Contamination and comprehensive risk assessment of heavy metals in Liangtan River, Chongqing, China

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ABSTRACT

Distribution and fraction of heavy metals (Pb, Cr, Zn, and Mn) in water and sediment in Liangtan River, Chongqing was analyzed using the atomic absorption spectrometry method. Pearson correlation coefficient, bioavailability index, geoaccumulation index and potential ecological risk index were introduced to classify the source and assess the environmental risk of the heavy metal. Pb, Cr, and Zn mainly existed in residual fraction and fraction bounded to Fe–Mn oxides while Mn mainly existed in the fraction bounded to carbonates and the residual fraction. Mn and Pb, Zn and Cr in the sediment were confirmed originating from separate common sources. Igeo and Ei were both in the order of Pb > Zn > Cr > Mn. Geoaccumulation indexes demonstrated that the Liangtan River has been heavily polluted by Pb and Zn with the class of 2–4 and 2–3, independently. From viewpoint of the whole Liangtan River, the mean RI (45.1) belonged to low risk level.

1. Introduction

Due to the toxicity, bio-accumulation, persistence and non-biodegradable character, the problem of heavy metals in aquatic ecosystems has attracted more attention.[1,2] Islam et al. investigated the concentration of globally alarming six kinds of heavy metals in surface water and sediment of an urban river in Bangladesh, the decreasing trend of metals were observed in water as Cr > Cu > As > Ni > Pb > Cd and in sediment as Cr > Ni > Cu > Pb > As > Cd.[3]

In general, the concentration of heavy metals presents the level of pollution. However, it can’t reflect the environmental behavior and ecological effect. Fraction analysis is an analysis of the heavy metals in actual form such as ion or molecular in the sediment which can help to get their portability.[4,5] The Tessier et al. approach or modifications thereof, has been widely applied even though problems have been identified with this method, is considerable justification of phase selectivity through the use of complementary techniques.[6] Previous research has found that Cu existed mainly in the form of residual and organic bound fraction, while Zn existed in the residual fraction in the sediment of Tai Lake, Nansi Lake, and Baiyangdian Lake, China.[7] It is reported that high stability constant occurred when Pb was combined with Fe–Mn oxides in sediments.[8–10]. The potential ecological risk index (RI) introduced by Hakanson was usually used to assess the risk of heavy metal in the sediment which contained heavy metal concentration, pollutant sorts, toxicity level and sensitivity to the metal contamination of the water body. Zhu[11] found that the potential ecological risk factors (Ei) of heavy metals in sediments of Xiawan Port were ranked in the order of Zn < Cu < Pb < Cd. The average ecological risk of Cd in the study area was 11172.00, indicating that Cd posed a very high risk to the local ecosystem. Dalia M.S. demonstrated the ecological risk of heavy metals in the surface sediments along the Egyptian Red Sea coast recorded a low risk.

The Liangtan River, branch of Jialing River is an important secondary river in Chongqing, China. In recent years, a large number of industrial wastewater and breeding wastewater has been emitted into the river and the basin has been polluted so heavily that it can cause a potential threat to the health of the people who live along the river.[12–17] More than 4335 thousand tons of wastewater was injected into the Liangtan River and the total COD was 1636 tons in 2010.[18] On the other hand, with the successful construction of Three Gorges Reservoir in China, the hydrological condition of the basin has changed a lot. Water flows slower than before, which makes the standing time of pollutants extend...
than before, so the pollutants are easily subsided into the sediment. Therefore, the Liangtan River undertakes a serious heavy metal pollution problem. However, few people have carried out researches about heavy metals in the sediment of Liangtan River. Therefore, the current study introduces the concentration of heavy metals in the water and sediment of Liangtan River and the comprehensive assessment of heavy metal contamination in sediment.

2. Materials and methods

2.1. Study sites

Liangtan River is located at the Beibei hills valley between Jinyun Mountain and Zhongliang Mountain. It originates from Jiulongpo District, Chongqing and inflow into Jialingjiang River in Beibei District, Chongqing, with a total length of 88 km and the basin area of 491 km².

2.2. Sampling and pre-treatment

The field surveys and sampling took place all along the river. The sample locations are shown in Figure 1.

Water and sediment samples were collected at each site from upstream to downstream. Water samples, to avoid incorporation of sediment into the samples, were carefully collected at the surface with 500 ml acid-washed polyethylene sample bottles. The samples were acidified with nitric acid to adjust the pH value to less than 2. Sediment samples were collected by bottom sampler and filled into pre-cleaned polyethylene bags.

All water samples were filtered using filter paper with a diameter of 0.450 microns and stored at temperature of 0–4 °C. All sediment samples were air-dried and filtered through a 1 mm clean plastic sieve to remove stones. Sieved sediments were grounded in an agate mortar. The powdered sediments were then transferred to a clean nylon membrane sieve (0.150 mm aperture) and shaken to obtain a fine homogeneous powder. Samples were digested in acid-cleaned microwave vessels containing 8 ml of aqua regia and 2 ml ultra pure, concentrated hydrofluoric acid (HF). Each digestion batch included at least one reagent blank and a representative standard reference material. Samples were digested for 1 hour at the temperature of 180 °C. After cooling for 1 h, the digested sample was transferred to a volumetric flask and diluted to volume of 50 ml with ultrapure water.

2.3. Analytical procedures

Pb, Cr, Zn, and Mn in water and sediment were measured by atomic absorption spectrometry (AAS). The digested samples were separately diluted for analysis by AAS with 2% of nitric acid. The instruments were calibrated daily using calibration standards. Results were quantified using an external calibration curve generated from the responses obtained from multiple dilutions of a multi-element calibration standard that was prepared from single-element standards. A 2% of ultrapure nitric acid blank experiment was conducted for quality control. The certified values were less than 10%.

Tessier sequential extraction was adopted for the present study; the quantities below refer to the sediment samples (dry weight of the original sample used for the initial extraction).[6] The summary of the Tessier sequential extraction is shown in Table 1.

2.4. Statistical analysis

All statistical analysis and the correlations between heavy metals were performed through the help of SPSS for Windows software version 18.0 (SPSS Inc., Chicago, IL, USA) at significance level of 0.05 and 0.01.

3. Theory/calculation

3.1. Correlation analysis

More than 90% of the heavy metal load in the aquatic ecosystems has been found to be associated with suspended particulate matter and sediments,[21,22] and sediments usually acted as a final reservoir of heavy metals.[23] Pearson correlation analysis is helpful to distinguish the source of heavy metal and examine the relationships between heavy metals concentrations in water and sediment environments.[24,25]
Table 1. Summary of the Tessier sequential extraction protocol.

| Extraction stage       | Tessier method                                | Sediment phase extracted         |
|------------------------|-----------------------------------------------|----------------------------------|
| F1 (exchangeable)      | 8 ml, 1 M MgCl₂, pH 7                         | Weakly adsorbed                  |
| F2 (bound to carbonates)| 8 ml, 1 M Sodium acetate, (CH₃COONa), pH 5 with 25% v/v acetic acid, (CH₃COOH) | Acid soluble (e.g. carbonates)   |
| F3 (bound to Fe–Mn oxides) | 20 ml, 0.04 M Hydroxyl ammonium chloride (NH₂OH·HCl) in 25% v/v acetic acid | Reducible (e.g. iron/manganese oxides) |
| F4 (bound to organic matter) | 5 ml, 30% v/v H₂O₂ and 3 ml, 0.02 M HNO₃. Extracted with 5 ml, 3.2 M ammonium acetate (CH₃COONH₄) | Oxidisable (e.g. organic matter and sulfides) |
| F5 (residual)          | Conc. 15 ml, Hf and 4 ml, HClO₄. Repeated and residue taken up in 5 ml HNO₃ | Residual (e.g. silicates and unreacive oxides) |

Table 2. Classes of Iₙgeo and corresponding pollution series.

| Level  | Iₙgeo | Sediment quality                             |
|--------|-------|---------------------------------------------|
| 0      | (∞, 0) | Unpolluted                                  |
| 1      | (0, 1) | Unpolluted to moderately                    |
| 2      | (1, 2) | Moderately polluted                         |
| 3      | (2, 3) | Moderately to highly polluted               |
| 4      | (3, 4) | Highly polluted                             |
| 5      | (4, 5) | Highly to very highly polluted              |
| 6      | (∞, +∞)| Very highly polluted                       |

3.2. Risk assessment by bioavailability index and geoaccumulation index (Iₙgeo)

Bioavailability index (BI) has been widely used to calculate the accumulated extent in living organisms and evaluate the potential harm of heavy metals [42]. Researchers developed an algorithm to calculate the BI of heavy metals in the sediment.[26] The calculation of BI is based on the fractions of heavy metals in Tessier and the equation is as follows:

\[ BI = \text{[Exchangeable (F1) + Bound to Carbonates (F2) + Bound to Fe–Mn Oxides (F3)]/[Bound to Organic Matter (F4) + Residual (F5)]} \]

The geoaccumulation index (Iₙgeo) was introduced by Müller [27] and it was widely used to quantify the level of heavy metal contamination in soil and sediment. [3,22,27–31] The equation for Iₙgeo is as follows:

\[ Iₙgeo = \log_{10}\left(\frac{C_i}{B_n}\right) \]

where \( C_i \) represents the measured concentration of the heavy metal in sediment and \( B_n \) is the geochemical background value of the heavy metal in the sediment,[32] where Pb is 23.88, Cr is 78.03, Zn is 69.88 and Mn is 573 mg/kg. The constant 1.5 is introduced to minimize the effect of possible variations in the background values which may be attributed to lithologic variations in the sediments. Table 2 shows the classes of geoaccumulation index:

3.3. Potential ecological RI’s

To get a further understand of contamination degree resulted in heavy metals in the sediment, potential ecological RI was used to assess the potential risk of heavy metals.[33,34]

The value of RI can be calculated by the following formulas:

\[ C'_i = C_i/C_n \]

\[ E'_i = T'_i \cdot C'_i \]

\[ RI = \sum E'_i = \sum T'_i \cdot C'_i \]

where RI is the sum of potential risk of individual heavy metal; \( E'_i \) is the potential risk of individual heavy metal; \( T'_i \) is the toxic-response factor for a given heavy metal; \( C'_i \) is the contamination coefficient; \( C'_i \) is the present concentration of heavy metals in sediments; \( C'_i \) is the pre-industrial record of heavy metal concentration in sediments. [32] Table 3 shows the indices and grades of potential ecological metals contamination.

4. Results and discussion

4.1. Distribution of heavy metals in the water and sediment

The concentrations of Pb, Cr, Zn, and Mn in water and sediment of Liangtan River are shown in Table 4. The concentration ranges of heavy metals in surface water of Liangtan River were as follows: Pb 0.0257–0.143 mg/L, Cr 0.142–0.158 mg/L, Zn 0.111–0.321 mg/L, and Mn 0.00890–0.400 mg/L. The concentration ranges of heavy metals in sediment of Liangtan River are shown in Table 4. The concentrations of Pb, Cr, Zn, and Mn in water and sediment of Liangtan River are as follows: Pb 0.0257–0.143 mg/L, Cr 0.142–0.158 mg/L, Zn 0.111–0.321 mg/L, and Mn 0.00890–0.400 mg/L. The concentration ranges of heavy metals in sediment of Liangtan River are as follows: Pb 78.0–361 mg/kg, Cr 45.4–170 mg/kg, Zn 145–382 mg/kg, and Mn 406–780 mg/kg, respectively. Similar results were found in the previous investigations in other rivers. [35–38]

According to the distribution of industrial enterprises, industrial discharge resulted in the irregularity and salination of concentration of heavy metals in the sediment. Waste water from factory machinery and electronic industry in the middle stream of Linagatan River led to the...
Mn and Pb may have the same origin. Zn and Cr had a highly significant positive correlation (0.842) at the level of 0.01 (two-tailed) and they were confirmed originating from some common sources such as electroplating process.

### 4.3. Fraction of heavy metals in the sediment

Figure 2 shows the fraction of heavy metals in the sediment. Due to the distribution of industrial enterprises and the ability of heavy metals to combine with the different chemicals, there was a great difference in percentages of various fractions of the different heavy metals.

Pb mainly took the forms of residual fraction and fraction bounded to Fe–Mn oxides, the summation of the two fractions ranging from 53.2 to 95.0% of the total amount which indicated that they can easily be combined with the mineral lattice which were difficult to break down or coprecipitated by hydrated manganese oxides. Cr and Zn had the same fraction distribution in the sediment with the summation of two fractions ranging from 55.6 to 72.9 and 74.4 to 92.1%, respectively. Mn mainly existed in the fraction bounded to carbonates and the residual fraction whose summation of the two fractions ranging from 59.9 to 89.1% of the total content. It introduced that Mn mainly combined with the mineral lattice and coprecipitated by carbonate.

### 4.2. Correlation of heavy metals in Liangtan River

According the distribution of heavy metal in the water and sediment, Table 5 shows the Pearson correlation coefficients of heavy metal between water and sediment all along the river. Cr, Zn, and Mn showed moderate positive correlations between each other while Pb presented a significant negative correlation. Heavy metal was consolidated in the sediment after injected into the river, so there should be positive relation of heavy metal between water and sediment. The data indicated that Pb has been released from the sediment in the downstream of the river. Meanwhile, the manifold correlations also demonstrated the various sources of Liangtan River sediment.

The correlation between heavy metal can reflect to some extent similar pollution sources and Pearson correlation coefficient is usually used to analysis the source of heavy metals.[39] The relationships between each of heavy metals were analyzed and the Pearson correlation coefficients are shown in Table 6. There were no notable correlations between Mn and Cr, Zn, but a significant positive correlation (0.657) with Pb which suggested that Mn and Pb may have the same origin. Zn and Cr had a highly significant positive correlation (0.842) at the level of 0.01 (two-tailed) and they were confirmed originating from some common sources such as electroplating process.

### Table 5. Correlation between heavy metals in water and sediment.

|     | Pb     | Cr     | Zn     | Mn     |
|-----|--------|--------|--------|--------|
| W   | 1      | 0.596  | 0.447  | 1      |
| S   | −0.598 | 1      | 0.596  | 1      |

Notes: W: water; S: sediment.

### Table 6. Heavy metal correlation matrix.

*Correlation is significant at the 0.05 level (2-tailed).
**Correlation is significant at the 0.01 level (2-tailed).

|     | Pb     | Cr     | Zn     | Mn     |
|-----|--------|--------|--------|--------|
| Pb  | 1      | −0.572 | −0.215 | 0.657* |
| Cr  | 1      | 1      | 0.842**| 1      |
| Zn  | −0.572 | 1      | 1      | 0.657* |
| Mn  | 0.657* | 0.842**| 0.657* | 1      |

### Notes

Increase of concentration of Mn and Pb. Concentration of Zn and Cr increased in the downstream due to the discharge of waste water from the industry, electronic and electroplate, respectively.

Heavy metals showed no degradation in water and were generally not found in high concentrations, which not only due to vertical transference and deposition, but also uptaked by plants and animals. Overall, the concentration of Pb and Mn showed a downward trend along the river, and it was contrary to that of Cr and Zn, which demonstrated that the river had a stronger self-purification capacity to Pb and Mn than Cr and Zn.

**Table 4.** The distribution of heavy metals in the water (mg/L) and sediment (mg/kg dw).

| Site | Water Pb | Sediment Cr | Water Zn | Sediment Mn |
|------|----------|--------------|----------|-------------|
| S1   | 0.0257   | 361          | 0.158    | 68.8        |
| S2   | 0.0845   | 241          | 0.142    | 50.9        |
| S3   | 0.0904   | 227          | 0.150    | 45.4        |
| S4   | 0.0845   | 291          | 0.144    | 45.4        |
| S5   | 0.143    | 264          | 0.145    | 57.8        |
| S6   | 0.108    | 130          | 0.148    | 71.6        |
| S7   | 0.126    | 104          | 0.157    | 61.2        |
| S8   | 0.102    | 86.0         | 0.154    | 115         |
| S9   | 0.102    | 78.0         | 0.154    | 71.6        |
| S10  | 0.120    | 79.6         | 0.158    | 170         |

**Table 6.** Heavy metal correlation matrix.
phase of heavy metals in the sediments were in the order of Mn > Pb > Cr > Zn. BI of Pb, and Mn in the midstream and downstream had saltations with a similar trend. The saltation of BI of Pb and Mn may be due to the change of water quality caused by industrial emission or human activity that imports active metals into the river or activated metals in the sediment. It indicated that the strategy of industrial pollution control should be focused on the distribution of industrial enterprises and the source reduction of heavy metals from industry waste water.

4.4.2. Index of geoaccumulation ($I_{\text{geo}}$)

$I_{\text{geo}}$ of the heavy metals of Liangtan River are presented in Table 8. According to Tables 2 and 8, the $I_{\text{geo}}$ values of Mn are 0 which indicated no pollution by manganese all along the river. Cr showed no pollution except in the 10th sample site. The $I_{\text{geo}}$ of Pb range from 1.12 (site S9) to 3.33 (site S1) which corresponded to class 2 of moderately polluted sediment samples (50%) and class 4 of highly polluted sediment samples (20%). 80.0% of the total sediment samples were classified into moderately polluted with Zn while 20.0% as moderately to highly polluted along the river. In general, assessed by the geoaccumulation index method, the threat to the aquatic ecosystem of heavy metals in Liangtan River followed a decreasing order of Pb > Zn > Cr > Mn.

4.4. Risk assessment of heavy metals in the sediment of Liangtan River

4.4.1. Index of bioavailability (BI)

Most of the heavy metals in the sediments existed in the instability fraction, once there were changes on chemical or physical conditions such as pH, bioturbation, etc.,[40] those metal elements were likely to enter the overlying water, which was a risk to the aquatic organism.

Table 7 shows the BI of the heavy metals in each sediment sample. The BI value of Mn was higher than that of Pb, Cr and Zn which suggested that Mn posed a higher potential risk to the aquatic ecosystem for its higher BI and it could easily enter the food chain and pose serious threat to the ecosystem due to its higher toxicity and availability. The relative amounts of easily dissolved phase of heavy metals in the sediments were in the order of Mn > Pb > Cr > Zn.

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Table 9. Ecological risk factor ($E_i^r$) and potential risk index (RI) of the surface sediments along the Liangtan River estimated from heavy metal contents.

| Site | Pb     | Cr     | Zn     | Mn     | RI    |
|------|--------|--------|--------|--------|-------|
| S1   | 75.5   | 1.76   | 3.72   | 1.36   | 82.4  |
| S2   | 50.5   | 1.30   | 2.47   | 1.07   | 55.3  |
| S3   | 47.5   | 1.16   | 2.18   | 0.925  | 51.8  |
| S4   | 60.9   | 1.16   | 2.21   | 0.861  | 65.1  |
| S5   | 55.2   | 1.48   | 3.92   | 0.876  | 61.5  |
| S6   | 27.2   | 1.84   | 3.72   | 1.13   | 33.9  |
| S7   | 21.6   | 1.57   | 2.07   | 0.708  | 26.2  |
| S8   | 18.0   | 2.95   | 4.21   | 0.814  | 26.0  |
| S9   | 16.3   | 1.84   | 2.45   | 0.760  | 21.4  |
| S10  | 16.7   | 4.36   | 5.47   | 0.801  | 27.3  |
| Min  | 16.3   | 1.16   | 2.07   | 0.708  | 21.4  |
| Max  | 75.5   | 4.36   | 5.47   | 1.36   | 82.4  |
| Average | 39.0 | 1.94   | 3.24   | 0.931  | 45.1  |
| ±SD  | 21.5   | 0.994  | 3.14   | 0.201  | 20.9  |

4.4.3. Ecological risk factor ($E_i^r$) and potential RI

Table 9 summarizes the calculated values of $E_i^r$ and RI for metals in the sediments of Liangtan River. It is found that the risk indices ($E_i^r$) of heavy metals were ranked in the order of Mn < Cr < Zn < Pb. From the viewpoint of pollution level in every sampling site, the sampling sites at the highest ecological risk degree caused by site 1 to site 5 for Pb. Among the studied heavy metals, Pb reported the highest ecological risk, because of its high toxicity factor. 50.0% of the sampling sites showed the moderate risk to the environment. The monomial ecological risk of Cr, Zn, and Mn denoted low risk to the environment. From viewpoint of the whole Liangtan River, the mean RI (45.1) belonged to low risk level.

$I_{geo}$ and $E_i^r$ showed the similar result that the heavy metals were ranked in the order of Mn < Cr < Zn < Pb, while the BI showed the BI of heavy metals in the sediments were in the order of Zn < Cr < Pb < Mn. According to the fraction and bioavailability analysis, the dissolving capacity of Mn was higher than the other heavy metals, while due to the calculation method of $I_{geo}$ and $E_i^r$, the background value of Mn was 573 mg/kg and was much more than Pb, Cr, and Zn, and $I_{geo}^{E_i}$ was 1 which was less than $I_{geo}^{Fe}(5)$ and $I_{geo}^{Cr}(2)$, so Mn showed the less accumulate capacity and less potential ecological risk at the same time.

5. Conclusion

From the present study, it is concluded that the concentration and distribution of heavy metals in the water and sediment in Lingatan River were attributed to a number of varying factors. Wastewater from mechanical manufacture and electronic industry in the middle stream of Lingatan River may have led to the increase of concentration of Mn and Pb and the concentration of Zn and Cr may also increase in downstream due to the discharge of wastewater from separate industries such as electronic and electroplate. Correlation analysis showed significant positive correlations on Cr and Mn between water and sediment, while a significant negative correlation on Pb and a moderate positive correlation on Zn; Mn and Pb, Zn and Cr were confirmed originating from some common sources, separately. Pb, Cr and Zn were mainly existed in residual fraction and fraction bounded to Fe–Mn oxides, the summation of the two fractions ranging from 53.2 to 95.0, 55.6 to 72.9, and 74.4 to 92.1% of the total content, singly. Meanwhile Mn mainly existed in the fraction bounded to carbonates and the residual fraction, which totally ranged from 59.9 to 89.1% of the total content. Based on the fraction distribution, bioavailability indexes of heavy metal in the sediment were in the order of Mn > Pb > Cr > Zn, which indicated that Mn could easily enter the food chain and pose serious threat to the ecosystem. $I_{geo}$ and $E_i^r$ were both in the order of Pb > Zn > Cr > Mn. Geoaccumulation indexes demonstrated that the Liangtan River has been heavily polluted by Pb and Zn with the class of 2–4 and 2–3, independently. From viewpoint of the whole Liangtan River, the mean RI (45.1) belonged to low risk level. The background value and $T_i^r$ resulted in the different order of BI, $I_{geo}$ and $E_i^r$ of heavy metals in the sediment of Liangtan River.

This research shows great potential for further researches on the risk assessment and pollution abate- ment of Liangtan River and the distribution, fraction and risk assessment of heavy metals in other rivers.

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References
[1] Bastami KD, Bagheri H, Kheirabadi V, et al. Distribution and ecological risk assessment of heavy metals in surface sediments along southeast coast of the Caspian Sea. Mar. Pollut. Bull. 2014;81:262–267.
[2] Fu J, Zhao C, Luo Y, et al. Heavy metals in surface sediments of the Jialu River, China: their relations to environmental factors. J. Hazard. Mater. 2014;270:102–109.
[3] Islam MS, Ahmed MK, Raknuzzaman M, et al. Heavy metal pollution in surface water and sediment: a preliminary assessment of an urban river in a developing country. Ecol. Indic. 2015;48:282–291.
[4] Wang B, Zhou Q, Nan Z, et al. Accumulation and migration of Cd and Pb in cole grown in the arid oasis soil. Acta Agriculturae Boreali-occidentalis Sinica. 2011;20:62–66, 80.
[5] Chen J, Fan WH, Sun RM, et al. Bioavailability and species distribution of heavy metals in sewage-irrigated soil from Xinhe. Acta Scientiae Circumstantiae. 2007;27:831–837.
[6] Tessier A, Campbell PGC, Bisson M. Sequential extraction procedure for the speciation of particulate trace metals. Anal. Chem. 1979;51:844–851.
[7] Lu C, Cheng J. Speciation of heavy metals in the sediments from different Eutrophic Lakes of China. Procedia Eng. 2011;18:318–323.
[8] González MJ, Ramos L, Hernández LM. Distribution of trace metals in sediments and the relationship with their accumulation in earthworms. Environ. Anal. Chem. 1994;57:135–150.
[9] Yuan X, Zhang L, Li J, et al. Sediment properties and heavy metal pollution assessment in the river, estuary and lake environments of a fluvial plain, China. CATENA. 2014;119:52–60.
[10] Zamani-Ahmadmahmoodi R, Esmaili-Sari A, Mohammadi J, et al. Spatial distribution of cadmium and lead in the sediments of the western Anzali wetlands on the coast of the Caspian Sea (Iran). Mar. Pollut. Bull. 2013;74:464–470.
[11] Zhu HN, Yuan XZ, Zeng GM, et al. Ecological risk assessment of heavy metals in sediments of Xiawan Port based on modified potential ecological risk index. Trans. Nonferrous Met. Soc. China. 2012;22:1470–1477.
[12] Liu G, Jin X, Peng X, et al. Risk assessment of heavy metals pollution of sediment of Liangtan River in Chongqing. J. Cent. S Univ. (Science and Technology). 2012;43:4962–4967.
[13] Min Z, Ma M, Song H. Investigation and assessment of soil pollution by heavy metals in fluvial sediment of Liangtan River, branch river of Three Gorges Reservoir. Environ. Sci. Technol. 2012;35:155–158.
[14] Gao J, Ke Z, Zhou B, Zhang K, et al. Characteristic analysis and risk assessment of heavy metal pollution in Liangtan River, a tributary of Three Gorges Reservoir area. J. Chongqing Univ. (Natural Science Edition). 2013;36:86–93.
[15] Li K, Gao X, Guo J. Study on Liangtan River basin pollution flux. Environ. Ecol. Three Gorges. 2011;33:6–9, 16.
[16] Zheng XO, Yang LJ, Lin-Jian WU, et al. Investigation on water pollution of Liangtan River watershed in the Three Gorges Reservoir area. Environ. Ecol. Three. Gorges. 2012;34:24–28.
[17] Liu Y, Yu N, Li Z, et al. Sedimentary record of PAHs in the Liangtan River and its relation to socioeconomic development of Chongqing, Southwest China. Chemosphere. 2012;89:893–899.
[18] Zhang K. Study on the complex pollution of heavy metals in Liangtan River. Chongqing: Chongqing University; 2011.
[19] Whiteley JD, Pearce NJG. Metal distribution during diagenesis in the contaminated sediments of Dulas Bay, Anglesey, N. Wales, UK. Appl. Geochem. 2003;18:901–913.
[20] Yi Y, Wang Z, Zhang K, et al. Sediment pollution and its effect on fish through food chain in the Yangtze River. Int. J. Sediment Res. 2008;23:338–347.
[21] Zheng N, Wang Q, Liang Z, et al. Characterization of heavy metal concentrations in the sediments of three freshwater rivers in Huludao City, Northeast China. Environ. Pollut. 2008;154:135–142.
[22] Amin B, Ismail A, Arshad A, et al. Anthropogenic impacts on heavy metal concentrations in the coastal sediments of Dumai, Indonesia. Environ. Monit. Assess. 2009;148:291–305.
[23] Caccia VG, Millero FJ, Palanques A. The distribution of trace metals in Florida Bay sediments. Mar. Pollut. Bull. 2003;46:1420–1433.
[24] Chen T, Yan B. Fixation and partitioning of heavy metals in slag after incineration of sewage sludge. Waste Manage. 2012;32:957–964.
[25] Zhang H, Luo Y, Song M, et al. Distributions and concentrations of PAHs in Hong Kong soils. Environ. Pollut. 2006;141:107–114.
[26] Lanno R, Wells J, Conder J, et al. The bioavailability of chemicals in soil for earthworms. Ecotoxicol. Environ. Saf. 2004;57:39–47.
[27] Müller G. Schwermetalle in den Sedimenten des Rheins-Veränderungen seit 1971 [Changes of heavy metals in the sediments of Rhine since 1971]. Umschau. 1979;79:778–783.
[28] Zahra A, Hashmi MZ, Malik RN, et al. Enrichment and geo-accumulation of heavy metals and risk assessment of sediments of the Kurang Nallah–Feeding tributary of the Rawal lake reservoir, Pakistan. Sci. Total Environ. 2014;470–471:925–933.
[29] Kabir MI, Lee H, Kim G, et al. Correlation assessment and monitoring of the potential pollutants in the surface sediments of Pyeongchang River, Korea. Int. J. Sediment Res. 2011;26:152–162.
[30] Usman ARA, Alkredaa RS, Al-Wabel MI. Heavy metal contamination in sediments and mangroves from the coast of Red Sea: *Avicennia marina* as potential metal bioaccumulator. Ecotoxicol. Environ. Saf. 2013;79:250–270.
[31] Hou D, He J, Lü C, et al. Distribution characteristics and potential ecological risk assessment of heavy metals (Cu, Pb, Zn, Cd) in water and sediments from Lake Dalinouer, China. Ecotoxicol. Environ. Saf. 2013;93:135–144.
[32] Tang J, Zhong Y, Wang L. Background value of soil heavy metal in the Three Gorges Reservoir district. Chin. J. Eco-Agriculture. 2008;16(4):848–852.
[33] Guo W, Liu X, Liu Z, et al. Pollution and potential ecological risk evaluation of heavy metals in the sediments around Dongjiang Harbor, Tianjin. Procedia Environ. Sci. 2010;2:729–736.
[34] Saeedi M, Li LY, Salmanzadeh M. Heavy metals and polycyclic aromatic hydrocarbons: pollution and ecological risk assessment in street dust of Tehran. J. Hazard. Mater. 2012;227–228:9–17.
[35] Jara-Marini ME, Soto-Jiménez MF, Páez-Osuna F. Bulk and bioavailable heavy metals (Cd, Cu, Pb, and Zn) in surface sediments from Mazatlán Harbor (SE Gulf of California). Rev. Environ. Contam. Toxicol. 2008;80:150–153.
[36] Liu C, Xu J, Zhang P, et al. Heavy metals in the surface sediments in Lanzhou reach of Yellow River, China. Bull. Environ. Contam. Toxicol. 2009;82:26–30.
[37] Rahman MS, Saha N, Molla AH. Potential ecological risk assessment of heavy metal contamination in sediment and water body around Dhaka export processing zone, Bangladesh. Environ. Earth Sci. 2014;71:2293–2308.
[38] Luo Y, Zhou X, Ao L, et al. Characteristics of heavy metals distribution and risk assessment in sediment of urbanization polluted river. Environ. Sci. Technol. 2014;37:264–267.
[39] Yu M, Zhang H, He X, et al. Pollution characteristics and ecological risk assessment of heavy metals in typical agricultural soils. Chin. J. Environ. Eng. 2016;10:1500–1507.
[40] Santino O, Giuseppe P. Fractionation of mercury in sediments during draining of Augusta (Italy) coastal area by modified Tessier method. Microchem. J. 2013;110:452–457.
[41] Orecchio A, Polizzotto G. Fractionation of mercury in sediments during draining of Augusta (Italy) coastal area by modified Tessier method. Microchem. J. 2013;110:452–457.
[42] Yoo JC, Lee CD, Yang JS, et al. Traction characteristics of heavy metals from marine sediments. Chem. Eng. J. 2013;228:688–699.