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RESEARCH ARTICLE

A comprehensive investigation and assessment of mercury in intertidal sediment in continental coast of Shanghai

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Abstract The aims of this paper were to survey the total Hg levels and distribution character in intertidal sediment in continental coast of Shanghai, and identify the environment factors that might influence the sediment Hg concentrations, and to assess the pollution degree and potential ecological risk of Hg in sediment. Eighty-eight surface sediment samples and 18 sediment cores were collected for Hg contamination analysis. Physicochemical properties including Eh, particle size, content of total organic carbon (TOC), and acid volatile sulfide (AVS) were also measured. Index of geo-accumulation (I_{geo}) and potential ecological risk index were used respectively to assess the pollution levels and the ecological risk of sediment Hg. The average of total Hg concentrations in surface sediments was 107.4±90.9 ng/g with the range from 0 to 465.9 ng/g. Higher Hg concentrations were generally found in surface sediments near sewage outfalls and the mouth of rivers. Total Hg concentrations were significantly correlated with TOC ($p<0.05$) both in surface ($r=0.24$) and core ($r=0.29$) sediments, but not with the other environment factors (Eh, AVS, and particle size). Geo-accumulation index indicated that Hg contamination in intertidal sediments was generally at none to moderate degree, while potential ecological risk index demonstrated that the risk caused by Hg were at moderate to considerable level. Intertidal sediment in continental coast of Shanghai has generally been contaminated by Hg, and it might pose moderate to considerable risk to the local ecosystem. The Hg contamination is related more to the coastal pollution sources and complicated hydrodynamic and sedimentary conditions than the other environment factors studied.

Keywords Mercury · Sediment · Intertidal zone · Distribution character · Assessment · Shanghai

Introduction

Mercury (Hg) is a global pollutant, and it has received worldwide concern due to its significant adverse impact on both environment and human health (Delaune et al. 2008; Covelli et al. 2009; Li et al. 2009). Hg cycling between air, water, sediment, soil, and organism cannot be biodegraded, but its chemical speciation may change (Canário et al. 2007). It is well known that inorganic Hg can be transformed to the far more toxic methylmercury (MeHg) which has a marked tendency to be bioaccumulated in organisms, particularly fish, and magnified through food chains (Canário et al. 2005; Duran et al. 2008; Lewis and Chancy 2008; Ouddane et al. 2008; Covelli et al. 2009). In an aquatic ecosystem, Hg tends to be associated with suspended particles and sediment particles due to its high affinity to solid phase (Rodríguez-Barroso et al. 2009).

The intertidal zone is the interactive area of ocean and continent where the hydrodynamic conditions change and suspended particles in water may deposit on sediment. So intertidal sediment is identified as one of the major reservoirs of natural and anthropogenic Hg, and it also plays an important role in the biogeochemical cycling of Hg (Duran et al. 2008; Ding et al. 2009). However, sediments may act not only as sinks but also as sources of Hg. Forms of Hg deposited in sediments can be transferred to the water column through

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diffusion, resuspension, and bioturbation resulting in the secondary pollution and then threatening the safety of aquatic ecosystem (Chen et al. 2007; Yu et al. 2008; Covelli et al. 2009; Oh et al. 2010). Therefore, it is of great significance to investigate the spatial distributions and assess ecological risks of Hg in intertidal sediments.

Shanghai is located in the east coast of China. In the past decades, with the exploitation and utilization of coastal zone, a large amount of municipal domestic sewage and industrial waste water were discharged into the tidal flat. Intertidal sediments were contaminated with heavy metals and organic pollutants (Chen et al. 2000; Yang et al. 2004; An et al. 2009). Previous studies have reported severe heavy metal contamination of the intertidal sediments in Shanghai coast (Chen et al. 2000; An et al. 2009; Zhang et al. 2009; Deng et al. 2010), but little information is available on Hg. The aims of this study are to examine Hg distribution in surface and core sediments from Shanghai continental intertidal zone; to explore the relationships between total Hg concentrations and environment factors including Eh, total organic carbon (TOC), acid volatile sulfide (AVS), and particle size of sediments; to evaluate the Hg contamination degrees by geo-accumulation index method; and to assess the potential ecological risk caused by Hg with the aid of potential ecological risk index method.

Materials and methods

Study area

Shanghai, which is one of the biggest and most developed cities in China, is situated in the Yangtze estuarine area. Yangtze River annually carries a large amount of suspending sediment to the estuary forming the coastal tidal flat and islands. The coastal zone of Shanghai city mainly includes the south bank of Yangtze River and the adjacent islands as well as the north bank of Hangzhou Bay. The continental coast is about 173-km long, which occupies 37.6 % of the total length of coast zone in Shanghai, from the south point, Jin Siniang Bridge of Jinshan District bordering with Zhejiang province, and to the north point, Liu River estuary bordering with Jiangsu province. Now almost all the continental coast is exploited.

Sampling and analysis

From north to south, 36 sampling transects were set up on the intertidal flat along the coastline of Shanghai, including five transects in Baoshan District, 17 in Pudong New District, eight in Fengxian District, and six in Jinshan District (Fig. 1). Among these transects, because of the exploration and deposition, the width of tidal flat is different. In order to avoid the heterogeneity at wider intertidal flat, more (two to four) sites were set up on the intertidal flat from dike to sea. The number of the sampling sites more than one was marked in parentheses beside the serial number of transects (Fig. 1). Totally, there were 88 sampling sites for surface sediment. At the same time, 18 sediment cores were collected from one site of 18 transects as shown in Fig. 1. Sewage outfalls along Shanghai continental coast monitored by the Shanghai Municipal Oceanic Bureau in 2006 are also illustrated in Fig. 1.

At each sampling site, four subsamples of surface sediment (0–5 cm) were collected randomly by a small plastic shovel within an area about 2.5 m^2 in June and July of 2006 and May of 2007, then mixed thoroughly to obtain a bulk sample. Three 50-cm-long sediment cores were sampled with PVC pipes at the corresponding sampling site and then sliced at the interval of 5 cm. Eh of each subsample, 0–5 cm, 25–30 cm, and 45–50 cm, was measured by potentiometer in situ immediately. All the collected samples were stored in Ziploc bags, and then transported to the laboratory for subsequent sample preparation and analyzing.

Samples were frozen dried (ALPHA 1-4/LD; Martin Christ Inc., Germany), then mixed thoroughly using mortars and pestles. In addition, 0.5 g surface sediment passed through a 63-μm sieve was digested with aqua regia in a water bath (Li et al. 2005), and then the concentrations of Hg were determined by an atomic fluorescence spectrophotometer (AFS-9230; Jitian Inc., China). Blanks and duplicate determinations were performed synchronously in each analytical batch to ensure the QA/QC. The standard deviation of Hg concentrations in duplicated samples ranged within 10 %. Moreover, the analytical accuracy was estimated by processing the sediment standard reference material (GSD-9, National Research Center for Certified Reference Materials, Beijing, China), and the recoveries were between 93 % and 109 %. All the containers using in the experiment were immersed in diluted HNO_3 for 24 h, then washed with fresh water and deionized water.

A small portion of each sample was ground to pass through a 150-μm sieve for total organic carbon analysis by the potassium dichromate–sulfuric acid oxidation method (Nelson and Sommers 1982; Zhang et al. 2009). AVS in sediment samples was determined by the methylene blue spectrophotometric method (Bowles et al. 2003). Grain size was measured by a laser granularity analyzer (LS 13 320; Beckman Coulter Inc., USA).

Contamination assessment methodology

Index of geo-accumulation

Pollution levels of Hg in sediment could be characterized by the geo-accumulation index (I_{geo}) put forward by Müller (1969). This contamination assessment index was commonly cited by researchers in environmental studies (e.g., Chen et al. 2007; Abrahim and Parker

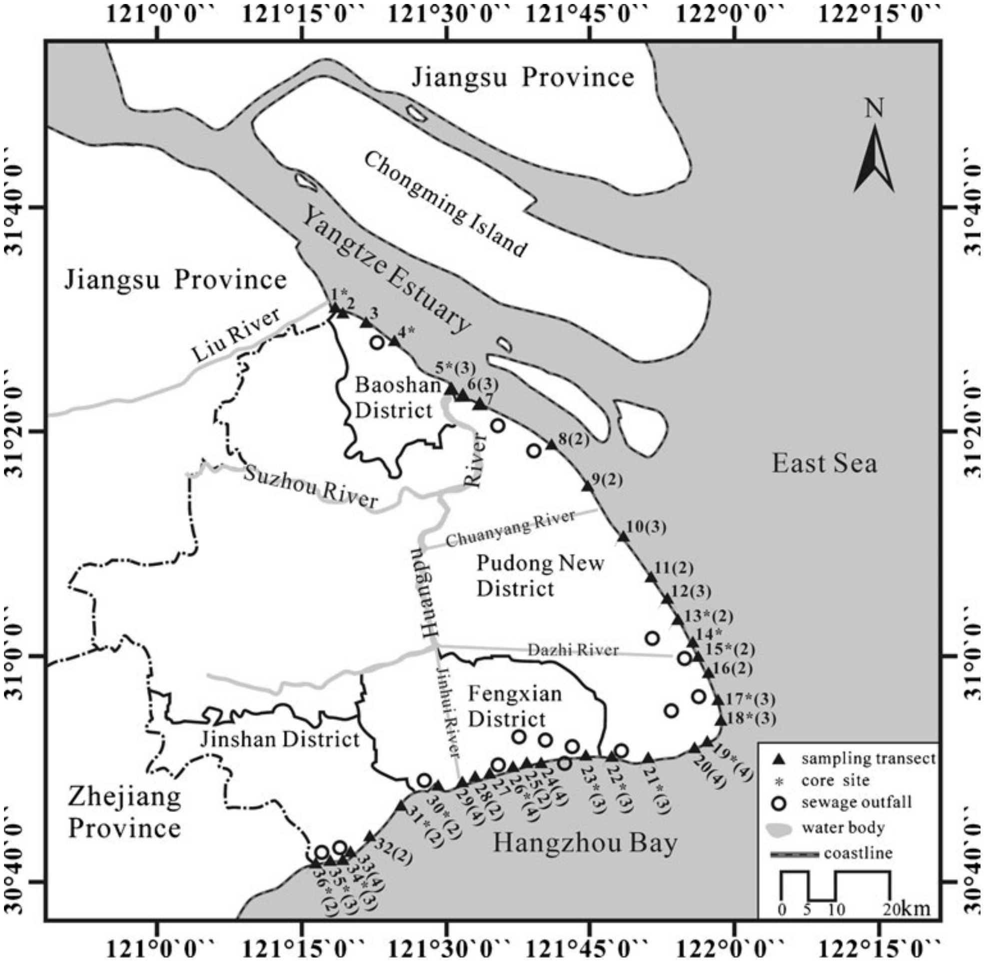

Fig. 1 Location of sampling transect

2008; García et al. 2008; Yu et al. 2008; Rodríguez-Barroso et al. 2009; Zhang et al. 2009; Shi et al. 2010a) and could be defined as the following equation:

$$I_{\mathrm{geo}} = \log_2 \frac{C_n}{1.5B_n} \tag{1}$$

C_n is the total Hg concentration in sediment; B_n is the background or pristine value of Hg concentration. Here, the background value of Hg in tidal flat of Shanghai is 50 ng/g (Zhu 1991), which was selected as the reference in assessment of the Hg pollution. The constant factor 1.5 was introduced to minimize the effect of possible variations in the background values which may be attributed to lithologic variations in the sediments (Abrahim and Parker 2008). Müller proposed seven classes of the geo-accumulation index as follows: if $I_{\mathrm{geo}} \leq 0$, uncontaminated (class 0); if $0 < I_{\mathrm{geo}} \leq 1$, from uncontaminated to moderately contaminated (class 1); if $1 < I_{\mathrm{geo}} \leq 2$, moderately contaminated (class 2); if $2 < I_{\mathrm{geo}} \leq 3$, from moderately to heavily contaminated (class 3); if $3 < I_{\mathrm{geo}} \leq 4$, heavily contaminated (class 4); if $4 < I_{\mathrm{geo}} \leq 5$, from heavily contaminated to extremely contaminated (class 5); if $I_{\mathrm{geo}} > 5$, extremely contaminated (class 6).

Potential ecological risk index

The assessment of ecological risk of Hg in intertidal sediment was carried out by using the potential ecological risk index (RI) proposed by Hakanson (1980):

$$RI = \sum\nolimits_{i=1}^{n} E_r^i = \sum\nolimits_{i=1}^{n} T_r^i \times C_f^i = \sum\nolimits_{i=1}^{n} T_r^i \times \left(\frac{C_n^i}{C_o^i}\right) \tag{2}$$

RI is the sum of the potential ecological risk factors (E_r^i) of eight pollutants, PCB, Hg, Cd, As, Cu, Pb, Cr, and Zn (Hakanson 1980). In this paper, only the potential ecological risk factor (E_r^i) of Hg was calculated. T_r^i is the metal toxic response factor, according to Hakanson (1980); the value for Hg is 40. C_f^i is the single pollution index which is equal to the ratio of the Hg concentration in samples (C_n^i) to the background value (C_0^i) of Hg in tidal flat of Shanghai (Zhu 1991), which is 50 ng/g. The assessment standard was as follows: if $E_r^i < 40$, the potential ecological risk of Hg in the sediment is low; if $40 \leq E_r^i < 80$, the risk of Hg is moderate; if $80 \leq E_r^i < 160$, considerable risk; if $160 \leq E_r^i < 320$, high risk; and if $E_r^i \geq 320$, very high risk.

Results and discussion

Physicochemical properties and total Hg concentrations in intertidal sediment

The range of physicochemical parameters of surface and core sediment is presented in Table 1. It could be found that there was great spatial difference in the properties of surface sediment especially for Eh and the AVS content. Overall, the means of TOC, AVS, Eh, and mean particle size in surface sediment were 9.3 mg/kg, 20.1 mg/kg, 15.3 mV, and 34.3 μm respectively, and the coefficient of variance were 40 %, 232 %, 656 %, and 40 %. The content of TOC in intertidal sediment was comparable to that found by Zhang et al. (2009) in the surface sediment of Yangtze River intertidal zone, but the mean particle size was obviously coarser than that found by Zhang et al. (2009). No obvious vertical changes were observed in TOC and mean particle size in the core sediment, while the mean content of AVS was highest in the bottom layer (45–50 cm), and the mean of sediment Eh was lowest in the surface layer (0–5 cm).

Total Hg concentration in four sediment samples collected from Nanhui District was below analyzing detection (<0.2 ng/g dry wt). The average total Hg concentration was 107.4±90.9 ng/g (ranged from <0.2 to 465.9 ng/g), and the coefficients of skewness and kurtosis were 1.70 and 3.48, respectively. The total Hg concentrations of the 88 surface sediment samples from Shanghai coastal area did not present a normal distribution ($p<0.05$, K–S Normality Test). Only 11.5 % of samples' total Hg concentration exceeded primary standard (200 ng/g) of Chinese National Standard for Marine Sediment Quality GB 18668-2002 (AQSIQ 2002), and all of the samples were lower than the corresponding secondary standard value (500 ng/g).

As shown in Table 2, the total Hg concentrations in intertidal sediments of Shanghai continental coast were similar to those observed adjacent tidal flat of Chongming

Table 1 Physicochemical properties of intertidal sediment in Shanghai

	District		TOC (mg/kg)	AVS (mg/kg)	Eh (mV)	Mean particle size (μm)
Surface sediment (*n*=88)	Baoshan (*n*=7)	Average	11.0	53.2	−29.6	36.7
		Min	8.7	2.4	−56.6	29.3
		Max	15.6	273.4	21.6	50.4
		SD	2.5	97.7	28.5	11.9
	Pudong (*n*=43)	Average	9.7	13.2	62.5	45.3
		Min	2.4	0.0	−378.0	10.5
		Max	16.9	156.2	180.0	143.8
		SD	3.9	29.9	120.1	40.5
	Fengxian (*n*=22)	Average	9.2	16.3	−15.8	26.4
		Min	4.1	0.0	−52.4	13.5
		Max	14.8	107.9	106.0	67.9
		SD	3.0	30.7	49.3	13.4
	Jinshan (*n*=16)	Average	7.8	29.2	−49.0	28.9
		Min	2.6	0.6	−148.2	12.2
		Max	16.5	214.2	14.6	52.2
		SD	4.5	64.9	36.1	17.2
Core sediment (*n*=54)	0–5 cm (*n*=18)	Average	5.49	39.5	18.3	35.4
		Min	2.00	0.0	−66.9	10.5
		Max	9.60	273.4	170.0	138.7
		SD	2.18	77.7	82.5	29.4
	25–30 cm (*n*=18)	Average	5.69	40.0	31.2	33.4
		Min	1.20	0.0	−72.8	9.0
		Max	10.10	517.1	162.0	90.0
		SD	2.62	121.4	84.2	25.4
	45–50 cm (*n*=18)	Average	5.39	62.6	31.3	38.2
		Min	1.30	0.0	−101.0	11.2
		Max	8.50	449.5	193.0	88.8
		SD	2.30	125.8	104.1	23.7

Table 2 Comparison of total mercury concentrations in intertidal sediments of Shanghai with other estuarine–coastal systems

	Mean (ng/g)	Range (ng/g)	Reference
Chongming Wetland	–	15–315	Song et al. (2009)
East China Sea	–	4.1–70	Fang and Chen (2010)
Guanabara Bay	870	<100–3,220	Covelli et al. (2012)
Gulf of Mexico	96.3	≤0.2–820	Lewis and Chancy (2008)
Kaohsiung Harbor	1,850	10–8,510	Chen et al. (2007)
Krka Estuary	–	101–1,418	Kwokal et al. (2002)
Mangrove Wetlands	189.4	2.3–903.6	Ding et al. (2009)
Pearl River Estuary	54.4	1.5–201.3	Shi et al. (2010b)
Öre Estuary	–	20.8–122.6	Kwokal et al. (2002)
Quanzhou Bay	400	170–740	Yu et al. (2008)
Seine-Vasière Nord	–	150–1,500	Ouddane et al. (2008)
Tagus	–	10–66,700	Canário et al. (2007)
Western coast of Venezuela	35.9	28.4–43.4	García et al. (2008)
Yangtze River Estuary	44.0	16.4–98.7	An et al. (2009)
Continental coast of Shanghai	107.4	≤0.2–465.9	This study
Primary standard[a]	200	AQSIQ (2002)	
Secondary standard[b]	500	AQSIQ (2002)	
Tertiary standard[c]	1,000	AQSIQ (2002)	

"–" means no data available. All data were reported on a dry weight basis

[a] Chinese National Standard for Marine Sediment Quality GB 18668-2002 (AQSIQ 2002); metal levels in primary standard are threshold values established to protect habitats for marine life including natural, rare, and endangered species, as well as places for human recreation and sports

[b] The secondary standard criteria are applied to regulate general industrial use and coastal tourism

[c] The tertiary standard values are for defining harbors and special use for ocean exploration

Island (Song et al. 2009) and Gulf of Mexico (Lewis and Chancy 2008), but relatively higher than Hg concentrations in sediments from the East China Sea (Fang and Chen 2010), the Pearl River Estuary (Shi et al. 2010b), and Yangtze River Estuary (An et al. 2009), China, western coast of Venezuela (García et al. 2008), and the pristine estuaries in Őre, Sweden (Kwokal et al. 2002). The mean and range of total Hg concentrations of Shanghai city coastal sediment were lower than those of Quanzhou Bay (Yu et al. 2008) and Mangrove Wetlands (Ding et al. 2009), and also far lower than those in contaminated sediments of Kaohsiung Harbor (Chen et al. 2007), Krka Estuary (Kwokal et al. 2002), Seine-Vasière Nord (Ouddane et al. 2008), Tagus (Canário et al. 2007), and Guanabara Bay (Covelli et al. 2012).

Spatial distribution character of Hg concentrations in intertidal sediment

The mean concentrations of total Hg in surface sediments from the four districts were significantly different ($p<0.05$, Kruskal–Wallis ANOVA) with the order decreasing as follows: Pudong (125.5 ng/g)>Fengxian (114.7 ng/g)> Baoshan (102.5 ng/g)>Jinshan (52.1 ng/g). As shown in Fig. 2, Hg concentrations of sampling sites in Baoshan and Jinshan were all below the primary standard value (200 ng/g), while in Pudong and Fengxian the percentages of sampling sites with Hg concentrations above the primary standard value were 16.7 % and 13.6 %, respectively.

There were also great spatial variations between transects even in the same district (Fig. 3). The coefficients of variance of total Hg concentrations in the four districts were in the order of Fengxian (71.2 %)>Pudong (53.4 %)>Baoshan (31.8 %)>Jinshan (25.1 %). The mean of total Hg concentrations on each transect higher than the primary standard value (200 ng/g) of GB 18668-2002 (AQSIQ 2002) was observed only on two transects, i.e., transect 10 and 21 in Pudong District (Fig. 3). Transects with high concentrations of total Hg had a close relationship with the sewage outfalls, inflow of rivers, and garbage landfills. Transect 5 and 6

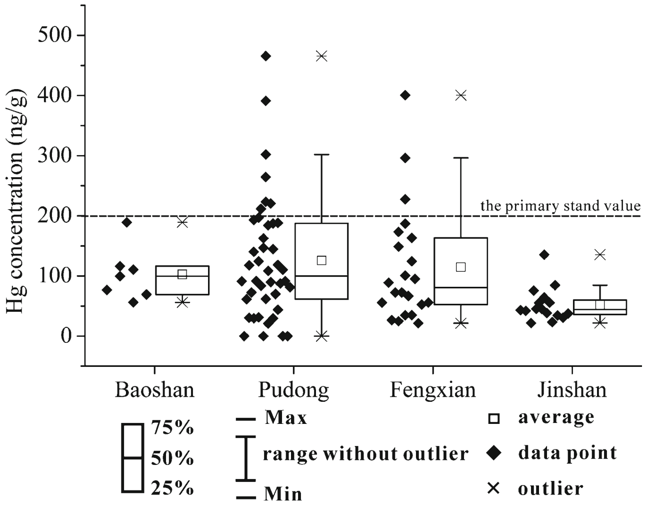

Fig. 2 Concentrations of total Hg in surface sediment of each district

were located around Wusongkou where Huangpu River pours into the Yangtze River (Fig. 1). Huangpu River flowing through Shanghai City receives a large amount of sewage both from the upper reaches and urban area of Shanghai City. In 2005 and 2006, Huangpu River carried 20×10^4 t and 21×10^4 t pollutants into Yangtze estuary, respectively, in which the amount of heavy metals was about 400 t annually (SMOB 2006). Transect 10 was located downstream of the mouth of Chuanyang River (Fig. 1) and might be affected by the pollutants in the river discharge. Transect 12 was around Chaoyang farmland, and the Hg concentration in sediments on this section might be related to the agricultural non-point pollution. High Hg concentrations in sediments on transect 14, 15, and 16 might be associated with the sewage discharge from the domestic and industrial outfalls, the outflow of Dazhi River as well as the leachate discharge from the largest municipal solid waste landfill in China, Laogang landfill. Transect 19 locates between Donghai Bridge and the gateway of Dishui Lake. There was a small river upstream of transect 19, named Luchaoyin River, flowing through one industrial park and several universities in Pudong New District. Transect 21 locates at the mouth of Luchao River. Luchaoyin River and Luchao River served as sewage drainage channels, so the water of these rivers was generally seriously polluted. The highest Hg concentration (465.9 ng/g) was found at transect 19, and transect 21 was also the only one that had two sampling sites with Hg concentrations higher than the primary standard value (200 ng/g). The high Hg concentrations on transect 22 to 26 were obviously related with the discharge of industrial and domestic sewage from the outfalls (Fig. 1). However, surface sediment on transect 4 located downstream of Shidongkou sewage outfall and transect 33 to 36 near sewage outfalls of SPC (Shanghai Petrochemical Company Ltd.) and drainage outlet of Jinshan District did not show high Hg concentrations. The sewage discharge way of Shidongkou outfall had been changed from the direct discharge into sea along the coast to the diffusion discharge into deep water in 2002 which had a relatively small environment impact on the tidal flat. The sewage of SPC was discharged after secondary biochemical treatment, and that might be the reason the surface sediment near these outfalls did not accumulate high Hg despite the sewage discharge amount of SPC was more than 1×10^8 t annually (SMOB 2006).

The concentrations of total Hg at different depths in core sediments are illustrated in Fig. 4. Generally, higher concentrations of total Hg were identified in the surface sediment, i.e., the first layer (1–5 cm) in most of the core samples than those in the other two layers. Nevertheless, at transect 15 and 22 of Pudong as well as transect 34 and 36 of Jinshan, the concentrations of total Hg increased obviously with the depth. Furthermore, total Hg concentrations over than the primary standard value (200 ng/g) of GB 18668-2002 (AQSIQ 2002) were found at the first layer (1–5 cm) only in one core sediment sample (transect 21) but three (transect 15, 22, and 34) at the third layer (45–50 cm) as well as one (transect 22) at the second layer (25–30 cm). Total Hg concentrations at the different sedimentary layers in the collected cores could indicate different temporal Hg inputs in the Shanghai coastal area in the past few years. Although no dating information for sediment cores was available in this study, it still could be inferred that human activities such as the reclamation of tidal flat, discharge of industrial and domestic sewage, and aquaculture activity had partly changed the hydraulic and sedimentary environment, and had become one of the dominant factors affecting the depth profile of total Hg in sediment cores. Moreover, the total Hg concentration in sediment cores might also be influenced by the windstorm tide which results in

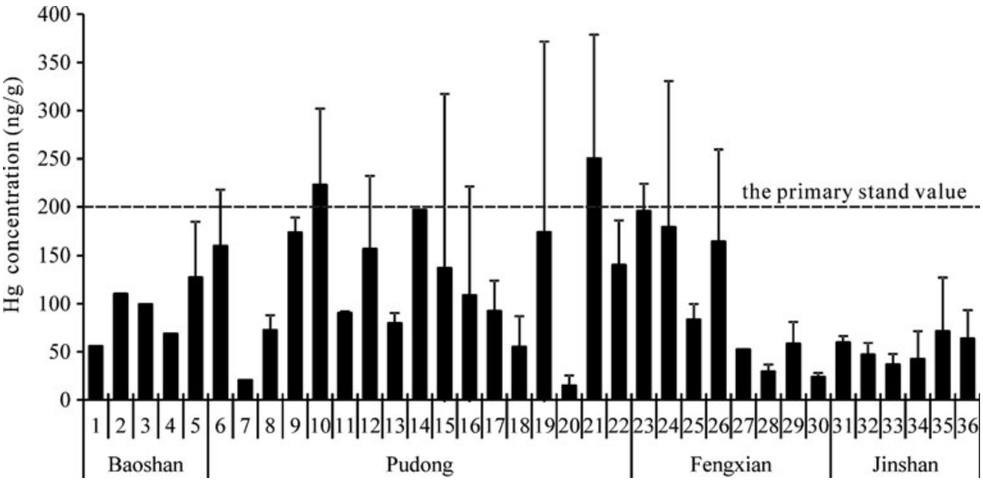

Fig. 3 Concentrations of total Hg in surface sediment on each section (*error bars* represent standard deviation of the samples if there are more than two sites at one section)

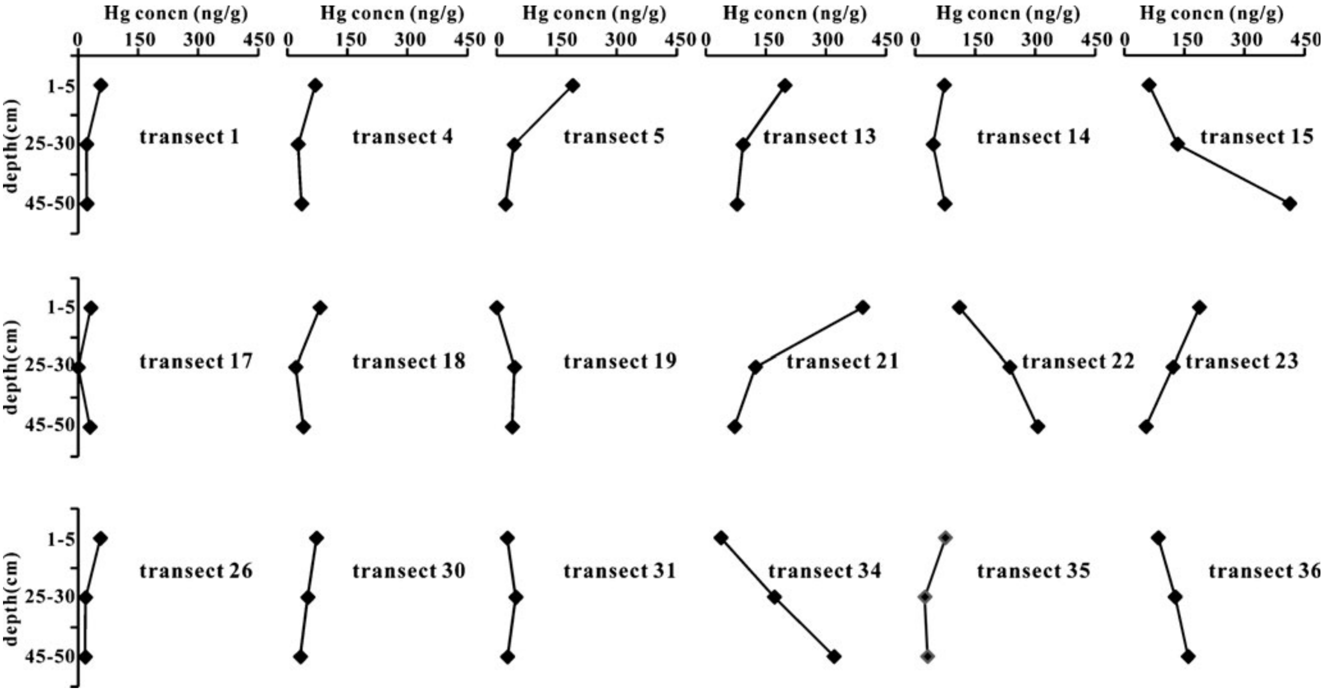

Fig. 4 Concentrations of total Hg in core sediment

nonlinear sedimentation in Shanghai coastal area (Chen et al. 2000).

Previous studies have indicated that various environmental parameters such as organic matter (OM), particle size, Eh, salinity, AVS, etc. may affect Hg distribution in sediments (Chen et al. 2007; García et al. 2008; Yu et al. 2008; Ding et al. 2009; Fang and Chen 2010; Oh et al. 2010). To determine whether environment factors can explain the variations of Hg concentrations in sediment, an analysis of the correlation between total Hg concentrations and TOC as OM content, Eh, AVS as well as mean particle size were performed. The results showed that total Hg concentrations had a significant correlation with TOC ($p<0.05$) both in surface sediment ($r=0.24$, $n=88$) and core sediment ($r=0.29$, $n=54$). However, in terms of surface sediment in each district, there was no significant correlation found between them, so it is with the core sediment at different depths except for sediment at 25–30 cm ($r=0.52$, $n=18$). No significant relationship ($p>0.05$) was observed between total Hg concentration and the other parameters, i.e., Eh, AVS, and mean particle size. The weak relationship between Hg and TOC might suggest that part of Hg associated with OM. OM is known to be a metal carrier, and it provides complexing agents for Hg^{2+}, thereby influencing the sediment Hg concentration. Overall, environment factors, TOC, Eh, AVS, and particle size, did not play an important role in the distribution of Hg in Shanghai intertidal zone. Local sources and complicated hydrodynamic conditions might be the important factors affecting Hg levels and distribution in the intertidal sediments.

Hg pollution assessment

Contamination degree based on I_{geo}

Geo-accumulation method I_{geo} was used to calculate Hg contamination degree in intertidal sediment. In terms of the surface sediment, the I_{geo} values for Hg in all the sampling sites ranged from −0.18 to 2.64 with an average of 0.18. About 43.4 % samples' I_{geo} values were below zero, suggesting none pollution degree. The percentages of I_{geo} values within the range from 0 to 1 and from 1 to 2 were 32.5 % and 19.3 %, respectively. Only 4.8 % of I_{geo} values ranged from 2 to 3 implying moderate to heavy contamination.

Considering the Hg pollution degree on each section, it was found that all the I_{geo} values were below 2, indicating none–moderate Hg pollution degree. I_{geo} values below zero accounted for 44.4 % of the 36 sections. Percentages of I_{geo} values within the range from 0 to 1 and from 1 to 2 were both 27.8 %. Sediment at section 7 in Pudong and section 3 in Fengxian was moderately polluted by Hg. Average I_{geo} values in the tidal flat sediment of investigated districts were in the increasing order of Jinshan (−0.69)<Fengxian (0.16)<Baoshan (0.35)<Pudong (0.53). It was implied that intertidal sediments were not contaminated by Hg in Jinshan District and were none–moderately contaminated in the other three districts.

As for the core sediment, the I_{geo} values for Hg ranged from −2.11 to 2.46 with an average of −0.21. At section 1 and 4 in Baoshan, section 14, 17, and 19 in Pudong, section 26 and 30 in Fengxian as well as section 31 in Jinshan, I_{geo} values of the sediment at three depths in sediment core were all below zero. I_{geo} values of samples in the other sediment cores were generally below 2, indicating that the core sediment at different depths was not contaminated or moderately contaminated by Hg. Sediment core samples at the depth of 45–50 cm in section 15 and 22 in Pudong and section 36 in Jinshan as well as at the depth of 1–5 cm in section 21 in Pudong were moderately–heavily polluted, in which I_{geo} values were between 2 and 3.

Potentially ecological risk assessment based on RI

Hg risk indices (E_r^i) of the surface sediment in all the sampling sites ranged from 16.8 to 372.8 with the mean of 90.1. Moreover, 33.7 % of E_r^i values were between 40 and 80, suggesting moderate risk. Percentages of E_r^i values between 80 and 160 (considerable risk) accounted for 28.9 % of all the samples, and 25.3 % of E_r^i values were below 40, meaning low risk. Only 12.0 % of E_r^i values were above 160, indicating high to very high risk.

In terms of the ecological risk value of Hg on each section, it was found that E_r^i values on three quarters of the sections were between 40 and 160. Thereinto, E_r^i values on 38.9 % of the sections were between 80 and 160 indicating considerable Hg risk, and 36.1 % between 40 and 160 suggesting moderate Hg risk. The E_r^i values below 40 accounted for 19.4 % of all the sections, meaning low ecological risk. There were two high ecological risk sections in Pudong New District, which E_r^i values were above 160 (high risk). On the whole, the average E_r^i values in the investigated districts were ranked in the following order: Jinshan (41.6)<Baoshan (82.0)<Fengxian (91.8)<Pudong (111.0). It indicated that the Hg pollution in intertidal sediments posed a moderate risk in Jinshan and considerable risk in the other three districts.

As for the core sediment, the E_r^i values ranged from 13.9 to 330.4 with an average of 75.6. E_r^i values of all the three depths samples of whole sediment core at section 1 and 4 in Baoshan, section 14, 17, 18, and 19 in Pudong, section 26 and 30 in Fengxian, and section 31 and 35 in Jinshan were below 80, indicating low or moderate risk. The E_r^i values between 80 and 160 suggesting considerable risk were generally at the depths of 1–5 cm and 25–30 cm in the other eight sediment cores. However, the E_r^i values above 160 indicating high or very high risk were generally distributed at the 45–50 cm of sediment core in section 15, 22, and 34, and the 1–5 cm and 25–30 cm of sediment core in section 21 and 22.

Conclusions

The average of total Hg concentrations in surface sediments of tidal flat along Shanghai continental coast was 107.4± 90.9 ng/g. Total Hg concentrations in surface sediments showed significant spatial differences along the continental coast. The distribution of Hg in intertidal sediments along the continental coast might be related with the local waste discharge from industrial and domestic sewage outfalls and garbage landfills along Shanghai coastal area as well as rivers flowing into sea. As for the core sediments, concentrations of total Hg at the layer of 1–5 cm were generally higher than those at the deeper layers. However, peaks were also identified at the layer of 25–30 cm or 45–50 cm. Total Hg concentrations in intertidal sediments were only significantly correlated with TOC, but not with Eh, AVS, and particle size. Considering the spatial distribution of sediment Hg and the weak correlations between total Hg concentrations and the environment factors, it could be inferred that local sources and complicated hydrodynamic and sedimentary conditions might be additional important factors affecting Hg levels and distribution in the intertidal sediments. The assessment results showed that the Hg pollution in intertidal sediments along Shanghai continental coast was generally at none to moderately contaminated level, which had potentially moderate to considerable risk on the local ecosystem.

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