PAPER • OPEN ACCESS

Plastic in global rivers: are floods making it worse?

To cite this article: Caspar T J Roebroek *et al* 2021 *Environ. Res. Lett.* **16** 025003

View the [article online](#) for updates and enhancements.

ENVIRONMENTAL RESEARCH
LETTERS

LETTER

Plastic in global rivers: are floods making it worse?

Caspar T J Roebroek^{1,2} , Shaun Harrigan¹ , Tim H M van Emmerik² , Calum Baugh¹, Dirk Eilander^{3,4} , Christel Prudhomme^{1,5,6} and Florian Pappenberger¹ ¹ Forecast Department, European Centre for Medium-Range Weather Forecasts (ECMWF), Reading, United Kingdom² Hydrology and Quantitative Water Management Group, Wageningen University, Wageningen, The Netherlands³ Institute for Environmental Studies (IVM), Vrije Universiteit Amsterdam, Amsterdam, The Netherlands⁴ Deltares, Delft, The Netherlands⁵ UK Centre for Ecology and Hydrology, Wallingford, United Kingdom⁶ Department of Geography and Environment, University of Loughborough, Loughborough, United KingdomE-mail: roebroek.jasper@gmail.com**Keywords:** floods, riverine plastic pollution, plastic mobilisationSupplementary material for this article is available [online](#)

RECEIVED

23 October 2020

REVISED

4 December 2020

ACCEPTED FOR PUBLICATION

22 December 2020

PUBLISHED

27 January 2021

Original content from this work may be used under the terms of the [Creative Commons Attribution 4.0 licence](#).

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

Abstract

Riverine plastic pollution is of global concern due to its negative impact on ecosystem health and human livelihood. Recent studies show a strong link between river discharge and plastic transport, but the role of floods is still unresolved. We combined high-resolution mismanaged plastic waste data and river flood extents with increasing return periods to estimate flood-driven plastic mobilisation, from local to global scale. We show that 10 year return period floods already tenfold the global plastic mobilisation potential compared to non-flood conditions. In the worst affected regions, plastic mobilisation increases up to five orders of magnitude. Our results suggest a high inter-annual variability in plastic mobilisation, previously ignored by global plastic transport models. Flood defences reduce plastic mobilisation substantially, but regions vulnerable to flooding often coincide with high plastic mobilisation potential during floods. Consequentially, clean-up and mitigation measures and flood risk management are inherently interdependent and need to be managed holistically.

1. Introduction

Riverine plastic pollution is a growing, global concern. Although most research efforts have been focussed on riverine plastic as the primary source of plastic material emitted to the oceans, the effects at the local scale can be equally, or more severe (van Emmerik and Schwarz 2020). Plastic pollution has been found to significantly disrupt economic activities such as fishing and tourism, hinder transportation over and along the river, and in some locations put the availability of clean freshwater at risk, endangering the livelihoods of the communities living next to and depending on the river (van Emmerik and Schwarz 2020). For riverine ecosystems, plastic is as detrimental as it is in the ocean, with the effects depending on the size of the debris. The negative effect of macroplastics (>0.5 cm) are mainly mechanical. For example, fish and mammals get entangled in the plastic and occasional ingestion can cause blockages of their intestinal tracts, enhancing mortality rates

(van Emmerik and Schwarz 2020). Microplastic pollution is found to break down into its initial—sometimes toxic—components (Staples *et al* 1997, Gallo *et al* 2018), while many of the plastic particles can also act as natural adsorbent of hydrophobic chemicals (Teuten *et al* 2007, Andrady 2011, 2015, Ziccardi *et al* 2016), thus acting as a vector of bioaccumulation of these substances. These chemical components move up through the food chain, although the resulting effect on riverine ecosystems and human health have not yet been conclusively studied. Of the globally produced 380 million metric tons (Mt) of plastic in 2015 (Geyer *et al* 2017), between 0.4 and 12.7 Mt has been reported to reach the ocean from rivers (Jambeck *et al* 2015, Lebreton *et al* 2017, Schmidt *et al* 2017). Plastic waste in the river system is potentially even higher, as many sinks have been identified, such as deposition on shores, deposition on and burial in riverbed sediments and accumulation within riverine species (van Emmerik and Schwarz 2020). Additionally, it needs to be considered that

the numbers presented here are expected to increase in the coming years (Borrelle *et al* 2020, Law *et al* 2020)

An increasing number of studies estimated river plastic transport, accumulation and emissions into the ocean on local, national and global scales (Jambeck *et al* 2015, Lebreton *et al* 2017, Schmidt *et al* 2017, Cordova and Nurhati 2019, Nihei *et al* 2020). The temporal dynamics of the plastic load is less well understood, as most observational studies are single instance measurements or measurements over a very short period of time (van Calcar and van Emmerik 2019). The first observational studies over longer periods have hinted at a strong link between discharge and the amount of plastic in the river (Castro-Jiménez *et al* 2019, van Emmerik *et al* 2019a, Schirrinzi *et al* 2020). This naturally leads to the question about the importance of extreme discharge events (Korshenko *et al* 2020). So far, the only observational study on plastic load in river systems with respect to flooding is a study by Hurley *et al* (2018), which demonstrates that riverbed microplastic concentration decreased by about 70% after the flooding of the winter 2015/2016 in the UK, linking high discharges to an increase in plastic (re)mobilisation. At the global scale, the effect of the seasonal change in discharge and extreme flow events have only been quantified with the use of models, using an aggregated, lumped approach for monthly discharge, precipitation and runoff (Lebreton *et al* 2017), potentially causing a severe underrepresentation of the effects of flooding on the mobilisation of plastic. Together with the observational evidence that macroplastics clog drainage infrastructure (Lebreton and Andrady 2019, Windsor *et al* 2019, Honingh *et al* 2020), consequentially raising urban flood risk, it shows the importance of studying the interaction between plastic mobilisation and floods at a global scale.

In this study we present the first global analysis of the impact of flood events on plastic mobilisation. In order to estimate this effect, we use publicly available global flood extent maps (Dottori *et al* 2016) together with recent, globally distributed data on mismanaged plastic waste (MPW) (Lebreton and Andrady 2019). By intersecting the flood extents with the distribution of MPW we approximate the mobilised plastic potential within a given extent, thus making it possible to compare the amount of plastic mobilised during floods with different severity to the non-flood situation (as estimated by intersecting data on the spatial extent of the river network with MPW). As flood defences are not accounted for in the flood extent maps directly, we use a global flood defence database (Scussolini *et al* 2016) to adjust the plastic mobilisation estimates accordingly. By aggregating the total amount of MPW in the flood extents, we show that floods dramatically increase global plastic mobilisation potential.

2. Methods

The potential for floods to mobilise plastic in rivers is quantified combining MPW data with information of flood/non-flood extents and flood defence. The resulting estimates are aggregated for an annual net plastic mobilisation risk, accounting for the likelihood of flood events

2.1. Input data

2.1.1. Flood extents

Global, openly available (<https://data.jrc.ec.europa.eu/collection/id-0054>), static flood extent maps at 30 arc second resolution (Dottori *et al* 2016) were used as an estimate of flood extent for different flood severity levels. The data were generated from streamflow climatologies derived from the Copernicus Emergency Management (CEMS) Global Flood Awareness System (GloFAS) (Alfieri *et al* 2013), using estimated river discharge maxima for the 10, 20, 50, 100, 200 and 500 years return period severity levels fed into the CA2D hydrodynamic model (Dottori and Todini 2011, Dottori *et al* 2016). Additionally, a river network map, based on the HydroSHEDS hydrologically corrected digital elevation model by Dottori *et al* (2016), was used to represent the non-flood conditions. Both the river network and flood extent data exclude river cells with an upstream area of less than 5000 km², and are defined at 30 arc second resolution. As the river network map does not extend above 60° N, all input data have been clipped to the same extent. Note that there will be some uncertainties matching flooded and non-flooded conditions at the edge of the domain resulting is a small number of overestimates, particularly in Canada and Russia.

2.1.2. Modelled mismanaged plastic waste

As observational data on the global abundance of land-based plastic pollution is scarce, we use a global modelling dataset of MPW (Lebreton and Andrady 2019). This dataset was created using country level data on total waste generation, estimates of the plastic fraction of this waste and estimates of the fraction of this waste that is not managed by the public waste systems. Subsequently, this data was distributed within countries on the basis of high-resolution gross domestic product (GDP) and population estimates, yielding a 30 arc second map of annual MPW generation. The data is publicly available as supplement to the paper of Lebreton and Andrady (2019).

2.1.3. Flood defences

As there is no global dataset of flood defence assets, flood defences were accounted for using the 'merged' layer of the publicly available, global flood protection database FLOPROS (Scussolini *et al* 2016). This dataset was constructed from local policy standards and the design return periods from technical documents on flood defences, with

gaps filled by using relationships between GDP and flood defences at global scale. The resulting dataset contains maximum flood return periods at sub-country administration level (using GADM polygons—<https://gadm.org/index.html>), for which the flood defences provide protection (Scussolini *et al* 2016).

2.2. Analysis procedure

The estimates of plastic mobilised potential were created by intersecting the footprint of the river network and flood extents with the annual modelled MPW layer and aggregating the sum of the data in the GADM administration units, obtained from the FLOPROS database. By intersecting MPW with the river network the base plastic mobilisation is defined, while the flood extents (including the river network) provide estimates of mobilisation during floods with different severities (for a visual step-by-step example in the Ganges–Brahmaputra basin see figure 1). With this procedure all plastic within the flood extents are

defined as potentially mobilisable, which would correspond to the worst case scenario real mobilisation. Under non-flood conditions this would be achieved during bankfull river flow.

To estimate the net annual effect of floods of different severities on plastic mobilisation we calculated the expected annual plastic mobilisation (EAM) following Tiggeloven *et al* (2020), where the EAM is given as the integral of the mobilised plastic over each return period using the flood extent maps (see figure 2). The method is often used to calculate damages that happen during flooding (Tiggeloven *et al* 2020), and is adjusted here to account for the plastic mobilisation that happens during non-flood conditions as well. The mobilised plastic during non-flood conditions is attributed to annual exceedance probabilities exceeding 50%, with the assumption that a 2 year return period flood does not exceed the natural water holding capacity of the riverbanks (Dunne and Leopold 1978). As the flood extent maps exclude any flood protection structure, EAM is calculated

Figure 2. Representation of the calculation of the expected annual plastic mobilisation (EAM), a compounding method of the information from the mobilisation during floods with different return periods. The final value for EAM is the integral of the points with respect to the probability of the return periods. Assumptions here are that a 2 year return period flood does not spill over the riverbank, thus having the same plastic mobilisation as the non-flood situation. Additionally, zero probability is assumed to have the same plastic emissions as a flood with a probability of 0.0002 (500 year return period). Due to the very small area under the graph that this represents the error this will induce is quite small. The return periods are plotted as a separate x-axis and represent the return periods for the given probability but are not used for the calculations. This figure includes the calculation of expected annual plastic mobilisation for both the situation with, and without flood defences. The difference between the curves thus represents the amount of plastic mobilisation that is avoided by introducing flood defences (hashed area).

twice: (a) excluding any flood defences and (b) while assuming EAM estimates of ‘non-flood conditions’ for return periods smaller than the critical return period of the flood defences from FLOPROS. To facilitate the interpretation of the results were aggregated to administration unit (FLOPROS), river basin (HydroSHEDS (Lehner *et al* 2008)), country and global scale.

3. Results

3.1. Global impact of floods on the mobilisation of plastic waste

Floods have the potential to substantially increase the amount of plastic that is mobilised by rivers, as displayed in figure 3(A). The factor of increase of mobilisation for undefended flood events show a large global variation, with some countries experiencing only a marginal increase during floods, while others could expect up to a 30-fold increase. Of the ten countries with the highest plastic mobilisation potential during non-flood conditions (table 1), the average factor increase during flooding is 10.5; whereas the ten countries with the lowest plastic mobilisation potential, the average factor increase is 2.3. According to our estimates, Bangladesh is the country with the highest increase in plastic mobilisation during floods, with a potential for

mobilisation 40.6 times higher than during non-flood conditions.

Globally, the most substantial increase in potential plastic mobilisation occurs between the non-flood and 10 year return period flood (see figure 3(B)). During non-flood conditions an estimated 0.8 Mt yr^{-1} of plastic is mobilised across the world. In contrast, 7.3 Mt yr^{-1} (almost a tenfold increase) is estimated to be mobilised globally under an undefended 10 year return period flood. Floods with higher return periods mobilise even more plastic, but the relative increase is not as large due to the fact that extreme floods increase inundation depth rather than extent, hence reaching less new deposited plastic (see figure 1). For example, the 500 year return period flood could potentially mobilise globally 9.6 Mt of plastic per year, a 12.7-fold increase from non-flood conditions, but relatively small compared with the tenfold generated by a 10 year flood.

3.2. Spatial patterns of plastic mobilisation during floods

The global patterns of MPW in the flood zones shows a similar picture as described in observational studies on riverine plastic pollution (Lebreton *et al* 2017). The most severely impacted region is (South-East) Asia, showing MPW in the 10 year return period

flood extent of over 2500 kg km^{-2} (see figures 4(A) and (C)). The spatial variability of the MPW in river floodplains is substantial, with areas of low population density such as Australia, southern Algeria and northern USA showing a less than 10 kg km^{-2} . Whilst those regions also have plastic hotspots, they are small compared to the total surface of the floodplain within the administration unit, resulting in a low overall amount of plastic.

Besides the between-country variability (figure 3(A)), the relative impact of floods on the plastic mobilisation potential shows a substantial within-country variability (figure 4(B)). Large countries show spatial heterogeneity in the factor

increase in plastic mobilisation in orders of magnitude, with for example the USA having low plastic mobilisation increase factors in mountainous states such as Wyoming and Colorado (~ 1.4), while that of the coastal state Louisiana exceeds 30 (~ 31). In fact, the same pattern is found across the globe, with only three out of the twenty administration units with the highest relative increase in plastic mobilisation not being coastal. The seven administration units with the highest factors of increase are located in Vietnam, Egypt and Gambia, respectively in the Mekong, Nile and Gambia river delta, together mobilising 11.6 tonnes during non-flood conditions and 0.1 Mt during a 10 year return period flood event,

Table 1. Representation of country data of figure 3, presenting the ten countries with highest/lowest plastic mobilisation potential under non-flood conditions.

Country	ISO code	Plastic mobilisation under non-flood conditions (Mt yr^{-1})	Plastic mobilisation under a 10 year return period flood (Mt yr^{-1})	Relative factor of increase with a 10 year return period flood (—)
Countries with highest plastic mobilisation potential				
China	CHN	1.84×10^{-1}	1.81×10^0	9.84
India	IND	1.19×10^{-1}	1.36×10^0	11.45
Brazil	BRA	3.90×10^{-2}	1.21×10^{-1}	3.11
Thailand	THA	3.17×10^{-2}	4.75×10^{-1}	15.00
Egypt	EGY	2.53×10^{-2}	5.47×10^{-1}	21.62
Philippines	PHL	2.48×10^{-2}	1.10×10^{-1}	4.43
Turkey	TUR	1.76×10^{-2}	5.42×10^{-2}	3.08
Congo	COD	1.72×10^{-2}	3.72×10^{-2}	2.16
Nigeria	NGA	1.67×10^{-2}	1.08×10^{-1}	6.47
Vietnam	VNM	1.66×10^{-2}	4.58×10^{-1}	27.61
Countries with lowest plastic mobilisation potential				
Ireland	IRL	1.02×10^{-5}	3.00×10^{-5}	2.95
Costa Rica	CRI	7.91×10^{-6}	2.70×10^{-5}	3.41
Western Sahara	ESH	7.31×10^{-6}	7.31×10^{-6}	1.00
Armenia	ARM	6.87×10^{-6}	1.76×10^{-5}	2.56
Oman	OMN	5.27×10^{-6}	1.45×10^{-5}	2.75
Somalia	SOM	4.19×10^{-6}	4.53×10^{-6}	1.08
Palestinian territory	PSE	3.95×10^{-6}	3.95×10^{-5}	1.00
Israel	ISR	2.51×10^{-6}	2.99×10^{-6}	1.20
Syria	SYR	4.71×10^{-7}	2.69×10^{-6}	5.72
United Arab Emirates	ARE	4.74×10^{-8}	5.19×10^{-8}	1.09

which is a four orders of magnitude increase (table 2). When aggregating the data at riverbasin level the same patterns arise: most of the administration units with a factor of increase higher than 10 fall within the 25 biggest basins.

3.3. Reduction of plastic mobilisation by flood defences

During floods with low return periods, flood defences avert a substantial part of the increment in plastic mobilisation (figure 3(B)). For a 10 year return period flood, the mobilised plastic potential is reduced by 53% (from 7.3 to 3.4 Mt yr^{-1}), while for a 20 year return period flood, this is estimated to reduce by 33% (from 7.9 Mt to 5.2 Mt). The effect of flood defences at higher return periods, however, is much lower, with an estimated reduction of less than 2% for a 100 year return period flood, and a reduction approaching zero for floods with higher return periods. This mirrors the global presence of flood defences; many regions have flood defences in place that protect against low severity floods, while relatively few flood defences can avert a 100 year return period flood (see figure S2).

As medium to severe floods do not occur every year, we have also estimated the expected annual plastic mobilisation potential (EAM) accounting for the probability of flood events in each year, by integrating the mobilised plastic over all available flood

extents (see figure 2 for a graphical representation). This yields an expected total of 2.8 Mt mobilised plastic per year, reduced to 1.8 Mt yr^{-1} when flood defences are accounted for (the integral under the curve presented in figure 2), compared to an estimated 0.8 Mt for a year without flood event (figure 3(B)).

Figure 5 shows the EAM for each country with and without the effect of flood defences. The 1:1 line represents the case in which flood defences have no effect on the mobility of plastic while the horizontal line represents the 100% reduction of flood induced plastic mobilisation. The reducing effect of flood defences on the EAM varies drastically, with half the countries showing less than a 10% reduction in EAM and only a handful of countries reducing the additional plastic mobilisation related to flooding to 0. Of the locations with the highest increase factor, both Gambia (GMB) and Vietnam (VNM) lie close or on the 1:1 line, suggesting that relatively few flood defences are present or only protecting against relatively low return period floods, while flood defences in Egypt achieve a 52% reduction in plastic mobilisation. Other countries that stand out are Pakistan (PAK) and Bangladesh (BGD), both showing expected annual plastic mobilisation that is more than ten times higher than what would be expected if no flood would happen, while their flood defences are not sufficient to reduce this number

Table 2. Plastic mobilisation potential during non-flood and 10 year return period flood conditions and their relative difference. The ten administration units with highest factor of increase are presented here.

Administration unit	Country	ISO code	Plastic mobilisation under non-flood conditions (Mt yr ⁻¹)	Plastic mobilisation under a 10 year return period flood (Mt yr ⁻¹)	Relative factor of increase with a 10 year return period flood (—)
Bến Tre	Vietnam	VNM	9.81×10^{-8}	1.03×10^{-2}	1.05×10^5
Lower River	Gambia	GMB	4.89×10^{-9}	1.26×10^{-4}	2.58×10^4
Tiền Giang	Vietnam	VNM	8.83×10^{-7}	1.93×10^{-2}	2.19×10^4
Al Qalyubiyah	Egypt	EGY	2.01×10^{-6}	3.15×10^{-2}	1.57×10^4
Ad Daqahliyah	Egypt	EGY	1.70×10^{-6}	1.38×10^{-2}	8.13×10^3
Vĩnh Long	Vietnam	VNM	2.99×10^{-6}	1.27×10^{-2}	4.23×10^3
Sóc Trăng	Vietnam	VNM	3.91×10^{-6}	1.55×10^{-2}	3.96×10^3
Wanica	Suriname	SUR	2.34×10^{-6}	3.26×10^{-3}	1.39×10^3
Greater Accra	Ghana	GHA	5.98×10^{-7}	6.32×10^{-4}	1.06×10^3
Glodeni	Moldova	MDA	5.65×10^{-8}	4.00×10^{-5}	7.05×10^2

significantly. Other strongly impacted countries are Japan and the Netherlands displaying an 86% and a 100% reduction in flood induced plastic mobilisation, respectively, as a consequence of their flood defences.

4. Discussion

We have conducted the first global assessment of the increase in plastic mobilisation caused by river flooding. In comparison with other global assessments of plastic transport through river systems, a simplified approach was used to solely focus on the mechanism of flood induced mobilisation. Nevertheless, our findings of potential annual plastic mobilisation (1.8 Mt yr^{-1} , accounting for existing flood defences)

fall in the same range as river plastic emissions found by Lebreton *et al* (2017) ($1.15\text{--}2.41 \text{ Mt yr}^{-1}$) and Schmidt *et al* (2017) ($0.4\text{--}4 \text{ Mt yr}^{-1}$), based on similar MPW data but using a hydrological modelling approach, accounting hydrological extremes (although lumped to monthly/yearly values and averaged over the catchment). Note that plastic mobilisation does not directly equate to plastic emissions (towards the ocean). Plastics will likely be deposited and remobilised multiple times before reaching the river mouth (Liro *et al* 2020), which in turn might be strongly spatially heterogeneous through its likely dependence on vegetation, floodplain and river channel characteristics.

Further, with our approach we were able to express plastic mobilisation potential as a function

of flood severity, which reveals a range of 0.8–9.6 Mt yr⁻¹ between the non-flooded and 500 year return period flood, suggesting that temporal variability cannot be ignored when assessing riverine plastic pollution. This opens up the potential to estimate both past trends with flood extent reanalysis data (Harrigan *et al* 2020b), and provide forecasts of flood plastic mobilisation potential in real-time by coupling flood inundation extents from an global flood forecasting system, such as GloFAS (www.globalfloods.eu/) (Alfieri *et al* 2013, Harrigan *et al* 2020a) to the MPW exposure data, thus enabling the implementation of targeted mitigation measures before, during and after pollution peaks.

Focussing on flood events specifically, the results show a tenfold worldwide potential plastic mobilisation increase even during low severity floods (10 year return period). The increase varies

substantially between and within countries, with the worst affected areas in the world showing a five orders of magnitude increase in plastic mobilisation potential during flood events. These worst affected regions are almost exclusively located in coastal regions, with the administration units showing the highest increase factors being situated in the Mekong, Nile and Gambia river delta. People have lived on the floodplains for millennia and many of today's megacities are (partly) situated in floodplain-rich delta areas. At the same time, both flood defence protection levels and MPW were found to negatively correlate with GDP (Scussolini *et al* 2016, Lebreton and Andradý 2019). Thus, in delta regions with inherently high flood risk and population pressure, low levels of flood protection and high levels of MPW are likely to co-occur. These patterns together yield severe flood induced plastic mobilisation potential, hence

defining a nexus between people, plastic, and flood defence on floodplains.

When interpreting the results, several assumptions and shortcomings in the data need to be considered. Firstly, MPW used in this study is an estimation based on GDP and waste statistics at national level. Although currently the most accurate global data available, it relies on simplified assumptions such as a linear relationship between GDP and waste collection, and excludes any informal waste collection. Additionally, it does not include intentional waste redistribution (e.g. dumping) which has been hypothesised to be substantial additional source of plastic load in rivers (van Emmerik and Schwarz 2020). Furthermore, the data is described as (plastic waste generation) rates, rather than quantities, ignoring a potential build-up of plastic over time, which is inherently hard to validate. Note also that this study only focuses on MPW, whilst actual plastic mobilisation during flood events is likely to be higher as properly disposed plastic waste and non-waste plastic can be generally transported as well. Future work should aim to quantify the uncertainties within the MPW estimates based on a large-scale field observation campaign.

Secondly, we only account for plastic mobilisation in inundated areas during flood events in larger rivers. Plastic mobilisation pathways and mechanisms through smaller (urban) streams (van Emmerik *et al* 2019b) are not resolved in the river network and flood extent maps in this global study, as they only include river grid cells with an upstream area of at least 5000 km². Note that only plastic within the floodplain is accounted for here. As floods are not always singular events, but also occur as complex, compound events (Zscheischler *et al* 2018, de Ruiter *et al* 2020, Eilander *et al* 2020, Ward *et al* 2020) plastic mobilisation potential might be considerably higher when for example including transport with surface runoff (especially in urban areas) and strong (gust) winds during such compound events. Additionally, storm surges or tsunamis can transport massive amounts of plastic, such as observed after the tsunami in Japan in 2011, when an estimated 5 Mt of plastic was transported into the ocean (Murray *et al* 2018). This catastrophic event attributed was attributed to have transported ‘thousands of years worth of “normal” litter flux from Japan’s urbanised coastline’ (Lebreton and Borrero 2013). Future research is needed to shed additional light on the role of natural hazards (e.g. floods, storms, tsunamis, landslides), especially when they co-occur, on plastic mobilisation, transport as well as emission into the ocean.

5. Concluding remarks

The results of our study have important management and future research implications. By intersecting high-resolution global flood extent estimates with

spatially distributed data on MPW, we highlight the vulnerability of individual countries and administration units to plastic pollution mobilisation during flood events. This was subsequently used to identify global hotspots, where floods have the greatest potential of increasing plastic mobilisation. Furthermore, it emphasises that in order to tackle the problem of riverine plastic pollution globally, the complex functioning of river systems—including flooding—needs to be considered holistically. As measures to reduce plastic mobilisation in the environment caused by natural hazards might differ substantially from those under normal conditions, increasing understanding of the connection between plastic and extreme events will contribute to improving countermeasures implemented by stakeholders and policymakers. Depending on the localities this could for example mean displacing waste management facilities outside the floodplain or creating a buffer zone between the river and floodplain that could function to retain the mobilised plastic, thus facilitating clean-up and preventing further displacement of the waste. Floods, and their ability to transport plastic pollution, are not contained by borders of the political entities and reducing river plastic mobilisation will therefore require multilateral policies on plastic waste and flood risk management. With the current predictions of increased occurrence of (compound) natural hazards, high urbanisation rates and an ever-increasing production of plastic, understanding the spatial and temporal distribution of flood induced mobilisation is an important step towards targeted policy and prevention/clean-up strategies in the global effort to reduce plastic waste in the environment.

Data availability statement

All data used in this study are openly available. The data on mismanaged plastic waste can be found as supplement to Lebreton and Andrady (2019) (https://figshare.com/articles/Supplementary_Data_for_Future_scenarios_of_global_plastic_waste_generation_and_disposal/5900335), the river flood extents as supplement to Dottori *et al* (2016) (<https://data.jrc.ec.europa.eu/collection/id-0054>), the FLOPROS flood defence database as a supplement to Scussolini *et al* (2016) (www.nat-hazards-earth-syst-sci.net/16/1049/2016/) and the HydroSHEDS basins are published in Lehner *et al* (2008) (www.hydrosheds.org/). The data produced in this study can be found on Figshare (DOI: [10.6084/m9.figshare.13270094](https://doi.org/10.6084/m9.figshare.13270094)).

Acknowledgments

We thank Francesco Dottori (JRC) for providing information and data on the flood extent and river network maps.

Author contribution

CR, TvE and SH designed the analysis, CR executed the analysis, DE contributed by introducing FLOPROS, CB obtained the data. All co-authors contributed to the interpretation of the results and the writing of the manuscript.

Conflict of interest

We declare that there are no competing interests.

ORCID iDs

Caspar T J Roebroek <https://orcid.org/0000-0002-1733-0845>

Shaun Harrigan <https://orcid.org/0000-0002-0992-3667>

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

Dirk Eilander <https://orcid.org/0000-0002-0951-8418>

Florian Pappenberger <https://orcid.org/0000-0003-1766-2898>

References

- Alfieri L, Burek P, Dutra E, Krzeminski B, Muraro D, Thielen J and Pappenberger F 2013 GloFAS-global ensemble streamflow forecasting and flood early warning *Hydrol. Earth Syst. Sci.* **17** 1161–75
- Andrady A L 2011 Microplastics in the marine environment *Mar. Pollut. Bull.* **62** 1596–1605
- Andrady A L 2015 Persistence of plastic litter in the oceans *Marine Anthropogenic Litter* (Berlin: Springer) pp 29–56
- Borrelle S B *et al* 2020 Predicted growth in plastic waste exceeds efforts to mitigate plastic pollution *Science* **369** 1515–8
- Castro-Jiménez J, González-Fernández D, Fornier M, Schmidt N and Sempéré R 2019 Macro-litter in surface waters from the Rhone River: plastic pollution and loading to the NW Mediterranean Sea *Mar. Pollut. Bull.* **146** 60–66
- Cordova M R and Nurhati I S 2019 Major sources and monthly variations in the release of land-derived marine debris from the Greater Jakarta area, Indonesia *Sci. Rep.* **9** 1–8
- de Ruiter M C, Couasnon A, van den Homberg M J C, Daniell J E, Gill J C and Ward P J 2020 Why we can no longer ignore consecutive disasters *Earth's Future* **8**
- Dottori F, Salamon P, Bianchi A, Alfieri L, Hirpa F A and Feyen L 2016 Development and evaluation of a framework for global flood hazard mapping *Adv. Water Resour.* **94** 87–102
- Dottori F and Todini E 2011 Developments of a flood inundation model based on the cellular automata approach: testing different methods to improve model performance *Phys. Chem. Earth* **36** 266–80
- Dunne T and Leopold L B 1978 *Water in Environmental Planning* (New York: WH Freeman)
- Eilander D, Couasnon A, Ikeuchi H, Muis S, Yamazaki D, Winsemius H and Ward P J 2020 The effect of surge on riverine flood hazard and impact in deltas globally *Environ. Res. Lett.* **15**
- Gallo F *et al* 2018 Marine litter plastics and microplastics and their toxic chemicals components: the need for urgent preventive measures *Environ. Sci. Eur.* **30**
- Geyer R, Jambeck J R and Law K L 2017 Production, use, and fate of all plastics ever made *Sci. Adv.* **3** e1700782
- Harrigan S *et al* 2020b GloFAS-ERA5 operational global river discharge reanalysis 1979–present *Earth Syst. Sci. Data* **12** 2043–60
- Harrigan S, Zoster E, Cloke H, Salamon P and Prudhomme C 2020a Daily ensemble river discharge reforecasts and real-time forecasts from the operational Global Flood Awareness System *Hydrol. Earth Syst. Sci. Discuss.* (<https://doi.org/10.5194/hess-2020-532>)
- Honingh D, van Emmerik T, Uijttewaalt W, Kardhana H, Hoes O and van de Giesen N 2020 Urban river water level increase through plastic waste accumulation at a rack structure *Front. Earth Sci.* **8** 28
- Hurley R, Woodward J and Rothwell J J 2018 Microplastic contamination of river beds significantly reduced by catchment-wide flooding *Nat. Geosci.* **11** 251–7
- Jambeck J R *et al* 2015 Plastic waste inputs from land into the ocean *Science* **347** 768–71
- Korshenko E, Zhurbas V, Osadchiv A and Belyakova P 2020 Fate of river-borne floating litter during the flooding event in the northeastern part of the Black Sea in October 2018 *Mar. Pollut. Bull.* **160** 111678
- Law K L, Starr N, Siegler T R, Jambeck J R, Mallos N J and Leonard G H 2020 The United States' contribution of plastic waste to land and ocean *Sci. Adv.* **6** eabd0288
- Lebreton L C M and Andrady A 2019 Future scenarios of global plastic waste generation and disposal *Palgrave Commun.* **5** 1–11
- Lebreton L C M and Borrero J C 2013 Modeling the transport and accumulation floating debris generated by the 11 March 2011 Tohoku tsunami *Mar. Pollut. Bull.* **66** 53–58
- Lebreton L C M, van der Zwet J, Damsteeg J W, Slat B, Andrady A and Reisser J 2017 River plastic emissions to the world's oceans *Nat. Commun.* **8** 1–10
- Lehner B, Verdin K and Jarvis A 2008 New global hydrography derived from spaceborne elevation data *Eos* **89** 93–94
- Liro M, Emmerik T V, Wyzga B, Liro J and Mikuš P 2020 Macroplastic storage and remobilization in rivers *Water* **12** 2055
- Murray C C, Maximenko N and Lippiatt S 2018 The influx of marine debris from the Great Japan Tsunami of 2011 to North American shorelines *Mar. Pollut. Bull.* **132** 26–32
- Nihei Y, Yoshida T, Kataoka T and Ogata R 2020 High-resolution mapping of Japanese microplastic and macroplastic emissions from the land into the sea *Water* **12** 951
- Schirrinzi G F, Köck-Schulmeyer M, Cabrera M, González-Fernández D, Hanke G, Farré M and Barceló D 2020 Riverine anthropogenic litter load to the Mediterranean Sea near the metropolitan area of Barcelona, Spain *Sci. Total Environ.* **714** 136807
- Schmidt C, Krauth T and Wagner S 2017 Export of plastic debris by rivers into the sea *Environ. Sci. Technol.* **51** 12246–53
- Scussolini P, Aerts J C J H, Jongman B, Bouwer L M, Winsemius H C, de Moel H and Ward P J 2016 FLOPROS: an evolving global database of flood protection standards *Nat. Hazards Earth Syst. Sci.* **16** 1049–61
- Staples C A, Adams W J, Parkerton T F, Gorsuch J W, Biddinger G R and Reinert K H 1997 Aquatic toxicity of eighteen phthalate esters *Environ. Toxicol. Chem.* **16** 875–91
- Teuten E L, Rowland S J, Galloway T S and Thompson R C 2007 Potential for plastics to transport hydrophobic contaminants *Environ. Sci. Technol.* **41** 7759–64
- Tiggeloven T *et al* 2020 Global-scale benefit-cost analysis of coastal flood adaptation to different flood risk drivers using structural measures *Nat. Hazards Earth Syst. Sci.* **20** 1025–44
- van Calcar C J and van Emmerik T 2019 Abundance of plastic debris across European and Asian rivers *Environ. Res. Lett.* **14** 124051
- van Emmerik T, Tramoy R, van Calcar C, Alligant S, Treilles R, Tassin B and Gasperi J 2019a Seine plastic debris transport tenfolded during increased river discharge *Front. Mar. Sci.* **6** 642

- van Emmerik T, Loozen M, van Oeveren K, Buschman F and Prinsen G 2019b Riverine plastic emission from Jakarta into the ocean *Environ. Res. Lett.* **14** [8](#)
- van Emmerik T and Schwarz A 2020 Plastic debris in rivers *WIREs Water* **7** [1](#)
- Ward P J *et al* 2020 Review article: natural hazard risk assessments at the global scale *Nat. Hazards Earth Syst. Sci.* **20** [1069–96](#)
- Windsor F M, Durance I, Horton A A, Thompson R C, Tyler C R and Ormerod S J 2019 A catchment-scale perspective of plastic pollution *Glob. Change Biol.* **25** [1207–21](#)
- Ziccardi L M, Edgington A, Hentz K, Kulacki K J and Driscoll S K 2016 Microplastics as vectors for bioaccumulation of hydrophobic organic chemicals in the marine environment: a state-of-the-science review *Environ. Toxicol. Chem.* **35** [1667–76](#)
- Zscheischler J *et al* 2018 Future climate risk from compound events *Nat. Clim. Change* **8** [469–477](#)