London's river of plastic: high levels of microplastics in the Thames water column

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This opportunistic study focussed on the quantification of microplastics in the River Thames water column, the catchment responsible for draining Greater London. Two sites on the tidal Thames were sampled; one upstream of the City of London at Putney, and the other downstream at Greenwich. Water column samples were collected from June through to October 2017, being taken on the ebb and flood tides, at the surface and a depth of 2 m. Microplastics (excluding microfibres) were identified to test whether the load varied between the two sites in relation to tide, depth and season. Secondary microplastics, films and fragments, contributed 93.5% of all those found at Putney and Greenwich. Site, tide, depth and month affected density, with the combined interaction of month and site found to have the greatest influence on microplastics. Fourier Transform Infrared Spectroscopy analysis showed that polyethylene and polypropylene were the most common polymers collected from the River, suggesting broken down packaging was the primary source of microplastics in these samples. Excluding microfibres, the estimate of microplastics in the water column was 24.8 per m^3 at Putney and 14.2 per m^3 at Greenwich. These levels are comparable to some of the highest recorded in the world.

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1. Introduction

The pervasive nature of plastic pollution in aquatic habitats is now well documented in a burgeoning literature with Eriksen et al. (2014) estimating that there are some 5 trillion pieces of plastic floating in the marine environment. Plastics have been recorded from the poles (Lusher et al., 2015) to the tropics (Acosta-Coley and Olivero-Verbel, 2015), from surface waters (Collignon et al., 2012) to the depths of the ocean (Woodall et al., 2014) and been shown to impact on a wide range of organisms (Gall and Thompson, 2015) from zooplankton (Cole et al., 2013) to seabirds and large cetaceans (de Stephanis et al., 2013; Wilcox et al., 2015). Increasingly, focus has moved to microplastics, especially as these smaller fragments are in a size range that makes them more prone to ingestion by aquatic organisms, which is dependent on life stage and feeding behaviour (Capillo et al., 2020; Savoca et al., 2020).

By definition, microplastics are particles <5mm, but greater than 333μm (Desforges et al., 2014). Microplastics found in marine and freshwater environments can be classified as being either primary or secondary. Primary microplastics are those that are specifically manufactured to be microscopic in size and secondary are those formed within the marine or freshwater environment itself, through the fragmentation of larger plastic debris, via processes that can be biological (microorganism break down) mechanical (abrasion, erosion), or chemical (Andrady 2017; Julienne et al., 2019). A range of studies have described how the ingestion of microplastics can impact on health of organisms, possibly lead to trophic transfer (Farrell and Nelson, 2013; Wright et al., 2013) and, in some cases, the transfer of chemicals from plastics to animal tissues (Browne et al., 2013; Avio et al., 2015). More recent concerns relate to the role of microplastics in the potential transport and transfer of microbiota, including pathogens (McCormick et al., 2016; Lamb et al., 2018). To date, however, the majority of studies have focused on the marine environment although reports from estuarine and freshwater habitats have documented similar issues. These studies include occurrence in the surface waters and sediments of North American and Italian Lakes (Zbyszewski and Cocoran, 2011; Eriksen et al., 2013; Imhof et al., 2013), in Argentinian Catchments (Blettler et al., 2017) and presence in freshwater fish (Sanchez et al., 2014) and invertebrate species (Imhof et al., 2013). While these studies suggest that a broad range of aquatic taxa are likely to ingest microplastic, the toxicological effects require further research (Wagner et al., 2014; Prokić et al., 2019).

McCormick et al. (2016) reported mean microplastic flow in excess of 1.3 million pieces per day downstream of water treatment plants in nine Illinois rivers and Lechner et al. (2014) described how the flow down the River Danube outnumbered fish larvae, potentially contributing 1,500 tonnes of plastics to the Black Sea per year. In the surface waters of the Rhine, Mani et al. (2015) reported densities of microplastics in excess of 890, 000 particles km^{-2}. While Zhao et al. (2015), from a study of three urban Chinese Estuaries, reported counts of between 100–4100 pieces m^{-3}. These are alarming figures! Indeed, the emerging issues and knowledge gaps in freshwater systems were reviewed by Eerkes-Medrano et al. (2015). This is important as, in many cases, riverine input is a major source of plastics to the marine environment, contributing to a truly colossal global problem. For example, it has been suggested that up to 95% of plastic polluting oceans is supplied by only ten rivers (Schmidt et al., 2017), whereas a modelling study by Lebreton et al. (2017) suggested that the top twenty most polluting rivers, mainly in Asia, contribute just under 70% of the global total amount of riverine plastics, up to an estimated 2.4 million tonnes per year, entering the oceanic environment.

The Thames flows through Southern England, drains the whole of Greater London, is populated by some 15 million people and, from Southend in the estuary to the west of London at Teddington (ca. 80 km), the River is strongly tidal. The River and its estuary is an important ecosystem, supporting many species of marine and freshwater fish at different developmental stages with 125 species being reported. For example, it is a key nursery area for European smelt, *Osmerus eperlanus* and flounder, *Platichthys flesus* (Colclough et al., 2002). In addition, the Thames Tideway is an important habitat for invertebrate species such as the rare depressed river mussel, *Pseudanodonta complanata*, and aquatic mammals such as the grey seal, *Helichoerus grypus*.

Although, in a number of respects, the Thames is far cleaner than it has been for many years (e.g., trace metals; Johnstone et al., 2016), the issue of plastic pollution in the river remains critical. Reports have recently described the occurrence of plastics in the River Thames and interactions with the biota. Sub-surface movements of macroplastic debris in the inner estuary were described by Morritt et al. (2014) and highlighted the high contribution made by food packaging and sanitary products. To date, ingested microplastics have been reported from 9 Thames fish species with up to 75% of European flounder, *Platichthys flesus*, containing plastic fibres (McGoran et al., 2017, 2018). Data from these studies suggest that bottom-feeding fish are more likely to be exposed to microplastics through their feeding activity although pelagic feeders e.g., *O. eperlanus*, have also been found to ingest plastic particles. In the freshwater reaches, microplastics, including high amounts derived from road marking paints, have been recorded in the sediments of some tributaries (Horton et al., 2017) and the presence of mainly fibres, reported in 33% of roach, *Rutilus rutilus* (Horton et al., 2018). Although there is evidence that a variety of Thames fish, with different feeding habits ingesting microplastics, there are currently no reports in the literature for the quantity present in the water column of the River. As such, the main aim of this study was to estimate the microplastic abundance in the River Thames water column, at two sites on the tidal Thames, namely Putney and Greenwich. Here the results are reported of an opportunistic study linked to ongoing research of larval ichthyoplankton in the River Thames by the Zoological Society of London (ZSL). In addition, the occurrence of high concentrations of microplastics (excluding fibres) in the water column are documented at Putney and Greenwich and factors potentially influencing microplastic densities at these two sites are considered.

2. Methods and materials

2.1. Sampling

Water column samples were taken from 2 River Thames sites (Fig. 1): Putney (51°28'09"N 000°13'09"W) and Greenwich (51°28'59"N 000°01'02"W). One survey at Greenwich and one survey at Putney were undertaken each month from June to October during 2017, with up to 20 water column samples collected at each survey day. As this was an opportunistic study, undertaken alongside an already funded ZSL larval fish survey of the Thames, the water column sampling regime was constrained by the needs of the primary study. Consequently, the ability to fully sample the hydrodynamic conditions of the tidal Thames was not possible.

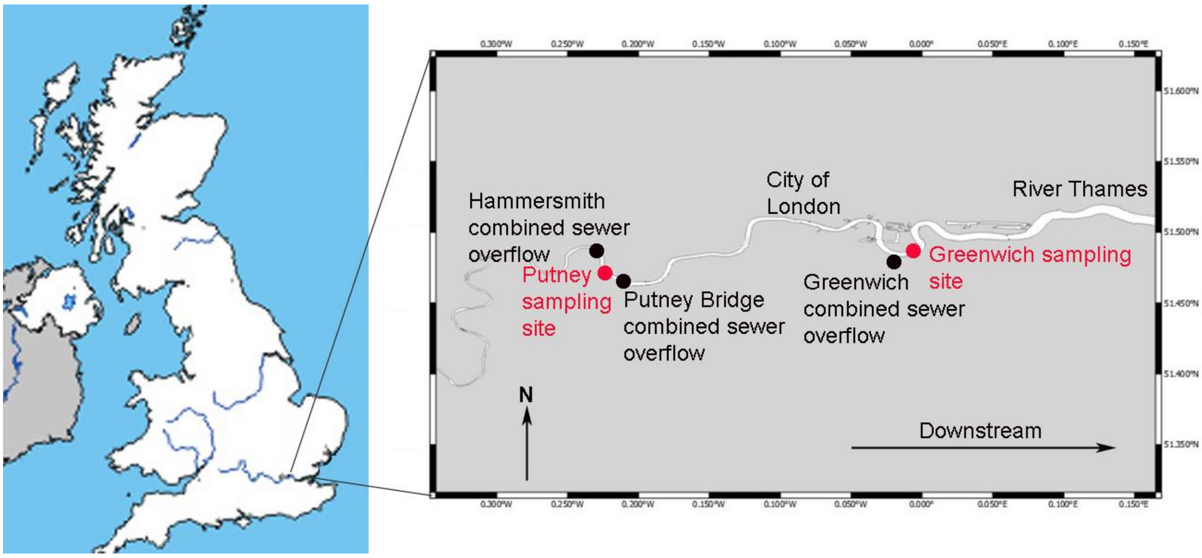


Fig. 1. The locations of the sampling sites at Greenwich (51°28'59"N 000°01'02"W) and Putney (51°28'09"N 000°13'09"W) on the River Thames. Also shown are the combined sewer overflows in the vicinity of the sampling sites.

Samples were collected during the daytime from the ebb and flood tide, within 2 hrs either side of high water, as well as at surface and 2 m depths. A 250 µm mesh ichthyoplankton net narrowing into a cod end, with a 1.5 m total length, and 300 mm × 300 mm square opening maintained by a steel collar and rope cradle, was used to collect each sample. A Hydro-bios 438 110 mechanical flow meter was placed at the net mouth, at the centre of the steel collar. Samples were collected from a stationary boat moored 10–15 m from the shore, where tidal movement allowed water to flow through the net. The net was deployed for 5 mins to collect each water column sample. Initial and end flow rates were recorded. A 4% formalin solution was used to ensure preservation of the larval fish captured. The samples were then stored until processing and subsequent transport to the Natural History Museum (NHM). Given time constraints a total of 69 randomly selected samples, but covering site, month, tide and depth, collected from the River were subsequently analysed for microplastic presence and abundance, 36 from Putney and 33 from

Greenwich. An average of 7 water column samples were used to calculate the mean number of 32 µm–5 mm plastics for each site within each month.

Both sites were located in close proximity to outfalls where raw sewage is known to be released into the catchment during periods of rainfall. There are ca. 23 Combined Sewer Overflows (CSO) discharging into the area of study on the tidal Thames (Thames Water, 2011). Greenwich CSO is located approximately 1.5 km upstream from the sampling site in that area. The Putney site is between 2 CSOs. Hammersmith pumping station is located approximately 2.1 km upstream from the Putney sampling site and is known to release raw sewage into the River Thames at times of rainfall. In fact, rowers release notifications of sewage release regularly for this site (British Rowing, 2018). In addition, half a kilometre downstream from the Putney site, a CSO is located under Putney Bridge. Again, raw sewage was released during periods of precipitation.

2.2. Laboratory Methods

Formalin-preserved samples were processed in the NHM clean room laboratory. Prior to analysis, the formalin was drained off by passing each sample through a 40 µm mesh sieve under a fume hood. The formalin was collected in a container and sealed for disposal. The wet weight to nearest 0.1 g was recorded for each sample.

A 20 cm diameter 1 mm mesh sieve was stacked on top of a 32 µm mesh sieve. Each sample from the Thames was placed on the surface of the 1 mm sieve and cold tap water was run gently over the sample. There were at least 3 intervals where the tap was turned off and forceps were used to remove plastics > 1 mm. To ensure all plastics were removed, the 1 mm sieve was placed under a Leica MZ6 modular stereomicroscope (magnification range of ×6.3 to ×40). The plastic was transferred to a Petri dish which was then sealed and labelled.

Finer organic material and plastics ranging from 32 µm to 1 mm were retained on the 32 µm mesh sieves surface. A wet weight was obtained to the nearest 0.1 g for all the material and plastics left on the 32 µm sieves surface. A subsample of 1 g was taken from the 32 µm sieve surface and placed in a 50 ml Falcon tube. Digestion in 40 ml of 40% KOH solution was used to remove organic matter from the 1g subsample obtained from the 32 µm sieves surface (adapted from Cole et al., 2014).

A batch of 4–6 samples was placed into a 40° C oven for 24 hrs to allow sufficient digestion of organic matter to take place. From previous trials, conducted during the method development stage, it was estimated that an average of 57.2% of the organic matter within each water column sample was lost during the digestion process when using the KOH solution. Digestion of over half of the organic matter present in the 1 g subsample allowed for easier observation of microplastics present when viewed under a dissection microscope.

Following digestion, samples were poured through circular Whatman Qualitative 125 mm diameter filter papers, able to retain particles >11 µm. All 32 µm to 1 mm plastics within the 1 g subsample were identified and classified under a stereomicroscope. Microplastics were identified and quantified within the 1 g subsample. By multiplying up the number of microplastics found within the 1 g subsample, to that of the equivalent in the original whole sample mass obtained, the total microplastics load in the sample was estimated.

Microplastics found in the water column samples were quantified and categorised by colour, shape, form and size. Two plastic size ranges were considered, namely those of 32 µm–1 mm and 1–5 mm. Microfibres were seen within all water column samples, and these were not quantified or analysed for this study due to the sampling methods used and subsequent risk of contamination. Microfibre colours were, however, recorded for each sample (See supplementary material, Table A). Given the substantial amount of organic matter within water column samples, microplastics smaller than 250 µm in diameter were expected to be trapped during the sampling process by debris such as leaves etc. Therefore, the size range studied for microplastics within samples was 32 µm–5 mm in diameter. The forms used to classify plastics were films, fragments, microbeads, glitter, nurdles and cylindrical plastics. Table 1 shows, with photographic examples, how the plastic forms were categorised. Most of the plastic forms as shown in Table 1 were classified by visual characteristics alone. Nurdles however, were often picked up and checked for hardness during the classification process.

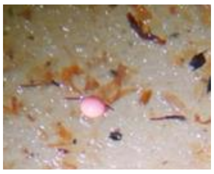
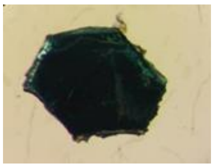
2.3. Procedural controls for airborne contamination

The NHM clean laboratory was used for the isolation and identification of microplastics from water column samples. To prevent samples being contaminated by other microplastics, as well as airborne particles such as textile fibres, the following precautions were taken. The laboratory ceiling and air vents were sealed to prevent potential atmospheric fallout contamination. No fleeces or glitter make-up were allowed in the laboratory. The door entrance to the clean room laboratory was covered with cotton curtain to prevent potential atmospheric fallout contamination when entering and leaving the room. The water outlet in the clean room was covered with a 40 µm mesh to remove contamination from microplastics present in the tap water. Latex gloves were worn at all times when handling samples. Once isolated, plastics were placed in Petri dishes and these were sealed with Parafilm®. Cotton clothing was worn underneath pure cotton laboratory coats during both the isolation and identification procedures in the clean room as well as during Fourier Transform Infrared Spectroscopy (FTIR) analyses in a separate NHM laboratory.

Throughout the plastic isolation and identification processes, a Petri dish containing a filter paper dampened with filtered water was placed at the working space within the clean room, either next to the sink or microscope, to record any potential sample contamination. Upon completion of the laboratory work, these Petri dishes were examined under a dissection microscope and only clear microfibres were found on the filter papers, which were potentially cotton or synthetic. This contamination had no effect on further analysis or results as microfibres were not considered in the present study.

Table 1

Description of different plastic forms encountered during this study.

Plastic Form	Characteristics	Image
Films	A 2-dimensional structure often irregular or rectangular shape.	
Fragments	A 3-dimensional structure that was not spherical or cylindrical, often irregular in shape.	
Microbeads	A regular spherical shape. Often blue, pink or green in colour.	
Glitter	Plastics with a hexagonal shape that reflected light.	
Nurdles	Rounded hard and compressed plastic.	
Cylindrical Plastics	Cylindrical shape with a filled or hollow centre.	

2.4. Estimating plastic density

To calculate plastic density in the River Thames, the number of items, ranging from 32 um–5 mm, within each water column sample were counted. The flow meter readings were used to calculate the volume of water filtered in each sample by applying the following formula:-

Volume of water (m^3) = **calculated flow** (number of revolutions/turns of the flow metre) × **rotor constant** (0.3) × **opening area (m^2) of the sampling net** (0.09)

The number of microplastics found within a standardised volume for each sample was used to calculate density. Plastics were subsequently estimated as plastics m^{-3} of water for each sample.

To estimate the average microplastic flow down the River Thames from June to October 2017 at Putney and Greenwich sites per second, discharge estimates for the River Thames (m^3 /s) were obtained from the Port of London Authority (A. Mortley, PLA, pers. comm.). Graphical models showing the River Thames discharge (m^3 /s) after high water tides at Lambeth Reach and Erith Reach were used to calculate overall microplastic abundance for Greenwich and Putney respectively. At Lambeth Reach, on peak ebb tides shortly after high water, the River Thames discharge rate was estimated at 1400 m^3 /s (A. Mortley, PLA, pers. comm.). At Erith Reach, on peak ebb tides shortly after high water, the River Thames discharge rate was estimated at 5000 m^3 /s (A. Mortley, PLA, pers. comm.). The average number of microplastics on the ebb tide from June to October 2017 at Putney and Greenwich sites was subsequently used to calculate the number of microplastics that flowed down the River Thames per second on peak ebb tides, from June to October during 2017. Total microplastic abundance estimates for the River Thames are exclusive of microfibres.

Microplastics / second in the River Thames at Putney = (microplastics m^{-3}) × 1400

Microplastics / second in the River Thames at Greenwich = (microplastics m^{-3}) × 5000

The calculated total number of plastics flowing down the Thames at Putney and Greenwich sites should be regarded as rough estimates and viewed with some degree of caution. The exclusion of microfibres from this study should also be noted when considering total microplastic abundance estimates for the River Thames.

2.5. Fourier transform infrared spectroscopy

FTIR analysis was conducted in order to identify the plastic polymers found in the River Thames samples. Due to the high concentration of plastic particles present, only a small fraction was investigated. Seventy-one plastic particles were analysed using FTIR. Plastic types (Table 1) from both sites, across all months, tides and depths, were randomly selected in approximate proportion to their overall abundance for polymer identification. A minimum spectral library match of 70% or more to a material in the Euclidean search hit list was accepted. A minimal spectral library match of 70% is an accepted level for microplastic polymer identification (Lusher et al., 2017). Eight of the 71 plastics analysed using FTIR did not reach the minimum spectral library match for polymer confirmation, so were not included in the results.

2.5.1. FTIR attenuated total reflection (ATR) spectroscopy

FTIR ATR spectroscopy was employed for 63 plastics that were 0.5–5 mm in diameter. For the FTIR ATR spectroscopy, a Perkin Elmer Spectrum One spectrometer was used with a Quest ATR accessory attached, Specac Ltd. Plastic samples were scanned 10 times in the range between 4000 cm^{-1} and 450 cm^{-1} and with resolution 4 cm^{-1}. A list of spectral libraries used is provided in a supplementary materials section (Table B)

2.5.2. FTIR micro spectroscopy

For 8 primary microplastics ranging from 32 µm–0.5 mm, FTIR microscopic analyses were performed on a Perkin Elmer Spectrum One spectrophotometer, with an AutoIMAGE microscope attached. FTIR analyses were performed on primary microplastics such as glitter, to better study the layers within these particles. Samples were pressed before being placed under the microscope and background scans were conducted before each scan. Plastics were scanned on a single diamond window (part of the DC-3 Diamond Compression Cell, Specac Ltd), where each sample was scanned

30 times in 3 different positions. The range between 4000 cm^{-1} and 700 cm^{-1}, at resolution 4 cm^{-1} was used for each sample.

2.6. Statistical analysis

IBM SPSS Statistics 21 software for Windows was used to analyse the results. Microplastic density data (plastics m^{-3}) were log transformed, and a univariate General Linear Model (GLM) identified whether site, tide, depth or month independently, or their combined interactions, had an effect on these microplastic density data. The number of 32 µm–5 mm plastics reported within all 69 samples were found to be non-normally distributed (Shapiro-Wilk = 0.785, d.f. = 69, $p < 0.001$). Therefore, these data were log-transformed to meet the precondition of normality for univariate GLM analysis (S-W = 0.984, d.f. = 69, $p = 0.515$). Fishers Least Significant Difference (LSD) tests were employed for pairwise *post hoc* comparisons of microplastic density for the 5 different months.

Mann Whitney U tests were employed to compare microplastic densities between sites for each month.

3. Results

Microplastics ranging from 32 µm–5 mm in diameter were found in all River Thames water column samples (N = 69). On average, 24.8 microplastics m^{-3} were found at Putney and 14.2 microplastics m^{-3} were recorded at Greenwich. Secondary microplastics, namely those of the film and fragment forms, contributed 93.5% of all microplastics found at Putney and Greenwich.

Across all months, microplastic density was found to be greater at Putney than Greenwich (Fig. 2). The greatest microplastic density was seen during the month of July at Putney, where on average, 36.7 microplastics ± 7.8 microplastics m^{-3}, were found during these surveys.

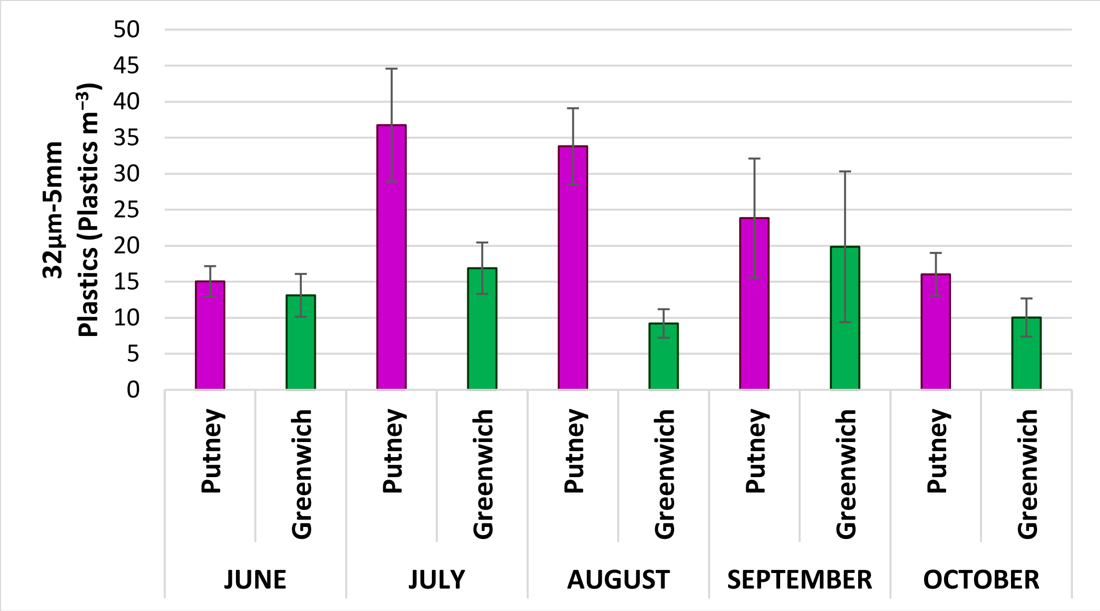


Fig. 2. The mean number of 32 µm–5 mm plastics (± standard error) estimated for each water column sample collected from the River Thames from June to October during 2017.

The interaction of Month*Site was found to have a significant influence on microplastic density ($F_{4,44}$ = 8.510, p < 0.001). There was a statistically significant greater density of microplastics at Putney, when compared to Greenwich during July (Mann-Whitney U =7, p = 0.026) and August (Mann-Whitney U =0.000, p = 0.003).

Secondary microplastics, namely films and fragments, consistently made up the majority of microplastics found at Putney and Greenwich sites (Fig. 3).

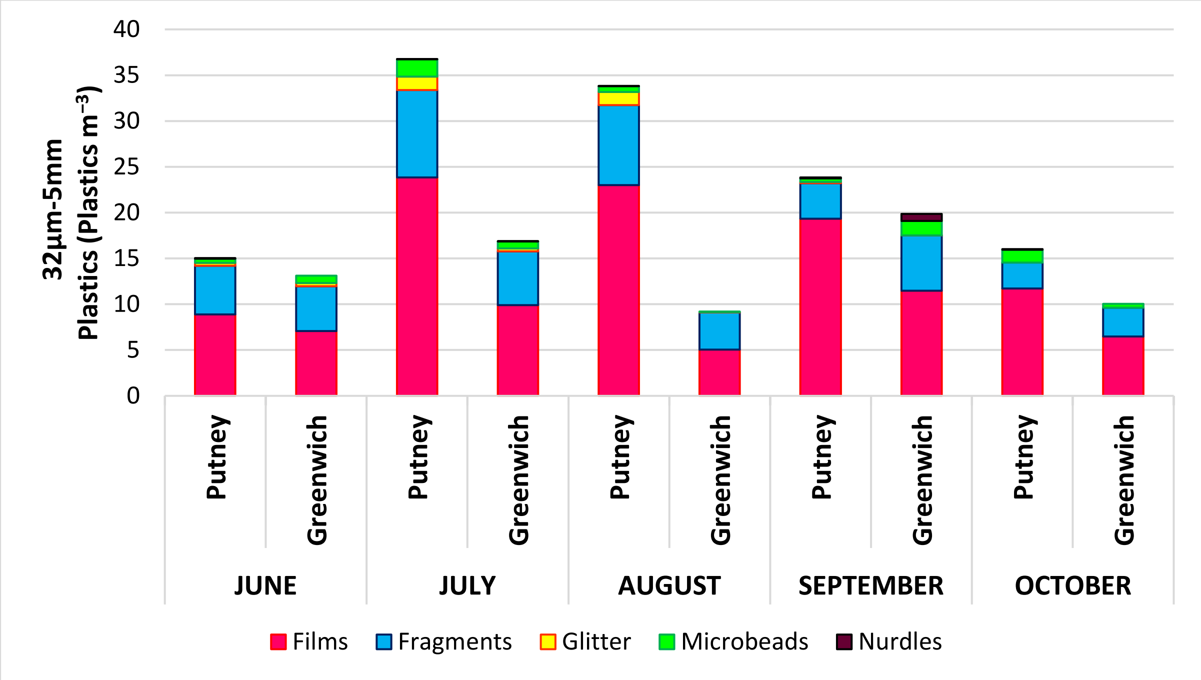


Fig. 3. The estimated mean number of 32 µm–5 mm microplastic forms at Greenwich and Putney from June to October 2017.

3.1. Univariate analysis

With Log10 [plastics m^{-3}] as the dependent variable, results from the GLM are shown in Table 2. Site, tide, depth and month were fixed factors for this analysis. In a step wise fashion, non-significant interaction values with a *p* value > 0.15 were removed from the univariate GLM, thus leaving only the significant interactions affecting microplastic density. Thus, in Table 2, only factors and interaction terms that were significant are presented. Effect size was estimated by calculating eta squared (η^2).

Table 2

Results from univariate general linear model analysis using sampling site, depth, tide and month as dependent variables. Microplastic density served as the dependent variable, defined as Log10 [plastics m^{-3}].

Factor	*d.f.*	*F*	*p*	η^2
Month	4	6.602	0.000	0.375
Site	1	16.504	0.000	0.273
Depth	1	4.397	0.042	0.091
Tide	1	14.818	0.000	0.252
Month * Site	4	8.510	0.000	0.436
Month * Depth	4	3.305	0.019	0.231
Site * Tide	1	11.411	0.002	0.206
Month * Site * Tide	8	2.332	0.035	0.298
Error	44			
Total	69			

The final model for analysing factors that influenced microplastic density (N = 69), included significant contributions from all four independent factors; Month ($F_{4,44}$ = 6.602, p < 0.001), Site ($F_{1,44}$ = 16.504, p < 0.001), Tide ($F_{1,44}$ = 14.818, p < 0.001) and Depth ($F_{1,44}$ = 4.397, p = 0.042), as well as significant contributions from several interactions; Month*Site ($F_{4,44}$ = 8.510, p < 0.001), Month*Depth ($F_{4,44}$ = 3.305, p = 0.019), Site*Tide ($F_{1,44}$ = 11.411, p = 0.002) and Month*Site*Tide ($F_{8,44}$ = 2.332, p = 0.035).

3.2. Independent factors affecting microplastic density

Month was shown to have a significant effect on microplastic density ($F_{4, 44}$ = 6.66.2, p < 0.001), where Fishers LSD *post hoc* analysis found a significantly lower microplastic density in

June (14.3 ± 6.1, (mean ± S.D.) plastics m^{-3}, $p = 0.015$), September (21.7 ± 25.4 plastics m^{-3}, $p = 0.012$) and October (12.8 ± 8.0 plastics m^{-3}, $p < 0.001$), when compared to microplastic density found during July (26.8 ± 18.6 plastics m^{-3}). A statistically lower microplastic density was also found during October (12.8 ± 8.0 plastics m^{-3}, $p = 0.005$), when compared to the density during August (23.6 ± 16.6 plastics m^{-3}). With regards site, Putney (24.8 ± 17.0 plastics m^{-3}) had a significantly higher density of microplastics than Greenwich (14.2 ± 15.7 plastics m^{-3}). Although depth was shown to have a significant influence on microplastic density ($F_{1, 44} = 4.397$, $p = 0.042$), with more being found at a 2 m depth the effect size was small ($\eta^2 = 0.091$). Tide was shown to significantly affect the number of microplastics, where overall, more were found on the ebb tide when compared to the flood tide. From the four independent factors, month was found to have the greatest effect size ($\eta^2 = 0.375$).

3.3. Combined factors affecting microplastic density

The interaction of Month*Site (Figure 2) was found to have the most significant influence on microplastic density ($F_{4,44} = 8.510$, $p < 0.001$), from all independent factors and combined factors presented in the GLM (Table 2). The interactions of Site*Tide ($F_{1,44} = 11.411$, $p = 0.002$) and Month*Site*Tide ($F_{8,44} = 2.332$, $p = 0.035$; Fig. 4) also had a significant effect on microplastic density.

For all months during 2017, at Greenwich, more microplastics were found on the ebb tide when compared to the flood tide (Fig. 4). This was also the situation at Putney, for July, August and October. This trend however, was reversed during the months of June and September, where there was a greater density of microplastics on the flood tide at Putney.

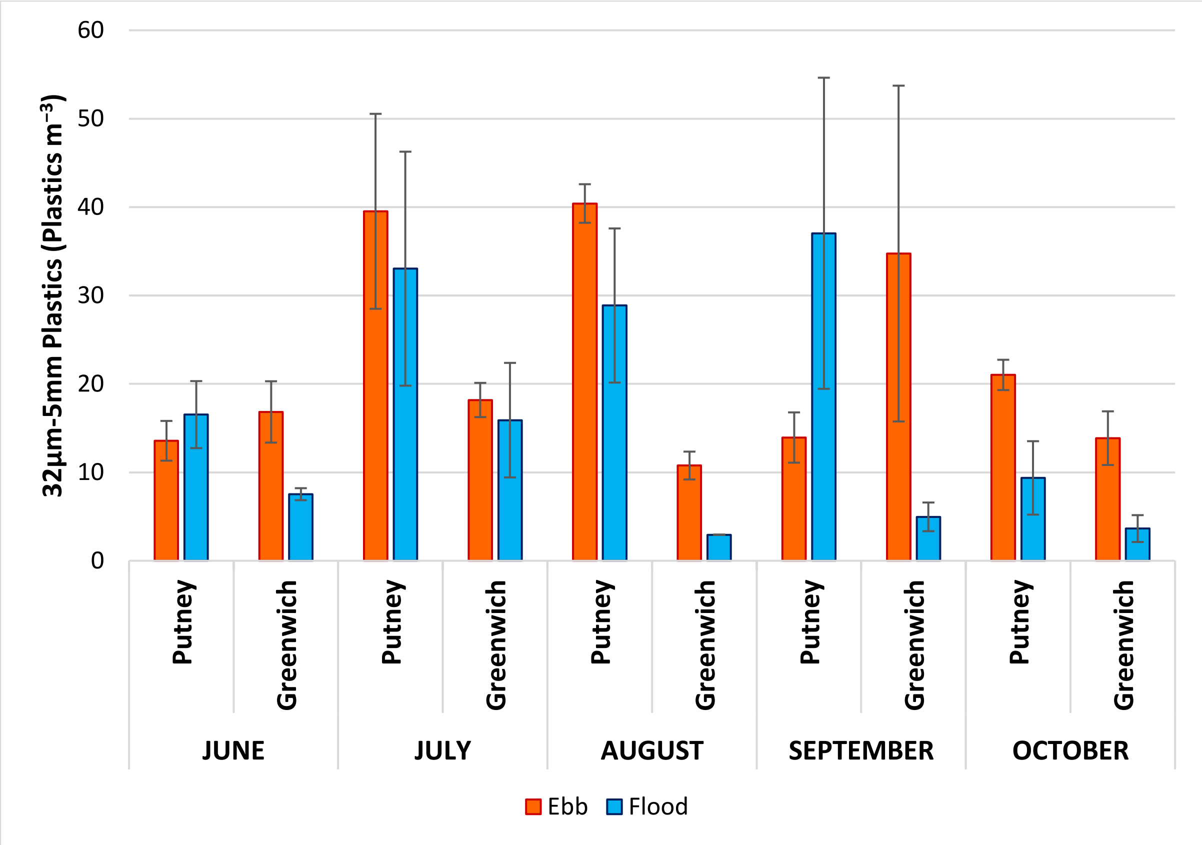


Fig. 4. A bar chart to show the mean number of 32 µm–5 mm microplastics m^{-3} on the ebb and flood tide at Putney and Greenwich, for each month of sampling during 2017. In total, 36 water column samples were analysed from the Putney and 33 from the Greenwich. Bars illustrate mean number of microplastics ± standard error.

The interaction of Month*Depth was found to significantly affect microplastic density ($F_{4,44}$ = 3.305, p = 0.019). This suggests that the depth of sample collection may affect microplastic density. When depth was combined with the factors of month and site (Month*Site*Depth), no statistically significant effect on microplastic density was found, this interaction therefore not included in Table 2.

3.4. The effect of CSOs on microplastic density

Figure 5 shows the relationship between sewage discharged from the Hammersmith pumping station CSO, and the overall microplastic density (plastics m^{-3}) found in the water column at Putney.

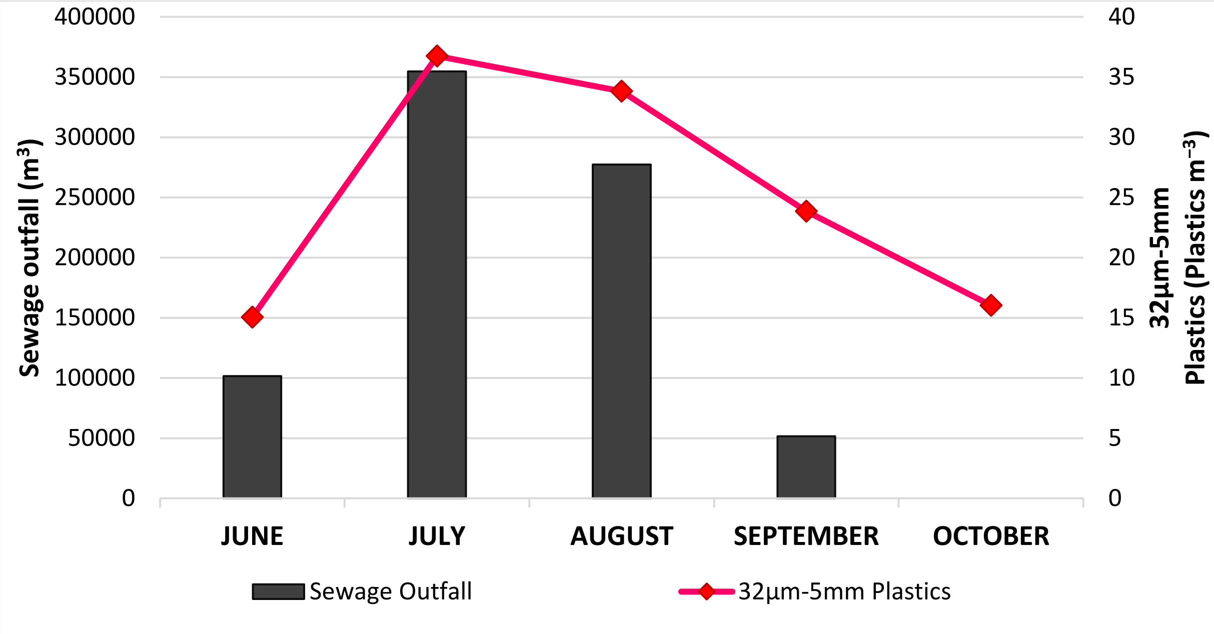


Fig. 5. The relationship between the sewage discharged (cubic metres) into the water column from the Hammersmith pumping station CSO from June to October 2017, and the mean number of 32 µm–5 mm microplastics found in the water column at Putney. (Thames Water data).

Microplastic density in the water column at Putney appears to be linked to sewage discharged from Hammersmith pumping station for all months of sampling during 2017 (Figure 5).

3.5. *Total plastic abundance calculated for the River Thames*

On peak ebb tides just after high water, there are approximately 35 thousand microplastics per second being discharged downstream at Putney, and 94 thousand microplastics being discharged downstream at Greenwich. It is important to note that, due to the tidal nature of the Thames, this rate is largely comparable on the flood tide. The total estimates of microplastic abundance on peak ebb tides at each site are shown in Table 3.

Table 3

An estimation of the average number of microplastics (32 µm–5 mm), excluding microfibres, that flow down the River Thames at Greenwich and Putney each second. Estimates of two primary microplastics, (glitter and microbeads), secondary microplastics (films and fragments), and the overall total number of microplastics estimated to flow down the Thames are included. Note: total includes less frequently recorded microplastics, e.g., nurdles.

Site	Microbeads/sec	Glitter particles/sec	Films and Fragments/s	Microplastic total / sec
Greenwich	**5041**	**523**	**86.6 K**	**94 K**
Putney	**1738**	**1403**	**31.6 K**	**35 K**

The majority of plastics found in the River Thames water column were secondary microplastics, films and fragments. During peak ebb tides, at Greenwich, secondary microplastics contribute to an estimated 92% of all microplastics, while at Putney this was estimated to be 90%.

At both sites, glitter was estimated in a lower abundance in the River when compared to microbead abundance. Greenwich was found to have a greater abundance of microbeads, in comparison to Putney (Table 3).

3.6. Plastic analysis

Figure 6 shows material composition found as a percentage for each plastic form. Polypropylene and polyethylene were the most frequent polymers found in the River Thames at Putney and Greenwich.

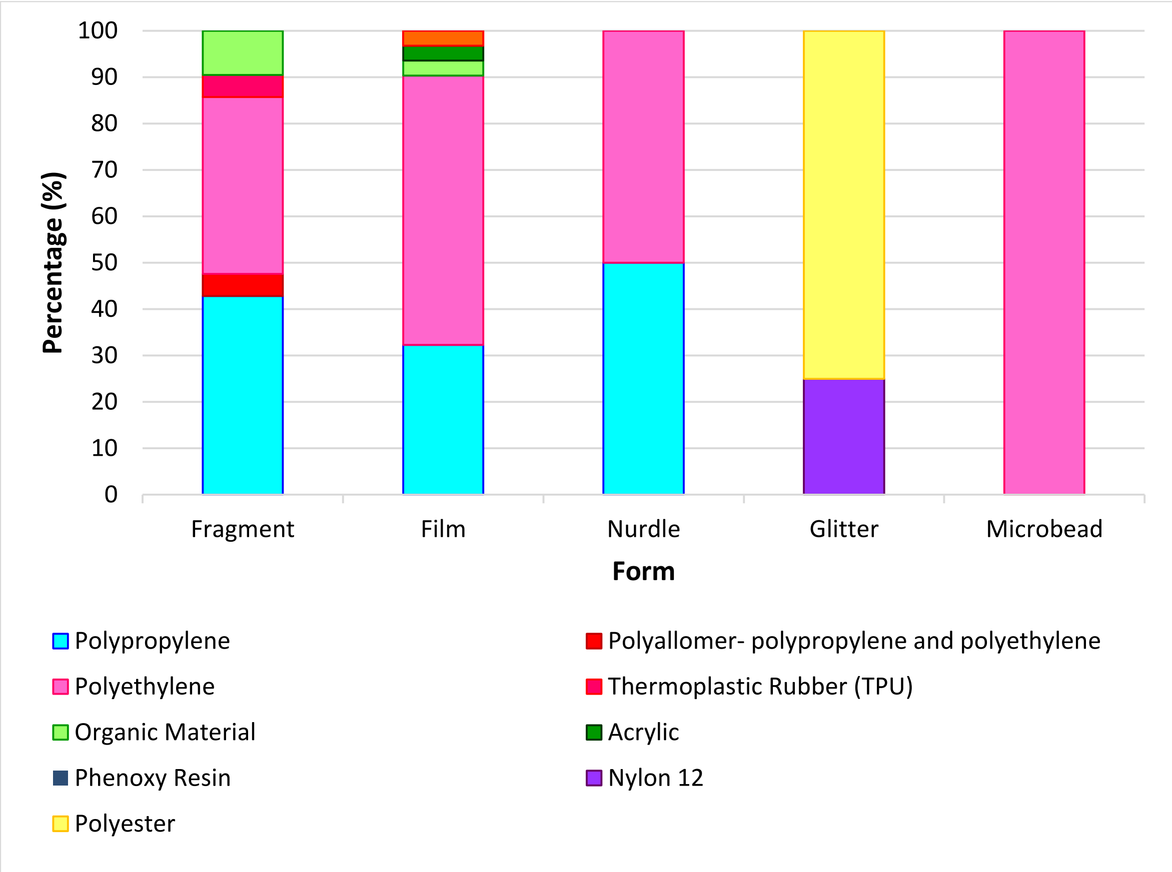


Fig. 6. A stacked bar chart showing the percentage material composition for each form. Polymer forms were identified using FTIR at a 70% minimum spectral library match. Sixty-three samples were analysed; 21 fragments, 31 films, 2 nurdles, 4 glitter particles and 5 microbeads.

Polyethylene is inclusive of low, medium and high densities of this material. Films and fragments were shown to have the most diversity in material composition. These secondary microplastics were largely composed of polypropylene and polyethylene, where 42.9% of fragments and 32.3% of films were made of polypropylene, and 38.1% of fragments and 58.1% of films were made of polyethylene. Low density polyethylene was found to be the most abundant polyethylene form, where 28.6% of all fragments and 29.0% of all films analysed were formed of this material density. Reinforced polypropylene was the most abundant polypropylene form for fragments

(38.1%). Few forms analysed were found to be non-polymers (9.5% of fragments and 3.2% of films). Nurdles were made of varying polyethylene densities (50%) and polypropylene (50%). Microbeads were made of high or low density polyethylene. From the glitter particles analysed, 80% were made of polyester.

4. Discussion

4.1. Microplastic density *and composition in the water column*

Whist methodologies vary between studies worldwide (Bruge et al., 2019; Eerkes-Medrano et al., 2015; Fok et al., 2020), the microplastic densities described here were high, bearing in mind that fibres were excluded. High densities of microplastics ranging from 32 µm–5 mm were found in all Thames water column samples. In total, it is estimated that, per second, 94 thousand microplastics at Greenwich and 35 thousand at Putney flow down the River Thames during peak ebb tides. It is important to note that, due to the tidal nature of the Thames, this rate is largely comparable on the flood tide. The net effect may be the concentration of high densities of microplastics in the Thames water column, some of which will ultimately find their way seawards. This may, in part, explain why such high densities are recorded in the Thames. Although a greater number of plastics per cubic metre was found at Putney when compared to Greenwich, due to the higher water flow rates at the latter, the overall plastic load per second is higher at this downstream site. It is also worth noting that, being further downstream, the River is much wider at Greenwich and has a much greater cross-sectional area when compared to that of Putney.

Putney was found to have an average of 24.8 plastics m^{-3}, in comparison to Greenwich where microplastic density was significantly less at 14.2 plastics m^{-3}. This microplastic density range is comparable to that found in freshwater environments worldwide. For example, microplastic density in the River Thames water column (Putney and Greenwich average of 19.5 plastics m^{-3}), is greater than microplastic densities estimated for surface waters from the River Rhine, Germany

(1.85–4.92 plastics m^{-3}), the River Danube, Romania (10.6 plastics m^{-3}), the River Dalälven, Sweden (4.54 plastics m^{-3}) the River Po, Italy (14.6 plastics m^{-3}; Van der Wal et al., 2015) and the River Chicago, U.S.A. (up to 18 plastics m^{-3}; McCormick et al., 2014). Importantly all these studies include microfibres in the estimates. Microplastic densities in the surface waters of streams around the City of Auckland, New Zealand (17–303 plastics m^{-3}; Dikareva and Simon, 2019) and surface water of the Yangtze River, China (4,137 plastics m^{-3}; Zhao et al., 2014) are greater than the microplastic densities estimated for the River Thames water column in the current study. Both of these studies, however, also included microfibres. These were found to comprise 34% of all plastics on average in Auckland streams (Dikareva and Simon, 2019) and 79% of all microplastics in the Yangtze Estuary (Zhao et al., 2014). With microfibre abundance being excluded in the present study of the Thames, the likely underestimate of overall microplastic abundance in the River is worth noting.

Secondary microplastics, namely films and fragments, were the most abundant plastic types found in the water column, comprising 93.5% of all microplastics found at both Thames sites. These results are in line with other studies, where the most abundant plastic types in freshwater environments were secondary microplastics. For example, a study of Auckland streams, reported that fragments and fibres respectively comprised 39% and 34% of all microplastics in surface water (Dikareva and Simon, 2019). From a study of Lake Hovsgol, Mongolia, fragments, films, and fibres were the most abundant types of pelagic microplastic pollution (Free et al., 2014) and in work of European rivers, fragmented particles were the most prevalent microplastics in the water columns of the River Po and Rhine (Van der Wal et al., 2015).

The most abundant plastic forms, films and fragments, are thought to be most likely derived from the fragmentation of plastic packaging, such as bottles, food wrappers and bags (Morritt et al., 2014), which would not be surprising given the high density of human activity along the River Thames (Free et al., 2014; Yan et al., 2019). The hypothesis that films and fragments are largely derived from packaging was supported by FTIR analysis, where polypropylene was found to comprise 42.86% of fragments and 32.26% of films, and polyethylene was found to comprise 38.10% of fragments and 58.06% of films. Polypropylene and polyethylene are two of the main non-fibre plastics produced worldwide (Geyer et al., 2017), used as packaging materials because of their low cost and good mechanical performance (Siracusa et al., 2008). Further evidence that packaging is likely to be a major source of secondary microplastics in the River Thames is provided by observations of the mesoplastics within samples. Mesoplastics were frequently seen to have writing on their surface, often the labelling of a food or drink product. Some secondary microplastics found in the samples appeared to be partially coated in a coloured surface layer, potentially from the paint on cars or boats. This indicated that degradation of these plastic particles had occurred, and that these fragments had the potential to breakdown further, producing more secondary micro and nano plastics (Horton et al., 2017).

With a significant source of secondary microplastics, films and fragments, thought to originate from packaging, it is doubted that runoff from land containing degraded litter is the only route of transfer for these plastics to enter the water column. Combined sewage overflows are a likely additional route of transfer for these secondary microplastics. It has also been suggested that landfill erosion may be contributing to the input of plastic waste into the Thames. Landfill erosion has already been observed at East Tilbury, Thames Estuary, causing the physical mobilisation of waste, inclusive of metal, asbestos and plastic (Brand et al., 2018). The fragmentation of plastics from these landfill sites is potentially an additional pathway of entry for secondary microplastics, films and fragments, into the Thames. Although microfibres were not quantified in this study, they were found to be present within all water column samples collected. Microfibres were often in a high abundance, where during the sieving process for microplastic isolation they were often seen in mats and clumps on the sieves surface. Microfibre dominance among collected microplastics is consistent with previous studies (Gallagher et al., 2016; Lahens et al., 2018; Jiang et al., 2019; Zhao et al., 2019).

From the present study it is estimated that 5041 microbeads flow down the River Thames at Greenwich per second on peak ebb tides, and 1738 per second on peak ebb tides at Putney (Table 3). Microbeads, likely to come from exfoliants in cosmetic products (Fendall and Sewell, 2009), are thought to enter the River Thames via CSOs (Thames Water, 2011), whereby untreated sewage containing micro and macroplastic waste is released to relieve drainage systems during high flow conditions (Horton and Dixon, 2018).

Combined Sewage Overflows were in close proximity to the sampling sites at Greenwich and Putney (Fig. 1). FTIR analysis found all microbeads analysed to be made of either high or low density polyethylene. Polyethylene is estimated to comprise 93% of all microbeads used in cosmetic products in Europe (Gouin et al., 2015). Glitter, a primary microplastic, is also expected to enter the water column via sewage effluent. At Greenwich, 523 glitter particles were estimated to flow down the Thames per second on peak ebb tides, and at Putney, 1403 glitter particles per second on peak ebb tides. In the literature, glitter is an incredibly understudied microplastic form, where there is no published data regarding its quantity in marine or freshwater environments. The estimates presented here may therefore be the first of glitter abundance in the freshwater environment. Most glitter is made of metalized polyethylene terephthalate (Yurtsever, 2019), however, in this study FTIR analysis found 80% of glitter particles to be made of polyester, and 20% Nylon 12. Similar small particle haberdashery products, such as beads and sequins, are also known to be formed mostly from plastic polymers such as Polyethylene terephthalate, Nylon and polyester (Yurtsever, 2019). Regarding composition, glitter is a complex microplastic composed of layered polymers as well as metallised (aluminium) film (Tagg and Sul, 2019). It has been suggested that the previous omission of glitter in microplastic studies may be due to a lack of understanding regarding its composition (Tagg and Sul, 2019). In the present study, microplastic particles which had a reflective surface and a hexagonal shape were defined as glitter. A set definition of glitter was used in this study due to small fragments of reflective organic material being present in water column samples. These reflective organic particles have the potential to be mistaken for glitter particles. The calculated values for glitter abundance may therefore be an underestimate due to the current methods of classification. Nano-glitter, commonly manufactured from polyethylene, is used by the cosmetic industry for makeup (Bakir et al., 2015). To gain a better idea of glitter abundance in the future, a size range inclusive of nano plastics (1 to 1000 nm) should be considered.

4.2. Factors affecting microplastic density

Across all months from June to October 2017, more microplastics were found at Putney when compared to that of Greenwich (Figure 2). This greater density of microplastics at Putney may be due to this sampling site being located between two CSO's. Sewage treatment works are a crucial link for microplastic transport and distribution, given that plastic particles such as glitter, microbeads and microfibres will enter these water treatment works (Horton et al., 2017). The greater microplastic densities at Putney across all months, when compared to Greenwich, was found to be statistically significant during July and August. This also corresponded to the greatest volumes of sewage discharged into the Thames from the Putney CSO pumping station (Figure 5). This appears to suggest that CSO release into the Thames may have a significant impact on microplastic abundance. Furthermore, this high volume of sewage discharged into the Thames at Putney may have caused the significant differences in microplastic abundance between the two sites. The apparent link between the volume of sewage discharged into the water column at the Hammersmith Pumping Station CSO and the overall microplastic density (plastics m^{-3}) in the water column at Putney, suggests that sewer input does affect the density of microplastic waste in the Thames. Plastic waste from sewer input is known to affect the abundance of plastic waste in the River Thames specifically, where a previous study found over 20% of the total rubbish items collected to be components of sanitary products (Morritt et al., 2014). Although CSO release may affect microplastic abundance there are clearly other sources by which microplastics are entering the Thames, unsurprising when samples were dominated by secondary microplastics, with broken down food packaging thought to be a significant source. Urban intensity (Yonkos et al., 2014; Fan et al., 2019; Luo et al., 2019) and riverside litter deposition (Rech et al., 2015) are reported to increase microplastic pollution in the environment. These factors were expected to contribute to the microplastic contamination in the water column at both sites, however, were not considered to greatly influence variation in microplastic abundance between sites, where Putney and Greenwich are both heavily urbanised areas with high population densities. Sewage outfalls were expected to have the greatest influence on microplastic abundance variation found in the water column between sites.

Surface run off from riversides during rainfall events has been suggested to increase microplastic abundance in freshwater environments (Zhao et al., 2014; Cheung et al., 2019). The greatest glitter particle abundance at Putney was found during July 2017, with this time having the greatest rainfall of the months covered by the sampling period (Met Office, 2017). Additionally, the water column samples collected from the Thames at Putney in July 2017 were collected on the 14th of July, 5 days after the Pride Festival took place in London (Pride Festival, 8–9 July 2017). It maybe that, combined with the increase in monthly rainfall, the Pride Festival and other summer events may have contributed to the increase in glitter abundance in the River Thames. During these celebrations, glitter is often worn in the forms of body paints and cosmetics. Due to the small size of glitter particles, dermal oils, or simply static force, this product adheres to the skin, often necessitating the rinsing of the product with water for removal (Tagg and Do Sul, 2019). This direct pathway to sewage treatment plants could therefore also explain a potential increase in glitter abundance in the water column of the Thames shortly after London festivals.

Site and tidal state were shown to have significant effects on microplastic density. A greater microplastic density was found on the ebb tide at Greenwich for all months during 2017, this trend was also reported at Putney, however, reversed for the months of June and September where a greater microplastic density was found on the flood tide. Again, at Putney, this trend may be due to two CSOs being in close proximity to the sampling site, where the episodic release of sewage may have caused this trend reversal. It has been suggested that estuarine environments may show a reduced microplastic abundance on the flood tide due to the addition of sea water during tidal exchange. This water contains lower levels of urban contaminants (Sutton et al., 2016). It is interesting, therefore, that this trend was seen at the downstream Greenwich site, where fewer microplastics were found on the flood tide in comparison to the ebb tide for all months (June to October 2017). Microplastics have also been reported in lower abundance on the ebb tide, perhaps due to particles returning with the incoming tides (Figueiredo and Vianna, 2018), and complex circulatory patterns (Sadri and Thompson, 2014), however, this is only likely near the mouth of an estuary (Wolanski, 2015).

Depth was not considered to significantly influence microplastic density in this study, with surface mixing thought to be responsible for this result. Surface mixing has been shown to occur at a greater depth than the 2 m range used in this study, where mixing was expected to cause no significance in microplastic density profiles at surface and 5m depths (Lattin et al., 2004). Additionally, the Thames is a busy water way and river traffic at times of sampling may have disrupted the surface layers of water, causing depth to not show a significant influence on microplastic density.

4.3. Impacts of microplastic pollution in the River Thames

Focussing on London, tap water is largely supplied by Thames Water, where 70% of this supplied water is collected from reservoirs upstream from the River Thames (Tap Water, 2019). In this study, where a combined average of both sites sampled, found an average of 19.85 microplastics per cubic metre of water in the River Thames, it is unsurprising that microplastics have been found in over 80% of tap water in London (Tap Water, 2019). Further research is needed to assess the likely transfer of microplastics in the food chain and its impacts on human health.

This study provides baseline data for microplastic contamination in the River Thames water column. In comparison to published estimates of microplastic contamination in marine and freshwater environments, the River Thames is shown to be a major source of this pollutant. With the potential threats of plastic pollution to both human and ecosystem health, it is of great importance that the input of plastic into marine and freshwater environments is reduced. In London, there are already schemes such as the *#OneLess* campaign led by ZSL and partners in the Marine Collaboration, aiming to reduce single use plastic water bottles in London. Similarly Thames21 supports regular cleaning of the Thames foreshore, and the PLA operates passive driftwood collectors, removing more than 400 tonnes of floating rubbish from the River Thames each year (Port of London Authority, 2019) as well as launching the *Cleaner Thames* campaign in 2015 (Port of London Authority Cleaner Thames Campaign, 2019). Additionally, the Thames Tideway Tunnel is currently under construction, this multibillion-pound project aiming to improve water quality and reduce sewage overflows into the River Thames (Thames Water, 2011; Tideway London, 2019). The data presented here clearly demonstrate that such developments cannot come too soon!

5. Conclusion

This study suggests that the River Thames is a significant source of microplastics, specifically secondary microplastics. Polyethylene and polypropylene were the most common polymers in the microplastic samples from the River, suggesting broken down packaging may be the primary cause of this pollution in the Thames. Combined sewer outfalls may be significant contributors of microplastic pollution into the River. The results from this present study highlight the severity of microplastic contamination in the River Thames, and the need for the reduction of plastic input to the freshwater environment.

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Figure legends

Fig. 1. The locations of the sampling sites at Greenwich (51°28'59"N 000°01'02"W) and Putney (51°28'09"N 000°13'09"W) on the River Thames. Also shown are the combined sewer overflows in the vicinity of the sampling sites.

Fig. 2. The mean number of 32 µm–5 mm plastics (± standard error) estimated for each water column sample collected from the River Thames from June to October during 2017.

Fig. 3. The estimated mean number of 32 µm–5 mm microplastic forms at Greenwich and Putney from June to October 2017.

Fig. 4. A bar chart showing the mean number of 32 µm–5 mm microplastics m^{-3} on the ebb and flood tide at Putney and Greenwich, for each month of sampling during 2017. In total, 36 water column samples were analysed from the Putney and 33 from the Greenwich. An average of 3 water column samples was used to calculate the mean number of 32 µm–5 mm plastics m^{-3} on the ebb and flood tide, at each site within each month. Bars illustrate mean number of microplastics ± standard error.

Fig. 5. The relationship between the sewage discharged (cubic metres) into the water column from the Hammersmith pumping station CSO from June to October 2017, and the mean number of 32 µm–5 mm microplastics found in the water column at Putney. (Thames Water data).

Fig. 6. A stacked bar chart to show the percentage material composition for each form. Polymer forms were identified using FTIR at a 70% minimum spectral library match. Sixty-three samples were analysed; 21 fragments, 31 films, 2 nurdles, 4 glitter particles and 5 microbeads.