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From Sea to Source: The Abundance and Characteristics of Microplastics in Surface Water in the Transboundary Ganges River

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Abstract

Microplastics (plastic < 5 mm in size) are now known to contaminate riverine systems but understanding about how their concentrations vary spatially and temporally is limited. This information is critical to help identify key sources and pathways of microplastic and develop management interventions. This study provides the first investigation of microplastic abundance, characteristics and temporal variation along the Ganges river; one of the most important catchments of South Asia. From 10 sites along a 2,575 km stretch of the river, 20 water samples (3,600 litres in total) were filtered (60 samples each from pre- and post-monsoon season). Overall, 140 microplastic particles were identified, with higher concentrations found in the pre-monsoon (71.6%) than in post-monsoon (61.6%) samples. The majority of microplastics were fibres (91%) and the remaining were fragments (9%). We estimate that the Ganges, with the combined flows of the Brahmaputra and Meghna rivers (GBM), could release up to 1 - 3 billion (10^9) microplastics into the Bay of Bengal (north-eastern portion of the Indian Ocean) every day. This research provides the first step in understanding microplastic contamination in the Ganges and its contribution to the oceanic microplastic load.

Main finding: We estimate that up to 1 - 3 billion microplastics are released into the Bay of Bengal every day.

1.0 Introduction

The durability, versatility, low cost and wide-scale use of plastic items means that plastic litter is now prevalent worldwide, even in remote areas (Free *et al.*, 2014; Obbard *et al.*, 2014; Geyer *et al.*, 2017; Waller *et al.*, 2017). Accumulation of plastic waste was initially documented in oceanic environments, with the first observation of buoyant plastics in the ocean dating back to 1972 (Carpenter and Smith, 1972;

Carpenter *et al.*, 1972). Since then, numerous studies have increased our understanding of oceanic plastic characterisation, transport and accumulation zones (Moore *et al.*, 2001; Thompson *et al.*, 2004; Law *et al.*, 2010; Goldstein *et al.*, 2012; Lebreton *et al.*, 2018). Within the last decade, there has been additional focus on plastic presence in estuarine systems (Bakir *et al.*, 2014; Gallagher *et al.*, 2016), freshwater (Klein *et al.*, 2015; Zhang *et al.*, 2015; Horton, Walton, *et al.*, 2017; Peng *et al.*, 2018; Eo *et al.*, 2019; Mai *et al.*, 2019; Mani *et al.*, 2019; Watkins *et al.*, 2019; Zhao *et al.*, 2019), and terrestrial environments (Rillig, 2012; Horton, Walton, *et al.*, 2017; Corradini *et al.*, 2019).

Plastic in the microplastic size range (0.1 μm–5 mm) is an environmental pollutant of substantial public and scientific concern (Thompson *et al.*, 2004; Paul *et al.*, 2020). Until recently, microplastics have been a largely overlooked part of plastic pollution monitoring but are thought to be ubiquitous within the environment (Rochman, 2018; Napper and Thompson, 2020). Within the last decade, microplastics have received increasing research interest due to the rapid increase in plastic production, the longevity of plastic and the disposable nature of plastic items (Thompson *et al.*, 2004); as such, data have been accumulating on the sources, distribution and impact (Andrady, 2011; Ivar Do Sul and Costa, 2014; van Sebille *et al.*, 2015). Due to their small size, microplastics are available for ingestion by a wide range of marine species, from microscopic zooplankton to large vertebrate predators (Botterell *et al.*, 2019; Nelms *et al.*, 2019), and can cause negative impacts on biological processes (Lo and Chan, 2018; Messinetti *et al.*, 2018)

An estimated 80% of plastic pollution in the ocean potentially originates from land-based sources (Jambeck *et al.*, 2015), such as leakage from wastewater treatment plants (WWTPs) (Kay *et al.*, 2018), urban centres and road runoff (Horton, Svendsen, *et al.*, 2017), industry (Lechner and Ramler, 2015), atmospheric pollution (Dris *et al.*, 2015; De Falco *et al.*, 2020) and degradation of larger items of plastic waste (Barnes *et al.*, 2009; Schmidt *et al.*, 2017; Schwarz *et al.*, 2019). Freshwater systems often connect inland and coastal communities to the ocean, and therefore represent a substantial downstream transport pathway for microplastic input (Rech *et al.*, 2014; Miller *et al.*, 2017; Schmidt *et al.*, 2017; Seo and Park, 2020; Weideman *et al.*, 2020). An estimated 0.4 – 265,000 million tonnes of plastic are released into coastal seas by the world's rivers annually (Wagner *et al.*, 2014; Lebreton *et al.*, 2017; Schmidt *et al.*, 2017; Mai *et al.*, 2020).

Most freshwater microplastic studies originate from North America, Western Europe (Horton, Walton, *et al.*, 2017; Peng *et al.*, 2018) and China (Peng *et al.*, 2018; Ding *et al.*, 2019). The Yangtze River was predicted to emit 16–20 trillion microplastic particles into the East China Sea in 2017 (Zhao *et al.*, 2019).

There are limited studies and empirical field data on plastic pollution from major Asian rivers such as the Ganges and Mekong (Blettler *et al.*, 2018; Chowdhury *et al.*, 2020). However, recent research by Duncan *et al.*, (2020) tracked plastic PET bottles through the Ganges river system and into the Bay of Bengal marine system by using both GPS (Global Positing System) cellular networks and satellite technology and found a maximum distance tracked of 2845 km over a period of 94 days. Additionally, Nelms *et al.*, (2020) found that fishing gear is a significant source of plastic pollution in the Ganges River system.

The Ganges is known as the Ganga in India and the Padma and Meghna in Bangladesh (hereafter known as the Ganges). The combined flows of the Ganges, Brahmaputra and Meghna rivers are the largest in South Asia and form the most populous basin in the world, where over 655 million inhabitants rely on the water it provides (The World Bank, 2014; Rahman *et al.*, 2020).

There is limited research on microplastic pollution in the Ganges river (Baroth, 2019) and currently no published data are available on microplastic contamination in the freshwater matrix of the Ganges. Additionally, there is limited understanding of how microplastic concentrations vary along a whole river course and over different seasons, particularly considering the major influences of the monsoon on the Ganges (Clift, 2020). It was hypothesized that microplastic abundance would increase as the river travels downstream and that lower microplastic concentrations would be observed during the post-monsoon season due to the high levels of rainfall resulting in increased volume and flow of freshwater; subsequently transporting more microplastics into the marine environment. The aims of this study were to provide the first investigation, over two different seasons, on the abundance, polymer type and characteristics of microplastics in water along the mainstream Ganges river, from sea to source.

2.0 Methods

2.1. Study area

The Ganges river originates from the Gangotri glacier in the Himalayas (India) at an elevation of nearly 7,010 m and traverses a length of about 2,575 km before it flows south-east, transforming into distributaries and ultimately flowing into the Bay of Bengal (Bangladesh) (Whitehead, 2018; Singh and Singh, 2019). The Ganges river is joined by a number of large and small tributaries. The river joins the Brahmaputra river in Bangladesh as the Padma and further down the combined discharge joins the Meghna river at Chandpur. The combined stream is called the Meghna river, which 90 km further downstream discharges into the Bay of Bengal. The total annual Ganga-Brahmaputra-Meghna (GBM) river basin inflow into Bangladesh from India is 1,110 km^3 (FAO, 2012). Over 138 700 m^3/s of water flows into the Bay of Bengal during flooding (particularly in the monsoon season) through a single outlet of the GBM river in Bangladesh. This is the largest in the world for a single outlet to the sea and exceeds even that of the Amazon discharge by about 1.5 times (Parua, 2001). The Ganges is a transboundary river basin distributed between five countries; India, China, Nepal, Bhutan and Bangladesh. The basin and its tributaries are diverse in social, economic and political terms as well as for water availability and use.

2.2 Site Selection

In this study, 10 sites in India and Bangladesh were selected along the length of the mainstream river to represent the whole length of the Ganges (Fig.1). In Bangladesh, three sites were included: Bhola (S1), Chandpur (S2), Rajbari (S3); the sample points were from the largest distributary of the Ganges or its confluence into the Meghna river. The other seven sampling sites were in India: Sahibganj (S4), Patna (S5), Varanasi (S6), Kannauj (S7), Anupshahar (S8), Rishikesh (S9) and Harsil (S10). The number signifies the site's position along the river, with S1 being closest to the ocean and S10 closest to the source; the position number will be used predominately in lieu of the sampling site name. The sites were selected on the basis of site characteristics (rural/urban/barrage/river confluence/Industry/tourism/religious), primary land use, logistics and possibility/ease of sampling.

2.3 Sampling method

To collect the samples, 30 L water was pumped from 0.5 m below the river surface and immediately filtered through a 330 µm nylon mesh placed across a polypropylene tube, using a hand-operated bilge pump. The pumping volume was adjusted to 30 L considering the target microplastic size range (>300 µm) and logistical challenges/practical challenges during sampling. Each nylon mesh filter was immediately double wrapped in foil and then placed in separate clear polypropylene bags for transportation. The samples were transported to the University of Plymouth (U.K.) for laboratory analysis. Contamination control measures were applied throughout the sample collection and transport process (see Section 2.5).

The samples were collected during pre-monsoon (May 2019 – June 2019) and post-monsoon (October 2019 – December 2019), to capture temporal variation in microplastic abundance. At each sampling site, a 5 km stretch of river was selected and samples were collected from three points at 2.5 km intervals (0, 2.5, and 5 km) from the centre of the river. Samples were replicated on two consecutive days (n = 6 per site). Post-monsoon sampling occurred at the same sites using the GPS locations from pre-monsoon. For tidal sections of the river (sites S1-S3), samples were collected on an ebbing tide to ensure microplastics within the outflowing river water were not those brought inshore from the Bay of Bengal.

2.4 Laboratory Analysis

Each mesh and subsequent foil packaging was examined for microplastics using a light microscope (S9E - Leica) and information on the type of particle (i.e. fragment or fibre), dimensions (length and diameter) and colour was recorded. Shape classifications include fragments, films, spherical beads and fibres.

Suspected microplastics were analysed with Fourier transform infrared spectroscopy (FT−IR) in transmission mode with a Hyperion 1000 microscope coupled to a Vertex 70 spectrometer (Bruker). Any spectra were recorded with 32 scans in the region of 4000− 600 cm^{-1}.The spectra obtained were compared against a spectral database of synthetic polymers (BPAD polymer and synthetic fibres ATR).

2.5 Contamination Control

The water pumping system (bilge pump and polypropylene hose) and polypropylene tube were checked for contamination before and after the expedition. A procedural blank of 30 L of filtered (1.6 µm) distilled (DI) water was used to simulate the sampling process and identify potential sources of contamination from the equipment. No contamination was observed. Additionally, before the expedition each mesh was inspected for contamination using a microscope (S9E - Leica), and any particles removed before use. The mesh was wrapped in two layers of clean foil before and after use to avoid subsequent contamination.

During field sampling, the pumping system was first flushed with water from the river. The inside of the propylene tube was also rinsed with distilled water (filtered to 330 µm) prior to use. To control for airborne microplastic contamination, a damp (300 µm filtered DI water) piece of filter paper (Whatman 47 mm diameter, 0.45 µm glassfiber filter) in an open petri dish was placed nearby while samples were collected. The petri dishes were kept open for the duration of the water pumping so that the blanks and samples were exposed to the same levels of airborne contamination.

During any laboratory analysis, all steps were conducted in a dedicated clean room for microplastic work, which had a positive pressure air system, limited access and procedural blanks. Cotton laboratory coats and clothes were worn to reduce contamination from synthetic textiles. All laboratory ware used was made of glass or stainless steel and thoroughly rinsed with filtered (1.6 µm) Milli-Q water before use.

2.6 Statistical analysis

Zero-Inflated regression analysis was carried out using a Poisson distribution to assess the spatial (site) differences in microplastic abundance, within the R Package 'pscl' (Jackman 2020). Microplastic concentrations (MP L^{-1}) were modelled as a function of site for Poisson counts and binomial zeros (Jackman 2020). Further analysis, by zero-inflated regression modelling, was used to assess the differences between sites and polymer types by factor order manipulation. The most parsimonious models were selected by sequential removal of terms and pairwise chi-square comparison using the 'lmtest' package in R (Zeileis and Hothorn, 2002). Thus, non-significant terms were deleted. Data were manipulated and visualized using 'tidyverse' packages within the R computer programming language (R Core Team 2019; Wickham et al. 2019).

Linear regression analysis was used to investigate the change in microplastic length (µm) as a function of sampling date and site. To fit model assumptions, lengths were transformed by natural logarithm for analyses. To plot the model predictions the values were converted back to their original scale for plotting using the exponential function.

2.7 Predicted Microplastic Discharge into the Ocean

To estimate microplastic discharge from the Ganges, the average microplastic concentrations at site 1 (Bhola) were used for both pre- and post-monsoon; 0.051 MP L^{-1} and 0.026 MP L^{-1}, respectively. The rivers in the watershed carry an average water discharge of 29,692 m^3/s into the Bay of Bengal, and 6,041 m^3/s during the low water season (Khan and Islam, 2008); these flow data were used for post- and pre-monsoon calculations, respectively. Following Miller *et al.,* (2017), flow rate (F_l) was multiplied by the depth proportion and the recorded microplastic concentration (MP_c) to calculate microplastic output at this site (MP_t). This is shown by equation i, where F_l is the flow rate (L s^{-1}); D_i and D_t are the sampling depth and total depth of the river (m) and MP_c is the sampled microplastic concentration (MP L^{-1}). As in Miller *et al.,* (2017), flow rate was assumed to be constant, which is an oversimplification.

Equation i: $MP_t = \frac{D_i}{D_t} \times F_l \times MP_c$

3.0 Results

In total, 120 samples were collected from 10 sites (60 from both pre- and post-monsoon) with a total 3,600 litres of freshwater filtered. Overall, 140 microplastic particles were identified; these were found in 43 (71.6%) of the samples for pre-monsoon, and 37 (61.6%) for post-monsoon. In total, the procedural controls (air blanks) (n = 40) had an average of 0.005 ± 0.002 MP L^{-1} day^{-1} (mean ± S.E.). Any contamination observed from a sampling day was subtracted from the microplastic total for each subsequent sample. Microplastic contamination in the lab was minimal; procedural blanks accumulated an average of 0.098 ± 0.042 MP $filter^{-1}$; only blue microfibres were found.

The average number of microplastics collected was 0.038 ± 0.004 MP L^{-1}. There were significant differences in microplastic concentration found among the sites ($p = <0.001$). The Bangladesh sites (S1, S2 and S3) had significantly more microplastics than Indian sites S5, S7, S9 and S10. There were also significantly greater concentrations of microplastics found at Indian sites S4, S6 and S8 compared to site S10. Additionally, site S6 had a greater concentration compared to site S7 and S9 (Fig. 1) ($p = <0.05$ for all significant interactions). Combining predicted microplastic concentration at the mouth of the river (S1; Bhola) with the discharge of the river, we estimate that 1- 3 billion (10^9) microplastics are released from the Ganges into the Bay of Bengal every day.

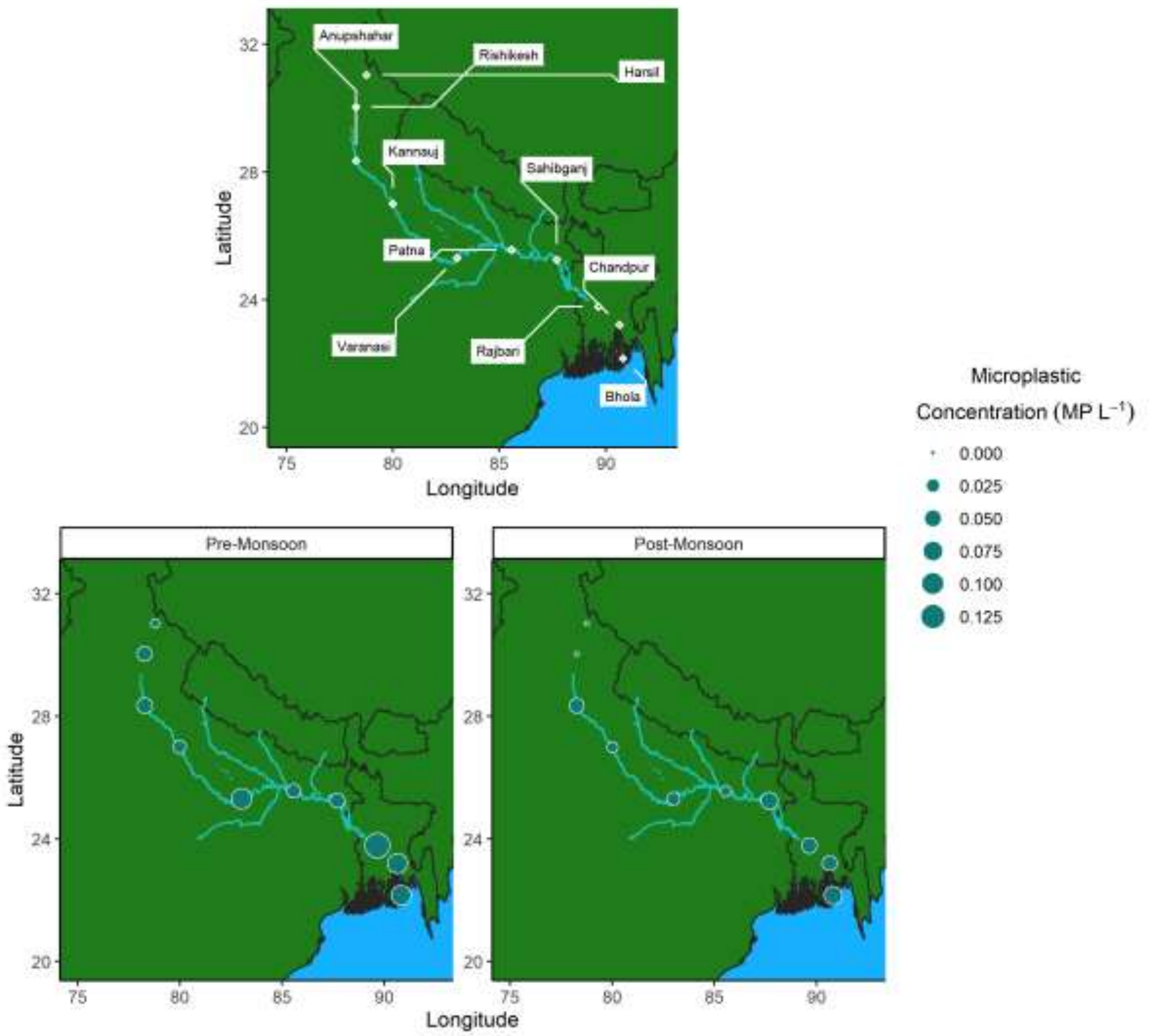

Figure 1. *Sample Sites along the Ganges, point size is relative to microplastic concentration pre and post-monsoon: a – sample site; b – pre-monsoon microplastic concentration; c – post-monsoon microplastic concentration. Point size indicates relative concentration (MP L^{-1}).*

There were a greater number of microplastics found on the pre-monsoon sampling occasions (0.051 ± 0.007 MP L^{-1}) than post-monsoon (0.026 ± 0.004 MP L^{-1}). Furthermore, microplastic concentration at the river mouth (S1; Bhola) had quadrupled compared to source concentrations (S10; Harsil) in pre-monsoon and doubled in post-monsoon seasons.

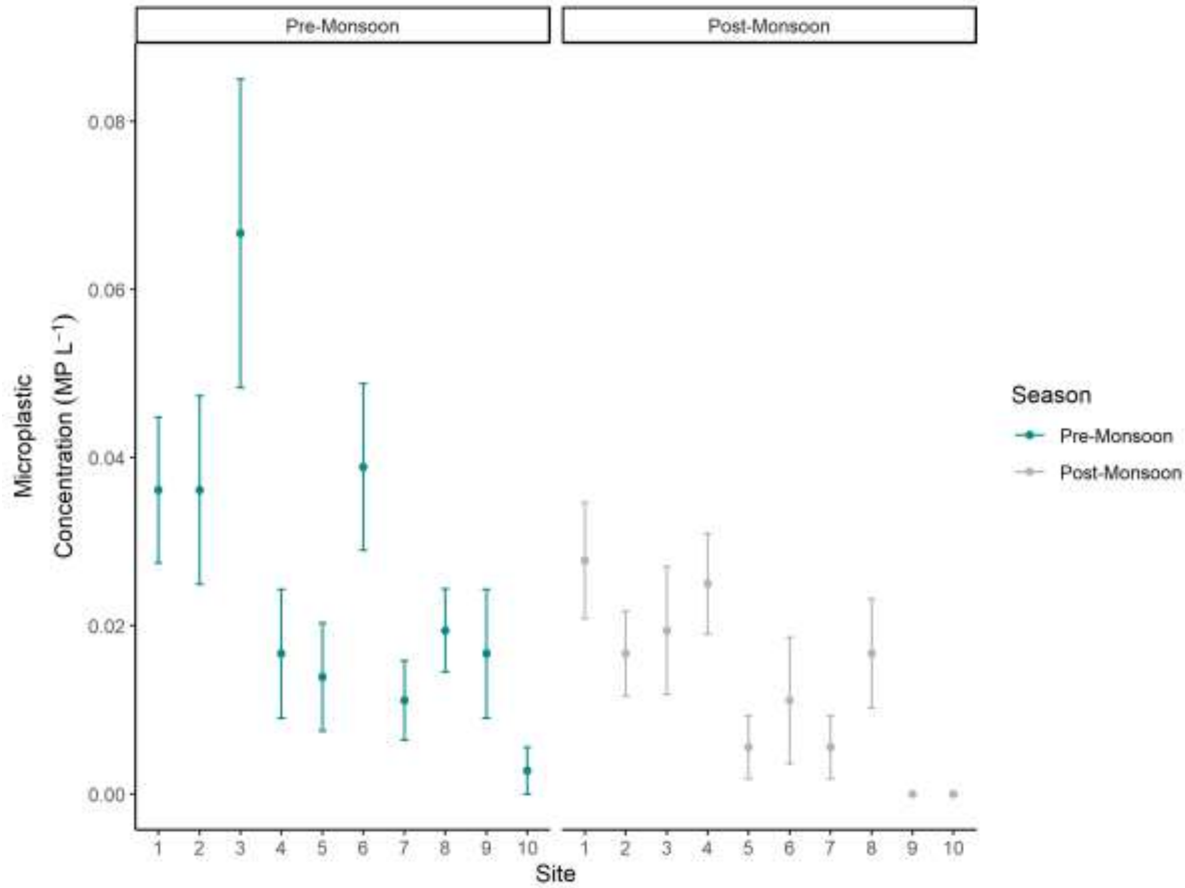

Figure 2. *Mean microplastic concentration (MP L^{-1}) for both pre and post-monsoon across all sites. Sites are in order travelling upstream (n = 6 (30 L), ± S.E.).*

In terms of microplastic types, across all sites 91% were fibres and 9% were fragments. Of the 140 suspected microplastics, FT-IR spectroscopy revealed rayon (synthetically altered cellulose) as the dominant polymer (54%), followed by acrylic (24%), PET (8%), PVC (6%), polyester (5%) and nylon (3%; Fig. 3). Considering all microplastics, the most dominant colour found was blue (74%), followed by black (11%), red (6%), purple (4%), and brown (2%). Green, yellow and clear particles each represented 1% of the sample total.

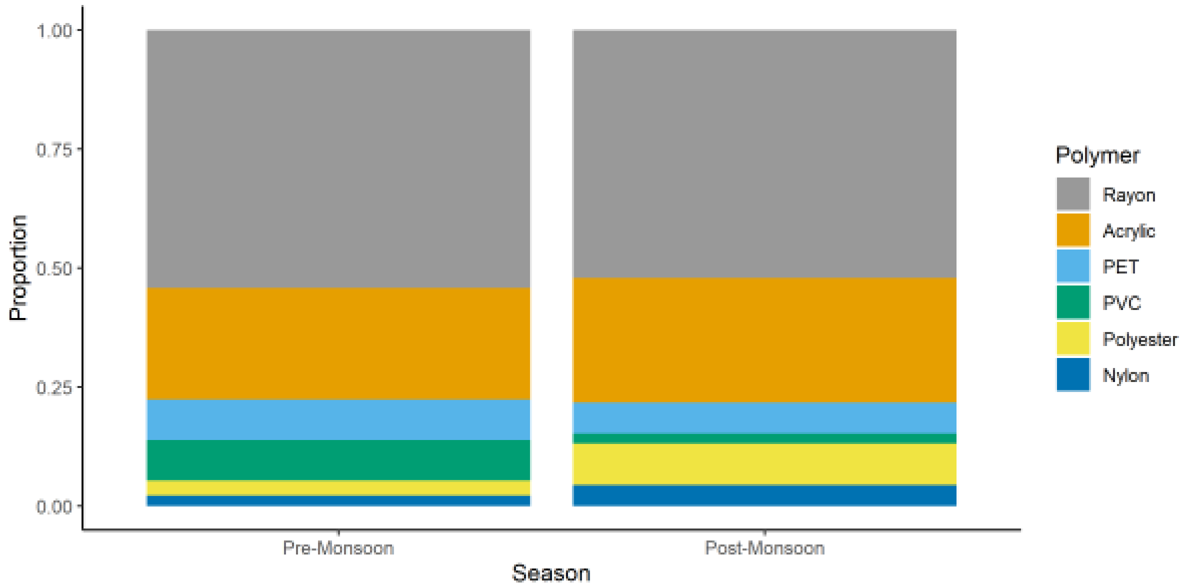

Figure 3. *Proportion of microplastic polymers for pre- and post-monsoon seasons, across 10 sites along the Ganges river (n = 6 (30 L)).*

The average size of microplastic was 2459 ± 209 µm. The average size was 2529 ± 263 µm in pre-monsoon season and 2317 ± 341 µm in post-monsoon. There was no significant difference between sites ($p = 0.16$) or sampling occasions ($p = 0.55$). Although not significant, a steady decrease in microplastic size was seen pre-monsoon when travelling downstream of the river from site 10 (Harsil) to site 1 (Bhola) (Fig. 4).

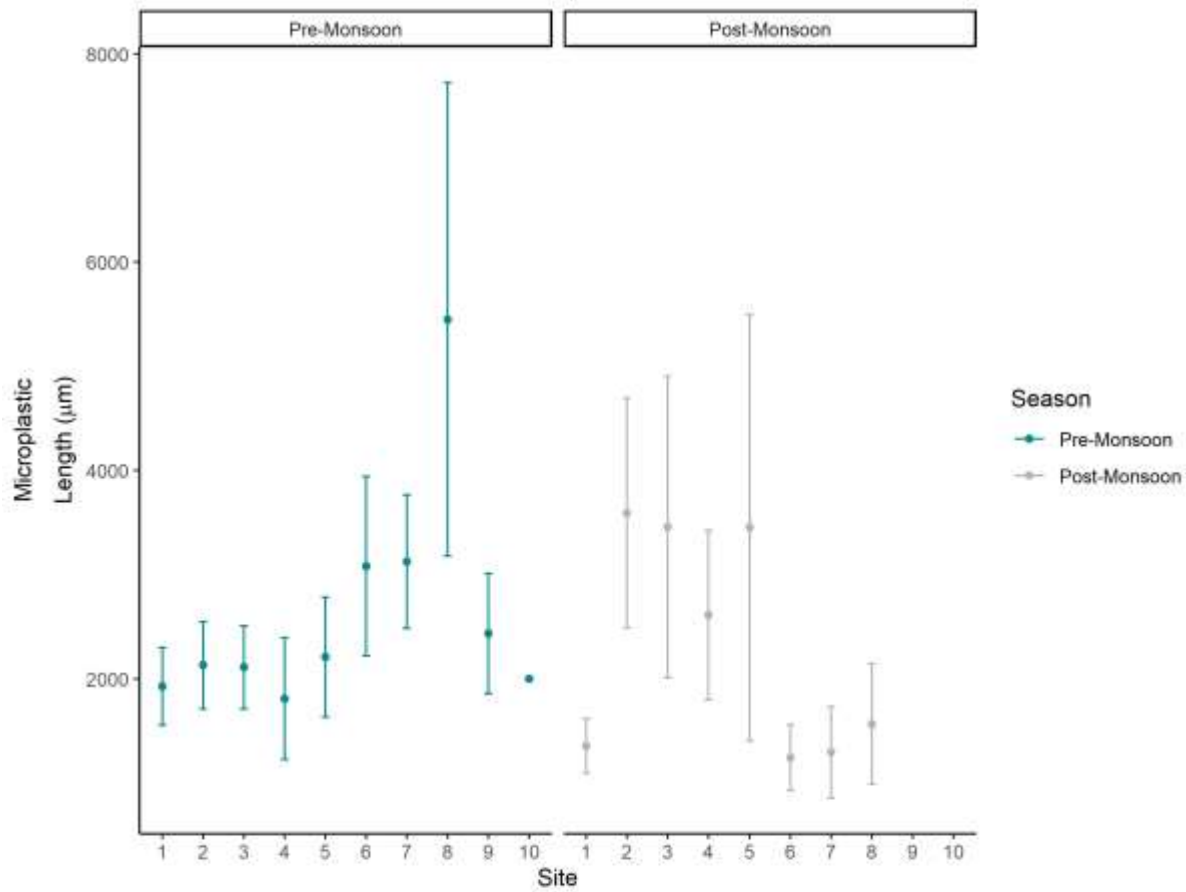

Figure 4. *Mean length of microplastic collected along the Ganges pre and post - monsoon seasons and across 10 sites; sites are in order travelling upstream. (n = 6 (30 L), ± S.E.).*

4.0 Discussion

It is widely reported that the large quantities of plastic entering coastal seas from land-based sources are transported by rivers, (Eerkes-Medrano *et al.*, 2015; Horton, Walton, *et al.*, 2017; Lebreton *et al.*, 2017; Schmidt *et al.*, 2017; Ding *et al.*, 2019). Yet there has been little empirical data from rivers themselves, and limited research understanding microplastic within the Ganges. The river faces a number of biophysical and socio-economic challenges (e.g. pollution, flooding, erosion, cyclones, salinization and water logging) which are increasing alongside the changing climate and anthropogenic developments (Rahman *et al.*, 2020; Sah *et al.*, 2020).

In our study, an average of 0.038 MP L^{-1} were detected in the surface water of the Ganges and microfibres were the prevalent microplastic shape (91%). In comparison, research on the Orange-Vaal river system (South Africa) found >99% microfibres, and a greater average concentration of 1.70 MP L^{-1}; this was conducted with 10 L replicates of freshwater gravity filtered through a 25 μm mesh. Miller et al., (2017) also studied microfibre contamination in the surface water of the Hudson river (U.S.A.) and found an average of 0.98 microfibres L^{-1}; this was conducted with 3 L replicates of freshwater vacuum filtered through a 0.45 μm mesh

Our lower concentrations of microplastic may be due to the volume of water sampled (30 L), filtration size (300 μm) or sampling method. Differences in filtration size has been shown to have a substantial effect for concentration estimations. A 2.5-fold increase in microplastics has been reported for a 100 μm net compared to 333 μm net (Lindeque *et al.*, 2020). Research by Song *et al.*, (2014) also identified substantial differences in abundance of microplastics when different sampling methods are used; such as surface microlayer (SML) sampling (16,272 ± 13,457 particles/m^3) > hand net (50 μm mesh) (1143 ± 3353 particles/m^3) > bulk water (213 ± 141 particles/m^3) > Manta trawl (330 μm mesh) (47 ± 192 particles/m^3).

The large river systems of the Ganges, Brahmaputra, and Meghna (GBM) combine to create the GBM delta, which is the third largest in the world in terms of water discharge (FAO, 2012; IUCN BRIDGE, 2018). Combining predicted microplastic concentration at the mouth of the river (S1; Bhola) with the discharge of the river, we estimate that 1- 3 billion (10^9) microplastics are released from the Ganges into the Bay of Bengal every day. As above, this is likely to be an under-estimation due to the sampling method. To put this into perspective against other riverine systems, research from Miller *et al.*, (2017) estimated that the Hudson River's watershed drainage area could contribute an average 300 million anthropogenic microfibres into the Atlantic Ocean per day. Globally, it has been estimated that 60 billion pieces of plastic are discharged into the ocean from rivers worldwide each day (GESAMP, 2016), with a global estimate for oceanic microplastic estimated at 4.85 trillion (Eriksen et al., 2014). The results presented here confirm that microplastic discharge from rivers is a substantial vector of microplastics into the marine environment.

Microplastics were also shown to increase in abundance downstream. Microplastics can be transported long distances in aquatic environments and have been found in remote areas far from large cities (Free *et al.*, 2014; Lusher *et al.*, 2015; Zhang *et al.*, 2016). However, the distances over which plastics of different sizes are transported to the sea are poorly known (Horton et al., 2017) because most rivers support human populations along their length, and it is hard to differentiate local plastics from those transported from up-river. Understanding the distance travelled and distribution of microplastics in a river is of importance and requires further research. As shown here, a proportion of microplastics are predicted to follow the flow of the river out towards the coast, but research has also reported that microplastic can sink and collect in riverbed sediments; a maximum concentration of approximately 517,000 MP m^{-2} of river sediment in the U.K. was found in research by Hurley et al., (2018) and approximately 40 microfibers per 250 g dry weight in Baltic Sea marine sediment (Zobkov and Esiukova, 2017).

Half of the microplastics were identified as rayon (regenerated cellulose fibres), followed by acrylic. Rayon is often reported as a common polymer type for microplastics in both freshwater and marine samples (Lindeque *et al.*, 2020; Nan *et al.*, 2020; Park *et al.*, 2020). Rayon and acrylic fibres are mainly used in clothing (Frias *et al.*, 2016; Comnea-Stancu *et al.*, 2017).

Increased rainfall, associated with monsoons, will impact estimated monthly river plastic inputs into the ocean. Research by Weideman et al., (2020) found microplastic concentration averaged slightly higher in the wet (2.1 ± 6. 9 MP L^{-1}) than dry season (1.3 ± 2.5 MP L^{-1}). On the contrary, our research reports that the pre-monsoon (dry) season had a higher concentration of microplastic compared to post-monsoon (wet). This could be due to the 'flushing' mechanism/role that the river plays during the monsoon season. However, the post-monsoon season did result in a greater microplastic discharge into the Bay of Bengal (>3 billion MP day^{-1}) due to the increased flow rate and increased volume of water in the wet season. It has been observed that the flooding events during the monsoon months are mostly experienced in the lower-middle and lower part of the Ganges basin thus increasing the discharge rate of water and other associated materials like silt, nutrients and subsequently microplastic. It has been previously estimated that the top 20 plastic-polluting rivers contribute over 74% of annual riverine plastic from May-October, according to a worldwide model (Lebreton et al., 2017).

There was no significant difference between sites or sampling occasions for microplastic size, but some sites showed substantially higher microplastic concentrations. Notably in Rajbari (S3) and Varanasi (S6) during pre-monsoon season. Sampling in Rajbari occurred the day after (23/05/2019) a large storm with substantial rainfall (20 mm). Rain and storm events have been suggested to increase microplastic contamination, with abundance up to 40-fold higher during a storm compared to before (Hitchcock, 2020); this is likely to have influenced the Rajbari data. Additionally, Rajbari is situated at the confluence of Jamuna-Ganges, which means Jamuna also contributes to the microplastic concentration. Another site where this was observed, Varanasi, is one of seven holy cities in India; it has around 84 ghats along the Ganges where over 60,000 people gather daily for holy ritual bathing (Kumar *et al.*, 2012). It is also heavily populated with a density of about

14,656 persons km^2 (Geetika Verma and Shrivastav, 2018). The higher tourist footfall also contributes to increased consumption and dumping of plastic at Varanasi. Therefore, it is suspected that the larger population density and waste generation from cities in India and Bangladesh would increase the quantity of microplastics in nearby river water.

Conclusion

A substantial quantity of microplastic (1- 3 billion pieces) is estimated to be discharged into the Bay of Bengal on a daily basis, with microplastic concentration increasing from source to sea. Understanding of how microplastic concentrations vary along a river's course is lacking but is critical to help identify key sources and pathways of microplastic and develop management interventions. This research provides the first step in understanding how the Ganges, as well as other major rivers, may contribute to oceanic microplastic. The study will also help provide a global context to plastic pollution in the Ganges when compared with similar studies in other rivers across the globe.

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