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Effect of cascade damming on microplastics transport in rivers: A large-scale investigation in Wujiang River, Southwest China

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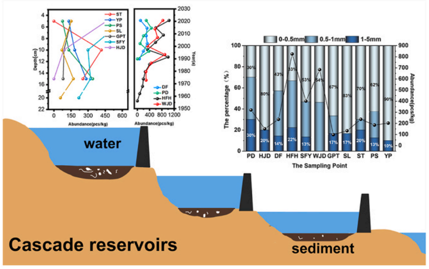
HIGHLIGHTS

- Effects of damming on microplastic was assessed based on a large-scale survey.
- Small-sized microplastics of 0–0.5 mm are easily migrated downstream.
- Abundance of microplastics in the sediment profiles increased over time.
- GDP and watershed area dominates the spatial distribution of microplastics.
- Cascade reservoirs form hot spots of microplastics along the rivers.

GRAPHICAL ABSTRACT



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ABSTRACT

Rivers are the important channels for transporting microplastics into the ocean from land. Prosperous dam construction changed the connectivity of rivers, thereby reducing the flux of microplastics to the ocean. However, this process currently lacks verification for the large-scale watersheds. In this study, we investigated the Wujiang River in China to evaluate the interception of cascade dams on microplastics. The results showed that: 1) The midstream exhibits a high abundance of microplastics (606.6–1046.2 items·kg^{-1}) while the upstream and downstream reach exhibits relatively low pollution levels. The small-sized microplastics of 0–0.5 mm are easily migrated into downstream while the large-sized microplastics of 0.5–5 mm tend to deposit. 2) Ten kinds of plastic materials were found, in which polyethylene and polypropylene, originated from the developed tourism and fishery, account for 74.2% in all samples. 3) The earliest microplastics were found in the sediments of 1962. The abundance of microplastics in the sediments in seven reservoirs increased over time, impling the contribution of increasing human activities. 4) Positive correlations between the abundance of microplastics in sediments and local gross domestic product (GDP) ($n = 33$, $R^2 = 0.89$, $p < 0.05$) and negative correlations between microplastics abundance and reservoir basin area ($n = 33$, $R^2 = 0.42$, $p < 0.05$) revealed that GDP and watershed

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area are the key factors that control the distribution of microplastics. Our results help to understand the migration of microplastics between terrestrial and marine ecosystems.

1. Introduction

Plastic was invented in early 20th century with diverse properties, such as high durability, light weight, and corrosion resistance. Civilian plastics was put into large production in the 1950s (Anil, 2020). From 1950 to 2015, the global total production of plastic products (polymer resins, synthetic fibers, and additives) was as high as 8.3 billion tons, of which about 59% was discarded later (Geyer et al., 2017). The plastics scattered in the environment was broken into small-sized plastic fragments due to physical crushing, weathering, and biological process (Song et al., 2017). Thompson et al. pointed out that the small-sized plastic fragments had been widespread in oceans and coasts, and thereafter, he defined the plastic fragments with a size of less than 5 mm as microplastics (Thompson et al., 2004). They were divided into primary and secondary microplastics. Primary microplastics originate from plastic microbeads present in products, such as cosmetics, medicines, and polishing machines, while secondary microplastics originate from the decomposition of large plastics, such as the loss during textile production and washing (Rochman et al., 2015; Xu et al., 2020).

So far, microplastic pollution has been found to be widespread in ecosystems, such as ocean, freshwater, glaciers, soil, and atmospheric fallout (Ambrosini et al., 2019; Guo and Wang, 2019; Toumi et al., 2019; Zhou et al., 2019; Dong et al., 2021). Oceans, such as the Atlantic Ocean, and the Bohai Sea are the known sinks of many pollutants, including a large number of microplastic particles (Alomar et al., 2016; Lusher et al., 2014; Zhang et al., 2017). Many rivers and lakes around the world are also facing microplastic pollution in varying degrees (Di et al., 2019; Yu et al., 2016). Major rivers in China, including the Yangtze River, Yellow River, and Pearl River, have been confirmed to be polluted by microplastics (Han et al., 2020; Jia et al., 2020; Xiong et al., 2019). Lakes, such as the Taihu Lake, Poyang Lake, and Dongting Lake, exhibit an abundance of microplastics at a concentration as high as 3400 items$\cdot$m^{-3} (Su et al., 2016; Wang et al., 2018; Yuan et al., 2019). Qinghai Lake, an inland lake with less human activities, could not escape from being polluted by microplastics either (Xiong et al., 2018). However, as a unique freshwater ecosystem, reservoirs are poorly investigated for the distribution of microplastics (Di et al., 2019).

As of 2021, there are nearly 60,000 dams built on rivers in the world, thereby forming a large group of reservoirs (https://www.icold-cigb.org/). Reservoirs perform economic and social functions, such as flood control, power generation, source of industrial, agricultural, and drinking water (Mulligan et al., 2020). Meanwhile, dam constructions have also caused environmental issues, such as obstruction in river continuity, changed in nutrient delivery, increased sedimentation, and changes in the community structure (Maavara et al., 2020; Wang et al., 2016). The existence of reservoirs changes the form and size of the water flow, intercepts a large amount of sediment, causes serious siltation in the reservoirs, and reduces the sediment volume downstream, as reported for the Yellow River in China, the Mississippi River in the United States (Coleman et al., 1998; Yue et al., 2021; Zhao et al., 2014). In natural water bodies, microplastics can be transported and maintained in the environment for a long time, but dam construction may change the fate of microplastics (Mai et al., 2018). The Wujiang River is a primary tributary of the Yangtze River with a natural high drop, which is conducive for the construction of hydropower stations. So far, 11 cascade reservoirs have been built on the trunkstream of the Wujiang River, forming a group of reservoirs with staggered heights (Yang et al., 2020). Reservoirs act as the sinks of sediments. The combined use of cascade dams on the Wujiang River Basin has aggravated the interception of sediment. Just the Wujiangdu Reservoir itself intercepts more than 50% of sediment, which greatly reduces the amount of sediment that is transported downstream (Wu et al., 2018). The construction of dams has changed the original water and sediment migration. Meantime, the coarse-grained sediment settles and deposits in the reservoir, while the fine-grained sediment deposits on the surface of the sediments or migrates into downstream (Wang et al., 2019).

Sediments and microplastics are the common solid particles found in watersheds, and exhibit similarities in their migration and transformation pattern. However, the impact of cascade dams on microplastics is unknown. In this study, we investigated the cascade dams on the Wujiang River to explore the temporal and spatial distribution of microplastics in the reservoirs, analyze the interception of microplastics in the cascade reservoirs, and factors influencing the accumulation of microplastics, and provide a foundation to better understand the fate of microplastics in cascade reservoirs.

2. Material and method

2.1. Study area and sampling sites

The Wujiang River originates from Wumeng Mountain in Guizhou, China, and meets the Yangtze River in Chongqing. It spans through a length of 1037 km and a drainage area of 88,000 km^2 (Guo et al., 2008; Li et al., 2009). With a total drop of 2124 m, its superior geographical conditions have resulted in intensive hydropower development. Since 1979, 11 reservoirs have been built on the mainstream of the Wujiang River, including the Wujiangdu Reservoir, Dongfeng Reservoir, and Hongjiadu Reservoir and so on (Yang et al., 2020). The wastewater pollution in the basin mainly comes from the industries, urban wastewater, agriculture, and animal husbandry (Li et al., 2009). The area of industrial and mining land in Wujiang River Basin accounts for 0.49% of the total basin area, mainly mining. In Wujiang River Basin, the land for agricultural production is about 22,000 km^2, mainly planting rice, corn, wheat and other crops.

In September 2019, as shown in Fig. 1, a gravity core sampler (5.9 cm in diameter) was used to collect sediment cores from 11 reservoirs on the Wujiang River, namely the Puding Reservoir (PD) and Hongjiadu Reservoir (HJD) in the upstream, HongfengLake Reservoir (HFH) on the tributary, and Dongfeng Reservoir (DF), Suofengying Reservoir (SFY), Wujiangdu Reservoir (WJD), Goupitan Reservoir (GPT), Silin Reservoir (SL), Shatuo Reservoir (ST), Pengshui Reservoir (PS), and Yinpan Reservoir (YP) on the trunk stream. Two parallel cores were collected at each sampling point, and the deposition cores were divided into 5 cm intervals. The sediment samples were stored in glass bottles.

2.2. Extraction of microplastics

A sediment sample was taken in a beaker and a solution of zinc chloride (1.7–1.8 kg L^{-1}) was added into it (Wen et al., 2018). The mixture was stirred thoroughly with a glass rod and incubated on bench overnight. The suspension was transferred to another beaker and 30% H_2O_2 was added to remove the organic matter. The mixture was placed on a shaker and then incubated, so that H_2O_2 could fully react with the organic matter and microplastic fragments could suspend completely in the supernatant (Adomat and Grischek, 2021). Using the cellulose acetate filter membrane no. 1 with a pore size of 0.45 μm, it was subjected to vacuum filtration. The membrane was rinsed with ultrapure water many times, and left in a clean Petri dish until it dried completely. Then, the surface of the dried filter membrane was observed under an optical microscope. The suspected microplastic samples were screened and counted, their size was marked, and were numbered in sequence. A small number of microplastic fragments were stuck in the filter membrane during filtration. To reduce the error, the filter membrane no. 1 was placed in methanol solution for ultrasonication, and then, the cellulose acetate filter membrane no. 2 was used to perform the filtration of the resulting solution. It was rinsed with ultrapure water many times, and then left in a clean Petri dish until it dried completely for further observation.

2.3. *Observation and identification of microplastics*

A stereo microscope (Shanghai Gexiang, HDS-200G) was used to identify and select the suspected microplastic fragments present on the filter membrane, which was based on the operation method of GB/T 19863-2005. The shape, color, and size of the suspected microplastic fragments were recorded under the microscope. Using the Fourier transform infrared spectroscopy (PerkinElmer, FT-IR microscope spotlight 400) and operating based on the method of GB/T35927-2018, the fragments were compared with known polymer spectra to determine the polymer type with 80% confidence.

2.4. *Abundance calculation of microplastics*

The water content (W_{H_2O}) of sediment was calculated based on the method of GB 17378.5-2007. The sample was mixed thoroughly and dried to a constant weight in an oven at 60 °C. The evaporating dish was weighed before and after loading the sample using an analytical balance.

$$W_{H_2O} = \frac{m_2 - m_3}{m_2 - m_1} \times 100\%$$

where, $W_{H_2O}-$ water content, m_1- weight of evaporating dish (g), m_2- weight of evaporating dish and wet sample (g), m_3- weight of evaporating dish and dry sample (g).

The abundance of microplastics (C) is the number of microplastics per kilogram of sediment (dry weight) (Wang et al., 2017).

$$C = \frac{n}{(m_2 - m_1)(1 - W_{H_2O})}$$

where, $C-$ abundance of microplastics (items·kg^{-1}(dry weight)), $n-$ number of microplastics, $W_{H_2O}-$ water content (100%).

2.5. *Chronology of sediments*

Four reservoirs with an age of 25 years or more, namely PD, DF, WJD, and HFH, were selected to explore the deposition history of microplastics in the reservoirs. The length of sediment core ranged from 30 cm to 60 cm. The cores were divided at 5 cm intervals. Six, six, eight and twelve samples were collected from PD, DF, WJD and HFH reservoirs respectively. The sediment deposition rates of the reservoirs in this study are quoted base on the previous research. The average sediment deposition rate of HFH is 0.85 cm·a^{-1}, while the rate of WJD is 0.73 cm·a^{-1} (Lv et al., 2008; Yang et al., 2017). Sediment deposition rates of DF and PD have not been documented previously, so the average rate of 0.81 cm·a^{-1} for the reservoirs on the mainstream and tributary of the Wujiang River is used for DF and PD (Yang et al., 2017). PD, DF, WJD, and HFH were built in 1995, 1995, 1983, and 1960, respectively. The results of dividing the sediment thickness of the collected cores based on the age of the reservoirs are similar to the sediment deposition rates mentioned above, which confirm the reliability of the data used.

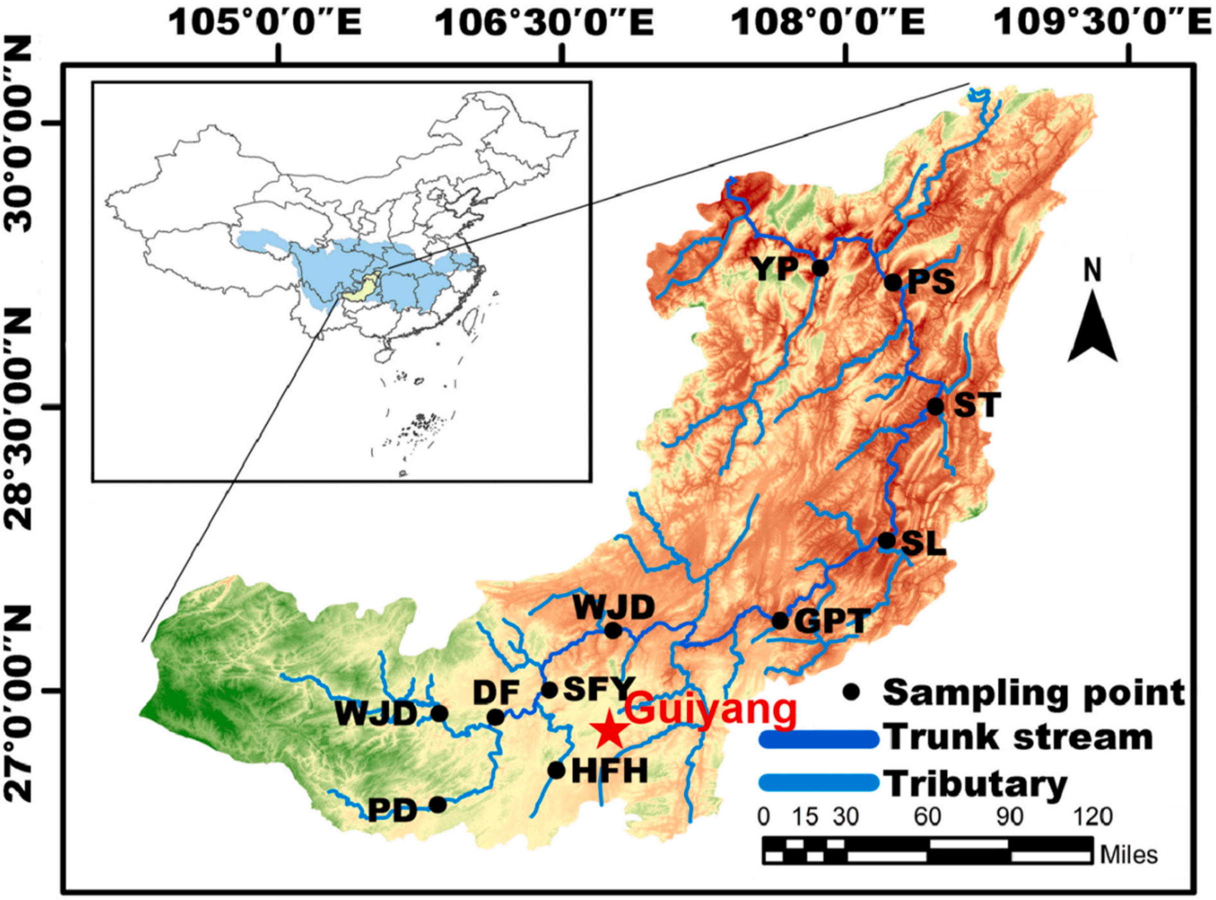

Fig. 1. Sampling sites in Wujiang River Basin, southwestern China.

3. Results and discussion

3.1. Characteristics of microplastics in sediments

In sediment samples of 11 reservoirs, microplastics with a flake shape exist in majority. As shown in the Fig. 2, lump, fiber, and flake shaped each accounts for 22.6%, 28.3%, and 49.1%, respectively, which are similar to the results of many previous studies conducted on freshwater systems (Xiong et al., 2018). Flake shaped ones are mostly the secondary microplastics. Plastics with high plasticity are used to produce thin and light bottles, bags, films and so on. These lightweight products are broken into small pieces and scattered in the environment through weathering and other processes (Xiong et al., 2018). The prosperous tourism is an important source of income in the Wujiang River Basin, but also a potential source of flake shaped microplastics (Feng et al., 2020b). Inappropriate dispersion of plastic products by the tourists is a potential source of microplastics in the reservoirs. The Wujiang River Basin has a large population in the agriculture sector, who may not perform agricultural mulching properly. Some of the broken mulching might enter the water body and settle into the sediments (Steinmetz et al., 2016). The fishery in the Wujiang River is also developed, which can lead to the loss of fishing nets that possibly fall into the water body and deposit (Xue et al., 2020). Additionally, the fine plastic fibers that are lost while washing the textiles make some contribution, too (Browne et al., 2011). Lump microplastics account for the least. Its contributing sources include the losses during plastic production and broken particles from the domestic waste (Lenaker et al., 2019).

In sediment samples of 11 reservoirs, microplastics with a size of 0–0.5 mm are found in majority. As shown in the Fig. 2, particle sizes of 0–0.5 mm, 0.5–1 mm, and 1–5 mm, each accounts for 57.2%, 30.2%, and 12.6%, respectively. There is a negative correlation between the particle sizes and quantity of microplastics. A large amount of small-sized microplastics was found to accumulate in the sediments, and other watersheds also exhibited similar distribution (Tien et al., 2020). The specific surface area of small-sized microplastics is large, and thus, heavy metals and hydrophobic organic pollutants in the sediments are more easily adsorbed onto the surface (Carbery et al., 2018, Feng et al., 2020a). Therefore, microplastic particles of small size deserve attention.

In sediment samples of 11 reservoirs, microplastics that are white in color are found in majority. As shown in the Fig. 2, white, black, brown, red, green, yellow, and other colors, each accounts for 48.4%, 12.6%, 8.8%, 8.8%, 8.2%, 7.5%, and 5.7%, respectively. White colored plastic products exhibit wide range of applications and variety in terms of products (Zhang et al., 2020). Colored plastics present in the environment may also fade or turn white due to bleaching and weathering (Kalogerakis et al., 2017; Stolte et al., 2015).

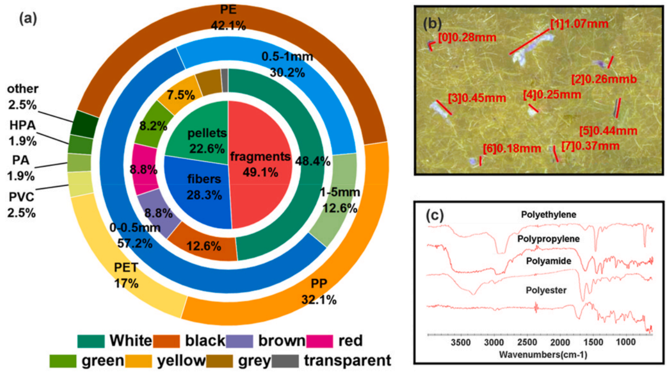

Fig. 2. Characteristics of microplastics in sediments of Wujiang River Basin. (a) Proportions of all microplastic samples, including shape, color, size, and polymer type. (b) Electron micrograph of microplastic fragments. (c) Raman spectra of the deceted microplastics. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

In sediment samples of 11 reservoirs, PE (polyethylene) is found in majority. PE, PP (polypropylene), PET (polyethylene terephthalate), PVC (polyvinyl chloride), and other polymers each accounts for 42.1%, 32.1%, 17.0%, 2.5%, and 6.3%, respectively. The material of microplastics present in the environment are closely related to the types of plastic products used. For instance, PP and PE, which account for large proportions in the samples, are widely produced worldwide (Geyer et al., 2017). This result is consistent with the studies conducted on the Yangtze River in China and the Venice Lagoon in Italy (Li et al., 2020; Vianello et al., 2013).

3.2. Temporal and spatial distribution of microplastics in sediments

3.2.1. Spatial distribution of microplastics

Among the surface sediments with a depth of 0–5 cm of 11 reservoirs included in this study, any microplastic was not detected in ST. The abundance of microplastics at other sampling points is between 75.6 and 1036.2 items·kg^{-1}. The spatial distribution of microplastics in the sediments of the Wujiang River Basin is uneven with obvious differences in the upper, middle, and lower reaches. Middle stream (823.6 items·kg^{-1}) > upstream (284.6 items·kg^{-1}) > downstream (101.6 items·kg^{-1}). Compared to other freshwater systems in the world (Table 1), the upper and lower reaches of the Wujiang River are at relatively low pollution level, while the middle reach is at relatively high pollution level. The maximum abundance of middlestream is at HFH (1036.18 items·kg^{-1}) and the minimum is at PS (75.6 items·kg^{-1}). The difference between the two is more than 13 times. HFH was built and began to store water in 1960. The early management of industry, tourism, agriculture, and fishery was not standardized, which might pollute the reservoir area and expose HFH to the plastic pollution (Jin et al., 2019., Liao et al., 2004; Wan et al., 2010). The effluent of HFH flows into the mainstream of the Wujiang River and accumulates in SFY. This may be the reason why the abundance of sediments in SFY is significantly higher than that of other upstream and downstream reservoirs. The abundance of microplastics in the sediments of WJD is 831.8 items·kg^{-1}. The fishery and tourism around WJD are well developed, and thus the plastic products used by people form the potential sources of microplastic pollution (Lin et al., 2018). GPT in the lower reach has a storage capacity of 6.454 billion m^3 and is 137 km away from the previous reservoir. Due to long-distance transportation and strong dilution, the influx of microplastics into GPT is effectively decreased (Zhou et al., 2017).

3.2.2. Vertical distribution of microplastics

At all sampling points, the abundance of microplastics in ST, YP, and PS increased with the depth of sediments, while the abundance of microplastics in 8 other reservoirs, including DF, decreased with the depth of sediments (Fig. 3). The history of microplastic sedimentation is an important indicator to understand human activities. The reservoirs discussed in this section are at least 25 years old. The abundance of microplastics in the sediments of HFH, WJD, DF, and PD increased significantly over time. HFH started water storage in 1960. Sediment with a depth of 55–60 cm belongs to before 1962, and no microplastic is found there. This might be the time when plastics just began to spread and no large-scale pollution had culminated (Rochman et al., 2013). At a depth of 55 cm in HFH, the abundance of microplastics is recorded as 75.3 items·kg^{-1}, indicating that the microplastic pollution in the sediments of the Wujiang River Basin traces back to 1962. This may be related to the extensive growth of plastic production at that time (Fig. 3) (Thompson et al., 2009). WJD was functionalized in 1983. Sediment with a depth of 30–35 cm should belong to 1979–1986. But at a depth of 35–40 cm in WJD, microplastic fragments are still found in the sediment samples, indicating that the original river channel had been exposed to microplastic pollution before the construction of this reservoir. PD and DF started water storage in 1995. The abundance of microplastics in the

Table 1
Microplastics abundance and characteristics in sediments of global freshwater systems.

Study regional	abundance	color shaped	polymers	references
Three Gorges Reservoir, China	25-300 items·kg^{-1}	Transparency dominates	Fibre33.9%–100%	Di and Wang (2018)
Brisbane River, Australia	10-520 items·kg^{-1}	White dominated	film > flake > fibre	He et al. (2020)
Thames, UK	660 ± 7.7 items·kg^{-1}	N/A	Flake49.3%,fibre47.4%,film3.3%	Horton et al. (2017)
Portugal,	18-629 items·kg^{-1}	White and black dominated	fragment43.6%,grain1.2%	Rodrigues et al. (2018)
Shanghai, China	802 ± 594 items·kg^{-1}	White occupied90%	sphere89.0%,fibre7.6%,fragment3.5%	Peng et al. (2018)
Venice Lagoon, Italy	672-2175 items·kg^{-1}	N/A	Flake87%,film2%,grain1%	Peng et al. (2018)
Danjiangkou Reservoir, China	708-3237 items·kg^{-1}	transparent dominated	fibers52.8%,fragments 42.3%,films3.87%),pellets.2%	Lin et al. (2021)
Ebro River in the Mediterranean	2052 ± 746 items·kg^{-1}	Color dominated	fibre > flake、film	(Sánchez et al., 2019)
Rhine, Germany	260 ± 10-11 070 ± 600 items·kg^{-1}	N/A	N/A	Mani et al. (2019)
Wujiang, China	0–1036.2 items·kg^{-1}	White dominated	Lump22.6%,fibrous28.3%,flake49.1%	This study

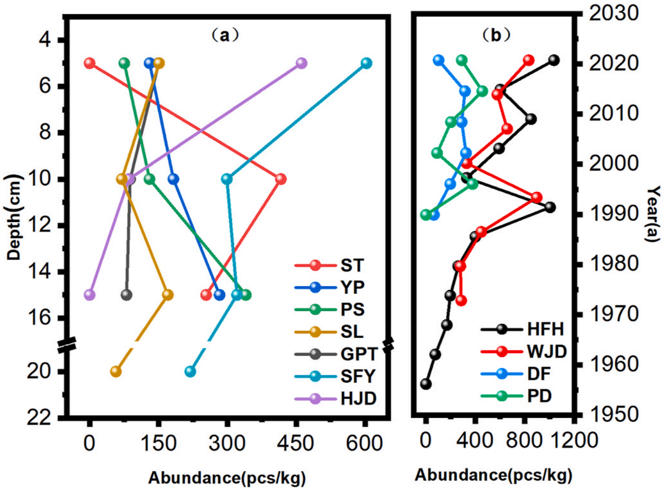

Fig. 3. Microplastics in sediment profiles of cascade reservoirs of Wujiang River Basin. (a) Variation of microplastic abundance with depth in seven young reservoirs; (b) Variation of microplastic abundance with time in sediments of four old reservoirs.

sediments with a depth of 25–30 cm are 0 items·kg^{-1} and 64.7 items·kg^{-1}, respectively. The abundance increased sharply from 1996 to 2002. That's probably because the consumption of plastic products increased with time.

3.3. Impact of cascade damming on distribution of microplastics

3.3.1. Interception of microplastics due to cascade damming

The Liuchong River and Sancha River merge into the mainstream of the Wujiang River. On the trunkstream, 71.4% of microplastics in the sediments of DF is present as fibers. While on the tributaries in the upper reach, majority of microplastics in PD and HJD are present as lump and flake shaped, and only 20% and 0% as fibers, respectively. On the one hand, the sedimentation speed of microplastics is affected by their shape. Lump and flake shaped with a larger volume are easier to settle (Khatmullina and Isachenko, 2017). On the other hand, dam construction may aggravate the difference to intercept large amount of lump and flake shaped microplastics first at PD and HJD in the upper reach, so more polyester and polypropylene as fiber would migrate to downstream of DF.

At a depth of 0–15 cm in HFH and WJD, the abundance of microplastics in sediments are 824.2 items·kg^{-1} and 683.33 items·kg^{-1}, respectively. The abundance of microplastics in SFY and GPT, which are downstream of the above-mentioned reservoirs, are 400.7 items·kg^{-1} and 98.6 items·kg^{-1}, respectively. Here, the microplastic pollution is found to be greatly reduced. This suggests that HFH and WJD "trap" the microplastics in the water and sediments and intercept them effectively. This process reduces the amount of microplastics transported to the downstream in SFY and GPT (Watkins et al., 2019). The abundance of microplastics in the sediments of YP, which is the last-stage reservoir of the Wujiang River, is recorded as 130.7 items·kg^{-1}. It greatly reduces the transportation of microplastics from the Wujiang River to the Yangtze River. This is consistent with the results of the river-reservoir system in New York, USA, that is, the abundance of microplastics in reservoir sediments was significantly higher than that in upstream and downstream river sediments, meanwhile, the abundance of microplastics in river and reservoir water was contrary to the results observed in sediments (Watkins et al., 2019). It indicates that microplastics in water tend to settle in the sediments of the storage system, such as reservoirs, and thus, a large number of microplastics are buried in the sediments (Witold et al., 2020). Firstly, the dam changed the water hydrodynamic conditions to become slow or static. In this case, the conveying force of water flow suffered by microplastics is sharply weakened. And then, because the density of microplastic is greater than that of water, it is bound to deposit at the bottom of the reservoir under the action of gravity and finally enter into the sediment. It can be confirmed by the abundance distribution of microplastics in upstream, reservoir and downstream sediments. Therefore, reservoir sediments act as a sink of microplastics in the river system (Watkins et al., 2019). The construction of cascade dams on the Wujiang River forms a large group of reservoirs, therefore cascade damming may act as a potential sink of microplastics.

3.3.2. Granularity effect of cascade damming on the interception of microplastics

Dams and reservoirs can change the flow regime of watersheds, the sediment flux, and the amount of water flow (East et al., 2018). Cascade damming makes the sediments with larger particle sizes deposit first in the upstream reservoirs and those with smaller particle sizes deposit more slowly, allowing them to flow into downstream reservoirs. This results in a decrease in the proportion of sediments with larger particle sizes from upstream to downstream reservoir areas, while increasing the proportion of sediments with smaller particle sizes (Guo et al., 2020; Wang et al., 2019). The transport of microplastics is similar to that of sediment. The coarse-grained components first settle into the sediment, and the fine-grained components can be transported downstream with the flow. Due to the blocking of the dam, the flow velocity in the water area near the dam has been weak. Most microplastics, whether coarse or fine particles, have enough time to slowly settle to the bottom of the reservoir. The dam outlet is the only channel for the transportation of microplastics in the reservoir water to the downstream. However, the dam outlet is usually designed at half the depth of the dam. Therefore, it is difficult for the discharge to disturb the microplastics that have entered the sediment, ensuring the burial of microplastics in the sediment.

Cascade damming exerts different interception effects on microplastics of varying sizes. Larger microplastics are intercepted in the upstream reservoir areas firstly, while smaller ones tend to flow downstream. Microplastics with smaller particle sizes (0–0.5 mm) in PD, HJD, DF in the upper reach account for 30.0%, 80.0%, and 42.9%, respectively. They gradually become dominating in three reservoirs in the middle reach with more than 50.0% in two of them. In GPT and downstream reservoirs, microplastics less than 0.5 mm in size become dominating, which accounts for 66.7%–90.0%. As shown in Fig. 4, the proportion of microplastics in the size range of 0–0.5 mm continues to increase from 30.0% in PD to 90.0% in YP. The proportion of larger microplastic fragments in the size range of 1–5 mm decreases with fluctuation from 30.0% in PD to 10.0% in YP. Generally, from upstream to downstream in the Wujiang River Basin, the dominant size of microplastics changes from large to small size.

3.4. Factors influencing abundance of microplastics

As shown in Fig. 5, statistical analysis revealed that the abundance of microplastics in the sediments of the Wujiang River Basin exhibits a positive correlation with local GDP (gross domestic product) ($R^2 = 0.894$, $p < 0.05$), and a negative correlation with catchment area of the reservoir ($R^2 = 0.422$, $p < 0.05$). However, it exhibits no significant correlation with the permanent population (data of permanent population and GDP are from http://www.resdc.cn/DOI/, data of catchment area of reservoirs is from https://www.dlzb.com/). Among them, the sampling points in HJD, DF, and SFY are all in the Qianxi County. The average abundance of microplastics at these three sampling points (234.3 items·kg^{-1}) represents the microplastic pollution in the Qianxi County.

Plastic is completely a product of human activity. Human activities of different types and frequencies exert direct impact on the abundance of microplastics. Studies have shown that the abundance of microplastics in densely populated areas is generally higher than that in suburban and rural areas (Wang et al., 2017). However, in this study, we found that the abundance of microplastics in the Wujiang River Basin is positively correlated to GDP of the counties, but not significantly correlated to the permanent population of the counties. The Hovsgol Lake in Mongolia is sparsely populated, while the Laurentian Great Lake in the United States is densely populated, but the abundance of microplastics in the former is higher than that in the latter. This implies that the population density may not be the decisive factor influencing the abundance of microplastics (Eriksen et al., 2013; Free et al., 2014).

Among all the microplastic samples, polyester products are that are commonly used for fishery production tools, such as fishing nets, accounts for more than 80.0% of fibrous plastics. PE and PP are commonly used for producing plastic bottles and bags, which are representations of tourism waste, and account for more than 80% of all samples. The tourists and migrant population contribute to the local economy as well as to the plastic pollution at the same time. The main sources of microplastics in the reservoir sediments are fishery and tourism, which are not closely related to the permanent population. This explains why the abundance of microplastics in the reservoirs of the Wujiang River Basin is less affected by the local permanent population, but is positively correlated with GDP. Additionally, reservoirs with large catchment areas might dilute the microplastic pollution effectively. For example, the abundance of microplastics at GPT (150.3 items·kg^{-1}) is only 18.1% of that at WJD (831.8 items·kg^{-1}). GPT has a catchment area of 15,460 km^2. Its wide watershed disperses the microplastic fragments from the upstream reservoir WJD.

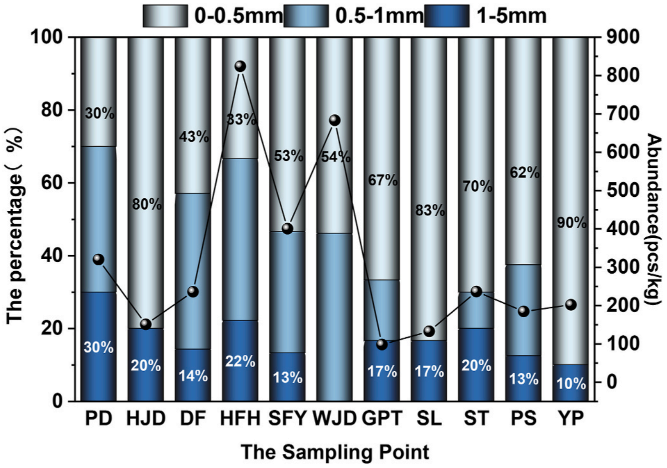

Fig. 4. Effect of step damming on microplastics abundance and particle size distribution.

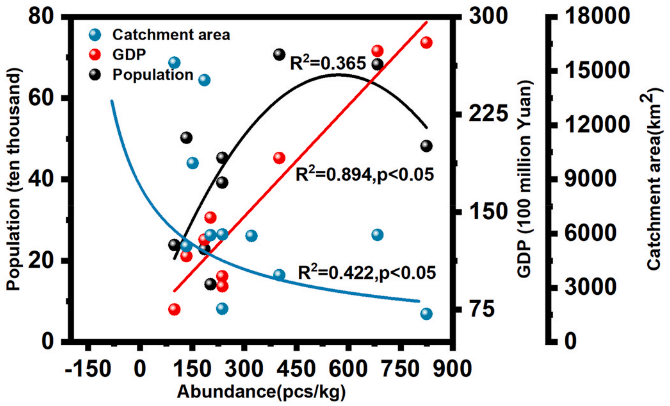

Fig. 5. Relationship between microplastics abundance and catchment area, GDP and population.

4. Conclusion

Effect of cascade damming on microplastics transportation was investigated in Wujiang River, China. The earliest microplastics were found in the sediment of 1962. The abundance of microplastics in the sediment profiles increased over time, impling the increasing contribution of human activities. Positive correlations between the abundance of microplastics and GDP ($R^2 = 0.89$, $p < 0.05$) and negative correlations with reservoir basin area ($R^2 = 0.42$, $p < 0.05$). Dams can modulate the shape and hydrodynamic conditions of rivers. In general, the density of large plastic is larger than that of water, and thus, plastic separates from water and settles in river ecosystems. However, rapid water flow can transfer microplastics actively and promote their migration. Damming can slow down or stop the water flow and weaken the transportation capacity of river water on microplastics. When the transportation effect is weaker than the sedimentation effect, microplastics end to deposit into the river or reservoir sediments over time. The existence of cascade damming in the Wujiang River has intercepted a large amount of microplastic fragments. Therefore, cascade damming acts as an important potential sink of microplastics. The abundance of microplastics in the environment mainly depends on the production and use of plastic products. Fine plastic particles are easily transported downstream under the background of cascade damming. This suggests that the microplastic pollution and its water ecological risk in the downstream area of cascade dams need to be evaluated in the future. From the perspective of pollution control, the prosperity of agriculture and tourism in the river basin is accompanied by the large production and flow of external microplastics. Therefore, the management of microplastic pollution needs to focus on the emission of microplastics from agriculture and tourism, strictly control the use of plastic products in main agricultural areas and scenic spots in the basin, strengthen plastic waste collection and resource recovery, to reduce the transportation of microplastics in the river ecosystem from the source.

Credit author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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Further reading

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