

Article

Stormwater Detention Reservoirs: An Opportunity for Monitoring and a Potential Site to Prevent the Spread of Urban Microplastics

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Abstract: Stormwater runoff carries pollutants from urban areas to rivers and has the potential to be a main contributing source of microplastics (MPs) to the ecosystem. Stormwater detention reservoirs (SDRs) differ from ponds and lakes in that SDRs retain most particulate matter and they are emptied after storm events. This paper investigates the occurrence of MPs in the SDR of the Alto-Tietê catchment area, Itaim stream in Poá city, São Paulo, Brazil. The MPs found were classified in different categories: shapes (fragment, line/fibre, film/sheet and pellet); size (<0.5 mm, between 0.5 mm and 1 mm and >1 mm); and polymer composition. Results have shown that most of the MPs found in the samples are fragments (57%), followed by pellets (27%), fibres/lines (9%), and then films/sheets (6%). Small particles (<0.5 mm) represented 89% of the total MPs, and this category mainly included fragments (62%) and pellets (30%). MPs were found in a vast variety of shapes and colours, which shows a likely variety of sources. Besides the occurrence of MPs in the stormwater samples, the potential of SDRs as a first sanitary barrier to retain MPs before they reach the ecosystem has been speculated.

Keywords: microplastics; stormwater detention reservoir; urban water; sediments; runoff

1. Introduction

Microplastics (MPs) are plastic particles within the range 1 µm–5 mm [1]. They may have been produced at this scale or have originated from the fragmentation of plastic waste (by physical, bio or photo-degradation). Microplastics are released from a large variety of industries, activities and even households and this diversity of sources also translates into heterogeneity of sizes, shapes, colours, compositions and densities of these pollutants in the environment [2].

MPs' impact on the environment is not well defined, in part because of methodological challenges [3], but consensus is that their potential effect is negative [4,5] and, given the high stability of polymers, the negative impact of MP may persist for considerable time periods. The effect of MP's shape on toxicity is yet to be established. Microfibers have been reviewed as the predominant type of microplastic ingested by freshwater biota [3]. Indeed, MPs with sharp edges such as fibres can cause a reduction in food intake, intestinal damage and oxidative stress in organisms such as snails [6]. The effects of MPs on different taxa have been identified, although there are also works describing

non-observed effects [3]. MPs, when sufficiently small (e.g., <20 µm), can enter the bloodstream of organisms [7] and can affect cells as has been found for some nanoplastics [8]. Small particles, bigger than 1 mm (coarse particulate organic matter—CPOM) and smaller than 1 mm (fine particulate organic matter—FPOM) can be ingested by invertebrates from the scrapers functional group or facultative in their morpho-behavioral feeding [9]. Examples of these invertebrates are Trichoptera and Diptera (filterer-collectors or suspension-feeders from water column), and Ephemeroptera and Chironomidae (collector-gatherers or deposit feeders from surface deposits or soft sediments) [9]. The presence of MPs was detected in multiple species of animals from riverine macroinvertebrates (by detritivore and filter-feeding) [10] to pelagic and demersal fish [11]; therefore, these particles end up in the food chain by these less selectively CPOM and FPOM eaters [12]. MPs transport and retention in streams and rivers have been studied [13] and the effects of MPs can be extended to the terrestrial environment, on sediments [14] and soil, impacting microbial ecology, animals, and nutrients cycles [15]. The structure and composition of MPs will determine their capacity to uptake and carry other pollutants [16].

MPs can be found in terrestrial, marine and freshwater ecosystems [2,3,17]. They can be introduced in the environment by inadequate disposal of plastic waste, wastewater effluents [18,19] and by stormwater [20], amongst other sources. Unlike oceans and rivers, urban lakes and reservoirs receive these pollutants mainly from the surrounding environment [20,21].

Cities are major sources of MPs to the environment because they concentrate many activities that result in the release of plastic (e.g., the disposal of packaging, use and washing of textiles) through processes related with construction, transport, wastewater treatment or overflowing of combined sewers [19]. During storm events, MPs can be transported to SDRs where they can remain. Hence, the study of MPs in stormwater reservoirs is of utmost importance for monitoring the MPs' journey to the environment.

With high levels of urbanization, big cities have serious historical problems of flooding in the summer [22] and in order to minimise the environmental impacts caused by the floods, several structural works, such as canalisation, expansion, rectification, deepening and unwandering of the channels of the main rivers are adopted to reduce flood impact.

Stormwater detention reservoirs (SDR) have also been applied as a hydraulic engineering solution to minimise the impact of the floods in Brazilian urban areas on the last decades (especially in São Paulo in the late 80s) [23]. They are usually built alongside the rivers and streams in urban areas to be used as a runoff control volume in extreme rainfall events and are empty during the dry season [24]. SDR differs from ponds and lakes used to attenuate peaks of floods due to its peculiar operation. Stormwater is pumped out of the detention reservoir after a rainfall event and so all density classes of particulate material, from low to high, remain inside the reservoir.

Due to the urban location of the sampling point, a large variety (of colours, shapes and types) of MPs is expected in the sediment of the SDR. The investigation of MP in the SDR can also determine the composition and degradation level of these pollutants when they are carried by the river and streams from urban areas during a raining event. Furthermore, because of the way SDR operates [25], it is speculated that SDRs may act as a preliminary barrier to prevent the spread of MP from the city to the ecosystem. Therefore, the aim of this work was to characterise and quantify MPs in the SDR sediment in an urban area located in Poá city at the São Paulo Metropolitan Area. Specifically, this work has been carried out in Piscinão da Vila Romana. However, this work also approaches the potential of SDR as a first barrier for retaining MPs and hence intends to complement the current knowledge on MPs in urban reservoir and stormwater ponds as a first case study of its kind [26].

2. Materials and Methods

2.1. General Hydrologic Data

The area's climate is Aw type (Köppen classification) [27]; that is, rainy tropical climate, with rains in summer and dry winter. The average monthly and annual rainfall in the Itaim Stream basin were obtained using data from the E3-091 rain station (23°29'00" S and 46°22'00" W), between 1944 and 2017.

There are no historical data on the stream flow for this specific case. Thus, to determine their average annual flows, the Equation (1) developed by DAEE (Departamento de Águas e Energia Elétrica—1988) was used.

$$Q = (a + b \times P) \times A, \quad (1)$$

where Q = mean annual discharge (L/s); P = mean annual rainfall (mm); A = drainage area (km²); and parameters " a " and " b " defined as -26.23 and 0.0278 , respectively.

The intensity–frequency–duration relationship presented in Equation (2) was based on the extreme data set events registered by a pluviometer at the catchment area [28]. This equation was used to evaluate the frequency of preceding trigger events that washed the urban surface out and end up in the SDR.

$$I = 31.62(d + 20)^{-0.8673} + 5.686(d + 10)^{-0.8071}(-0.4847 - 0.9062 \text{Ln}\left(\text{Ln}\left(\frac{TR}{TR - 1}\right)\right)), \quad (2)$$

valid for $10 \leq d \leq 1440$ min, where I = rainfall intensity (mm/min); d = rainfall duration (min); TR = year return period (year).

2.2. Sampling and Preparation Method

The São Paulo Metropolitan Area (SPMA) covers 39 municipalities and is located at the Alto-Tietê River catchment, which has an area of 5868 km² and approximately 20 million inhabitants [29]. Its main tributaries are the Tietê, Pinheiros, Tamaduateí, Claro, Paraitinga, Jundiá, Biritiba-Mirim and Taiacupeba rivers.

The Itaim Stream, in the city of Poá, is one of the tributaries of the Alto-Tietê River catchment with an area of approximately 14.7 km². It is located in SPMA, between 23°30'30" and 23°33'30" S and 46°19'42" and 46°22'55" W, covering the municipalities of Ferraz de Vasconcelos and Poá (Figure 1a). The land of the study area is mainly occupied by urban buildings (79.9%), meadow (6.4%), bare soil (3.5%) and trees and shrubs (10.2%) as analysed from aerial photography of the area (Figure 1a).

The SDR located at the Poá city centre (Piscinão da Vila Romana) has ~250 m length and 14 m depth, with the capability to store up to 210 million litres of water (Figure 1b). It started to be used in 2018 to reduce flooding in Poá city centre [30]. It must be stressed that SDRs do not operate as continuous flow, but as an intermittent mode. The studied SDR was only used twice (December 2018 and January 2019) before the sampling for this present study was carried out. During these storm events, it received around 60 million litres and 180 million litres in 2018 and 2019, respectively [31]. Therefore, samples from the SDR sediment represent the sediments carried by the overland flow from the two described events, given that the SDR was not cleaned in between events.

Sediment samples were collected from the empty reservoir from two different points chosen at the same visit, i.e., one sample of approximately 2 kg of sediment from each sample point: SP 1 close to the inlet and SP 2 close to the outlet of the SDR (shown in Figure 1c,d, respectively). Emptying for the SDR depends upon operational criteria, such as the storm duration and stream flow capacity, and it is generally done less than 24 h after the storm. The study samples were collected around both the reservoir inlet and outlet. They were stored in suitable containers and transported immediately to the Environmental Geochemistry Laboratory at the Department of Geography and Environmental Planning—UNESP in Rio Claro. Samples were dried at room temperature and prepared by density separation with ZnCl₂, adapting a previously published method [26,32,33]. Representative samples

(triplicates of 30 g of sediment of each point totalising 6 samples analysed) were added to a glass beaker with 300 mL of $ZnCl_2$ ($\geq 98\%$, from Sigma-Aldrich, São Paulo, Brazil) at a dose of $1.6 \text{ g } ZnCl_2/cm^3$ solution. The mixture was homogenised and left overnight at ambient temperature. The solutions were transferred to an Imhoff cone where, after 24 h of precipitation and sedimentation, the supernatant was collected. This step was repeated twice and the extracted solution was filtered through a $0.45 \mu\text{m}$ cellulose nitrate membrane filter with 47 mm of diameter (Sartorius, São Bernardo, Brazil) before being left to dry at ambient temperature for 24 h in petri dishes in a closed, low-temperature controlled room (to control any possible airborne contamination) prior to analysis.

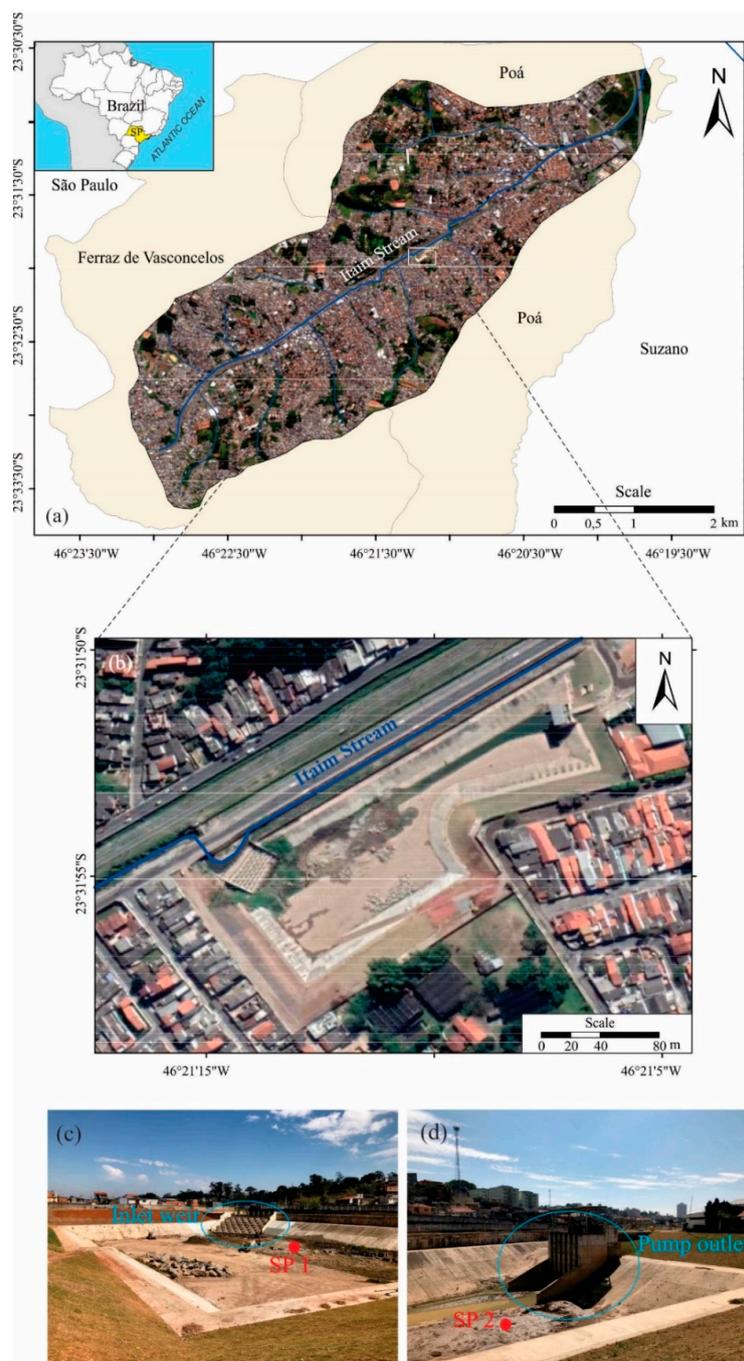


Figure 1. Sampling Area. (a) Itaim Stream catchment; (b) Poá Stormwater detention reservoir (Piscinão da Vila Romana); (c,d) Sampling points SP 1 (c) and SP 2 (d).

2.3. Quantification and Characterization of Microplastics

MPs were identified visually using a microscope (Zeiss Discovery V12 SteREO, São Paulo, Brazil) with an integrated camera (AxioCam ERc 5s). They were categorised by shape, size and composition [32] (see Table 1). Particles were counted according to their physical properties (texture, colour and flexibility), and soft organic materials other than plastic sheets (such as small pieces of leaves and insects) were discarded.

Table 1. Microplastics categories.

Category	Definition
Shape	
Line/Fibres	Length \gg diameter
Film/Sheets	Length \ll thickness
Fragments	Irregular shape
Pellets	Spheres and microbeads made of this size
Size	
	(<0.5 mm, 0.5–1 mm, >1 mm)
Composition	
	Based on spectroscopy bands

Some frequent particle types were selected to try to represent the samples and then were individually separated, cleaned (with distilled water) and analysed by ATR FT-IR (Varian) with a wavelength range from 400–4000 cm^{-1} or Raman spectroscopy (Olympus BX51, Princeton Instruments Action SP2500, 632 nm HeNe laser, Raman shift 390–600 cm^{-1} , Princeton, United Kingdom). Spectra were compared to the literature and online databases (Bio-Rad Sadtler, São Paulo, Brazil) [34,35]. Finally, morphology and weathering of the MPs were studied using scanning electrical microscopy with energy dispersive spectroscopy (SEM-EDS, JEOL—JSM-6010 LA).

3. Results

3.1. Hydrological Data Analysis

The monthly rainfall (average of 115.9 mm per month) in the study site peaks in January, whereas August is the driest month, with monthly averages of 241.5 and 33.4 mm, respectively (Figure 2a). The average annual rainfall was 1387.3 mm, with the years 1976 (1990 mm) and 1983 (1986 mm) showing the highest annual averages, while the years 1955 and 1984 had the lowest rainfall (906 and 1026 mm, respectively) (Figure 2b). The average annual flow obtained for Itaim Stream was 181.8 L/s, with the annual averages concentrated in the range of 150–250 L/s.

To calculate the annual rainfall between 1944 and 2017, the annual average flow of the Itaim Stream was used [28]. Thus, through the precipitation–flow ratio it was possible to obtain the average annual flow for those years (Figure 2c). Figure 2d, derived from Equation (2), illustrates the rainfall intensities (mm/h) for different durations (min) and return periods (year). These data were used to characterise stormwater events before sampling. The maximum preceding precipitation event registered resulting in flow going into the detention reservoir was 57.3 mm/h, thus resulting in a return period of 8 years. This indicate a probability $P(x \geq X)$ of 73% for 10 consecutive years. However, lower intensities (return period of 5 years) have also resulted in flow to the detention reservoir, due to the high impervious surface on the catchment area (80%).

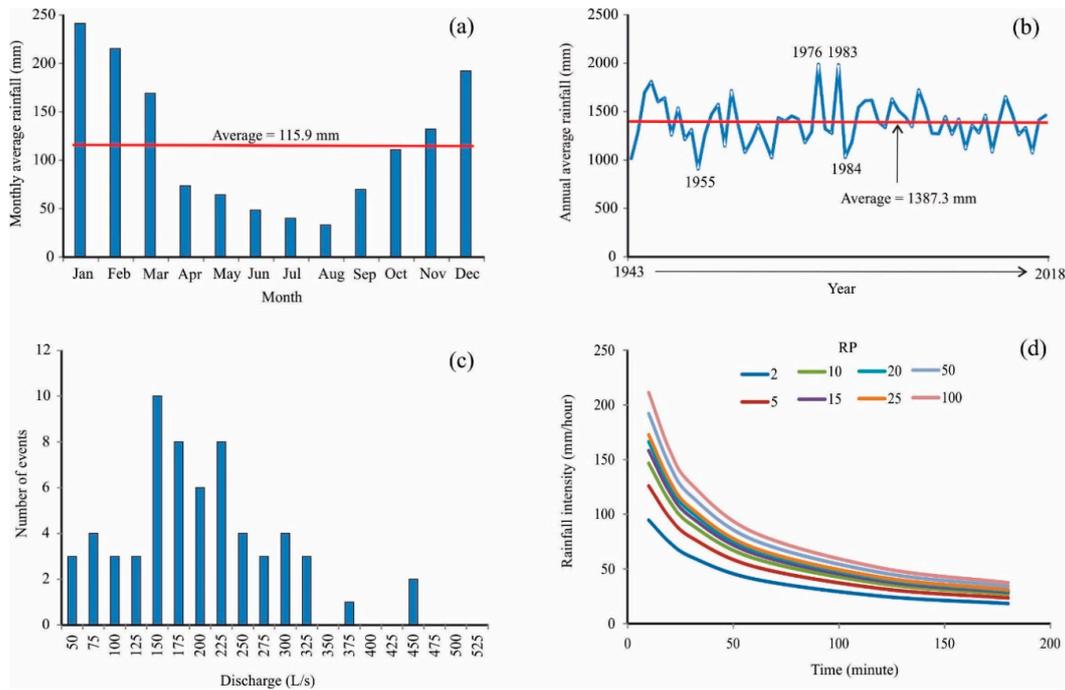


Figure 2. Rainfall data for the catchment area. (a,b) Monthly (a) and annual (b) averages rainfall; (c) frequency of discharge for a 73-year period (1944–2017) in the Itaim Stream catchment (DAEE); (d) rainfall intensity with different return periods (RP) in the Itaim Stream catchment. Graphs made by the authors based on raw data available on DAEE database.

3.2. Microplastics Quantification

The number of MPs per size range found in the SDR sediment samples are shown in Table 2. Further information on their distribution by shape and size is displayed in Figure 3.

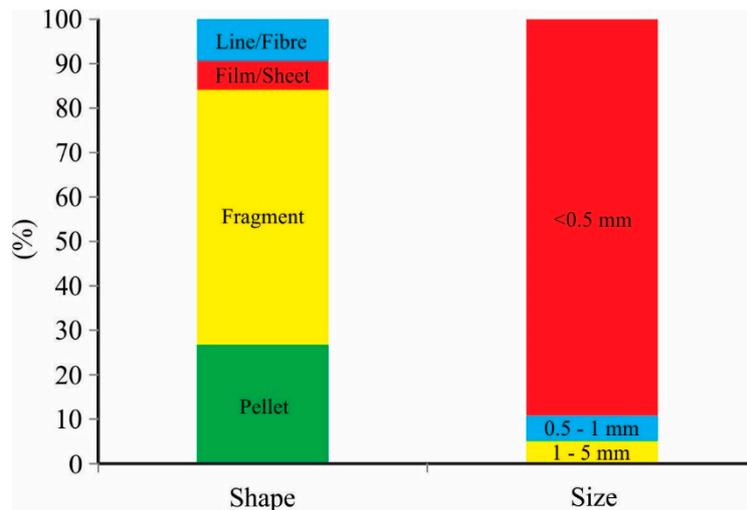


Figure 3. Shape and size of the identified MPs from the SDR sediments.

Different MP size, colours and materials were identified inside the same shape classification (Figure 4). The main type of polymers in the samples were polyethylene (PE), polyester (PES), polypropylene (PP), polystyrene (PS), and polyamide (nylon) (PA) according to analysis with FT-IR and Raman. Black particles were identified as tyre fragments by Raman spectroscopy and optical microscopy (Figure 5). Photomicrographs illustrate a typical rough surface and the etch pits due to the

weathering of polyethylene (Figure 6a), the size of pellet (Figure 6b) and the smooth surface of lines (Figure 6c,d).

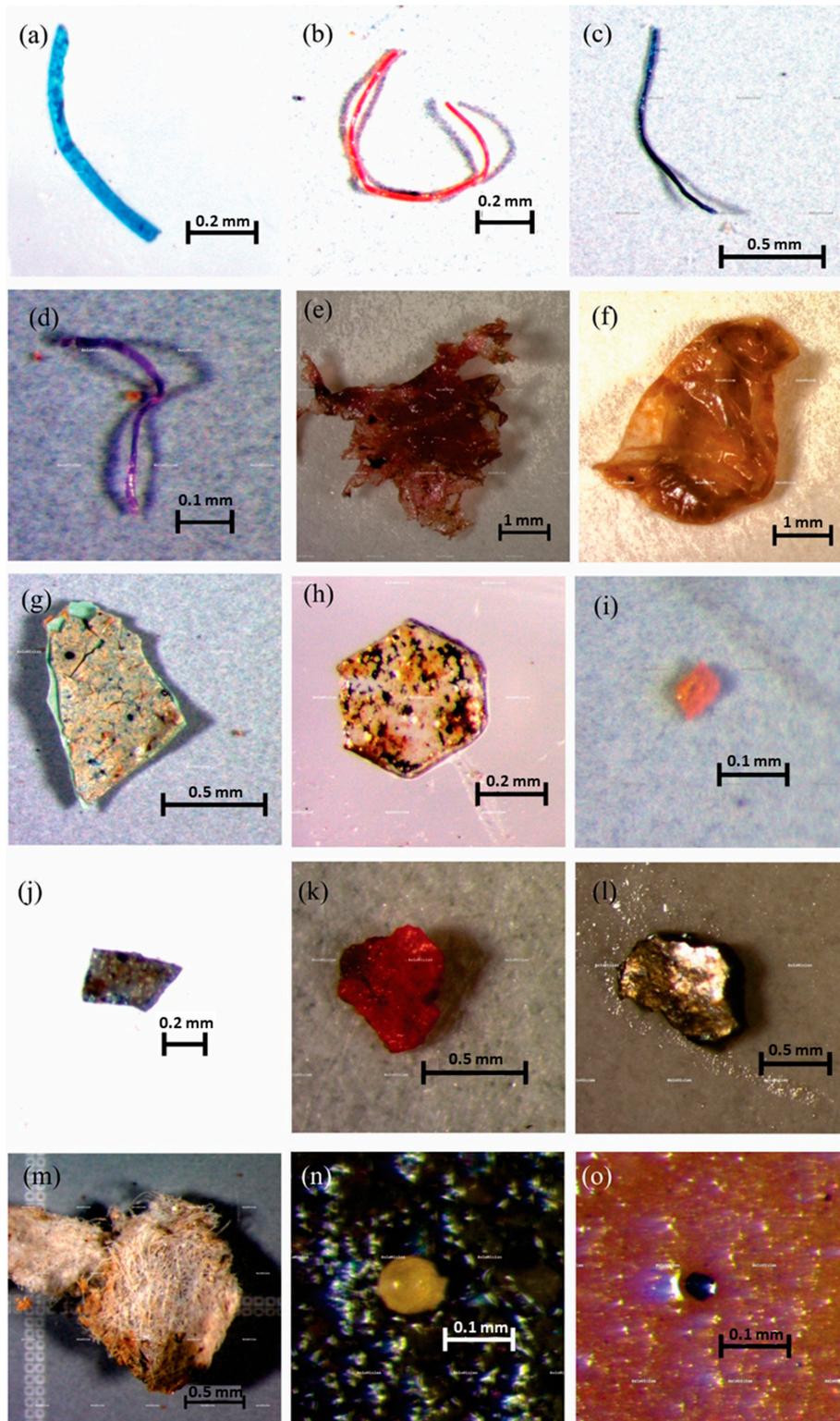


Figure 4. Types of MPs found in sediments from the SDR: (a–d) lines/fibres; (e–h) films and sheets, (i–m) fragments; and (n,o) pellets.

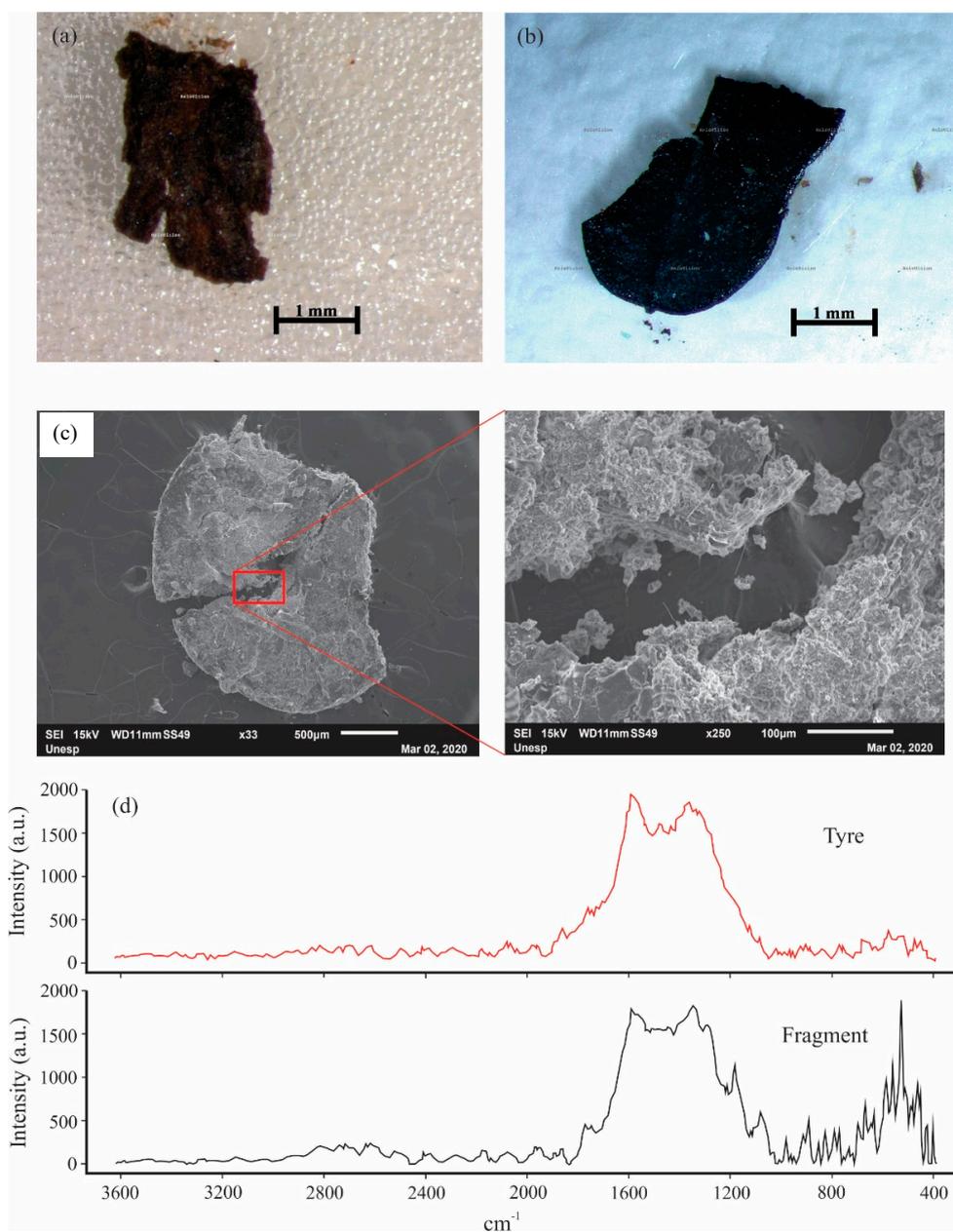


Figure 5. MPs identified as tyres. (a,b) Optical microscopy images; (c) SEM micrographs showing the morphology of this MP; and (d) Raman Spectra of tyre (used as comparison standard) and fragments from the sediments in the stormwater detention reservoir.

Table 2. Characteristics of the MPs found in the sediment samples (30 g) from the SDR by shape and size (unit/kg). The relative standard deviation (RSD%) from n = X is given in brackets.

Microplastic	<0.5 mm (MP Units/kg)	0.5–1 mm (MP Units/kg)	1–5 mm MP Units/kg)	Total (MP Units/kg)
Line/Fibre	2217 (±56%)	1567 (±58%)	1583 (±36%)	5367 (±41%)
Film/Sheet	2092 (±46%)	825 (±47%)	858 (±73%)	3775 (±45%)
Fragment	31,608 (±22%)	883 (±59%)	492 (±52%)	32,984 (±22%)
Pellet	15,417 (±57%)	-	-	15,417 (±57%)
Total	51,333 (±32%)	3275 (±48%)	2933 (±32%)	57,542 (±31%)

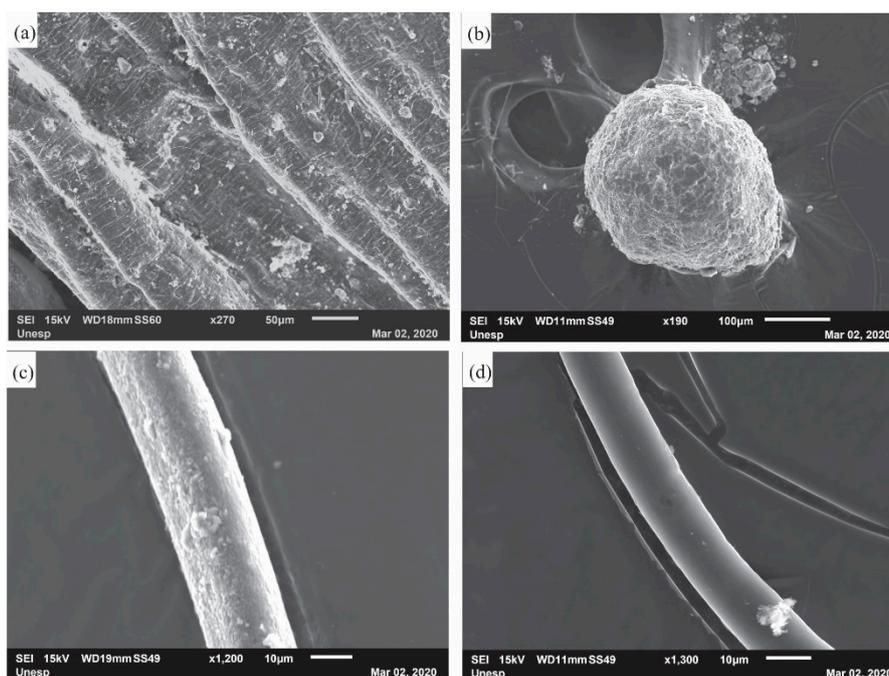


Figure 6. SEM-EDS micrographs of MPs. (a) plastic bag film); (b) black pellet; (c) red fiber; and (d) blue line.

4. Discussion

The opportunity of SDRs in retaining MPs as a first barrier against contamination, and the types of MP contamination that could reach ecosystems from urban runoff, are assessed here.

4.1. Microplastic Size Distribution

The MPs found in the SDR originated mostly from the urban runoff, as the SDR is designed for stormwater flow peak attenuation. However, some interference with non-regular sewage connections, atmospheric MP contamination [36] and runoff through milder events may also have contributed to the MPs found in the samples. These MPs from the SDR sediment came from the two main rainfall events: one of 164 mm (with average intensity 54.6 mm/h) and another of 172 mm (average intensity of 57.3 mm/h), with return periods of around 8 years (according to IDF, Equation (2)). This means that the likelihood of future events having equal or higher intensities are 49% in the next 5 years and 93% in the next 20 years. Therefore, they cannot be considered extreme events, although they resulted in excess volume of water collected into the stormwater reservoir due to the high impervious catchment area (c.a. 80%).

The most common MPs found in the samples were fragments (57%) followed by pellets (27%), fibres/lines (9%) and then films/sheets (6%). The high number of fragments is result of the degradation and breakage of big plastics in smaller particles [21]. Previous works studying microplastic in urban environment [25] also found fragments to be the most abundant type of MP [37]. In contrast, fibres were the most abundant microplastic in effluent from urban wastewater [19].

The classification highlights the total number of small particles, as 89% of the MPs are between 0.02 mm to 0.5 mm. This finding agrees with the literature [18,38]. The <0.5 mm fraction of the MPs were mainly formed by fragments (62%) and pellets (30%). The fragments were usually debris of bigger plastics such as tyres, bottles and other plastic materials [20]. Some fragments were identified as polystyrene (PS). PS MPs can be easily transported by runoff because of their low density [2] and are commonly used in food packaging.

Pellets (e.g., Figure 4n,o) were only found in sizes smaller than 0.5 mm in this study. This agrees with other works in highly populated and industrial areas [20]. These could be primary MPs, although some spheres could also be fragments that had been smoothed by physical forces [2,39]. Pellets were not characterised in this study. Previous research has found that they were polyethylene (PE) microbeads used in personal care products, cleaning compounds and industrial sandblasting [17,40].

This smaller MP range (<0.5 mm) can easily be transported through the water cycle, and these particles may be light enough for being transported by the wind and spread. The surface area of this fraction for MP may be larger, and since MPs can interact with other pollutants and act as a carrier [41], collecting them in SDR preventing their further spread is important. These MP particles can also easily enter the food chain as they resemble—in their size and shape—naturally supplied FPOM and consequently, could be ingested (from suspension and deposition) by benthic invertebrates (filterers and gatherers) [9–12].

The bigger fraction of MPs (from 1 to 5 mm) is mainly fibres/lines (54%). One thing that is important to highlight is that some fibres were found in agglomerates as showed in Figure 4m. These agglomerates were considered one single fragment. The fibres found in the SDR sediments were mostly polyester (PES) and were found in a vast variety of colours, which shows that the high number of fibres are not debris from a unique source, but they possibly came from diverse range of polluters. Previous works have indicated that fibres mainly originate from textile products. Fibres have been reported to be the main source of MPs in the oceans (add 30) and have high prevalence in freshwater environments [3].

Films and sheets were also an important category of the bigger fraction MPs (from 1 to 5 mm) (29%); however, they were mainly found in small sizes in the study sediments (55% < 0.5 mm, 22% 0.5–1 mm, 23% > 1 mm). Films were identified as made from PE for plastics bags or wrappers. Sheets were not identified, but the literature states that they are probably made from acrylic (PMMA) [20].

This research only identified PE, PES, PP, PS and PA as the polymers making up MPs. Given that this study analysed a limited number of samples, other MPs, such as polyethylene terephthalate (PET), polyurethane (PU), polyvinylchloride (PVC), acrylic, acrylamide, polyacrylate, alkyd resin, polyphenylene oxides (PPO), ethylene vinyl acetates (EVA) and others, may be potentially present in the samples, as other works have indicated [26,39,40].

Interestingly, a large number of the MPs found within the fragments fraction were black particles (around 30%). Raman analysis allowed these to be identified as fragments from tyres (Figure 6). Tyres are made from natural and synthetic rubber (polyisoprene or styrene-butadiene rubber (SBR)) that can get eroded. Tyre debris has been found to be a second major source of MP fragments in oceans [42], and synthetic fibres represent two-thirds of MP at sea [43]. Tyres have been also found to be a main source of MP in sediment samples [25]. The amount of tyre particles varies from each region, and in Brazil, the emissions of tyre wear and tear per capita are of 1.4 kg/year, which means they are a very significant source of MP in the environment [44].

The degradation degree of the samples varies considerably, as is demonstrated by the SEM results (Figure 6). This might be potentially caused by the stress and friction forces acting on MPs surfaces during transportation, as transportation takes place over a turbulent condition. Therefore, MPs can have their surface damaged or become broken during transportation, depending on their resistance to stress forces and friction. Fibres and pellets were usually found without degradation, while fragments and films had a high degree of degradation.

The low degradation of fibres and pellets can be explained by the direct discharge of these MPs by the wastewater system, while fragments and films are usually carried to the reservoir by the urban runoff. Since the smaller plastics may have a greater degree of toxicity [7,8], policymakers should consider restricting the use of plastics that can degrade to small fraction of fragments. Wastewater treatment must be adjusted to improve the removal of fibres and pellets.

Furthermore, given that SDRs retain MPs, these sites could be used as a preliminary barrier that would prevent ecosystem contamination, as long as regular maintenance is performed between rain

events. It is recommended that long-term sampling of the SDR sediment is studied to understand this further.

4.2. Comparing the Amount of Microplastic with Other Areas Elsewhere

The amount of microplastics found in the Poá SDR was 57,542 units/kg, which is compared with the MPs found in sediment samples elsewhere in Table 3. The average value obtained here is much larger than previous studies on MPs in lakes, mangrove, creek, rivers and beaches. In most previous studies, the sediment samples were taken with water columns and therefore the amount of debris was smaller. In addition, it is similar to the quantities of MP in sediments at the San Francisco Bay Region (up to 60,000 units/kg) [25], which was explained by wastewater and urban stormwater runoff at the bay. However, a quantity of up to 950,000 units/kg of MPs was found in a stormwater pond in Viborg, Denmark [45]. This high MP concentration was generated by the accumulated sediments of runoffs from urban and highway areas.

Table 3. Previous studies on MP in sediments.

Location	Country	MP Quantity	Reference
Lakes	Italy	Up to 234 units/kg	[46]
	China	Up to 300 units/kg	[21]
Mangrove	Singapore	Up to 63 units/kg	[47]
Creek	Canada	Up to 28,000 units/kg	[48]
Rivers	Germany	Up to 3763 units/kg	[39]
	South Africa	Up to 563 units/kg	[49]
	China (Tibet)	Up to 195 units/kg	[50]
	China	Up to 544 units/kg	[51]
	UK	Up to 660 units/kg	[52]
	New Zealand	Up to 80 units/kg	[38]
Beach	Belgium	Up to 390 units/kg	[53]
Bay	US	Up to 60,000 units/kg	[25]
Stormwater Pond	Denmark	Up to 950,000 units/kg	[45]
Poá SDR	Brazil	57,542 units/kg	Present study

In Poá SDR, the high amount of MPs can be explained by the way the reservoir works. The reservoir is filled in extreme intermittent rainfall events with urban runoff and then, after rain ceases and the level of river decreases, its water is pumped to the river, leaving behind all the sediments (i.e., settled and floated particles at the reservoir).

Therefore, it is expected that MPs are found in larger quantities in creeks, rivers, bays and SDRs located at urban areas than isolated areas, lakes and ocean. Urban areas are the centre of the contamination sources, and SDRs constitute an opportunity for monitoring and removing MPs from the urban environment.

This work acted as a first case study of MP in SDR, and parallel studies are suggested in various SDRs of the Sao Paulo Metropolitan area. Furthermore, samples from the SDR water layer and sediment should be taken after several events during at least one year for microplastic and microfibers characterization. Other physico-chemical parameters such as plastic degraded products and microbiological characteristics of the water accumulated in SDRs should be analysed.

5. Conclusions

This case study focused on quantification of MPs in the SDR in Poá, São Paulo Metropolitan Area. Rainfall events such as the ones analysed at this study result in flow to the detention reservoir, which has a probability of 73% to recur within 10 consecutive years. The operational model of

the reservoir and its location close to the MP sources generate a high quantity of MPs (57,542 MP units/kg sediment) in different degradation degrees. Specifically, these MPs consisted of fragments <0.5 mm (89%). These MPs can have ecotoxicity and can also act as carrier of other pollutants and microorganisms, which can be ultimately carried to the oceans and enter the food chain.

Most of the particles within the fragments fraction (around 30%) were identified as tyre debris, which represents a significant source of pollution to the environment. The degradation level of the MPs was assessed qualitatively and may be low in fibres and pellets and higher in fragments and films.

Due to the way SDRs operate, it can be speculated that they might work as a preliminary barrier to prevent the further spread of MP in the ecosystem and be used for MP removal, thus having a great ecological benefit. However, more research is needed to confirm what efficiency is expected overall and in what conditions removal may take place, without affecting the primordial purpose of SDR regarding flood control.

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