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A framework to assess the impact of flooding on the release of microplastics from waste management facilities

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ABSTRACT

The impact of flood on waste management facilities can induce the release of micro pollutants to freshwater systems with concerning impacts on the marine environment, agricultural ecosystems, and human health. Almost 30% of the total waste managed in the UK in 2019 was characterised by Microplastic Releasers (MPRs): plastic waste, synthetic textile, rubber waste, and mix/undifferentiated materials that are able to or contain items that can deteriorate and fragment into micro components. In recent years, the management of solid waste and its contribution to flood-driven microplastic pollution has been limited with a focus on plastic waste mismanagement specifically, and the assessment of the risk is long overdue. We present a new methodology combining publicly available data on waste with pluvial and fluvial flood extent maps. The methodology was applied to the UK where the impact of pluvial flood on waste management facilities shows a 3-fold increment between 20 and 50-year return period in waste at risk of releasing microplastics during inundation resulting in almost 5 million tonnes per day. The methodology was applied to the UK where the impact of pluvial flood on waste management facilities shows a 3-fold increment between 20 and 50-year return period resulting in almost 5 million tonnes of waste per day at risk of releasing microplastics during inundation. We conclude that further studies at the local scale are necessary to establish site-specific mitigation measures and containment systems able to decrease the flood-induced microplastic mobilisation from waste management facilities.

1. Introduction

Floods are amongst the most frequent natural hazards to cause industrial accidents that may result in fires, explosions, and the release of hazardous materials (Piccinelli and Krausmann, 2013). These events are defined as 'Natech' accidents (i.e., natural hazards triggering technological accidents) because of the capacity of natural hazards to cause technological disaster. Natech accidents mainly refer to refineries, petrochemical complexes, and oil and gas pipelines that deal with dangerous substances as identified by the Seveso-III-Directive (2012/18/EU), which is the main EU legislation aiming at the prevention of technological disasters involving dangerous substances. However, the types of synthetic products that can cause harm are not limited to the list included in the Seveso-III-Directive. For example, plastic items are made from polymers mixed with a complex blend of additives, some of which belong to the list of emerging contaminants, which are released due to plastic degradation with potential risks to the environment and human health (Gunaalan et al., 2020). In recent years, plastic pollution has become one of the major environmental concerns, with an exponential increase in plastic created (Geyer et al., 2017; PlasticsEurope, 2021) and an expected 3-fold increase in plastic waste by 2030 (Borrelle et al., 2020). However, despite the growing interest developed by the scientific community, flood-induced plastic debris mobilisation from terrestrial sources has yet to be fully understood.

It is estimated that between 4 and 12 million metric tons (Mt) of plastic end up in the marine environment, globally, per year (Jambeck et al., 2015; Geyer et al., 2017; Boucher et al., 2020). The issue is exacerbated by the persistence of plastic debris in the environment and the inevitable breakdown processes resulting in the fragmentation of the initial (microplastic) component into microplastics (MPs). The origin of ocean plastics has been increasingly attributed to terrestrial sources (Hurley et al., 2018), and recent attention has been given to rivers, considered as a major pathway for plastic transport from inland areas to the ocean (van Emmerik et al., 2019; B. He et al., 2021; Wang et al., 2021). The consequences of flooding on plastic loads in rivers was extensively studied by Hurley et al. (2018), which investigated 40 rivers across the northwest of England before and after a period of severe flooding in winter 2015/2016. The study confirmed firstly the presence of MPs in all of the studied river channel beds, and secondly the capacity of flooding to export approximately 70% to 100% of the total MPs load stored in the riverbeds.

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The interaction between plastic transport and river flood events has been further investigated by Roebroek et al. (2021), with the introduction of global mismanaged plastic waste (MMPW) as a terrestrial diffuse source of plastic debris. By combining MMPW data with river flood extents for different return periods, the study was able to estimate the flood-driven plastic mobilisation per country with results showing a tenfold global increase in potential plastic transport during 10-year return period flood compared to non-flood conditions. amongst the methodology's limitations listed by Roebroek et al. (2021), two aspects are particularly relevant for the purpose of this research. The first is data on MMPW are estimated on the waste generation rates per country that ignore the potential build-up over time. The second is that Roebroek et al. (2021) only focuses on mismanaged plastic, while plastic waste properly disposed could also be mobilised by flood waters. Data on waste characteristics and quantity received per facility (tonnes) are reported annually by Member States (European Parliament and Council of the European Union, 2008) and made publicly available. In the UK, in 2019, the total amount of waste received by waste facilities was equal to 257 million tonnes. Although it may overestimate the actual quantity of waste produced for the same year due to the complex movement of discarded items through the waste management network, the information on waste received provides a greater detail and richness compared to national statistics on waste produced annually because it includes data on the location, quantity, and characteristics of waste dealt with by each waste management facility rather than a gross value at a national scale (a list with type and description of waste management facilities selected for this study is available in the supplementary materials, Table S1).

Waste management facilities become potential terrestrial sources for plastic mobilisation and therefore plastic pollution when the discarded materials are temporary stored, treated, or disposed within sites located in areas at risk of flooding. During recent decades, few works have investigated the impacts of flooding on managed waste. Arrighi et al. (2018) is one of the few studies available in literature that clearly defines wastewater treatment plants, waste handling facilities, and contaminated sites as environmental hotspots because of the risk posed by the presence of contaminants within sites located in flood-prone areas. Comparatively, the potential inundation of solid waste landfills has received more attention in the literature (Laner et al., 2009; Neuhold and Nachtnebel, 2011; Neuhold, 2012) although many questions remain unanswered. For example, Nicholls et al. (2021) recently published a comprehensive European study on coastal landfills and the rising of sea levels, highlighting a lack of data and a general underestimation of the threat posed by the potential release of solid and liquid waste from coastal landfills.

The purpose of this study is to better understand quantity and characteristics of waste received and stored by waste management facilities, with the assumption that managed waste is potentially one of the biggest terrestrial sources of flood-induced MPs mobilisation. The novel methodology developed within this study was applied to the UK by combining publicly available data on waste received by waste facility in 2019 together with flood likelihood map extents for different return periods and source (fluvial and pluvial). The research aims to (i) identify waste at risk of releasing MPs amongst the European Waste Catalogue (EWC) code in addition to the well-known plastic waste, (ii) estimate the quantity of waste at risk of flooding in the UK which could lead to MPs' mobilisation in flood waters, and (iii) identify spatial patterns where the level of risk requires further studies at the local scale.

2. Methods

The study introduces a framework to estimate the quantity of waste at risk of releasing MPs in flood waters by combining publicly available annual data on waste received by waste management facilities with flood extent maps for different sources (fluvial and pluvial) and likelihoods of flooding (5, 10, 20, 50, 100, 200, 500 and 1000 years) at the national level. Due to the novelty of this assessment, three methodologies are presented to (1) identify the codes within the List of Waste (European Commission, 2000) referring to solid waste that could deteriorate and fragment into MPs, (2) estimate the waste facilities' footprint from a point coordinate based on the INSPIRE Cadastral Parcel dataset, and (3) determine the quantity of waste at risk of flooding based on the percentage of overlapping between the estimated facilities' footprint and flood map extents.

The methods were applied to the UK where datasets on annual quantity, type, and location of waste received by waste facilities, and Cadastral Parcel polygons (which represent land ownership) are publicly available (with the exception of the Cadastral Parcel dataset for Northern Ireland which is not publicly available). The datasets were subsequently combined with flood map extents in a geographical information systems (ArcGIS and ArcGIS Pro) to determine national and local quantities of waste at risk of releasing MPs during inundation.

2.1. Identification of waste at risk of deteriorating into synthetic micro components within the European waste catalogue (EWC) code: not just plastic waste

The waste classification code, also referred to as LoW (List of Waste) or EWC (European Waste Catalogue) code was introduced in 2000 by the European Commission Decision 2000/532/EC (further revised in 2014 and 2017). Unlike more straightforward legislation on chemicals, because of the complexity and alterability of discarded substances, the LoW does not refer to a waste's chemical components for classification purposes but rather to alternative criteria such as (i) the waste source, (ii) the waste type, and (iii) the recognition of waste not otherwise specified because it is mixed or undifferentiated. The classification system was conceived to help operators to assign a standardised, accurate six-digit code to each entry of waste. The first two digits of the LoW refer to the waste source (e.g. 17 Construction and demolition wastes), the second series of digits assign the waste type (e.g. 17 02 Construction waste wood, glass and plastic), and the last two digits represent the final entry description (e.g. 17 02 03 Plastic construction waste). The LoW recognises three types of entry and marks with an asterisk (*) what is considered as hazardous waste. Absolute hazardous (AH*) entries display one or more of the fifteen hazardous property as indicated in Annex III to the Directive on waste 2008/98/EC (Waste Framework Directive or WFD), such as explosive, ecotoxic, mutagenic, infectious, etc.; absolute non-hazardous (ANH) entries identify waste lacking any hazardous component. Finally, mirror entries represent the case of mixed substances where further assessment needs to be undertaken to classify the waste as mirror hazardous (MH*) or mirror non-hazardous (MNH) (EA, 2014).

The absence of cross-categories (e.g. the substance state such as solid, liquid or gaseous) and the lack of a controlled vocabulary for the entries' description does not allow straightforward data inquiries and the same type of waste can be found throughout different LoW groupings. The European Commission published the Commission Notice On Technical Guidance On The Classification Of Waste in 2018 (2018/C 1 24/01), which added a substance-orientated identifier approach, including a non-exhaustive list of plastic waste entries. Out of 842 LoW codes (Table 1), there are 29 plastic waste classification codes identified by the commission notice, divided into (6) absolute non-hazardous, (10) mirror hazardous, and (13) mirror non-hazardous categories. The word 'mirror' in the legislation indicates the case of entries presenting a mix of hazardous and non-hazardous materials. Surprisingly, no entries were selected amongst the absolute hazardous substances, even if within the LoW there are several absolute hazardous codes that identify mix waste, which are likely to have some plastic components: for example code 18 01 10* amalgam waste from dental care. In addition, although MPs in waste is an increasingly explored issue in literature (e.g. MPs in wastewater treatment plants and in landfill leachate (P. He et al., 2019; Sun et al., 2021)), in the commission notice there is no reference to the presence of MPs in waste. The description of the source of waste for entries related to plastic waste versus Microplastic Releasers is available in the supplementary materials, Table S2.

Table 1
Number of codes from the European Waste Catalogue (EWC) code per entry type (AH, MR, MNH, ANH) based on discarded materials' hazardous properties.

842 Entries in the List of Waste (LoW)			
408 Hazardous entries		434 Non-hazardous entries	
230 Absolute Hazardous	178 Mirror Hazardous	188 Mirror Non Hazardous	246 Absolute Non Hazardous

The source of MPs can be direct: primary microplastic, specifically manufactured for commercial use such as cosmetics; and indirect: secondary microplastic, resulting from the deterioration and fragmentation of certain materials such as plastic items, synthetic fabrics and rubber, due to mechanical stress, photo-oxidation and weathering processes (Golwala et al., 2021). Although the presence of primary MPs is well known within the waste industry, for example in landfill leachate or within waste-water treatment plants, for this study we focused on secondary MPs only, leaving the assessment of primary MPs to future work. The release of MPs from fabric is prominently documented, with studies reporting from 10 to 1700 mg of MPs per kg of washed fabric (Kärkkäinen and Sillanpää, 2021). Another important source of MPs is road tyre wear emissions which was calculated ranging from 0.2 to 5.5 kg of global emissions of Tyre Wear Particles (TWPs) per capita (Baensch-Baltruschat et al., 2020; Evangeliou et al., 2020). Other potential emission sources include plastic manufacturers and industries where plastic is used (for example carpet, wallpaper and cosmetic/pharmaceutical manufacturers), waste management facilities, agricultural areas, road networks (beyond tyre and brake wear) and urban residential/commercial areas (Xu et al., 2020; Allen et al., 2022). It is noted that direct and diffuse source emission rates beyond fabric washing/drying and tyre wear have yet to be quantitatively characterised to date and is an important focus of future research.

For the purpose of this study, and in an effort to clearly identify waste that could degenerate into synthetic micro components, an extended description of the selection of plastic waste identified by the European Commission Notice (2018) has been adopted (European Commission 2018). The description of plastic waste by the European Commission Notice (2018) has been extended to include possible sources of secondary MPs in waste, defined as Microplastic Releasers (MPRs) (Fig. 1) described as: (i) codes related to synthetic textile and rubber waste that could release microfibers and rubber polymers, and (ii) codes referring to mixed and undifferentiated materials (e.g. mixed household waste). These waste products are selected specifically as they are likely to contain larger plastic materials, synthetic clothes, and discarded items with rubber components and therefore act a source of MPs.

In addition to the physical stress due to transportation, treatment, and weathering phenomena (especially when waste is accumulated outside in containers and/or piled on hard surfaces), the deterioration and fragmentation of materials can be accelerated by flood water (as a mechanical force that may break particles) (Zhang et al., 2021). In the case of flooding, discarded items could be subjected to the flow's rapidly changing conditions and the presence of suspended sediments, which could lead to turbulent mixing (mechanical abrasion and wear) and the collision with debris and other built infrastructures. Micro waste components could escape the perimeter of the facility within flood waters, with the flood water acting as the micro waste's transport vector and mixing or discharging into waterways, ecosystems, flooded areas and floodplains downstream. Therefore, it is important that waste facilities located in flood-prone areas are identified, alongside the information on the quantity and location of discarded items prone to release MPs in flood waters.

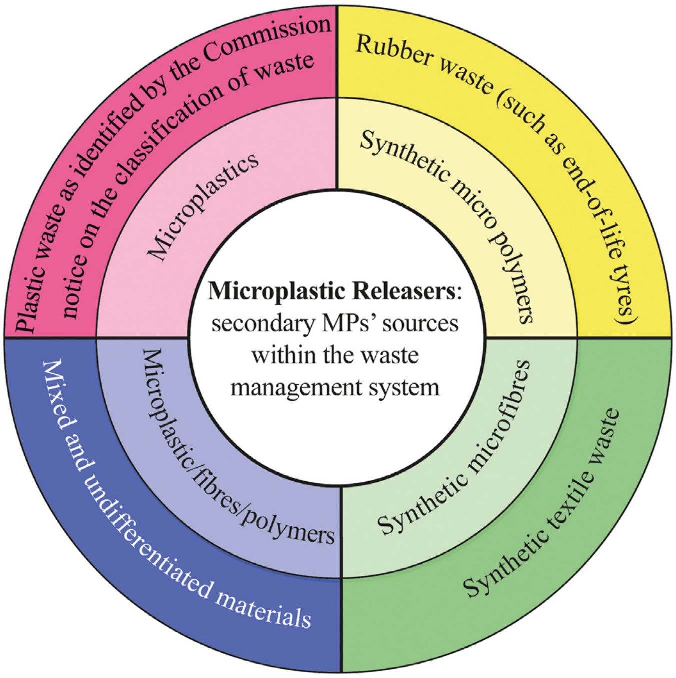


Fig. 1. Four types of waste at risk of deteriorating and fragmentise into micro components: main type of waste on the outside of the circle and the related micro components on the inside. The study has named the selected waste as Microplastic Releasers (MPRs) to differentiate it from research referring exclusively to plastic waste. The full list of MPRs codes selected from the European Waste Catalogue is available in the supplementary materials.

2.2. Defining the waste management facilities' footprint estimation

The publicly available UK waste facility datasets (SEPA, 2019a; EA 2019a; Natural Resources Wales, 2019; NIEA, 2019) report the postcodes and/or geographic coordinates for each facility, but no surface area or boundaries information are associated with each entry. To enable the assessment of both data describing waste at the facilities' location and the flood map extents, an averaged footprint area for each type of facility in Great Britain (GB) was estimated by regulatory region (per country) using the publicly available INSPIRE Cadastral Parcels spatial dataset (HM Land Registry, 2021; Registers of Scotland, 2021), which is available for Scotland, England, and Wales, and applied to all licensed waste facilities in the UK. Unfortunately, the cadastral parcel dataset is not currently publicly available for Northern Ireland. The INSPIRE cadastral parcels dataset complies to the European directive 2007/2/EC of the European Parliament and of the Council of 14 March 2007 establishing an Infrastructure for Spatial Information in the European Community (INSPIRE), and contains the ownership polygon at ground level for each registered property. Unfortunately, the dataset has several limitations: (i) the spatial extent of the database is limited, especially outside main cities where big portions of land are unmapped; (ii) the land ownership polygon may not match the actual footprint of a site but includes green areas, residential properties, and parking areas; (iii) polygons may not have been kept up-to-date and therefore they may not represent the sites' current extent. To overcome the limitations two methodologies were designed and tested to understand how to best represent the footprint of a waste facility when the only information available are: 1) the geographic coordinates indicating a point randomly located within or

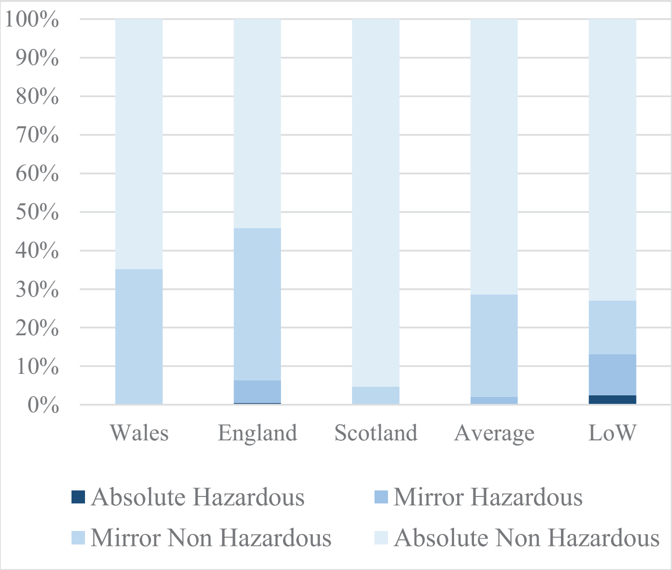


Fig. 2. Microplastic Releasers distribution per List of Waste entry type. Each code within the European Waste Catalogue has an entry type associated to it based on the hazardous characteristics of the discarded items (Absolute Hazardous, Mirror Hazardous, Mirror Non Hazardous, and Absolute Non Hazardous). Fig. 2 shows the distribution of the selected MPRs waste codes amongst the four entry types for each country in the 2019, with the exception of Northern Ireland, and allow the comparison with the average distribution for Great Britain and within the full List of Waste.

nearby the facility boundaries; 2) the category of waste facility (e.g. landfill, transfer station, etc.); and 3) the quantity of annual waste intake.

Methodology no.1 investigated the potential correlation between waste sites' footprint (manually checked and corrected when necessary from INSPIRE polygons for 154 sites in Scotland, 22% of the total Scotland registered waste sites), and the annual waste intake (tonnes of waste received on site per year). Unfortunately, no significant correlation was discovered ($r = 0.377$, p-value = 0.516), especially for waste transfer stations which are the prevalent category (75%) amongst the 154 sites' dataset but the most unpredictable in terms of surface area. Therefore, Methodology no.2 was developed. All the waste facilities in the Great Britain (GB) having a cadastral polygon were selected (1052 from the more than 7000 waste sites recorded), and circular buffer areas (the creation of polygons around input features to a specified distance) were created based on the cadastral polygon average size per category of waste facility and per country (Scotland, England and Wales). Consequently, three flood risk map extents (fluvial high likelihood (1 in 10-year return period), medium likelihood (1 in 200-year return period) and low likelihood (1 in 1000-year return period)) were selected by looking at the most common approach adopted in terms of flood risk perception by different countries in the UK (EA, 2018; NI Department for Infrastructure, 2018; SEPA, 2020; Natural Resources Wales, 2021) although these will need to be reconsidered in the future due to climate change. To compare the performance of buffer areas versus cadastral parcels, both datasets were combined with flood likelihood maps to estimate the number of facilities affected by flood and the extension of the interactions (percentage of overlap) in the Geographical Information System (GIS) environment (Fig. 3). The differences were analysed to establish the applicability of the methodology for this study and to other (non-microplastic specific) purposes. The INSPIRE dataset is not only available for Great Britain (GB) but it is a European dataset publicly available for most Member States, which opens up the possibility of applying the methodology for waste management analysis for other countries in Europe, providing a possible comparable future risk assessment of microplastic release from waste facilities across Europe due to flooding.

The correlation coefficient values between buffer areas and cadastral parcels obtained for the tested flood risk return periods showed a constant improvement from the higher flood likelihood to the medium and lower flood likelihood: respectively $r = 0.846$, 0.897, and 0.900. The medium likelihood presents values closer to the best fit line, and the highest significance level (0.07) in terms of extreme results probability value (P-value). Low and high likelihood have less statistically significant results presenting respectively p-value=0.16, and p-value=0.28. In terms of the coefficient of determination (R-squared) values, the medium likelihood (1 in 200-year return period) has the best result with 0.888, followed by the low likelihood with 0.810 and high likelihood 0.717. Despite the limitations, methodology n.2 was considered fit for the purpose of recreating waste facilities' footprint at the national level where cadastral parcel datasets are not available but a facility point coordinate is known. Further studies should be undertaken toward advancing this methodology for future studies.

2.3. *Defining and mapping the different likelihoods for fluvial and pluvial flood risk map extents*

The Fathom-UK flood map extents, indicating the spatial probability of flooding, were made available by SSBN UK Limited (SSBN UK Limited, 2021). The method used to derive the fluvial maps refers to the global model detailed by Sampson et al. (2015), further improved with higher quality data such as terrain, hydrography, stream gauge, rainfall, and flood defence data.

Fathom's hydraulic modelling is an implementation of the LISFLOOD-FP numerical scheme (Bates et al., 2010), combined with Neal et al. (2018) approach to improve and optimise central and graphical processing units through parallelization to significantly reduce the model runtime. The hydraulic model is executed at 1 arc second (between 20 and 25 m resolution) across the UK using a composite Digital Elevation Model (DEM) built using LiDAR elevation data from relevant national government agencies (which covers ~70% of UK land area), together with Ordnance Survey terrain data. Extreme flows on every river were predicted via statistical modelling based on a dense array of river gauges with long historical records available within the National River Flow Archive (NRFA). Channel locations were defined using Ordnance Survey channel location data, and used to construct a flow accumulation grid together with the DEM.

In terms of river bathymetry, the Global River Widths from Landsat (GRWL) database from Allen and Pavelsky (2018) was used to estimate river widths, while an estimate of channel beds elevations was produced by adopting an innovative channel solver (Neal et al., 2021), and by combining data on an estimate of bank-full discharge (for return period of ~ 1 in 2 years), channel widths and slope from the DEM. The reason behind linking channel geometry to discharge return period is to ensure channels are appropriately sized for the simulated flow. For the pluvial model, Intensity-Duration-Frequency curves were calculated from CEH-GEAR1h, an hourly gridded rainfall dataset at 1 km spatial resolution, and 1-hour, 6-hour, and 12-hour intensity-frequency relationships were computed. The rainfall dataset input water directly onto the 2D base model LIDFLOOD-FP's staggered grid, with the addition of a 1D model solver for channels smaller than the grid size.

In terms of flood defences, data came primarily from the Environmental Agency and Natural Resource Wales. For location missing data, particularly in Scotland, a levee detection algorithm was adopted to fill the gaps (Wing et al., 2019).

Fathom-UK hazard map extents were validated against Environmental Agency (England) and Natural Resources Wales flood maps, unfortunately at this stage no validation is available for Scotland and Northern Ireland. Results indicated that the two datasets are within proximity of each other, with the error potentially due to typical uncertainties in extreme flow estimation and terrain data accuracy. However, validation

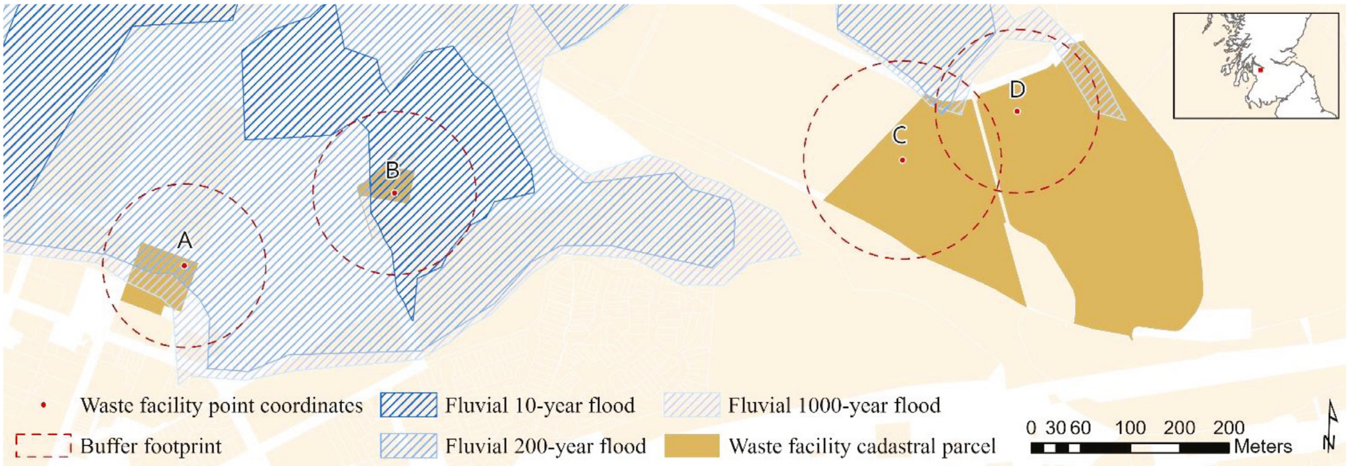


Fig. 3. An example of overlap between flood map extents for different return periods and buffer areas (dashed circles) originated by the average size of the INSPIRE Cadastral Parcels polygons (Registers of Scotland, 2021) for site category and country. The figure shows the difference in size of buffer areas compared to cadastral parcels and their relationships with flood maps. Site (A) is overlapped by 72.5% by 1 in 200-year fluvial flood, and 85% by 1 in 1000-year return period; Site (B) is completely overlapped by 200 and 1000-year flood maps and partially overlapped (70%) by the 10-year fluvial return period. Sites (C) and (D) present opposite results both for the size of the cadastral parcels compared to the buffer areas and for the minimal overlap reported with the medium and low flood likelihoods.

tests focussed only on extreme floods (<100-year return period), ongoing research at Fathom will further validate the methodology against both observed and lower return period flood events.

The Fathom-UK flood map extents adopted for the scope of the presented study included several return periods (5, 10, 20, 50, 100, 200, 500 and 1000 years), for fluvial (considering flood defences) and pluvial flooding. Data were given in flood modelling output (as a GeoTIFF raster) at 1/3 arc second (~10 m) resolution for the entire UK, with cell values representing maximum inundation depths in centimetres from 0 to 9999 (9999 = permanent water). Unfortunately, no indication of the flood velocity was provided, nor was coastal flood likelihood extent mapping available. Therefore, a simplistic approach was adopted to differentiate flooded versus non-flooded pixels based on water depth: for fluvial, a binary map of wet and dry was established considering as flooded any depth higher than 0 cm; while for pluvial flooding, the same was applied to depths higher than 15 cm. The 15 cm threshold adopted was based on Environmental Agency's flood risk information (EA, 2019b) suggesting that at 15 cm flooding would likely exceed kerb height and damp-proof course. Raster maps were merged for the UK, reclassified with two intervals representing wet and dry, and converted in polygons in the GIS environment to allow further spatial analysis with the waste dataset.

3. Estimating the quantity of managed waste at risk of releasing microplastics in flood waters

The estimation of the quantity of waste at risk of being mobilised and releasing MPs in flood waters at any given day in 2019 was estimated based on the selection of Microplastic Releasers, from datasets on annual total waste received by facilities per country in the UK. Annual quantities were summarized per operator and divided by 365 to give approximate daily quantities. The simplification was necessary because of the lack of daily data on waste received and the average time spent by waste materials stored on site, which are both relevant considerations when simulating the impact of flooding on waste facilities. As a result of the limitations, the flooding event is considered as a single day duration only, which may underestimate the quantity of waste at risk of being affected. An additional build-up component was adopted only for landfills for their intrinsic accumulation properties. Therefore, for landfills operative in 2019, MPRs were selected amongst the annual quantity of total waste and summarised for every year from 2007 to 2018, and the relative quantities added on top of the daily tonnage from 2019.

3.1. *Estimation of daily quantities (tonnes) of microplastic releasers received per facility in the UK in 2019*

Data about annual quantities of waste received per facility for each typology (based on the LoW classification) are publicly available for all countries in the UK: Scottish waste sites and capacity tool (SEPA, 2019a), Waste Data Interrogator (EA, 2019a), Waste Permit Returns Data Interrogator (Natural Resources Wales, 2019), and Authorised waste sites (NIEA, 2019). From the public datasets, the operative facilities in 2019 were selected together with the category of waste facility, discarding sites with incomplete information (e.g., missing coordinates, waste codes, etc.). Subsequently, MPRs' codes were selected for each country and annual quantities (tonnes) were summarised per facility. The dataset for Northern Ireland doesn't specify quantities of waste for each LoW code, therefore the percentage of Microplastic Releasers was estimated by referring to the average obtained for Scotland, England and Wales (32% of the total amount of waste received). As indicated in Table 2, the total annual amount of waste received by facilities in 2019 in the UK was 257 million tonnes, of which almost 30% (~74 million tonnes) were MPRs, consisting of mixed and undifferentiated materials (70%), plastic waste (29%), synthetic textile (7%), and rubber (1%). Although not all the operational waste management sites dealt with MPRs in 2019, results show approximately 66% of facilities for Scotland, 47% for England, 64% for Wales and 53% for Northern Ireland managed MPRs waste.

3.2. *Microplastic releasers accumulation in landfills*

In the UK in 2018 50.7 million tonnes of waste were landfilled (44.1 in England) amongst 629 operative disposal sites (534 in England), with a remaining capacity of 129.3 million tonnes (converted from 415,069,000 m^3 by considering a waste density of 311.73 kg/m^3) (DEFRA and Government Statistical Service, 2021). On top of this, in England alone, around 20,000 historical landfills (where there is no environmental permit in force, including sites that existed before landfills were regulated) were mapped by the Environment Agency in 2022. Approximately 1200 of those are located within flood zones of 1 in 200-year return period (Brand et al., 2018), and ~3400 are at risk for low likelihood but high intensity flooding (CCC, 2018). Awareness of the risk presented by landfills to the environment has been raised and has led to a significant increase of landfill-related publications in the last two decades: from 662 in 2000 to 2335 in 2017 (Sabour et al., 2020).

Table 2
Quantity (tonnes) of total waste and Microplastic Releasers received by waste facilities in 2019 in the UK.

	Active waste facilities in 2019	Annual total waste received (tonnes)	Annual Microplastic Releasers received (tonnes)	Percentage of Microplastic Releasers waste on the total
UK	7,676	$257{\times}10^5$	73.8×10^5	29%
Scotland	697	16.7×10^5	5.8×10^5	35%
England	6,151	222.9×10^5	62.1×10^5	28%
Wales	444	9.9×10^5	3.5×10^5	35%
Northern Ireland	384	7.5×10^5	*2.4×10^5	32%

*Results for Northern Ireland were estimated based on the average found for the other countries in the UK (32%).

However, despite the increase in severity of landfill related regulations, Directive 1999/31/EC on the landfill of waste and the Amending Directive (EU) 2018/850 and encouraging governmental strategies in response of the Zero Waste movement, more measures need to be put in place to control and contain the potential leakage of waste from disposal areas to the environment.

In this study, the publicly available data on waste received by landfills for different countries in the UK were used for two objectives: firstly, to advance the quantitative assessment of Microplastic Releasers received by landfills for the period 2007 – 2019 compared to the total amount of waste; and secondly, to select the quantities of MPRs accumulated by landfills classified as operative in 2019 to be added to the daily estimates of waste at risk of releasing MPs in flood waters. The latter is an attempt to approximate the build-up of MPRs that occurred through the years in landfills, which is relevant when simulating the impact of flood on disposal sites.

For the first part of the analysis, although historical landfills (intended as opposite to licensed/permitted sites) pose the highest risk due to their predominant location in low-lying estuarine and coastal areas, and the absence of leachate management systems (Brand et al., 2018), inadequate records on the waste received and/or landfilled prevented them from being included in the current study. Instead, for landfills licensed/permitted in the UK, publicly available datasets were analysed to quantify the waste annually received per facility from 2007 to 2019 (EA, 2019a; Natural Resources Wales, 2019; NIEA, 2019; SEPA, 2019b). Subsequently, waste codes identified as potential Microplastic Releasers (MPRs) were selected for each country, summarised per year, and divided by the country's population to allow the comparison amongst different sizes of countries in the UK. Results shown in Fig. 4 reveal a significant decrease of the total amount of waste received by disposal sites in Scotland, England and Wales from 2007 to 2014, with a slightly rise of approximately 3 million tonnes between 2014 and 2015. The percentage of MPRs compared to the total amount of waste also substantially reduced from 65% in 2007 to 38% in 2014, and 35% in 2019 (the available data for Northern Ireland are only for the period 2014–2019).

The tendency of sending less waste to landfills is likely the result of the European Landfill Directive 99/31/EC, which aimed to reduce or prevent, as far as possible, negative impacts from landfill to the environment. Some of the Directive's consequences can be read through the UK achievement in terms of (i) biodegradable waste going to landfills that decreased from 10.3 million tonnes in 2012 to 7.2 in 2018; (ii) the rates of packaging waste recycled or recovered increased from 61.4% in 2012 to 62.1% in 2018; and (iii) the imposed rise in price for accepted discarded materials, to include the costs related to the closure and after-care of a site, translated in a reduction of more than 5 million tonnes between 2012 and 2014 in the total amount of commercial and industrial waste produced (Department for Environment Food & Rural Affairs and Government Statistical Service, 2021).

For the second objective of the analysis, an approximation regarding the quantity of MPRs accumulated in landfills was estimated with the intent of recreating the condition faced by flood waters during a hypothetical flood event occurring on any day in 2019. Unfortunately, disposal sites' data lacks consistency, especially regarding the location of landfills. For example, for England, sites' geographic coordinates are available from 2012, before that permit numbers were reported from 2010, and for the period 2007–2010 only site names or operators are available to identify a landfill's location. Therefore, the accumulation factor was performed only for landfills operative in 2019, and the total sum of MPRs for the period 2007–2018 was added to daily quantities for 2019. The aim of the methodology is to highlight the importance of considering what has been buried in landfills in previous years that could be mobilised in the case of a flood event. It does not take into consideration the MPs already contained in the disposal site's body and/or leachate, and does not investigate additional mechanisms such as waste decomposition, degradation, and landfill erosion which are left to future studies.

4. Results

A dataset with daily quantities of waste at risk of releasing MPs in flood waters was created for facilities operative in the UK in 2019, with the addition of accumulation estimates for landfills. A buffer area for each facility was created based on the methodology described and combined with Fathom-UK flood map extents for different return periods (from 1 in 5 to 1 in 1000-year return periods) and flood type (fluvial and pluvial flooding). Both the number of waste facilities at risk of flooding, and the extent of the interaction (percentage of overlap) between buffer areas and flood map extents were estimated. The percentage of overlap was subsequently used to determine the quantity of waste at risk of releasing MPs in flood waters per site. For example, in Fig. 3 the waste management facility (A) is a transfer station which dealt with 3204 tonnes of MPRs waste in 2019 for an approximate daily quantity of 9 tonnes. The medium (200-year) fluvial flood likelihood for the waste facility in Fig. 3 is overlapping the facility's buffer area by 72.5% which means that 6.4 daily tonnes of waste are considered as at risk of releasing MPs in 200-year flood waters.

4.1. Impact of floods on waste management facilities: quantity and location of waste at risk of releasing MPs

The results across the UK are heavily influenced by the population spatial variation between England and the rest of the UK, however a general common trend was identified. As expected, Fig. 5A shows a steady increase in the number of facilities affected by fluvial flooding from high to low likelihood scenarios, starting with approximately 450 sites for the 5-year return period (with 78% of the sites located in England, 10% in Scotland, 8% in Wales, and 3.5% in Northern Ireland), and consistently rising with an addition on average of 54 sites per return period. Pluvial flooding presents a significantly higher impact on waste management facilities compared to fluvial, with numbers almost doubling (from 737 to 1266) in between the 20 and 50-year return periods. This reaches the highest impact with the low likelihood scenario affecting 65% of the total number of facilities which dealt with MPRs in 2019. For the same return period, the landfills at risk of flooding are 135 for pluvial flooding, and 44 for fluvial flooding. This translates respectively to 10.8 and 1.2 million tonnes of MPRs at risk of flooding, predominantly landfill type waste facilities, in the pe-

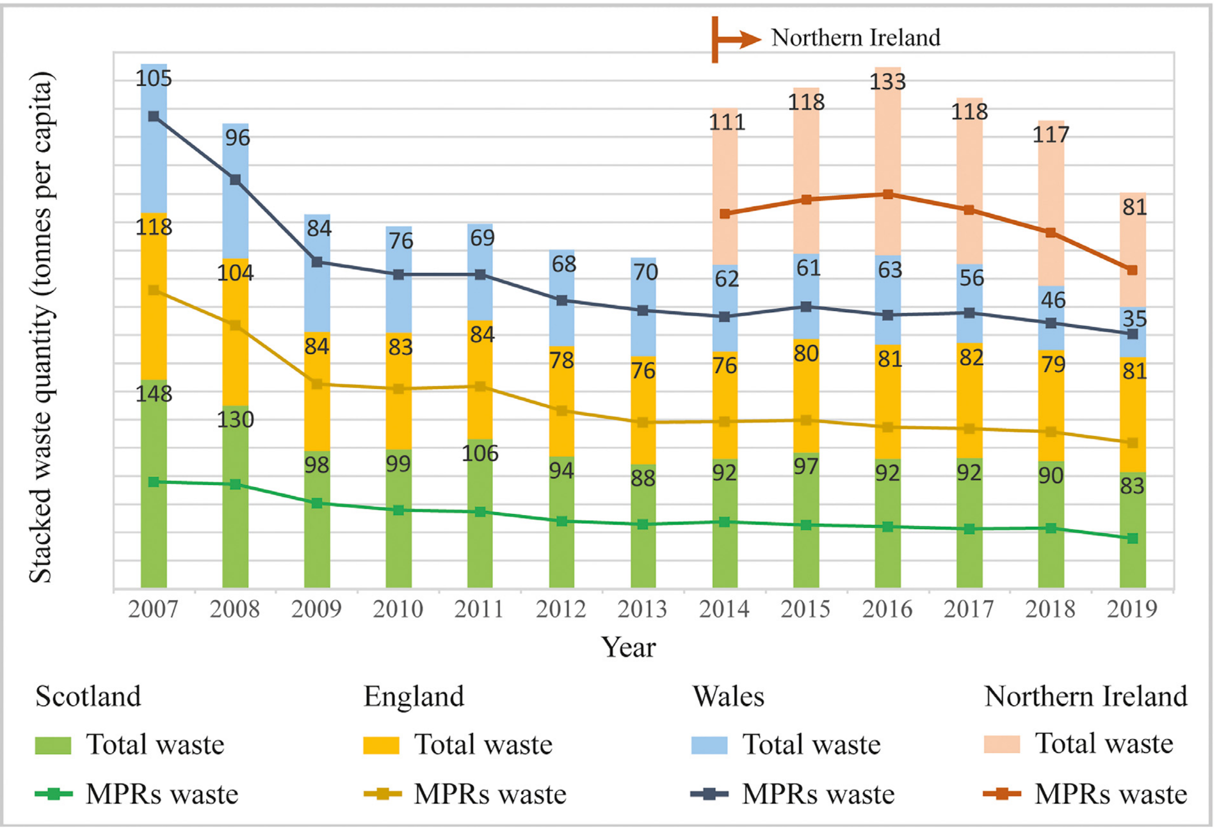


Fig. 4. Per capita annual waste and Microplastic Releasers waste received by landfills per country and per year. MPRs waste was selected from annual quantity of total waste received by landfills from 2007. Both total waste and MPRs quantities were divided by population and organised in a stacked bar graph to highlight the differences between different years and countries in the UK (Scotland at the bottom, then England, Wales, and Northern Ireland). Each bar has a number on it referring to the quantity of total waste (tonnes per capita). Data for Northern Ireland are only available from 2014 and the quantity of MPRs was estimated based on the average for the other countries (32%).

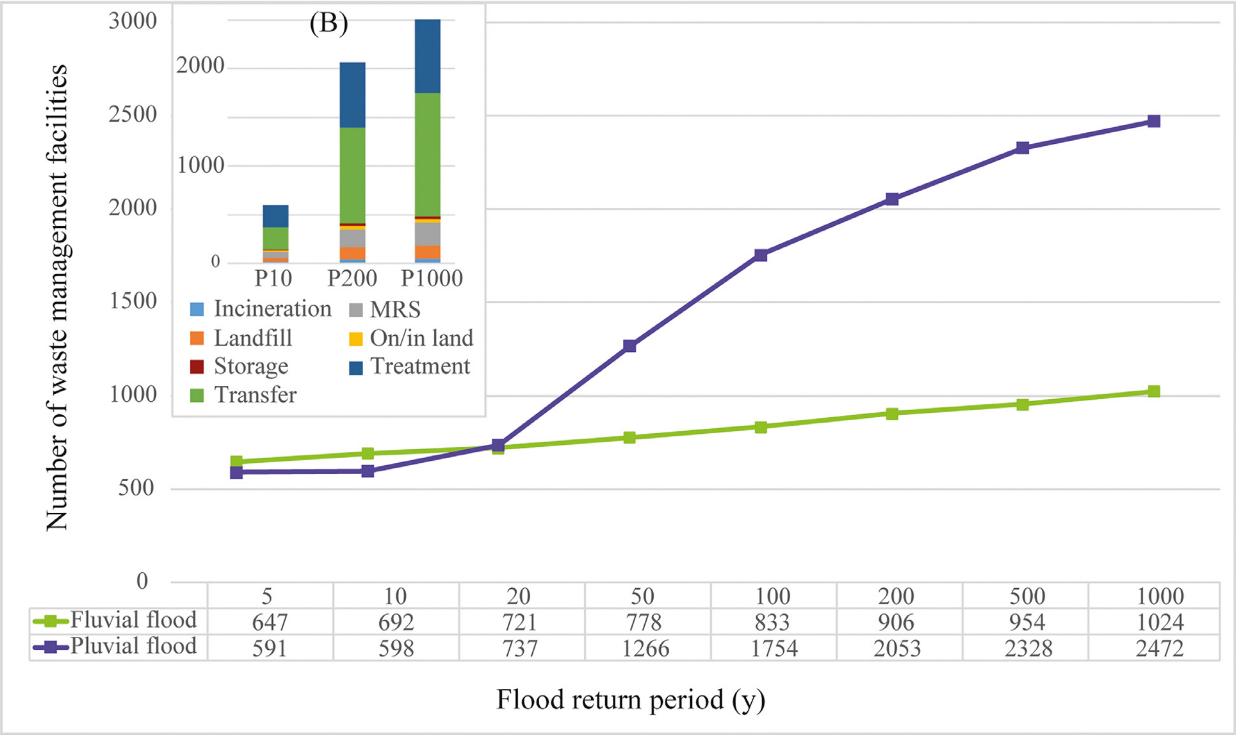
riod 2007–2018. A focus on the different categories of waste facilities affected by pluvial flood is available in Fig. 5B, highlighting treatment facilities and transfer stations as the categories most affected. This is not surprising due to their higher number compared to other types of facilities.

Fig. 5C represents the estimation of the quantity (million tonnes) of MPRs at risk of flood for different return periods and sources. The quantity of MPRs affected by fluvial flood is increasing consistently by ~30,000 tonnes per return period, starting at nearly 1 million tonnes for the high likelihood flooding (647 facilities affected) and reaching 1.2 million tonnes with the low likelihood flooding (1024 facilities). Variations in quantities of waste at risk of flooding compared to the number of facilities affected depend on the quantity of MPR waste received by each facility in 2019, and by the presence of landfills where the waste accumulation was estimated for the period 2007–2018. The estimated numbers of MPRs affected by pluvial flooding are significantly higher, showing a 10-fold increase from 5 to 1000-year return flood event, at the same time the number of facilities exposed drastically grows from 591 to 2472 and the number of landfills increases from 39 to 135. In both cases, the percentage of sites located in England is approximately 80%. The biggest increment is between 20 and 50-year pluvial return period where the amount of MPRs at risk is 3 times higher (from ~1.5 to ~5 millions of tonnes) for the 50-year return period flood. The reasons behind the greater numbers obtained by pluvial versus fluvial flood can be partially explained by the simulation of extreme rainfall events when floods are created both from overflowing water bodies and independently from them. This results in a flood extend comprised in part by the fluvial flood map extent but will additional areas also present as a result of the pluvial map.

4.2. *Microplastic releasers (MPRs) at risk of flood per local authority: emerging spatial patterns*

Fig. 6 spatially represents the MPRs distribution in the UK summarised by Local Authorities (LA) at risk of pluvial and fluvial flooding for high (1 in 10-year), medium (1 in 200-year) and low likelihoods (1 in 1000-year) scenarios. Results were normalised based on local authorities' area (km^2) in the GIS environment and graphically divided into same values intervals to allow a direct comparison amongst different likelihoods. This is used to identify hotspots where elevated concentrations of MPRs at risk of flood require further analysis at a local scale.

Regionally, in Scotland, the impact of the 10-year fluvial flood on waste facilities is particularly high in Fife (141 tonnes/km^2 of MPRs), followed by Moray (34 tonnes/km^2), East Lothian, and North Ayrshire with respectively (14 and 10 tonnes/km^2). Interestingly, the numbers estimated for both the cities of Glasgow and Edinburgh are significantly lower compared to areas in the immediate proximity, suggesting waste is mainly received and treated by facilities located in other districts (a tendency encountered also for other main cities in England, Wales and Northern Ireland). In England, MPRs are concentrated in the area north of London including the authorities from Peterborough through Cambridge and Harlow, with an average of 70 tonnes/km^2 and highest concentration between Peterborough and Cambridge (212 tonnes/km^2). The impact on Wales is predominantly localised in Caerphilly, north of Newport, with a high number of 1040 tonnes/km^2 for a total of ~300,000 tonnes of MPRs at risk of flooding in the district. In terms of medium and lower fluvial flood likelihoods, the local authority of Leeds stands out with an increase in the MPRs' concentration from 1 tonne (high likelihood) to 74 and 77 tonnes/km^2 respectively.


(A)
Number of waste management facilities at risk of releasing microplastics in flood waters

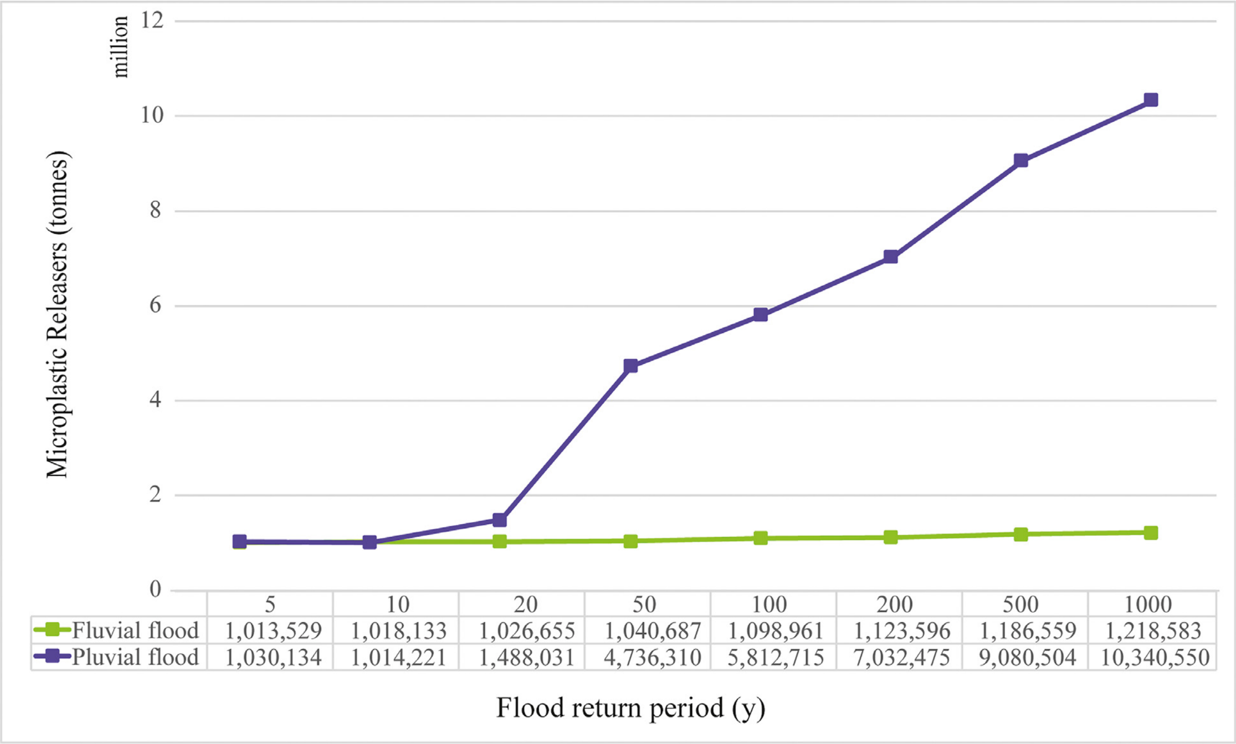

(C)
Quantity of Microplastic Releasers at risk of pluvial and fluvial flood for different return periods

Fig. 5. (A) Quantity of waste management facilities which received MPRs on site in 2019 at risk of flood for different return periods and peril (fluvial and pluvial flood). (B) Category of waste management facilities based on the Environment Agency in England Waste Data Interrogator at risk of flooding for each pluvial flood returning period organised on stack bar graph. (C) Estimated amount (million tonnes) of Microplastic Releasers at risk of flooding for different return periods and source (fluvial defended and pluvial flood).

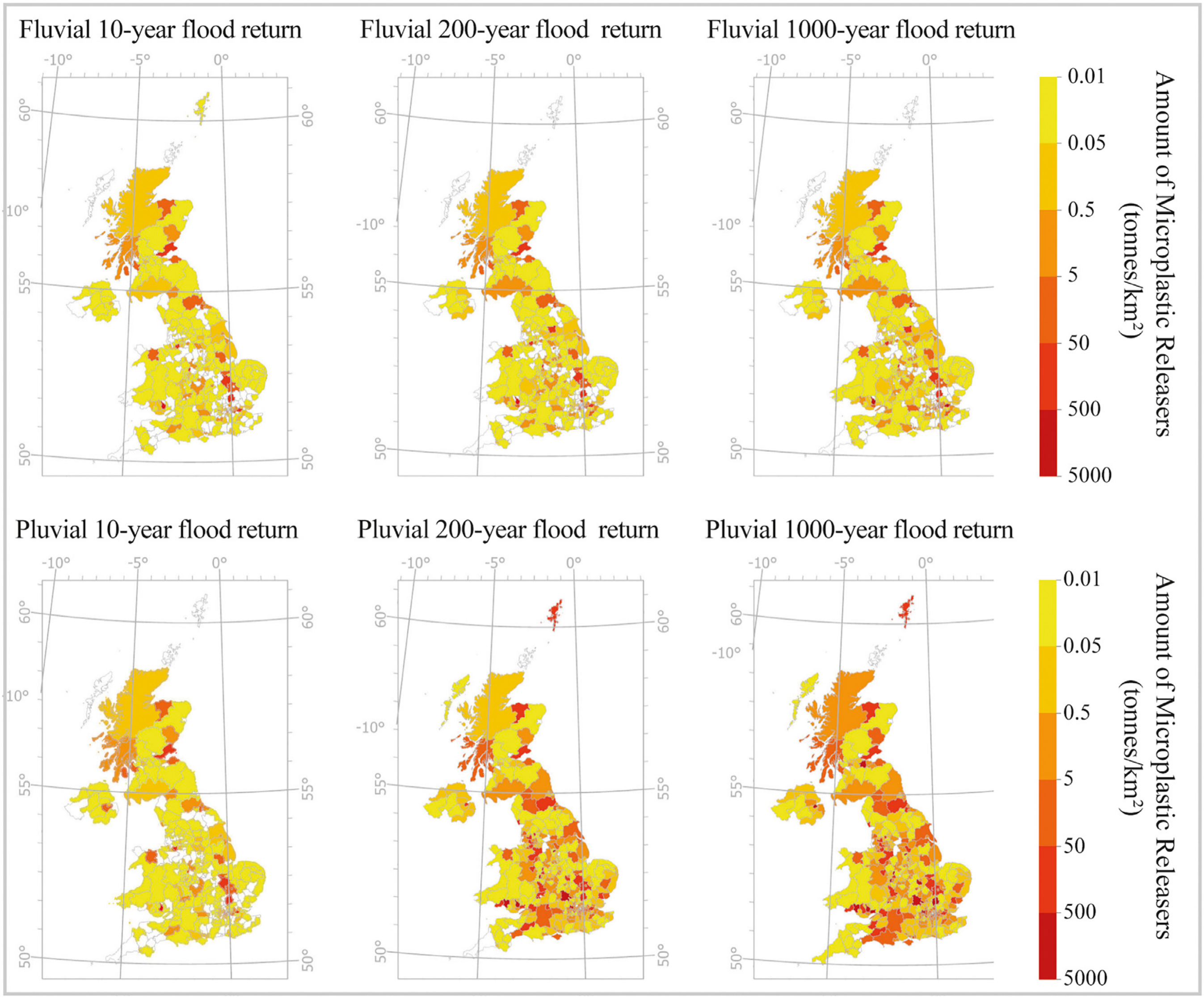


Fig. 6. Amount of managed waste at risk of releasing microplastics in flood waters for different flood likelihoods and sources (fluvial defended and pluvial), summarised and normalised per Local Authority area (km^2).

The overlap of pluvial flood map extent on MPRs for the 1 in 10-year is very much similar to the fluvial, but far more interesting is the impact estimated for the medium likelihood. For example, in the local authority of Moray, Scotland, the number of MPRs affected is 3 times higher: from 34 (high likelihood) to 97 tonnes/km^2 (medium likelihood), for a total of ~220,000 tonnes if considering the entire district's surface. A similar significant increase is evident for the Shetland Islands, rising from 1 to 101 tonnes/km^2 from high to medium likelihood. In England, when considering LAs with quantity of MPRs higher than 50 tonnes/km^2, several spatial patterns can be recognised (Fig. 6). In particular, in addition to the districts already mentioned located north of London, another hotspot with an average of 230 tonnes/km^2 can be recognised between Blackburn, Liverpool, Manchester and Stoke-on-Trent. The spatial pattern with the highest concentration of MPRs at risk of medium pluvial flood likelihood is a corridor of 13 LAs in between England and Wales, from Telford south to Bristol and then splitting both west toward Swansea and south in direction of the South Somerset districts; data suggests an average of 700 tonnes per square kilometre. Finally, in the low likelihood but high intensity pluvial flooding, numbers are generally increasing compared to medium and high likelihood with peaks in West Lothian (1437 tonnes/km^2), Newport area (4456 tonnes/km^2), the zone in between Oxford and Luton (Aylesbury Vale with 3416 tonnes/km^2), and Belfast with the highest concentration in the UK: 4789 tonnes/km^2.

5. Discussion

This research presents a novel methodology based on publicly available data on the characteristics and quantity of waste annually received by waste management facilities. A new terminology was introduced to refer to waste able to deteriorate and fragmentise into synthetic microplastic components: Microplastic Releasers (MPRs). MPRs are a selection from the European Waste Catalogue code, comprised of (1) plastic waste (as defined by the European Commission in 2018), (2) synthetic textile and rubber waste (well-known for releasing fibres and micro particles under mechanical stress), and (3) mix and undifferentiated materials which are likely to contain different sizes and types of plastic items, synthetic clothes, and rubber components. The new terminology was essential to enable a quantitative estimation of plastic waste occurring in waste facilities across the UK.

Quantities of MPRs at risk of fluvial and pluvial flood were estimated for the UK for different return periods. Coastal flood risk was not taken into consideration at this stage, but we strongly recommended its inclusion in future analyses, including considering global sea level rise projections. Results from the simulated impact of flood on MPRs were significantly higher for pluvial flooding compared to fluvial flooding, with a 10-fold increase from the high likelihood to the low likelihood (from approximately 1 to 11 million tonnes). The biggest increment was a 3-fold increase between 20 and 50-year return periods. Interestingly, a similar result was obtained by Roebroek et al. (2020) in their global assessment of flood induced mobilisation of plastic, where mismanaged plastic waste was generically estimated as a percentage of total waste generation per country relative to gross domestic profit, where they reported the biggest increment (4-fold increase) between 20 and 50-year return periods versus the 3.5-fold increase between 1 and 10-years. This represents the average at the global scale of approximately 151 tonnes of plastic mobilisation potential per administration unit were estimated (accounting for flood defences) for the 1 in 20-year return period, which became ~612 tonnes for the 1 in 50-year return period.

The methodologies introduced can be applied elsewhere providing appropriate supporting assumptions and the limitation in data are considered. MPRs were selected from all the available origins (households, commercial and industrial activities, construction, and demolition and excavation), by considering only waste that is physically solid, therefore, sludge from waste-water treatment plants, leachate from landfills, used oils and derivates were not included. By not considering waste-water treatment plants and landfill leachate, we excluded at this stage some of the main well-known sources of primary MPs, which we strongly recommend to be added in the estimation of the total MP load in future studies. In addition, due to the complexity and uncertainties related to the movement and storage of waste in a country's waste management system, the length of time required by plastic items to fragment into different sizes of microplastics was not included in the scope of the present work. Further study could assess the feasibility of adding a modelling component to take into account (1) the eventual transport and fate of MPs already present in flood waters, (2) the waste storage periods within facilities, and (3) the extent of MPR degradation into MPs during those storage periods. Undertaking future work will improve this new methodology to estimate the contribution of waste facilities to the total load of MPs in freshwaters due to flooding. The estimation of the footprints of the facilities was achieved through the creation of buffer areas based on the average size of the cadastral parcels per facility type and country. Additional data about actual facility dimensions and boundaries description could be included in future mandatory reports on annual quantity of waste received. The latter would be extremely beneficial for more accurate predictions since the quantities of waste at risk of releasing MPs in flood waters were estimated based on the overlap between flood maps and the footprint of the facilities. Another useful piece of information would be data on flood velocity that could be used to estimate potential impact scenarios and significantly improve the assessment of waste at risk of flooding. At this stage, partially because of the adopted national scale, and partially due to the lack of available data, site-specific analysis on flood risk exposure could not be implemented. This includes the consideration of the design of the waste facilities, waste containment systems, and the existence of flood protection measures other than flood defences included within the Fathom flood risk map extents. In addition, available data on waste received for each waste management facility could be improved by including information on waste storage conditions and the build-up period (residency time) to allow the simulation of multiple days' flood scenarios. Finally, the adopted methodology to estimate the amount of MPRs buried in landfills for the period 2007–2018 was the first step in understanding the risk they pose when located in areas at risk of flood. No additional mechanisms of the landfill sites were considered, such as leachate formation, percolation through the body, decomposition stage for different type of waste, or erosion.

6. Conclusion

Within our study we developed a framework to identify waste at risk of releasing MPs amongst the European Waste Catalogue (EWC) code in addition to the well-known plastic waste, which allows the estimation of the quantity and location of potential MPs' sources at the national scale as long as datasets about waste are publicly available. In order to overlap the information about waste type and location with flood extent maps, the footprint of waste management facilities has been estimated with the use of buffer areas based on the publicly available European INSPIRE Cadastral Parcel dataset. The methodology was applied to the UK to estimate the quantity of waste at risk of flooding which could lead to MPs' mobilisation in flood waters. Daily quantities of Microplastic Releasers ware estimated for all waste management facilities for the year 2019, only for the landfills operative in the same year, an accumulation factor has been considered by summarising annual quantities of MPRs received from 2007 to 2018 to approximate the real conditions potentially faced in case of inundation.

Results show the impact of pluvial flood being much higher compared to fluvial which can be partially explained by the simulation behind the flood map extents where floods were created both from overflowing water bodies and independently from them, but also it further proves the necessity of assessing the risk related to present and future extreme rainfall events. Results at the national scale were investigated further with the identification of spatial patterns at the local scale for pluvial and fluvial floods for the high, medium and low likelihood. Quantities of MPRs at risk of flooding were combined per Local Authority and normalised per area (km^2) identifying UK hotspots in need of future research in terms of risk management and mitigation measures at the local scale. Depending on the localities, stakeholders and policymakers could rethink the location of existing and new waste management facilities outside flood-prone areas, if the location cannot be changed, mitigation measures can be applied both to the flood origin and pathways with additional flood defences, and by intervening on site-specific containment systems able to limit the mobilisation of synthetic micro components during an event of flood.

Microplastics are recognised as a significant material of concern to environmental and human health, a manmade hazardous material entering the environment due to waste mismanagement. There is a significant research gap when considering land microplastic pollution discharge in to rivers, the pollution of flood waters and the marine environment from specific terrestrial souses. In this study we present a novel method and first analysis of the hazard and risk of Waste Management Facilities unintended microplastic release into flood waters. This study will initiate a new line of enquiry and research focused on hazard and risk quantification of terrestrial microplastic pollution.

Declaration of Competing Interest

The authors declare no conflict of interest.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.hazadv.2022.100105.

References

Allen, G.H., Pavelsky, T.M., 2018. Global extent of rivers and streams. Science 361 (6402), 585–588.

Allen, S., Allen, D., Karbalaei, S., Maselli, V., Walker, T.R., 2022. Micro(nano)plastics sources, fate, and effects: what we know after ten years of research. J. Hazard. Mater. Adv. 6, 1–12.

Arrighi, C., Masi, M., Iannelli, R., 2018. Flood risk assessment of environmental pollution hotspots. Environ. Model. Software 100, 1–10.

Baensch-Baltruschat, B., Kocher, B., Stock, F., Reifferscheid, G., 2020. Tyre and road wear particles (TRWP) - A review of generation, properties, emissions, human health risk, ecotoxicity, and fate in the environment. Sci. Total Environ. 733, 137823.

Bates, P.D., Horritt, M.S., Fewtrell, T.J., 2010. A simple inertial formulation of the shallow water equations for efficient two-dimensional flood inundation modelling. J. Hydrol. (Amst) 387 (1–2), 33–45.

Borrelle, S.B., Ringma, J., Law, K.L., Monnahan, C.C., Lebreton, L., McGivern, A., Murphy, E., Jambeck, J., Leonard, G.H., Hilleary, M.A., Eriksen, M., Possingham, H.P., De Frond, H., Gerber, L.R., Polidoro, B., Tahir, A., Bernard, M., Mallos, N., Barnes, M., Rochman, C.M., 2020. Predicted growth in plastic waste exceeds efforts to mitigate plastic pollution. Science 369, 1515–1518.

Boucher, J., Billard, G., Simeone, E., Sousa, J., 2020. The Marine Plastic Footprint. IUCN, Gland, Switzerland.

Brand, J.H., Spencer, K.L., O'shea, F.T., Lindsay, J.E., 2018. Potential pollution risks of historic landfills on low-lying coasts and estuaries. Wiley Interdisc. Rev. Water 5 (1), 1–12.

CCC, 2018. Managing The Coast in a Changing Climate. CCC Publications. [Online]. Available at: https://www.theccc.org.uk/publication/managing-the-coast-in-a-changing-climate (Accessed: 27 January 2022).

DEFRA and Government Statistical Service, 2021. *UK Statistics on Waste*. Gov.uk [Online]. Available at: https://www.gov.uk/government/statistics/uk-waste-data (Accessed: 25 April 2022).

EA, 2014. Waste Classification - Guidance On the Classification and Assessment of Waste (Edition 1.1) Technical Guidance WM3 gov.uk: Natural Resources Wales.

EA, 2018. Preliminary Flood Risk Assessment for England Gov.uk. [Online]. Available at: https://www.gov.uk/government/publications/preliminary-flood-risk-assessment-for-england (Accessed: 25 April 2022).

EA, 2019a. Waste Data Interrogator. 25 April 2022. Gov.uk: Environment Agency Available at: https://data.gov.uk/dataset/d409b2ba-796c-4436-82c7-eb1831a9ef25/2019-waste-data-interrogator.

EA, 2019b. What is the Risk of Flooding from Surface Water map? [Online]. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/842485/What-is-the-Risk-of-Flooding-from-Surface-Water-Map.pdf (Accessed: 25 April 2022).

European Commission, 2018. Commission Notice On Technical Guidance On the Classification of Waste (2018/C 124/01). Official Journal of the European Union: European Commission [Online]. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52018XC0409(01)&from=EN (Accessed: 25 April 2022).

Evangeliou, N., Grythe, H., Klimont, Z., Heyes, C., Eckhardt, S., Lopez-Aparicio, S., Stohl, A., 2020. Atmospheric transport is a major pathway of microplastics to remote regions. Nat. Commun. 11 (1), 3381.

Geyer, R., Jambeck, J.R., Law, K.L., 2017. Production, use, and fate of all plastics ever made. Sci. Adv. 3 (7), e1700782.

Golwala, H., Zhang, X., Iskander, S.M., Smith, A.L., 2021. Solid waste: an overlooked source of microplastics to the environment. Sci. Total Environ. 769, 144581.

Gunaalan, K., Fabbri, E., Capolupo, M., 2020. The hidden threat of plastic leachates: a critical review on their impacts on aquatic organisms. Water Res. 184, 116170.

He, B., Smith, M., Egodawatta, P., Ayoko, G.A., Rintoul, L., Goonetilleke, A., 2021. Dispersal and transport of microplastics in river sediments. Environ. Pollut. 279, 116884.

He, P., Chen, L., Shao, L., Zhang, H., Lu, F., 2019. Municipal solid waste (MSW) landfill: a source of microplastics? -Evidence of microplastics in landfill leachate'. Water Res. 159, 38–45.

HM Land Registry (2021) 'INSPIRE Index Polygons spatial data for England and Wales'. Available at: https://use-land-property-data.service.gov.uk/datasets/inspire (Accessed: 25 April 2022).

Hurley, R., Woodward, J., Rothwell, J.J., 2018. Microplastic contamination of river beds significantly reduced by catchment-wide flooding. Nat. Geosci. 11 (4), 251–257.

Jambeck, J.R., Roland, G., Chris, W., Theodore, R.S., Miriam, P., Anthony, A., Ramani, N., Kara, L.L., 2015. Plastic waste inputs from land into the ocean. Science 347 (6223), 768–771.

Kärkkäinen, N., Sillanpää, M., 2021. Quantification of different microplastic fibres discharged from textiles in machine wash and tumble drying. Environ. Sci. Pollut. Res. Int. 16253–16263, doi:10.1007/s11356-020-11988-2. Epub 2020 Dec 18. https://link.springer.com/article/10.1007/s11356-020-11988-2.

Laner, D., Fellner, J., Brunner, P.H., 2009. Flooding of municipal solid waste landfills–an environmental hazard? Sci. Total Environ. 407 (12), 3674–3680.

Natural Resources Wales (2019)'Waste Permit Returns Data Interrogator'. Available at: https://naturalresourceswales.sharefile.eu/share/view/sae217ec1e71419c8/fo32643a-bb38-4031-b6a8-ae66a79b848e (Accessed: 25 April 2022).

Natural Resources Wales, 2021. Different Types of Flood Risk Available at: https://naturalresources.wales/evidence-and-data/maps/different-types-of-flood-risk/?lang=en (Accessed: 25 April 2022).

Neal, J., Dunne, T., Sampson, C., Smith, A., Bates, P., 2018. Optimisation of the two-dimensional hydraulic model LISFOOD-FP for CPU architecture. Environ. Model. Software 107, 148–157.

Neal, J., Hawker, L., Savage, J., Durand, M., Bates, P., Sampson, C., 2021. Estimating river channel bathymetry in large scale flood inundation models. Water Resour. Res. 57 (5).

Neuhold, C., 2012. Identifying flood-prone landfills at different spatial scales. Nat. Hazards 65 (3), 2015–2030.

Neuhold, C., Nachtnebel, H.P., 2011. Assessing flood risk associated with waste disposals: methodology, application and uncertainties. Nat. Hazards 56 (1), 359–370.

NI Department for Infrastructure, 2018. Northern Ireland Flood Risk Assessment (NIFRA) 2018 infrastructure-ni.gov.uk/. [Online]. Available at: https://www.infrastructure-ni.gov.uk/articles/2nd-cycle-northern-ireland-flood-risk-assessment-2018 (Accessed: 25 April 2022).

Nicholls, R.J., Beaven, R.P., Stringfellow, A., Monfort, D., Le Cozannet, G., Wahl, T., Gebert, J., Wadey, M., Arns, A., Spencer, K.L., Reinhart, D., Heimovaara, T., Santos, V.M., Enríquez, A.R., Cope, S., 2021. Coastal landfills and rising sea levels: a challenge for the 21st century. Front. Mar. Sci. 8.

NIEA (2019) 'NIEA - Authorised waste sites (treatment & storage)'. 25 April 2022. Gov.uk. Available at: https://data.gov.uk/dataset/4c9ae0a2-0238-459e-8b4d-1172bec9dc3c/niea-authorised-waste-sites-treatment-storage.

Piccinelli, R., Krausmann, E., 2013. *Natech Risk Analysis Methodologies For Floods* (JRC 86771) Joint Research Centre. [Online]. Available at: https://www.researchgate.net/publication/259828652_Natech_risk_analysis_methodologies_for_floods.

PlasticsEurope, 2021. Plastics the Facts 2021: An analysis of European Plastics production, Demand and Waste Data [Online]. Available at: https://plasticseurope.org/wp-content/uploads/2021/12/Plastics-the-Facts-2021-web-final.pdf.

Registers of Scotland (2021) 'INSPIRE Cadastral Parcels for Scotland'. Available at: https://data.gov.uk/dataset/b6c24c13-03c0-428a-b579-36e5b0029b0a/ros-cadastral-parcels-download-service.

Roebroek, C.T.J., Harrigan, S., van Emmerik, T.H.M., Baugh, C., Eilander, D., Prudhomme, C. and Pappenberger, F. (2020)'Supplementary information to "Plastic in global rivers: are floods making it worse?"'.

Roebroek, C.T.J., Harrigan, S., van Emmerik, T.H.M., Baugh, C., Eilander, D., Prudhomme, C., Pappenberger, F., 2021. Plastic in global rivers: are floods making it worse? Environ. Res. Lett. 16 (2).

Sabour, M.R., Alam, E., Hatami, A.M., 2020. Global trends and status in landfilling research: a systematic analysis. J. Mater. Cycles Waste Manage. 22, 711–723.

Sampson, C., Smith, A., Bates, P., Neal, J., Alfieri, L., Freer, J., 2015. A high-resolution global flood hazard model'. Water Resour. Res. 51 (9), 7358–7381.

SEPA (2019a) 'Scottish waste sites and capacity tool'. 25 April 2022. sepa.org.uk: Scottish Environment Protection Agency. Available at: https://www.sepa.org.uk/environment/waste/waste-data/waste-data-reporting/waste-site-information/.

SEPA (2019b)'Site Returns Q1 2007 - Q1 2020′ Available at: https://www.sepa.org.uk/data-visualisation/waste-sites-and-capacity-tool/ (Accessed: 25 April 2022).

SEPA, 2020. Impact of Flooding (flood risk maps) summary: Methodology and Mapping sepa.org.uk. [Online]. Available at: https://www.sepa.org.uk/media/532833/impacts_of_flooding_summary_v2.pdf (Accessed: 25 April 2022).

Sun, J., Zhu, Z.R., Li, W.H., Yan, X., Wang, L.K., Zhang, L., Jin, J., Dai, X., Ni, B.J., 2021. Revisiting microplastics in landfill leachate: unnoticed tiny microplastics and their fate in treatment works. Water Res. 190, 116784.

van Emmerik, T., Strady, E., Kieu-Le, T.C., Nguyen, L., Gratiot, N., 2019. Seasonality of riverine macroplastic transport. Sci. Rep. 9 (1), 13549.

Wang, Z., Zhang, Y., Kang, S., Yang, L., Shi, H., Tripathee, L., Gao, T., 2021. Research progresses of microplastic pollution in freshwater systems. Sci. Total Environ. 795, 148888.

Wing, O.E.J., Bates, P.D., Neal, J.C., Sampson, C.C., Smith, A.M., Quinn, N., Shustikova, I., Domeneghetti, A., Gilles, D.W., Goska, R., Krajewski, W.F., 2019. A new automated method for improved flood defense representation in large-scale hydraulic models. Water Resour. Res. 55 (12), 11007–11034.

Xu, C., Zhang, B., Gu, C., Shen, C., Yin, S., Aamir, M., Li, F., 2020. Are we underestimating the sources of microplastic pollution in terrestrial environment? J. Hazard Mater. 400, 123228.

Zhang, K., Hamidian, A.H., Tubic, A., Zhang, Y., Fang, J.K.H., Wu, C., Lam, P.K.S., 2021. Understanding plastic degradation and microplastic formation in the environment: a review. Environ. Pollut. 274, 116554.