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Microplastics in freshwater river sediments in Shanghai, China: A case study of risk assessment in mega-cities☆

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ABSTRACT

Microplastics, which are plastic debris with a particle diameter of less than 5 mm, have attracted growing attention in recent years. Its widespread distributions in a variety of habitats have urged scientists to understand deeper regarding their potential impact on the marine living resources. Most studies on microplastics hitherto are focused on the marine environment, and research on risk assessment methodology is still limited. To understand the distribution of microplastics in urban rivers, this study investigated river sediments in Shanghai, the largest urban area in China. Seven sites were sampled to ensure maximum coverage of the city's central districts, and a tidal flat was also included to compare with river samples. Density separation, microscopic inspection and μ-FT-IR analysis were conducted to analyze the characteristics of microplastics and the type of polymers. The average abundance of microplastics in six river sediment samples was 802 items per kilogram of dry weight. The abundance in rivers was one to two orders of magnitude higher than in the tidal flat. White microplastic spheres were most commonly distributed in river sediments. Seven types of microplastics were identified, of which polypropylene was the most prevailing polymers presented. The study then conducted risk assessment of microplastics in sediments based on the observed results, and proposed a framework of environmental risk assessment. After reviewing waste disposal related legislation and regulations in China, this study conclude that *in situ* data and legitimate estimations should be incorporated as part of the practice when developing environmental policies aiming to tackle microplastic pollution.

1. Introduction

The usage of plastics has alarmed human society with growing scientific evidence concerning the deleterious impacts of end-of-life plastic products on wildlife. The rapid increase of plastics production in the 21st century has witnessed growth from 200 million tons in 2002 to 311 million tons in 2014 (Plastics Europe, 2015), with China, the EU, and North America being the major contributors. China's upward trend in plastics production, along with its mismanagement of waste, has been much debated (Jambeck et al., 2015). Plastic marine debris accumulation in ocean gyres poses an even greater threat to the marine environment, with microplastics being one of the contributors (Thompson et al., 2004).

Public and academic interest in microplastics has grown exponentially over the past several years. Microplastics, commonly defined as plastic particles smaller than 5 mm (Arthur et al., 2009), are widely distributed in many types of habitats from land to the ocean. Microplastics are found in the most remote places, such as the deep sea (Van Cauwenberghe et al., 2013), the Tibet plateau (Zhang et al., 2016), and the Arctic (Obbard et al., 2014). The growth of microplastic research in recent years reflects the attention it has garnered in academia, yet most microplastic studies focused on marine microplastics (Rillig, 2012). Data collected from freshwater environments is scarce (Wagner et al., 2014). Thus far, microplastic data in freshwater ecosystems has concentrated on lakes, e.g., the Great Lakes (Eriksen et al., 2013) and the Taihu Lake (Su et al., 2016). The spatial distribution of microplastics in river shore sediments has been previously studied (Klein et al., 2015). Ecological effects of microplastics include ingestion by biota (Remy et al., 2015), bioaccumulation and transport of persistent organic pollutants (POPs) (Andrady, 2011), and transport of microbial community and pathogens attached to microplastics (Zettler et al., 2013). The effects mentioned above may also apply to freshwater ecosystems,

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therefore studies on freshwater and terrestrial microplastics require more scientific attention. A recent study in urban surface waters confirmed that anthropogenic factors affect the abundance of microplastics (Wang et al., 2016). In the terrestrial environment, Dris et al. (2016) found microplastic concentration was higher at an urban site than that at a suburban site, revealing a possible atmospheric source of microplastics. To assess the environmental risk associated with microplastics, it is imperative that more data be collected from different ecosystems.

Here, we show that urban freshwater river sediments are a possible reservoir for land-based microplastics, and a source of marine microplastics. The lack of studies of microplastics in freshwater ecosystems has now become a hindrance to the understanding of the source and fate of microplastics. The study of river sediments throughout Shanghai urban river systems may provide a representative example of urban river input of microplastics in coastal cities. Evidence of microplastic transport pathways from land sources to the seas and oceans is still lacking. Shanghai is currently the most populated city in China, with a population of 24.15 million within a land area of 6340 km^2 in 2015 (Shanghai Statistical Yearbook, 2016). Gross Domestic Product (GDP) of Shanghai in 2015 reached 2512.34 billion yuan (approximately 370 billion USD), ranking first among Chinese cities (including Hong Kong). Shanghai is located in the Changjiang River Estuary, in which Changjiang River Plume is a significant hydrological process that affects the distribution of microplastics. Under the pressure of population growth and economic development, natural environment protection should be taken into consideration to achieve green development. The study is a pioneering research to conduct risk assessment of microplastics using data collected from bed sediments from urban river systems in mega-cities. Microplastic concentration data, possible sources, and the environmental behavior of urban plastic (microplastic) input were investigated. This study attempted to establish risk assessment indicators specific to sediments. Recommendations for constructing risk assessment systems were proposed in the Chinese context. To evaluate sources of microplastics and make suggestions for policy-makers, current legislation and regulations related to waste disposal in China were also summarized.

2. Materials and methods

Seven sampling sites covered six rivers and one tidal flat (NH) in Shanghai urban districts (Fig. 1). Detailed information on each sampling site is given in Table 1. Samples were collected during July and August 2016. River sediments were sampled during July 15 and August 1, 2016. Sediments from a tidal flat were sampled on July 13, 2016. The six rivers covered different river scales – small, medium and large rivers. Riverside samples include one from a park in Caohejing in Xuhui District (XH), one from a residential area in Beishagang in Songjiang District (SJ), one from a rural area in Jiangjiagang in Minhang District (MH), one from a park in Yujiabang in Pudong New Area (PD), one from a park in Shajinggang in Hongkou District (HK), and one from Gongqing park on a branch of Huangpu River in Yangpu District (YP). Sediments from a tidal flat located in Nanhuizui foreland (NH) were chosen to compare the concentration of microplastics in different environments. In the tidal flat, three sampling sites from high tide line to low tide line were chosen, and these samples were collected using a 0.5*0.5 m quadrat, where a quarter of the sediments were taken from the upper 5 cm in the quadrat. For each sampling site, 3 replicates were randomly collected along the accessible banks (for rivers) due to limited width in the river banks, or using a quadrat (for the tidal flat). Samples were collected with a shovel and moved to clean tin cups (for rivers) or aluminum foil (for the tidal flat) to avoid direct

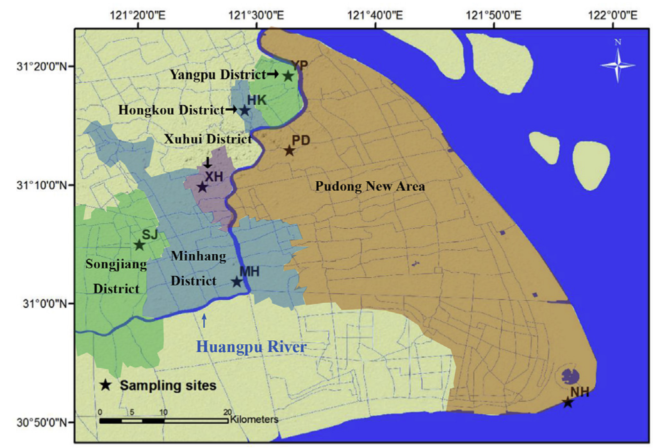

Fig. 1. Sampling sites of sediments from rivers and a tidal flat in Shanghai. Seven sites include YP, HK, XH, SJ, MH, PD and NH, with the land area of each municipal district shown in 4 colors. Black stars represent sampling sites. Blue lines on the map illustrate the urban river system, with the thick blue line being the Huangpu River. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

contact with bags during transfer. Then, sediments were placed in sealed bags, marked and transferred to the laboratory. Approximately 500 g sediments per replicate were collected from each sampling site.

The density separation process was carried out using the methods by Thompson et al. (2004), with modifications adjusted according to Masura et al. (2015). We excluded wet sieve and wet peroxide oxidation (WPO) during the process because no visible debris was found. To avoid airborne microfiber contamination, we took measures according to Zhao et al. (2017). Samples were first dried in an oven at 70 °C to constant weight. Then, a sample of 100 g dry sediment was weighed and placed in a glass beaker pre-rinsed with Milli Q water. Concentrated saline solution of NaCl (1.2 g mL^{-1}) was added to the beaker and stirred with a clean glass rod for 2 min. After it settled for 24 h, the supernatant containing microplastics was vacuum-filtered. We chose filter paper (Whatman GF/B, $\varphi = 1$ μm) that would collect the majority of microplastics. The last step of filtration was adding Milli Q water to remove chemicals. Filter paper containing microplastic particles was then dried to constant weight. The same process was repeated for all of the samples. Microscopic observations were carried out using Leica M165 FC. Photos of all suspected microplastic particles were taken and categorized according to shape, color and size. Then, microscopic Fourier transform infrared spectroscopy (μ-FT-IR) was applied to identify polymer types of suspected microplastics. μ-FT-IR analysis was carried out using Thermo Fisher Nicolet™ iN™10 in Shanghai Jiao Tong University and Bruker LUMOS in East China Normal University. Transmittance mode was chosen for Nicolet™ iN™10 and ATR (Attenuated Total Reflection) mode was chosen for LUMOS to acquire spectra. Library comparison results that match >70% confidence can be concluded to be plastic polymers. Summarized steps for two kinds of μ-FT-IR analysis are listed in Table S1. Statistical analyses were processed with IBM SPSS Statistics 22.

The ecological risk index method was proposed by Håkanson (1980), and is one of the most important ways to assess the potential ecological risks of sediments. Not only does this method take into account the environmental impact of various pollutants in particular environments, it also fully reflects the combined effects of multiple pollutants, thus rating the potential ecological risk. This method has been widely applied in the study of heavy metals (e.g.,

Table 1
Microplastic abundance, geographical coordinates, municipal districts and their population density, and types of functional zones of each sampling site. (*Source from Shanghai Statistical Yearbook, 2016).

Sampling site	Latitude (N)	Longitude (E)	Abbrev.	Municipal District	Density of Population* (person/km^2)	Functional Zone	Site Location	MP abundance (items 100 g^{-1} d.w.)
1	31.3208	121.5447	YP	Yangpu District	21 657	Park	Huangpu River branch	72.3 ± 30.6
2	31.2725	121.4836	HK	Hongkou District	34 501	Park	Shajinggang river	76.5 ± 27.6
3	31.1647	121.4242	XH	Xuhui District	19 889	Park	Caohejing river	153.5 ± 77.1
4	31.0831	121.3358	SJ	Songjiang District	2906	Residential	Beishagang river	160 ± 19.1
5	31.0314	121.4725	MH	Minhang District	6845	Rural	Jiangjiagang river	112 ± 5.6
6	31.2161	121.5467	PD	Pudong New Area	4523	Park	Yujiabang river	41 ± 12.7
7	30.8619	121.9378	NH	Pudong New Area	4523	Tourism	Nanhuizui tidal flat	5.3 ± 1.2

Rezaee et al., 2011). According to Håkanson (1980), C^i_f is used to assess the degree of microplastic pollution over a long time period. For a single pollutant, the C^i_f, T^i_r and E^i_r are calculated as follows:

$$C_f^i = C^i \Big/ C_n^i \tag{1}$$

$$T_r^i = \sum_{n=1}^{n} \frac{P_n}{C^i} \times S_n \tag{2}$$

$$E_r^i = T_r^i \times C_f^i \tag{3}$$

where C^i and C^i_n are the concentrations of pollutant *i* (i.e., microplastic) in polluted and unpolluted samples, respectively. P_n is the concentration of the specific polymer in microplastic samples, while S_n is the hazard score of plastic polymers (highest level) (Table 3). T^i_r is the toxicity coefficient introduced by Håkanson (1980), representing toxicity level and biological sensitivity. It is the sum of the percentage of certain polymers in the total sample (P_n/C^i) multiplied with the hazard score of plastic polymers (S_n).

Depending on the hazard score of the plastic polymer (UN GHS, 2009; Lithner et al., 2011), E^i_r is the potential ecological risk factor. Here, we suggest C^i_n represents the microplastic concentration in sediments before the boom of the plastics industry, in view of the history of the development of plastics industry. The value of C^i_n is a constant/reference value calculated by the concentration of microplastics in the past samples. It can be obtained by the analysis of sediment core samples in a certain area to acquire the abundance of microplastics before the mass production of plastics, alternatively, by the analysis of current data to simulate data in the past. Although determining how to set the value is not the focus of this study, it is however, worth simulating the accumulation process of microplastics through time in future research. Because there is no existing method to assess the risk of microplastics, we must obtain inspiration from other evaluation methods and rely on historical data to establish an appropriate framework of the assessment of ecological risk.

3. Results and discussion

3.1. Microplastic abundance in freshwater sediments

Microplastics were detected in all samples. The average microplastic abundance in six river sediment samples was 80.2 ± 59.4 items 100 g^{-1} dry weight (i.e., 802 ± 594 items kg^{-1} d.w.). Due to the prevalence of spherical particles in samples, concentrations of white spheres were calculated based on number of particles in a certain area of a filter. Seven sampling sites covered various urban functional zones, e.g., residential area and recreational area. Population densities and quantities of industrial waste contribute differently to plastic waste accumulation at each site. Therefore, microplastic abundance showed differentiated pattern in each sampling site (Fig. 2a). Based on Kruskal-Wallis *H* test, there was a statistically significant difference in the mean abundance in the seven sampling sites ($p = 0.027 < 0.05$). The mean abundance in the seven sampling sites was 72.3 ± 30.6, 76.5 ± 27.6, 153.5 ± 77.1, 160 ± 19.1, 112 ± 5.6, 41 ± 12.7, and 5.3 ± 1.2 items 100 g^{-1} d.w. in YP, HK, XH, SJ, MH, PD, and NH, respectively (Table 1).

Classified by shapes (Fig. 3a), spheres constituted of the majority of total microplastics (88.98%), followed by fiber (7.55%) and fragments (3.47%). Among all of the river samples, spheres outnumbered fragments and fibers. No spherical particles were found in tidal flat samples. The composition of different types of microplastics varied according to sampling sites. Sites close to large rivers had a relatively low abundance of microplastics (e.g., YP). Spheres were the most abundant in MH (94.57%) and HK (94.48%). In terms of color (Fig. 3b), most of the microplastics observed were white spheres (an example of a spherical particle is shown in Fig. 2b). In total, white spheres made up 90% of all microplastic particles. Blue (3%), transparent (3%), white (2%) and red (2%) microplastics were

Table 2
Identification results in sediments of seven sampling sites in Shanghai. Seven polymer types were identified, with the source of each polymer and instrument used specified.

Polymer type	Items (total)	Percentage	Site	Items (each site)	Instrument used
polypropylene	20	57.1%	XH	18	Thermo Fisher
			MH	2	Thermo Fisher
polyester	6	17.1%	SJ	3	Bruker
			NH	2	Bruker
			PD	1	Thermo Fisher
rayon	4	11.4%	YP	1	Thermo Fisher
			SJ	2	Bruker
			NH	1	Bruker
cotton + viscose(82:18)	2	5.7%	SJ	2	Bruker
phenoxy resin	1	2.9%	SJ	1	Bruker
poly(vinyl stearate)	1	2.9%	MH	1	Thermo Fisher
76%rayon+24%polyester	1	2.9%	SJ	1	Bruker
Total	35	100.0%	N/A	35	N/A

Table 3
Evaluation of microplastic ecological risk in sediments from urban rivers in Shanghai.

Site	Key polymer	The value of S_n[d]	The value of E^i_r/C^i_n[e]	Predicted level of risk
YP	Rayon	N/A	N/A	Friendly
HK[a]	N/A	N/A	N/A	N/A
PD	Polyester	4	4	Friendly
XH	Polypropylene	1	18	Friendly
SJ	Polyester	4	1504	Unfriendly
	phenoxy resin	1500		
MH[b]	Polypropylene	1	N/A	Unsure
	poly(vinyl stearate)	N/A		
NH[c]	Polyester	4	8	Friendly
	Rayon	N/A		

[a] Plastic composition of HK samples were not able to be identified.
[b] Poly (vinyl stearate) lacks ecological toxicity data, therefore its toxic degree cannot be determined.
[c] Rayon, for this method, is non-toxic.
[d] The value of S_n and hazard score of each polymer are taken from Lithner et al. (2011).
[e] Because the value of the constant (C^i_n) is not known, the value of E^i_r/C^i_n is applied here to compare risk among sites.

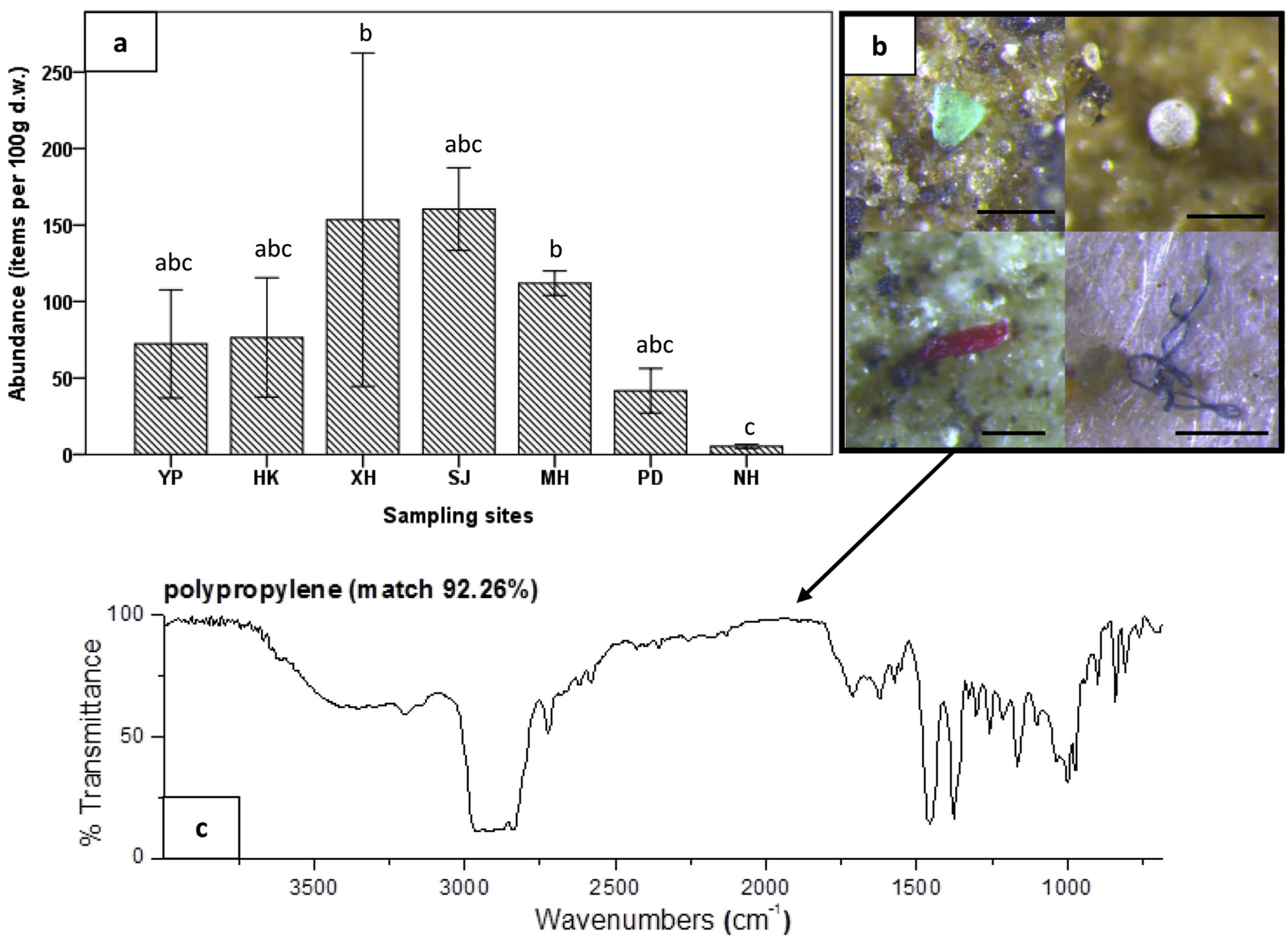

Fig. 2. (a) The average abundance of microplastics per 100 g dry weight sediment in seven sampling sites (error bars indicate standard error of the mean). Bars with the same letter have no significant difference (Mann-Whitney U test, $p < 0.05$). (b) Photos of observed microplastic particles in the shape of fragments, pellets, and fibers, and of various colors. All scale bars indicate 200 μm. (c) Infrared spectrum of the red fragment particle in 2b, which was identified as polypropylene by μ-FT-IR (match 92.26%). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

the minority among all the samples. For size distribution, 31.19% of total particles were smaller than 100 μm. 62.15% particles were between 100 and 500 μm, constituting the majority of all samples. 3.56% particles were between 500 and 1000 μm, and 2.8% particles were between 1000 and 5000 μm. 0.3% particles were larger than 5000 μm. River samples showed clearly different distribution patterns compared to the tidal flat (NH). Mean abundance of microplastics in river sediments in XH, SJ, and MH was two orders of magnitude greater than in tidal flat sediments (NH), and one order of magnitude greater in YP, HK and PD. Spheres were the majority

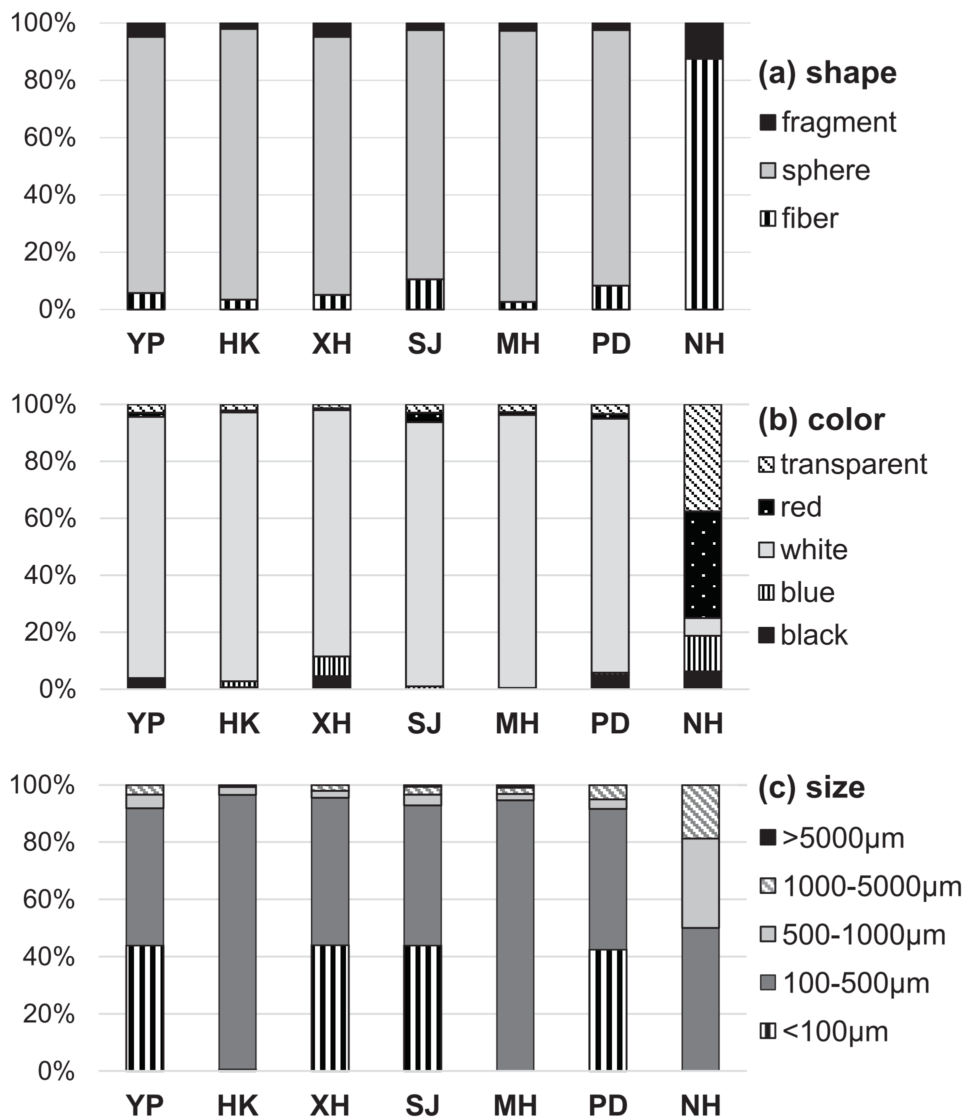

Fig. 3. (a) Shape, (b) color and (c) size distribution of microplastics in sediments from seven sampling sites, including six river samples and one tidal flat sample (NH). Microplastics in rivers showed a completely different distribution pattern from those in the tidal flat samples.

of particles in all of the river sediments. In contrast, tidal flat sediments mostly consisted of microplastic fibers. Color categories were more numerous in tidal flat sediments, while river sediments concentrated primarily of white spheres. The results revealed that rivers suffered more from human activities than tidal flats in tourist areas, thus becoming the hotspot for microplastic pollution in mega-cities.

3.2. Identification results of microplastics

Identification results are shown in Table 2. Seven polymer types were identified using μ-FT-IR, including 1) polypropylene, 2) polyester, 3) rayon, 4) cotton + viscose (82 + 18), 5) phenoxy resin, 6) poly(vinyl stearate) and 7) 76%rayon+24%polyester. In this study, the identification rate for Nicolet™ iN™10 was 53.5%, while for LUMOS it was 40%. Polypropylene (Fig. 2c) constituted of the majority of the identified polymers and was concentrated in the site XH. This may be a case of fragmentation in sediments, where an abandoned plastic debris particle fragments into many smaller pieces of microplastics. White granules were identified as polypropylene as well, and they constituted a large majority in the samples. Polypropylene (PP) is widely used in food packaging, folders, and car bumpers (Plastics Europe, 2015). Polyester is also a common polymer type of microplastics encountered in microplastic studies. Polyester is sometimes identified as polyethylene terephthalate (PET). When it shows up as a fiber, it can be regarded as polyester, the material commonly applied in the textile industry. Fabric synthetic fibers are the trend in fashion industry, aiming at designing cotton-like properties and eco-friendly products. Blending two to four kinds of natural fibers with synthetic fibers is a common practice of the textile industry, which may be the reason that two kinds of fabric fibers were identified in this study: cotton + viscose(82:18) and 76%rayon+24%polyester. Viscose has been identified in other microplastic studies (Remy et al., 2015). Similar to viscose, rayon is also a common type of microfiber derived from natural fibers and has been found in various habitats (Frias et al., 2016). While some studies decided not to include cellulose-based polymers in the results (Cózar et al., 2015), fibers do represent a major portion of microplastics around the world (Browne et al., 2011), although the abundance varies among habitats. Phenoxy resin is a thermoplastic resin made from bisphenol A and epichlorohydrin. Because of its excellent processing characteristics, including its thermal stability, phenoxy resin is widely used in the adhesive, paint and other industrial sectors. No polyethylene microbeads were identified. In conclusion, according to the identification results, polypropylene identified from XH may be a case of fragmentation, so we conclude that most microplastics in river sediments are secondary microplastics. Abandoned, weathered and fragmented, microplastics enter river sediments and become the source of marine microplastics.

3.3. Source of microplastics in urban freshwater ecosystems

As many studies have noted (Ryan, 2015), secondary microplastics make up the majority of microplastics in the environment. In this study, a probable process of fragmentation was observed, indicating microplastics are derived from land-based sources. Clothes washing also constitutes a large portion of microplastics entering the seas, as is suggested by the identification of polyester, rayon and other fibers. There remains the possibility that microplastics originate from upstream runoff, as Huangpu River is still a busy shipping lane. However, both international and national regulations and legislation have set a standard for dumping in the seas and inland waters (refer to Section 3.5 for an extended discussion). Therefore, it is unlikely that microplastics in this study were derived from shipping or waste dumping. Due to a lack of awareness regarding waste separation in China, consumers dispose of plastics without recycling, which leads to the potential that primary microplastics are directly discharged into various environmental habitats, e.g., spills from small plastic product factories. Large plastics debris degrades into secondary microplastic through process in garbage disposal plants, wastewater treatment plants and photooxidative degradation effects in the environment. When plastics are treated in combustion, solid particles account for 30%–50% of the exhaust gas (Durlak et al., 1998). Through precipitation, surface water erosion, sedimentation and other pathways, microplastics enter the atmosphere, soil, water and sediment. However, the proportion of microplastics entering each pathway is still unknown. Possible pathways of microplastics entering local freshwater ecosystems are shown in Fig. 4.

3.4. Risk assessment in urban freshwater ecosystems

Plastics, a class of polymers that was composed with monomers, are designed to satisfy the properties required in various usages (OECD, 2004). Polymerization reaction cannot occur completely, which results in the presence of residual toxic monomers in the polymer, and affects the properties of the polymer (Araújo et al., 2002). We incorporated environmental toxicity of the chemical composition of microplastics into risk assessment. The hazard score of each polymer is taken from the methods used by Lithner et al. (2011), and the value of S_n and E^i_r is therefore calculated based on Equations (1)–(3) from Section 2. Although the value of a constant (C^i_n) is unknown, during the comparison of risks among sites, we used the value of E^i_r/C^i_n to indicate the environmental risk factor for simplicity. The results are shown in Table 3.

Based on the evaluation method in Section 2, we predicted one unfriendly chemical composition of microplastics and three relatively friendly components. The average density in NH is less than PD, but its E^i_r is greater. The potential ecological risk in SJ is three orders of magnitude higher than in other sites because of phenoxy resin, a highly toxic substance. Although direct toxicity data on phenoxy resin is lacking, its main ingredient, bisphenol A, has been shown to be highly toxic to mammals and aquatic organisms. Therefore, even if the microplastic concentration is low, its chemical toxicity should not be ignored due to the presence of phenoxy resin in SJ. So far, the shortage of toxicity data on PP, PET and rayon cannot support the complete assessment of their risk. However, a high microplastic concentration will surely result in certain degree of environmental risk.

With the fast development of microplastic research, a growing number of results have revealed distribution patterns of microplastics across various habitats, and have accumulated baseline data (Lusher, 2015). Risk assessment models were developed for the chemical toxicity of plastic monomers (Lithner et al., 2011) and plastic thermodynamics (Gouin et al., 2011). We attempted to create a risk assessment framework of microplastics by using the method of the sedimentological approach, taking urban rivers in Shanghai as an example. The results indicate that a comprehensive assessment of ecological risk of microplastics should not only be evaluated simply by using concentration data but also chemical toxicity of microplastics. From a literature review, a number of studies on ecological risk of microplastics have concentrated on the damage to organisms. As a result, it is difficult to evaluate the seriousness of microplastic pollution over an entire area, which will deter decision-makers from developing relevant policies. We selected a typical microplastic contaminated area, and combined with *in situ* data to predict the potential risk of microplastics in urban river sediments. Our method consulted the risk assessment of China's major pollution accidents using hierarchical access to make the evaluation process more systematic (Fig. 5). Starting with an urban area of a mega-city, the framework can be applied to a larger scale in future studies.

An ecological risk assessment of microplastics can be analyzed qualitatively and quantitatively using data on their source, sink, fate, and abundance in different habitats, migration pathways, combined toxicity of persistent organic pollutants, transport of harmful microbes attached to microplastics and ecotoxicological effects etc. Assessing ecological risks is particularly challenging for microplastics. There remain problems in microplastic risk assessment, including a lack of unified sampling/quantification methods and well-defined environmentally relevant concentrations of microplastics.

Sediment samples can reflect the long-term interaction between waters and land interfaces (Yu et al., 2016), and provide important information on the migration and fate of pollutants (Greenpeace, 2006; Andrady, 2011; Wagner et al., 2014; Wang et al., 2017). A number of studies have indicated that density was not the only factor influencing distribution of microplastics (Thompson et al., 2004; Lima et al., 2014; Long et al., 2015). Hence, analyzing sediment samples is ideal for characterizing microplastics' long-term accumulation in aquatic habitats. The selected river systems flow through urban areas of Shanghai, and are disturbed by different types of human activities. Microplastics in the study area may come from land-based abandonment in recreational areas. In addition, upstream river runoff, where wastewater treatment effluents are discharged, may also bring microplastics into local river systems. Through sedimentation, microplastics in rivers tend to accumulate in river sediments. These complex transport processes have increased the difficulty of assessing the risk of microplastics in freshwater sediments. The key issue in risk evaluation is to identify the background values of pollutants, which in this case, are microplastics in urban freshwater ecosystems.

3.5. Waste disposal related legislation and regulations in China

Dumping plastic waste from land-based sources or operational plastic wastes at sea is banned under the London Dumping

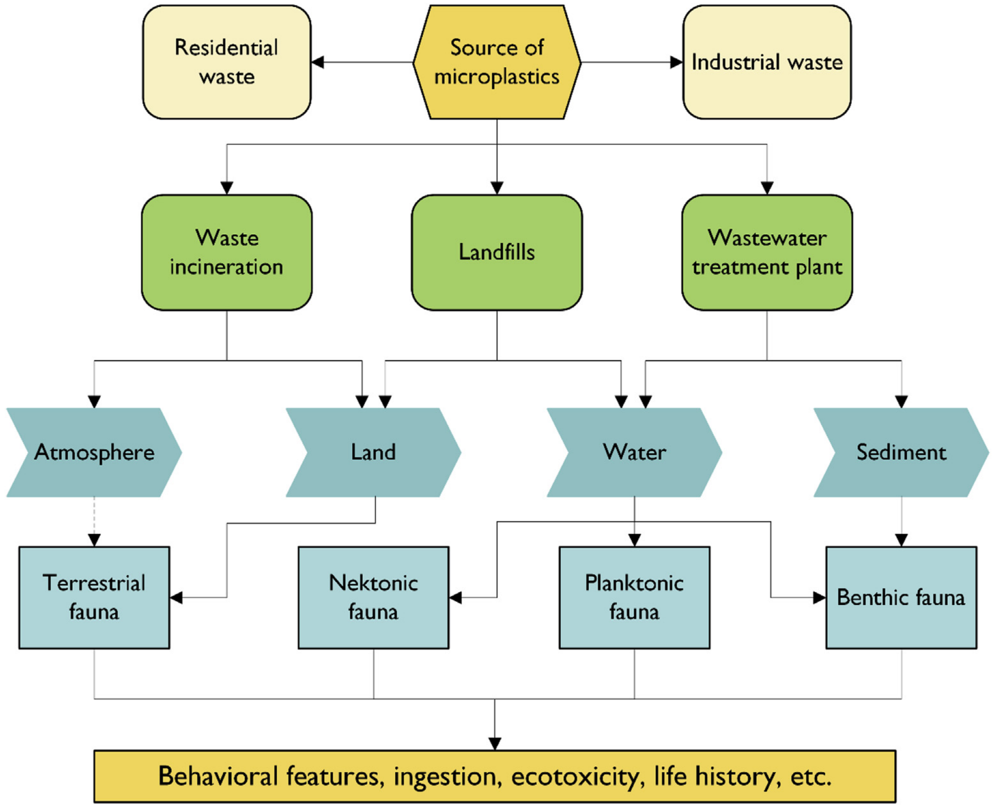

Fig. 4. Land-based sources, pathways into local freshwater ecosystems and relevant ecological effects of microplastics. The dotted line indicates a potential pathway that lacks direct evidence.

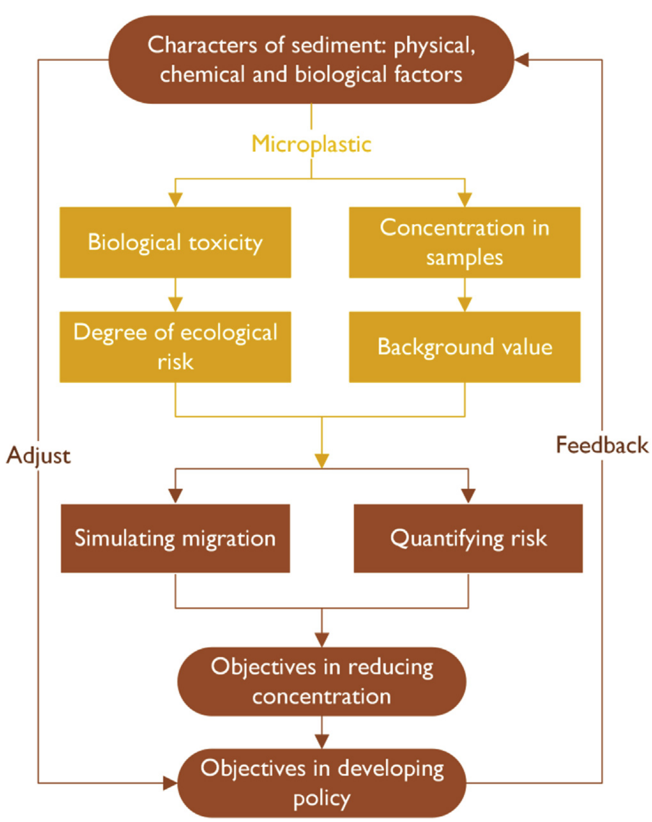

Fig. 5. Framework of ecological risk assessment of microplastics in urban freshwater ecosystems.

Convention in 1972 (Lentz, 1987) and the Annex V of the International Convention for the Prevention of Pollution from Ships (MARPOL) in 1988 (www.imo.org). China acceded to MARPOL in 1985 and has earnestly implemented the convention. Domestic laws include “Marine Environment Protection Law of the People's Republic of China” (Adopted in 1982, in force in 1983 and revised on Nov. 4, 2017), which banned dumping any wastes into the sea without approval of the competent State administrative department in charge of marine affairs. Chapter VII (Prevention and Control of Pollution Damage to the Marine Environment by Dumping of Wastes) requires assessing procedures and standards of dumping, following classified management in accordance with the categories and quantities of the wastes, and developing a list of wastes permitted to be dumped. “Regulations on Control over Dumping of Wastes in the Ocean” was promulgated in 1985. The regulations were specially formulated for the implementation of the “Marine Environmental Protection Law of the People's Republic of China” in order to maintain a strict control over the dumping of wastes into the ocean. Moreover, “Implementation measures of Regulations on Control over Dumping of Wastes” and “Interim Provisions on Dumping Sites Management” are important regulations issued by the State Oceanic Administration of PRC in 1990 and 2003, respectively. “Provisions on the Prevention of Pollution Damage to Yangtze River by Ship Garbage and Bankside Solid Waste” was issued in 1997, which regulated shipping and land-based waste discharge into the Yangtze River. “Regulations on the Prevention of Pollution Damage to the Marine Environment by Land – based Pollutants” was promulgated in 1990 to supervise land pollution sources and prevent damage to the marine environment. “Proposals on Strengthening the Management of the Plastic Package Wastes along Main Roads, in River Basins and at

Tourist Attractions" was approved in 1998 to prevent "White Pollution". In addition to being the world's largest plastic producer, China has also been the largest importer of solid waste for nearly three decades, which contributes to plastic input from land to sea. "Law of the People's Republic of China on the Prevention and Control of Environmental Pollution by Solid Waste" was promulgated in 1995, which restricted the types and quantities of solid waste to be imported, under supervision. "Measures on the Administration of Import of Solid Waste" was issued in 2011. In July 2017, the State Council approved an action plan to ban trash imports and reform the solid waste import management system to protect the environment. Links to specific laws and regulations can be found in Table S2. Based on the summary, plastic-related policies in China are still lacking, yet there has been no legislation on microplastics.

When managing regions affected by intensive human activities, combining environmental research and economic factors will greatly enhance awareness among policy-makers and decision-makers regarding the need to study microplastic pollution (Hardesty and Wilcox, 2017). Using *in-situ* data and environmental relevant concentration may avoid exaggeration of ecological impacts of microplastics when developing related policies. In view of the seriousness of the status of microplastic pollution in China, it is recommended to select an index, integrate statistical data, consistently follow expert opinions and construct a comprehensive evaluation method and ecological risk assessment system for the Chinese context.

4. Conclusion

All sediment samples from six urban river sites and one tidal flat contained microplastics with varying abundance. Microplastic abundance in rivers near densely populated areas was one to two orders of magnitude greater than in the tidal flat in rural areas of Shanghai. Moreover, features of microplastics in rivers were different from those in the tidal flat. White spheres composed the majority of microplastics in all river samples, while fibers and fragments outnumbered spheres in the tidal flat. Our study corroborates other similar studies in terms of the source of microplastics – the river input – at the estuary. A possible fragmentation process was observed, and seven polymer types were identified in total based on μ-FT-IR analysis. Polypropylene was the dominant type of microplastic. Our study closed gaps in knowledge between field study and risk assessment for the mega-city context. An attempt to conduct a risk assessment was carried out and we found one site had greater environmental risk than other sites. Existing researches have mostly examined the impact of exposure experiments on high-dose and short-term exposure rather than conducting a field investigation of environmentally relevant concentrations. By summarizing waste-related legislation and regulations in China, we conclude that currently microplastic-related policy is still lacking. It is imperative that microplastic/plastic related regulations and legislations be developed (Pettipas et al., 2016) based on *in situ* studies and legitimate estimations. The key to solving the problem of marine debris is designing sustainable raw materials and reducing their usage, consumption and production. Therefore, future research requires scientists from different fields and regions to work collaboratively in dealing with the worldwide issue of marine debris, and the microplastic legacy. This will help us understand their distribution, source, fate and trends over time, with a focus on monitoring and regulating the threat of microplastics to the marine environment.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.envpol.2017.11.034.

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