Comparison of arsenic and heavy metals contamination between existing wetlands and wetlands created by river diversion in the Yellow River estuary, China

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Abstract Samples were collected at 71 sites in the Yellow River Delta Natural Reserve in December 2010 to represent soil conditions before and after the Yellow River (YR) diversion. The As, Cd, Cu, Pb, Zn, and Ni concentrations were measured to determine metal contamination levels. Results suggest that Cd concentrations were significantly higher after the YR diversion than before. The As, Cd, Cr, Cu, Ni, Pb, and Zn soil contamination indices did not exceed contamination levels, although the heavy metal content increased after the YR diversion. The mean concentrations of these heavy metals were lower than the Class I criteria. Correlation analysis shows significant correlations between As and Cr, Cu, Ni, Pb, and Zn concentrations both before and after the YR diversion. However, no significant correlations were observed between heavy metal concentration and pH before the diversion, and no heavy metal concentration was correlated with salinity. The principal component analysis indicates that these trace elements, including As, were closely correlated with each other and therefore likely originated from shared pollution

sources before the diversion. These results are useful for assessing the heavy metal contamination and proposing feasible suggestions to improve soil quality.

Keywords Heavy metal contamination · Coastal wetland soils · Pollution assessment · Yellow River Delta Natural Reserve

Introduction

Heavy metals often accumulate in coastal wetlands due to natural conditions and human activities in these areas (Williams et al. 1994; Bai et al. 2012; Xiao et al. 2012; Gan et al. 2013; Gao et al. 2013). Arsenic (As) is an important trace element in environmental research because its presence in drinking water has affected more than 400 million people worldwide (González et al. 2006). Estuarine and coastal wetlands are crucial ecosystems in which many critical ecological processes occur (Suntornvongsagul et al. 2007; Zhang et al. 2007; Bai et al. 2011a; Xie et al. 2011). Estuaries are sedimentary environments with fluvial–marine interactions where important biomass exchange occurs (Spencer et al. 2003; Delgado et al. 2010; Bai et al. 2011b). Coastal estuaries provide valuable ecosystem goods and services. However, these estuaries are also a large heavy metals sink (Li et al. 2007; Mitsch and Gosselink 2007; Bai et al. 2011c). Since the 1980s, large amounts of heavy metal pollutants from rivers, runoff and land-based point sources that may cause health risks have been introduced into estuarine and coastal zones because of rapid industrialization and economic development, leading to degraded wetland ecosystems (Gorenc et al. 2004; Lotze et al. 2006; Denton et al. 2009). Surveys of heavy metals concentrations in estuarine areas are imperative to evaluate heavy

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metal contamination levels in large river delta (Apitz et al. 2009; Bai et al. 2011b).

The ecological risk of heavy metal pollution has been estimated based on various soil quality standards (Ip et al. 2007; Zhang et al. 2009; Jamshide-Zanjani and Saeedi 2013). Many previous studies have reported that long-term industrialization and urbanization may lead to heavy metal contamination in aquatic sediment (Wang et al. 2011; Zhang et al. 2012). Pekey et al. (2004) adopted the United States Environmental Protection Agency sediment quality guidelines (SQGs) to evaluate trace elements toxicity in surface sediments of Izmit Bay, Turkey. Zhang et al. (2012) sampled 87 soil profiles from five wetland types in the Pearl River estuary and analyzed the surficial and vertical distributions, and the pollution sources of heavy metals. Nabuloa et al. (2006) reported that roadside crops leaves could accumulate high trace metal concentrations, causing a serious health risk to consumers. Bai et al. (2009) investigated the total As, Cd, Cr, Cu, Ni, Pb, and Zn concentrations and compared road transportation pollution levels. Understanding heavy metal contents and accumulation play a crucial role in ecological risk assessment and facilitates wetland restoration. Therefore, precise heavy metal concentration measurements are urgently needed to evaluate the potential ecological risks.

The Yellow River (YR) remains the second largest river in the world in terms of sediment loading, which causes frequent shifts in the course of the lower reaches (Zhang 2011a; Bai et al. 2012). The modern Yellow River Delta (YRD) has exhibited the most pronounced spatio-temporal changes among any river deltas (Ye et al. 2007; Zhang 2011b). Because the YR breached at Tongwaxiang, Henan Province and shifted from northern Jiangsu Province to the Daqing River course, entering the Bohai Sea in 1855, the rump channel has frequently shifted on the alluvial fan plain of the modern YRD (Fan et al. 2006; Zhang 2011a).

Previous studies have focused on investigating heavy metals characteristics in tidal wetlands before and after flow-sediment regulations (Bai et al. 2012). Cui et al. (2009) also reported that freshwater input substantially reduced soil salinity after a long-term monitoring period from 2001 to 2007; the river diversion led to increased soil organic carbon (SOC) from the increased freshwater input. These studies found that As and Cd concentrations were substantially higher in marsh soils after regulation than before. Monitoring the heavy metal contents and accumulation status before and after the YR diversion plays an important role in wetland restoration and assists in understanding the ecological effects and human activities (Chu et al. 2006). However, few studies probing heavy metal contamination levels and sources resulting from the YR diversion in different wetland types have been investigated.

Therefore, the primary objectives of this study are (1) to assess heavy metal pollution in the surface soil both before and after the YR diversion (e.g., in pre-existing and newly formed wetlands) and (2) to investigate heavy metal sources and provide suggestions for restoring abandoned coastal wetlands.

Materials and methods

Study areas

The Yellow River Delta Nature Reserve (YRDNR) covers 1,530 km² of the YR estuary (117°31'–119°18'E, 36°55'–38°16'N) and is situated on the south side of the Bohai Sea, which is northeast of Dongying City, Shandong Province, China (Bai et al. 2011a). The wetland is not only the most complete estuary wetland, but also the youngest wetland ecosystem in the warm-temperate zone in China with fragile and unstable characteristics (Bai et al. 2011c). In 1992, the YRDNR was established to protect the newly formed wetland ecosystem and the rare and endangered birds at the YR mouth. Large amounts of silt produced by the erosion of the Loess Plateau created a fast-growing natural wetland at the YR mouth (Liu et al. 2010; Wang et al. 2011; Bai et al. 2012). The area has a warm-temperate and continental monsoon climate with an annual precipitation of around 600 mm and annual evaporation of 1,900–2,400 mm. The YRDNR consists of two separate parts: the Diaokouhe Natural Reserve (DKHNR) in the north, which is defined as old wetlands (before the YR diversion) and the Yellow River Mouth Natural Reserve (YRMNR) in the south, which is termed as new wetlands (after the YR diversion) (Fig. 1).

The YR diversion and abandoned wetland restoration

The YR was artificially shifted from its Shenxiangou course to the Diaokouhe course near Yuwa in July 1964. The tail reach of the Diaokouhe River, i.e., the reserved flow path for the YR, has a length of 52 km and flowed northward to the ocean before the YR diversion in May, 1976; every shift in the YR has abandoned river courses (Ye et al. 2007). Then, the YR was again artificially shifted from the Diaokouhe course to the Qingshuigou course at Yuwa in May 1976 to prevent the flow path estuarine sway from sandy deposition. In August 1996, the YR was shifted along the north bank of the 8th section of the Qingshuigou course (Bi et al. 2011). The original Diaokouhe River flow path was barren with no water flowing into the ocean for nearly 37 years. Moreover, landform features and ecosystems changed greatly due to changes in hydrology, sand loadings, marine dynamics and human activities. The

Fig. 1 Location and sampling sites in the YRDNR

Fig. 2 Typical landscape before and after the water transfer in the DKHNR. **a**, **b** Barren landscape of tail reaches. **c**, **d** The transferred water in the abandoned Diaokouhe riverbed. Source: <http://www.sdh.gov.cn/ztgz/stds/07/14502.shtml>

freshwater wetland area and riverbed in the tail reaches of the Diaokouhe River have been shrinking and drying due to the lack of water transport. Deteriorated salinization and

decreased biodiversity have also occurred (Fig. 2a, b). Due to the lack of freshwater and sand supplies, the seawater continued to intrude; the coastal line retreated substantially

Fig. 3 Typical landscape in the YRDNR. **a** AL, arable land; **b** F, forest; **c** SH, *Suaeda heteroptera*; **d** MF, mudflat with *Tamarix chinensis* Lour; **e** TR, thin reed; **f** RS, reed swamp

(a) AL

(b) F

(c) SH

(d) MF

(e) TR

(f) RS

while the YRMNR continued to expand wetland areas (Huang et al. 2012). The vegetation type has degraded from freshwater wetland meadow to salt marsh (Fig. 3). From 1976 to 2009, the DKHNR, which covers 485 km², has eroded and retreated by 10 km. Moreover, the oil well located in the DKHNR was threatened. In 1992, the State Planning Commission has approved the Plan Report of Flow Path to Ocean of YR compiled by the Yellow River Conservancy Commission, which decided that the Diaokouhe River would serve as the YR reserved flow path (Huang et al. 2012).

From July 2002 to June 2008, seven water and sediment regulations of the YR have been implemented. The change

in water and sediment conditions would inevitably have an impact on the YRD ecosystem (Bai et al. 2012). In 2009, the State Council formally approved the Yellow River Delta High Ecological Economic Zone Development Plan suggesting that the central government should stabilize the current YR flow path and reuse the abandoned Diaokouhe River course (Huang et al. 2012). The Yellow River Conservancy Commission performed ecological water transfer engineering during the 10th flow-sediment regulation regime in July 2010 (during flood season) to restore the estuarine ecosystem and wetland landscape in the abandoned Diaokouhe flow path and sand functionality. The water transfer project lasted 20 days. Approximately

60 million m³ of water was poured into the DKHNR and the restored wetland area reached 17,000 ha (Huang et al. 2012). This restoration will provide ecosystem protection in estuarine areas. The restoration project also aims to utilize the original Diaokouhe River for reserve flow to expand the period in which the flow is stable. Other goal of the restoration work includes improving the implementation strategies for estuarine governance, preventing the Diaokouhe flow path from continuing to shrink, ensuring estuarine flood control safety, and ameliorating the wetland areas. The areas of *Phragmites* have increased from 10,000 to 22,000 ha; the water surface has increased from 15 to 60 %, and the vegetation coverage has increased 10 % since the water transfer (Huang et al. 2012). The original wetland vegetation, i.e., mudflat, *Tamarix chinensis* Lour, and *Suaeda heteroptera*, has been replaced by *Phragmites*. Moreover, wetland soil salinity levels have decreased; the surface soil water content has increased.

Soil sampling and analysis

Samples were collected at 43 sites in the new wetlands and 28 sites in the old wetlands in December 2010 to represent soil conditions before and after the YR diversion, respectively. The land use types in the sample sites were mudflat, reed swamp, thin reed, forest, arable land, and *S. heteroptera* (Fig. 3). At each sampling site, three replicate surface soil (0–20 cm) samples were taken. The physical and chemical properties of each replicate sample and a composite sample formed by mixing the replicate samples were analyzed. All soil samples were placed in polyethylene bags for transport to the laboratory where they were air-dried at room temperature for 7 weeks. The air-dried soil was ground and passed through a 2-mm nylon sieve to remove coarse debris. The soil samples were then ground with a mortar and pestle until all particles passed through a 0.15-mm nylon sieve for analyzing soil chemical properties (Bai et al. 2011b).

To analyze the total As, Cd, Cu, Pb, Zn, Ni, and Cr concentration, samples were digested by a HClO₄–HNO₃–HF mixture in Teflon tubes at 160 °C for 6 h in an oven. The digested sample solution was analyzed using inductively coupled plasma atomic emission spectrometry. Quality assurance and control were assessed using duplicates, method blanks and standard reference materials (GBW07401) from the Chinese Academy of Measurement Sciences for each batch sample (1 blank and 1 standard for each 10 samples). To ensure the accuracy and precision of the experimental results, two standard reference materials, i.e., GSS-2-1 and GSS-2-2, were used as quality control samples (Zhang et al. 2012). The standard deviations of concentration of As, Cd, Cr, Cu, Ni, Pb, and Zn were 0.18, 0.01, 0.08, 0.74, 0.47, 0.54, and 1.74, respectively.

Duplicate samples were taken for 5 % of the soil samples; the standard deviations were within 7 %. SOC was measured using dichromate oxidation, which was determined using a CHNOS Elemental Analyzer. Soil pH and salinity were measured in the supernatant part of a 1:5 soil–water mixture using a pH meter and a salinity meter, respectively (Bai et al. 2011c). The physical and chemical properties of the tested soils are listed in Table 1. All experiments were performed at the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences.

Generally, the element recovery percentages (Eq. 1, below) for As, Cd, Cr, Cu, Ni, Pb, and Zn ranged from 80.63 to 98.50 %. No recovery percentage was obtained for Cd, because Cd did not have certified reference values (Delgado et al. 2010). A good agreement is found between our analysis results and the reference values

$$\% \text{ Recovery} = (\text{obtained value} / \text{certified values}) \times 100. \quad (1)$$

Assessment of trace element contamination

Two indicators, i.e., contamination index (P_i) and integrated contamination index (P), were used to assess the heavy metal contamination in the soil. The contamination index (P_i) proposed by Huang (1987) was used to evaluate heavy metal pollution (Bai et al. 2011a; Zhang et al. 2012):

$$P_i = \frac{C_i}{X_a} \quad (C_i \leq X_a) \quad (2)$$

$$P_i = 1 + \frac{C_i - X_a}{X_b - X_a} \quad X_a \leq C_i \leq X_b \quad (3)$$

$$P_i = 2 + \frac{C_i - X_b}{X_c - X_b} \quad X_b \leq C_i \leq X_c \quad (4)$$

$$P_i = 3 + \frac{C_i - X_c}{X_c - X_b} \quad C_i \geq X_c \quad (5)$$

where C_i is the observed pollution content, X_a represents the no-contaminant threshold value, X_b expresses the low-polluted threshold value and X_c is the highly polluted threshold value based on toxic substances effects (Bai et al. 2011a). According to the Chinese Environmental Quality Standard (GB 18668-2002) (National Standard of PR China 2002), Class I quality is suitable for mariculture, nature reserves, endangered species reserves, and leisure activities, e.g., swimming. Class I is suitable for maintaining natural background values levels. Moreover, Class II and Class III can be used as thresholds for protecting human health and food security and to encourage plant growth (Bai et al. 2011c). Class II areas are appropriate for industry and tourism sites. This contamination level is expected to cause no substantial damage or pollution to plants and the environment. Class III areas are only

Table 1 Soil property and heavy metal concentrations statistics for before and after the YR diversion (mg/kg)

	Before river diversion (old wetlands)	After river diversion (new wetlands)	Average	Maximum	Minimum	Cv (%)
Moisture (%) (mean $\pm$ SD)	21.560 $\pm$ 2.180	21.590 $\pm$ 4.010	21.580	28.500	9.710	16.310
Bulk density (g/cm ³)	1.437 $\pm$ 0.128	1.443 $\pm$ 0.113	1.441	1.656	1.126	8.090
SOC (g/kg)	5.320 $\pm$ 1.840	6.548 $\pm$ 3.704	6.047	15.694	1.482	51.680
Salinity (g/kg)	9.414 $\pm$ 8.348	8.646 $\pm$ 8.071	8.966	34.650	0.278	90.790
pH	7.452 $\pm$ 0.327	7.451 $\pm$ 0.279	7.452	8.099	6.877	3.990
TN (g/kg)	0.539 $\pm$ 0.220	0.528 $\pm$ 0.338	0.533	1.458	0.046	55.200
As (mg/kg)	8.064 $\pm$ 1.698	8.543 $\pm$ 2.013	8.333	13.350	4.040	22.690
Cd (mg/kg)	0.162 $\pm$ 0.160	0.293 $\pm$ 0.218*	0.264	0.840	0.020	80.130
Cu (mg/kg)	14.732 $\pm$ 4.133	17.584 $\pm$ 5.332	16.413	28.580	6.620	30.740
Pb (mg/kg)	12.423 $\pm$ 3.692	14.650 $\pm$ 5.265	13.802	26.340	4.100	34.760
Zn (mg/kg)	54.912 $\pm$ 12.986	59.104 $\pm$ 15.860	57.332	95.320	21.430	25.810
Cr (mg/kg)	17.339 $\pm$ 4.355	20.843 $\pm$ 5.033	19.405	31.680	7.880	25.980
Ni (mg/kg)	22.289 $\pm$ 4.620	25.199 $\pm$ 5.298	24.008	35.590	10.510	21.660

SD standard deviation, Cv coefficient of variation

appropriate for harbors, forest soils, or farmland soils near mining areas. In the above equations, X_a , X_b , and X_c correspond to Class I, Class II, and Class III criteria, respectively (Bai et al. 2010, 2011a).

The following terminologies were used to describe the contamination index: $P_i \leq 1$ signifies no contamination, $1 < P_i \leq 2$ signifies low contamination, $2 < P_i \leq 3$ signifies moderate contamination, and $P_i \geq 3$ signifies high contamination. The integrated contamination index P is calculated using the following equation (Huang 1987; Bai et al. 2011a):

$$P_c = \sum_{i=1}^7 (P_i - 1)$$

where if $P_i < 1$, then $P_i - 1 = 0$. The following terminologies were defined for the integrated contamination index: $P = 0$ for no contamination, $0 < P \leq 7$ for low contamination, for moderate contamination, and $P > 14$ for high contamination.

Statistical analysis

Data analysis was performed using the SPSS 19.0 software package. Pearson correlation was conducted to reveal the relationship between soil properties and heavy metals, and to identify the pollution sources in the old and new wetlands. Moreover, ANOVA was used to test for the difference between trace elements concentrations and soil properties. The factor analysis technique considerably reduces the number of variables and can detect relationships between metals. This technique is considered an effective tool to identify heavy metal sources (Han et al. 2006; Bai et al. 2012). Principal component analysis (PCA)

was applied by estimating the principal components and computing the eigenvectors of the heavy metal concentrations in all soil samples. The relationship between the spatial distributions and soil properties associated with the river diversion was then analyzed.

Results and discussion

Soil properties before and after the river diversion

The soil physical–chemical properties of the new and old wetlands are summarized in Table 1. Table 1 shows that the mean As concentrations have larger variations compared to other heavy metals; the variations coefficient is 22.69 %. The salinity difference can be explained by the abundant upstream freshwater inputs that dilute the soil in new wetlands; the old wetlands lack freshwater inputs, and therefore have a higher salinity. Sun et al. (2013) explored the P cycling in the two *Suaeda salsa* marshes and low *S. salsa* marsh of the YR estuary and showed seasonal fluctuations and vertical distribution of P in different marsh soils, and variations in P content in different parts of plants due to water and salinity status. Further research should focus on the vertical pattern of heavy metals in YRD wetland soils to explore the distribution pattern of trace element.

Heavy metal concentrations

The As, Cu, Cd, Cr, Pb, Ni, and Zn concentrations before and after the YR diversion are summarized in Table 1. The concentrations in the new wetlands are relatively higher

than in the old wetlands, which may be associated with an anthropogenic source. Significant changes in heavy metals were observed after the river diversion ($p > 0.05$). Moreover, Cu, Pb, Cr, Ni and Zn increased slightly, however not significantly ($p > 0.05$). The Cd concentrations in the old and new wetlands are 0.16 and 0.29 mg/kg, respectively, with an average value of 0.26 mg/kg. The Cd concentration increased by a factor of ~ 1.6 ($p < 0.05$, Table 1) after the river diversion. The As concentrations in the old and new wetlands are 8.06 and 8.54 mg/kg, respectively, with an average content of 8.33 mg/kg. The increased As and Cd levels in the new wetlands may be associated with decreased in salinity because salinity can affect the adsorption and desorption of these trace metals (Tang et al. 2010; Bai et al. 2012). Table 1 shows that the mean As and Ni concentrations have small variations (the variation coefficient is 22.69 %) than the concentrations of other heavy metals. Rapid agricultural development and the upstream application of agrochemicals and fertilizers are likely responsible for the large augmentation in heavy metal concentrations. Contaminants resulting from agricultural development and industrial wastewater led increased heavy metals concentrations after the YR diversion. Arsenic (As) is a human carcinogen and can damage ecological communities (Sadiq et al. 2003). Copper and zinc are the two micronutrients for aquatic life in all natural waters and sediments. Soil pollution caused by Cu might originate from Cu-based agrochemicals related to specific agronomic practices. Generally, atmospheric deposition is the main Pb source in soils near roads with considerable traffic or factories discharging solid particles and toxic fumes into the atmosphere (Turer et al. 2001). In addition, wastewater is also considered the primary source for some agricultural sites due to sewage irrigation (Bai et al. 2011b). Higher heavy metals contents are attributable to long-term domestic sewage and agrochemical discharge.

Heavy metal pollution sources

Correlation matrix (CM)

Correlation matrix analysis and PCA are effective methods for determining heavy metal sources. The matrices of correlation coefficients between major soil properties and heavy metal concentrations before and after the YR diversion are listed in Table 2. Cu, Pb and Zn concentrations were closely related to SOC in both old and new wetlands. The correlation analysis suggests significant correlations between As and Cr, Cu, Ni, Pb, and Zn in both old and new wetlands. The narrow soil pH range contributes to the immobilization of large portions of some trace elements because of the subalkaline environment (Bai et al. 2011c). Moreover, significant correlations between As and

Ni suggest that they might originate from a common source. No significant correlations were observed between Cd and other heavy metals or soil properties, which suggest that Cd might originate from a different source. Soil TN (total nitrogen) content decreases significantly after the river diversion and exhibits poor correlations with As, suggesting that As might originate from local agricultural development. However, not all heavy metals found in the soil are correlated with the soil pH and salinity because these latter quantities only differ slightly between the sampling sites (Zhang et al. 2007; Bai et al. 2011c). Previous studies identified the importance of pH and SOM in determining heavy metal concentrations (Bai et al. 2010), because SOC can be a major heavy metal sink due to the large sorption capacities for metals (González et al. 2006). Kumpiene et al. (2008) also found that the application of SOC to immobilize heavy metals might not always succeed in samples with high anthropogenic inputs.

SOC is positively correlated with As, Cr, Cu, Ni, Pb, and Zn ($p < 0.05$) and TN ($p < 0.01$) in both old and new wetlands. The observations of Du Laing et al. (2009) support the idea that SOC can maintain low Cu mobility in soils through chemisorptions. The positive correlation between Cr and SOC in both regions ($p < 0.05$) shows that the reduction from toxic Cr to a more stable Cr could be accelerated by the presence of organic matter. Both elements are products of rock and soil weathering on land and are usually used to discriminate between natural and anthropogenic metal sources by identifying correlations with metal concentrations. The significant relationships between heavy metals demonstrate that these elements have good paragenetic association. Moreover, As concentrations are significantly and positively correlated with TN in new wetlands ($p < 0.05$); no significant differences are observed in TN ($p < 0.05$) in old wetlands. Significant positive correlations are also found for soil TN and pH in both wetland regions; positive correlations exist between most heavy metals. Du Laing et al. (2009) concluded that Cr solubility can be enhanced by increasing salinity without significantly affecting Pb mobility. Although heavy metal concentrations are not significantly correlated with the observed soil pH due to the observed narrow pH range, heavy metal mobilities are usually low in slightly alkaline soils (such as those used in the current study), which favor metal accumulation in the soil.

Principal component analysis (PCA)

The PCA assisted in identifying heavy metal sources (Tables 3, 4) (Bai et al. 2010). Only eigenvalues >1 and providing more than 85 % cumulative variance were retained (Bai et al. 2012). The principal components were

Table 2 Correlation coefficient matrices between soil heavy metal concentrations and other selected soil properties

	As	Cd	Cr	Cu	Ni	Pb	Zn	pH	Salinity	TN	SOC
Old wetlands											
As	1										
Cd	−0.059	1									
Cr	0.830**	−0.001	1								
Cu	0.965**	−0.118	0.872**	1							
Ni	0.966**	−0.107	0.873**	0.981**	1						
Pb	0.813**	−0.233	0.765**	0.836**	0.851**	1					
Zn	0.900**	−0.001	0.840**	0.868**	0.897**	0.797**	1				
pH	−0.128	0.093	−0.218	−0.158	−0.088	−0.021	−0.047	1			
Salinity	0.067	−0.222	0.213	0.168	0.102	0.098	−0.117	−0.699	1		
TN	0.150	0.177	0.143	0.228	0.170	0.360*	0.179	0.395*	−0.286	1	
SOC	0.322*	0.166	0.303*	0.371*	0.310*	0.487*	0.353*	0.171	−0.198	0.872**	1
New wetlands											
As	1										
Cd	0.026	1									
Cr	0.837**	0.277	1								
Cu	0.907**	0.016	0.860**	1							
Ni	0.894**	0.065	0.870**	0.981**	1						
Pb	0.835**	0.120	0.797**	0.906**	0.883**	1					
Zn	0.847**	0.135	0.864**	0.925**	0.919**	0.838**	1				
pH	0.180	−0.140	0.163	0.183	0.178	0.155	0.252	1			
Salinity	0.120	0.095	0.089	0.126	0.145	0.100	0.022	−0.780*	1		
TN	0.325*	0.230	0.435*	0.385*	0.375*	0.377*	0.530*	0.479*	−0.484	1	
SOC	0.317*	0.235	0.402*	0.362*	0.353*	0.340*	0.517*	0.407*	−0.393	0.953**	1

** Correlation is significant at the $p < 0.01$ level

* Correlation is significant at the $p < 0.05$ level

then rotated using the Varimax normalization method; the results are reported as factor loadings of the rotated matrix. The total variance in the metal concentrations is explained by two factors. In the old wetlands, two principle components (PCs) explained 91.52 % of the variance. These two PCs were extracted and used; the other PCs were discarded. Heavy metals, such as Ni, Cu, As, Zn, Cr, and Pb, dominate PC1, explaining 76.69 % of the total variance. These PC1 metals are clearly distinct from Cd in the old wetlands. The second principal component, PC2, explains 14.83 % of the total variance and exhibits highly positive factor loadings for Cd (Table 4). Similarly, two factors explain 92.09 % of the total variance for the new wetlands (Table 5). The PC1 explains 77.22 % of the total variance and is also strongly and positively related to Cu, Ni, Zn, As, Pb, and Cr. The PC2 explains 14.87 % of the total variance and also exhibits highly positive factor loadings for Cd. In the rotated principal component matrix, the first PC (PC1, explaining 76.35 % of the variance) includes Cr, Cu, Ni, and Zn; while the second PC (PC2, explaining 15.17 % of the variance) is dominated by Cd in the old wetlands. This

implies that Cd might have a different source than Cu, Pb and Zn. Moreover, Cd could be defined as an exogenous metal because it is found at high levels after the salinity decreased. Tang et al. (2010) reported that higher Cd concentrations in seawater of the YRD were primarily affected by YR inputs. Because of upstream rapid agricultural development, heavy applications of agrochemicals and fertilizers have contributed to the large increase in heavy metal concentrations in the YRD. These degrees of covariance indicate that the heavy metals in the new and old wetlands come from similar sources (Table 5).

Previous studies have demonstrated that the relationships among heavy metals within the PCs can be explained by anthropogenic influences or geogenic and pedogenic characteristics (Bai et al. 2012). Pb, Cd, Zn, Cu, Ni and Cr are associated with factor 1. Therefore, PC1 could be defined as an anthropogenic component due to the higher levels of these metals in soils in the study region compared with other coastal areas in China. Moreover, PC2 indicates that all the metals had the same sources, which has a stronger lithogenic component and seems to be controlled

Table 3 Total variance explained and rotated component matrix (two principal components selected) for heavy metal concentrations

Initial eigenvalues Total variance explained				Rotation sum of squared loadings			Rotated component	
Total	% of variance	Cumulative %		Total	% of variance	Cumulative	PC1	PC2
Principal component in the old wetlands								
1	5.368	76.688	76.686	Ni	5.344	76.345	0.981	−0.070
2	1.038	14.827	91.516	Cu	1.062	15.171	0.973	−0.081
3	0.211	3.015	94.531	As			0.968	−0.020
4	0.194	2.777	97.307	Zn			0.940	0.048
5	0.144	2.061	99.368	Cr			0.918	0.052
6	0.028	0.398	99.766	Pb			0.879	−0.238
7	0.016	0.234	100.000	Cd			−0.037	0.994

Extraction method: principal component analysis; rotation method: Varimax

Table 4 Total variance explained and rotated component matrix (two principal components selected) for heavy metal concentrations

Initial eigenvalues Total variance explained				Rotation sum of squared loadings			Rotated component	
Total	% of variance	Cumulative %		Total	% of variance	Cumulative	PC1	PC2
Principal component in the new wetlands								
1	5.405	77.221	77.221	Cu	5.370	76.716	0.987	−0.036
2	1.041	14.870	92.091	Ni	1.076	15.375	0.978	0.014
3	0.198	2.829	94.920	Zn			0.944	0.096
4	0.153	2.182	97.102	As			0.939	−0.028
5	0.113	1.607	98.709	Pb			0.922	0.071
6	0.076	1.088	99.796	Cr			0.902	0.263
7	0.014	0.204	100.000	Cd			0.046	0.995

Extraction method: principal component analysis; rotation method: Varimax

by anthropogenic influences (Mico et al. 2006; Bai et al. 2011b).

Assessment of heavy metal contamination

General comparison with worldwide river deltas

The mean heavy metal concentrations in soils from major worldwide river deltas are listed in Table 5. The Cd, Cu and Zn concentrations in the YRD are much lower than in the Pearl River Delta, which has experienced rapid industrial development in recent decades (Bai et al. 2011b, 2012). This finding suggests that some heavy metals in the YRDNR are less abundant than in other deltas, such as the Pearl River Delta and western Xiamen Bay, and more abundant than in Yangtze River Delta in 2005 and 2009 (Table 5). However, the heavy metal and As concentrations are nearly the same or higher than in deltas where anthropogenic effects are not substantial. Table 5 shows that heavy metal and As concentrations are higher in 2007, suggesting that

substantial accumulation occurs in the YRD soil. Heavy metal pollution has increased in recent decades, most likely because of intense human activities and sediment movement resulting from the river diversion, the rapid development of the petroleum oil industry and irrigated agriculture near the delta (Nie et al. 2010). The numerous heavy metals that are discharged from coastal metropolitan areas are carried into the estuary by adsorption onto fine grain-suspended sediments (Chen et al. 2004). Therefore, human activities are believed to be responsible for the increase in metal concentrations. Environmental degradation of wetlands is a major issue in the YRD. Natural threats and human activities such as flow cut-off of the YR and droughts, population growth and urbanization, cause wetlands degradation of the delta during the last century (Wang et al. 2012). Although landscape changes of wetlands area, surface water and groundwater pollution were tremendous in the delta, the heavy metal in soils should also be given enough attention during the wetland restoration process in the YRD.

Table 5 Mean soil heavy metal concentrations and As concentrations in the major worldwide river deltas, and the sediment quality guidelines in various countries (mg/kg)

Location	Country	Sample date	Cu	Pb	Zn	Cd	Cr	As	Ni	Sample no	References
Yellow River Delta	China	1996	6.82	8.84	24.87	0.02		13.07			Rui et al. (2008)
		2006	12.48	10.99	39.18	0.04		18.16			Rui et al. (2008).
		April 2007	26.70	27.23	78.10	0.57		27.60			Bai et al. (2012)
		Aug 2007	31.39	29.24	95.79	0.88	64.06	31.66	28.12		Bai et al. (2011a, b, c)
		Dec 2010	16.41	13.80	57.33	0.26	19.41	8.33	24.01		This study
Pearl River Delta	China	March 2009	321.48	49.89	221.12	2.26	125.21		56.70		Bai et al. (2012).
		Jan 2010	34.54	46.60	137.00	0.19	50.80	16.43	25.20		Zhang et al. (2012)
Yangtze River		Aug 2005	26.49	25.88	82.13	0.19					Zhang et al. (2009)
Bohai Bay	China	May 2008	38.50	34.70	131.10	0.22	101.40		37.40		Gao et al. (2012)
Western Xiamen Bay	China	July 2005	44.00	50.00	139.00	0.33	75.00		28.80		Zhang et al. (2007)
Yenisey River	Russia	1998	120.80	28.74	193.80	1.85					Guay et al. (2010)
Mississippi River	USA	June 2007	17.50	1.10	57.20	1.20	29.50	8.90			Seo et al. (2008)
Masan Bay	Korea	June 2005	43.40	44.00	206.30	1.24	67.10				Hyun et al. (2007)
Izmit Bay	Turkey	Aug 2005	67.60	102.00	930.00	4.90	74.30				Pekey (2006)

Assessment of heavy metal pollution using quality guidelines and potential risk

Furthermore, the mean As concentrations exceed the Class I criterion values, while other metals remain below the Class I criteria (Table 6). Moreover, the mean heavy metal concentrations, especially As, are higher than in the YR estuary in the 1990s (Rui et al. 2008). This indicates that the wetland soil was increasingly contaminated by heavy metals due to industrial and agricultural development in the nearby region. Numerous sediment quality guidelines have been developed to assess soil conditions; three guidelines were chosen to evaluate the surface soil heavy metal contamination levels in the YRDNR. The National Standard of China (NSC) GB18668-2002 has defined three soil grades; no samples in this study exceeded the effects range-low (ERL) contamination level (Long et al. 1995). In the case of individual metals, all sites are below the ERL guideline for Cr, Cu, Zn, and Pb. However, 76.39 % of the 71 Ni samples exceed the ERL guideline, which indicates potential harm for benthic organisms. No soil samples exceed the effects range-median (ERM) at which no seriously adverse effects on the majority of sediment-dwelling organisms are expected (Table 2). It is necessary to dynamically monitor the heavy metal concentrations and their bioavailability in wetlands since the YR diversion to protect wetland soil quality.

Table 6 Threshold heavy metal concentrations from the Chinese Environmental Quality Standard for soil (GB GB 18668-2002) (mg/kg)

	As	Cd	Cu	Pb	Zn	Cr	Ni
X_a	15	0.2	35	35	100	90	40
X_b	25	0.6	100	350	300	250	60
X_c	40	1.0	400	500	500	300	200
ERL guideline		1.2	34	47	150	81	20.9
ERM guideline		9.6	270	218	410	370	51.6

The effects range-low (ERL) guideline indicates concentrations below which adverse effects on biota are rarely observed (Long et al. 1995); the effects range-median (ERM) guideline indicates concentrations above which adverse effects on biota are frequently observed (Long et al. 1995)

Based on the Chinese Marine Sediment Quality Criteria (National Standard of PR China 2002) and the Chinese Agricultural Soil Environmental Quality Criteria, the average Pb, Zn, and Cr concentrations are as low as several times the threshold, suggesting that heavy metal pollution has not caused serious ecological risk. No soil samples are considered polluted by Zn, Cu, Pb, Cr, Ni, and As before or after the river diversion because the concentrations are within Class I. This finding indicates that the YRDNR contains natural background levels of these metals. Jams-hide-Zanjani and Saeedi (2013) sampled the surface sediment from Anzali wetland and determined the metal

Fig. 4 Heavy metal contamination indices (i.e., As, Cd, Cr, Cu, Ni, Pb, and Zn) and integrated contamination indices. Land use types are as in Fig. 3

concentration. Assessment of ecological risk of sediment samples based on the SQGs revealed considerable ecological risk and moderate degree of contamination in eastern part of the study areas. The pollution status differences can be explained the difference of industrial development. The fishing activity and ecotourism in Anzali wetland are prevalent, while the YRD has less developed industry.

Assessment of heavy metal pollution using the contamination index

The possible heavy metal enrichment in the soil was computed using a contamination index. The As and heavy metal contamination indices in the soil are shown in Fig. 4. No significant differences are observed for As, Cu, Ni, Pb, or Zn

Fig. 5 Contamination indices from before and after the YR diversion

because of the river diversion. However, significant differences in Cd before and after the river diversion are observed. Although the mean Cu, Pb and Zn concentrations increase after the diversion, these increases are not significant.

Figure 4 illustrates the heavy metal contamination levels for various land use types. The contamination indices suggest low As contamination levels and no Cu contamination. Moreover, the contamination indices are below the contamination levels for all heavy metals. The average contamination indices of Ni and Zn are higher than for the other heavy metals. Therefore, some elements have low-contamination levels and scientific measures should be taken to reduce these concentrations (Bai et al. 2011a). The heavy metal contamination levels of the land where *S. heteroptera* grows are higher than for the other five land use types, suggesting the extreme affinity for heavy metals in this soil (Cui et al. 2011). According to the above classification, the contamination indices for each land use type generally exhibit low As, Cu, Pb, and Pb contamination levels. However, no contamination level is found for these metals (Fig. 4); the contamination index values for Cr indicate low-contamination levels.

The wetland restoration at abandoned Yellow River of before the diversion

The wetland restoration effects based on the water transfer project in the YRD were also evaluated (Huang et al. 2012). The results suggest that the water transfer from the YR has greatly improved the abandoned channel flow conditions. The river water area has increased by 526 ha. Moreover, the hydrological situation of the river floodplain has ameliorated, and 437 ha of degraded wetlands in the YRDNR has been restored, which is beneficial to biodiversity maintenance and habitat improvement in the YRD.

Figure 5 demonstrates that the As, Cd, Cr, Cu, Ni, Pb, and Zn contamination indices from before and after the diversion of the YR have slowly changed. All heavy metal concentrations have an increasing trend. Specifically, the Cd concentrations increase most rapidly; the other measured heavy metal concentrations increase slower.

Conclusions

In estuarine ecosystems, coastal wetlands are increasingly recognized as important pollutant sinks, heavy metal carriers and possible future contaminant sources. The YRD is a typical fragile coastal wetland ecosystem where excessive anthropogenic activities have caused extensive wetland degradation. Wetlands in the delta are being unscrupulously degraded at a rather alarming rate due to economic development and human activities (Wang et al. 2012). Degradation of wetlands in the delta is due to changes in water quality and quantity, flow rates, and increase in pollution inputs. This study compared soil heavy metal concentrations before and after the YR diversion, finding that all heavy metal concentrations were significantly higher after the diversion than before. The integrated contamination index values suggested low heavy metal contamination levels for all land use types. The PCA indicates that these trace elements, including As, were closely correlated with each other and therefore likely originated from shared pollution sources before the diversion. The first principal component, which explained 77.22 % of the total variance, was strongly and positively related to the Cu, Ni, Zn, As, Pb, and Cr concentrations. The second PC, which explained 14.87 % of the total variance, exhibited high positive factor loadings for the Cd concentration. Several studies have proved that the association of these metals with the PCs can be indicated by anthropogenic effects or geogenic and pedogenic characteristics (Mico et al. 2006). The As, Cd, Cr, Cu, Ni, Pb, and Zn soil contamination indices did not exceed contamination levels, although the heavy metal content increased after the YR diversion. Long-term monitoring and contamination assessment are needed for wetland ecosystem health and regional ecological security.

Some physical–chemical properties have been shown to be the major controlling factors for the stabilization of trace metals (Du Laing et al. 2009). The river diversion led to an increase in SOC and reduced soil salinity due to the increase in freshwater input (Cui et al. 2009). Because the upstream abundant freshwater inputs diluted the soil salinity of the tidal freshwater marshes after regulation, soil salinity levels were significantly reduced in both wetlands types after flow-sediment regulation (Bai et al. 2012). The average soil salinity levels were significantly reduced after the diversion due to abundant freshwater inputs. The strengthened hydrodynamic condition may be the major cause for heavy metal redistribution, deposition and accumulation. Wetlands directly connected with rivers have much higher metal concentrations than those indirectly connected with rivers (Wang et al. 2011; Zhang et al. 2012). The Xiaolangdi Reservoir began storing water in 1999. Considerable siltation occurred in the reservoir after commissioning, with a

total sediment trapping of 32.47×10^8 t from 1997 to 2007 (Peng et al. 2010). The flow-sediment regulation scheme has greatly influenced wetland landscape patterns in the lower reach of the YR since 2002; As and Cd concentrations were significantly higher in both marsh soils after the regulation (Mitsch and Gosselink 2007; Bai et al. 2012; Li et al. 2009). This result is a major limiting factor of soil heavy metal mobilization and transformation in wetland ecosystems. The ecological transfer of water from Diaokouhe will supply a scientific basis for implementing highly efficient eco-economic construction.

Some heavy metals are released from wetland soils after wetland reclamation, while a cultivated wetland would have elevated heavy metal concentrations and become a sink after abandonment (Bai et al. 2010). Abandoned wetlands that are accompanied with seawater intrusions are important factors that result in coastal wetland degradation. Further studies are required to confirm the changes in heavy metal concentrations and accumulation processes both before and after the YR diversion. Therefore, it is necessary to monitor the water level, flow quantity, and the effect of transfer water to protect the water quality of adjoining rivers after the wetland diversion because heavy metals could be released into the soil during floods (Bai et al. 2010). Although soil heavy metal pollution is less serious in the YRD than in many other major worldwide deltas, increased heavy metal concentrations were observed by comparing the concentrations measured in this study with those obtained during the 1990s. In addition, based on local government development plans, the YRD will become a large eco-economic region in China in the coming decade (Huang et al. 2012). Therefore, rigorous measures are required to prevent pollution caused by intensive anthropogenic activities from affecting this region.

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References

Apitz S, Degetto S, Cantaluppi C (2009) The use of statistical methods to separate natural background and anthropogenic concentrations of trace elements in radio-chronologically selected surface sediments of the Venice Lagoon. *Mar Pollut Bull* 58:402–414

- Bai J, Cui B, Wang Q, Gao H, Ding Q (2009) Assessment of heavy metal contamination of roadside soil in Southwest China. *Stoch Environ Res Risk Assess* 23:341–347
- Bai J, Cui B, Yang Z, Xu X, Ding Q, Gao H (2010) Heavy metal contamination of cultivated wetland soils along a typical plateau lake from southwest China. *Environ Earth Sci* 59:1781–1788
- Bai J, Huang L, Yan D, Wang Q, Gao H, Xiao R, Huang C (2011a) Contamination characteristics of heavy metals in wetland soils along a tidal ditch of the Yellow River Estuary, China. *Stoch Environ Res Risk Assess* 25:671–676
- Bai J, Xiao R, Cui B, Zhang K, Wang Q, Liu X, Gao H, Huang L (2011b) Assessment of heavy metals pollution in wetland soils from the young and old reclaimed regions in the Pearl River Estuary, South China. *Environ Pollut* 159:817–824
- Bai J, Zhang K, Cui B, Liu X, Huang L, Xiao R, Gao H (2011c) Trace element contaminations of roadside soils from two cultivated wetlands after abandonment in a typical plateau lakeshore, China. *Stoch Environ Res Risk Assess* 25:91–97
- Bai J, Xiao R, Zhang K, Gao H (2012) Arsenic and heavy metal pollution in wetland soils from tidal freshwater and salt marshes before and after the flow-sediment regulation regime in the Yellow River Delta, China. *J Hydrol* 450:244–253
- Bi X, Wang B, Lu Q (2011) Fragmentation effects of oil wells and roads on the Yellow River Delta, North China. *Ocean Coast Manage* 54(3):256–264
- Chen Z, Saito Y, Kanai Y, Wei T, Li L, Yao H, Wang Z (2004) Low concentration of heavy metals in the Yangtze estuarine sediments, China: a diluting setting. *Estuar Coast Shelf Sci* 60:91–100
- Chu Z, Sun X, Zhai S, Xu K (2006) Changing pattern of accretion/erosion of the modern Yellow River subaerial delta, China: based on remote sensing images. *Mar Geol* 227:13–30
- Cui B, Yang Q, Yang Z (2009) Evaluating the ecological performance of wetland restoration in the Yellow River Delta, China. *Ecol Eng* 35:1090–1103
- Cui B, Zhang Q, Zhang K, Liu X, Zhang H (2011) Analyzing trophic transfer of heavy metals for food webs in the newly-formed wetlands of the Yellow River Delta, China. *Environ Pollut* 159:1297–13026
- Delgado J, Nieto JM, Boski T (2010) Analysis of the spatial variation of heavy metals in the Guadiana Estuary sediments (SW Iberian Peninsula) based on GIS-mapping techniques. *Estuar Coast Shelf Sci* 88(1):71–83
- Denton GRW, Morrison RJ, Bearden BG, Houk P, Starmer JA, Wood HR (2009) Impacts of a coastal dump in a tropical lagoon on trace metal concentrations in surrounding marine biota: a case study from Saipan, Commonwealth of the Northern Mariana Islands (CNMI). *Mar Pollut Bull* 58:424–431
- Du Laing G, Rinklebe J, Vandecasteele B, Meers E, Tack FM (2009) Trace metals behaviour in estuarine and riverine floodplain soils and sediments: a review. *Sci Total Environ* 407:3972–3985
- Fan H, Huang H, Zeng T, Wang K (2006) River mouth bar formation, riverbed aggradations and channel migration in the modern Yellow River Delta, China. *Geomorphology* 74:124–136
- Gan H, Lin J, Liang K, Xia Z (2013) Selected trace metals (As, Cd, and Hg) distribution and contamination in the coastal wetland sediment of the northern Beibu Gulf, South China Sea. *Mar Pollut Bull* 66:252–258
- Gao X, Chen CTA (2012) Heavy metal pollution status in surface sediments of the coastal Bohai Bay. *Water Res* 46:1901–1911
- Gao H, Bai J, Xiao R, Liu P, Jiang W, Wang J (2013) Levels, sources and risk assessment of trace elements in wetland soils of a typical shallow freshwater lake, China. *Stoch Environ Res Risk Assess* 27:275–284
- González AZI, Krachler M, Cheburkin AK, Shotyk W (2006) Spatial distribution of natural enrichments of arsenic, selenium, and

- uranium in a minerotrophic peatland, Gola di Lago, Canton Ticino, Switzerland. *Environ Sci Technol* 40:6568–6574
- Gorenc S, Kostaschuk R, Chen Z (2004) Spatial variations in heavy metals on tidal flats in the Yangtze Estuary, China. *Environ Geol* 45:1101–1108
- Guay CKH, Zhulidov AV, Robarts RD, Zhulidov DA, Gurtovaya TY, Holmes RM, Headley JV (2010) Measurements of Cd, Cu, Pb and Zn in the lower reaches of major Eurasian arctic rivers using trace metal clean techniques. *Environ Pollut* 158:624–630
- Han Y, Du P, Cao J, Posmentier ES (2006) Multivariate analysis of heavy metal contamination in urban dusts of Xi'an, Central China. *Sci Total Environ* 355:176–186
- Huang R (1987) *Environmental pedology*. Higher Education Press, Beijing (in Chinese)
- Huang C, Liu G, Fu X, Li Y, Liu Q, Wang X (2012) Monitoring and evaluation of wetland restoration in the abandoned Diaokou Estuary of Yellow River Delta based on HJ-1 remote sensing data. *Prog Geog* 31(5):570–576 (in Chinese)
- Hyun S, Lee CH, Lee T, Choi JW (2007) Anthropogenic contributions to heavy metal distribution in the surface sediments of Masan Bay, Korea. *Mar Pollut Bull* 54:1059–1068
- Ip CCM, Li X, Zhang G, Wai OWH, Li Y (2007) Trace metal distribution in sediments of the Pearl River Estuary and the surrounding coastal sea, South China. *Environ Pollut* 147:311–323
- Jamshide-Zanjani A, Saeedi M (2013) Metal pollution assessment and multivariate analysis in sediment of Anzali international wetland. *Environ Earth Sci* 70:1791–1808
- Kumpiene J, Lagerkvist A, Maurice C (2008) Stabilization of As, Cr, Cu, Pb and Zn in soil using amendments- a review. *Waste Manag* 28:215–225
- Li Q, Wu Z, Chu B, Zhang N, Cai S, Fang J (2007) Heavy metals in coastal wetland sediments of the Pearl River Estuary, China. *Environ Pollut* 149:158–164
- Li S, Wang G, Deng W, Hu Y, Hua W (2009) Influence of hydrology process on wetland landscape pattern: a case study in the Yellow River Delta. *Ecol Eng* 35:1719–1726
- Liu E, Shen J, Yang L, Zhang E, Meng X, Wang J (2010) Assessment of heavy metal contamination in the sediments of Nansihu Lake Catchment, China. *Environ Monit Assess* 161:217–227
- Long ER, MacDonald DD, Smith SC, Calder FD (1995) Incidence of adverse biological effects within ranges of chemical concentrations in marine and estuarine sediments. *Environ Manag* 19:81–98
- Lotze HK, Lenihan HS, Bourque BJ, Bradbury RH, Cooke RG, Kay MC, Kidwell SM, Kirby MX, Peterson CH, Jackson JBC (2006) Depletion, degradation, and recovery potential of estuaries and coastal seas. *Science* 312:1806–1809
- Mico C, Recatala L, Peris M, Sanchez J (2006) Assessing heavy metal sources in agricultural soils of an European Mediterranean area by multivariate analysis. *Chemosphere* 65:863–872
- Mitsch WJ, Gosselink JG (2007) *Wetlands*, 4th edn. Wiley, New York
- Nabuloa G, Oryem-Origa H, Diamond M (2006) Assessment of lead, cadmium, and zinc contamination of roadside soils, surface films, and vegetables in Kampala City, Uganda. *Environ Res* 101:42–52
- National Standard of PR China (2002) Marine sediment quality (GB 18668-2002). Standards Press of China, Beijing (in Chinese)
- Nie M, Xian N, Fu X, Chen X, Li B (2010) The interactive effects of petroleum-hydrocarbon spillage and plant rhizosphere on concentrations and distribution of heavy metals in sediments in the Yellow River Delta, China. *J Hazard Mater* 174:156–161
- Pekey H (2006) The distribution and sources of heavy metals in Izmit Bay surface sediments affected by a polluted stream. *Mar Pollut Bull* 52:1197–1208
- Pekey H, Karaka D, Ayberk S, Tolun L, Lu MB (2004) Ecological risk assessment using trace elements from surface sediments of Izmit Bay (Northeastern Marmara Sea) Turkey. *Mar Pollut Bull* 48:946–953
- Peng J, Chen S, Dong P (2010) Temporal variation of sediment load in the Yellow River, basin, China, and its impacts on the lower reaches and the river delta. *Catena* 83:135–147
- Rui Y, Qu L, Kong X (2008) Effects of soil use along the Yellow River basin on the pollution of soil by heavy metals. *Spectrosc Spectr Anal* 28:934–936
- Sadiq R, Husain T, Bose N, Veitch B (2003) Distribution of heavy metals in sediment pore water due to offshore discharges: an ecological risk assessment. *Environ Model Softw* 18:451–461
- Seo DC, Yu K, DeLaune RD (2008) Comparison of monometal and multimetal adsorption in Mississippi River alluvial wetland sediment: batch and column experiments. *Chemosphere* 73:1757–1764
- Spencer KL, Cundy AB, Croudace IW (2003) Heavy metal distribution and early-diagenesis in salt marsh sediments from the Medway Estuary, Kent, UK. *Estuar Coast Shelf Sci* 57:43–54
- Sun ZG, Mou XJ, Tian HQ, Song HL, Jiang HH, Zhao JY, Sun WL, Sun WG (2013) Phosphorus biological cycle in the different *Suaeda salsa* marshes of the Yellow River estuary, China. *Environ Earth Sci* 69:2595–2608
- Suntornvongsagul K, Burke DJ, Hamerlynck EP, Hahn D (2007) Fate and effect of heavy metals in salt marsh sediments. *Environ Pollut* 149:79–91
- Tang A, Liu R, Ling M, Xu L, Wang J (2010) Distribution characteristics and controlling factors of soluble heavy metals in the Yellow River Estuary and Adjacent Sea. *Procedia Environ Sci* 2:1193–1198
- Turer D, Maynard JB, Sansalone JJ (2001) Heavy metal contamination in soils of urban highways: comparison between runoff and soil concentrations at Cincinnati, Ohio. *Water Air Soil Pollut* 132:293–314
- Wang S, Lin C, Cao X (2011) Heavy metals content and distribution in the surface sediments of the Guangzhou section of the Pearl River, southern China. *Environ Earth Sci* 64:1593–1605
- Wang MJ, Qi SZ, Zhang XX (2012) Wetland loss and degradation in the Yellow River Delta, Shandong Province of China. *Environ Earth Sci* 67:185–188
- Williams TP, Bubbs JM, Lester JN (1994) Metal accumulation within salt marsh environments: a review. *Mar Pollut Bull* 28:277–290
- Xiao R, Bai JH, Gao HF, Wang JJ, Huang LB, Liu PP (2012) Distribution and contamination assessment of heavy metals in water and soils from the college town in the Pearl River Delta, China. *Clean-Soil Air Water* 10(10):1167–1173
- Xie Z, Liu J, Zhu G, Xu X, Shao Q (2011) Evaluating habitat change and boundary adjustment of nature reserve in coastal wetland—a case study of Beidagang Nature Reserve of Tianjin, China. *J Coast Res* 27(5):966–972
- Ye Q, Chen S, Huang C, Xue Y, Tian G, Chen S (2007) Characteristics of landscape information Tupu of the Yellow River swamps and its sub-delta during 1855–2000. *Sci China* 50:1566–1577
- Zhang Y (2011a) Coastal environmental monitoring using remotely sensed data and GIS techniques in the Modern Yellow River delta, China. *Environ Monit Assess* 179:15–29
- Zhang Y (2011b) Environmental monitoring of spatial-temporal changes using remote sensing and GIS techniques in the abandoned Yellow River Delta coast, China. *Int J Environ Pollut* 45(4):327–341
- Zhang L, Ye X, Feng H, Jing Y, Ouyang T, Yu X, Liang R, Gao C, Chen W (2007) Heavy metal contamination in western Xiamen Bay sediments and its vicinity, China. *Mar Pollut Bull* 54:974–982

- Zhang W, Feng H, Chang J, Qu J, Xie H, Yu L (2009) Heavy metals contamination in surface sediments of Yangtze River intertidal zone: an assessment from different indexes. *Environ Pollut* 157:1533
- Zhang H, Cui B, Zhang K (2012) Surficial and vertical distribution of heavy metals in different estuary wetlands in the Pearl River, South China. *Clean-Soil Air Water* 40:1174–1184