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Is the Paraíba do Sul River colourful? Prevalence of microplastics in freshwater, south-eastern Brazil

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ABSTRACT

Context. Plastic pollution can be even more problematic to the environment when this material is fragmented into small pieces forming microplastics (MPs). **Aims.** The objectives of the present study were to investigate the abundance, morphotypes, predominant polymers, and colour of MPs on surface waters, and compare the effect of the hydrologic cycle on the abundance and richness of MP categories along a stretch of the Paraíba do Sul River basin, the water system of which flows through the most populous area in Brazil. **Methods.** Samples were taken from the superficial layer of the water column in high-water and low-water periods 2021, using bottles and plankton net. **Key results.** In total, 15 categories of MP were determined and 290 plastic particles were collected in both periods. A greater abundance of MPs was found during the high-water period than in the low-water period, considering both sampling methods. **Conclusions.** The MPs in the surface waters of the Paraíba do Sul River are significantly influenced by the rainfall regime. **Implications.** In view of climate change, which encompasses an increase in the frequency and intensity of river floods, our results present significant implications for the management of MPs in riverine and marine systems, within the context of global climatic alterations.

Keywords: disturbance, flooding, freshwater, hydrology, lotic, pollution, surface water, water column.

Introduction

Synthetic polymers have been mass-produced since the 1950s, surpassing most materials produced by mankind (Geyer 2020) and reaching an annual production of 3.00×10^8 tonnes (Mg) (Plastic Oceans 2020). Projections indicate that if this trend is maintained, by 2050, $\sim 1.1 \times 10^9$ Mg of plastic waste will have been introduced into the environment (Geyer 2020).

Studies have shown that more than 250 000 Mg of plastic waste are floating on the surface of the ocean worldwide (Lebreton *et al.* 2018). Rivers are the main pathways for plastics from terrestrial sources to reach the sea (Lebreton *et al.* 2017; Zhang *et al.* 2017), especially through direct discharges (Bellasi *et al.* 2020). Estimates have indicated that between 0.4 and 0.265×10^6 Mg of plastic are introduced into the marine environment through rivers globally every year (Lebreton *et al.* 2017; Schmidt *et al.* 2017; Mei *et al.* 2020). A shorter distance to rivers has been considered one of the main predictors for the prevalence of land-based plastic in marine environments (Schuyler *et al.* 2021).

Plastic pollution can be even more problematic to the environment when this material is fragmented into small pieces forming microplastics (MPs), which are defined as plastic particles between 0.1 and 5 mm in size (Yu *et al.* 2020). Because they are broadly distributed across natural environments, MPs can be incorporated by various organisms, including phytoplankton (Mota *et al.* 2021), zooplankton (Botterell *et al.* 2019), bivalves (Su *et al.* 2018), shrimp (Wang *et al.* 2019), fish (Jabeen *et al.* 2017) and large vertebrates (Nelms *et al.* 2019). The consequences are mechanical lesions, low growth rates, decreased fecundity, and even death (Ma *et al.* 2020). Moreover, MPs can facilitate the transference of adsorbed pollutants from the aquatic environment to the biota, promoting biomagnification and hindering, especially, higher trophic levels (Mammo *et al.* 2020). These issues are of great public concern and the number of studies on MPs has increased exponentially over the past years (Zhang *et al.* 2021).

Plastic pollution in the ocean attracts considerable public attention and financial investment for research, given the high number of studies that have documented the presence and ecological effects of this pollutant in the marine environment (Cole *et al.* 2011; Bessa *et al.* 2018; Dantas *et al.* 2020). Freshwater systems do not have the same visibility; however, recent studies have indicated that the level of contamination by plastic waste in continental waters is comparable to that of marine areas (Horton *et al.* 2017; Pegado *et al.* 2018). Freshwater bodies have been identified as hotspots for MP pollution (Li *et al.* 2020), which is attributed to several sources of emission, including illegal untreated wastewater discharges, effluents from wastewater-treatment plants, litter, and stormwater runoff (Eckert *et al.* 2018).

In the present study, we conducted a MP survey along a stretch of the Paraíba do Sul River basin, the water system of which flows through the most populous area in Brazil (Lima *et al.* 2021; Meneguelli-Souza *et al.* 2021). The states located in the Paraíba do Sul River basin have expressive industrial production and the highest water demand in the country (Almeida and Souza 2008). The basin has gone through alterations for many years, at a local and regional scale, as a result of human stressors (Simões Vitule *et al.* 2015). Given the important ecological role of this large river and the implications of MP pollution in this system, the objectives of the present study were (1) to investigate the abundance, morphotypes, predominant polymers, and colour of MPs on surface waters through two common sampling methods (bottles and plankton nets) and (2) to compare the effect of the hydrologic cycle on the abundance and richness of MP categories. The null hypothesis was that the abundance and richness of MPs do not vary among the hydrologic cycle seasons (high- and low-water seasons) in the Paraíba do Sul River, because the input of MPs in this environmental compartment happens from the discharge of domestic and industrial effluents, which occurs continuously and regularly.

Materials and methods

Study area

The Paraíba do Sul River basin covers an area of 62 074 km^2 and extends across 1145 km, with its springs located in the Serra da Bocaina Mountain range, south-eastern Brazil (Pereira *et al.* 2006). The river flows into the ocean in the northern coast of the state of Rio de Janeiro (20°26′–23°38′S, 41°00′–46°30′W). The main human activities in the basin are agriculture (particularly sugar cane production), industry and urban settlements. Maximum and minimum discharges happen in the summer (~4384 $m^3\ s^{-1}$) and winter (~181 $m^3\ s^{-1}$) (Agência Nacional de Águas 2009). The austral summer period is characterised as rainy (November–April), whereas the austral winter (May–October) is drier (Marengo and Alves 2005).

Sampling and preparation

Water was collected from four sampling points along the Paraíba do Sul River, extending across 57 km (Fig. 1). These sites are located in the lower part of the basin and receive a high volume of water from one of the main tributaries of the Paraíba do Sul River (Pomba River), thus comprising an area of significant concentration of particles in the basin. Samples were taken ~10 cm below the water surface in February (high-water) and June (low-water) 2021, using 4-L glass bottles (two samples, 8 L in total; Barrows *et al.* 2017) and a plankton net (30 cm in diameter, 70 cm in length, and mesh size of 50 μm; two samples; Isobe *et al.* 2015; Barrows *et al.* 2017) at each sampling point.

The water samples were collected from the central region of the river, accessed through urban bridges. To collect water with bottles, we used a graduated sisal rope with a 30-kg dumbbell (ballast) tied to the end. The opening (mouth) of the bottle was tied to the string, and a measurement of 10 cm above the mouth of the bottle was marked on the string with a coloured (non-synthetic) cloth tape. For sampling water with the net, a buoy was connected to the ring of the plankton net at a distance of ~10 cm, and on the opposite side of the ring, a 30-kg dumbbell was tied. A flowmeter attached to the plankton net was used to measure local current velocity and to estimate the volume of water sampled. Water velocity varied between 0.13 and 0.15 $m\ s^{-1}$ and the volumes sampled were 0.0041 and 0.0047 m^3 (respectively 4.1 and 4.7 L) at each site.

So as to evaporate all sample water, the glass jars were covered tightly with aluminium foil with small holes, and remained for 72 h at 70°C in a drying oven. Subsequently, 200 mL 30% (v/v) H_2O_2 (Synth, Brazil) was added to the dry mass, and retained for a 3-day incubation period at 40°C. All samples were filtered using 0.45-μm Whatman GF/C glass microfibre filter papers with a vacuum pump. The filters were later observed through stereomicroscopy (Wang *et al.* 2017).

Quality-control and quality-assurance (QA/QC) procedures

Following the recently published QA/QC criteria, strict control measures were implemented (Schymanski *et al.* 2021). All sampling equipment was cleaned right after each sampling, and the plankton net and catch cup were rinsed twice with filtered Milli-Q water before the next sampling procedure, to reduce cross-contamination. So as to avoid artificial

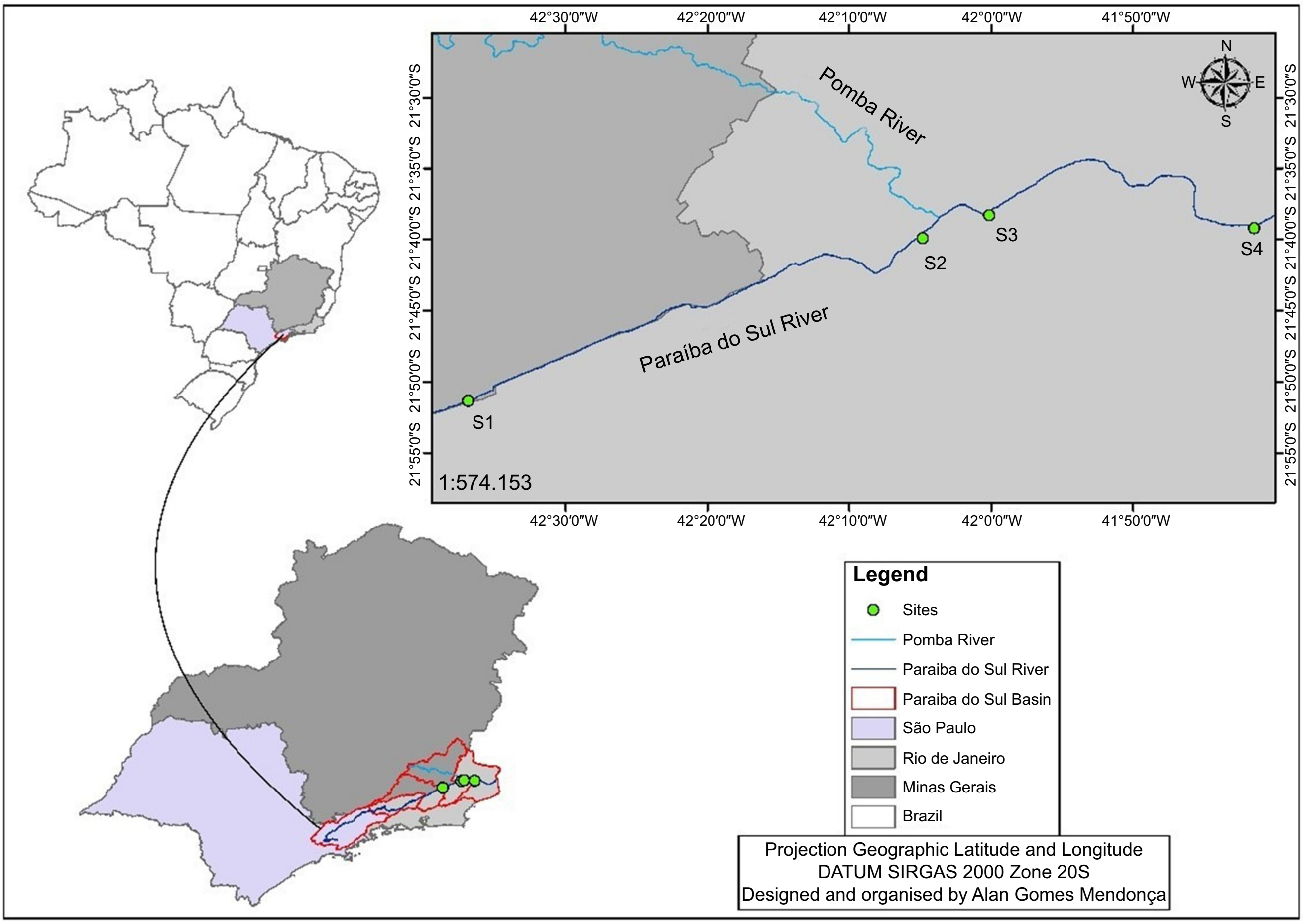

Fig. 1. Location of the Paraíba do Sul River basin in south-eastern Brazil and sampling locations (circles).

microplastic contamination and atmospheric transport, all equipment was washed with filtered Milli-Q water and tightly wrapped in aluminium foil. The field plastic control consisted of two empty glasses pre-washed with Mili-Q water, which remained open during the water sampling and then were filled with ultrapure water in the laboratory. Subsequently, the blank field controls were inspected following the same laboratory procedures of all other samples. For the blank correction, we followed Brander *et al.* (2020); MPs with characteristics identical to those found in laboratory and field blanks were removed from further analyses. Before starting the analysis in the laboratory, the bench was cleaned with filtered 70% alcohol, and all tools were previously rinsed three times with filtered Milli-Q water and then dried in the environment with a cover of aluminium foil. During the entire process of sample collection and laboratory analysis, cotton garments were used. The samples were analysed in a closed laboratory, where only one researcher operated the samples, which were always covered with aluminium foil. To monitor air contamination, three Petri dishes were positioned beside the sample, and each blank from the procedure was then rinsed with filtered Milli-Q water, followed by vacuum filtration using 0.45-μm Whatman GF/C glass microfibre filter papers. After the analysis of each filter, this control was assessed to estimate external contamination by MPs (Bessa *et al.* 2018). The results demonstrated there was no contamination during the field and laboratory procedures.

Observation and identification of microplastics

After digestion with H_2O_2, remaining non-plastic particles were just sediment grains, which could be isolated from synthetic plastics by characteristics such as colour, consistency, shine, and presence of fractures accompanied by flaking and crumbling when pressed. We considered only microplastics between 0.1 and 5 mm. All particles extracted were observed using a stereomicroscope (Zeiss Stemi 305 compact stereo microscope; Zeiss, Thornwood, NY, USA) at 80× magnification (PL10 × 23 Br Foc). MPs were categorised on the basis of morphotype as fibres (elongated), fragments (angular and irregular pieces), and films (fine and transparent), and according to colour (Galgani *et al.* 2013).

In total, 60 MPs (filaments, n = 35; fragments, n = 25) were randomly selected for identification of their polymer composition. The MPs were analysed through Fourier transform infrared spectroscopy (FTIR; detailed information about the technical procedures and preparation of samples are available in Frias et al. 2014). The samples were compressed in a Thermo diamond anvil cell and infrared spectra were acquired in a Nicolet Nexus spectrophotometer coupled to a continuous microscope (15× objective) with MCT-A detector cooled by liquid nitrogen. The spectra were collected in transmission mode, 4000–600 cm^{-1}, with resolution of 4 cm^{-1}, and scanned 128 times. Only polymers corresponding to the reference spectra >85% (compared to Open Specy – MicroplasticSpectra) were considered.

Statistical analysis

The abundance of MPs was defined as the number of MP particles, whereas richness was considered as the amount of morphotypes (including colour) in each sample. The concentration of MPs in each sample was calculated as the ration between the number of MPs and the total volume of water (m^3).

The permutational multivariate analysis of variance (PERMANOVA, Anderson 2001) was used to evaluate the effects of sampling methods (bottle v. net) and seasons (high v. low water) on the abundance and richness of MPs, and the interactions between these factors (Anderson 2001). The analysis was based on dissimilarity coefficients using the Bray–Curtis index (richness and abundance data, previously log-transformed) and under 10 000 permutations.

A similarity percentage analysis (SIMPER) allowed the determination of individual contributions of each type of MP (vegan, ver. 1.17-2, J. Oksanen, F. G. Blanchet, M. Friendly, R. Kindt, P. Legendre, D. McGlinn, P. R. Minchin, R. B. O'Hara, G. L. Simpson, P. Solymos, M. H. H. Stevens, E. Szoecs, and H. Wagner, see https://cran.r-project.org/web/packages/vegan/), detailing which items had the greatest influence over each period of the hydrologic cycle. All analyses were conducted using R-software (ver. 4.1.1, R Foundation for Statistical Computing, Vienna, Austria, see https://www.r-project.org/).

Results

MPs were found in all samples. In total, 15 categories of MP were determined and 290 plastic particles were collected in both periods (high water n_{Hw} = 201, 69%; and low water n_{Lw} = 89, 31%). The concentration of MPs varied between 1 and 12 particles m^{-3} during the low-water season and between 1 and 18.3 particles m^{-3} during the high-water season (Table 1).

Greater abundance (P = 0.02) and a medium level of richness (P = 0.01) of MPs was found during the high-water period, than in the low-water period, considering both sampling methods. The richness and abundance of plastic particles was greater in bottles sampled during the high-water period (abundance, P = 0.01; richness, P = 0.03), than in the net samples in both seasons (Table 2).

Blue filaments (n = 65; 22%) were the predominant type of MP for both periods, followed by blue fragments (n = 60; 20%) and black filaments (n = 51; 17%). During the low-water season, blue filaments (n = 47; 53%) were also the most abundant, followed by black filaments (n = 21; 24%) and transparent filaments (n = 7; 8%). During the high-water season, blue filaments (n = 57; 28%) were again the most representative, followed by multicoloured fragments (n = 47; 23%) and black filaments (n = 30; 15.2%) (Fig. 2).

Ten MP categories contributed to 80% of the dissimilarity in the abundance of plastic particles between the hydrological seasons. Blue fragments (3.5%), multicoloured fragments (2.9%), black filaments (1.8%), blue filaments (1.1%), and red filaments (1.0%) showed the highest abundance during the high-water season. In turn, blue filaments (2.9%), black filaments (1.3%), transparent filaments (0.4%), and red filaments (0.2%) were the predominant types of MPs during the low-water season (Fig. 3).

The types of polymers identified were polyethylene terephthalate (51%), polyvinylchloride (32%), high-density polyethylene (10%), and polystyrene (7%) (Fig. 4 and 5).

Discussion

The composition and abundance of MPs differed seasonally in the Paraíba do Sul River, thus rejecting the null hypothesis.

Table 1. Abundance (N), relative abundance (M%), and concentration of MP (particles m^{-3}) collected with bottles and nets during the periods of high- and low-water seasons in the Paraíba do Sul River, Brazil.

Site	Low water						Total	High water						Total
	Bottle			Net				Bottle			Net			
	N	M%	Particles (m^3)	N	M%	Particles (m^3)		N	M%	Particles (m^3)	N	M%	Particles (m^3)	
1	48	75	12.0	4	16	1.0	52	73	47	18.3	11	24	2.8	84
2	4	6	1.0	7	28	1.8	11	14	9	3.5	4	9	1.0	18
3	6	9	1.5	9	36	2.3	15	38	24	9.5	24	53	6.0	62
4	6	9	1.5	5	20	1.3	11	31	20	7.8	6	13	1.5	37

Table 2. Mean ± s.e. and PERMANOVA results for comparisons of the abundance and richness of MPs in high-water (HW) and low-water (LW) seasons and sampling method (bottle and net) in the Paraíba do Sul River.

Source of variation	d.f.	MS	Pseudo-*F*	*P*(perm)	Pair-wise test
Abundance					
Period	1	801.34	5.89	**0.02**	Mean_{Hw} (12.5 ± 15.8) > Mean_{Lw} (5.5 ± 8.5)
Sampling method	1	703.13	4.93	**0.03**	Bottle_{HW} (19.5 ± 20.1) > Net_{LW} (3.12 ± 1.64)
Period × Sampling method	1	162.0	1.13	0.01	
Richness					
Period	1	13.78	7.09	**0.01**	Mean_{Hw} (3.4 ± 2.3) > Mean_{Lw} (2.1 ± 0.7)
Sampling method	1	14.20	7.34	**0.01**	Bottle_{HW} (4.8 ± 2.1) > Net_{LW} (2.2 ± 0.8) > Net_{HW} (2.0 ± 1.5) > Bottle_{LW} (2.0 ± 0.5)
Period × Sampling method	1	19.5	10.0	**0.00**	

Significant differences ($P < 0.01$) are indicated in bold. d.f., degree of freedom; MS, mean square.

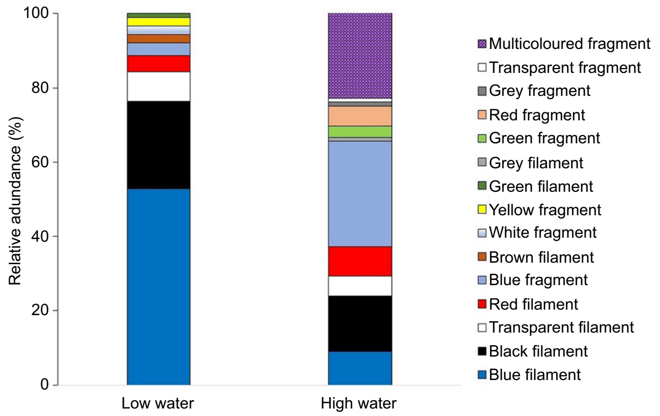

Fig. 2. Relative abundance (%) of MP categories in high- and low-water seasons in the Paraíba do Sul River, state of Rio de Janeiro, Brazil.

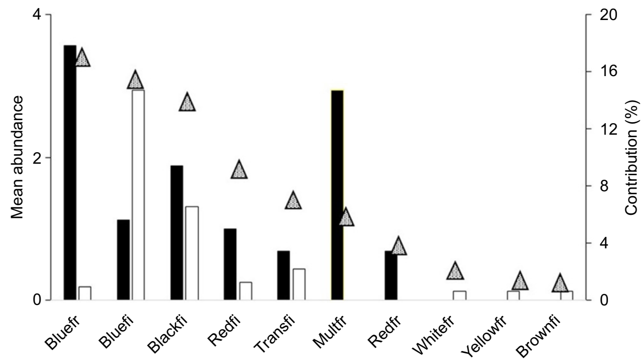

Fig. 3. Mean abundance (bars) and relative contribution of MPs (triangles) to the dissimilarity between low-water (white bars) and high-water (black bars) seasons estimated through a SIMPER analysis. Bluefr, blue fragment; Bluefi, blue filament; Blackfi, black filament; Redfi, red filament; Transfi, transparent filament; Multfr, multicoloured fragment; Redfr, red fragment; Whitefr, white fragment; Yellowfr, Yellow fragment, and Brownfi, brown filament.

Significantly greater amounts of MPs were sampled during the high-water period than in the low-water period. Surface runoff could be one of the main forms of transporting plastic particles from terrestrial to aquatic environments (Su *et al.* 2020), and rainfall is a preponderant factor for this process (Dikareva and Simon 2019). Similar to our results, Baptista Neto and Fonseca (2011) and Olivatto *et al.* (2019) when studying the Guanabara Bay (Brazil), and Hitchcock and Mitrovic (2019) evaluating an estuary in Australia identified a greater contribution of MPs to water bodies during rainy seasons, than during dry periods.

Rainfall events promote the leaching of soils near rivers and streams, introducing plastic waste into the aquatic environment (Su *et al.* 2020). Moore *et al.* (2002), considering rivers in Los Angeles, USA, highlighted that ~2 billion plastic particles are transported by these environments every 3 days, and this amount increases under heavy rainfall conditions (Barnes *et al.* 2009). The degradation rate of MPs in the soil is higher than in the aquatic environment, owing to a greater exposure to temperature variations and UV light (Andrady 2011). This decreases the size of MPs over time, increasing the availability of particles that can undergo surface runoff and leach to water bodies (Waldman and Rillig 2020). Thus, it is expected that rain both intensifies processes of particle transport and supports the role of hydrological cycles as determinant factors for the abundance and composition of MPs in rivers, even if the discharge of domestic and industrial effluents is regular.

In fluvial systems, MPs, being similar to natural particles, are not transported uniformly (Frei *et al.* 2019). Transport mechanisms and time scales depend on the hydrodynamic properties of MPs, such as particle size, shape, density, and surface rugosity, and on the hydrodynamic conditions of the river channel (Frei *et al.* 2019). Thus, in addition to rainfall, the hydrodynamics of compartments within the river influence the distribution of MPs in the water (Wang *et al.* 2017). Sediments accumulate more MPs than do surface waters (Xia *et al.* 2020). Therefore, the increased currents caused by rainfall can also promote vertical exchanges,

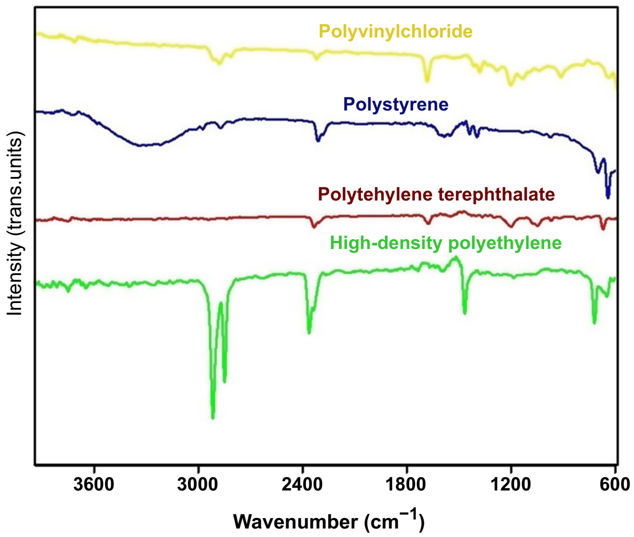

Fig. 4. Infrared spectra of the main microplastic particles found in the surface waters of the Paraíba do Sul River, state of Rio de Janeiro, Brazil.

such that this remobilisation can potentially generate a wide-scale release of MPs present in the sediment to surface waters (Ockelford *et al.* 2020; Xia *et al.* 2020). The austral summer has well defined rainy (December–April) and dry (June–August) seasons and is characterised by strong rainfall that promotes intense runoff and flooding of low-lying marginal areas (Alcântara and Washington 1989). Specifically, for the Paraíba do Sul River basin, the summer months (high-water season) are characterised by strong frontal rains, whereas the winter months show a generalised decrease in rainfall rates, characterising a typical tropical climate regime (Nimer 1979).

The highest concentration of MPs (~18 MPs m^{-3} sampled with bottles, see Table 1) in the Paraíba do Sul River was registered during the high-water season. Thus, we highlight the elevated concentrations of MPs reported for the Paraíba do Sul River, which raises an alarm about the levels of MP contamination in freshwater environments and in adjacent coastal systems in the region. The type of MP that predominated in the surface water of the Paraíba do Sul River (black and blue filaments) was also the most prevalent in

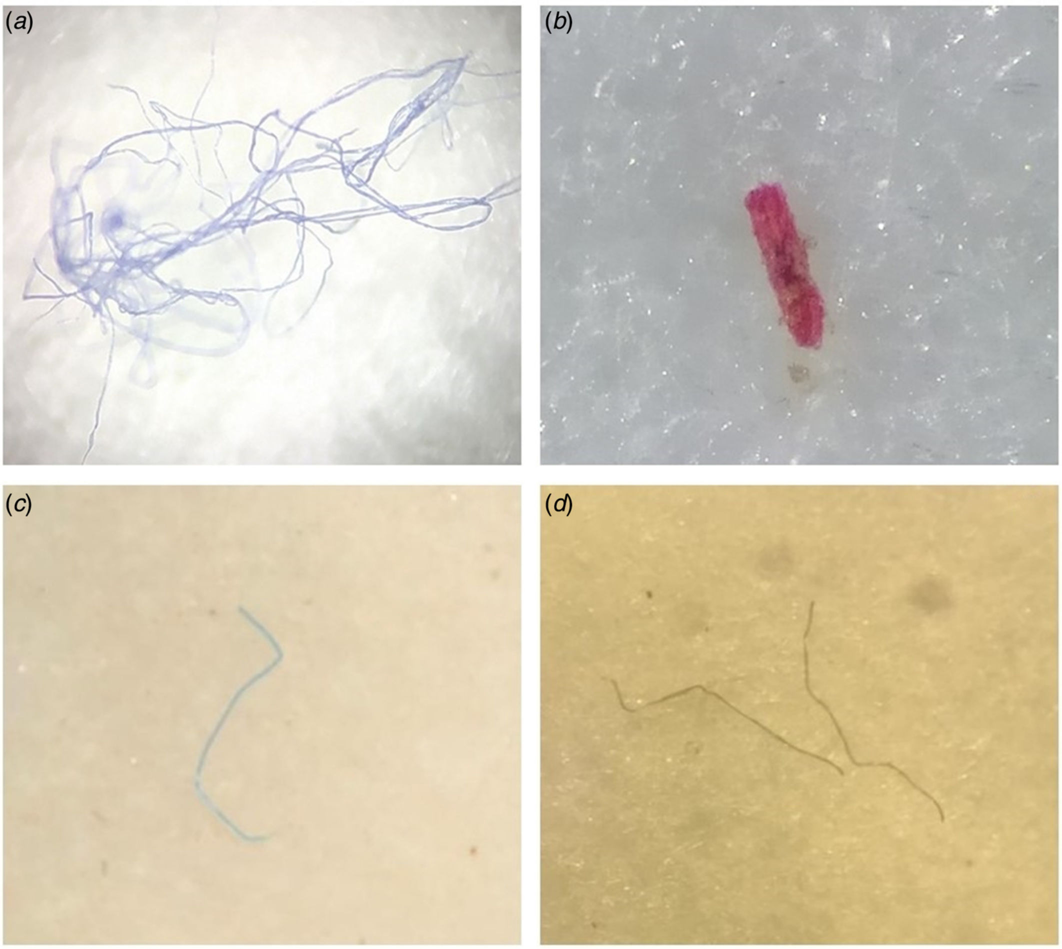

Fig. 5. Examples of MP from the Paraiba do Sul River: (*a* and *c*) blue filament, (*b*) red fragment, and (*d*) grey filament.

the digestive tract of crustaceans that inhabit ocean beaches in the region (Costa *et al.* 2019).

The decreasing distribution in abundance of blue filaments, blue fragments and black filaments in our results has also been observed in Ciwalengke River, Indonesia (Alam *et al.* 2019), in Baram River, Borneo Island (Choong *et al.* 2021) and Manas River, China (Wang *et al.* 2021). Synthetic filaments were the most representative among the different types of MP sampled when analysing the seasons jointly, corroborating the results of Neves *et al.* (2015), Vendel et al. (2017), and Dantas *et al.* (2020). Synthetic fibres are widely used in the textile industry and in civil construction (Dupont Sorona, see http://sorona.com/apparel, accessed 17 May 2022). Although synthetic fibres present high resistance (Washer *et al.* 2009), they can suffer degradational processes after absorbing water or UV radiation, which hinder the structure of the fibres and alter their chemical composition (Prasad and Grubb 1990). The easy degradation of this material by means of physical and chemical agents explains the high abundance of this item in the environment and its ability to become a MP in a short period of time. This MP originates mainly from domestic effluents, especially wastewater from washing machines, which is then directed to wastewater treatment plants, and domestic sewage is then discharged directly into the environment (Sillanpää and Sainio 2017). Moreover, Dris *et al.* (2017) reported that synthetic fibres suspended in the atmosphere also represent an important pathway for MP pollution into aquatic environments.

The colours of the MP in our study were similar to those found in other investigations (e.g. Bessa *et al.* 2018; Dikareva and Simon 2019; Dantas *et al.* 2020; Xia *et al.* 2020); blue, black, and transparent were the most representative colours. The colour of these plastic particles is similar to the colour of the food resources present in the environment, which could contribute to a higher probability of MP ingestion by aquatic species (Ferreira *et al.* 2018; Kuśmierek and Popiołek 2020; Atamanalp *et al.* 2021; Parvin *et al.* 2021). In addition to organisms perceiving and capturing MPs through visual acuity, Savoca *et al.* (2019) also highlighted aquatic organisms that are induced to consume MPs because of the odours released by these plastic particles, especially because of the development of a biofilm around the item.

As with the filaments, plastic fragments were also highly representative, especially during the high-water season. Klein *et al.* (2015), who studied the Rhine River (Europa), and Constant *et al.* (2020), who studied two watersheds connected to the Mediterranean Sea, reported fragments as the predominant type of MP. These authors associated the higher abundance of this category of MP with the greater population densities in the areas analysed. The Paraíba do Sul River basin (>8 million inhabitants; Instituo Estadual do Ambiente 2014) is located within the most populous and urbanised region of South America, where basic sanitation services are precarious (Obraczka *et al.* 2019) and the number of industries is high (Santana *et al.* 2020). Kataoka *et al.* (2019) highlighted that small plastic fragments floating on the surface of rivers are associated with places where sewage systems are inexistent, where domestic wastewater is drained directly into rivers without going through wastewater treatment plants. When a sewage system is implemented, domestic wastewater and wastewater from agricultural (livestock) and industrial activities are directed to rivers after the removal of most debris by the treatment plants (Dris *et al.* 2017). Thus, the presence of MPs in rivers depends on the size of the waste filters used at the water treatment facilities.

Some MPs that float on the surface of the rivers can originate, for example, from the fragmentation process of plastic that is trampled by vehicles in an urban area (Nizzetto *et al.* 2016). MPs in urban areas are transported to rivers mainly by rainwater through street gutters and by wind (Kataoka *et al.* 2019). Landfills and the margins of the river itself (floodplain) may be sources of MPs for the body of water. Plastic waste deposited along the margins can be introduced into the water column when the level of the water reaches it, which occurs during high-water season (Schmidt *et al.* 2017), after which the waste is carried to the ocean. Similarly, to the residence time of MPs on beaches (Kataoka *et al.* 2013; Kataoka and Hinata 2015), the time of debris in diffuse sources is an important parameter that influences the generation of plastic fragments in a watershed (Kataoka *et al.* 2019).

The most common polymer in the surface of the Paraíba do Sul River was PET. This polymer, also known as polyester, is used abundantly to manufacture fabric for clothes and, in general, consumer product industry (Wang *et al.* 2019); this is a typical synthetic polymer with high annual production worldwide (Wang *et al.* 2017). PET is light, tear-resistant, repels water and is resistant against chemical products, making it a popular option for bottling water and soft drinks (Käppler *et al.* 2016). PET filaments are widely used for textile products, such as clothes, blankets, and synthetic yarn (Wang *et al.* 2017), and can be released into the environment through the discharge of domestic and industrial effluents (Kay *et al.* 2018).

PET filaments present in domestic effluents are in fact the main source of MP filaments in freshwater environments (Wang *et al.* 2017), corroborating the present results. Approximately 2 g of microfibres are released in a single wash of a piece of clothing made of polyester (Hartline *et al.* 2016). The plastic materials that are most commonly used to manufacture fishing nets (e.g. ropes and netting) also include PET fibres in their composition (Qiu *et al.* 2015). Lost rope and fishing gear and tools used in recreational navigation that are irregularly discarded are considered another source of fibres to the environment (Welden and Cowie 2017). PET is used in food and cosmetic packaging, plastic containers, tubes, and clingfilm (He *et al.* 2020; Chinfak *et al.* 2021), which are all materials that can be commonly observed along the margins of the Paraíba do Sul River, carried away by the current and disposed by inhabitants that live near the river.

The PVC was the second most abundant polymer in the surface waters of the Paraíba do Sul River. The occurrence of PVC in water samples indicates the spill or disposal of products near the sampling site (Huang *et al.* 2021), considering that the most relevant toxic effects are related to this polymer. Browne *et al.* (2013) described that PVC with adsorbed nonylphenol and triclosan can damage immunological functions, besides causing physiological stress and mortality among various organisms (Browne *et al.* 2013).

MPs composed of high-density polyethylene (HDPE) and polystyrene (PS) were less representative in the area studied, following the same trend observed by Sarkar *et al.* (2019), Fan *et al.* (2019) and Liu *et al.* (2021). Most multicoloured fragments sampled were identified as HDPE. Plastic fragments are composed mainly of polyethylene (PE) polymers (Fan *et al.* 2019) and are more abundant in surface waters than in sediments; they can originate from the degradation of many types of plastic waste, such as agricultural equipment, packaging, and plastic bags (Antunes *et al.* 2013). PS, which is mainly present in polystyrene foam, is used as a thermal insulator (Simul Bhuyan *et al.* 2021). Studies by Tan *et al.* (2019), with organic pollutants (PAHs) and persistent organic pollutants (POPs) associated with MPs in surface waters in China, described PS as the polymer with greatest adsorption of contaminant. Organic pollutants associated with MPs form complex contaminants that can be transferred to different trophic levels through the food chain, representing potential threats to ecosystems (Dantas *et al.* 2020).

Conclusions

The Paraíba do Sul River is more one aquatic system becoming 'colourful' because of the omnipresence of assorted microplastics, the main footprint of the Anthropocene. Our results indicated that the abundance and richness of MPs in the surface waters of the Paraíba do Sul River are significantly influenced by the rainfall regime. However, in view of climate change, which encompasses an increase in the frequency and intensity of river floods (Fiorillo and Ghosn 2018), our results present significant implications for the management of MPs in riverine and marine systems, within the context of global climatic alterations. Rainfall volume is expected to increase between 1 and 2% for every 1°C of warming observed in mean ocean temperature, promoting a decrease in the intervals between floods (Marrafon and Reboita 2020). Any increase in the frequency of floods is likely to increase the exchanges of MPs between the riverbed and the water column, as well as the availability of these particles to pelagic organisms (Xia *et al.* 2020). We emphasise that although our results present relevant information on the temporal dynamics of MPs in a large river system in south-eastern Brazil, we recognise the need for sampling larger volumes of water (~100 L). In addition, we recommend more frequent sampling in the assessment of MP pollution and its relation to rainfall regime.

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Data availability. All data generated or analysed during this study are included in this published article. In case more data are needed for specific purposes, they are available from the corresponding author on request.

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