Plastic pollution in UK's rivers: a 'snapshot' survey of macro- and micro-plastic contamination in surface waters of 13 river systems across England, Wales, Scotland and Northern Ireland

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Summary

Although the problem of plastic pollution at sea is widely documented, the situation in rivers that carry much of that pollution has been far less well studied to date. As a contribution to greater understanding of the problem, in February and March 2019, Greenpeace UK (supported by the People's Postcode Lottery) carried out a geographically widespread 'snapshot' survey of levels of plastics, including microplastics, in 13 rivers across the UK (9 in England, 2 in Wales, 1 in Scotland and 1 in Northern Ireland) using a floating 'manta' net placed mid-stream. Plastics were counted, weighed and sized and their identities determined using forensic infrared analysis (FT-IR).

At least one piece of plastic (microplastics <5mm in all dimensions and/or larger items) was found in samples from 28 of the 30 locations, and in samples from at least one of the locations on each river. Across all sampling locations, a total of 1271 pieces of plastic were captured in the nets, ranging in size from plastic straw and bottle top fragments down to tiny microbeads less than 1mm across. Plastic fragments and microbeads less than 2mm in size were the most commonly found, followed by fragments and pellets between 2mm and 5mm. Although concentrations per unit volume or per unit surface area of river water varied widely between locations, on average our results fall in a similar range to those reported in studies of individual rivers in other parts of Europe.

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The majority of the plastic items recovered fell into three main plastic types, namely polyethylene (46%), polystyrene (23%) and polypropylene (17%), all used widely for packaging and other single use applications and all having a relatively low density that keeps them floating at the surface of the river. Among 12 other plastic types found were fragments of EVA, PVC, PET and polyamide.

Samples from 5 locations contained plastic microbeads, mostly polyethylene though with a small number identified as polypropylene, despite the ban coming into force on their use in certain personal care products. Two samples also contained some microbeads which, though of almost identical appearance to the conventional microbeads, were nonetheless made from softer paraffin-wax type material (the environmental fate and effects of which are not known).

Samples from 7 locations contained ‘nurdles’, or pre-production pellets (made of polyethylene or polypropylene), with one sample collected downstream from a plastics manufacturing facility being particularly heavily contaminated. In addition, 4 samples contained dark-coloured and slightly irregular polyethylene pellets identified as ‘biobeads’ washed out of water treatment works. Expanded polystyrene spheres were also conspicuous contaminants in samples from two of the 13 rivers.

Among the larger items of plastics found (>5mm in at least one dimension) were sections of clear plastic films and foils, a piece of PVC cable sheath, part of a bottle cap, sections of plastic straw, some packing strap, fragments of strimmer line and a plastic tag from a clothing label.

Taken together, the results of this geographically widespread ‘snaphot’ survey of 13 UK rivers demonstrate that plastic pollution is common to all of the rivers we investigated at some level, and can be locally severe. Once plastics, especially microplastics, are released to freshwater environments, they cannot be effectively retrieved. Furthermore, as our manta net samples only the top 10 cm of each river, we have documented only the tip of the plastic iceberg, as many plastics are denser than water and may be carried beneath the surface or even along with the sediments. In addition, in common with many previous studies, we sampled microplastics down to 0.3 mm; the majority of microplastics of smaller size ranges will not have been captured in our study.

Every sample collected yielded a unique result in terms of the numbers, types, sizes and forms of microplastic found floating at the river surface. Were we to repeat this snapshot survey, while the same broad patterns might be preserved, we would nonetheless expect to get equally varied, complex and unpredictable results, making any assessment of risk extremely difficult.

In our study, we have not investigated the risks to wildlife from the presence of the plastics we have detected, though clearly the potential exists for widespread exposure of freshwater species to microplastics, right across the food web. Furthermore, at this stage, we can also only speculate at the complexity of the chemical contamination on the surfaces of the plastics we have found, though this will be subject to further investigation in due course.

Introduction

The pollution of our seas with plastics, including larger recognisable items (macroplastics) and smaller microplastics (<5mm), along with the harm these pollutants can cause to marine wildlife, have been extensively studied and increasingly widely documented and reported in recent years (GESAMP 2015, 2016). Marine plastic pollution is an issue that has, as a result, become one of increasing familiarity and growing public concern around the world. However, despite the inevitability that a high proportion of the plastics contaminating our oceans arises from land-based sources (Li *et al.* 2018) and is carried out to sea by rivers and streams, there has to date been far less attention paid to the nature and severity of plastic pollution in freshwater environment, and less still on the potential impacts of plastics (both macro- and microplastics) on aquatic species (Lambert & Wagner 2018).

Research on this issue has begun to expand in recent years, but there are still many fundamental gaps in scientific understanding of the distribution, complexity and impacts of plastics as contaminants in freshwater ecosystems (Wagner *et al.* 2014). Given that the solutions to preventing further increases in pollution of the marine environment with plastic lie in large part upstream, understanding the ways in which rivers contribute to the transfer and concentration of plastics, including microplastics, is of critical importance. Furthermore, it is vital to recognise that waterways are not simply conduits that carry water, sediments and associated pollutants to the coast, but are also complex and in some cases fragile ecosystems in their own right, as well as being invaluable sources of water for human use, and therefore warrant high levels of protection from all sources of pollution.

When it comes to plastics pollution, those sources are diverse and widespread, including both point sources, such as storm drains, landfill sites, wastewater treatment plant effluents (McCormick *et al.* 2014, Murphy *et al.* 2016) and industrial discharges (Eriksen *et al.* 2013, Lechner *et al.* 2014), and more diffuse inputs, including airborne and windblown macro and microplastics, run-off from urban and agricultural land (Rillig 2012) and littering along waterways (Bruge *et al*. 2018, Crosti *et al.* 2018, Kiessling *et al.* 2019). Levels of plastic contamination in waters or in sediments at any one location along a river will depend on a number of interacting factors, including human activity upstream, proximity to specific sources, river flow (including seasonal and weather-related variability) and river channel topography (including depth and width and sediment characteristics) (Eerkes-Medrano *et al.* 2015). As a result, quantities and variability in plastic loads carried by any one river over time may continue to be difficult to measure or estimate with accuracy, though using suitable hydrographic modelling techniques, GESAMP (2016) estimated that somewhere in excess of 60 billion particles of plastic, of various sizes and compositions, may be carried and discharged to the sea by rivers globally each day. Whatever the scale of the uncertainty surrounding this estimate, plastic pollution of rivers and other waterways is clearly an issue of great relevance to communities and ecosystems in all parts of the world.

Since Lechner *et al.* (2014) described with some irony 5 years ago how the Danube was 'so colourful' with its 'pot pouri' of plastic pollution, a problem similarly identified in Italy's River Po in the previous year (Vianello *et al.* 2013), research into plastic pollution of Europe's river waters and associated sediments has slowly expanded, including studies on the Rhine (Mani *et al.* 2015, 2019, Klein *et al.* 2015), the Elbe (Kiessling *et al.* 2019), the Seine (Dris *et al.* 2015) and several rivers and lakes in Switzerland (Faure *et al.* 2015). Plastic loadings of rivers have also been investigated in South Korea (Song *et al.* 2015), China (Zhang et al. 2015), the United States (Casteñada *et al.* 2014) and Chile (Rech *et al.* 2014, 2015). Methods applied vary, but tend to focus either on collection of plastics floating at or near the river surface using plankton or neuston nets (commonly with a 330 um, or one third of a mm, mesh), trapping of either macro-or microplastics using modified fish net traps attached to the river bed in order to capture denser plastic items or separation of microplastics from sediments, either in situ or using standardised systems under laboratory conditions. As may be expected, results vary widely both within and between studies, depending in part on proximity of sampling sites to urban and/or industrial environments, as well as showing significant seasonal variation (Vianello *et al.* 2013, Eerkes-Medrano *et al.* 2015). Taken together, however, such studies indicate that plastics, including microplastics (fragments, pellets, fibres, etc.), have become widely dispersed through aquatic environments.

Within the United Kingdom, studies to date have focused on a number of significant river systems, including the Thames, Mersey and Trent catchments and several rivers in Yorkshire. Studies conducted on the Rivers Mersey and Tame (a tributary of the Trent), as well as one study on the River Thames, have documented widespread microplastic contamination of river sediments, with particularly high levels recorded in the vicinity of industrial facilities (Horton *et al.* 2017, Tibbets *et al.* 2018, Hurley *et al.* 2018). On the Thames, Morrit *et al.* (2014) documented significant presence of macroplastics entrained in currents close to the river bed, while Kay *et al.* (2018) reported a similar phenomenon for microplastics in 6 river catchments in Yorkshire, the latter suggesting that the wide variety of plastic types and morphologies found gave an indication of the likely diversity of sources. Studies conducted of plastics (macro- and micro-) floating at the water surface in UK rivers, and potentially presenting different routes of exposure for wildlife than those within or close to the river bottom, appear so far to be yet more limited in geographical scope, including studies of plastics flowing through the estuary of the River Tamar, adjoining Devon and Cornwall (Sadri & Thompson 2014) and in three rivers discharging to Southampton Water and the Solent (Gallagher *et al.* 2015). There is therefore clearly value in conducting surveys of macro- and microplastic pollution in UK rivers over a wider geographical range and including a wider variety of catchments.

Although evidence of the potential for plastics, including microplastics, to cause harm to marine species has been accumulating for some time, research on exposures and effects in freshwater ecosystems remains in its relative infancy. Several species have been recorded informally to have interacted with or even ingested plastic litter, but controlled studies remain limited. Perhaps the clearest evidence to date that freshwater species are at least exposed directly to microplastic pollutants is provided by the work of Hurley *et al.* (2017) and of Windsor *et al.* (2019) who recently documented the presence of microplastics in the guts or other tissues of several species of invertebrates (including insect larvae) collected at locations along the rivers Usk, Taff and Wye in South Wales. These findings raise the possibility that those ingested microplastics may subsequently be transferred up through the food web to predators such as fish and birds, though this remains to be confirmed. At the same time, recent laboratory studies on mosquito larvae have suggested that there are mechanisms by which microplastics taken up by aquatic larval stages of insects may even be carried over through pupation into adult insect tissues and thereby distributed out of catchment (Al-Jaibachi *et al.* 2018). Further studies of exposure to, and physiological effects of, microplastics within aquatic species are expected to emerge over time. Nonetheless, even in the absence of such impact studies, it is important to recognise that plastics of all forms entering rivers today are likely to persist for some considerable time in the environment, whether they are captured within freshwater ecosytems or eventually flow out to sea, and that once they have been lost from material flows and waste streams and have reached a river or stream, they may be lost from any reasonable level of control and be effectively irretrievable. It remains important, therefore, to continue to investigate and document the extent and complexity of plastic loadings within rivers, and to use those data in order to inform work aimed at tracing and addressing all sources, in advance of greater certainty regarding the nature and severity of adverse impacts of those plastics on aquatic wildlife and ecosystems.

As a further contribution to that greater understanding, during February and March 2019, Greenpeace UK (supported with funding from the People's Postcode Lottery) carried out what we believe to be the most geographically widespread survey to date of plastic pollution in the surface waters of rivers in the UK, by using a specially designed floating 'manta' net to collect samples from a total of 30 locations along 13 different rivers (9 in England, 2 in Wales, 1 in Scotland and 1 in Northern Ireland). Despite being a relatively simple method, and a 'snapshot' survey of the pollution loading at one particular period for each location, the study does, nonetheless, provide original and unique data on the diversity and spread of plastic pollution, including microplastics, on a number of rivers and/or sections of rivers for which there are so far no previous data available.

Materials and methods

During the period from 6th February and 29th March 2019, samples of floating debris were collected from the water surface at a total of 30 locations distributed across 13 river systems in the United Kingdom (9 in England, 2 in Wales, 1 in Scotland and 1 in Northern Ireland). All sampling locations were above the tidal limits for each river and were selected to include different reaches, from rural to more urban or industrial (see Figure 1 for approximate locations, and Table 1 for coordinates). Precise sampling locations were determined in part by the need for ease and safety of access to the river to enable deployment of the equipment.

Samples were collected using a small, self-buoyant 'manta' design neuston net (Hydrobios, net mouth diameter 30cm, operating depth from surface to approximately 10cm, mesh size 330 um, or one third of a millimetre) which was deployed mid-stream at each location for a period of between 20 and 140 minutes (depending on flow rate and observed densities of larger floating debris, which was monitored to avoid the net overfilling and clogging). The net was held in position in each case either by suspending it from a suitable bridge or by secure tether to the river bed. Total flow of water through the net during each sampling period was recorded by means of a Hydrobios Mechanical Flow Meter (Model 438 110).

At the end of each sampling period, the net was retrieved and the entire contents were transferred to clean glass jars with screw-cap metal lids, using several jars for samples containing a lot of debris (each assigned a unique sample number). Jars were placed in the dark and kept cool ready for transport to the Greenpeace Research Laboratories for processing and analysis. The sampling net was then turned inside out and rinsed with plenty of deionised water before continuing to the next sampling location.

On receipt at our laboratory, each sample was transferred into a large glass trough and re-suspended using a sufficient volume of deionised water. The samples were then inspected carefully under a 3 x magnification, illuminated lens, removing any suspected plastic items, including large and small fragments, fibres, pellets and pieces of film, all of which were retained for further analysis. Inspection of each individual sample was continued for at least an hour in each case, or longer in cases in which a lot of organic debris (primarily leaves or other vegetation) or other material had been retrieved by the net, in order to give reasonable confidence that all potential plastic items down to a size range of approximately 0.5 mm diameter could be isolated and separated from the sample. The material remaining after removal of all suspected plastic items has been retained to enable subsequent independent inspection of a random sub-set of samples in order to cross-check the efficiency of the initial inspection.

Fig 1: map of sampling locations

All suspected plastic items from an individual sample were collected in glass petri dishes (either 52 mm or 100 mm) that had been pre-inspected under a binocular dissecting microscope in order to verify that they were free from microplastic fragments and fibres before use. Petri dishes containing the suspected plastics were dried at 40 ‘C, with the lids in place and with no air flow, for a period of at least 48 hours, until each reached a constant weight when measured to the nearest milligramme (mg). The identity of the suspected pieces of plastic or microplastic in each of the dried samples was then determined using Fourier-Transform Infra-red (FT-IR analysis), using a PerkinElmer Frontier spectrometer. FT-IR analysis was carried out using a universal diamond –ATR attachment, placing each fragment or fibre onto the crystal surface (after precleaning the surface with analytical grade ethanol) and applying a consistent force using the sample clamp.

FT-IR spectra (mid-infrared) were obtained for each candidate microplastic piece by scanning in the wave number range between 4000 and 650 cm-1, at a resolution of 4 cm-1, and acquiring a minimum of 4 scans per item (up to a maximum of 16 scans per item for some samples in order to obtain clearer spectra). All spectra obtained were processed using PerkinElmer's Spectrum software (version 10.5.4), enabling post-acquisition background subtraction and normalisation of the data and subsequent comparison against a number of commercially available spectral databases, including PerkinElmer's standard Polymers Library, as well as against a custom built database prepared In cases in which a sample contained a number of pieces of plastic or microplastic that showed a very high degree of physical similarity (size, shape, colour, surface texture), only a subset (between 10 and 20%) were analysed in detail using FT-IR.

Any items in the petri dishes for which the FT-IR spectrum indicated that the material was something other than plastic or for which the spectrum was of such poor quality that an identity could not be confirmed were then removed from the petri dishes before each dish within its remaining, confirmed plastic contents was weighed on a calibrated top-pan balance to an accuracy of 1 mg. The petri dish was reweighed after removal of all plastic items to another container in order to determine by difference the total mass of plastics captured by the net during the sampling period.

All items of plastic and microplastic were then counted and assigned to one of four size classes/types: (i) macroplastics > 5mm in at least one dimension, (ii) microplastics between 5mm and 2mm in their largest dimension, (iii) microplastics <2mm (but greater than 0.3 mm) in all dimensions and (iv) fibres of varying length and thickness, only a proportion of which would have been expected to have been retained by the net, given that most fibres found had diameters far lower than 0.3 mm.

Within the microplastics size range (<5mm), plastic items were further subdivided into five other classes: (a) microbeads (generally <1mm in diameter and spherical in shape), (b) 'nurdles' or pre-production plastic pellets (generally <4 mm diameter, with a smooth surface, varying in colour from transparent through white and yellow to pale brown and varying in form from globular to more cylindrical), (c) 'biobeads', or plastic pellets used in water treatment processes (up to 5mm in length, cylindrical or lenticular in shape, grey to black in colour and commonly with a rough surface texture), (d) expanded polystyrene beads (white or off-white in colour, soft texture and in the size range from approximately 2mm to 5mm), (e) pieces of plastic film and (f) other plastic fragments (between 0.3 and 5 mm, and of widely varying colour, size, shape and density).

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Figure 2: workflow for sampling and analysis of river plastics samples. (a) the ‘mouth’ of the manta net ready for deployment, (b) the manta net deployed mid-stream by suspension from a bridge, (c) retrieval of a sample form the cod end of the net, (d) sieving the sample through a 250 µm sieve, (e) a whole sample collected in a glass jar ready for shipment to the laboratory, (f) hand sorting samples to retrieve candidate materials for analysis and (g) analysis of individual fragments of plastic using Fourier-Transform Infrared (FT-IR) spectroscopy (PerkinElmer Frontier) to determine polymer type.

River	Sample code(s)	Sampling location	Latitude	Longitude	Date	Sampling period (minutes)	Total quantities of plastic captured during whole sampling period (mass and number of items/fragments)	
							Mass (mg)	Number
Exe	1	Footbridge over the Exe in central Exeter	50º43'04.2''N	3º31'54.9''W	06/02/2019	not recorded	1	7
Exe	2	Footbridge over the Exe in central Exeter	50º43'04.2''N	3º31'54.9''W	06/02/2019	not recorded	3	4
Exe	3	Footbridge over the Exe in central Exeter	50º43'04.2''N	3º31'54.9''W	06/02/2019	60	13	12
Thames	4&5	Mid-river, approx. 1.3km above Teddington Lock, between built up areas	51º25'15.7''N	0º18'22.1''W	11/02/2019	60	568	66
Thames	19 & 20	Pedestrian bridge in Oxford, built up, housing estate	51º44'49.33''N	1º15'38.61''W	12/03/2019	20	69	21
Thames	21	Footbridge, close to canal, semi-urban	51º31'59.80''N	0º41'54.47''W	12/03/2019	30	35	13
Thames	22	Road bridge in Chertsey - lots of traffic. River wide, downstream of lock	51º23'19.97''N	0º29'10.37''W	12/03/2019	60	56	8
Severn	8	Stone pedestrian bridge at Atcham, downstream of road bridge	52º40'46.31''N	2º40'51.14''W	19/02/2019	67	9	21
Severn	11 & 12	On pedestrian (Diglis) suspension bridge, below sewage outlet and lock.	52º10'34.59''N	2º13'29.03''W	04/03/2019	60	147	15
Severn	13	Small footbridge near Gloucester docks over east branch of the Severn above NTL	51º51'52.34''N	2º15'11.79''W	04/03/2019	53	4	6
Great Ouse	23	Some way below road bridge, near town, but quite rural	52º5'15.95''N	0º43'0.03''W	14/03/2019	85	2	1
Great Ouse	24	Next to cluster of houses, 1 mile above Denver Sluice, rural	52º33'54.75''N	0º20'38.86''E	15/03/2019	140	0	0
Trent	39	Pedestrian suspension bridge in central Nottingham between park and urban area	52º55'59.75''N	1º8'21.00''W	28/03/2019	90	56	21
Trent	40	Small village near Cottam Power Station. Grassy bank near road, farmland on other side.	53º17'2.55''N	0º46'41.88''W	29/03/2019	95	3	14
Mersey	25, 26 & 27	Pedestrian suspension bridge between housing estate and large park	53º23'14.46''N	2º34'43.28''W	19/03/2019	30	11224	875
Mersey	28 & 29	Pedestrian bridge between industrial estates in Stockport	53º24'20.82''N	2º11'10.91''W	19/03/2019	30	185	67
Aire	30	Pedestrian suspension bridge in central Leeds above a weir	53º47'39.42''N	1º32'16.19''W	20/03/2019	60	120	25
Aire	31	Rural, close to canal lock (above this), grassy banks and agricultural land around. V flat with some flooding beyond banks	53º42'51.87''N	1º8'13.65''W	20/03/2019	40	571	38
Derwent	34	Pedestrian bridge between Cockermouth Town & park	54º39'52.46''N	3º22'4.13''W	22/03/2019	67	1	1
Derwent	35 & 36	Pedestrian bridge between Workington town & green space on north side	54º38'48.79''N	3º32'38.28''W	22/03/2019	75	85	9
Wear	32	Pedestrian bridge in Durham, below main town, urban, a few weirs just upriver	54º46'48.18''N	1º34'36.03''W	21/03/2019	95	2	3
Wear	33	Below stone bridge entering Lambton Estate, just after a small waterfall	54º51'53.31''N	1º33'31.33''W	21/03/2019	80	1	2

Table 1a: locations at which surface water neuston net tow samples were collected across nine rivers in England, along with raw data for total mass and total number of pieces of plastic (macro- and microplastics combined) retrieved from the net after the sampling periods as indicated.

River	Sample code(s)	Sampling location	Latitude	Longitude	Date	Sampling period (minutes)	Total quantities of plastic captured during whole sampling period (mass and number of items/fragments)	
							Mass (mg)	Number
Conwy	6	Small footbridge in Betws-y-Coed	53º5'32.20''N	3º47'56.16''W	18/02/2019	65	0	0
Conwy	7	Pont Gower - small footbridge above tidal limit	53º8'35.31''N	3º48'24.90''W	19/02/2019	75	4	9
Wye	14 & 15	Stone bridge in Monmouth - Wye Bridge - lots of traffic	51º48'40.84''N	2º42'35.64''W	04/03/2019	35	5	3
Wye	16, 17 & 18	Metal bridge (Bigg Bridge) - dropped off upstream side and ran under	51º47'6.85''N	2º40'25.93''W	05/03/2019	43	46	7
Clyde	37	Between Glasgow Green and housing in central Glasgow - from a boat. Above weir	55º50'57.81''N	4º14'22.13''W	27/03/2019	113	5	6
Clyde	38	Pedestrian bridge between motorway and Strathclyde Country Park	55º47'6.97''N	4º1'35.23''W	27/03/2019	60	4	5
Lagan	9	Upstream of road and footbridge at Ballynacross Rd in Lisburn. Just below sewage outlet	54º31'42.00''N	6º1'28.49''W	28/02/2019	65	9	10
Lagan	10	Above Stranmillis Weir (NTL) in middle of river	54º34'6.34''N	5º55'41.42''W	01/03/2019	90	1	2

Table 1b: locations at which surface water neuston net tow samples were collected across two rivers in Wales, one in Scotland and one in Northern Ireland, along with raw data for total mass and total number of pieces of plastic (macro- and microplastics combined) retrieved from the net after the sampling periods as indicated.

River	Sampling location	Date	Total number of plastic items / fragments captured during whole sampling period	Number of macroplastics >5mm	Number of microplastics <5 - >2mm	Number of microplastics <2mm	Number of plastic microfibres (diameter <1mm, various lengths)
Exe	Footbridge over the Exe in central Exeter	06/02/2019	7	1	1	4	1
Exe	Footbridge over the Exe in central Exeter	06/02/2019	4	0	3	1	0
Exe	Footbridge over the Exe in central Exeter	06/02/2019	12	2	2	3	5
Thames	Mid-river, approx. 1.3km above Teddington Lock, between built up areas	11/02/2019	66	10	24	22	10
Thames	Pedestrian bridge in Oxford, built up, housing estate	12/03/2019	21	5	10	3	3
Thames	Footbridge, close to canal, semi-urban	12/03/2019	13	0	5	4	4
Thames	Road bridge in Chertsey - lots of traffic. River wide, downstream of lock	12/03/2019	8	3	2	2	1
Severn	Stone pedestrian bridge at Atcham, downstream of road bridge	19/02/2019	21	0	6	4	11
Severn	On pedestrian (Diglis) suspension bridge, below sewage outlet and lock.	04/03/2019	15	2	3	2	8
Severn	Small footbridge near Gloucester docks over east branch of the Severn above NTL	04/03/2019	6	0	0	0	6
Great Ouse	Some way below road bridge, near town, but quite rural	14/03/2019	1	0	0	1	0
Great Ouse	Next to cluster of houses, 1 mile above Denver Sluice, rural	15/03/2019	0	0	0	0	0
Trent	Pedestrian suspension bridge in central Nottingham between park and urban area	28/03/2019	21	2	2	16	1
Trent	Small village near Cottam Power Station. Grassy bank near road, farmland on other side.	29/03/2019	14	1	2	11	0
Mersey	Pedestrian suspension bridge between housing estate and large park	19/03/2019	875	105	374	386	10
Mersey	Pedestrian bridge between industrial estates in Stockport	19/03/2019	67	16	21	26	4
Aire	Pedestrian suspension bridge in central Leeds above a weir	20/03/2019	25	8	7	8	2
Aire	Rural, close to canal lock (above this), grassy banks and agricultural land around. V flat with some flooding beyond banks	20/03/2019	38	2	29	7	0
Derwent	Pedestrian bridge between Cockermouth Town & park	22/03/2019	1	0	1	0	0
Derwent	Pedestrian bridge between Workington town & green space on north side	22/03/2019	9	7	0	1	1
Wear	Pedestrian bridge in Durham, below main town, urban, a few weirs just upriver	21/03/2019	3	0	1	2	0
Wear	Below stone bridge entering Lambton Estate, just after a small waterfall	21/03/2019	2	0	0	2	0

Table 2a: size distributions of plastic pieces isolated from net tow samples collected at each location across the nine rivers in England, including macroplastics (>5mm in at least one dimension), two classes of microplastics (<5mm but > 2mm in major dimension, and <2mm in all dimensions) and microfibers (of varying lengths but with diameters always <1mm)

River	Sampling location	Date	Total number of plastic items / fragments captured during whole sampling period	Number of macroplastics >5mm	Number of microplastics <5 - >2mm	Number of microplastics <2mm	Number of plastic microfibres (diameter <1mm, various lengths)
Conwy	Small footbridge in Betws-y-Coed	18/02/2019	0	0	0	0	0
Conwy	Pont Gower - small footbridge above tidal limit	19/02/2019	9	0	2	1	6
Wye	Stone bridge in Monmouth - Wye Bridge - lots of traffic	04/03/2019	3	0	2	0	1
Wye	Metal bridge (Bigg Bridge) - dropped off upstream side and ran under	05/03/2019	7	2	2	1	3
Clyde	Between Glasgow Green and housing in central Glasgow - from a boat. Above weir	27/03/2019	6	0	0	5	1
Clyde	Pedestrian bridge between motorway and Strathclyde Country Park	27/03/2019	5	2	0	3	0
Lagan	Upstream of road and footbridge at Ballynacross Rd in Lisburn. Just below sewage outlet	28/02/2019	10	2	6	2	0
Lagan	Above Stranmillis Weir (NTL) in middle of river	01/03/2019	2	0	0	0	2

Table 2b: size distributions of plastic pieces isolated from net tow samples collected at each location across the two rivers in Wales, one in Scotland and one in Northern Ireland, including macroplastics (>5mm in at least one dimension), two classes of microplastics (<5mm but > 2mm in major dimension, and <2mm in all dimensions) and microfibers (of varying lengths but with diameters always <1mm)

River	Sampling location	Date	Total number of plastic items / fragments captured during whole sampling period	Number of microbeads	Number of 'nurdles'	Number of 'biobeads'	Number of expanded polystyrene spheres	Number of pieces of plastic film/wrapping
Exe	Footbridge over the Exe in central Exeter	06/02/2019	7	0	0	0	0	0
Exe	Footbridge over the Exe in central Exeter	06/02/2019	4	0	0	0	0	0
Exe	Footbridge over the Exe in central Exeter	06/02/2019	12	0	0	0	0	0
Thames	Mid-river, approx. 1.3km above Teddington Lock, between built up areas	11/02/2019	66	0	2	0	0	6
Thames	Pedestrian bridge in Oxford, built up, housing estate	12/03/2019	21	0	1	0	0	2
Thames	Footbridge, close to canal, semi-urban	12/03/2019	13	0	1	0	0	0
Thames	Road bridge in Chertsey - lots of traffic. River wide, downstream of lock	12/03/2019	8	0	1	0	0	0
Severn	Stone pedestrian bridge at Atcham, downstream of road bridge	19/02/2019	21	0	0	0	0	0
Severn	On pedestrian (Diglis) suspension bridge, below sewage outlet and lock.	04/03/2019	15	0	0	2	0	2
Severn	Small footbridge near Gloucester docks over east branch of the Severn above NTL	04/03/2019	6	0	0	0	0	0
Great Ouse	Some way below road bridge, near town, but quite rural	14/03/2019	1	1	0	0	0	0
Great Ouse	Next to cluster of houses, 1 mile above Denver Sluice, rural	15/03/2019	0	0	0	0	0	0
Trent	Pedestrian suspension bridge in central Nottingham between park and urban area	28/03/2019	21	10	0	0	0	0
Trent	Small village near Cottam Power Station. Grassy bank near road, farmland on other side.	29/03/2019	14	7	0	0	0	0
Mersey	Pedestrian suspension bridge between housing estate and large park	19/03/2019	875	36	79	59	127	17
Mersey	Pedestrian bridge between industrial estates in Stockport	19/03/2019	67	0	2	2	18	3
Aire	Pedestrian suspension bridge in central Leeds above a weir	20/03/2019	25	0	1	0	1	1
Aire	Rural, close to canal lock (above this), grassy banks and agricultural land around. V flat with some flooding beyond banks	20/03/2019	38	1	0	12	5	1
Derwent	Pedestrian bridge between Cockermouth Town & park	22/03/2019	1	0	0	0	0	0
Derwent	Pedestrian bridge between Workington town & green space on north side	22/03/2019	9	0	0	0	0	5
Wear	Pedestrian bridge in Durham, below main town, urban, a few weirs just upriver	21/03/2019	3	0	0	0	0	0
Wear	Below stone bridge entering Lambton Estate, just after a small waterfall	21/03/2019	2	0	0	0	0	0

Table 3a: frequency of detection of some specific types of plastic pollutant in net tow samples collected at each location across the nine rivers in England, including microbeads, pre-production pellets (‘nurdles’), ‘biobeads’ arising from wastewater treatment works, expanded polystyrene spheres and pieces of plastic film (transparent or coloured)

River	Sampling location	Date	Total number of plastic items / fragments captured during whole sampling period	Number of microbeads	Number of 'nurdles'	Number of 'biobeads'	Number of expanded polystyrene beads	Number of pieces of plastic film/wrapping
Conwy	Small footbridge in Betws-y-Coed	18/02/2019	0	0	0	0	0	0
Conwy	Pont Gower - small footbridge above tidal limit	19/02/2019	9	0	0	0	0	0
Wye	Stone bridge in Monmouth - Wye Bridge - lots of traffic	04/03/2019	3	0	0	0	0	0
Wye	Metal bridge (Bigg Bridge) - dropped off upstream side and ran under	05/03/2019	7	0	0	0	0	0
Clyde	Between Glasgow Green and housing in central Glasgow - from a boat. Above weir	27/03/2019	6	0	0	0	0	0
Clyde	Pedestrian bridge between motorway and Strathclyde Country Park	27/03/2019	5	0	0	0	0	1
Lagan	Upstream of road and footbridge at Ballynacross Rd in Lisburn. Just below sewage outlet	28/02/2019	10	0	0	0	0	0
Lagan	Above Stranmillis Weir (NTL) in middle of river	01/03/2019	2	0	0	0	0	0

Table 3b: frequency of detection of some specific types of plastic pollutant in net tow samples collected at each location across the two rivers in Wales, one in Scotland and one in Northern Ireland, including microbeads, pre-production pellets (‘nurdles’), ‘biobeads’ arising from wastewater treatment works, expanded polystyrene spheres and pieces of plastic film (transparent or coloured).

River	Sampling location	Date	Total plastic mass (mg) per km river flow	Total number of plastic items / fragments per km river flow	Number of microplastics (<5mm) per km river flow	Equivalent number per square km	
						Total plastics	Microplastics (<5mm)
Exe	Footbridge over the Exe in central Exeter	06/02/2019	flow rate not recorded				
Exe	Footbridge over the Exe in central Exeter	06/02/2019	flow rate not recorded				
Exe	Footbridge over the Exe in central Exeter	06/02/2019	3.76	3.47	1.45	11571	4821
Thames	Mid-river, approx. 1.3km above Teddington Lock, between built up areas	11/02/2019	196.06	22.78	15.88	75938	52926
Thames	Pedestrian bridge in Oxford, built up, housing estate	12/03/2019	60.88	18.53	11.47	61761	38233
Thames	Footbridge, close to canal, semi-urban	12/03/2019	16.57	6.16	4.26	20518	14205
Thames	Road bridge in Chertsey - lots of traffic. River wide, downstream of lock	12/03/2019	21.38	3.05	1.53	10181	5090
Severn	Stone pedestrian bridge at Atcham, downstream of road bridge	19/02/2019	3.34	7.78	3.71	25940	12353
Severn	On pedestrian (Diglis) suspension bridge, below sewage outlet and lock.	04/03/2019	99.17	10.12	3.37	33731	11244
Severn	Small footbridge near Gloucester docks over east branch of the Severn above NTL	04/03/2019	2.57	3.85	0.00	12833	0
Great Ouse	Some way below road bridge, near town, but quite rural	14/03/2019	0.54	0.27	0.27	897	897
Great Ouse	Next to cluster of houses, 1 mile above Denver Sluice, rural	15/03/2019	0.00	0.00	0.00	0	0
Trent	Pedestrian suspension bridge in central Nottingham between park and urban area	28/03/2019	24.38	9.14	7.84	30481	26127
Trent	Small village near Cottam Power Station. Grassy bank near road, farmland on other side.	29/03/2019	0.76	3.54	3.28	11785	10943
Mersey	Pedestrian suspension bridge between housing estate and large park	19/03/2019	10527.11	820.67	712.81	2735572	2376040
Mersey	Pedestrian bridge between industrial estates in Stockport	19/03/2019	64.37	23.31	16.35	77708	54512
Aire	Pedestrian suspension bridge in central Leeds above a weir	20/03/2019	61.14	12.74	7.64	42461	25476
Aire	Rural, close to canal lock (above this), grassy banks and agricultural land around. V flat with some flooding beyond banks	20/03/2019	412.33	27.44	26.00	91469	86655
Derwent	Pedestrian bridge between Cockermouth Town & park	22/03/2019	0.14	0.14	0.14	455	455
Derwent	Pedestrian bridge between Workington town & green space on north side	22/03/2019	39.68	4.20	0.47	14006	1556
Wear	Pedestrian bridge in Durham, below main town, urban, a few weirs just upriver	21/03/2019	0.40	0.61	0.61	2019	2019
Wear	Below stone bridge entering Lambton Estate, just after a small waterfall	21/03/2019	0.34	0.68	0.68	2254	2254

Table 4a: total quantities of plastics (total mass in milligrammes, total number of plastic items/fragments and number of microplastics) retrieved from the net tows at all sites across the nine rivers sampled in England, normalised for differences in river flow between sites by expressing the values per kilometre of river flow through the net and per km^2. For comparison with other published studies, results have also been normalised on the basis of numbers per m^2 and per m^3 in the Results section below.

River	Sampling location	Date	Total plastic mass (mg) per km river flow	Total number of plastic items / fragments per km river flow	Number of microplastics (<5mm) per km river flow	Equivalent number per km^2	
						Total plastics	Microplastics (<5mm)
Conwy	Small footbridge in Betws-y-Coed	18/02/2019	0.00	0.00	0.00	0	0
Conwy	Pont Gower - small footbridge above tidal limit	19/02/2019	1.08	2.42	0.81	8065	2688
Wye	Stone bridge in Monmouth - Wye Bridge - lots of traffic	04/03/2019	3.50	2.10	1.40	7003	4669
Wye	Metal bridge (Bigg Bridge) - dropped off upstream side and ran under	05/03/2019	15.84	2.41	1.03	8033	3443
Clyde	Between Glasgow Green and housing in central Glasgow - from a boat. Above weir	27/03/2019	43.29	51.95	43.29	173160	144300
Clyde	Pedestrian bridge between motorway and Strathclyde Country Park	27/03/2019	2.14	2.68	1.61	8925	5355
Lagan	Upstream of road and footbridge at Ballynacross Rd in Lisburn. Just below sewage outlet	28/02/2019	6.38	7.09	5.67	23646	18917
Lagan	Above Stranmillis Weir (NTL) in middle of river	01/03/2019	flow too low to calculate reliable estimates				

Table 4b: total quantities of plastics (total mass in milligrammes, total number of plastic items/fragments and number of microplastics) retrieved from the net tows at all sites across the two rivers sampled in Wales, one in Scotland and one in Northern Ireland, normalised for differences in river flow between sites by expressing the values per kilometre of river flow through the net and per km^2. For comparison with other published studies, results have also been normalised on the basis of numbers per m^2 and per m^3 in the Results sec

Figure 3: microscopic images of some of the microplastics identified from one site on each river (including fragments, fibres, nurdles, biobeads and microbeads) as an illustration of the diversity of microplastic pollution present. Note that in the case of the Trent, the image shows a combination of three pink microbeads later identified as being polyethylene, plus four others of almost identical appearance (though more variable diameter and colour) that were subsequently identified as paraffin-wax type microbeads (and therefore excluded from the counts)

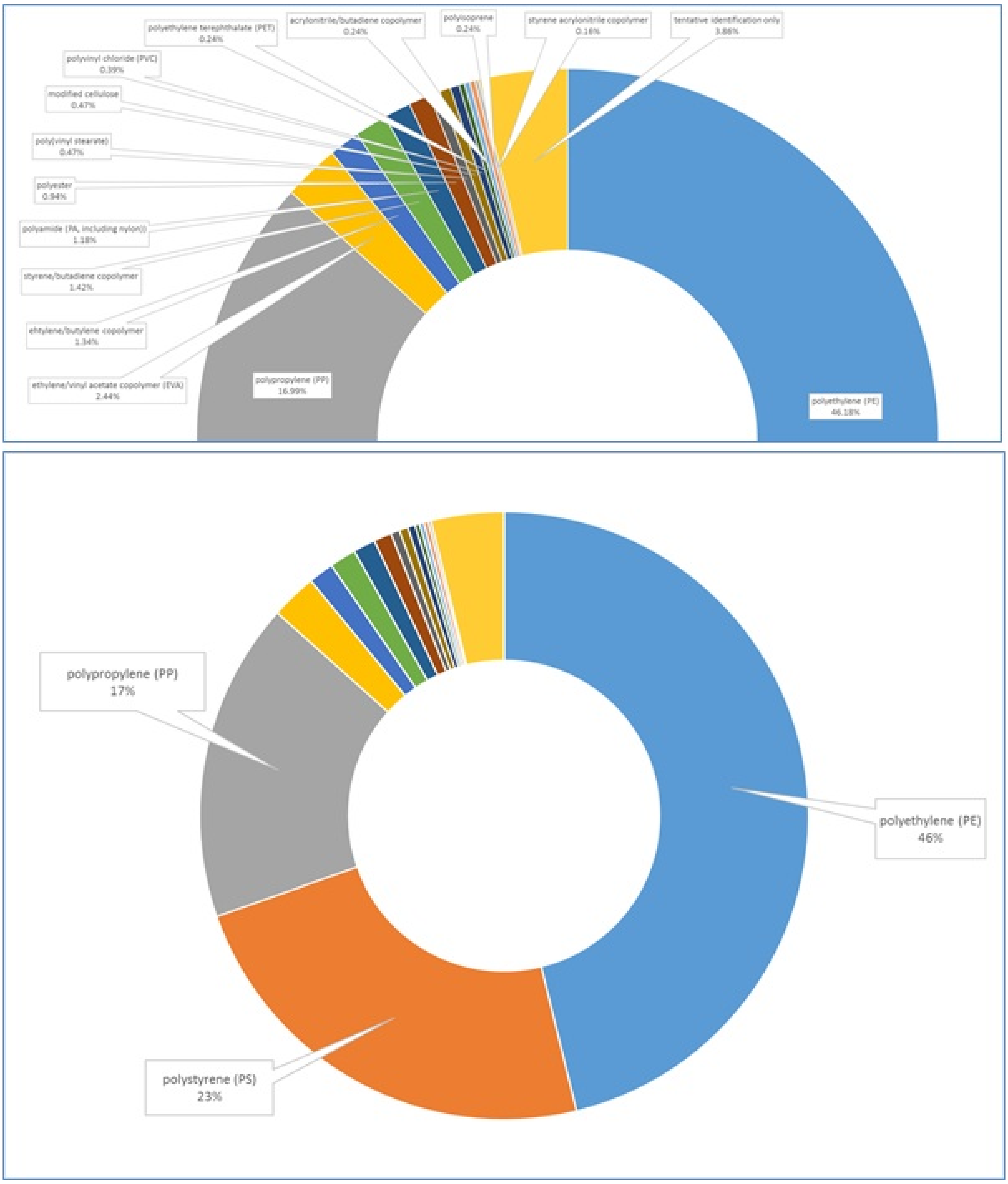


Figure 4: proportions of different polymers identified using FT-IR across the total of 1271 pieces of plastic, including macro- and microplastics. The category 'tentative identification only' indicates items or fragments yielding FT-IR spectra showing strong characteristics of specific plastics, as well as in physical appearance, but for which spectral matching was considered insufficient to enable definitive characterisation.

Results and Discussion

At least one piece of plastic (macro or microplastic) was found in samples from 28 of the 30 locations sampled, and in samples from at least one location on all 13 rivers. The two locations revealing no plastic pollution during the time of sampling were relatively rural sites on the Conwy and Great Ouse Rivers (samples 6 and 24 respectively).

Across all 30 sampling locations, a total of 1271 pieces of plastic were captured in the nets, ranging in size from plastic straw and bottle top fragments down to tiny microbeads less than 1mm across. Plastic fragments and microbeads less than 2mm in size were the most commonly found (517 pieces), closely followed by fragments and pellets between 2mm and 5mm in size (505 pieces). An illustrative selection of the microplastics found at one site on each river is included in Figure 3 above.

In total, 170 fragments or pellets of plastic with at least one dimension greater than 5 mm (here classed as macroplastics) were recovered, as well as 80 plastic fibres of varying widths and lengths (ranging from fine polyester fibres likely to have arisen from clothing to thicker fibres of polypropylene from other sources). Given that the net has a mesh diameter of 330 micrometres (one third of a mm), any plastic fragments or microbeads of a smaller size would not have been retained efficiently by the net and cannot therefore be investigated in detailed quantitative terms in this study. For the same reasons, fine fibres may also be under represented in these samples because, irrespective of their length, many may well have slipped through the net under the pressure of the water flow.

Figure 4 (above) indicates that the majority (>80%) of plastic items recovered from all the net tows combined fell into three polymer types, namely polyethylene (PE), polystyrene (PS) and polypropylene (PP). This result is perhaps to be expected given the quantities of these plastics produced, the wide range of 'disposable' single-use packaging and other products in which they are used and their relatively low physical density (<1 gramme per cm^3) which tends to keep them floating at or near the surface even within freshwater systems. Typical spectra given by the infrared spectrometer (FT-IR) for these three polymers are shown in Figure 5 below.

A further 12 polymer types were identified among the 1271 pieces of plastic collected by the nets, including small fragments of EVA, PVC, PET and polyamide (PA), though all at much lower relative abundances compared to PE, PS and PP.

Of the three main polymers, polyethylene was the most commonly found (46% of all plastics found), in the form of irregular coloured fragments, sections of transparent or coloured film (such as may be used for food packaging), microbeads of the type formerly permitted for use in toothpastes, shower gels and other personal care products, 'nurdles' or pre-production plastic resin pellets arising from plastics manufacturing operations and 'biobeads', dark coloured irregular pellets used to provide surfaces for bacterial and fungal growth within wastewater treatment plants (see below).

The relatively high abundance of polystyrene was explained largely by the presence in a small number of samples of numerous expanded polystyrene spheres, presumably having broken loose from larger items of EPS packaging material, though there were also some white and coloured fragments of microplastic that were also identified as PS. Polypropylene was present largely in the form of 'nurdles' (in roughly the same proportion as for PE) or of variously coloured fragments, which may have broken away from larger PP items such as bottle tops or food containers, though some polypropylene fibres were also identified.

In terms of both numbers and overall mass of pieces of plastic captured per km of water flow through the net, or per hour of net deployment, one of the two samples collected from the River Mersey (sample 25, 26 & 27 combined, labelled *'pedestrian suspension bridge between housing estate and* *large park'*) was by far the most contaminated of all the samples. In just half an hour of the net being placed in the water at that location, it had captured a total of 875 pieces of plastic, weighing a total of over 11 grammes. Taking into account the speed of flow of the water, that's equivalent to just over 10g of plastic per km of river flow, or 820 different plastic pieces per km of river flow, at the time of sampling.

Aside from this sample from the Mersey, the two samples noted above in which no plastics were found, one sample from the Lagan River in which the extremely low flow makes quantitative comparison difficult and two samples from the River Exe in which no flow rates were recorded at the time of sampling, the quantities of plastics retained by the net at the other 24 locations sampled varied from 0.14 to 52 pieces per km of river flow (median 4.03 pieces/km, average 9.44 pieces/km), making up a total mass per sample of between 0.14 and 412 milligrammes (mg) plastic per km river flow (median 11 mg/km, average 45 mg/km).

In terms of quantities captured calculated per hour (equivalent) of net deployment, the ranges for these 24 sample locations were 0.71-134 pieces captured per hour (median 8.84 pieces/h, average 20.3 pieces/h), equivalent to a mass range of 0.67-856 mg plastic captured by the net per hour (median 8.57 mg/h, average 104.9 mg/h).

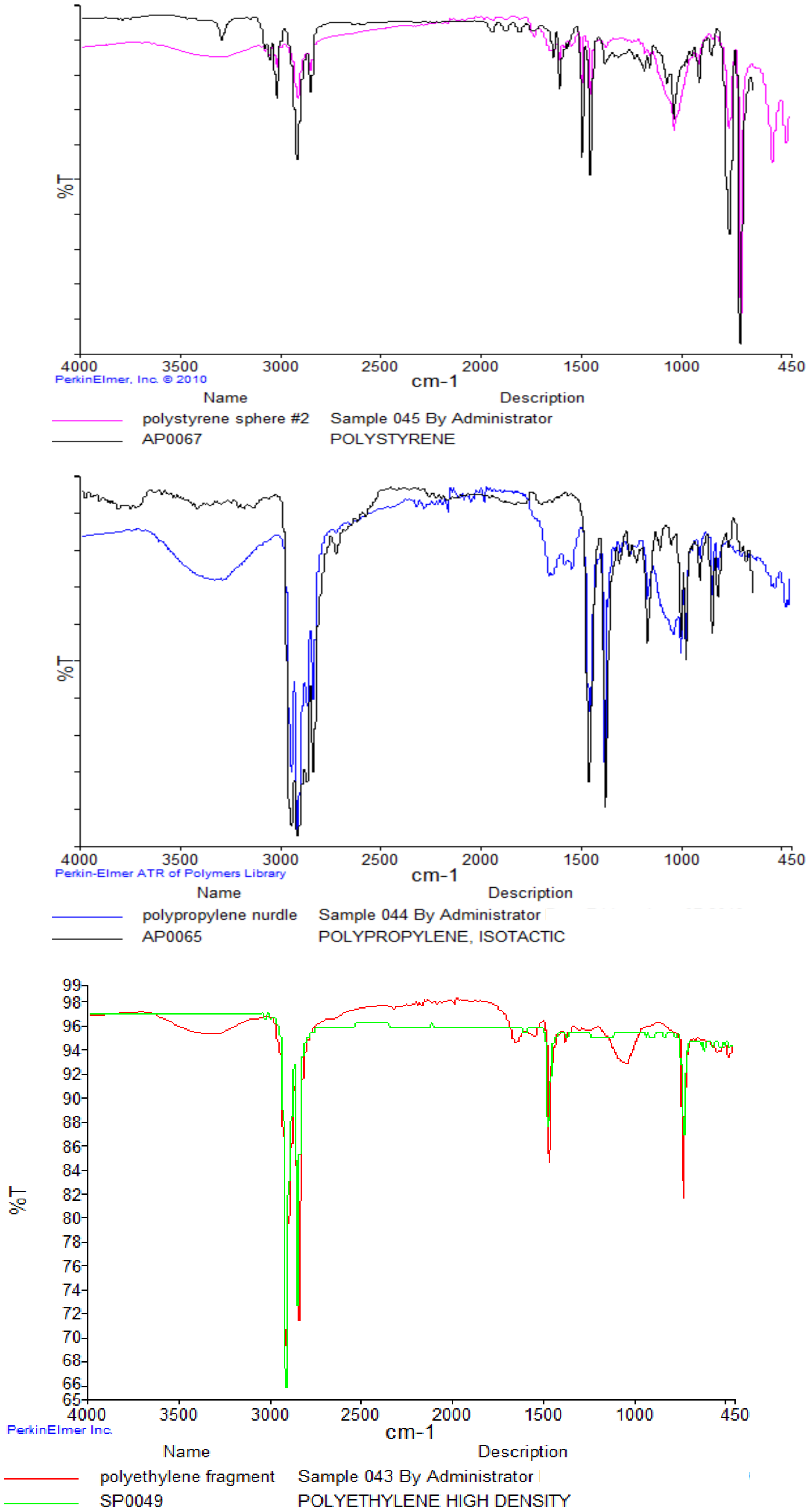
Samples collected from 5 locations contained microbeads, in the size range 0.5-2 mm and in various colours (predominantly pink, green or blue). The most contaminated sample from the Mersey (samples 25, 26 & 27 combined, as noted above) contained a total of 36 microbeads. The two samples from the River Trent (samples 39 & 40) contained 10 and 7 microbeads respectively and one sample from each of both the Great Ouse (sample 23) and Aire (sample 31) each contained 1 microbead.

In addition to the polyethylene microbeads, we also found a number of 'softer' pink and blue microbeads of more irregular diameter and colour (in both the Trent and Mersey), which were identified by FT-IR as a paraffin wax-based material and which were therefore not included in the overall counts of microplastics. These may be replacements for conventional plastic (polyethylene or polypropylene) microbeads. The environmental fate and potential impacts of such wax-based microbeads have yet to be investigated in any detail, though their size range is very similar to conventional microbeads and their waxy nature could make them particularly absorptive to certain persistent organic pollutants.

Samples from 7 locations contained plastic pellets identified as 'nurdles' or pre-production plastic resin pellets (in the size range from 3-5 mm diameter). Again the most contaminated sample was that from the Mersey (samples 25, 26 & 27 combined) with a total of 79 nurdles captured, while the other sample from the Mersey (samples 28 & 29 combined) and one of the samples from the Thames (samples 4 & 5) contained 2 nurdles. The remaining three samples from the Thames (samples 19 & 20 combined, and samples 21 and 22) and one sample from the Aire (sample 30) contained one nurdle each.

Another conspicuous type of plastic pellet, generally more cylindrical in shape, around 5mm in length, black or dark grey in colour and with a much rougher surface than the nurdles, were identified as being 'biobeads', or plastic pellets that are used in water treatment works to provide surfaces for micro-organism growth. These were found in samples from 4 of the locations, again the two samples from the Mersey (containing 59 and 2 biobeads respectively), one sample from the Severn (2 biobeads in samples 11 & 12 combined) and one sample from the Aire (12 biobeads in sample 31).

Figure 5: typical FT-IR spectra for the three major types of microplastic polymer identified in this study



The two samples from the Mersey and both samples from the Aire also contained expanded polystyrene beads. 127 such beads were captured in the most contaminated sample from the Mersey, and 18 in the other Mersey sample, while samples 30 and 31 from the River Aire contained 1 and 5 polystyrene beads respectively.

Among the larger plastic items (>5 mm in one or more dimensions) recovered from the nets at various locations were:

a. sections of clear (transparent) or partly coloured plastic film or foil, in samples 4 and samples 19 & 20 combined from the Thames, in samples 11 & 12 combined from the Severn, in samples 25, 26 & 27 combined from the Mersey and in samples 35 & 36 combined from the Derwent;
b. a small section of PVC cable sheath in sample 4 (Thames);
c. part of a bottle cap, a section of packing strap, some strimmer line, a section of plastic straw and a plastic ring of unidentified origin in samples 25, 26 & 27 combined from the Mersey; and
d. part of a clothing label tag in samples 16, 17 & 18 combined from the River Wye.

It must be kept in mind that the 30 samples collected in the current study provide single ‘snapshots’ of the absolute and relative levels of plastic pollution at each of the locations sampled, i.e. the status of plastic pollution of surface waters on the day that each was sampled. While it is clear that the levels of plastic pollution in the Mersey at the time of sampling were by far the highest of all samples, caution must be taken in drawing comparisons between the other rivers sampled based on results from these single net tow samples. These were necessarily collected on different days and therefore under differing weather conditions and cannot be assumed to be wholly representative of the longer-term status of plastic pollution levels in those respective rivers.

Sampling at each of the sites on different days, or even over a different period on the same day, may have yielded a different pattern of results between rivers, not least because plastics are discrete pollutants (rather than being more evenly dissolved within the water) and because their inputs to river systems are likely to depend on many different factors, including rainfall, wastewater discharges, wind speeds and directions, overall river flow, and the particulars of human activity upstream at the time of sampling. Repeat sampling at the same locations on several different days, and even in different seasons, would be necessary in order to obtain an indication of variability of plastic pollution levels on any one stretch of river and of what may constitute ‘typical’ conditions for that location.

Nonetheless, taking the sample set from this study as a whole, it is possible to compare the overall results with those reported from other studies (many of which are also subject to the same uncertainties and limitations) by normalising our data in various ways.

For example, of the few studies to date that have quantified plastic contamination of surface river water (within and beyond Europe), most express their data in terms of number of total plastics and/or microplastics per cubic metre of water (i.e. per m^3). On that basis, assuming that our neuston net was routinely sampling to a depth of 10 cm as it floated on its buoyant ‘wings’, the average number of pieces of plastic across the 27 samples for which volumes sampled could be estimated was 1.293 pieces per m^3 (median 0.129 pieces per m^3, maximum at one of the two sites on the Mersey at 27.35 pieces per m^3). Using similar net systems, Sadri & Thompson (2014) recorded an average of 0.028 plastic pieces per m^3 in the River Tamar in the South West of England, lower even than the median value in our study.

However, Lecher *et al.* (2014) report average levels for the Danube of 0.317 pieces per m^3, and a maximum of 141.6 pieces per m^3, while average values for the River Seine (0.28-0.47 pieces per m^3, Dris *et al.* 2015), the Rhine (0.09 - 0.937 pieces per m^3, Mani et al. 2015) and a number of rivers in Chile (0.05-0.74 pieces per m^3, Rech *et al.* 2015) are also within a similar range as in our study. Slightly higher ranges have been reported by others for the River Po in Italy (especially in winter, at 12.2 pieces per m^3, Vianello *et al.* 2013), for the North Shore Channel in Chicago (1.94-17.93 pieces per m^3, McCormick *et al.* 2014) and for a number of rivers in Switzerland (average of 7 pieces per m^3, but with a maximum of up to 64 pieces per m^3 in one river after a heavy rainfall event, Faure *et al.* 2015).

Another study in the UK recorded levels of plastics in the surface estuarine waters of three rivers flowing in to the Solent in Southampton, but expressed the data in terms of number of plastic pieces per m^2, i.e. surface are sampled rather than total volume swept (Gallagher *et al.* 2015). On this basis, the average values for those estuaries (between 0.4 and 5.86 pieces per m^2) are higher than the average values determined from our sample set (0.129 total pieces of plastic per m^2, 0.108 microplastics per m^2), though of a similar order. The maximum area-based abundance of microplastics recorded in our study, at the more contaminated of the two sites we sampled on the Mersey, is, at 2.376 microplastics per m^2, more similar to the values determined by Gallagher *et al*. (2015) for the Rivers Hamble, Itchen and Test that flow to the Solent.

Given that levels of microplastics present in surface seawater, especially in most offshore areas, are lower than those that may be found in rivers, they are often expressed on the basis of counts per square kilometre of sea surface (km^2), rather than per m^2. Recalculating on that basis for purely illustrative purposes (recognising that this involves very considerable extrapolation from actual measured values) indicates that the levels of total plastic and microplastic pollution recorded across all locations in our study are, as may be expected, generally higher than we recorded for both inshore and offshore marine waters around Scotland in 2017 (Santillo *et al.* 2018). They are, however, of a similar order (thousands to tens of thousands of microplastics per km^2 equivalent) to some of the more contaminated coastal waters and embayments, such as the Gulf of Lyon in the Mediterranean (Schmidt *et al.* 2017) and in parts of the Arabian Gulf (Abayomi *et al.* 2017).

At an equivalent concentration of more than 2 million pieces of microplastic per km^2, the levels of floating plastics at the most contaminated site in our study (on the River Mersey) are higher than the most contaminated locations recorded to date within the so-called Great Pacific Garbage Patch that accumulates within the North Pacific Gyre (Moore *et al.* 2001, Law *et al.* 2014).

Conclusions and implications

1. The results of this geographically widespread 'snapshot' survey of 13 UK rivers demonstrate that plastic pollution is common to all the rivers investigated at some level, at almost all the locations sampled and at some locations is already severe. Once plastics, especially microplastics, have reached a river, it becomes increasingly difficult, if not impossible, to remove them again; they have regrettably become part of the hidden landscape of Britain's waterways. We can use nets to help us detect and quantify what is flowing past, but we cannot filter entire rivers in an attempt to remove plastic pollutants, and certainly not without destroying the very fabric of the ecosytems we would be aiming to protect. However much plastic is there already in total is largely there to stay, whether retained within the rivers themselves or in the seas into which those rivers flow, with the potential to impact wildlife and our own health on the way.

2. While the use of the floating manta net provided us with a way to collect samples in a consistent and controlled manner across all the rivers we sampled, by focusing on the surface 10cm of the rivers, we are undoubtedly only seeing a small proportion of the overall loading of plastics in our samples - the tip of the plastic iceberg. This is in part because we were able within the limits of this study to sample only midstream at each location, only for a single period (and a relatively short period in the annual life of a river) and in one season, when levels of pollution may not be at their worst. Our net only filters a small proportion of the total surface area of water flowing past the sampling locations at any one time and, perhaps more importantly still, only enables us to collect those plastics that are carried at or close to the surface of the river. There could well be just as much, if not more, plastic beneath the surface or mixed up within the sediments at the locations sampled, especially as many commonly used plastics (such as PET and PVC) are generally denser than river water and would be expected to accumulate more in deeper water or at the river bed. Simultaneous sampling of surface water, sub-surface water and sediments from each location could have yielded valuable additional information regarding the ways in which plastics partition and move through these river systems, but was not possible within the limits of the current study.

3. We have also investigated only those plastics down to a size range of around one third of a millimetre, in common with many previous studies of microplastics both in marine and freshwaters. Such nets are not able to retain with any efficiency the smallest size ranges of microplastics, including most microfibres, unless they become caught up with larger materials that are retained. Studies that have employed nets with a finer mesh, or even the filtration of whole water samples through meshes or filters of much smaller pore size, often report higher concentrations of microplastics per unit volume than are recorded through the use of manta net surveys. At the same time, however, it is generally much more difficult to obtain a truly representative sample of the water in a river at any one time when collecting and filtering whole water samples as there are often limits to the volumes that can be collected and passed through fine filters. In addition, while some studies have reported particularly high concentrations of the very smallest microplastics (<10 um) in samples of river water or even drinking water (e.g. Pivokonsky *et al.* 2018), it must be kept in mind that verification that such small particles are plastic can be extremely difficult.

4. Although we found high numbers of 'nurdles', 'biobeads', expanded polystyrene spheres and even microbeads in some of the samples, the majority of microplastics we found were fragments formed from the break-up of larger plastic items, perhaps household products or single use packaging. In most cases, in the absence of legible printing, it will remain impossible to trace the fragment back to a

specific product or source, though clearly they all started somewhere as something made from plastic and assumed to be 'disposable', despite the environmental persistence of the polymers identified.

5. As was the case for the samples of microplastics collected from surface seawater around the coast of Scotland in 2017 (Santillo *et al.* 2018), each and every sample in the current study yielded a unique result in terms of the numbers, types, sizes and forms of plastic found. While this may be typical, even inevitable, for a contaminant of such discrete nature as microplastic, given the vast diversity of uses of plastic and routes to the environment, it does emphasise a fundamental challenge with respect to any future attempts to quantify the risks posed by microplastics within the aquatic environment. Even defining a typical or average exposure for something as diverse and complex as microplastic loading within any one stretch of river over time is likely to remain highly subjective at best, with unavoidably high uncertainties attached. By allowing the discharge and loss of plastics to our freshwater ecosystems, we have essentially created a problem of enormous complexity and unpredictability, and one to which we are adding every hour of every day until we stop the flows of plastics at source.

6. In this study, we have not been able to investigate what the possible implications of exposure the plastic pollution we have measured might be for Britain’s aquatic wildlife or human health. Nevertheless, given what is known already about the effects of both macro and microplastics on marine wildlife, and the observations from other studies that microplastics can be consumed by a range of freshwater species, it is clearly reasonable to assume that plastic pollution of our rivers poses some level of threat to freshwater ecosystems and the species and food webs that comprise them. There is an urgent need for greater research focus on exposures, food web transfer and mechanisms of biological effect arising from plastic pollution of our waterways, as well as for effective measures to identify, control and as far as possible eliminate current sources upstream.

7. We also know from other studies (again mainly in the marine environment) that plastics, including microplastics, can additionally carry a complex chemical burden, in the form of both additives in the original plastic as manufactured and contaminants subsequently taken up from the environment (Browne *et al* .2013, Rochman *et al.* 2013, Gauquie *et al.* 2015, Rani *et al.* 2017). In our earlier work on microplastics collected from the sea surface around the coast of Scotland we reported that the mixtures of chemicals associated with accumulations of microplastics showed the same characteristics of complexity and unpredictability typical of the nature and form of the microplastics themselves (Santillo *et al.* 2018), and there is no reason to expect this to be fundamentally different in the case of microplastics within freshwater environments. Given their use in water treatment plants, and the evidence that some are made from relatively low grades of recycled plastic (Turner *et al.* 2019), ‘biobeads’ may be expected to carry particularly high burdens of chemical (as well as biological) contaminants. Nevertheless, without further detailed study, it is not possible to dismiss the possible significance of chemical loadings associated with other diverse components of the floating plastic miscellany revealed by our nets at each location.

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