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Variation in microplastics composition at small spatial and temporal scales in a tidal flat of the Yangtze Estuary, China

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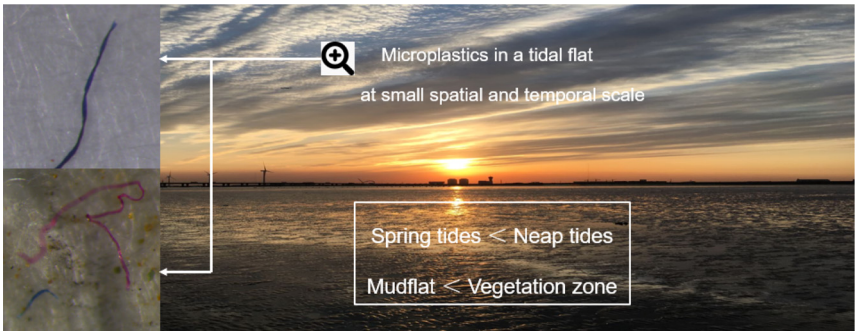
HIGHLIGHTS

- More microplastics were found during neap than spring tide period.
- Microplastic particles were larger during the neap than the spring tide period.
- No variation in the abundance of microplastics on the semidiurnal scale.
- Microplastics were more abundant in the vegetation zone than in the mudflat.
- Variation in microplastics abundance was driven by local hydrology.

GRAPHICAL ABSTRACT



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ABSTRACT

Microplastics are small, degrade slowly, and easily persist in the water column because they are close to neutrally buoyant. Understanding the distribution of microplastics is fundamental to evaluating the ecological risks that they cause and to identifying ways to control microplastics pollution. Most of the existing research on the distribution of microplastics in the coastal zone has focused on large spatial and temporal scales. To build on past work, we investigated variation in microplastics in a tidal flat of the Yangtze Estuary on small spatial (sediment depth, mudflat vs. vegetation zone) and temporal (fortnightly and semidiurnal) scales. Microplastics were more abundant in surface (0–2 cm) sediments during neap versus spring tide cycles, likely indicating increased deposition during periods with calm waters and increased suspension when water was more turbulent, but did not vary at greater depths in the sediment. Individual microplastics particles were also larger during neap versus spring tide periods. In contrast to the variation between spring and neap tide periods, we found no variation in the abundance of microplastics on the semidiurnal scale. Microplastics were also more abundant in the transect in the vegetation than at slightly lower elevations in the adjacent mudflat. Across all samples, the abundance of microplastics was negatively correlated with the strength of hydrological processes such as submergence time and flow velocity. Our results showed that sampling of microplastics in the intertidal environment needs to consider variation among spring and neap tide cycles, and also among different intertidal habitats that may differ only slightly in elevation. We encourage coupling sampling with direct measures of hydrological processes so that variation in microplastics abundance and size can be rigorously linked to hydrological processes.

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1. Introduction

The production of plastics has increased rapidly since mass production began in the 1940s, with wide applications of plastics in commercial, industrial and other industries (Cole et al., 2011; Li et al., 2016). As demand for plastics and its production increased, more and more plastic waste entered the environment. Of particular interest and concern are small plastic fragments <5 mm in size, called microplastics. Microplastics are small, chemically stable, and difficult to degrade naturally (Andrady, 2011). A fundamental characteristic of microplastics is that they are close to neutrally buoyant, and so are easily transported throughout aquatic and marine environments (Hidalgo-Ruz et al., 2012). A variety of processes, such the leaching of additives, biofouling and incorporation within marine aggregates, can alter the buoyancy of microplastics once they are in the water, encouraging eventual deposition into benthic habitats (Wang et al., 2016). Numerous studies have examined microplastics pollution in the ocean (Lusher et al., 2014), rivers (Mani et al., 2015), lakes (Hu et al., 2018; Xiong et al., 2018), and even Arctic sea ice (Obbard et al., 2014). Microplastics have also been widely detected in many organisms, including fish, benthic fauna, and birds, where they not only harm the growth of these organisms, but may also enter the human body through the food chain (Li et al., 2015; Rochman et al., 2015; Zhao et al., 2016; Lourenço et al., 2017; Su et al., 2018). Another concern is that microplastics can be a carrier of some toxic chemicals such as POPs and heavy metals that absorb onto the plastic particles (Bakir et al., 2014; Holmes et al., 2014).

Estuarine and coastal ecosystems may be particularly vulnerable to microplastics pollution. These habitats are located in the transition zone between land and sea, which is often the area with highest human population density. Plastic waste generated by human activities is transported to the coastal zone from terrestrial habitats by rivers, and from the ocean by currents and tides (Lima et al., 2015; Peng et al., 2017). At the same time, estuarine and coastal ecosystems provide habitat for many plants, birds and benthic organisms (Day Jr. et al., 1989). Therefore, a number of studies have examined the abundance of microplastics in coastal zone waters, sediments and organisms around the world (Claessens et al., 2011; Zhao et al., 2015; Cheung and Cheung, 2016; Jabeen et al., 2016).

Studying the distribution of microplastics provides the fundamental information needed for controlling microplastics pollution and assessing its ecological risks. The degree of microplastics pollution in coastal zones is closely related to the intensity of regional human activities (Claessens et al., 2011; Nor and Obbard, 2014; Blumenröder et al., 2017). In addition, physical processes in the coastal zone may transport, suspend or bury microplastics, and therefore affect the spatial and temporal distribution of microplastics pollution. These physical processes mainly include wind and hydrological processes (Vianello et al., 2013; Kim et al., 2015). Hydrological processes are the most important physical processes in the coastal area, playing a key role in the retention and transportation of inorganic substances (Wang et al., 2016). Meanwhile, because surface sediments in shallow marine environments are highly dynamic, being reworked by biota and hydrological processes, the abundance of microplastics in the surface sediments is likely to vary not only over space but also over time as materials are deposited onto the sediments, turned over in surface sediment layers, and re-suspended into the water column. In terms of the spatial distribution of microplastics, many studies have shown that the abundance of microplastics in coastal sediments is closely related to regional runoff, waves, tides and currents (Lee et al., 2013; Kim et al., 2015; Yu et al., 2018). In particular, sites with stronger hydrodynamic processes tend to have lower abundances of microplastics (Claessens et al., 2011; Vianello et al., 2013). In addition, some studies suggested that salinity is also an important factor affecting the spatial distribution of microplastics in coastal zones (Lima et al., 2015). Finally, microplastics abundance in the coastal zone is higher in the dry season than the rainy season, indicating that precipitation plays an important role in transporting microplastics in or out of coastal habitats (Lee et al., 2013; Zhu et al., 2018).

Most of the existing research on the distribution of microplastics in coastal habitats has focused on large spatial and temporal scales. A number of studies have called for the establishment of a large-scale monitoring database of microplastics in order to provide a scientific basis for managing them (Blumenröder et al., 2017; Peng et al., 2017). In order to accomplish this, we also need to know how the abundance of microplastics varies on small spatial and temporal scales, so that large-scale sampling programs can standardize their sampling in a manner that minimizes variation due to small-scale processes.

More generally, the importance of spatial and temporal scale cannot be ignored in environmental research. When studies are based on different scales, different processes and patterns can be detected and different results are obtained (Schneider, 2001). Therefore, the distribution of microplastics on small spatial and temporal scales is likely to be driven by factors other than those that determine distribution patterns at large spatial scales, such as variation in human activity. In particular, it is likely that local variation in hydrological processes is increasingly important in determining the distribution of microplastics on small spatial-temporal scales.

We worked in a tidal flat in the Yangtze Estuary to test three hypotheses. First, the abundance of microplastics would vary as a function of intertidal elevation, spring versus neap tidal cycles, and among days within a tidal cycle. Second, the variation among samples could be explained by variation in local hydrological processes. Third, by focusing on small spatial and temporal scales, our study would identify different drivers of microplastics abundance than have studies that focus on large spatial and temporal scales. To test these hypotheses, we quantified hydrological processes and the abundance, size and composition of microplastics in two intertidal zones on a fortnightly and semidiurnal temporal scale, and correlated microplastics abundance with different hydrological processes.

2. Methods

2.1. Study site

We worked at the Nanhui tidal flat in the Yangtze Estuary in China (Fig. 1A). The Yangtze Estuary is the largest estuary in China. The climate of the area is subtropical, with an average annual temperature of 15–16 °C and an average annual rainfall of 1.2×10^3 mm (You et al., 2018). The Nanhui tidal flat is located on the southern side of the third order branch of the Yangtze Estuary (Fig. 1A). Tides are semidiurnal, with an average tidal range at the Nanhui tidal flat area of 2.7 m (Wu et al., 2019). The upland habitat, protected by a large levee, consists of aquaculture ponds, agricultural fields and areas being filled with sediment for future development as part of a coastal reclamation project. The intertidal habitat is mainly mudflats, with a strip of vegetation about 200 m wide dominated by the native plant species *Scirpus mariqueter* Tang & F. T. Wang between the levee and the mudflat. The sediment consists of clayey silt and silt (You et al., 2018).

We established two parallel transects, one in the *Scirpus mariqueter* zone, about 150 m away from the levee, and the second in the mudflat, about 200 m away from the first transect (Fig. 1B).

We marked eight sampling locations along each transect with PVC pipes; sampling locations were ~100 m apart from each other. All the sampling locations were flooded at high tide during the study period, and all were exposed at low tide.

2.2. Sample collection

We collected sediment samples in April 2018 at every low tide during three consecutive days with spring tides (April 16, 17 and 18, for a total of six samples, taken ~12.5 h apart), and during the following neap tide period (April 23, 24 and 25, for another six samples, taken ~12.5 h apart). On each sampling event, we collected one core (10 cm deep; 4.5 cm diameter) from each plot using a stainless steel, split tube sampler. We did not observe any compaction of the sediments while taking the cores. Each core was removed from the sampling tube and immediately cut into three depth layers (0–2 cm, 2–5 cm, 5–10 cm) with a stainless-steel knife. The resulting sediment samples were stored in clean cylindrical iron boxes for later analysis in the laboratory.

We deployed four pairs of hydrological instruments, two pairs along each transect about 400 m apart (Fig. 1B), to monitor hydrology during the sampling period. Each instrument was mounted approximately 10 cm from the sediment surface. At all four locations, flow velocity was measured with an electromagnetic current meter (ALEC-Infinity, Japan), and salinity, turbidity, and water depth were measured with an optical backscatter turbidity sensor (OBS-3A, USA). Hydrological data were recorded at 10 s intervals when the instruments were submerged under water during the spring and neap tidal cycles.

2.3. Laboratory processing

We extracted microplastics from the sediment using the density separation method (Thompson et al., 2004; Peng et al., 2017). Samples were first dried in an oven at 60 °C to a constant weight, and a sample of 10 g of dry sediment was weighed and placed in a glass beaker. We added 50 ml of 30% H_2O_2 (Sinopharm, China) for 24 h to degrade the organic matter in the sediment, and then dried the samples again at 60 °C to a constant weight. We then added 300 ml of a filtered, saturated NaCl solution to the beaker and stirred with a glass rod for 2 min. The mixture was allowed to settle for 24 h and then the supernatant was vacuum-filtered through a 1 μm pore size glass filter paper. We avoided contact between the sample and any plastic product at all times during the experiment. All containers were cleaned with Milli-Q water before use. Three procedural blanks were run to ensure that there was no contamination from the laboratory setting.

Immediately after the sample was filtered, we counted and assessed the microplastic particles on the filter under a dissecting microscope (Saike SK2500H, China). We identified and classified microplastics following Peng et al. (2017): we divided the microplastics into three categories based on shape (fibers, fragments, and pellets) (Fig. 1 in Appendix), and into five categories based on color (black, transparent, white, red, and blue). We also measured the size (maximum dimension) of each particle under the microscope using a micrometer.

To confirm that the particles that we were counting were in fact made of plastic as opposed to some other material, we identified the polymer type of 80 representative particles (50 fibers, 20 fragments, 10 pellets) using a Micro Fourier Transform Infrared Spectrometer (Thermo Scientific Nicolet iN10 MX, USA) under the transmittance mode. The spectrum range was 4000–675 cm^{-1} with a collection time of 3 s and 16 co-scans for each measurement (Jabeen et al., 2016). All spectra were post-processed under an automatic baseline correction mode via the OMNIC™Picta™ software. This software compares the spectra of the sample with a library of known spectra in order to identify the polymer type (Peng et al., 2017).

2.4. Statistical analysis

We analyzed microplastic abundance and size data using IBM SPSS Statistics v.22. Hydrological data that did not meet the requirement of homogeneity of variance were square-root transformed before analysis. We compared the abundance and the size of microplastics between different tidal periods and transects with *t*-tests. We compared the abundance of microplastics between different sediment layers with ANOVA, using the least significant difference (LSD) for multiple comparison tests. We used principal component analysis (PCA) to reduce the 5 hydrological factors to two PCA components (eigenvalue = 1), and used stepwise linear regression to identify the effects of the principal components on the abundance of microplastics (Wu et al., 2019).

3. Results

3.1. Abundance of microplastics

We found a total of 824 microplastic particles in all the samples combined, with an average concentration of 1.43 ± 0.30 items/10 g (mean ± se) of sediment. The average abundance of microplastics (averaged across the entire depth range) in the neap tide samples (mean ± se: 1.53 ± 0.23 items/10 g) was significantly higher than in spring tide period (mean ± se: 1.31 ± 0.28 items/10 g, $df = 575$; $t = -3.054$; $P = 0.002$). This difference was caused by variation in

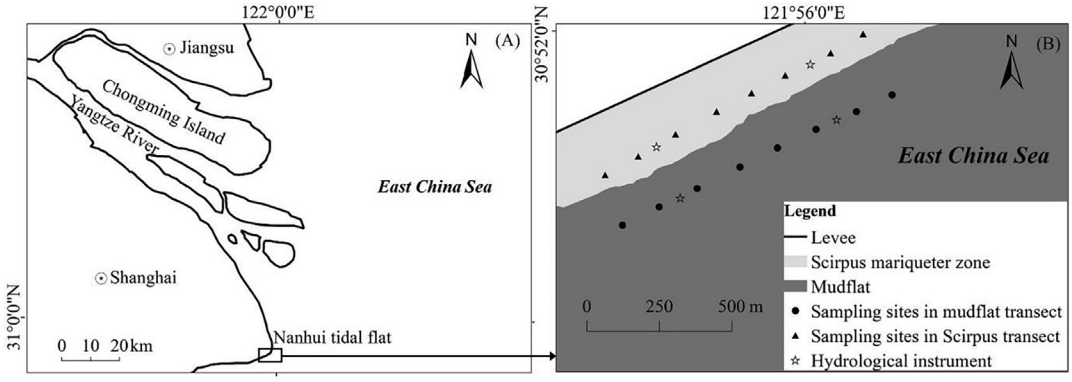

Fig. 1. A) location of the study area at the southern side of the Yangtze Estuary. B) Layout of the two transects in the Nanhui tidal flat.

the abundance of microplastics in the surface sediments (0–2 cm depth, $df = 190$, $t = -2.708$, $P = 0.007$), because there was not a significant difference between spring and neap tide samples at greater depths (2–5 cm, $df = 190$; $t = -1.373$; $P = 0.17$ and 5–10 cm, $df = 190$; $t = -0.804$; $P = 0.34$).

The concentration of microplastics did not differ among the six sampling events at any depth during either the spring or neap tide periods (Appendix Table 1, Figs. 2, 3). Similarly, the abundance of microplastics did not differ between transects during the spring tide cycle (Appendix Table 2, Fig. 2). However, the abundance of microplastics in the surface (0–2 cm) sediments was higher in the *Scirpus mariqueter* transect than the mudflat transect during the neap tides (Appendix Table 2, Fig. 3).

The concentration of microplastics differed among depth layers on both spring ($df = 286$; $F = 62.353$; $P < 0.001$) and neap ($df = 286$; $F = 43.886$; $P < 0.001$) tidal cycles. The concentration of microplastics was highest in the 0–2 cm layer compared to the two deeper layers ($P < 0.001$). In addition, the concentration of microplastics was more variable over space and time in the surface (0–2 cm) depth layer than in deeper sediments in both transects (Table 1).

3.2. Size, shape, color and polymer type of microplastics

The size of the microplastic particles that we observed ranged from 50 μm to 4950 μm (mean ± se: 1161.23 ± 34.71 μm). Particles were larger in neap tide samples than in spring tide samples (Fig. 4 A, $t = -2.370$, $df = 23$, $P = 0.027$). Particle size did not differ significantly between the two transects (Fig. 4 B, $t = -0.088$, $df = 23$, $P = 0.93$).

Table 1
Coefficient of variation (%) of the abundance of microplastics in three depth layers in the two transects. Data were all samples (96) at each depth from each transect.

	Mudflat	*Scirpus mariqueter*
0–2 cm	71.3	67.0
2–5 cm	40.0	54.2
5–10 cm	62.5	56.5

The most common shape of the microplastics was fiber (94%) followed by fragment (4.5%) (Fig. 5A). Pellets were rare (1.9%). The most common color of the microplastics was black (79%), followed by red (10%) with white, transparent and blue microplastics all rare (Fig. 5B).

The microplastics that were analyzed ($n = 80$) were categorized as belonging to 8 polymer types: rayon, polyester, polypropylene, polyethylene, polyethylene terephthalate, polystyrene, cellophane and polystyrene. Rayon was the most prevalent polymer type (45%), followed by polypropylene (20%) and polyethylene (14%).

3.3. Hydrological parameters

Most hydrological parameters did not differ among sampling periods during the spring tide cycle; in contrast, most of them differed among sampling periods during the neap tide cycle (Table 2). All of the hydrological parameters except salinity differed between spring and neap tidal cycles and between the two transects, with values higher during the spring tides and in the mudflat transect. All of the hydrological variables except salinity were correlated with each other (Fig. 6).

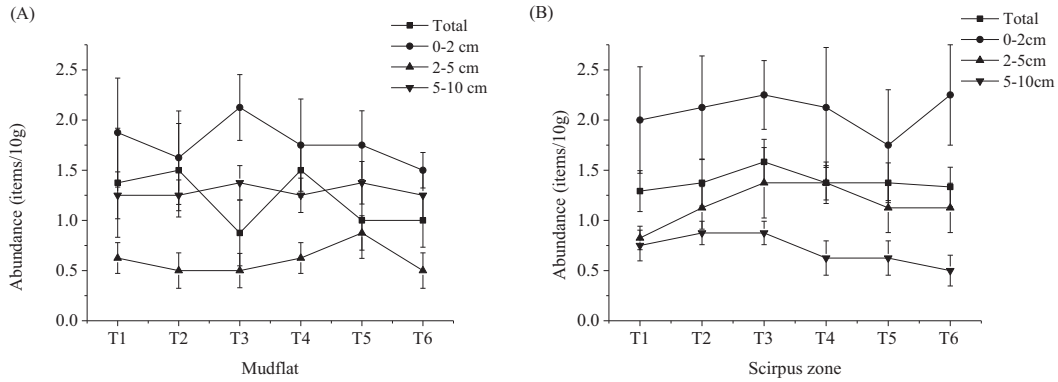

Fig. 2. Abundance of microplastics (means ± se) at three depths in the mudflat (A) and *Scirpus mariqueter* zone (B) during the spring tide sampling period. T1–T6 represent the six sampling events.

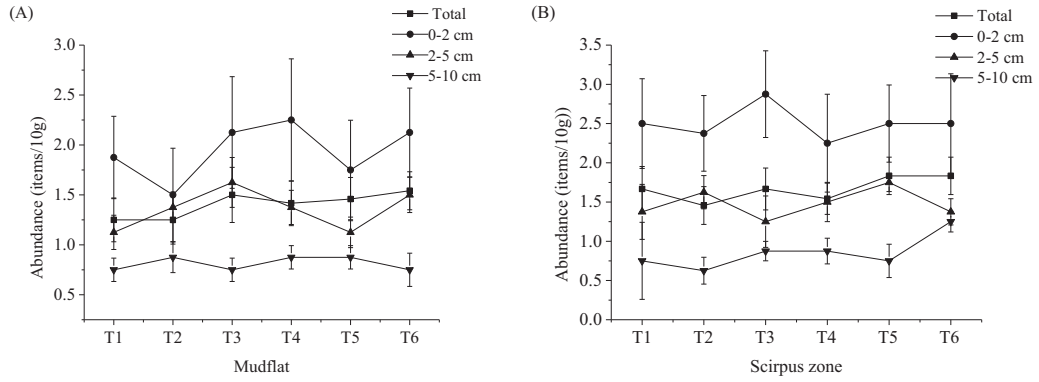

Fig. 3. Abundance of microplastics (means ± se) at three depths in the mudflat (A) and *Scirpus mariqueter* zone (B) during the neap tide sampling period. T1–T6 represent the six sampling events.

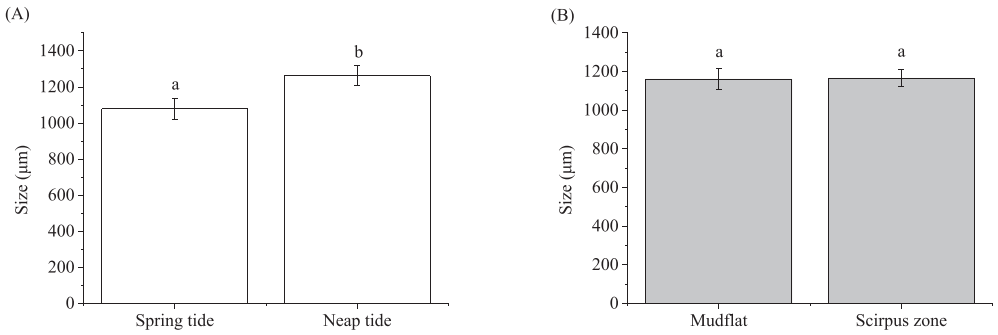

Fig. 4. Comparisons of the size of microplastics between spring and neap tide periods (A) and transects (B) (means ± se). Any two columns with the same letter are not significantly different ($P > 0.05$, Student *t*-test).

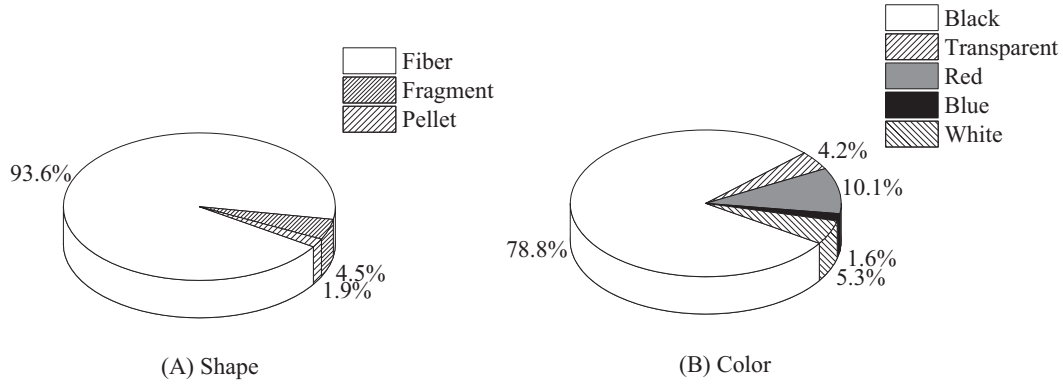

Fig. 5. Relative abundance of different shapes (A) and colors (B) of microplastics in the samples.

Table 2
Hydrological parameters during different tidal periods when water flooded the Nanhui tidal flat. Data are means ± se. *F* values assess variation within a spring or neap cycle over the six low tide periods (the semidiurnal scale, $df = 23$). The *t transect* values assess variation between the two transects ($df = 46$), and the t^* *spring* vs. *neap* values assess variation between spring and neap tide periods ($df = 46$). Significance values: *, $P < 0.05$; **, $P < 0.001$.

Parameters	Tidal period	Mudflat transect	*Scirpus mariqueter* transect	*F semidiurnal*	*t transect*	t^* *spring* vs. *neap*
Submergence time (min)	Spring	243.9 ± 11.85	201.7 ± 12.51	1.246	2.44*	2.82*
	Neap	217.5 ± 20.83	153.7 ± 15.16	13.308*	2.47*	
Water depth (m)	Spring	0.60 ± 0.07	0.39 ± 0.06	1.343	2.39*	2.72*
	Neap	0.44 ± 0.08	0.12 ± 0.06	3.940*	3.01**	
Turbidity (NTU)	Spring	1597 ± 160.38	1156 ± 138.56	2.368	3.15**	3.92**
	Neap	933 ± 132.90	460 ± 83.98	4.631*	4.19**	
Flow velocity ($cm \cdot s^{-1}$)	Spring	30.3 ± 1.8	16.48 ± 2.33	2.659*	4.68**	2.81*
	Neap	20.1 ± 2.4	5.6 ± 4.46	4.042*	2.12*	
Salinity (‰)	Spring	7.7 ± 0.36	7.86 ± 0.49	1.206	−0.31	0.76
	Neap	7.7 ± 0.43	7.98 ± 0.04	0.364	−0.45	

The first two principal components explained 75.5% of the variation in the hydrological factors (Fig. 7). All the factors related to water depth and flow (submergence time, water depth, flow velocity and water turbidity) loaded heavily onto PC1, which explained most (55.5%) of the variation (Table 3 in Appendix). Salinity loaded onto PC2, which explained 22.1% of the variation.

Forward stepwise linear regression identified a strong relationship between microplastics abundance and PC1. This relationship was significant for the whole sample and for the top 2 cm of the sediment separately (Fig. 8), but not for the 2–5 or 5–10 cm depth layers separately (results not shown). PC2 was not retained into any of these regression models.

When the hydrological variables were examined individually, most of them were correlated with the abundance of microplastics (Fig. 2 in the Appendix). The variables related to water depth and flow (submergence time, water depth, water turbidity, flow velocity) were negatively correlated with microplastics, while salinity was not significantly correlated with microplastics abundance. The single variable that best predicted microplastics abundance was submergence time ($R^2 = 0.62$, $P < 0.001$).

4. Discussion

Understanding the distribution of microplastics in tidal flat sediments is fundamental to evaluating the ecological risks that they cause and to identifying ways to control microplastic pollution. Because they are close to neutrally buoyant, the spatial and temporal distribution of microplastics are strongly affected by

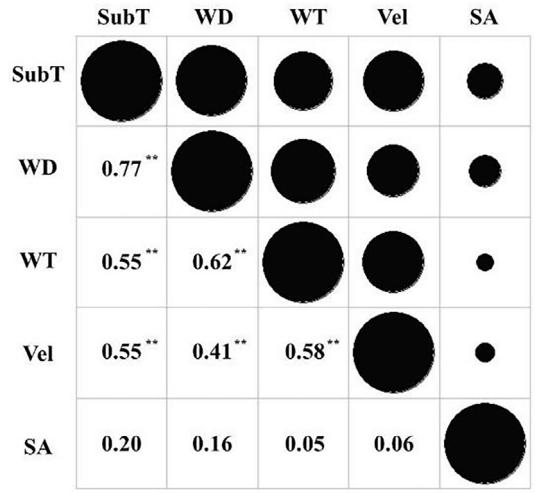

Fig. 6. Correlations between each hydrological parameter. The size of the black circle represents the correlation coefficient. SubT: submergence time; WD: water depth; WT: water turbidity; Vel: flow velocity; SA: Water salinity.

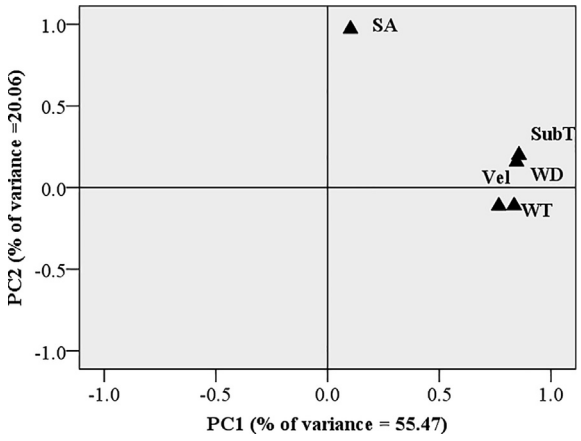

Fig. 7. PCA of hydrological parameters in Nanhui tidal flat.

hydrological processes (Claessens et al., 2011; Vianello et al., 2013). However, except for some studies done in beach habitats (McDermid and McMullen, 2004; Liebezeit and Dubaish, 2012), most of the existing studies have focused on relatively large spatial and temporal scales. We built on past work by investigating variation in microplastics in a tidal flat on small spatial and temporal scales.

We found the most temporal variation in microplastics abundance between spring and neap tidal periods, with most of the variation occurring in surface (0–2 cm) sediments. Across all sampling dates, the abundance of microplastics was negatively related to the intensity of hydrological processes. This suggests that microplastics, which are close to neutrally buoyant in salt water, are eroded from surface sediments during periods of strong water flow, and deposited during periods of low water flow. This is consistent with previous work done at larger scales that also concluded that strong hydrological processes such as high-intensity precipitation events and the tides could reduce the abundance of microplastics in the surface sediments of tidal flats (Zhu et al., 2018). Consistent with this interpretation, the abundance of microplastics in the coastal water column is higher during the spring tidal cycle than during the neap tidal cycle, presumably due to increased suspension of microplastics from the sediment surface into the water column (Sadri and Thompson, 2014). The fact that we found no temporal variation in microplastics abundance deeper in the sediment column is consistent with this interpretation, and also suggests that the differences in abundance were not a procedural artifact, because then the differences would have been found at all depths.

We found that the average size of microplastics in the sediment was greater during neap than spring tide periods. This result is also consistent with the findings of Sadri and Thompson (2014), who found larger microplastics in the water column during spring tide periods. These results suggest that the larger microplastics particles require stronger water flows, such as occur during spring tides, in order to suspend them into the water column. If so, the movement of the larger particles from the sediment to the water column during spring tide cycles might decrease the average particle size in the sediments while increasing it in the water column.

In contrast to the variation between spring and neap tide periods, we found no variation in the abundance of microplastics on the semidiurnal scale (among tides within the spring or neap tidal cycles). Although some hydrological parameters differed among sampling periods within both spring and neap tide cycles, this variation was less than between the spring and neap tides, and not large enough to cause measurable differences in microplastics abundance. This result was similar to our previous study on benthic invertebrates at a nearby site which found differences in abundance between spring and neap tidal cycles but not within them (Wu et al., 2019). Together, these results suggest that sampling to quantify microplastic pollution needs to account for the spring-neap tidal cycle, but that results will be less affected by semi-diurnal variation within either the spring or the neap tidal stage.

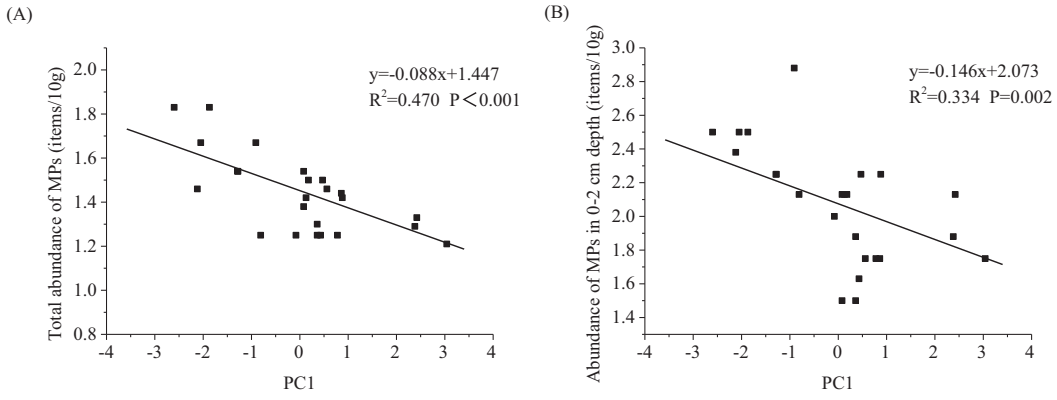

Fig. 8. Relationship between PC1 and A) total abundance of microplastics, and B) abundance of microplastics in the 0–2 cm depth layer.

We also found spatial differences in microplastics, with a greater abundance in the transect in the vegetation than in the mudflat, but only in surface (0–2 cm) sediments and only during the neap tide period when microplastics were more abundant overall. This likely also relates to differences in hydrological processes between the two transects. One difference between the two transects was their elevation. Hydrodynamic processes will often be weaker at higher elevations (in shallower water), as we found in this study, promoting settling of particles which might be eroded away in more vigorous water flows at lower elevations (McDermid and McMullen, 2004; Liebezeit and Dubaish, 2012). A second difference between the two transects was the presence of vegetation. Vegetation reduces flow velocity and thus should promote settling of microplastics out of the water column. In addition, vegetation captures sediment particles out of the water column that stick to plant stems (Mudd et al., 2010), and it is likely (although not to our knowledge explicitly demonstrated) that microplastics are trapped along with this intercepted sediment. We found no difference in microplastics size between the two transects, which perhaps favors the second explanation rather than the first, but focused studies will be necessary to rigorously address this issue.

We found a greater abundance of microplastics in the surface sediment than at the deeper depth, consistent with previous results (Willis et al., 2017). One reason for this gradient might be that some microplastics in the water column are deposited on the sediment surface at low tide (when we sampled) but resuspended into the water column at high tide, and so are not permanently sequestered into deeper sediments. Another reason might be that the inputs of microplastics into the environment are increasing over time (Cole et al., 2011), and so are more concentrated in recently deposited sediments.

The microplastics that we found were mostly fibers made of rayon. This was consistent with the survey results of Peng et al. (2017) in the sediments of the Yangtze Estuary. However, the color composition of the microplastics found in this study (mostly black) was different from their findings (mostly transparent), perhaps due to differences in the survey season and location.

Any study in the natural sciences has to consider the issue of scale. When the resolution of time and space changes, the object of a study tends to show different characteristics (Schneider, 2001). Our study focused on small spatial and temporal scales, and found variation in the abundance of microplastics on the fortnightly scale, but not on the semidiurnal scale, suggesting that the effects of changing hydrodynamics on microplastics abundance in the sediment take several days to manifest.

Other studies of microplastics have focused on larger spatial and temporal scales, and again found that scale was important, but identified different factors driving variation at these larger scales. In our study, the key factors affecting the abundance of microplastics were hydrological factors that varied at small scales, such as submergence time, water depth, and flow velocity. In contrast, in studies at larger scales, human inputs (Claessens et al., 2011; Blumenröder et al., 2017) and spatial differences in salinity, waves and currents (Lima et al., 2015; Kim et al., 2015) may explain spatial differences in microplastics abundance. In contrast, seasonal differences in microplastics abundance are often explained by hydrological factors such as precipitation, river discharge and runoff that vary over long temporal scales (Lee et al., 2013; Zhu et al., 2018). Thus, as the resolution of the study changed, different processes became the primary drivers at different spatial and temporal scales. Many of these studies, however, did not directly measure hydrological variables, leaving it unclear which of many correlated hydrological variables was the ultimate factor controlling microplastics abundance at each spatial scale.

5. Conclusions

Our results show that sampling of microplastics in the intertidal area needs to consider variation among spring and neap tide cycles, and also among different intertidal habitats that may differ only slightly in elevation. Our work was based on a single study site in a single season; future studies should replicate our sampling in other coastal areas and seasonal conditions to develop a more general understanding of what hydrological processes are important in controlling microplastics abundance and size at which spatial scales. We also encourage coupling the sampling with direct measures of hydrological processes so that variation in microplastics abundance and size can be rigorously linked to hydrological processes.

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

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2019.134252.

References

Andrady, A.L., 2011. Microplastics in the marine environment. Mar. Pollut. Bull. 62, 1596–1605.
Bakir, A., Rowland, S.J., Thompson, R.C., 2014. Enhanced desorption of persistent organic pollutants from microplastics under simulated physiological conditions. Environ. Pollut. 185 (4), 16–23.
Blumenröder, J., Sechet, P., Kakkonen, J.E., Hartl, M.G.J., 2017. Microplastic contamination of intertidal sediments of Scapa Flow, Orkney: a first assessment. Mar. Pollut. Bull. 124, 112–120.
Cheung, P.K., Cheung, L.T.O., Fok, L., 2016. Seasonal variation in the abundance of marine plastic debris in the estuary of a subtropical macro-scale drainage basin in South China. Sci. Total Environ. 562, 658–665.
Claessens, M., Meester, S.D., Landuyt, L.V., Clerck, K.D., Janssen, C.R., 2011. Occurrence and distribution of microplastics in marine sediments along the Belgian coast. Mar. Pollut. Bull. 62, 2199–2204.
Cole, M., Lindeque, P., Halsband, C., Galloway, T.S., 2011. Microplastics as contaminants in the marine environment: a review. Mar. Pollut. Bull. 62 (12), 2588–2597.
Day Jr., J.H., Hall, C.A.S., Kemp, W.M., Yáñez-Arancibia, A., 1989. Estuarine Ecology. John Wiley & Sons, Inc., Hoboken, New Jersey.
Hidalgo-Ruz, V., Gutow, L., Thompson, R.C., Thiel, M., 2012. Microplastics in the marine environment: a review of the methods used for identification and quantification. Environ. Sci. Technol. 46, 3060–3075.
Holmes, L.A., Turner, A., Thompson, R.C., 2014. Interactions between trace metals and plastic production pellets under estuarine conditions. Mar. Chem. 167, 25–32.
Hu, L., Chernick, M., Hinton, D.E., Shi, H., 2018. Microplastics in small waterbodies and tadpoles from Yangtze River Delta, China. Environ. Sci. Technol. 52 (15), 8885–8893.
Jabeen, K., Su, L., Li, J., Yang, D., Tong, C., Mu, J., Shi, H., 2016. Microplastics and mesoplastics in fish from coastal and fresh waters of China. Environ. Pollut. 221, 141–149.
Kim, I.S., Chae, D.H., Kim, S.K., Choi, S.B., Woo, S.B., 2015. Factors influencing the spatial variation of microplastics on high-tidal coastal beaches in Korea. Arch. Environ. Con. Tox. 69 (3), 299.

Lee, J., Hong, S., Song, Y.K., Hong, S.H., Jang, Y.C., Jang, M., Heo, N.W., Han, G.M., Lee, M.J., Kang, D., 2013. Relationships among the abundances of plastic debris in different size classes on beaches in South Korea. Mar. Pollut. Bull. 77 (1–2), 349–354.
Li, J., Yang, D., Li, L., Jabeen, K., Shi, H., 2015. Microplastics in commercial bivalves from China. Environ. Pollut. 207, 190–195.
Li, W.C., Tse, H.F., Fok, L., 2016. Plastic waste in the marine environment: a review of sources, occurrence and effects. Sci. Total Environ. 566-567, 333–349.
Liebezeit, G., Dubaish, F., 2012. Microplastics in beaches of the East Frisian Islands Spiekeroog and Kachelotplate. B. Environ. Contam. Tox. 89 (1), 213–217.
Lima, A.R.A., Barletta, M., Costa, M.F., 2015. Seasonal distribution and interactions between plankton and microplastics in a tropical estuary. Estuar. Coast. Shelf S. 165, 213–225.
Lourenço, P.M., Gonçalves, C.S., Ferreira, J.L., Catry, T., Granadeiro, J.P., 2017. Plastic and other microfibers in sediments, macroinvertebrates and shorebirds from three intertidal wetlands of southern Europe and west Africa. Environ. Pollut. 231 (Pt 1), 123–133.
Lusher, A.L., Burke, A., O'Connor, I., Officer, R., 2014. Microplastic pollution in the Northeast Atlantic Ocean: validated and opportunistic sampling. Mar. Pollut. Bull. 88 (1–2), 325–333.
Mani, T., Hauk, A., Walter, U., Burkhardt-Holm, P., 2015. Microplastics profile along the Rhine River. Sci. Rep. 5, 17988.
McDermid, K.J., McMullen, T.L., 2004. Quantitative analysis of small-plastic debris on beaches in the Hawaiian archipelago. Mar. Pollut. Bull. 48 (7), 790–794.
Mudd, S.M., Alpaos, A.D., Morris, J.T., 2010. How does vegetation affect sedimentation on tidal marshes? Investigating particle capture and hydrodynamic controls on biologically mediated sedimentation. J. Geophys. Res-Earth 115 (F03029).
Nor, N.H.M., Obbard, J.P., 2014. Microplastics in Singapore's coastal mangrove ecosystems. Mar. Pollut. Bull. 79 (1–2), 278–283.
Obbard, R.W., Sadri, S., Wong, Y.Q., Khitun, A.A., Baker, I., Thompson, R.C., 2014. Global warming releases microplastic legacy frozen in Arctic Sea ice. Earths Future 2 (6), 315–320.
Peng, G., Zhu, B., Yang, D., Su, L., Shi, H., Li, D., 2017. Microplastics in sediments of the Changjiang Estuary, China. Environ. Pollut. 225, 283–290.
Rochman, C.M., Tahir, A., Williams, S.L., Baxa, D.V., Lam, R., Miller, J.T., Teh, F.C., Werorilangi, S., Teh, S.J., 2015. Anthropogenic debris in seafood: plastic debris and fibers from textiles in fish and bivalves sold for human consumption. Sci. Rep. 5, 14340.
Sadri, S.S., Thompson, R.C., 2014. On the quantity and composition of floating plastic debris entering and leaving the Tamar Estuary, Southwest England. Mar. Pollut. Bull. 81 (1), 55–60.
Schneider, D.C., 2001. The rise of the concept of scale. BioScience 51 (7), 545–553.
Su, L., Cai, H., Kolandhasamy, P., Wu, C., Rochman, C.M., Shi, H., 2018. Using the Asian clam as an indicator of microplastic pollution in freshwater ecosystems. Environ. Pollut. 234, 347–355.
Thompson, R.C., Olsen, Y., Mitchell, R.P., Davis, A., Rowland, S.J., John, A.W.G., McGonigle, D., Russell, A.E., 2004. Lost at sea: where is all the plastic? Science 304, 838.
Vianello, A., Boldrin, A., Guerriero, P., Moschino, V., Rella, R., Sturaro, A., Ros, L.D., 2013. Microplastic particles in sediments of lagoon of Venice, Italy: first observations on occurrence, spatial patterns and identification. Estuar. Coast. Shelf S. 130 (3), 54–61.
Wang, J., Tan, Z., Peng, J., Qiu, Q., Li, M., 2016. The behaviors of microplastics in the marine environment. Mar. Environ. Res. 113, 7–17.
Willis, K.A., Eriksen, R., Wilcox, C., Hardesty, B.D., 2017. Microplastic distribution at different sediment depths in an urban Estuary. Front. Mar. Sci. 4, 419.
Wu, F., Tong, C., Feng, H., Gu, J., Song, G., 2019. Effects of short-term hydrological processes on benthic macroinvertebrates in salt marshes: a case study in Yangtze Estuary, China. Estuar. Coast. Shelf S. 5 (218), 48–58.
Xiong, X., Zhang, K., Chen, X., Shi, H., Luo, Z., Wu, C., 2018. Sources and distribution of microplastics in China's largest inland lake - Qinghai Lake. Environ. Pollut. 235, 899–906.
You, D., Tong, C., Wu, F., 2018. Effects of sediment erosion and deposition variation on the benthic macroinvertebrate functional groups in an intertidal salt marsh of Nanhui Dongtan during the dry season, Changjiang River Estuary. Acta Oceanol. Sin. 8 (40), 63–78 (in Chinese).
Yu, X., Ladewig, S., Bao, S., Toline, C.A., Whitmire, S., Chow, A.T., 2018. Occurrence and distribution of microplastics at selected coastal sites along the southeastern United States. Sci. Total Environ. 613-614, 298–305.
Zhao, S., Zhu, L., Li, D., 2015. Microplastic in three urban estuaries, China. Environ. Pollut. 206, 597–604.
Zhao, S., Zhu, L., Li, D., 2016. Microscopic anthropogenic litter in terrestrial birds from Shanghai, China: not only plastics but also natural fibers. Sci. Total Environ. 2016 (550), 1110–1115.
Zhu, X., Yi, J., Qiang, L., Cheng, J., 2018. Distribution and settlement of microplastics in the surface sediment of Yangtze Estuary. Environ. Sci. 39 (5), 2068–2074 (in Chinese).