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The impact of floods on plastic pollution

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Abstract

Non-Technical Summary. Plastic harms ecosystem health and human livelihood on land, in rivers, and in the sea. To prevent and reduce plastic pollution, we must know how plastics move through the environment. Extreme events, such as floods, bring large amounts of plastic into rivers around the world. This article summarizes how different flood types (excessive rainfall, high river flow, or floods from the sea) flush or deposit plastic pollution, and how this impacts the environment. Furthermore, this paper also discusses how improved resilience to floods is important to prevent and reduce plastic pollution.

Technical Summary. Plastic pollution is ubiquitous in the environment and threatens terrestrial, freshwater, and marine ecosystems. Reducing plastic pollution requires a thorough understanding of its sources, sinks, abundance, and impact. The transport and retention dynamics of plastics are however complex, and assumed to be driven by natural factors, anthropogenic factors, and plastic item characteristics. Current literature shows diverging correlations between river discharge, wind speed, rainfall, and plastic transport. However, floods have been consistently demonstrated to impact plastic transport and dispersal. This paper presents a synthesis of the impact of floods on plastic pollution in the environment. For each specific flood type (fluvial, pluvial, coastal, and flash floods), we identified the driving transport mechanisms from the available literature. This paper introduces the plastic-flood nexus concept, which is the negative feedback loop between floods (mobilizing plastics), and plastic pollution (increasing flood risk through blockages). Moreover, the impact of flood-driven plastic transport was assessed, and it was argued that increasing flood resilience also reduces the impact of floods on plastic pollution. This paper provides a perspective on the importance of floods on global plastic pollution. Increasing flood resilience and breaking the plastic-flood nexus are crucial steps toward reducing environmental plastic pollution.

Social Media Summary. Floods have a large impact on plastic pollution transport, which can be reduced through improved flood resilience

1. Introduction

Plastic is an emerging pollutant that poses an environmental threat to terrestrial, freshwater, and marine ecosystems (Borelle et al., 2020; MacLeod et al., 2021). Recently, plastic pollution has been included as novel entity within the planetary boundaries framework, underscoring the potential danger it brings to sustainable life on Earth (Persson et al., 2022; Villarrubia-Gómez et al., 2022). One of the key challenges is assessing the full impact of plastic pollution on the environment. For this, the full exposure of humans, animal and plant species, and ecosystems as a whole to plastic pollution needs to be better characterized (Schwarz et al., 2023). The transport and retention dynamics of plastics from sources to (temporary) sinks across environmental matrices remain however unresolved (González-Fernández et al., 2023; van Emmerik et al., 2022). Another complicating factor is that plastic pollution comes in countless different polymer types, shapes, rigidity, and sizes, which all influence the way they move through in the environment (van Emmerik & Schwarz, 2020). It is clear that plastic is a purely anthropogenic pollutant, and increased concentrations are generally observed close to densely populated areas (Kuizenga et al., 2023; Tasseron et al., 2023). However, large accumulations are found around the world in parallel. Examples include the 'Garbage Patches' in the five major oceanic gyres, submarine canyons, mangrove forests, estuaries, and riverbanks (Lebreton, 2022; Martin et al., 2020; Schreyers et al., 2024; Zhong & Peng, 2021).

Several drivers have been hypothesized to drive the transport of plastic from land toward and into the ocean, including river hydrodynamics, wind speed and direction, river morphology, and tidal dynamics (Meijer et al., 2021; Roebroek et al., 2021b; 2022). Most of these findings are based on case studies and the findings are often not generalizable or transferable to other rivers. River discharge has found to correlate positively, negatively, and not at all with plastic transport (Roebroek et al., 2022; van Emmerik et al., 2019; 2023b). When comparing different rivers, this may not seem surprising, but such inconsistent correlations have also been found within the same river system (e.g. the Rhine; van Emmerik et al., 2022). Under normal conditions, variations in plastic pollution levels are not trivial to attribute to single driving forces. A growing number of observational studies however reported a strong impact of (extreme) floods on the mobilization and dispersal of plastics through river systems.

In this paper, a perspective is provided on how floods impact the mobilization, transport, and retention of plastic pollution through the terrestrial and riverine environments. Examples are given of how specific flood types (fluvial, pluvial, coastal, flash floods) have been demonstrated to exacerbate plastic pollution. The available studies are synthesized into an overview of the most relevant transport and retention mechanisms, and impact that has been demonstrated. Note that this paper focuses on transport and retention in terrestrial and riverine environments, and the impact of flood-driven plastic transport on the marine environment is outside the scope. Finally, an outlook for future research is provided, and how improving resilience of global communities to extreme events may support prevention and reducing plastic pollution in the environment is explored.

2. The connection between floods and plastic

Floods can generally be classified into fluvial, pluvial, coastal, and flash floods (e.g. Merz et al., 2010; O'Donnell & Thorne, 2020; Rosenzweig et al., 2018). In the following, these flood types are briefly described, including examples of their effects on plastic pollution in river systems globally. An overview of the response to different floods is presented in Figure 1.

2.1. Fluvial floods

Fluvial floods occur when the river discharge results in water levels that exceed the embankment of the river cross-section, leading to inundation of the floodplains. In case settlements are built on the natural floodplains, which is the case in many rivers around the world, urban areas can flood. The flow direction during fluvial floods can change direction during the event. When river discharge increases, the flow is generally directed from the river toward the floodplain, and reverses when the discharge decreases again. Fluvial flood can therefore have two effects. The inundation of floodplains and urban areas leads to mobilization of plastic, which may be transported toward or parallel to the river. However, if the flow from the river toward the floodplain already contains plastic, this may also be retained during inundation, for example, in vegetation or other obstructions of the flow and debris. Roebroek et al. (2021a) provided a first global assessment of the potential plastic mobilization (PPM) from inundated floodplains, by combining the best estimates of mismanaged plastic waste [kg/y/km^2] (Lebreton & Andrady, 2019) with flood extent maps for events with return periods from 5 to 500 years. Globally, the PPM from floods was found to be ten times higher than during non-flood conditions. In several regions that are both flood prone and heavily polluted, factors as high as 40 were found. Hauk et al. (2023) looked at the effect of the 2021 flood in the Meuse on 100 specific plastic item types, demonstrating the response varies considerably between categories. Smaller items were generally flushed and larger items were mainly deposited during the flood. This is in line with Hurley et al. (2018), who found that microplastic in river sediments decreased with 70% after a flood event. Fluvial floods may lead to both additional mobilization and retention of plastic, depending on the direction of the flow and the plastic characteristics.

2.2. Pluvial floods

Pluvial floods occur when the rainfall intensity exceeds the drainage or infiltration capacity, leading to ponding on the land surface or on the streets and subsequently surface runoff. Plastics can be mobilized through both the pressure forces of the water layer on their surface, and through flotation and suspension when the inundation depth is large enough. The eventual travel distance is determined by a combination of the driving forces and the resisting forces, the latter mainly influenced by surface roughness and physical obstructions. Plastic items that remain mobile can enter rivers through direct entry of surface runoff, and through urban drainage networks that discharge in rivers (Treilles et al., 2021). Especially in urban areas that are closely connected to waterways, pluvial floods may result in an increase in plastic pollution in rivers. Research on such travel dynamics in urban areas remains scarce. A recent study on Amsterdam found no significant correlations between rainfall and floating plastic transport in either of the six measured canals (Tasseron et al., 2023). For the Huveaune River in Marseille, Tramoy et al. (2022) found that 36% of the annual macroplastic transport occurred during heavy rainfall events. Treilles et al. (2021) estimated that 20–36% of the total annual plastic transport in stormwater was discharged through untreated stormwater, which mainly occurs when the precipitation included runoff exceeds the urban drainage capacity. Pluvial floods are mainly associated with increased plastic transport, especially through urban drainage systems.

2.3. Flash floods

Flash floods can occur when high-intensity precipitation falls on a relatively small surface area. Water level may rapidly increase, leading to high flow velocities, and therefore high plastic mobilization (Moore et al., 2011). During the 2021 European floods, floating plastic transport was found to have increased with a factor over 100 compared to non-flood conditions, which was partly explained by flash floods that occurred in several tributaries of the Meuse (van Emmerik et al., 2023a). Flash floods may result in high forces that mobilize items and objects that are generally not found in or around rivers. Bayón et al. (2023) showed that besides large plastic items, caravans, furniture, garbage bins, and even larger objects can also be mobilized. Anecdotal evidence from the 2021 European floods confirms that indeed much larger items were found on riverbanks and floating at the surface than under non-flood conditions (van Emmerik et al., 2023a). When flash floods occur in areas close to river mouths, these may lead to flushing of accumulated plastics. Pierdomenico et al. (2022) found increased burial of plastics in sediment around river mouths after flash floods in the mouth of the Mazzarrà River. In some cases, flash floods flush large amount of plastics to submarine canyons near river mouths (Pierdomenico et al., 2019). Flash floods are events that mobilize additional, and larger plastic items and objects, and specifically can cause a flushing effect of accumulated plastic in river systems.

2.4. Coastal floods

Coastal floods can be caused by storm surges or tsunamis, and are characterized by progressing and retreating flow direction. Similar to fluvial floods, coastal floods may therefore lead both to mobilization and deposition of plastic. As many of the world's largest cities are located in delta areas, coastal floods are potentially high-

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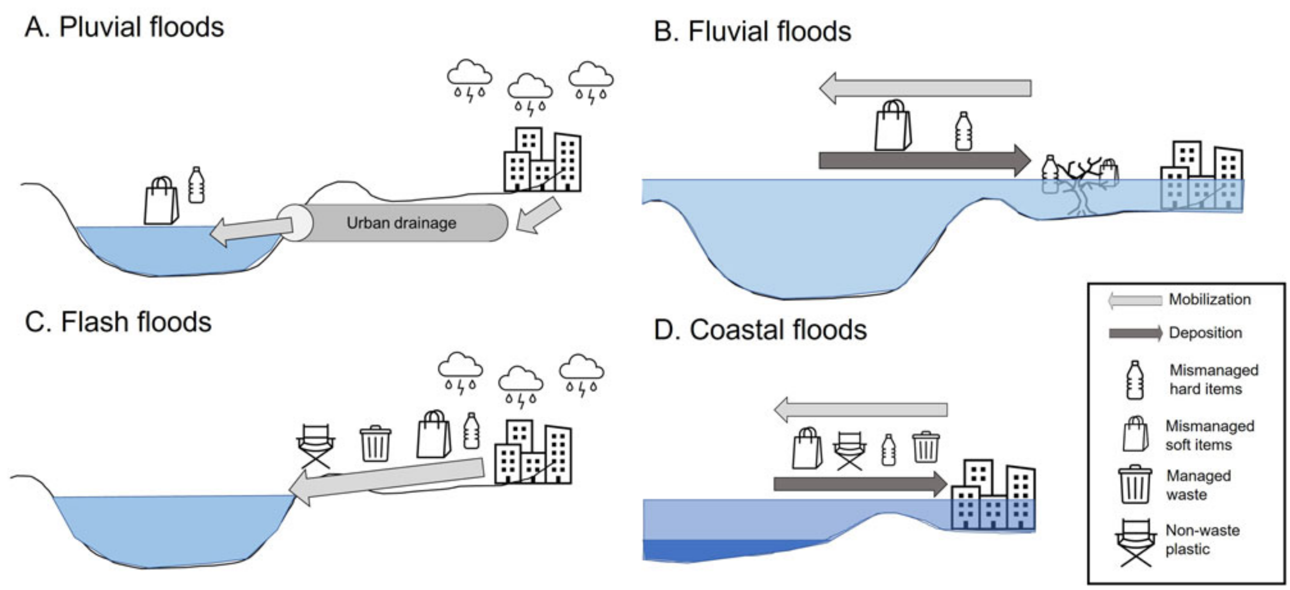

Figure 1. Plastic transport dynamics during different flood types, including (a) pluvial floods, (b) fluvial floods, (c) flash floods, and (d) coastal floods. The arrows indicate mobilization or deposition in response to the flood type, and the different items indicate the type of plastic items that are impacted.

impact events for plastic transport. However, only few work has been done to quantify the impact of coastal floods on plastic pollution. Several efforts have been made to study the impact of 2011 Tohoku tsunami that hit Japan. Lebreton and Borrero (2013) estimated that an amount equal to thousands years of normal plastic leakage entered the ocean during this extreme event. Murray et al. (2018) estimated that the tenfold increase of beach plastic density in North America and Hawaii could be attributed to this single event. Coastal floods mainly lead to mobilization of plastics, and large additional input into the ocean. Over time this may also result to increased beached plastic on shorelines elsewhere.

2.5. Impact of flood-driven plastic transport

Here the three main additional direct impacts of flood-driven plastic transport are identified. First, floods lead to direct additional impact of plastics on the environment. Larger plastic items, especially foils and other flexible items, can accumulate around infrastructure. Honingh et al. (2020) combined field measurements during high discharge and lab experiments to estimate that plastic pollution blockage in the Cikapundung River around Bandung, Indonesia, could lead to a water level increase of 1 m per hour. This increase was much higher than blockages caused by organic debris, and the studied event was not even under (extreme) flood conditions. Plastic blockage of bridges and other types of infrastructure was also reported by Tjia (2020) in urban rivers in Kumasi, Ghana. Small rivers draining densely populated areas are assumed to be among the most polluted globally, and exactly those rivers are sensitive for blockage by plastic pollution. The Odaw River, draining Ghana's capital Accra, was found to transport similar amounts of plastic as the Saigon, Vietnam, and Chao Phraya, Thailand (Pinto et al., 2024; van Calcar & van Emmerik, 2019). However, the Odaw is around 5–10 times narrower, and full of bridges, weirs, and other locations where plastic can easily accumulate. In turn, the increased inundation depths upstream may lead to additional plastic being mobilized.

Second, floods have a large impact on the annual plastic budget of river systems. In the United Kingdom, it was estimated that the 2015 floods resulted in a 70% microplastic concentration in river sediments (Hurley et al., 2018). It was unknown how far these particles traveled in response to the flood. For the 2021 Meuse flood, the total plastic transported during the six-day flood event equaled one-third of the annual plastic transport (van Emmerik et al., 2023a). In this specific case study, the observations were done as part of an ongoing one-year monitoring campaign, allowing to rapidly and safely mobilize observers to relevant locations. However, during other large-scale and long-term monitoring efforts, no observations were done during extreme events. Not accounting for flood-driven plastic transport may therefore introduce large errors in the assessment of annual plastic budgets, and understanding of transport and retention dynamics.

Finally, flood-related plastic deposition may threaten vegetation species globally. Gonçalves et al. (2020) found flooded forests to be large accumulation zones for riverine plastic pollution. As introduced in Section 2.1, fluvial floods may also lead to deposition of plastics in vegetation on the floodplains, known as the Christmas tree effect (Williams & Simmons, 1999). Although the effect of plastic pollution on vegetation is not globally quantified, complete coverage of root zones of, for example, mangrove trees leads to tree death (van Bijsterveldt et al., 2021).

3. Reducing plastic pollution through flood resilience

One of the large challenges for future research is to better understand the negative feedback-loop between flood-driven plastic mobilization, and increased flood risk by plastic accumulation. This phenomenon is known as the plastic-flood nexus, and is most relevant in densely populated areas with relatively small rivers or waterways, and low resilience against floods.

The main pathway to reducing flood-driven plastic mobilization is by increasing the resilience of communities globally. Roebroek et al. (2021a) included flood defenses as proxy of resilience, in the assessment of PPM, and found that resilient countries reduced their PPM by 86% (Japan) to 100% (the Netherlands). Flood-prone countries including Bangladesh, Vietnam, and Pakistan showed almost no reduction of PPM, which may be an additional incentive to invest in improving the resilience against various flood types. Globally, only 53% of PPM is decreased by current flood defenses, emphasizing the room for improvement.

In this paper, only individual flood types were considered. However, compound events have been demonstrated to put a large part of the global population at additional risk. The effect of compound events, such as coastal and fluvial flooding, has not been studied to date. Due to the ambiguous net effect of single flood types, further research is crucial to better forecast the effect of compound events on plastic mobilization and dispersal in the environment. The same holds for other types of extreme events. Seo and Park (2020) showed that a flood event caused by a typhoon led to plastic pollution traveling hundreds of kilometers on the open ocean. Several studies showed that river mouths in Southeast Asia temporarily accumulate large quantities of plastic pollution, which may be flushed at once during typhoons or floods resulting from those (Schreyers et al., 2024; van Emmerik et al., 2020).

Observations during extreme events are challenging and often unsafe, but they are absolutely crucial to better quantify and understand their impact on plastic pollution. Recent advances have been made in the development of near-field and spaceborne remote sensing of plastic pollution on land, rivers, and oceans. The 2019 flood event in Durban, South Africa, lead to large quantities of plastic to cover surface water. This event was used as validation for one of the first satellite remote-sensing methods for plastic detection in the open ocean (Biermann et al., 2020). In tropical rivers, floods may lead to mobilization and downstream transport of floating vegetation, which can carry up to 80% of the floating plastic pollution. These plastic-plant aggregates can also be detected and monitored from space (Schreyers et al., 2022). Floods may result in carpet formation of plastic debris around infrastructure, including weirs or dams. These have also been shown to be detectable from space (Garaba & Park, 2024). In the field, cameras can be used to continuously monitor plastics in rivers, independent of the hydrological conditions (Manfreda et al., 2024; van Lieshout et al., 2020). Such techniques may offer a safe and reliable alternative for continuous monitoring during extreme events, and rapid ad hoc detection direction after an extreme event.

4. Concluding remarks

Floods play a crucial role in the mobilization and deposition of plastic pollution from land to rivers and into the ocean. The exact dynamics largely depend on the type of flood, and the characteristics of the plastic pollution. Depending on the size, polymer type, and shape, some items or particles are more likely to be flushed downstream, where others may be deposited in vegetation or obstructions.

The additional flood risk resulting from plastic accumulation around urban water infrastructure may be one of the most severe direct effect of flood-driven plastic transport. Future research should therefore prioritize understanding and quantifying the plastic-flood nexus (negative feedback-loop), especially in densely populated urban areas with small-sized waterways.

Flood-driven plastic transport can be reduced by increasing the flood resilience of global communities. Each flood type, and combinations therefore, requires different approaches. Although flood resilience should have ample direct benefits for the livelihood of communities, it is argued that plastic pollution reduction may be an additional benefit to invest in such measures.

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