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Sources and distribution of microplastics in the east China sea under a three-dimensional numerical modelling☆

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ABSTRACT

Microplastics are new pollutants found in various environments; moreover, high concentrations of microplastics have been proved to harm aquatic organisms. To understand the high abundance of microplastics in the East China Sea (ECS), where the Zhoushan fishing ground is located, this study investigated the transportation and spatial distribution of microplastics from the Changjiang River Estuary (CE) to the ECS via three-dimensional numerical modelling. Utilising observations of microplastics at the surface of the ECS and backward particle tracking, three sources of microplastics were identified: the Changjiang River, Hangzhou Bay, and coastal area of Nantong city. Moreover, Southern Korea contributed to the microplastics in ECS. After microplastics are released from these sources, monsoons, currents, the Changjiang plume, and tides cause significant seasonal differences in the hot spots for microplastics in the ECS; moreover, the generation of ocean fronts may promote microplastic accumulation. In addition, the settling characteristics of microplastics were shown to influence their distributions; for example, large amounts of microplastics accumulated at the bottom of the riverbeds. This study enables a more complete assessment of microplastic transport from estuaries to the open sea and provides a spatial and temporal distribution of microplastics at the surface of the ECS.

1. Introduction

Recently, microplastic pollution in water systems has become an urgent environmental problem. An estimated 368 million and 367 million tons of plastics were produced in 2019 and 2020, respectively (PlasticsEurope, 2021). Owing to ineffective management, plastic waste enters marine environments through various channels, such as rivers and sewage treatment plants. In 2030, 53 million tons of plastics are predicted to enter aquatic ecosystems (Borrelle et al., 2020). Most plastics are chemically stable; hence, they resist self-degradation in the ocean. Nevertheless, they gradually break into small pieces via solar radiation (photodegradation and embrittlement) or waves (Zhou et al., 2015). When their diameter is less than 5 mm, they are considered microplastics (Barnes et al., 2009; Cózar et al., 2014). Compared with plastics, microplastics have a higher specific surface area, allowing them to absorb a variety of organic contaminants, heavy metals, and microorganisms. This may increase the density and size of low-density microplastic particles, thereby altering their settling characteristics (Ashton et al., 2010; Ogata et al., 2009; Sun et al., 2020). Microplastics are prevalent in almost every type of marine habitat, including surface and subsurface water columns (Rowley et al., 2020), beach and wetland sediments (Sarkar et al., 2021), polar regions (Fragão et al., 2021), and the deep ocean (Cunningham et al., 2020). Furthermore, owing to their small size, microplastics can be accidently ingested by aquatic organisms and even enter the human bloodstream, posing health risks (Cao et al., 2017; Kashiwada, 2006; Lu et al., 2016; Leslie et al., 2022). Therefore, microplastic pollution is a potential risk to humans, wildlife, and ecosystems (Rochman et al., 2019, 2015).

Approximately 75% of microplastics in marine environments originate from land-based sources (Morales-Caselles et al., 2021); thus, rivers are considered an important path for plastic transport to the oceans. Additionally, estuaries are considered an important area for understanding and quantifying the transport of microplastics from land to sea (González-Fernández et al., 2021). In 2014, Zhao et al. estimated that the average abundance of microplastics in the Changjiang River Estuary (CE) was 4137.3 ± 2461.5 N/m^3 (Zhao et al., 2014). In 2015, the

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abundances of microplastics in the estuaries of three major cities in China were estimated to be 955.6 ± 848.7 N/m^3 (Zhao et al., 2015), and those in the coastal waters of the East China Sea (ECS) were 0.167 ± 0.138 N/m^3 (Table S1). Microplastics in the ocean are not uniformly distributed but are transported via ocean dynamics, such as wind, waves, tides, thermohaline gradients, surface flow, Stokes drift, mesoscale eddies, and the influence of benthic sediments (Iwasaki et al., 2017; Onink et al., 2019; Zhang, 2017). Properties such as density, size, shape, buoyancy, surface tension, and polarity of the microplastics also influence their trajectories (Guo and Wang, 2019; Stolte et al., 2015; Van Melkebeke et al., 2020; Zhang, 2017). Thus, systematically studying the sources, fluxes, and accumulation of microplastics in transition waters is necessary to clarify their actual transfer path from rivers to the open seas and accurately evaluate microplastic pollution in the oceans (Sousa et al., 2021).

Owing to their unique physical characteristics and the complex dynamic and biological processes they undergo, microplastics exhibit complex motion processes in water, including subsidence, deposition, and resuspension; hence, numerical simulation of their transport is challenging. Thus, many recent studies have investigated the transport of microplastics in marine environments. Several studies have focused on the Mediterranean coast, which has one of the highest concentrations of microplastics worldwide (Karkanorachaki et al., 2018; Lots et al., 2017; Miramontes et al., 2019; Renzi et al., 2018). However, owing to limited observations of the major rivers and transition areas that flow into the Mediterranean, large inconsistencies exist in the observed data. Although the majority of microplastics in aquatic environments converge in the ocean, transport in river areas is critical for determining their migration from land to the open ocean. Ding et al. developed a comprehensive hydrodynamic model to investigate microplastics originating from four different rivers around Laizhou Bay. In this model, the lattice Boltzmann method was coupled with a Lagrangian particle tracking method to accurately simulate the pathways taken by microplastics (Ding et al., 2019). In addition, Wong et al. explored the relationship between microplastic transport in rivers and discharges from wastewater treatment plants (WWTPs) and found that WWTPs are both sinks and sources of microplastics (Wong et al., 2020). Holmes et al. utilised a mass balance model to investigate microplastic discharges from WWTPs in the United States and rivers in Ontario, Canada, and demonstrated that a portion of microplastics in the rivers originated from the WWTPs (Holmes et al., 2019). Microplastics have complex trajectories in rivers, and significant uncertainties remain that prevent determining whether microplastics will settle at the bottom of a river or drift into the ocean. A lack of knowledge about the transport of microplastics in river environments may cause incorrect estimations of the sources of microplastics entering the ocean, making it difficult to recover and regulate them.

Microplastics are discharged into the ocean primarily from domestic and industrial wastewater. Improper solid waste management is another contributing factor; plastic waste entering the environment due to improper management accounts for 27.7% of the total plastic produced in China yearly (Jambeck et al., 2015). Approximately 370 million people live in the Changjiang River basin, which is 26.4% of the total population of China. Nearly 700 industrial parks and economic development zones are located there (Li et al., 2021), which is a significant source of microplastics. Zhao et al. collected a large number of surface water samples (100 L per sample) from the CE and ECS during various seasons to study the spatial and temporal patterns of microplastics and found an irregular distribution (Zhao et al., 2019). Owing to the limited observations based on cruises and in-situ measurements, obtaining a comprehensive understanding of the sources and sinks of microplastics in estuaries remains difficult but important for microplastic control and evaluation. Therefore, a hydrodynamic model is necessary. The flow field in the ECS is complex and controlled by various hydrodynamic conditions, which affect the movement of pollutants (Wu et al., 2011). Therefore, the combined effects of monsoon, tidal, and continental currents must be considered when modelling microplastics transport. In the present study, we assumed that the microplastic sources in the ECS were consistent, and the distribution was seasonal. A hydrodynamic model combined with a Lagrangian particle tracking module was utilised to simulate the transport of microplastics in the CE and ECS, identify potential sources of microplastics in the ECS, and analyse the seasonal distributions of microplastics with different sinking velocities. This study can provide guidance for microplastic pollution management in the ECS, and the methods are applicable to other coastal areas worldwide.

2. Data and methods

2.1. Study area

The ECS is a vast, shallow continental shelf, which gradually deepens from northwest to southeast, and has complex underwater topography with steep slopes (Yuan et al., 2020). It is located between the eastern edge of Eurasia and the Pacific Ocean, surrounded by the Ryukyu Islands, Kyushu Island, Korea, and Taiwan Island. Moreover, it has complex tides and currents (Fig. 1). The ECS is strongly influenced by the East Asian monsoon, with cold and dry north-westerly prevailing winds in winter due to the influence of high pressure, and warm and humid south-easterly prevailing winds in summer (Guo et al., 2004). The Yellow Sea coastal current (YSCC), the Zhe-Min coastal current (ZMCC), and Taiwan warm current (TWC) occur in the ECS, as shown in Fig. 1. The coastal currents flow northward in summer and southward in winter. The TWC is a tributary of the Kuroshio, which has high temperatures and salinity, and flows north-westward into the coastal waters of Zhejiang and Fujian at approximately 31°N (Chen and Sheu, 2006; Zhu et al., 2004). The Changjiang River is the largest river that flows into the ECS and generates the Changjiang plume (CP), which extends offshore near Jeju Island in summer and flows southward along the Chinese coast in winter (Zhang et al., 2020b).

2.2. Numerical model

This study utilised a Semi-implicit Cross-scale Hydro science Integrated System Model (SCHISM) to model the transportation of microplastics in the ECS. This model uses a highly efficient and accurate semi-implicit finite-element/finite-volume method with a Eulerian–Lagrangian algorithm (Zhang et al., 2016) and a highly flexible vertical gridding system, which robustly and faithfully resolves the complex topography in estuarine and oceanic systems without any smoothing (Zhang et al., 2014). The Lagrangian particle tracking method in this model tracked the advection and diffusion of each microplastic particle, and the turbulent diffusion effect was coupled with the random displacement model. The study area was 28–33°N, 120–125°E. The model resolutions were approximately 300 m in the ECS, 50 m in the major rivers, and 100 m along the shoreline. Overall, there were approximately 31,000 nodes and 57,700 triangles in the horizontal dimension and 31 nonuniform layers in the vertical dimension.

The bottom topography and coastline used in the model were based on the ETOPO1 dataset (http://www.ngdc.noaa.gov/mgg/global/global.html), and the initialisation of this model included sea level height, horizontal velocity, salinity, and temperature from the global HYCOM model output. Additionally, the global tidal FES model was used with eight tidal constituents (M2, S2, N2, K2, K1, P1, O1, and Q1). Hence, the velocity boundary conditions were generated using HYCOM and FES (Carrere et al., 2013). The six-hourly sea-surface momentum and heat flux were provided by the European Centre for Medium-Range Weather Forecasts (ECMWF), which also provided the wind speed, air temperature, air pressure, precipitation, humidity, shortwave fluxes, and dew point temperature at a spatial resolution of 0.125° × 0.125°. The climatological daily mean discharge data for the Changjiang River

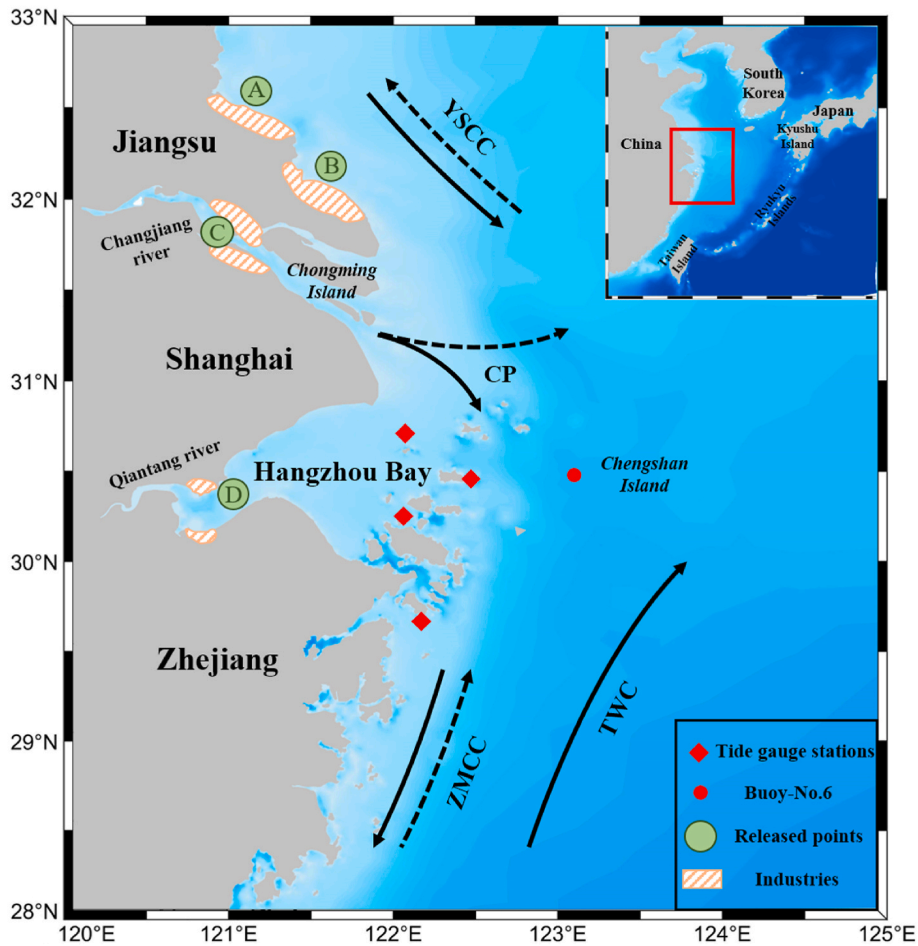

Fig. 1. Map showing the main currents. TWC, Taiwan Warm Current; YSWC, Yellow Sea Warm Current; ZMCC, Zhe-Min Coastal Current; YSCC, Yellow Sea Coastal Current; CP, Changjiang River plume. The area where the particles are released are labelled as A, B, C and D. The industrial area is designated as the region. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

from the Datong station were provided by the Changjiang Water Resource Commission.

2.3. Numerical experiment settings

The release point for microplastics in the Changjiang River was set at 31.85°N, 120.87°E (point C in Fig. 1) where many industrial parks are located, and 10 modelled particles were released every 6 h at a depth of 0 m. The microplastic transport routes were track lines connecting the daily positions of the microplastics. To estimate the distribution of microplastics, the simulation domain was divided into $0.01° \times 0.01°$ grid cells. The accumulated time was calculated as the time between the release of the microplastics and when they emerged in each grid cell; the relative abundance was also calculated. To determine potential sources of microplastics and verify the reliability of the model, backward particle tracking was utilised, and the movements of microplastics in summer and winter were simulated and compared with observational data from Zhao et al., which was regarded as Experiment 1 in this study (Zhao et al., 2019). Subsequently, a seasonal analysis of the temporal and spatial distributions of microplastics was conducted in Experiment 2, and hot spots were detected. As the sinking velocity differed according to the characteristics of the microplastics, Experiment 3 was set to simulate the movements of floating and suspended microplastics with different sinking velocities under the same climatological conditions, tides, and random walk used in Experiment 2, and the vertical distribution of microplastics in each season based on the distance to the coast was analysed.

3. Results

3.1. Sources of microplastics in the ECS

To understand the sources of microplastics, the observed microplastic distributions in winter and summer from Zhao et al. were compared with our models (Zhao et al., 2019). Owing to the CP, TWC, and summer monsoon, approximately 76% of the microplastic particles released during summer moved northeast to the open sea, whereas approximately 24% were transported to the northern coastal areas. In contrast with Zhao et al., the microplastics released from the CE did not result in high concentrations in the open sea of the Hangzhou Bay in summer (Zhao et al., 2019); they may have originated from other sources. Backward particle tracking experiments for each release point were conducted in August for 90 d (Fig. S7a). According to the trajectory analysis, approximately 97% of microplastics in this region came from Hangzhou Bay outside the Qiantang River, where many factories are located (Xie et al., 2018). The observations of Wang et al. also confirmed the accumulation of microplastics in the surface waters of Hangzhou Bay due to mariculture and industry (Wang et al., 2020). Therefore, Hangzhou Bay was regarded as a source of microplastic pollution.

Similarly, we analysed the distribution of microplastics discharged from the Changjiang River during the winter. Owing to the CP, ZMCC, and winter monsoon, many particles moved southward along the Zhe-Min coast. In the previous study, a region in the north-eastern CE showed a high abundance of microplastics; however, this was not observed in our study. Additionally, backward particle tracking was conducted in February for 90 d (Fig. S7b). The pathways of plastic particles indicated multiple pollution sources. Approximately 12% of microplastics came from the Changjiang River. Approximately 46% of the particles came from the coastal area of Nantong City, where there are many industrial zones, via the YSCC (Zhang, 2013; Feng et al., 2016). Therefore, the coastal area of Nantong City was regarded as the third source of microplastics. The remainder of the particles may have originated along the Korean coast and moved southwest during the winter via the Korean coastal current.

Therefore, three main release points exist for microplastics in the study area: the Changjiang River, Hangzhou Bay, and the coast of Nantong City. To further validate the model, the correlation between the observed and modelled abundances of microplastics was investigated using these three release points. All observations of microplastic abundances in the study area were selected for validation. The resulting correlation coefficients were 0.89 in summer and 0.87 in winter (Fig. 2). Therefore, the numerical model accurately captured the spatial and temporal distributions of microplastic pollution and confirmed that the main sources of microplastic pollution were the coastal areas of the Changjiang River, Hangzhou Bay, and Nantong City.

3.2. Seasonal variations in microplastic transportation

To further understand the spatial and temporal distributions of microplastics in the study area, the accumulated time after their release in each season was continuously calculated to determine the relative abundance. Fig. 3 shows the microplastic abundance in each season; significant differences in the distribution patterns were found among the seasons. During spring and autumn, a hot spot formed in the estuaries of both the Changjiang and Qiantang rivers. During spring, approximately 10% of the microplastics moved eastward after leaving the ECS, and approximately 3% of them were stranded on the coast. During autumn, approximately 7% of microplastics were transported southward and eastward out of the studied area, and 8% were stranded on the coast. In contrast, during summer and winter, there were multiple hot spots, as shown in Fig. 3b and d. During summer, microplastics accumulated in the estuary of the Qiantang River and inshore and outscore of the Changjiang River. Relatively large amounts of microplastics (approximately 12%) were transported outside of the study area, to the north and east; only 2% of the microplastics remained on the coast. During winter, the CE did not show a high abundance of microplastics, but two hot spots formed in the northern CE and southern Qiantang River estuary. Approximately 8% of the microplastics moved outside the studied area, whereas 5% were stranded on the coast. In addition, a large proportion of microplastics accumulated near the Zhoushan Sea area (31%, 27%, 29%, and 17% in spring, summer, autumn, and winter, respectively), which may have had an adverse impact on the organisms in the Zhoushan fishing grounds.

3.3. Microplastic distributions with various sinking velocities

Diverse types of microplastics can enter the ocean from terrestrial sources. Twelve polymer types were identified in the CE and ECS using Fourier-transform infrared (FTIR) spectrometry (Zhao et al., 2019); polyethylene (PE) and polypropylene (PP) were the main types. The sinking velocity of microplastic particles is a function of their physical properties and largely determines their ultimate fate. Different types of microplastics have different densities, which determines their buoyancy and fluidity in water. PP, PE, and polystyrene (PS) were widely observed on the sea surface and coastlines; hence, these three types of microplastics were chosen to study the influence of sinking velocity on distribution. The densities and corresponding sinking velocities of PP, PE, and PS are listed in Table 1. Those with a density higher than water have negative sinking velocities, meaning they sink in water and are normally regarded as suspended particles. In contrast, particles less dense than water will generally float at or near the surface as floating particles; however, some will be suspended in the water column. In the case of PP, these particles essentially float on water and rapidly drift considerable distances via surface currents and winds.

After their release from the Changjiang River, microplastics with different sinking velocities were distributed as shown in Fig. 4. During summer, all three types of microplastic particles flowed north-eastward due to the monsoon and CP. Compared with PS, PP and PE particles were more widely distributed in the ECS because of their low density and positive buoyancy, and eventually entered the Sea of Japan through the Tsushima Strait. Nevertheless, PP flowed into the open sea during summer, whereas PE particles tended to accumulate within approximately 100 km offshore. During winter, all three types of microplastic particles spread southward directly along the Tsushima Strait due to the CP, YSCC, ZMCC, and winter monsoon. As the settling rate and density of microplastics decreased, their hot spots moved southward; specifically, the PP released from the Changjiang River accumulated in the southern part of the Zhoushan Islands.

3.4. Vertical distribution of microplastic particles in the Changjiang River

Microplastics entering the ocean are first transported through rivers. To estimate the total amount of microplastics transported to the ocean, we examined the vertical distribution of microplastics at ten points along the Changjiang River (Fig. S8). Density is an important factor in the vertical transport of microplastics. PP (v = 0.01 m/s) floats in the water surface layer and, thus, flows into the ocean. Hence, we only

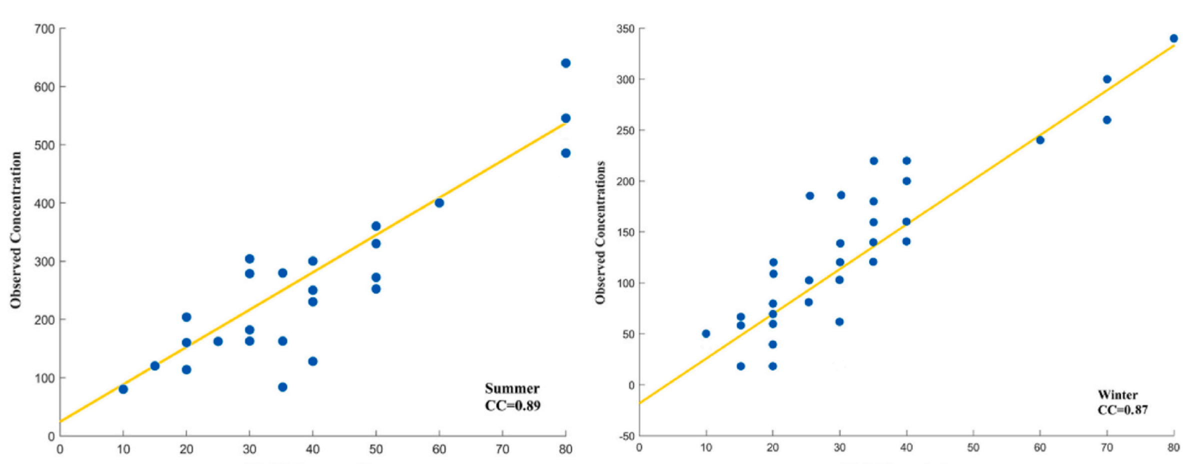

Fig. 2. Validations of all the sample points between model abundance and observed abundance in summer and winter.

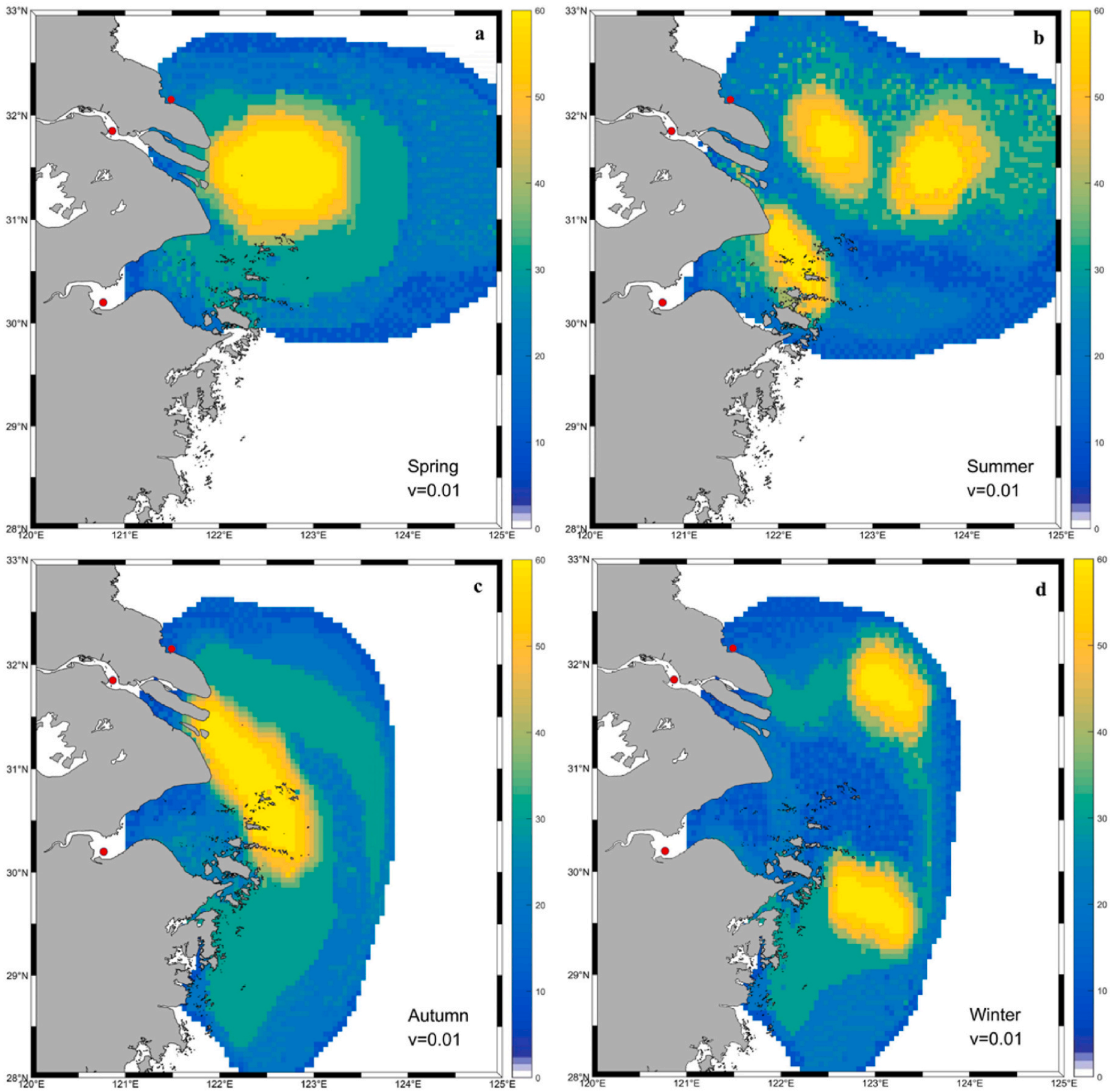

Fig. 3. The transport pathways of particles released in different seasons. Identification of the main transport path was carried out by calculating the proportion of times that particles appear in each grid cell.

Table 1
Application and modelling parameters used for selected microplastics.

Plastic	Density	Product application (Li et al., 2016)	Sinking velocity (m/s)
PP	0.83–0.92 g/cm^3	Straws, Food containers, Bottlecaps	0.01[a]
PE	0.89–0.98 g/cm^3	Plastic bags, Bottles, Netting,	0.0065[b]
PS	1.05 g/cm^3	Plates, Cutlery, Toys	−0.015[c]

[a] (Kowalski et al., 2016).
[b] (Waldschläger et al., 2019).
[c] (Khatmullina and Isachenko, 2017).

analysed the vertical distributions of PE and PS, which have sinking velocities of 0.065 m/s and −0.015 m/s, respectively (Fig. 5). PE particles were positively buoyant and mainly remained suspended within 5 m of the surface during transport. They were transported to hot spots 30–50 km from the CE, near Changxing Island, owing to the flow of the Changjiang River. In contrast, the PS particles mainly accumulated at 5–10 m deep and generated a hot spot 10–20 km from the end of Changxing Island. Moreover, the vertical distribution of microplastic particles in the CE was also characterised by a seasonal distribution. During the winter dry period, the migration distance of the microplastics decreased, probably due to tidal influence, and microplastics accumulated in shallower water than that during summer.

4. Discussion

The complex hydrodynamic structures in coastal areas play significant roles in microplastic transport; therefore, modelling a credible hydrodynamic environment is important (Zhang et al., 2020b). The comparison between our model results and the observed data showed that the simulated temperature and salinity were highly correlated between the two, and the tidal components of the elevation were also accurately captured by the model. (Complete validation details are shown in the supporting information.) Therefore, this model is highly credible for simulating the transport of microplastics. Moreover, backward particle tracking provides an important tool for examining potential sources and drift paths (Kanhai et al., 2020). In this study, this method was adopted to determine the potential sources of microplastics in the ECS, excluding the Changjiang River, based on the observations of

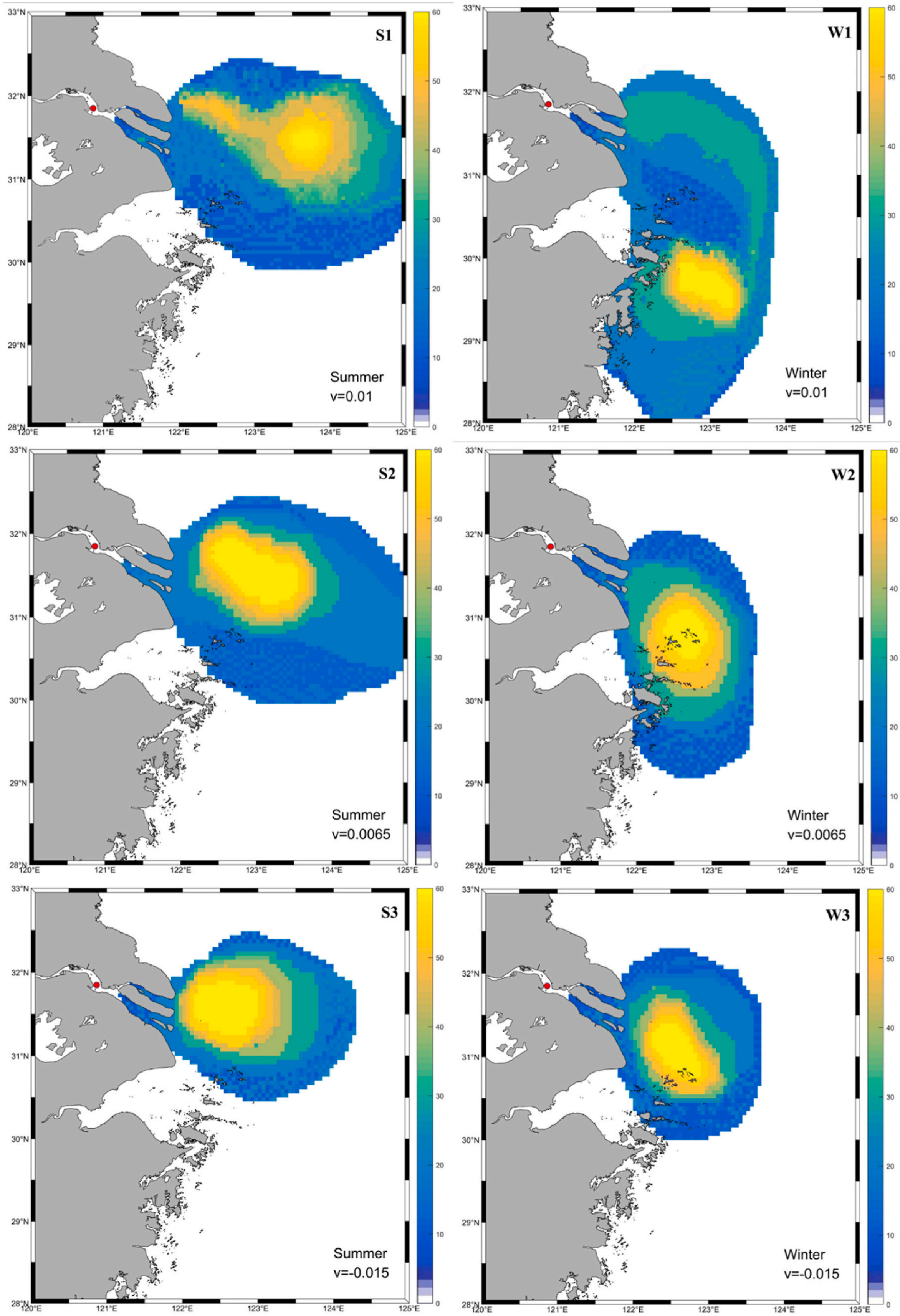

Fig. 4. The transport pathways of particles with different sinking velocity released in summer and winter. Identification of the main transport path was carried out by calculating the proportion of times that particles appear in each grid cell.

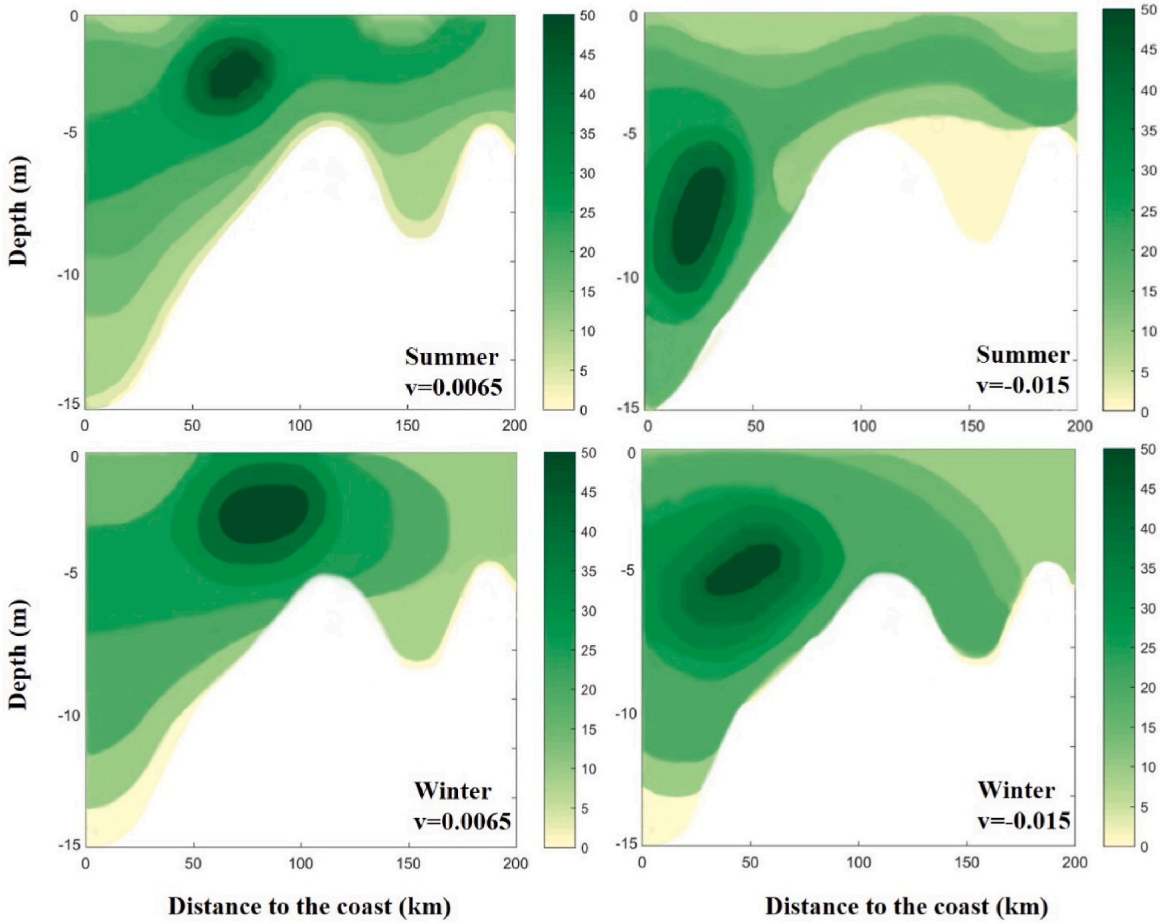

Fig. 5. Vertical distribution of microplastic particles along the Changjiang River from the release point to the mouth of the Changjiang River Estuary at two sinking velocities (0.065 m/s and −0.015 m/s).

Zhao et al. during summer and winter (Zhao et al., 2019). The results indicated that Hangzhou Bay and Nantong city were two additional sources of microplastics. In Hangzhou Bay, industrial zones and wastewater treatment plants (WWTPs) are located in the southern part, and mariculture and fisheries are located in the central bay area. Both are important sources of microplastics (Wang et al., 2020; Xie et al., 2018). In Nantong City, large amounts of microplastics were found in the land-based wastewater from the Yangkou Port industrial zone, which is located there (Wang et al., 2021). To verify this, the forward Lagrange particle tracking method was utilised by releasing modelled particles from the CE, Hangzhou Bay, and Nantong City; the simulated results highly corresponded to the observations by Zhao et al. Therefore, the floating microplastics in the ECS were primarily from the Changjiang River, Hangzhou Bay, and the coast of Nantong City. In addition, the results indicated that Southern Korea may serve as a potential source of microplastic emissions to the ECS, which agreed with Zhang et al., who found that microplastics released from Hampyeong, South Korea during winter would be transported to the coasts of Zhejiang and Fujian due to the winter monsoon and Korean Coastal Current (Zhang et al., 2020b).

Owing to seasonal changes in coastal circulation, the distribution of microplastics shows seasonal characteristics (Cózar et al., 2015; Lyubartseva et al., 2016). During spring, microplastics released from the Changjiang River flowed offshore due to the CP and a weak northeast monsoon. Microplastics released in Hangzhou Bay flowed to the northeast under the intense east/northeast current originating from the TWC. The microplastics released in Nantong City flowed southward due to the YSCC; hence, most of the released microplastics gathered in the CE to generate a hot spot (Chang and Isobe, 2003). In summer, low-salinity water diluted by the Changjiang is mixed with the high-salinity TWC to generate a plume front outside the CE (Cao et al., 2021), and pollutants have been found to accumulate in this area (Elliott and Wolanski, 2015). Similarly, in our study, microplastics released from the mouth of the Changjiang River gathered northeast of the CE, near 122.5°E, which was north of the plume front. Therefore, the front area may be a hot spot for microplastics. In addition, some of the microplastics released from the Changjiang River were transported to the northeast due to mixing caused by tides, the summer monsoon, and the Coriolis force (Chang and Isobe, 2003; Zhu et al., 1997), forming another hot spot. Microplastics released from Hangzhou Bay gathered offshore to form the third hot spot, which may have been due to strong tides. Therefore, three hot spots formed during the summer. During autumn, the YSCC flows southward, the CP extends south-westward along the Zhejiang coast, the ZMCC flows south-westward, and the TWC flows northward (Chang and Isobe, 2003). Thus, microplastics gathered offshore between the Changjiang River and Hangzhou Bay. During winter, the cold YSCC is diluted by the Changjiang, flows to the south, and, combined with the ZMCC, meets the warm TWC to generate a front outside of the CE and Hangzhou Bay at 123°E (Cao et al., 2021), which may prevent microplastic transport to the east. Therefore, most of the microplastics released from the Nantong coast eventually converged with this cold flow in the north-eastern waters of the CE to form a hot spot. Similarly, microplastic particles released from the mouth of the Changjiang River and Hangzhou Bay were transported southward with the cold water and formed another hot spot. Therefore, two hot spots formed during the winter. The seasonal microplastic distributions in our study were similar to the biomass distributions of zooplankton described in Xu et al. and

Chen et al., who found high concentrations near the shore of the Changjiang River in spring, east of the CE during summer, and near the shore from northern Jiangsu to Zhejiang during autumn (Chen et al., 2011; Xu et al., 2003, 2004). In addition, this study found large amounts of microplastics in the vicinity of the Zhoushan fishing grounds; a previous study confirmed that there were 9.2 microplastic particles in the intestines of each mussel on the Zhoushan coast (Kolanthasamy et al., 2017). Therefore, focusing on these hot spots in the ECS is necessary to prevent adverse impacts on organisms when the abundance of microplastics exceeds threshold values.

Nevertheless, only some microplastics float on the surface, whereas large amounts are suspended in the water column or sink to the bottom of the sea. Studies have widely detected microplastics in water columns and marine sediments (Vaughan et al., 2017; Zhang et al., 2020a). Evidence suggests that deep-sea marine life in the Western Pacific, Atlantic, and Indian Oceans is threatened by microplastic pollution (Courtene-Jones et al., 2017; Taylor et al., 2016). Therefore, settling characteristics influence microplastic distributions. In the present study, microplastics with higher sinking velocities released from the Changjiang River tended to gather closer to the CE. Theoretically, floating microplastic particles on the surface of the water are influenced by winds and surface currents and eventually accumulate to form a garbage patch in the ocean (Critchell and Lambrechts, 2016). In contrast, the horizontal transportation of suspended microplastics is mainly influenced by vertical mixing, which increases with increasing particle density (Ballent et al., 2012; Reisser et al., 2015). For example, in Indonesia, microplastics were not found at 100 m deep but were found at 50 m deep and at 300 m deep and below (Cordova and Hernawan, 2018). Therefore, the vertical distribution of microplastics is influenced by their density. Microplastics may accumulate at specific depths; however, more studies are required.

Rivers play a vital role in transporting plastic debris of all sizes from inland areas to marine environments. Most studies now assume that microplastics will eventually enter in the ocean; however, their migration and transformation patterns in river systems are not fully understood. For example, some microplastics released into rivers may still accumulate in fresh water (Koutnik et al., 2021). To determine whether microplastics are deposited in estuaries or transported to the ocean, this study analysed the vertical spatial distributions of particles with different sinking velocities released from the CE. High abundances of PE and PS accumulated at a certain distance from the release points and did not flow into the CE directly. This agrees with Xiong et al., who found that some plastic particles from the Changjiang River basin were not transported to the sea and were deposited at the bottom of the riverbed (Xiong et al., 2019). Owing to turbulent vertical mixing processes, some of the dense PS particles deposited at the bottom of riverbeds are resuspended into the water column (Wagner and Lambert, 2017), whereas positively buoyant PE particles may be transported to deeper water layers due to wind-induced Langmuir turbulence (Kukulka et al., 2012). Therefore, microplastics may accumulate from a specific depth to the bottom of the river, which requires further investigation. When microplastics reach an estuary, hydrodynamic forces such as turbulence caused by waves and tides, stratification, and plume fronts caused by freshwater act on the particles, resulting in both floating and suspended microplastic particles in each layer (Eerkes-Medrano et al., 2015; Krelling et al., 2017; Lima et al., 2015; Sadri and Thompson, 2014; Vermeiren et al., 2016). Thus, global microplastic models should also be based on the settling of microplastics and river estuary hydrodynamics, rather than only waste management, population density, and hydrological information (Lambert and Wagner, 2018).

5. Conclusions

The main sources of microplastics in the ECS were the Changjiang River, Hangzhou Bay, and the coast of Nantong City. Floating microplastics showed a seasonal distribution pattern, in which plume fronts may have played an important role. During summer, microplastics released from the Changjiang River stopped at the front generated by the low-salinity water from the Changjiang and the high-salinity TWC. During winter, microplastics accumulated within the front generated by cold coastal water and the warm TWC. Therefore, hot spots for microplastics may be located in fronts. However, this requires further investigation. Settling velocity is also an important characteristic for microplastic transportation, and we explored its influence on the horizontal distribution in the ECS and vertical distribution in the Changjiang River. However, we only used specific settling velocities and ignored the influence of size and adsorption on the settling velocities. Nevertheless, the horizontal distribution of microplastics in each layer varied with settling velocity. For the microplastics released along the Changjiang River, some were not transported to the sea but accumulated at a distance from the CE at a specific depth; therefore, this, as well as waste management and population density, should be fully considered to accurately estimate the contribution of microplastics to the ocean. However, current studies ignore several processes, such as sedimentation, aggregation, biological fouling, resuspension, attachment, and burial. Further research should be conducted to fully investigate sinking behaviours. Considering all these processes in a model should enable a comprehensive assessment of the transport of microplastics from coastal areas to the open sea.

Credit author statement

Yichen Sun (First Author): Conceptualization, Methodology, Software, Investigation, Formal analysis, Visualization, Writing – original draft. Lu Cao (Corresponding Author): Conceptualization, Funding acquisition, Resources, Supervision, Writing – review & editing. Yutao Wang: Resources, Supervision, Writing – review & editing. Wei Chen: Visualization, Investigation. Yan Li: Visualization, Investigation. Xizeng Zhao: Writing – review & editing.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2022.119910.

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