Environmental Science and Pollution Research (2022) 29:48453–48464
https://doi.org/10.1007/s11356-021-18284-7

RESEARCH ARTICLE

Characteristics and distribution of microplastics in shoreline sediments of the Yangtze River, main tributaries and lakes in China—From upper reaches to the estuary

Wenfeng Li[1,2,3] · Jia Duo[1,2,3] · Rehemanjiang Wufuer[1,2,3] · Shuzhi Wang[1,2,3] · Xiangliang Pan[1,2,3,4]

Received: 26 August 2021 / Accepted: 19 December 2021 / Published online: 22 February 2022

Abstract
Microplastics (MPs) pervade the environment and increasingly threaten both natural ecosystems and human health. In this study, we investigated MP particle concentrations in sediment samples collected from 54 sites along the banks of the Yangtze River and its major tributaries and on lakeshores. The main polymer types found in the samples were polypropylene (PP), polystyrene (PS) and polyethylene (PE). MP particle abundance in the various types of locations was 35–51,968 particles/kg dry weight (d.w.) on the banks of the main river, 52–1463 particles/kg (d.w.) on the banks of tributaries and 2574–23,685 particles/kg (d.w.) on lakeshores. Correlation between MP abundance and mean annual runoff of each upstream tributary was significant, which suggests that increased runoff brings more microplastic waste to streambank sediments. The most common shape of MP particles in all upstream samples was flake, and in downstream samples it was foam. Small microplastic particles (< 0.50 mm) were predominant at all sites in this study, and the minimum particle size in samples from the Yangtze river banks was 0.065 mm. Average abundance of MP particles on the shores of the source lake was 9069 particles/kg around the inlet but only 866 particles/kg around the outlet; the difference was due to interception associated with sedimentation and precipitation in the lake. Our study represents the large-scale study of MPs contamination in sediment along the Yangtze River and provides important data regarding the accumulation and distribution of MPs in shoreline sediments of the upper, middle and lower reaches of the Yangtze River, main tributaries and lakes in China.

Keywords Microplastics · Sediment · Characteristics · Distribution · Yangtze River

Responsible Editor: Xianliang Yi

✉ Rehemanjiang Wufuer
reheman319@ms.xjb.ac.cn

✉ Xiangliang Pan
panxiangliang@163.com

1 National Engineering Technology Research Center for Desert-Oasis Ecological Construction, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, 818 South Beijing Road, Urumqi 830011, Xinjiang, China

2 Xinjiang Key Laboratory of Environmental Pollution and Bioremediation, Xinjiang Institute of Ecology and Geography, Chinese Academy of Science, Urumqi 830011, China

3 University of Chinese Academy of Sciences, Beijing 100049, China

4 Key Laboratory of Microbial Technology for Industrial Pollution Control of Zhejiang Province, College of Environment, Zhejiang University of Technology, Hangzhou 310014, China

Introduction

Microplastics (MPs) are plastics < 5 mm in size that originate from primary and secondary MPs (Endo et al. 2005; Ryan et al. 2009). Since the concept of MPs was first proposed by Thompson et al. (2004), MPs have received considerable academic attention in recent years due to their persistence and questionable bioavailability in environments (do Sul and Costa 2014; Rachman 2018). MPs are found not only in surface water, but also in deep water, sediment, soil and organisms (Bergmann et al. 2017; Chae and An 2018). In general, small MPs cause the most harm to the natural environment because they are easily available to higher species and are concentrated as they move up the biological food chain (Canesi et al. 2015). MPs can also become vectors of toxic and harmful substances that can cause food or water pollution (Zhang et al. 2018a, b).

With respect to the presence of MPs in water, the importance of marine microplastic pollution research is self-evident

(Hidalgo-Ruz et al. 2012; Woodall Lucy et al. 2014; Desforges et al. 2014; do Sul and Costa 2014; Nguyen et al. 2019). At the same time, the study of MPs in freshwater areas is of great significance (Wu et al. 2018; Wang et al. 2018; Yin et al. 2020; Sekudewicz et al. 2021). Numerous studies have shown that most MPs in the ocean originate on land, and it has been estimated that globally 4.8–12.7 Mt plastic debris from inland water systems and terrestrial ecosystems has been transported to the ocean by riverine transport in 2010 (Jambeck et al. 2015). However, that 262.3–270.2 Mt plastic wastes remain the terrestrial environment, which is widely distributed in river headwaters, basins and estuaries, particularly nearby cities are hotspots of MP pollution (Xu et al. 2018; Hu et al. 2018; Jang et al. 2020).

As one of the largest rivers in the world, the Yangtze River is considered to be the largest plastic-export river to the ocean in all existing modeling studies (Lebreton et al. 2017; Schmidt et al. 2017) due to its high population density of its catchment and high consumption of plastics in China. However, the current research on the Yangtze River was mainly focused on the middle and lower reaches and major lakes, while relevant research has not been common in the source and main tributaries of the Yangtze River. Moreover, there have been few studies on characteristics and distribution of MPs in shoreline sediments of the Yangtze River, main tributaries and lakes in China. Therefore, systematic research on MPs in shoreline sediments of the Yangtze River, main tributaries and lakes can not only fill the data gap of MPs pollution in the whole Yangtze river valley area, but also provide reference for the better understanding of MPs distribution regularity in the upper and lower reaches of its tributaries, major urban basins and the import and export of main lakes.

The aims of this study are: (1) to illustrate the characteristics, abundance and spatial distribution of MPs in the banks of the upper, middle and lower reaches of the Yangtze River, main tributaries and the shores of lakes of China and (2) to explore the potential sources, influencing factors and their relationship to the distribution and retention of MPs in the Yangtze river valley area shoreline sediments. Results of this study can provide important data on the processes influencing microplastic distribution in shoreline sediments of the Yangtze River, main tributaries and lakes in China. At the same time, it also provides certain data support for local authorities in China to formulate microplastic pollution prevention measures and corresponding laws and regulations.

Materials and methods

Study area

Yangtze River, the third longest river in the word, flows through 11 provinces, regions and cities, from glaciers on Qinghai–Tibet Plateau into the East China Sea at Shanghai in China. The Jinsha River is the upper reaches of the Yangtze River, from Qinghai, Tibet into Sichuan province, and the Yalong River is the largest tributary of the Jinsha River. Tuo River, Jialing River and Wu river are also important tributaries of the upper reaches of the Yangtze River, located in southwest China. The Han River, the largest tributary of the Yangtze River, flows through Shaanxi and Hubei provinces and joins in Wuhan area. These tributaries are extremely important hydropower resources in China because of their large river fall and water flow. By 2013, there were 80 large reservoirs and 381 medium-sized reservoirs in the upper reaches of the Yangtze River (Yao et al. 2016). There are about 760 freshwater lakes mainly distributed in the plain of the middle and lower reaches of the Yangtze River with a total area of 17 093 km^2, including Dongting Lake, Poyang Lake, Chao Lake and Tai Lake and so on. These lakes have accelerated the development of local agriculture, industry, shipping, aquaculture and tourism (Dong and Wang 2013). Samples were collected from Yushu, Qinghai province, to the river estuary at Shanghai, including major urban basins in the upper, middle and lower reaches of the Yangtze River, the upper and lower reaches of tributaries, and the import and export areas of lakes. The sampling site locations are shown in Fig. 1, and coordinates are shown in Table S1. This, to the best of knowledge, is the first work to characterize the spatial distribution of MPs, along with influencing factors, in shoreline sediments along the Yangtze River on a large scale.

Sampling

A total of 162 sediment samples were taken from 54 sites along the Yangtze River banks in major urban basins, along the upper and lower banks of main tributaries and at the entrances and exits shores of major lakes, during May and June 2018. Sediment samples from each sample site were collected using a multi-quadrat mixture method. The samples of each quadrat was collected in a 0.1×0.1 m^2 quadrant to a depth of 0.2 m using a narrow stainless shovel (Murray and Cowie 2011). The detailed sampling method is as follows: At each site, three quadrats are randomly selected at 20-m intervals along the S-shaped route, and then, the samples of the three quadrats were uniformly mixed and placed in a fabric bag; approximately 4–5 kg sediment specimens were collected. The samples were sealed and stored in the laboratory at room temperature until required for analysis. Wet sediment samples were placed on the clean stainless steel plate covered with aluminum film and air-dried in a clean laboratory-ventilated kitchen to prevent contamination of airborne MPs in the laboratory. MP particle abundance was determined based on the dry weight of the sediment sample.

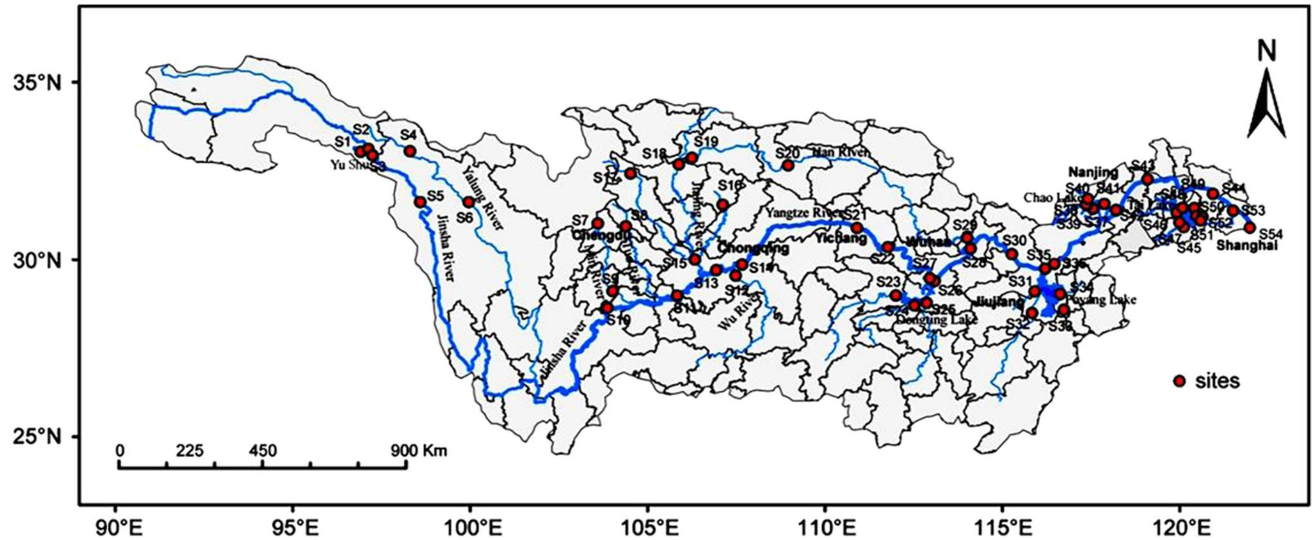

Fig. 1 Sketch map showing the sampling sites along the Yangtze River valley. Drawing number: GS(2019)1653

Sample and data analysis

Each sample was homogenized in the laboratory without cross-contamination. About 500 g of each sample was sieved in a stainless steel sieve (300 mesh, $\Phi = 0.050$ mm) and leached using pressurized water until the leaching water ran clear (Lin et al. 2021). Sieve residue was collected in a volumetric flask that had been cleaned using ultrapure water and then, for flotation of microplastic particles, mixed and shaken with NaCl-saturated solution (1.12 g/cm^3) and $ZnCl_2$ solution (1.6 g/cm^3) three times successively. The supernatant of each flotation was decanted into a 500-mL glass beaker and vacuum-filtered with 10–20 µm quantitative paper ($\Phi = 9.0$ cm, Xinxing, China). The filter membrane was washed with deionized filtered water, and the residue was carefully transferred to a clean Petri dish using a washed metallic needle before being covered and dried in a drying oven at 50–60 °C for > 12 h. The dried MPs samples were treated with 30% H_2O_2 (50 ml) at room temperature in the dark for 48 h in covered glass conical flask (250 ml) to digest the biological and abiological materials and then passed through the 0.45-µm glass microfiber papers (GF /F, 47mmΦ, Whatman), using a vacuum pump. After that, the filter paper was washed with deionized filtered water again and transferred into clean glass petri dish, dried and examined carefully under magnifying glass (PDOK 10X, Germany) and microscope (Olympas, IX81). Particles > 0.15 mm that were visually identified as or suspected to be plastics were transferred from the residues onto clean, black, smooth cardboard and classified according to shape (Nor and Obbard 2014; Zhou et al. 2018). All particles transferred to the cardboard were photographed using a digital camera (Nikon D3200, Japan), and particle counting and size measurement were taken using Nano Measurer 1.2 software (Zhou et al. 2018). MPs were classified the size ranges into < 0.5 mm, 0.5–1.0 mm, 1.0–2.0 mm, 2.0–3.0 mm, 3.0–4.0 mm, and 4.0–5.0 mm.

The MPs extracted from 500 g of dry sediment were divided into 10 parts on average, and two parts were selected to identify the chemical components by attenuated total reflection with Fourier transform infrared spectroscopy (ATR-FTIR). ATR-FTIR spectra were recorded on a Bruker Tensor 27 FTIR spectroscope (Bruker Optics, GmbH, Germany) with Pike Miracle ATR accessories (Pike Technologies, Wisconsin, USA). A set of representative microplastic particles (> 0.15 mm) from each site was selected to identify the chemical component by ATR-FTIR (He et al. 2021). In this research, there were two rules for the selection of microplastic particles: (i) at each sampling site, > 20 particles were selected and (ii) for each type (shape and size) of MPs, > 20 particles were selected (Wu et al. 2019). The European Commission's Marine Strategy Framework Directive recommends that at least 10% of recorded fragments and filaments should be analyzed by FTIR (Galgani et al. 2013). In our ATR-FTIR analysis, the proportion of MPs detected accounted for more than 20% of the total microplastics, higher than the 10% regulated by the European Commission, so it was well representative. Some of the MPs might be indiscernible based on their morphologies and so two or three representative MPs of these types were selected for polymer identification (zhou et al. 2018).

ArcGIS10.2 (Environmental Systems Research Institute Inc, Redlands, CA, USA) was used to map the sampling sites of MP particles. WPS Office 2019 and OriginPro 8.5 (OriginLab Corporation, Northampton, MA) were used for data analysis. Statistical differences were analyzed by one-way analysis of variance (ANOVA) using the SPSS 17.0 software package. All results concerning MP particle abundances are presented as the number of microplastic particles per dry mass of sediment (particles/kg).

Quality assurance and quality control

In order to guarantee the accuracy of our data, a series of quality assurance and quality control (QA/QC) measures were taken during the process from field sampling to laboratory analysis (Brander et al. 2020). During field sampling, all tools were carefully rinsed three times with ultrapure water at each individual step to avoid pollution. The samples were kept in closed spaces to reduce pollution from airborne MPs. Field blank tests were conducted in three randomly selected sampling sites. On each site, 100 g of quartz sand was washed by pressurized distilled water and passed through a 50-μm stainless steel sieve (300 mesh). The duplicates were set in triple. Subsequent treatment for blank samples was identical with that for shoreline sediments as above mentioned. Finally, only 3.15 ± 1.24 plastic particles were detected under the microscope in the blank samples. The results showed that potential microplastic contamination was minimal and can be negligible.

To avoid potential background contamination during the analysis process in the laboratory, the following preventive measures described in the literature were taken in this study. MP particles were separated and enumerated in different clean rooms. Cotton laboratory coats were worn at all times during analysis. All materials and vessels were covered with aluminum foil after each individual step. All liquid used in the experiment was filtered through the 0.45-μm filter (GF/F, 47mmΦ, Whatman). During the processing of MP in the laboratory, procedural blank samples (3 ultrapure water samples and 3 NaCl solution samples) were included. Potential airborne particles were examined by sucking the air in the workplace through the 0.45-μm filter paper for 2 h under vacuum filtration, and no plastic particles were found under the microscope. Each test was set in triple. The results of blank samples indicated that the contamination from transportation to processing was negligible.

The MP recovery of the extraction procedure was also ascertained by 100 of MP particles of dimensions (0.1–5.0 mm) into clean artificial sediment (quartz sand; 0.25 mm; 500 g) and processing under the same conditions that were described above for environmental samples. Same procedure was repeated for three times. The recovery rate was $93.5 \pm 4.3\%$.

Results

Shape categories, polymer type and distribution of MPs

According to their shapes and features, the plastic/microplastic particle were categorized into pellets, foams, fragments, flakes, films, fibers and sponges, as shown in Fig. 2. In general, pellet was hard, regular, disc-shaped, oval or cylindrical plastic particles. Foam was white expanded polystyrene particles. Film was thin, soft and light-transmitting particles of plastic sheet. Fiber was long, curly remnants of dust screen or fishing nets. Fragment was hard, thick pieces of plastic with irregular shape. Flake was usually opaque, regular flat particles of various plastic woven bags. Sponge was particles that were yellow, porous and irregular honeycomb. The composition and classification of sediment samples were determined by attenuated total reflectance–Fourier transform infrared (ATR-FTIR) spectrometry using the detected spectra, as shown in Fig. S1.

Flake particles decreased from 46.3% of MPs in the upper reaches of the Yangtze River bank sediments to 10.2% in the lower reaches. In the middle reaches, the proportion of flake particles was 68.0%; the greatest abundance was in the Wuhan section, 88.1%. In contrast, foam particles were 4.9% in the upper reaches of the Yangtze and 59% in the lower reaches, a tenfold increase, as shown in Fig. 3(a). In the tributaries of the upper reaches of the Yangtze River, particles were primarily flake (maximum 76.1%) and film (maximum 46.0%), and the average proportion of foam particles was $< 10\%$. No spherical particles were found in the tributary sediments, as shown in Fig. 3(b). Particles representative of all seven shape categories were found in the lakeshore sediments: the average proportion of foam particles was 41.7%, with a maximum of 64.4% for Poyang Lake; the average proportion of flake was 20.05% and of film, 13.8%, as shown in Fig. 3(c).

Abundance and size of MPs in the Yangtze River basin

The abundance of MP particles in the Yangtze River banks is shown in Fig. 4(a). The abundance of MP particles in the beach sediments of the main urban basins along the Yangtze River varied greatly. The abundance of MP particles in riverbank sediments from Chongqing to Yueyang was relatively small, in the range 35–322 particles/kg. However, from Wuhan to Shanghai, the abundance of MP particles was relatively high, mainly in the range 278–51 968 particles/kg. The greatest abundance of MP

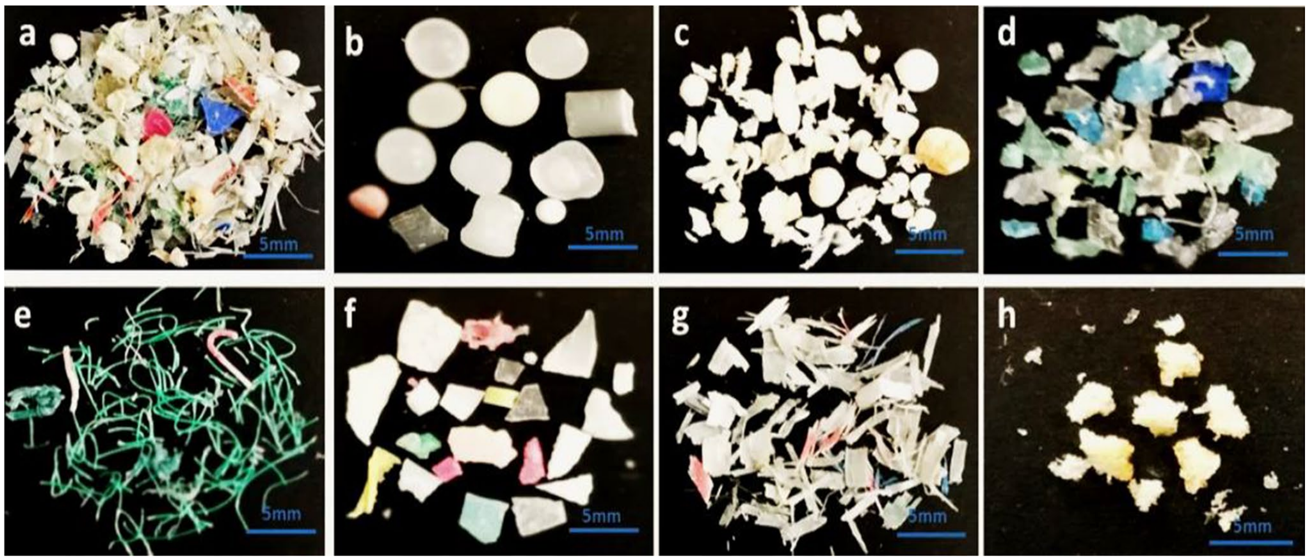

Fig. 2 Different shape categories of partial plastic/microplastic samples collected from the shoreside sediments along the Yangtze River; **a**. mixed MPs, **b**. pellets, **c**. foams, **d**. films, **e**. fibers, **f**. fragments, **g**. flakes, **h**. sponges

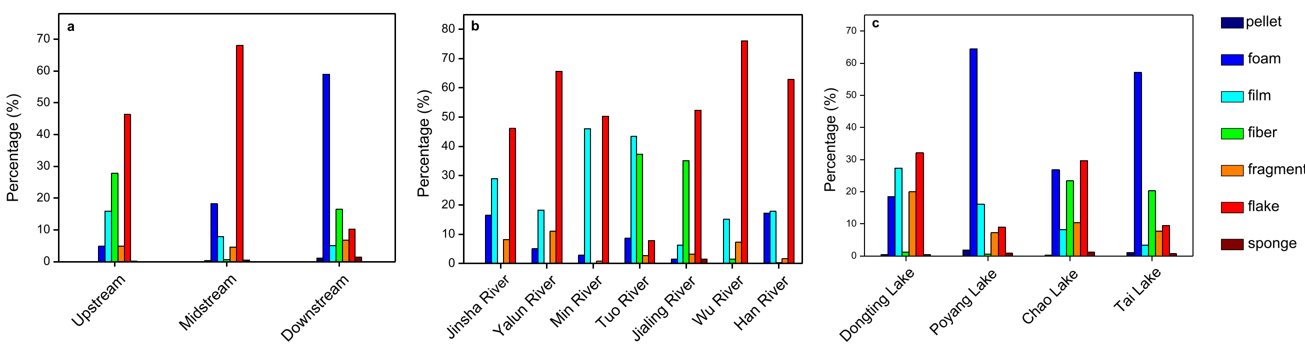

Fig. 3 Shape categories of MPs in sediments along the Yangtze River: (**a**) Upper, middle and lower reaches of the Yangtze River; (**b** tributaries; (**c**) lakes

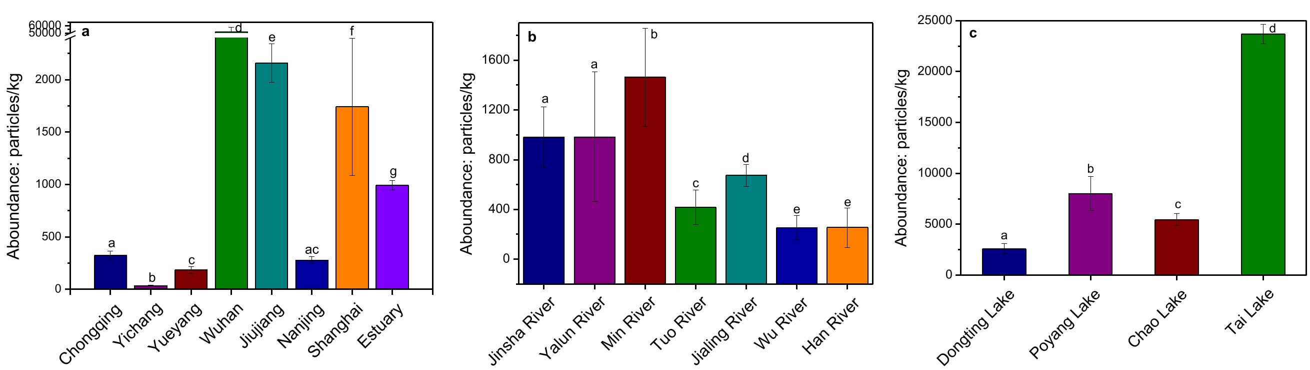

Fig. 4 MPs abundance in sediments along the Yangtze River: Upper, middle and lower reaches of the Yangtze River (**a**, $n = 3$); tributaries (**b**, $n = 3$); lakes (**c**, $n = 3$). Different letters above the bars indicate significant differences ($P < 0.05$), while same letters indicate no significant difference ($P > 0.05$)

particles in sediment samples was found in the Wuhan region, followed by the Jiujiang, Shanghai and Nanjing regions. The abundance of MP particles in the Yangtze estuary was 992 particles/kg. Abundance in the upstream tributaries was in the range 254–1463 particles/kg, as shown in Fig. 4(b); the highest abundance was found in the Ming River bank. The abundance of MP particles in the shores of Dongting Lake (2576 particles/kg), Poyang Lake (8017 particles/kg), Chao Lake (5460 particles/kg) and Tai Lake (23 685 particles/kg) was significantly greater than in the banks of the tributaries, as shown in Fig. 4(c).

Zhao et al. (2014) and He et al. (2021) reported that MPs with particle size < 0.5 mm were the most abundant MPs in the surface waters of the Yangtze River, which was attributed to long-term degradation of small plastic debris. The size distributions of MPs in sediment determined by our experiments are shown in Fig. 5. The size range of MPs detected in the sediments of the main stream was 0.065 ± 0.013–4.02 ± 0.452 mm, in tributaries 0.071 ± 0.008–3.91 ± 0.883 mm, and in lakes 0.073 ± 0.016–4.10 ± 0.593 mm (Table S2). MPs < 0.5 mm were predominant in the sediments of the Yangtze River banks (average 66.7%), tributary riverbanks (average 64.1%) and lakeshores (average 65.9%); the greatest proportions were 88.1% in the Wuhan region, 70% in Tuo River banks and 79.3% in Chao Lakeshores. The general trend was that larger MP particles (> 2 mm) were less abundant in the sediments of the Yangtze River banks (in the range 0.0–12.85%), tributary riverbanks (in the range 3.9–7.5%) and lakeshores (in the range 5.5–24.56%). We found that sample sites with high abundance of flake (PP) and foam (PS) particles had higher proportions of small particles.

MPs contamination in tributary riverbanks

The distributions of MP particles showed different trends upstream and downstream in each tributary (Table S3 and Fig. S2). Flake particles were predominant in upstream samples, accounting for 73% on average. The greatest proportion of flake particles was 98.8% in the Ming River samples. The proportion of fiber particles was 74.3% in upstream samples of the Tuo River. No pellet or sponge particles were found in the upstream samples. Downstream in the tributaries, film (average 39.2%), flake (average 20.1%), fragment (average 13.5%) and foam (average 14.4%) were the most common particle shapes found in the sediment samples. Fiber particles were found in the Jialing (41.8%) and Wu River (43.3%) samples. Sponge particles were found only in the Jialing samples (3.6%), and no pellet particles were found in any tributary samples. Abundance of MP particles in samples from the upper reaches of the tributaries was in the range 192–1004 particles/kg (average 418 particles/kg), and samples from the lower reaches were in the range 30–580 particles/kg (average 252 particles/kg) (Fig. 6a).

Microplastic contamination characteristics of lakeshores

Flake particles accounted for 32.6% on average, followed by fragment (24.2%), foam and film accounted for 21.5% and 19.2%, respectively, in the Dongting Lake samples. Foam, flake and fiber particles accounted, respectively, for 27.3%, 36.4% and 26.8% of the Chao Lake samples. Foam particles were predominant in samples from both Poyang Lake (58.4%) and Tai Lake (70.4%). Foam particles were widespread; we found them in every lake sample, with abundance in the range 21.5%–70.4%. At the outlet of Dongting Lake, film and flake particles accounted for 90% of particles found in the samples. Foam particles accounted for 88.5% of the particles found in the Poyang Lake outlet samples. Foam, fragment, film, fiber and flake particles were predominant in both the Chao (81.7%) and Tai Lake outlet samples (82.9%). Pellet and sponge particles had an abundance of < 10% in the inlet and outlet samples of these two lakes (Table S4 and Fig. S3). The abundance of MP particles differed significantly between inlet and outlet samples for all lakes, as shown in Fig. 6(b). The abundance of MP particles in lake inlet samples was in the range 2546–21,112 particles/

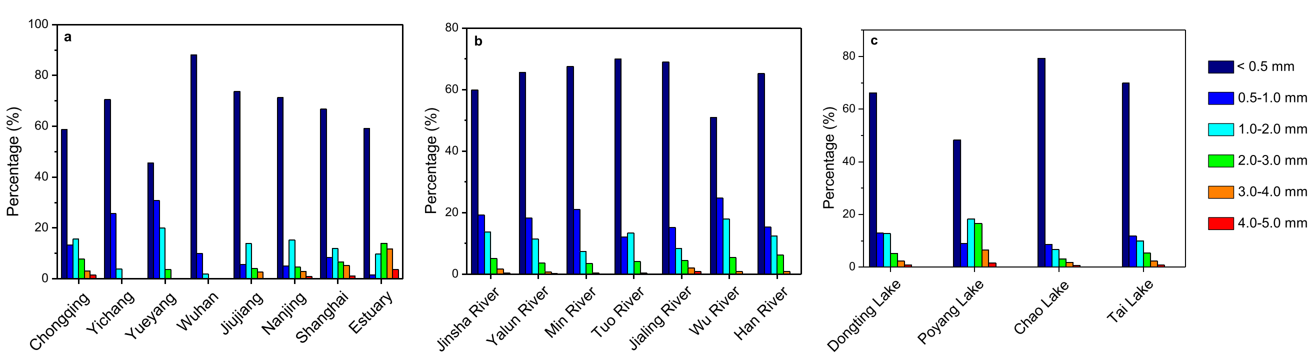

Fig. 5 Size distribution of MPs in shoreside sediments; (**a**) upper, middle and lower reaches of the Yangtze River; (**b**) tributaries; (**c**) lakes

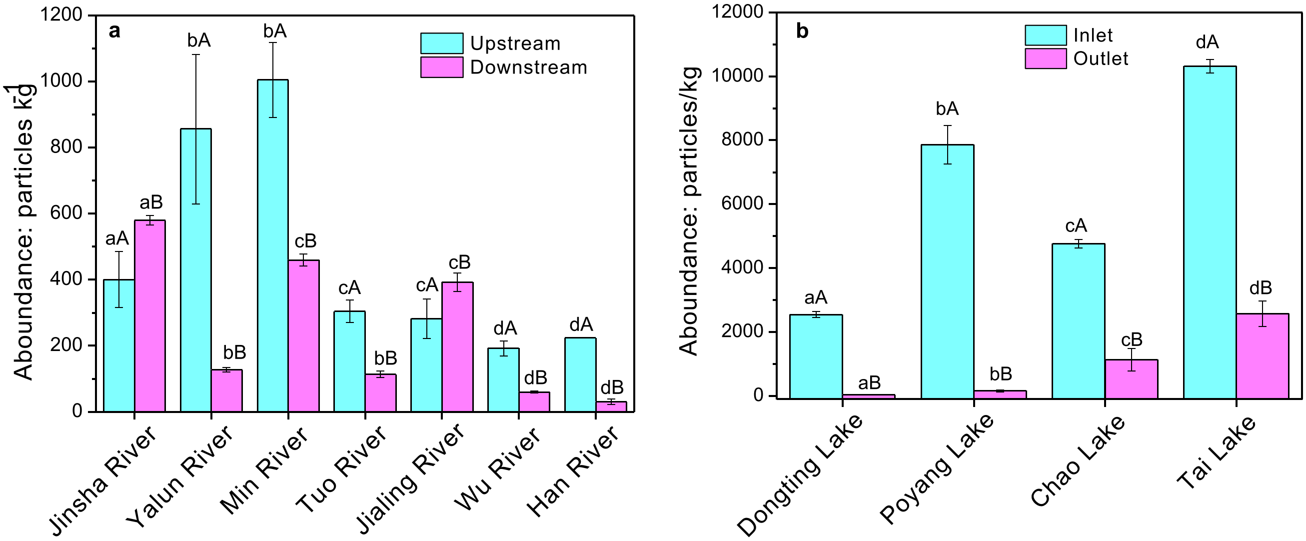

Fig. 6 Microplastic abundance in the sediments of each tributary upstream and downstream (**a**) and the inlet and outlet of lakes (**b**). One-way analysis of variance (ANOVA) with Dunnett T3 post hoc test was performed to determine differences in particle number among different treatment groups (**a**, **b**, $n = 3$). The letters above the bars indicate significant differences ($p < 0.05$). Different capital letters represent significant differences between upstream and downstream of the same tributary / inlet and outlet of the same lake, and different lowercase letters represent significant differences between different tributaries / lakes at the same site

kg (average 9069 particles/kg); in lake outlet samples, abundance was in the range 30–2573 particles/kg (average 866 particles/kg).

Correlates of MPs in the Yangtze River basin

We found significant correlations between particle abundance in tributary samples and water runoff (Fig. 7a and Table S5). The abundance of flake particles along the Yangtze River banks was positively correlated with the total MP abundance in the main tributary (Fig. 7b and Table S6). There were significant correlations between the abundance of foam particles and total MP particle abundance in the main sampling areas of the Yangtze River (Fig. 7c and Table S7).

Discussion

Source and distribution of MPs

There may be a close relationship between human activities along the Yangtze River and the different types of MP particles found in our sampling (Wang et al. 2017; Yang et al. 2021). Different factors contribute to the spatial differences observed in MP contaminants along the river. We frequently observed discarded foam floats and containers, plastic drums and bottles, fishing nets, woven plastic bags and food wrappers on the banks of the Yangtze River and its main tributaries and on the lakeshores during field sampling, all of which are potential sources of MP particles.

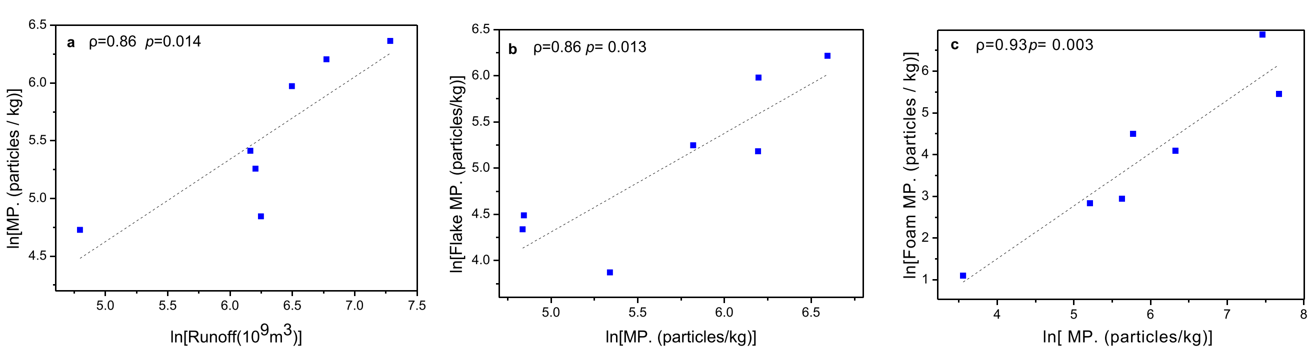

Fig. 7 Significant correlations of MPs abundance and other parameters. (**a**) MPs of abundance and mean annual runoff in the main tributary; (**b**) abundance of flake MPs and total MPs in the main tributary; (**c**) abundance of foam MPs and total MPs in the main sampling areas of the Yangtze River

Flake particles predominated in the upstream Yangtze River samples. These have originated from gradual damage to discarded plastic woven bags. Polystyrene foam particles were found mainly in the Yangtze River bank samples; these originated primarily from aquatic product packing boxes and discarded foam floats, as reported by Free et al. (2014) and Lee et al. (2015). Fiber particles were widely distributed in the Yangtze River bank samples, mainly due to the large use of wind fences in the economically less developed areas of the upper reaches of the Yangtze River, and to the fishery that has developed in the lower reaches of the river. Film particles originated mainly from the degradation of discarded plastic bags and agricultural mulch (Sintim and Flury 2017). The main sources of fragment particles were discarded objects that resulted from human lifestyles and the industrial production of hard plastic products; over the long term, hard plastic products break and produce fragments (e.g., broken plastic tubs, buckets and bottles). Film and fragment particles were widely present in samples throughout the survey area, with a relatively high distribution in more populated areas that further illustrates the close relationship between MPs and human activities. Pellet particles were found in the middle and lower reaches of the Yangtze River bank samples, which we mainly attributed to improperly discarded industrially manufactured primary materials. More pellet particles were found in lakeshore sediments because a lake is an important destination for pellet particle migration in the drainage basin. Sponges are widely used in industry and commerce for shock absorption, packaging and heat insulation, and they increase pollution by PEU MPs (Zhou et al. 2018).

Microplastic contamination along the Yangtze River

MP particle concentrations in different reaches of the Yangtze River were dissimilar because they were influenced by different environmental conditions and had different sources (Feng et al. 2021). Previous studies have suggested that MP concentrations in aquatic environments were mainly driven by population density or economic development (Lahens et al. 2018; Peng et al. 2018; Eriksen et al. 2013; Yonkos et al. 2014; Liu et al. 2019). We found that the abundance of MP particles along the Yangtze River banks was relatively high in major urban watersheds, but there was no significant correlation between abundance and local population size or economic development indicators. We conclude that MP particles in shoal sediments have a complex of sources, including local discarding of plastic products and continuous input from upstream rivers, and that local hydrological conditions maybe have an important effect on plastic deposition. The abundance of MPs in riverbank sediments is also a consequence of long-term accumulation. Over time, different types of plastic products and MPs are weathered by various factors, a process that continuously increases MP particle abundance (Song et al. 2017). In addition, lower density particles of polymer PE, PP and expanded PS that are distributed on the surfaces of rivers and lakes are more likely to be trapped in the riverbank and shoreline sediments because they are influenced by tides and wind, thus increasing the proportion of small MPs in the sediments of riverbanks and lakeshores. The Yangtze River has long been considered to be the largest source of MPs entering the ocean, but previous studies ignored the retention of MPs in shoal sediments, leading to overestimates of the flux of MPs from rivers into the ocean (Siegfried et al. 2017).

In contrast to previous studies of MP accumulation, we found that the abundance of MPs in the sediments of the main Yangtze River basin is at an intermediate level (Ding et al. 2019; Lin et al. 2018; Klein et al. 2015). A single shape category of MPs is common in the upper reaches of the Yangtze River, and the abundance of MP particles is also relatively low, due to less human activity in the region. However, in the middle and lower reaches, as opposed to the upper reaches, the shape category and abundance of MP particles were greater. Among them, the greatest abundance was found around Wuhan, and the particles were mainly flakes. This is related to the long-term use of plastic woven bags in local long-term flood defenses and remediation. There were more foam and fiber MP particles in the lower reaches due to the developed fishery and transportation of aquatic products. The significant positive correlation between the abundance of foam particles and the total abundance of MP particles implies that PS plastic products are the main sources of MPs in the sediment samples of the main sampling areas of the Yangtze River. MP particle abundance was relatively high in the Yangtze estuary, which indicates that urban estuarine river input was an important source of MPs entering the ocean (Rech et al. 2014; Zhao et al. 2015). Tides may also be an important factor in the accumulation of MPs in estuaries (Xiong et al. 2019).

MPsin the tributaries of the upper Yangtze River

In the tributaries of the upper reaches of the Yangtze River, where human activities are less relevant, the abundance of MP particles is nonetheless relatively high. This is related to the types of polymer; Song et al. (2017) reported that polypropylene (PP) and polystyrene (PS) are more prone to fragmentation under natural conditions. The significant positive correlations between the abundance of flake particles and the total abundance of MP particles in tributary riverbank samples indicate that flake particles are predominant.

In the upper reaches of the tributaries, which are undeveloped, woven plastic bags and netted wind fencing discarded during the construction and maintenance of water conservancy, and hydropower facilities produced a high abundance of MP particles. Particle shapes were mainly flake and fiber, and flake particles were predominant. Agriculture and other human activity are more frequent in the lower reaches of each tributary, and both overall abundance and the number of film and fragment categories in our samples increased. However, flake particles decreased significantly in the lower reaches of each tributary. This observation suggests that the dam on the upper reaches of a tributary may have trapped considerable amounts of MPs that originated upstream of the dam (Zhang et al. 2015, 2017; Xiong et al. 2019; Lin et al. 2021). This suggested that different human activities can affect the types, abundance and spatial distribution of MPs in the upper and lower reaches of tributaries.

Runoff is believed to contribute to microplastic pollution (Gasperi et al. 2014; Dai and Zhang 2013). A significant correlation between MP particle abundance and mean annual runoff was found for each tributary of the upper Yangtze River. This suggests that increased runoff transports more surface microplastic waste into the rivers, and as a result, the abundance of MP particles remaining in riverbank sediments may be increased by waves or wind. These particles will, over time, flow into the upper reaches of the Yangtze River and continue to be transported downstream, possibly into the oceanic system, thus becoming an important source of marine MPs.

Characteristics of MPs contamination in lakeshores

The sediment MP particle concentrations found in lakeshore samples were high in comparison with some other studies, such as of the Caofeidian reclamation area (Zhou et al. 2016), Halifax Harbor in Nova Scotia, Canada (Mathalon and Hill 2014), the Poyang Lake system (Jian et al. 2020), Dongting Lake (Hu et al. 2020) and Tai Lake (Su et al. 2016).

Particles in all seven shape categories were found in all lakeshore sediment samples. Abundance of MP particles in lakeshore samples was significantly greater than in riverbank sediment samples because particles in rivers are mainly transported downstream, whereas particles in lakes are mainly deposited and thus remain in place. Abundances in the lake outlet samples were significantly less than those found at inlets. This is because the lake water outflow rate was low; still water provides good conditions for a large number of MP particles to be trapped in lake and lakeshore sediments (Xiong et al. 2019). Our findings imply that previous models may have overestimated the flux of MPs from land to ocean because they did not take into account the retention of MPs in river and lake systems.

Conclusions

Our results show the ubiquity of MPs in sediments from the banks of the Yangtze River and tributaries and lakeshores. We also characterized the accumulation and distribution of MPs in the survey region. We identified seven shape categories across the entire Yangtze River basin and analyzed the main polymer types as polypropylene (PP), polystyrene (PS) and polyethylene (PE). The sources of the different categories of MPs were closely related to human activity along the Yangtze River. The higher abundance of MPs near urban centers and large lakes that are part of the Yangtze River system, and in the river estuary, indicates that both human activity and large bodies of open water affect MPs density in shore and bank sediment. Flake particles were the major constituents in all upstream samples, and foam particles were predominant in downstream samples. The distribution of foam particles displayed an east–west pattern of stepwise descent, but flake and film particles showed the opposite distribution. Small MP particles (< 0.50 mm) were predominant at all sites in this study; the minimum size of particles in the Yangtze River banks was 0.065 mm. There was a significant correlation between MP particle abundance and mean annual runoff of the tributary basin in the upper Yangtze River tributaries. There was an order of magnitude reduction in average abundance of MP particles in lakeshore sediments between lake inlet and outlet due to particle interception associated with sedimentation and precipitation in the lake. Systematic surveys of hydro-sedimentary parameters and better characterization of primary plastics sources are needed to better understand the hydrodynamic drivers of the distribution and persistence of plastic particles in the Yangtze River. The MP particle abundances in sediments can act as a proxy for the spatial extension of human activities that are propagated across the Yangtze River basin, and they are also a fingerprint of pollution sources.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11356-021-18284-7.

Author contribution All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Wenfeng Li, Jia Duo, Rehemanjiang Wufuer and Shuzhi Wang. The first draft of the manuscript was written by Wenfeng Li. Professor Xiangliang Pan supervised the research and did the critical revision of the manuscript. All authors have contributed considerably, and all authors are in agreement with respect to the manuscript content. The authors read and confirmed the final manuscript.

Funding The authors gratefully acknowledge the financial support by Science and Technology Department of Xinjiang Uyghur Autonomous Region (2018D04013), the National Natural Science Foundation of China (No. 41907140), the Natural Science Foundation of Xinjiang Uygur Autonomous Region (No. 2018D01A38), the West Light Foundation of Chinese Academy of Sciences (No. 2017-XBQNXZ-B-0114), High-level Talents Introduction Project in Xinjiang Uygur Autonomous

Region (2017) and the West Light Foundation of Chinese Academy of Sciences (No. 2018-XBQNXZ-B-01).

Availability of data and materials All data generated or analyzed during this study are included in this published article (and its supplementary information files).

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

References

Brander SM, Renick VC, Foley MM, Steele C, Woo M, Lusher A et al (2020) EXPRESS: sampling and QA/QC: a guide for scientists investigating the occurrence of microplastics across matrices. Appl Spectrosc. https://doi.org/10.1177/0003702820938993

Bergmann M, Wirzberger V, Krumpen T, Lorenz C, Primpke S, Tekman MB, Gerdts G (2017) High quantities of microplastic in arctic deep-sea sediments from the HAUSGARTEN observatory. Environ Sci Technol 51:11000–11010. https://doi.org/10.1021/acs.est.7b03331

Canesi L, Ciacci C, Bergami E, Monopoli MP, Dawson KA, Papa S et al (2015) Evidence for immunomodulation and apoptotic processes induced by cationic polystyrene nanoparticles in the hemocytes of the marine bivalve Mytilus. Mar Environ Res 111:34–40. https://doi.org/10.1016/j.marenvres.2015.06.008

Chae Y, An Y (2018) Current research trends on plastic pollution and ecological impacts on the soil ecosystem: a review. Environ Pollut 240:387–395. https://doi.org/10.1016/j.envpol.2018.05.008

Dai ML, Zhang MB (2013) Research on temporal and spatial distribution law of runoff in Yangtze River Basin. Yangtze River 44(10):88–91

Desforges JPW, Galbraith M, Dangerfield N, Ross PS (2014) Widespread distribution of microplastics in subsurface seawater in the NE Pacific Ocean. Mar Pollut Bull 79(1):94–99. https://doi.org/10.1016/j.marpolbul.2013.12.035

Ding L, Mao RF, Guo XT, Yang XM, Zhang Q, Yang C (2019) Microplastics in surface waters and sediments of the Wei River, in the northwest of China. Sci Total Environ 667:427–434. https://doi.org/10.1016/j.scitotenv.2019.02.332

Dong YH, Wang XL (2013) Preliminary Research on Watershed Division and Stream Order Classification of the Yangtze River. J Yangtze River Sci Res Inst 230:1–5

do Sul JAI, Costa MF (2014) The present and future of microplastic pollution in the marine environment. Environ Pollut 185:352–364. https://doi.org/10.1016/j.envpol.2013.10.036

Endo S, Takizawa R, Okuda K, Takada H, Chiba K, Kanehiro H et al (2005) Concentration of polychlorinated biphenyls (PCBs) in beached resin pellets: Variability among individual particles and regional differences. Mar Pollut Bull 50(10):1103–1114. https://doi.org/10.1016/j.marpolbul.2005.04.030

Eriksen M, Mason S, Wilson S, Box C, Zellers A, Edwards W et al (2013) Microplastic pollution in the surface waters of the Laurentian Great Lakes. Mar Pollut Bull 77(1):177–182. https://doi.org/10.1016/j.marpolbul.2013.10.007

Feng S, Lu HW, Yao TC, Liu YL, Tian PP, Lu JZ (2021) Microplastic footprints in the Qinghai-Tibet Plateau and their implications to the Yangtze River Basin. J Hazard Mater 407:124776–124785. https://doi.org/10.1016/j.jhazmat.2020.124776

Free CM, Jensen OP, Mason SA, Eriksen M, Williamson NJ, Boldgiv B (2014) High-levels of microplastic pollution in a large, remote, mountain lake. Mar Pollut Bull 85(1):156–163. https://doi.org/10.1016/j.marpolbul.2014.06.001

Galgani F, Hanke G, Werner S, Oosterbaan L, Nilsson P, Fleet D, Kinsey S, Thompson RC (2013) Guidance on monitoring of marine litter in European seas contact information. Report EUR 26113 EN. Sci Techn Res Ser 128

Gasperi J, Dris R, Bonin T, Roche V, Tassin B (2014) Assessment of floating plastic debris in surface water along the Seine River. Environl Pollut 195:163–166. https://doi.org/10.1016/j.envpol.2014.09.001

He D, Chen XJ, Zhao W, Zhu ZQ, Qi XJ, Zhou LF, Chen W, Wan CY, Li D, Zou X, Wu N (2021) Microplastics contamination in the surface water of the Yangtze River from upstream to estuary based on different sampling methods. Environ Res 196:110908–110917. https://doi.org/10.1016/j.envres.2021.110908

Hidalgo-Ruz V, Gutow L, Thompson RC, Thiel M (2012) Microplastics in the Marine Environment: A Review of the Methods Used for Identification and Quantification. Environ Sci Tech 46(6):3060–3075. https://doi.org/10.1021/es2031505

Hu L, Chernick M, Hinton DE, Shi H (2018) Microplastics in Small Waterbodies and Tadpoles from Yangtze River Delta. China Environ Sci Techol 52(15):8885–8893. https://doi.org/10.1021/acs.est.8b02279

Hu DF, Zhang YX, Shen MC (2020) Investigation on microplastic pollution of Dongting Lake and its affiliated rivers. Mar Pollut Bull 160:111555–111562. https://doi.org/10.1016/j.marpolbul.2020.111555

Jambeck JR, Geyer R, Wilcox C, Siegler TR, Perryman M, Andrady A et al (2015) Plastic waste inputs from land into the ocean. Science 347(6223):768–771. https://doi.org/10.1126/science.1260352

Jang M, Shim WJ, Cho Y, Han GM, Song YK, Hong SH (2020) A close relationship between microplastic contamination and coastal area use pattern. Water Res 171(15):115400–115410. https://doi.org/10.1016/j.watres.2019.115400

Jian MF, Zhang Y, Yang WJ, Zhou LY, Liu SL (2020) Occurrence and distribution of microplastics in China's largest freshwater lake system. Chemosphere 216:128186–128195. https://doi.org/10.1016/j.chemosphere.2020.128186

Klein S, Worch E, Knepper TP (2015) Occurrence and Spatial Distribution of Microplastics in River Shore Sediments of the Rhine-Main Area in Germany. Environ Sci Technol 49(10):6070–6076. https://doi.org/10.1021/acs.est.5b00492

Lahens L, Strady E, Kieu-Le TC, Dris R, Boukerma K, Rinnert E, Gasperi J, Tassin B (2018) Macroplastic and microplastic contamination assessment of a tropical river (Saigon River, Vietnam) transversed by a developing megacity. Environ Pollut 236:661–671. https://doi.org/10.1016/j.envpol.2018.02.005

Lebreton LCM, Van der Zwet J, Damsteeg JW, Slat B, Andrady A, Reisser J (2017) River plastic emissions to the world's oceans. Nat Commun 8.https://doi.org/10.1038/ncomms15611

Lee J, Lee JS, Jang YC, Hong SY, Shim WJ, Song YK et al (2015) Distribution and Size Relationships of Plastic Marine Debris on Beaches in South Korea. Arch Environ Con Toxicol 69(3):288–298. https://doi.org/10.1007/s00244-015-0208-x

Li J, Liu H, Paul Chen J (2018) Microplastics in freshwater systems: A review on occurrence, environmental effects, and methods for microplastics detection. Water Res 137:362–374. https://doi.org/10.1016/j.scitotenv.2020.141948

Lin L, Pan X, Zhang S, Li DW, Zhai WL, Wang Z, Tao JX, Mi CQ, Li QY, Crittenden JC (2021) Distribution and source of microplastics in China's second largest reservoir - Danjiangkou Reservoir. J Environ Sci 102:74–84. https://doi.org/10.1016/j.jes.2020.09.018

Lin L, Zuo LZ, Peng JP, Cai LQ, Fok L, Yan Y, Li HX, Xu XR (2018) Occurrence and distribution of microplastics in an urban river: a case study in the Pearl River along Guangzhou City, China. Sci Total Environ 644:375–381. https://doi.org/10.1016/j.scitotenv.2018.06.327

Liu C, Li J, Zhang Y, Wang L, Deng J, Gao Y et al (2019) Widespread distribution of PET and PC microplastics in dust in urban China and their estimated human exposure. Environ Int 128:116–124. https://doi.org/10.1016/j.envint.2019.04.024

Mathalon A, Hill P (2014) Microplastic fibers in the intertidal ecosystem surrounding Halifax harbor, Nova Scotia. Mar Pollut Bull 81:69–79. https://doi.org/10.1016/j.marpolbul.2014.02.018

Murray F, Cowie P (2011) Plastic contamination in the decapod crustacean Nephrops norvegicus (Linnaeus, 1758). Mar Pollut Bull 62(6):1207–1217. https://doi.org/10.1016/j.marpolbul.2011.03.032

Nguyen B, Claveau-Mallet D, Hernandez LM, Xu EG, Farner JM, Tufenkji N (2019) Speparation and analysis of microplasits and nanoplastics in complex environmental samples. Acc Chem Rews 52:858–866. https://doi.org/10.1021/acs.accounts.8b00602

Nor NHM, Obbard JP (2014) Microplastics in Singapore's coastal mangrove ecosystems. Mar Pollut Bull 79(1):278–283. https://doi.org/10.1016/j.marpolbul.2013.11.025

Peng G, Xu P, Zhu B, Bai M, Li D (2018) Microplastics in freshwater river sediments in Shanghai, China: A case study of risk assessment in mega-cities. Environ Pollut 234:448–456. https://doi.org/10.1016/j.envpol.2017.11.034

Plastics Europe (2018) Plastics-the Facts 2018, an Analysis of European Plastics Production, Demand and Waste Data. https://www.plasticseurope.org/en/resources/market-data, Accessed date: 22 March 2019. Plastics Europe.

Rachman CM (2018) Microplastics research-from sink to source. Science 360:28–29. https://doi.org/10.1126/science.aar7734

Rech S, Macaya-Caquilpán V, Pantoja JF, Rivadeneira MM, JofreMadariaga D, Thiel M (2014) Rivers as a source of marine litter- A study from the SE Pacific. Mar Pollut Bull 82(1):66–75. https://doi.org/10.1016/j.marpolbul.2014.03.019

Ryan Peter G, Moore Charles J, van Franeker JA, Coleen M (2009) Monitoring the abundance of plastic debris in the marine environment. Ser B Biol Sci 364(1526):1999–2012. https://doi.org/10.1098/rstb.2008.0207

Schmidt C, Krauth T, Wagner S (2017) Export of plastic debris by rivers into the sea. Environ Sci Technol 51:12246–12253. https://doi.org/10.1021/acs.est.7b02368

Sekudewicz I, Dabrowska AM, Syczewski MD (2021) Microplastic pollution in surface water and sediments in the urban section of the Vistula River (Poland). Sci Total Environ 762(25):143111–143123. https://doi.org/10.1016/j.scitotenv.2020.143111

Siegfried M, Koelmans AA, Besseling E, Kroeze C (2017) Export of microplastics from land to sea. A modelling approach. Water Res 127:249–257. https://doi.org/10.1016/j.watres.2017.10.011

Sintim HY, Flury M (2017) Is biodegradable plastic mulch the solution to agriculture's plastic problem? Environ Sci Technol 51(3):1068–1069. https://doi.org/10.1021/acs.est.6b06042

Song YK, Hong SH, Jang M, Han GM, Jung SW, Shim WJ (2017) Combined effects of UV exposure duration and mechanical abrasion on microplastic fragmentation by polymer type. Environ Sci Technol 51:4368–4376. https://doi.org/10.1021/acs.est.8b00172

Statista (2018) https://www.statista.com/statistics/282732/globalproduction-of-plasticssince-1950/. Accessed April 2018

Su L, Xue Y, Li L, Yang D, Kolandhasamy P, Li D et al (2016) Microplastics in Taihu Lake, China. Environ Pollut 216:711–719. https://doi.org/10.1016/j.envpol.2016.06.036

Thompson RC, Olsen Y, Mitchell RP, Davis A, Rowland SJ, John AWG, McGonigle D, Russell AE (2004) Lost at sea: where is all the plastic? Science 304(5672):838. https://doi.org/10.1126/science.1094559

Turner A, Holmes L (2011) Occurrence, distribution and characteristics of beached plastic production pellets on the island of Malta (central Mediterranean). Ma Pollut Bull 62(2):377–381. https://doi.org/10.1016/j.marpolbul.2010.09.027

Wang W, Ndungu AW, Li Z, Wang J (2017) Microplastics pollution in inland freshwaters of China: a case study in urban surface waters of Wuhan, China. Sci Total Environ 575:1369–1374. https://doi.org/10.1016/j.scitotenv.2016.09.213

Wang W, Yuan W, Chen Y, Wang J (2018) Microplastics in surface waters of Dongting Lake and Hong Lake, China. Sci Total Environ 633:539–545. https://doi.org/10.1016/j.scitotenv.2018.03.211

Woodall Lucy C, Sanchez-Vidal A, Canals M, Paterson Gordon LJ, Coppock R, Sleight V et al (2014) The deep sea is a major sink for microplastic debris. Roy Soc Open Sci 4:140317. https://doi.org/10.1098/rsos.140317

Wu C, Zhang K, Xiong X (2018) Microplastic pollution in inland waters focusing on Asia. Spring Chem 58:85–99

Wu N, Zhang Y, Zhang X, Zhao Z, He J, Li W, Ma Y, Niu Z (2019) Occurrence and distribution of microplastics in the surface water and sediment of two typical estuaries in Bohai Bay, China. Environ Sci Proc Impacts 21:1143–1152. https://doi.org/10.1039/c9em00148d

Xiong X, Wu C, Elser J, Mei Z, Hao Y (2019) Occurrence and fate of microplastic debris in middle and lower reaches of the Yangtze River-From inland to the sea. Sci Total Environ 659:66–73. https://doi.org/10.1016/j.scitotenv.2018.12.313

Xu P, Peng G, Su L, Gao Y, Gao L, Li D (2018) Microplastic risk assessment in surface waters: A case study in the Changjiang Estuary, China. Mar Pollut Bull 133:647–654. https://doi.org/10.1016/j.marpolbul.2018.06.020

Yang L, Zhang YL, Kang S, Wang ZQ, Wu CX (2021) Microplastics in freshwater sediment: A review on methods, occurrence, and sources. Sci Total Environ 754:141948–141968. https://doi.org/10.1016/j.scitotenv.2020.141948

Yao L, Chen PP, Hu LL, Li YQ (2016) Research on the Status and Problems of the Upper Yangtze River Hydropower Development. J Mianyang Teachers'college 35:91–97

Yin LS, Wen XF, Du CY, Jiang J, Wu LX, Zhang Y, Hu ZH, Hu SP, Feng ZQ, Zhou ZY, Long YN, Gu Q (2020) Comparison of the abundance of microplastics between rural and urban areas: A case study from East Dongting Lake. Chemosphere 244:125486–125493. https://doi.org/10.1016/j.chemosphere.2019.125486

Yonkos L, Friedel EA, Perez-Reyes A, Ghosal S, Arthur CD (2014) Microplastics in Four Estuarine Rivers in the Chesapeake Bay, U.S.A. Environ Sci Technol 48(24):14195–202. https://doi.org/10.1021/es5036317

Zhao S, Zhu L, Wang T, Li D (2014) Suspended microplastics in the surface water of the Yangtze Estuary System, China: First observations on occurrence, distribution. Mar Pollut Bul 86(1):562–568. https://doi.org/10.1016/j.marpolbul.2014.06.032

Zhao S, Zhu L, Li D (2015) Microplastic in three urban estuaries, China. Environ Pollut 206:597–604. https://doi.org/10.1016/j.envpol.2015.08.027

Zhang H, Zhou Q, Xie Z, Zhou Y, Tu C, Fu C et al (2018a) Occurrences of organophosphorus esters and phthalates in the microplastics from the coastal beaches in north China. Sci Total Environ 616–617:1505–1512. https://doi.org/10.1016/j.scitotenv.2017.10.163

Zhang K, Gong W, Lv J, Xiong X, Wu C (2015) Accumulation of floating microplastics behind the Three Gorges Dam. Environ Pollut 204:117–123. https://doi.org/10.1016/j.envpol.2015.04.023

Zhang K, Xiong X, Hu HJ, Wu CX, Bi YH, Wu YH, Zhou BS, Lam PKS, Liu JT (2017) Occurrence and characteristics of microplastic pollution in Xiangxi Bay of Three Gorges Reservoir, China.

Environ Sci Technol 51:3794–3801. https://doi.org/10.1021/acs.est.7b00369
Zhang K, Shi H, Peng J, Wang Y, Xiong X, Wu C, Lam PKS (2018b) Microplastic pollution in China's inland water systems: a review of findings, methods, characteristics, effects, and management. Sci Total Environ 630:1641–1653. https://doi.org/10.1016/j.scitotenv.2018.02.300
Zhou Q, Zhang H, Fu C, ZhouY DZ, Li Y et al (2018) The distribution and morphology of microplastics in coastal soils adjacent to the Bohai Sea and the Yellow Sea. Geoderma 322:201–208. https://doi.org/10.1016/j.geoderma.2018.02.015
Zhou Q, Zhang HB, Zhou Y, Li Y, Xi Y, Fu C, Tu C, Luo YM (2016) Separation of microplastics from a coastal soil and their surface microscopic features. Chin Sci Bull 61:1604–1611. https://doi.org/10.1360/N972015-01098