at least a medium amount of MPW.

Based on future scenarios of medium or higher MPW exposure by river type (Fig. 7B), a 2060 scenario C implementation will have the largest impact on rivers currently classified as free-flowing. In particular, we see that the surface area of rivers exposed to significant amounts of MPW in migrating meandering rivers and non-migrating braided rivers is reduced by 5.6 and 3 %, respectively. However, proportionally, rivers with impacted flow due to human intervention, will have the largest change in MPW exposure. In total, impacted rivers will see a reduction in medium or higher MPW exposure by nearly 3-fold compared to 2-fold of free-flowing rivers based on a 2060 Scenario C trend (Fig. 7B).

4. Discussion

4.1. Exposure of MPW by river type

The morphology of a river is an important marker to predict the potential storage of plastics within river systems (Fig. 8) (Waldschläger et al., 2022).

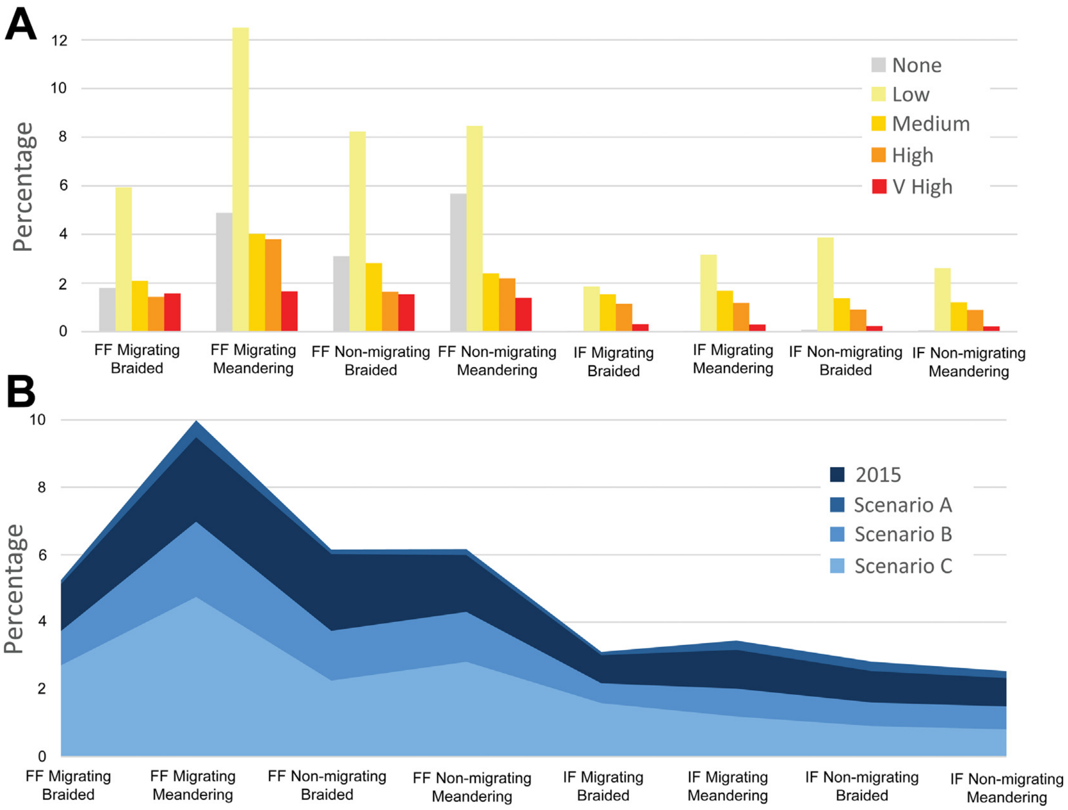

Fig. 7. Future Scenarios of MPW by River Morphology and State. (A) Shows the proportion of river systems exposed to different levels of MPW by river morphology and state. (B) Shows the change in medium or higher levels of MPW risk based on the different scenarios of MPW input by river morphology and state. IF - Impacted flow, FF - Free flowing.

Generally, depositional alluvial systems characterized by the accretion of thick clastic sediment wedges are formed by the tectonic uplift of a major sediment source area (e.g. the Himalayas or the European Alps). In contrast, tectonically quiescent environments leave a thinner sheet-like body of alluvial sediment (Miall, 1992). Rivers that have experienced a relative lowering of base level will be net erosional and may be actively eroding into underlying sediments forming incised valleys (Boyd et al., 2006).

A spectrum of different types of alluvial depositional environments therefore exists between these endmembers. A range of possible outcomes must exist in terms of the retention or expulsion of plastic pollution within different river systems depending upon their geomorphology, relation to sea level and tectonic setting. However, it turns out that there are essentially two principal alluvial river types: braided and meandering rivers (Leopold and Wolman, 1957). Furthermore, braided and meandering river geomorphology is controlled by two primary factors: sediment load and river discharge (Fig. 8) (Schumm, 1985). These geomorphic river types are potentially very informative with respect to the retention or expulsion of plastic along the river course.

For example, consider a meandering river system having a low sediment load (Fig. 8). The channel does not significantly migrate and hence there is very little sediment accumulation along the river course. Therefore, the river water column (rather than fluvial sediment deposits) will contain most of the MPW that has entered the system. This pollution is not retained in the river but rather it is delivered to the oceans (unless otherwise entrapped by vegetation, aquatic life, dams or other human actions that would retain plastic in the river system).

On the other hand, a river system with a high sediment load has a much higher likelihood to store waste within its sedimentary deposits (Fig. 8). For meandering river systems, the inside bend of the river and associated flow patterns results in the creation of point bars. Point bars are depositional elements that will retain and store plastic material. The plastic will remain buried within the deposit for possibly decades to centuries (Barnes et al., 2009; van Emmerik et al., 2022) until such a time when the river channel meanders, and the point bar is either rebuilt or left stranded within the accumulating flood plain depositional system. Meandering river systems also have a higher channel stability (Schumm, 1985) resulting in less frequent but more catastrophic flood events due channel levee breaches causing significant transport of material on floodplains (Fryirs, 2017) including plastic waste (Weber and Opp, 2020).

The low current energy and fine-grained (silt and clay) sediments characteristic of meandering rivers contrast with the high current energy and coarse (sand and gravel) sediments of braided river systems. Actively bifurcating braided rivers build lateral accretion bars as well as reshaping mid-channel bars. The MPW stored in the bar and channel deposits is therefore expected to be gradually reduced in size moving downstream from source areas. The lower stability of braided channels is associated with more frequent flooding and hence deposition of plastic waste on the floodplains (Fryirs, 2017; Schumm, 1985).

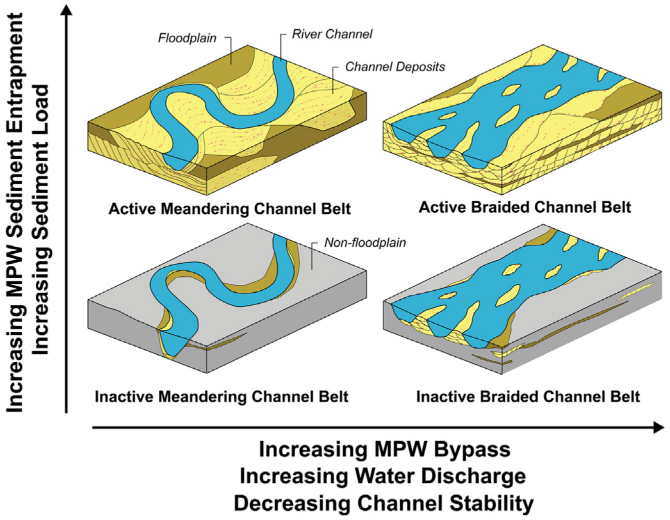

Fig. 8. Influence of River Morphology on Plastic Distribution. Illustration showing the impact of river morphology and migration rate on MPW deposition and transport within river systems.

The morphology of a river system is also an indication of river behavior with greater water discharge in braided systems compared to meandering rivers (Schumm, 1985). The greater water discharge of braided river systems increases the likelihood of MPW bypassing the fluvial sedimentary environment and its export to the marine environment (Fig. 8). Hence, actively migrating meandering rivers are likely to have the highest retention rate of MPW within their deposits. Our results show that actively mitigating meandering river systems received roughly 137 thousand tonnes of MPW in 2015 (Fig. 4) and represent 1 in 5 of all rivers that are exposed to accumulation of plastic waste (Fig. 7).

4.2. Fragmentation of MPW by river type

The fragmentation of MPW in river systems is controlled based on the interplay between mechanical, biological and chemical processes (Barnes et al., 2009; Born and Brüll, 2022; Shah et al., 2008; van Emmerik et al., 2022). The rates of plastic degradation by different processes in riverine environments are varied but not well documented (van Emmerik et al., 2022). However, solar UV radiation appears to be a dominant factor whereby equatorial rivers would likely receive higher rates of UV light degradation, although this will furthermore depend on temperature, cloud coverage and the ozone health (Andrady et al., 2019). It is also important to note that while high latitude regions receive less UV radiation, mechanical abrasion from seasonal freezing and thawing play an important aspect. The focus in this section is to discuss the contributing factor of river type on plastic fragmentation (Fig. 8) that may play a secondary but also an important role that has previously been overlooked.

For inactive meandering river systems, the lower discharge environment will decrease the physical abrasion of plastic within the water column. At the same time, the increased residence time of plastic within the environment will lead to increased biological (Bellasi et al., 2020; Leslie et al., 2017) and/or chemical degradation, including by UV light (Born and Brüll, 2022). The increased residence time of plastic within freshwater environments is particularly concerning given that it is subsequently consumed by biota (Bellasi et al., 2020). Currently, non-migrating meandering river systems receive 22 % of MPW input (or 0.18 MT/yr; Fig. 3B) and represent 23 % of river systems by area that may receive MPW downstream (Fig. 7A).

For an active meandering river system, the water discharge may be similar but mechanical weathering of plastics may be slightly higher due to sediment abrasion. Furthermore, plastic waste stored within the pointbars and floodplains of active meandering rivers will likely have increased residence time providing further opportunity for biological and chemical breakdown. Actively migrating meandering river systems currently receive 29 % of MPW input (or 0.23 MT/yr; Fig. 3B) and represent 33 % of river systems by area that may receive accumulation of MPW (Fig. 7A).

The higher discharge and energy of braided rivers will expose plastic material to more physical abrasion producing secondary plastic fragments. In inactive braided (or anabranching) river systems, MPW is likely to stay within the water column, fragmented by suspended and bedload material and bypassed further downstream. For active braided systems, the rivers retain plastics within their deposits, but the coarse sediment and high current energy also cause fracturing and fragmentation. The retention of plastic waste in the lateral accretion bars, mid channel bars and floodplains of active braided river systems will increase the probability of physical, biological and chemical fragmentation. Our current estimates show that the initial input of MPW is 0.19MT/yr for inactive braided systems (23 %) and 0.2MT/yr for active braided systems (25 %), Fig. 3B. The accumulation of MPW in those river systems are similar accounting for 25 % and 19 % of rivers by surface area, respectively (Fig. 7A).

4.3. MPW estimates and future scenarios

This study estimates MPW input to rivers, in 2015, at 0.8MT/yr (Fig. 3). This value is significantly less than the proposed 19 to 23 MT/yr of MPW entering aquatic ecosystems in 2016 by Borrelle et al. (2020). However, it is important to note this previous study includes wetlands and lakes that encompass an area that is 7 times larger than rivers, globally (George and Tamlin, 2018; Nyberg et al., 2022). Furthermore, the current model is a conservative estimate, calculating the volume based on the average concentration of MPW for each sub-catchment as opposed to a relationship to the distance from plastic source (e.g., Borrelle et al., 2020; Meijer et al., 2022). Nonetheless, the current study shows the spatial distribution in MPW input contributing to the different types of river systems by surface area for an assessment on the fate of plastic waste in riverine environments.

Future scenarios show that by 2060, maintaining a business-as-usual approach will increase the input of MPW to rivers from 0.8MT/yr to 2.2MT/yr (Fig. 3B). The potential accumulation of MPW means that very high-risk exposure regions will increase 46 % in river surface area by 2060 (Fig. 6A). Here we see that free-flowing actively meandering river systems are the most important, representing 27 % of total surface area of rivers globally (Fig. 2), and also are likely to see the largest increase in very high MPW exposure (66 %, Fig. 7B). This suggests that the relative increase in river surface area that will entrap plastic material within the terrestrial environment will see concomitant growth (Fig. 7); thus, the potential direct spatial impact of MPW will be larger, requiring more significant mitigation and remediation measures.

An improved waste recycling scenario combined with reduced plastic use by 2060 will reduce input of MPW 3.6-fold to 0.22MT/yr (Fig. 3B). The most noteworthy improvement is expected in Asia (Figs. 3A and 4) related to highly regulated river systems which will likely decrease 5-fold based on the observed relative decrease in MPW exposure (Figs. 3B and 4). To the contrary, river systems on the African continent are still likely to be exposed to a significant area of MPW. Many of those river systems, for example the Congo Basin, are currently inactively migrating meandering and braided (anabranching) river systems that will likely see MPW export to the marine environment.

Most input of MPW (49 %; Fig. 3) occurs along impacted river systems, yet these represent only 23 % in the surface area of rivers globally (Fig. 2). However, the potential exposure of MPW due to the accumulation of plastic waste is associated with free-flowing river systems (73 %; Fig. 7A). Since MPW generation generally occurs in populated centers (Lebreton and Andrady, 2019), these regions also tend to have nearby rivers with an impeded flow (Grill et al., 2019). As a result, impacted flow of river systems may receive and store a significant amount of MPW behind human infrastructure (e.g., reservoirs) that do not impact downstream ecosystems. At the same time, the longer residence time of plastic debris confined within the water column may also breakdown into microplastics that may eventually be transported to our oceans (Harris et al., 2021b; Lebreton and Andrady, 2019; van Emmerik and Schwarz, 2020) or consumed by aquatic life in freshwater systems (Bellasi et al., 2020; Dris et al., 2015; Leslie et al., 2017; Wagner et al., 2014).

4.4. Policy and implementation

Significant knowledge gaps in relation to the absolute volumes of plastics in different habitats remain, hampered by limited sampling coverage and the absence of standardized sampling protocols (Harris et al., 2021a). The mitigation of environmental impacts resulting from MPW requires knowledge of the distribution and concentrations in our natural terrestrial environment. In turn, monitoring the effectiveness of mitigation efforts will also rely on this information. The current study provides an indication of the exposure level and sedimentary processes that govern the transport and deposition of MPW in the future. The 'improved waste management' and 'improved waste management and reduce plastic usage' scenarios for 2060 are in line with the four strategic goals which are being discussed as part of the international legally binding instrument on plastic pollution (Cowan and Tiller, 2021; UNEP, 2022). These strategic goals aim to deliver the system change to a circular economy for plastics: (i) eliminate and substitute problematic and unnecessary plastic items, including hazardous additives; (ii) design plastic products to be circular (reusable, recyclable or compostable); (iii) ensure that plastic products are circulated in practice; and (iv) manage plastics that cannot be reused or recycled, including existing pollution, in an environmentally responsible manner. A circular economy for plastics thus needs to consider not only the economics of waste reuse but also the economics resulting from improved environmental benefits (Hoang et al., 2022).

National and administrative level summaries of the different river types influencing MPW distribution are provided through the interactive map of this publication, to help focus research on implementation of targeted-mitigation measures. Consolidated and effective policies must be adopted to control plastic contamination in the environment. Actions to curb MPW within the terrestrial environment will be the priority for all governments and knowledge of which fluvial systems are at greater risk of exporting MPW to the ocean is of great value in setting government priorities for policy and legislative interventions (Vince and Hardesty, 2018). Investing in the prevention of waste and pollution at source is less expensive than remediation, however, insight into natural processes and remediation at relevant intervention points can be an effective way to eliminate plastic pollution and avoid downstream ecosystem contamination.

5. Conclusions

This study has aimed to highlight the different types of river systems currently exposed to MPW and future predictions based on different plastic usage / mitigation scenarios. In conclusion, we find that:

- Constraining plastic pollution in both terrestrial and marine environments requires a holistic source-to-sink approach that considers the different processes and mechanisms that transport, remobilize and store waste; this requires an understanding of the spatial variability of MPW exposure in different global river systems, how different sedimentary processes transport and store plastic waste, and how different river types influence the physical, biological and chemical weathering of plastics.
- An estimated 84 % of rivers, by surface area, are potentially exposed to accumulation of MPW. Nearly half of all MPW input occur along anthropogenically modified river reaches (49 %) yet represent only 1/4th of rivers by surface area (23 %).
- The majority of rivers are free-flowing (77 %), actively migrating (50 %) and of a meandering profile (58 %) by surface area. This indicates that a large proportion of rivers have built new deposits over the last ~4 decades of satellite observations, and likely stored plastic material within those environments as MPW has increased.
- Rivers on the Asian and African continents include both free-flowing migrating meandering and braided river systems that are likely to retain a portion of plastics within the sands of building point bars and mid-channel bars. However, there are also a significant proportion of rivers that are non-migrating braided systems that will likely bypass plastics further downstream from its original source complicating remediation efforts.
- Improved recycling and reduced plastic reliance can reduce significant MPW exposure in river systems by as much as 72 % in the year 2060. Proportionally the largest difference will be noticed along river systems with impacted flow due to human river management. However, free-flowing rivers will continue to represent the largest surface area of rivers exposed to MPW which will be problematic in any environmental mitigation of plastic pollution given the large area of dispersion.

CRediT authorship contribution statement

Björn Nyberg: Conceptualization, Methodology, Investigation, Writing – original draft. **Peter T. Harris:** Conceptualization, Writing –

review & editing. **Ian Kane:** Writing – review & editing. **Thomas Maes:** Writing – review & editing.

Data availability

The datasets are publicly available at doi.org/10.5281/zenodo.6894684 and an interactive map at https://bit.ly/3rYPnkz.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.161821.

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