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## Plastic in global rivers: are floods making it worse?

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## LETTER

## Plastic in global rivers: are floods making it worse?

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Christel Prudhomme<sup>1,5,6</sup> and Florian Pappenberger<sup>1</sup> <sup>1</sup> Forecast Department, European Centre for Medium-Range Weather Forecasts (ECMWF), Reading, United Kingdom<sup>2</sup> Hydrology and Quantitative Water Management Group, Wageningen University, Wageningen, The Netherlands<sup>3</sup> Institute for Environmental Studies (IVM), Vrije Universiteit Amsterdam, Amsterdam, The Netherlands<sup>4</sup> Deltares, Delft, The Netherlands<sup>5</sup> UK Centre for Ecology and Hydrology, Wallingford, United Kingdom<sup>6</sup> Department of Geography and Environment, University of Loughborough, Loughborough, United KingdomE-mail: [roebroek.jasper@gmail.com](mailto:roebroek.jasper@gmail.com)**Keywords:** floods, riverine plastic pollution, plastic mobilisationSupplementary material for this article is available [online](#)**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

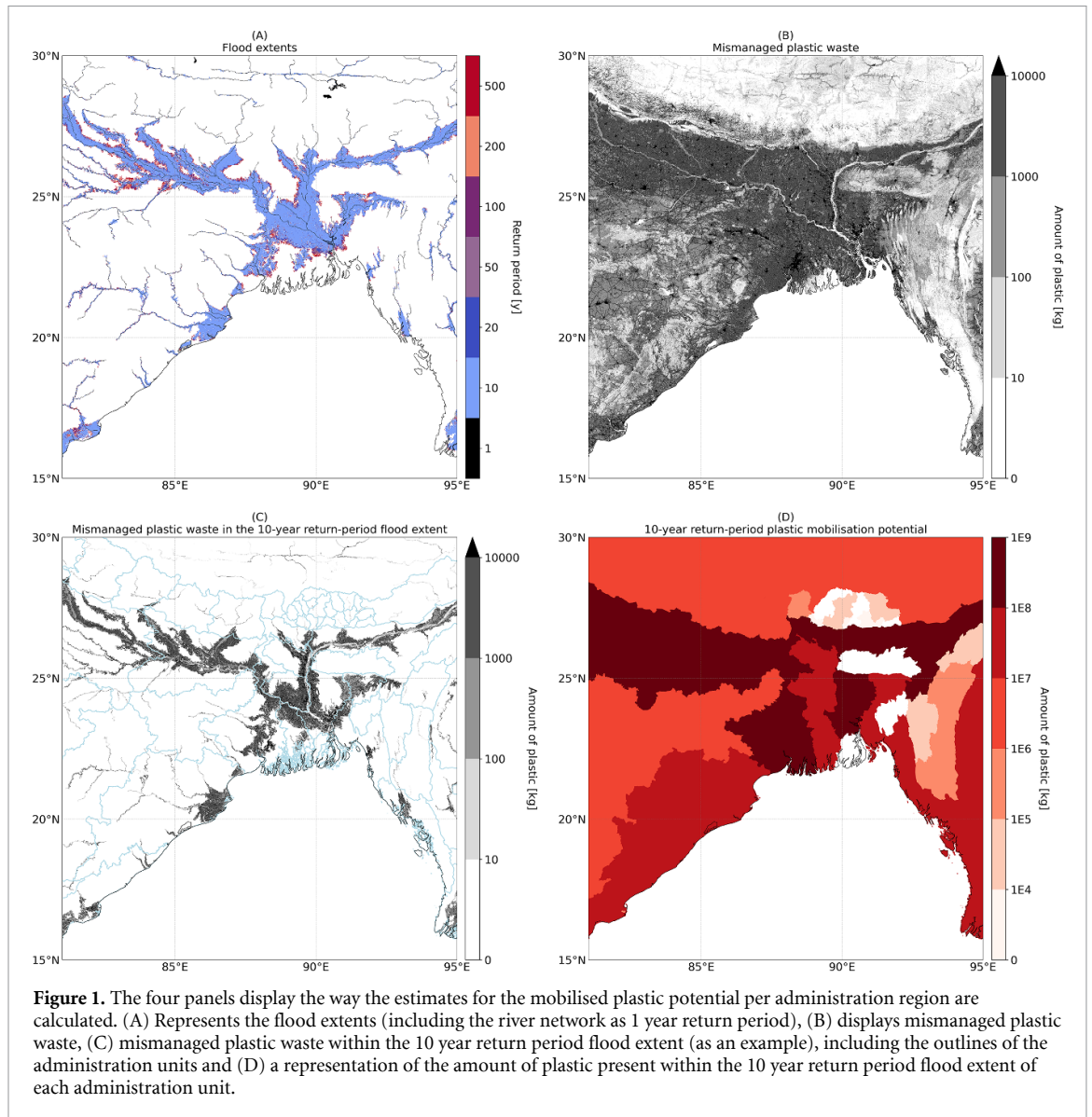
Global, openly available (<https://data.jrc.ec.europa.eu/collection/id-0054>), static flood extent maps at 30 arc second resolution (Dottori *et al* 2016) were used as an estimate of flood extent for different flood severity levels. The data were generated from streamflow climatologies derived from the 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 km<sup>2</sup>, 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



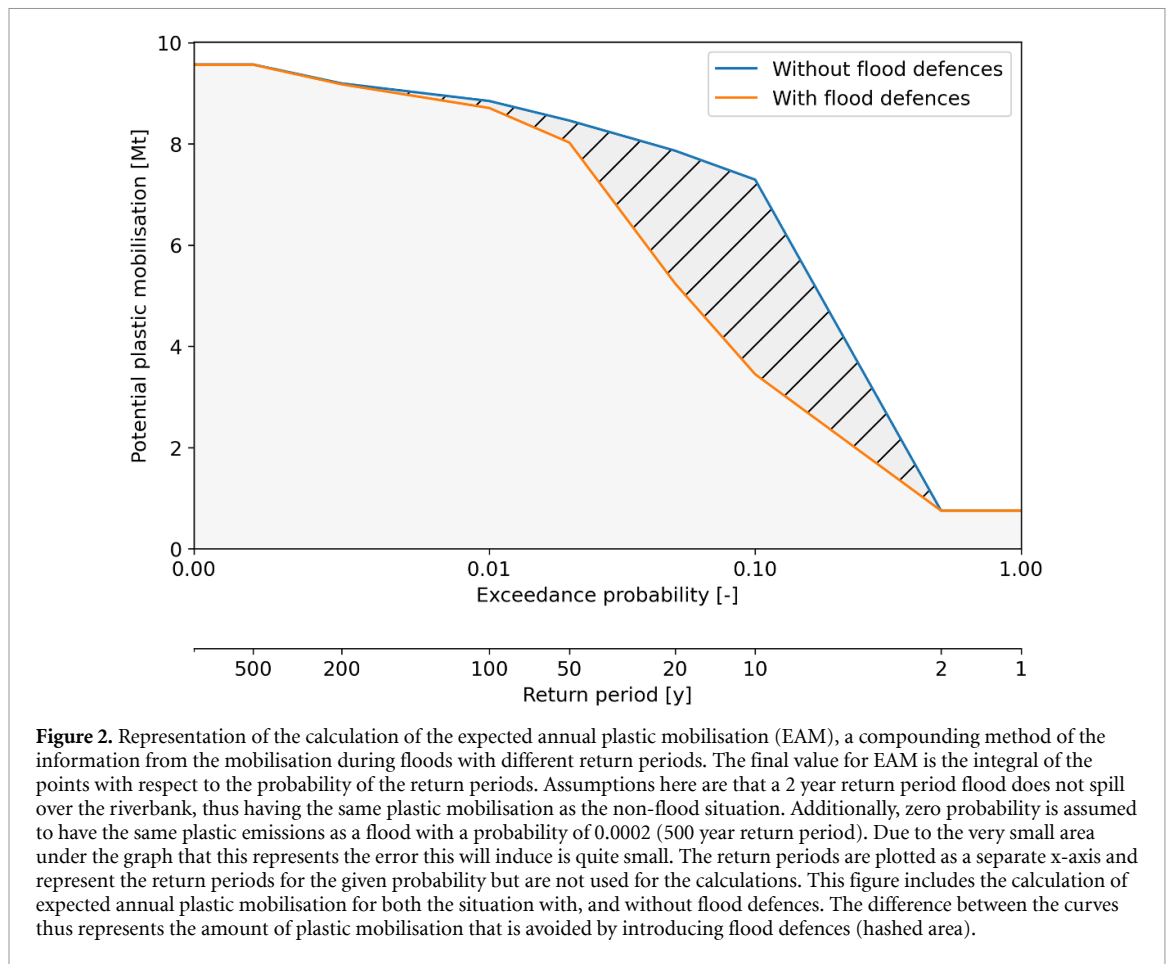
gaps filled by using relationships between GDP and flood defences at global scale. The resulting dataset contains maximum flood return periods at sub-country administration level (using GADM polygons—<https://gadm.org/index.html>), for which the flood defences provide protection (Scussolini *et al* 2016).

## 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

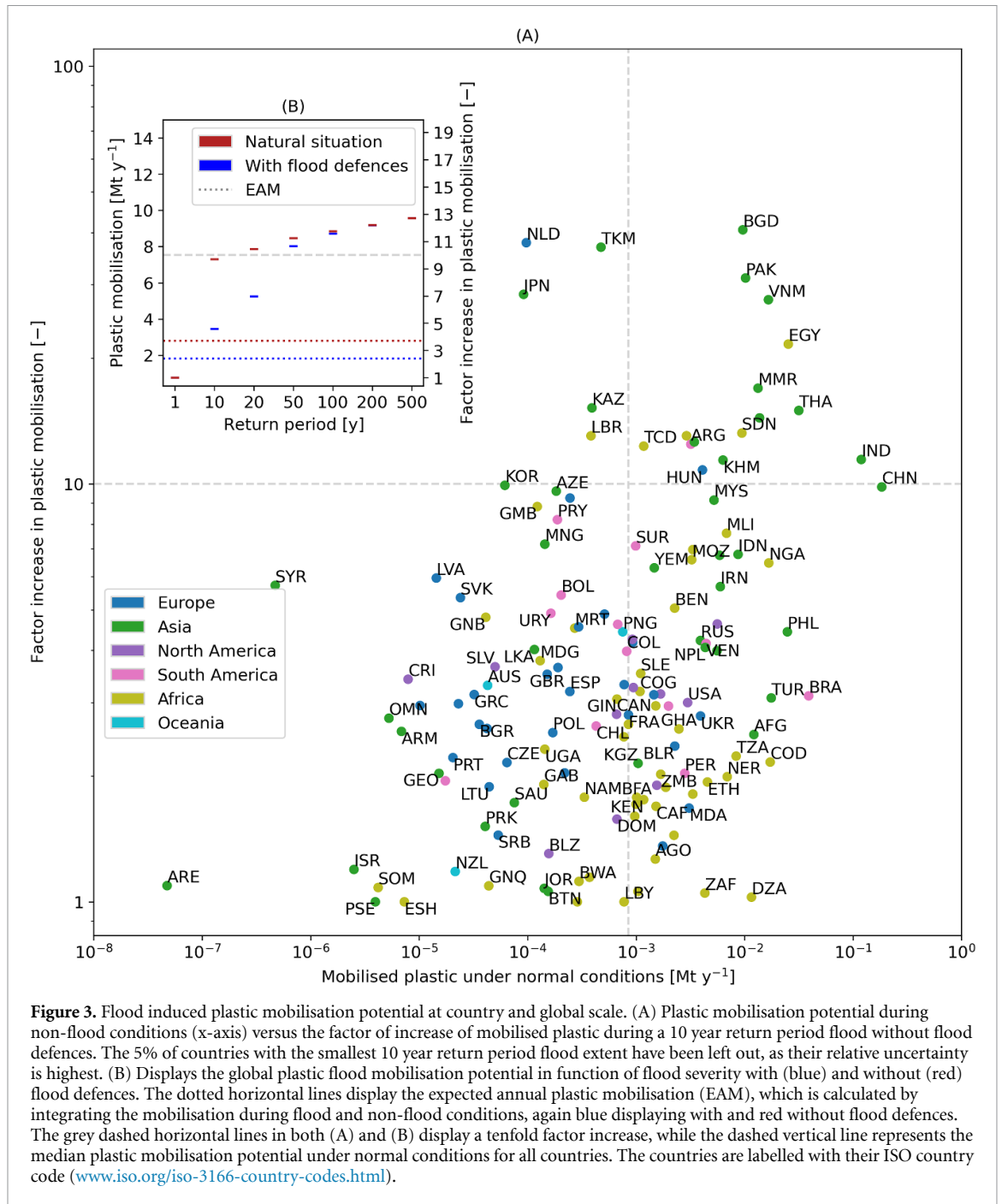
Floods have the potential to substantially increase the amount of plastic that is mobilised by rivers, as displayed in figure 3(A). The factor of increase of mobilisation for undefended flood events show a large global variation, with some countries experiencing only a marginal increase during floods, 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  $0.8 \text{ Mt yr}^{-1}$  of plastic is mobilised across the world. In contrast,  $7.3 \text{ Mt yr}^{-1}$  (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  $9.6 \text{ Mt}$  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



**Figure 3.** Flood induced plastic mobilisation potential at country and global scale. (A) Plastic mobilisation potential during non-flood conditions (x-axis) versus the factor of increase of mobilised plastic during a 10 year return period flood without flood defences. The 5% of countries with the smallest 10 year return period flood extent have been left out, as their relative uncertainty is highest. (B) Displays the global plastic flood mobilisation potential in function of flood severity with (blue) and without (red) flood defences. The dotted horizontal lines display the expected annual plastic mobilisation (EAM), which is calculated by integrating the mobilisation during flood and non-flood conditions, again blue displaying with and red without flood defences. The grey dashed horizontal lines in both (A) and (B) display a tenfold factor increase, while the dashed vertical line represents the median plastic mobilisation potential under normal conditions for all countries. The countries are labelled with their ISO country code ([www.iso.org/iso-3166-country-codes.html](http://www.iso.org/iso-3166-country-codes.html)).

flood extent of over  $2500 \text{ kg km}^{-2}$  (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  $10 \text{ kg km}^{-2}$ . 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 ( $\sim 1.4$ ), while that of the coastal state Louisiana exceeds 30 ( $\sim 31$ ). 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 <sup>-1</sup> )	Plastic mobilisation under a 10 year return period flood (Mt yr <sup>-1</sup> )	Relative factor of increase with a 10 year return period flood (–)
Countries with highest plastic mobilisation potential				
China	CHN	$1.84 \times 10^{-1}$	$1.81 \times 10^0$	9.84
India	IND	$1.19 \times 10^{-1}$	$1.36 \times 10^0$	11.45
Brazil	BRA	$3.90 \times 10^{-2}$	$1.21 \times 10^{-1}$	3.11
Thailand	THA	$3.17 \times 10^{-2}$	$4.75 \times 10^{-1}$	15.00
Egypt	EGY	$2.53 \times 10^{-2}$	$5.47 \times 10^{-1}$	21.62
Philippines	PHL	$2.48 \times 10^{-2}$	$1.10 \times 10^{-1}$	4.43
Turkey	TUR	$1.76 \times 10^{-2}$	$5.42 \times 10^{-2}$	3.08
Congo	COD	$1.72 \times 10^{-2}$	$3.72 \times 10^{-2}$	2.16
Nigeria	NGA	$1.67 \times 10^{-2}$	$1.08 \times 10^{-1}$	6.47
Vietnam	VNM	$1.66 \times 10^{-2}$	$4.58 \times 10^{-1}$	27.61
Countries with lowest plastic mobilisation potential				
Ireland	IRL	$1.02 \times 10^{-5}$	$3.00 \times 10^{-5}$	2.95
Costa Rica	CRI	$7.91 \times 10^{-6}$	$2.70 \times 10^{-5}$	3.41
Western Sahara	ESH	$7.31 \times 10^{-6}$	$7.31 \times 10^{-6}$	1.00
Armenia	ARM	$6.87 \times 10^{-6}$	$1.76 \times 10^{-5}$	2.56
Oman	OMN	$5.27 \times 10^{-6}$	$1.45 \times 10^{-5}$	2.75
Somalia	SOM	$4.19 \times 10^{-6}$	$4.53 \times 10^{-6}$	1.08
Palestinian territory	PSE	$3.95 \times 10^{-6}$	$3.95 \times 10^{-5}$	1.00
Israel	ISR	$2.51 \times 10^{-6}$	$2.99 \times 10^{-6}$	1.20
Syria	SYR	$4.71 \times 10^{-7}$	$2.69 \times 10^{-6}$	5.72
United Arab Emirates	ARE	$4.74 \times 10^{-8}$	$5.19 \times 10^{-8}$	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.

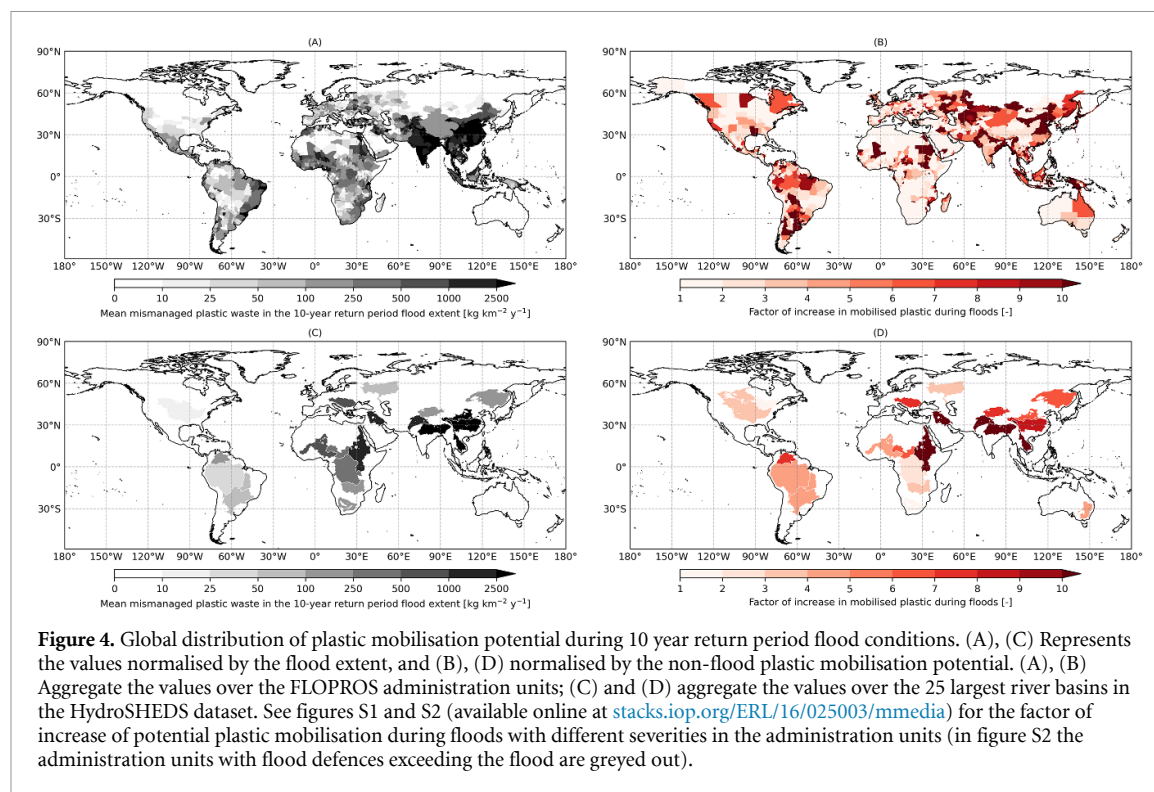
### 3.3. Reduction of plastic mobilisation by flood defences

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<sup>-1</sup>), 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<sup>-1</sup> 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



**Figure 4.** Global distribution of plastic mobilisation potential during 10 year return period flood conditions. (A), (C) Represents the values normalised by the flood extent, and (B), (D) normalised by the non-flood plastic mobilisation potential. (A), (B) Aggregate the values over the FLOPROS administration units; (C) and (D) aggregate the values over the 25 largest river basins in the HydroSHEDS dataset. See figures S1 and S2 (available online at [stacks.iop.org/ERL/16/025003/mmedia](https://stacks.iop.org/ERL/16/025003/mmedia)) for the factor of increase of potential plastic mobilisation during floods with different severities in the administration units (in figure S2 the administration units with flood defences exceeding the flood are greyed out).

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

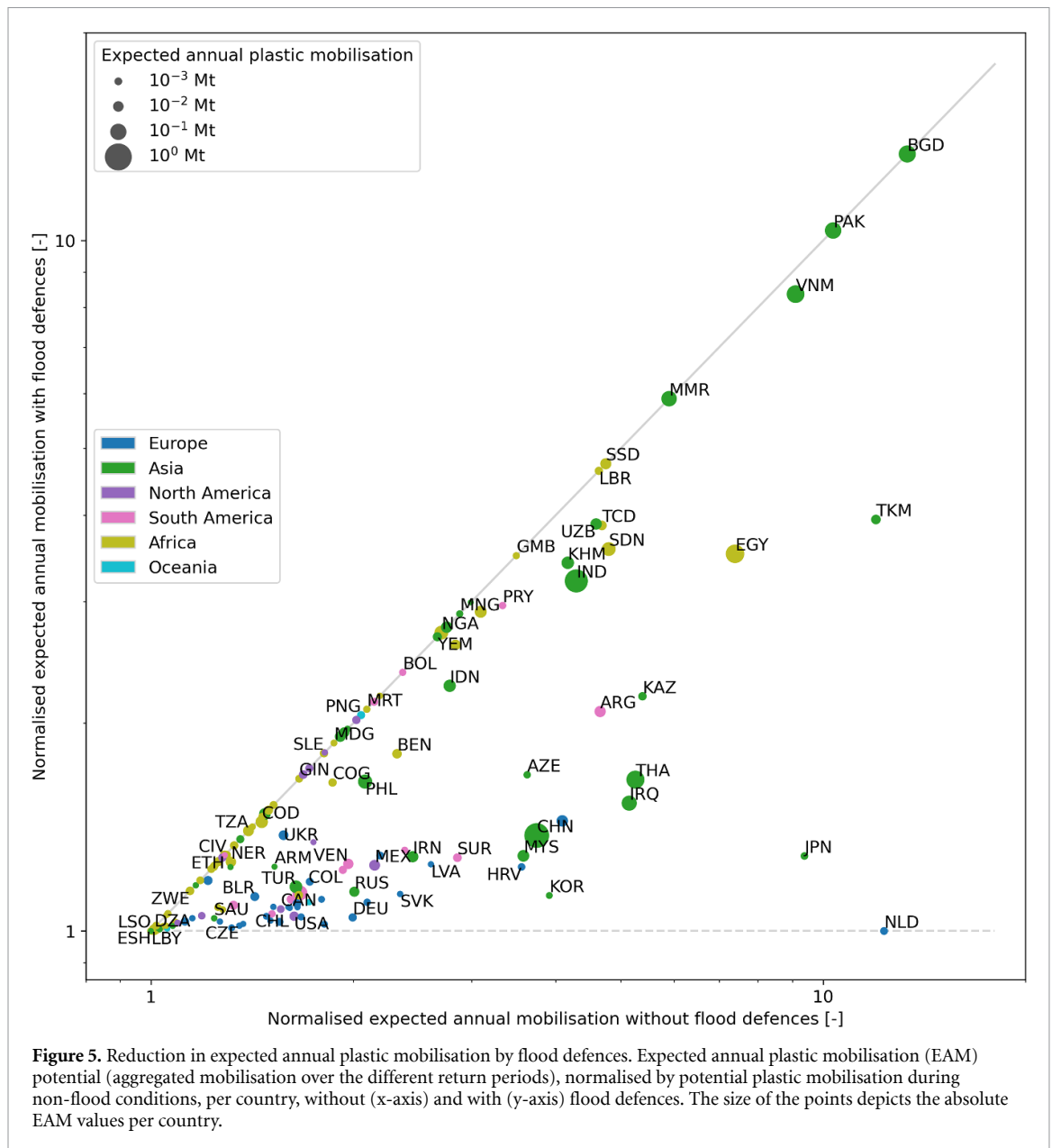
significantly. Other strongly impacted countries are Japan and the Netherlands displaying an 86% and a 100% reduction in flood induced plastic mobilisation, respectively, as a consequence of their flood defences.

#### 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 ( $1.8 \text{ Mt yr}^{-1}$ , 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<sup>-1</sup> 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/](http://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 Andrady 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 km<sup>2</sup>. 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](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/](http://www.nat-hazards-earth-syst-sci.net/16/1049/2016/)) and the HydroSHEDS basins are published in Lehner *et al* (2008) ([www.hydrosheds.org/](http://www.hydrosheds.org/)). The data produced in this study can be found on Figshare (DOI: 10.6084/m9.figshare.13270094).

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## 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.

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