



## Pollution level and risk assessment of heavy metals in sewage sludge from eight wastewater treatment plants in Wuhu City, China

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### Abstract

**Aim of study:** To investigate the content, contamination levels and potential sources of five heavy metals (Hg, Pb, Cd, Cr, As) in sewage sludge from eight wastewater treatment plants (W1 to W8).

**Area of study:** Wuhu, located in southeastern Anhui Province, southeastern China.

**Material and methods:** The sewage sludge pollution assessment employed the single-factor pollution index, Nemerow's synthetic pollution index, monomial potential ecological risk coefficient and potential ecological risk index. The potential sources among the five heavy metals were determined using the Pearson's correlation analysis and principal component analysis (PCA).

**Main results:** The mean concentrations of the heavy metals were 0.27 mg/kg (Hg), 70.78 mg/kg (Pb), 3.48 mg/kg (Cd), 143.65 mg/kg (Cr) and 22.17 mg/kg (As). W1, W5 and W6 sewage sludge samples showed the highest levels of heavy metal contamination, and cadmium had the highest contamination level in the study area. Pearson's correlation analysis and PCA revealed that Pb and Cd mainly derived from traffic emissions and the manufacturing industry and that As and Cr originated from agricultural discharges.

**Research highlights:** The pollution of cadmium in Wuhu should be controlled preferentially. The heavy metal pollution of W1, W5 and W6 sewage treatment plants is relatively high, they should be key prevention targets.

**Additional keywords:** contamination evaluation; source identification

**Abbreviations used:**  $I_{geo}$  (geoaccumulation index); PI (single-factor pollution index); PN (Nemerow's synthetic pollution index);  $E_i^i$  (monomial potential ecological risk coefficient); RI (potential ecological risk index); PCA (principal component analysis);

**Authors' contributions:** Conceived and designed the experiments: YH. Analyzed the data: HZ and YH. Wrote the paper: HZ, YH, SZ, LW, ZG and JL. Revised the paper: HZ and YH. All authors read and approved the final manuscript.

**Citation:** Zhang, H; Huang, Y; Zhou, S; Wei, L; Guo, Z; Li, J (2020). Pollution level and risk assessment of heavy metals in sewage sludge from eight wastewater treatment plants in Wuhu City, China. Spanish Journal of Agricultural Research, Volume 18, Issue 2, e1103. <https://doi.org/10.5424/sjar/2020182-15796>

**Received:** 26 Sep 2019. **Accepted:** 25 May 2020.

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Funding agencies/institutions	Project / Grant
Natural Science Foundation of Anhui Province	1608085MH220
Excellent Young Talents Fund Program of Higher Education Institutions of Anhui Province	gxyqZD2016180
Key Projects of Wuhu Science and Technology Plan	2014cxy08
Doctoral Scientific Research Foundation of Wannan Medical College	WYRCQD201703
Students' Innovation and Entrepreneurship Training Program of Anhui Province	S201910368103

**Competing interests:** The authors have declared that no competing interests exist.

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## Introduction

Sewage sludge is generated during the process of treating municipal wastewater, and it is rapidly increasing (Dong *et al.*, 2013). In China, approximately 56% of

sludge is associated with disposed building materials, incineration waste, fertilizer, sanitary landfills, and the other sources; therefore, nearly half of the sludge has not been treated safely. Approximately one-third of the sludge is disposed of by "temporary means", and more

than 10% of the sludge is disposed of by unknown means (He *et al.*, 2016).

Sludge that is not treated in a timely manner continues to accumulate and occupy a large amount of land, and it can contain various heavy metals, organic pollutants and other toxic substances, which can cause secondary pollution (Lister & Line, 2001). Urban industrial sewage, domestic sewage, commercial water mixed emissions, and surface runoff inevitably lead to heavy metal accumulation in urban sludge, and these metals are not easily biodegraded once they reach into the soil environment and pose a threat to human health once they enter into the food chain (Dou *et al.*, 2013; Grotto *et al.*, 2015). Heavy metals in sewage sludge can eventually be taken up by humans, accumulating in fatty tissues and influencing the nervous system, immune system, endocrine system and hematopoietic function (Zhao *et al.*, 2014; Xu *et al.*, 2016). However, sludge can also be disposed in the form of soil conditioners or fertilizers, and improper disposal leads to a loss of organic matter and nutrient elements, thus representing a waste of resources. Sludge is rich in organic matter and nutrients, by improving soil physical and chemical properties and increasing soil organic matter, nitrogen and phosphorus, has positive and long-term effects on soil remediation or improvement (Singh & Agrawal, 2008; Kendir *et al.*, 2014; Liu *et al.*, 2015). To evaluate the environmental risk and sources of heavy metals in sewage sludge, the geo-accumulation index ( $I_{geo}$ ), single-factor pollution index (PI), Nemerow pollution index (PN), monomial potential ecological risk coefficient ( $E_r^1$ ) and potential ecological risk index (RI), together a multivariate statistical analysis have been widely applied (Abraham & Parker, 2008; Shafie *et al.*, 2013; Kowalska *et al.*, 2016; Birch, 2017; Yang *et al.*, 2017; Zhu *et al.*, 2018).

To use sewage sludge in an environmentally safe manner in Wuhu City, a risk assessment should be implemented. The aims of this research were to assess the contamination status of five heavy metals (Hg, Pb, Cd, Cr, and As) from different angles via  $I_{geo}$ , PI, PN,  $E_r^1$  and RI and to identify the potential sources of the heavy metals via Pearson's correlation coefficient analysis and a principal component analysis (PCA).

## Material and methods

### Study area

The city of Wuhu is located in southeastern Anhui Province in southeastern China, and ranks 10<sup>th</sup> out of 26 cities in the Yangtze River Delta City Group. The eight sewage treatment plants are located in: W1) Zhujiqiao,

in the Jinghu District; W2) Tianmenshan, in the Jiujiang District; W3) Binjiang, in the Yijiang District; W4) Chengnan, in the Sanshan District; W5) Wuhu Mingyuan, in the Nanling County; W6) Nanling County, in the Wuhu County; W7) Fanchang County, in the Fanchang County; and W8) Wuwei Modern, in the Wuwei County. The main sources of sewage were industrial and domestic effluents. The properties of these eight wastewater treatment plants are shown in Table 1.

### Determination of the total heavy metal concentration

Dry sludge was collected from the terminals of the sewage treatment plants in the second and fourth quarters of 2014. Each month, 3~5 500-g samples were collected from each of the sewage treatment plants. The collected samples were dried at room temperature, ground, and then separated into 0.149-mm particles through a sieve. The samples were weighed and digested with HNO<sub>3</sub>-HCl-H<sub>2</sub>O<sub>2</sub> and then used to determine the content of Cd, Cr and Pb (USEPA, 1996). Cd was analyzed using an atomic absorption spectrophotometer (AA-6300 Atomic Absorption Spectrometer, Shimadzu International Trading Co., Ltd., Shanghai, China). Pb and Cr were calculated using inductively coupled plasma mass spectrometry (ICP-OES 700 Inductively Coupled Plasma Mass Spectrometer, Agilent Technologies Inc., Tokyo, Japan). The sludge samples were also digested with HNO<sub>3</sub>:HCl (10 mL, 1:1 v/v) at 95 °C for 2 h to determine the content of As and Hg (Lacerda *et al.*, 2004) using the atomic fluorescence method (AFS-830 Dual-Channel Atomic Fluorescence Spectrometer, Beijing Titan Instruments Co., Ltd., Beijing, China).

### Geoaccumulation index ( $I_{geo}$ )

The  $I_{geo}$  was introduced by Müller (1969) to assess the contamination of heavy metals in soils and sediments, and it is defined as follows:

$$I_{geo} = \log_2 [C_n / (1.5 \times B_n)]$$

where  $C_n$  is the content of heavy metal n in samples, mg/kg;  $B_n$  is the background content of the metal n using the Nanjing background concentration of heavy metal in the soils (Hg = 0.12 mg/kg, Pb = 24.80 mg/kg, Cd = 0.19 mg/kg, Cr = 59.00 mg/kg and As = 10.60 mg/kg); and 1.5 is a constant factor applied to address the lithospheric effects. The classification of the  $I_{geo}$  is shown in Table 2

**Table 1.** Some properties of eight wastewater treatment plants in this study

Wastewater treatment plants	Wastewater treatment capacity (m <sup>3</sup> /day)	Daily sludge production (m <sup>3</sup> /day)	Primary treatment	Secondary treatment <sup>[1]</sup>	Tertiary treatment
W1	450,000	90	Centrifugal dewatering	A <sup>2</sup> /O	Incineration or landfill
W2	60,000	25	Belt pressure dewatering	Carrousel oxidation ditch	Incineration or landfill
W3	30,000	15	Centrifugal dewatering	Multimode A <sup>2</sup> /O	Incineration or landfill
W4	100,000	20	Centrifugal dewatering	A <sup>2</sup> /O	Incineration or landfill
W5	30,000	1	Plate-frame pressure filtration	A <sup>2</sup> /O	Incineration or landfill
W6	20,000	8	Belt pressure dewatering	A <sup>2</sup> /O	Incineration or landfill
W7	30,000	9	Belt pressure dewatering	Orbal oxidation ditch	Incineration or landfill
W8	40,000	20	Centrifugal dewatering	Carrousel oxidation ditch	Landscaping

<sup>[1]</sup> A<sup>2</sup>/O: Anaerobic-Anoxic-Oxic

### Assessment of heavy metal pollution

The PI was used to evaluate the comprehensive level of heavy metals for each study site (Tomlinson *et al.*, 1980), and it is defined as follows:

$$PI = C_i/S_i$$

where  $C_i$  is the concentration of the heavy metal  $i$ , mg/kg; and  $S_i$  is the standard of the heavy metal  $i$  according to CJT 309-2009 (Ministry of Housing and Urban-Rural Development, 2009). Nemerow's synthetic pollution index (PN) was applied to assess heavy metal contamination caused by all the heavy metals at each study site. PN is defined as follows:

$$PN = \sqrt{(P_{max}^2 + P_{ave}^2)/2}$$

where  $P_{ave}$  is the average value of the single-factor pollution index of the heavy metal  $i$ ; and  $P_{max}$  is the maximum value of the single-factor pollution index of the heavy metal  $i$ . The classification of PI and PN is shown in Table 3.

### Assessment of potential ecological risk

The RI was proposed by Hakanson (1980) and is widely utilized to assess potential ecological risk, including heavy metal pollution risk. The index is defined as follows:

$$C_f^i = c_s^i/C_n^i$$

$$E_r^i = T_r^i C_f^i$$

$$RI = \sum_{i=1}^n E_r^i$$

where  $C_f^i$  is the pollution factor of the metal  $i$ ;  $c_s^i$  is the concentration of heavy metal in samples;  $C_n^i$  is the standard of the heavy metal  $i$  according to Chinese Soil Environmental Standard (pH 6.5-7.5) GB15618-1995 (Ministry of Ecology and Environment, 1995) and the corresponding standard values  $C_n^i$  for Hg, Pb, Cd, Cr, and As are 0.5, 300, 0.6, 300 and 25 mg/kg, respectively;  $E_r^i$  is the monomial potential ecological risk coefficient; and  $T_r^i$  is the metal toxic response factor (Hg = 40, Pb= 5, Cd=

**Table 2.** Classifications for geoaccumulation index ( $I_{geo}$ )

$I_{geo}$ value	Class	Class quality
$\leq 0$	0	Practically unpolluted
0-1	1	Unpolluted to moderately polluted
1-2	2	Moderately polluted
2-3	3	Moderately to heavily polluted
3-4	4	Heavily polluted
4-5	5	Heavily to extremely polluted
$>5$	6	Extremely polluted

**Table 3.** Classification for single-factor pollution index (PI) and Nemerow's synthetic pollution index (PN)

PI value	Contamination level	PN value	Contamination level
PI ≤ 1.0	No contamination	PN ≤ 0.7	Safety
1.0 < PI ≤ 2.0	Low level of contamination	0.7 < PN ≤ 1.0	Warning line of pollution
2.0 < PI ≤ 3.0	Moderate level of contamination	1.0 < PN ≤ 2.0	Slight pollution
3.0 < PI ≤ 5.0	Strong level of contamination	2.0 < PN ≤ 3.0	Moderate pollution
PI > 5.0	Very strong level of contamination	PN > 3.0	Heavy pollution

**Table 4.** Classification for monomial potential ecological risk coefficient ( $E_r^i$ ) and potential ecological risk index (RI)

$E_r^i$ value	RI value	Ecological risk value
$E_r^i \leq 40$	RI ≤ 150	Low
40 < $E_r^i \leq 80$	150 < RI ≤ 300	Moderate
80 < $E_r^i \leq 160$	300 < RI ≤ 600	Considerable
160 < $E_r^i \leq 320$	RI > 600	High
$E_r^i > 320$		Very high

**Table 5.** Heavy metal concentrations in sewage sludge from different sewage treatment plants (mg/kg)

Sample sites	Hg	Pb	Cd	Cr	As
W1	0.12±0.022	266.00±8.82	15.30±1.75	143.50±7.50	25.05±0.32
W2	0.33±0.045	73.30±2.14	0.04±0.01	102.40±4.44	24.60±0.77
W3	0.28±0.08	28.80±0.78	0.72±0.06	68.70±1.02	22.10±1.16
W4	0.27±0.04	58.65±2.21	1.35±0.11	65.85±4.81	5.17±0.19
W5	0.15±0.02	42.30±1.17	5.11±0.42	535.00±121.45	36.40±1.99
W6	0.15±0.02	25.55±3.39	4.80±0.40	84.00±1.95	35.15±4.31
W7	0.23±0.05	23.40±2.30	0.03±0.00	68.25±1.26	12.90±1.00
W8	0.60±0.08	48.20±2.17	0.47±0.03	81.50±6.08	16.00±0.54
Mean	0.27	70.78	3.48	143.65	22.17
SD	0.16	80.75	5.19	160.19	10.68
CV (%)	57.73	114.08	149.53	111.51	48.16
Class B <sup>[1]</sup>	15	1000	15	1000	75
Class A	3	300	3	500	30

<sup>[1]</sup> CJT 309-2009 (Ministry of Housing and Urban-Rural Development, 2009)

**Table 6.** Geoaccumulation index ( $I_{geo}$ ) for heavy metals in sewage sludge of eight sampling sites

Sample sites	Hg	Pb	Cd	Cr	As	Mean
W1	-0.58	2.84	5.75	0.70	0.66	1.87
W2	0.87	0.98	-2.83	0.21	0.63	-0.03
W3	0.64	-0.37	1.34	-0.37	0.48	0.34
W4	0.58	0.66	2.24	-0.43	-1.62	0.29
W5	-0.26	0.19	4.16	2.60	1.19	1.58
W6	-0.26	-0.54	4.07	-0.08	1.14	0.87
W7	-0.47	-0.67	-3.25	-0.37	-0.30	-1.01
W8	1.74	0.37	0.72	-0.12	0.01	0.54
Mean	0.28	0.43	1.53	0.27	0.27	0.56

30, Cr = 2 and As = 10). The classification of  $E_R^I$  and RI is displayed in Table 4.

### Statistical analysis

The relationships among five heavy metals were determined using the Pearson's correlation analysis. A principal component analysis (PCA) was used to reduce the dimensionality, and the highly correlated heavy metal elements were extracted into independent factors (Li *et al.*, 2013; Lu *et al.*, 2010).

## Results and discussion

### The concentration of heavy metals in sewage sludge

The measured concentrations of heavy metals are presented in Table 5. According to the mean concentration values, the corresponding order of heavy metals in sewage sludge samples was Cr > Pb > As > Cd > Hg. The variation coefficients of heavy metals were ranked in decreasing order as follows: Cd > Pb > Cr > Hg > As. Heavy metal content in the study area varied greatly among sewage treatment plants, which occurs probably because the sewage sludge samples were collected from different sites (Yang *et al.*, 2014). The maximum concentrations of the heavy metals of the eight sewage treatment plants did not exceed the permissible content limits in the discharge standards (Class B) of CJT 309-2009, except for Cd at W1. Cd exceeded the permissible content limits at this site probably because the W1 sewage treatment plant collects water from an industrial area. The above results are consistent with other Chinese studies (*e.g.*, Zhao *et al.*, 2019), which showed that the electronics industry is a pollution source for Cd.

### Three assessment methods of heavy metals contamination

#### *Geoaccumulation index values for heavy metals in sewage sludge*

The  $I_{geo}$  values for five heavy metals are presented in Table 6. The mean  $I_{geo}$  values for five heavy metals were in the following decreasing order: Cd > Pb > Cr = As > Hg. The pollution order of stations was W1 > W5 > W6 > W8 > W3 > W4 > W2 > W7.

The  $I_{geo}$  values were less than zero for Hg at sites W1, W5, W6 and W7; Pb at sites W3, W6 and W7; Cd at sites W2 and W7; Cr at sites W3, W4, W6, W7 and W8; and As at sites W4 and W7; these findings indicate that these sites were not polluted by these metals. The  $I_{geo}$  values were between 0 and 1 for Hg at sites W2, W3, W4 and W8; Pb at sites W2, W4, W5 and W8; Cd at site W8; Cr at sites W1 and W2; and As at sites W1, W2, W3 and W8; these findings indicate that the pollution level of these metals at these stations ranged from unpolluted to moderately polluted. The  $I_{geo}$  values were between 1 and 2 for Hg at site W8, Cd at site W3 and As at sites W5 and W6; and these findings indicate that the pollution levels of these metals at these stations were moderate. The  $I_{geo}$  values were between 2 and 3 for Pb at site W1, Cd at site W4 and Cr at site W5; these findings indicate that these metals at these stations were polluted at moderate to heavy levels. The  $I_{geo}$  values were higher than 3 for Cd at sites W1, W5 and W6, what indicates that the pollution level of Cd at these stations was heavy.

#### *Assessment of heavy metal pollution*

The PI values of heavy metals are presented in Table 7. According to the mean PI values, heavy metals were sorted in the following decreasing order: Cd > As > Cr > Pb > Hg. According to these results, the sewage sludge

**Table 7.** Single-factor pollution index (PI) and Nemerow's synthetic pollution index (PN) for heavy metals in sewage sludge of eight sampling sites

Sample sites	PI					PN
	Hg	Pb	Cd	Cr	As	
W1	0.04	0.89	5.10	0.29	0.84	3.62
W2	0.11	0.24	0.01	0.20	0.82	0.59
W3	0.09	0.10	0.24	0.14	0.74	0.53
W4	0.09	0.20	0.45	0.13	0.17	0.33
W5	0.05	0.14	1.70	1.07	1.21	1.28
W6	0.05	0.09	1.60	0.17	1.17	1.16
W7	0.04	0.08	0.01	0.14	0.43	0.31
W8	0.20	0.16	0.16	0.16	0.53	0.40
Mean	0.08	0.24	1.16	0.29	0.74	0.88

**Table 8.** Monomial potential ecological risk coefficient ( $E_r^i$ ) and potential ecological risk index (RI) for heavy metals in sewage sludge of eight sampling sites

Sample sites	$E_r^i$					RI
	Hg	Pb	Cd	Cr	As	
W1	9.60	4.43	765.00	0.96	10.02	790.01
W2	26.40	1.22	2.00	0.68	9.84	40.14
W3	22.40	0.48	36.00	0.46	8.84	68.18
W4	21.60	0.98	67.50	0.44	2.07	92.58
W5	12.00	0.71	255.50	3.57	14.56	286.33
W6	12.00	0.43	240.00	0.56	14.06	267.05
W7	18.40	0.39	1.50	0.46	5.16	25.91
W8	48.00	0.80	23.50	0.54	6.40	79.25
Mean	21.30	1.18	173.88	0.96	8.87	206.18

in the study area exhibited low pollution levels for most heavy metals except for Cd at sites W1, W5 and W6 and As at sites 5 and 6. According to the mean PN values, the heavy metals were sorted in the following decreasing order: W1 > W5 > W6 > W2 > W3 > W8 > W4 > W7. The PN values for sites W2, W3, W4, W7 and W8 were lower than 0.7, and the maximum concentrations of the heavy metals of five sampling sites did not exceed the permissible content limits in the discharge standards (Class B) of CJT 309-2009. This finding suggests that the sewage sludge in these sites was safe in terms of heavy metal discharged into the environment and could be directly used in agriculture. The PN values for sites W5 and W6 were between 1 and 2, and the value at W1 was higher than 3, indicating that sewage sludge at these sites had risk levels of heavy metals; therefore, heavy metal pollution should be considered when using sewage sludge from these sites for land treatments.

#### The potential ecological risk

The RI and  $E_r^i$  values for each studied site are shown in Table 8. The mean  $E_r^i$  value of five heavy metals decreased in the following order: Cd > Hg > As > Pb > Cr. The  $E_r^i$  values for Hg, Pb, Cr and As in all sampling sites were lower than 40 except for Hg at site W1, suggesting that these sites did not pose a potential ecological risk. The  $E_r^i$  values for Cd at sites W5 and W6 were between 160 and 320, and the value for Cd at site W8 was higher than 320,

suggesting that sewage sludge at these sites had high RI for Cd. W5 and W6 exhibited high risk, and W1 very high risk. The mean RI values for sites W2, W3, W4, W5, W7, and W8 were < 150, indicating that these sites had low RI. The RI values for sites W5 and W6 ranged from 150 to 300, indicating that these sites had moderate RI. For site W1, the RI values were > 600, indicating that this site had very high risk.

According to the results of  $I_{geo}$ , PI, PN, RI and  $E_r^i$  results show that the highest risk levels of heavy metal contamination in W1, W5 and W6 wastewater treatment plants, possibly may because W1 and W5 wastewater treatment plant is located near industrial area, and W6 sewage treatment plant is located in suburban areas, which is near steel wool, cement, textile and pharmaceutical manufacturing industries (Lin *et al.*, 2002). Such heavy metal contamination emitted from industries is also consistent with other regions in China, In Shanxi Province, Cd pollution might be caused by the rich coal resources, and the large number of coal industries (Duan *et al.*, 2017). In Guangzhou City, Cu and Cr pollution may be related to the industrial wastewater such as electroplating, chemical and machinery manufacturing industries (Li *et al.*, 2015).

#### Correlation coefficient

Table 9 displays the correlation coefficients as a linear correlation matrix. The results of the correlation analysis

**Table 9.** Pearson's correlation matrix for the metal concentrations in sewage sludge

	Hg	Pb	Cd	Cr	As
Hg	1				
Pb	-0.279*	1			
Cd	-0.550**	0.862**	1		
Cr	-0.341**	0.005	0.249*	1	
As	-0.440**	0.062	0.394**	0.555**	1

\*\*,\*: correlation is significant at the 0.01 level or 0.05 (2-tailed), respectively.

**Table 10.** Eigenvalues, variables and rotation of principal component analysis (PCA) for heavy metals in sewage sludge

Component	Initial eigenvalues			Rotation sums of squared loadings			Rotated component matrix		
	Total	of variance (%)	Cumulative (%)	Total	of variance (%)	Cumulative (%)	Variables	Total PC1	Component PC2
1	2.545	50.902	50.902	2.026	40.524	40.524	Hg	-	-0.596
								0.470	
2	1.385	27.706	78.608	1.904	38.084	78.608	Pb	0.960	-0.076
3	0.580	11.596	90.204				Cd	0.931	0.302
4	0.431	8.628	98.832				Cr	-	0.847
								0.022	
5	0.058	1.168	100.000				As	0.125	0.857

PC1, PC2: first and second principal component factor, respectively

suggested a low correlation occurred between Hg and Pb ( $r = -0.279$ ), Cd and Cr ( $r = 0.249$ ) at 0.05 level and between Hg and Cr ( $r = -0.341$ ), Hg and As ( $r = -0.440$ ) and Cd and As ( $r = 0.394$ ) at 0.01 level. Furthermore, high correlation was observed between Hg and Cd ( $r = -0.550$ ), Pb and Cd ( $r = 0.862$ ) and Cr and As ( $r = 0.555$ ) at 0.01 level.

The positive correlations among metals may reflect the fact that these metals had similar pollution levels, the same behavior during transport, and common sources or at least one major source (Suresh *et al.*, 2011). The negative correlation between Hg and Pb, Cd, Cr and As indicated that the adsorption capacity of Hg may be restrained because of the competitive adsorption of the other coexisting heavy metals in sediments (Zhang & Zheng, 2007).

### Factor analysis

PCA was performed to identify the probable sources between the heavy metals when they were interrelated (Mirzaei Aminiyan *et al.*, 2018). Table 10 depicts the factor loadings as well as the eigenvalues, percentile of variance, and cumulative percentages of the total loadings. According to Table 10, two principal components with eigenvalues of 2.15 and 1.39 were obtained, and they accounted for 78.61% of the total variance. The first principal component was dominated by Pb (0.96) and Cd (0.93) and accounted for 50.90% of the total variance. These observations show that Cd and Pb probably originated from a similar source. Previous studies (Kabata-Pendias & Mukherjee, 2007; Wei *et al.*, 2009; Al-Khashman, 2013; Zhang *et al.*, 2013) have reported that vehicle emissions, diesel fuel, and fossil fuel combustion are the primary sources of Cd and Pb pollution. Cd and its compounds are also known to originate from different manufactured products, such as paints, batteries, and electrical appliances (Mico *et al.*, 2006). Thus, the component loading of PC1

can be defined as traffic emissions and the manufacturing industry. The second principal component was dominated by As (0.86) and Cr (0.85), and it accounted for 27.70% of the total variance. Based on the correlation analysis, a highly positive correlation was observed between As and Cr, suggesting that they may share a common source. A previous study reported that the main fertilizer products in China contain Cr, As and other harmful metals (Feng *et al.*, 2009). Anhui is a major agricultural province, and the input of chemical pesticides and chemical fertilizers per unit area of cultivated land in Wuhu is well above the average level of Anhui Province of China as a whole. In addition, several studies (Yongming *et al.*, 2006; Sharma *et al.*, 2008; Duan & Tan, 2013) have reported that industrial and agricultural activities are major sources of As and Cr. In the study area, many industrial activities are observed, including cement and asphalt plants, a paperboard factory, a shipyard, sand mining operations, and electrical industries. Thus, the component loading of PC2 can be considered to be agriculture activities.

In summary, the maximum concentrations of the heavy metals in the eight sewage treatment plants did not exceed the permissible content limits in the discharge standards (Class B) of CJT 309-2009, except for Cd at W1. Based on the total concentration results and the  $I_{geo}$ , PI, PN, RI and  $E_r^I$  results described above, heavy metal pollution reached the highest contamination levels in the ecosystem for W1, W5 and W6 sewage sludge samples in the city of Wuhu. Pb at site W1, Cd at sites W5 and W6 and As at sites W5 and W6 were identified as the main contributors to metal pollution. Thus, measures should be taken to control these metals at these sampling sites. Cd exhibited the highest contamination level in the eight wastewater treatment plants, and the strongest ecological risk posed by Cd was primarily attributed to the fact that the toxicity coefficients of Cd were far higher than those of the other metals, although its concentration in the study area was relatively lower than those of the other metals. The correlation and

PCA suggest that Pb and Cd mainly derived from traffic emissions and the manufacturing industry and that As and Cr originated from agriculture discharge.

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