Science of the Total Environment 408 (2010) 726–733

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Health risk assessment of heavy metal exposure to street dust in the zinc smelting district, Northeast of China

Na Zheng [a,*], Jingshuang Liu [a], Qichao Wang [a], Zhongzhu Liang [b]

[a] Northeast Institute of Geography and Agricultural Ecology, Chinese Academy of Sciences, Changchun, Jilin 130012, China
[b] National Key Laboratory of Applied Optics, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun, Jilin 130033, China

ARTICLE INFO

Article history:
Received 12 March 2009
Received in revised form 22 October 2009
Accepted 27 October 2009
Available online 18 November 2009

Keywords:
Heavy metals
Street dust
Huludao city
Atmospheric deposition
Health risk

ABSTRACT

Heavy metal contamination in the street dust due to metal smelting in the industrial district of Huludao city was investigated. Spatial distribution of Hg, Pb, Cd, Zn and Cu in the street dust was elucidated. Meanwhile, noncancer effect and cancer effect of children and adults due to exposure to the street dust were estimated. The maximum Hg, Pb, Cd, Zn and Cu contents in the street dust are 5.212, 3903, 726.2, 79,869, and 1532 mg kg^{-1}, and respectively 141, 181, 6724, 1257 and 77.4 times as high as the background values in soil. The trends for Hg, Pb, Cd, Zn and Cu are similar with higher concentrations trending Huludao zinc plant (HZP). The exponential equation fits quite well for the variations of Pb, Cd, Zn and Cu contents with distance from the pollution sources, but not for Hg. The biggest contribution to street dust is atmospheric deposition due to metal smelting, but traffic density makes slight contribution to heavy metal contamination. According to the calculation on Hazard Index (HI), in the case of noncancer effect, the ingestion of dust particles of children and adults in Huludao city appears to be the route of exposure to street dust that results in a higher risk for heavy metals, followed by dermal contact. The inhalation of resuspended particles through the mouth and nose is almost negligible. The inhalation of Hg vapour as the fourth exposure pathway to street dust is accounting for the main exposure. Children are experiencing the potential health risk due to HI for Pb larger than safe level (1) and Cd close to 1. Besides, cancer risk of Cd due to inhalation exposure is low.

1. Introduction

Heavy metals may come from many different sources in urbanized areas, including vehicle emissions, industrial discharges and other activities (Harrison et al., 1981; Gibson and Farmer, 1986; Thornton, 1991). Metal smelting is regarded as one of the most important anthropogenic heavy metal emission sources (Niragu and Pacyna, 1988). During smelting process, heavy metals in the ores are evaporated from the matrix, and eventually go into the atmosphere, if no pollution control technology is applied (Pacyna and Pacyna, 2002). Huludao city was an industrial base in Liaoning province, northeast of China. Some domestic large industrial corporations, such as Huludao zinc plant (HZP) and Jinxi petroleum chemical factory (JPCF), were centralized in the industrial area (Longgang District and Lianshan District) of Huludao. HZP was the largest zinc plant in Asia. Metal smelting activities at HZP had seriously contaminated soil, water and atmosphere (Zheng et al., 2007a,b).

Street dust in urban area is an indicator of heavy metal contamination from atmospheric deposition (Li et al., 2001). Street dust makes a significant contribution to the pollution in the urban environment (Arslan, 2001; Al-Khashman, 2004). Heavy metals can accumulate in street dust from atmospheric deposition by sedimentation interception and may affect population health if they reach a level of being considered as toxic pollutants (Ferreira-Baptista and De Miguel, 2005). With the increase of population, the tightly packed buildings limit air circulation, leading to increases of heavy metal accumulations in the street dust (Madany et al., 1994). Street dust contaminated by heavy metals poses higher health risk to children and adults than that of automobile emissions.

Health risk is especially high for children because of their low tolerance to toxins as well as the inadvertent ingestion of significant quantities of dust (or soils) through hand-to-mouth pathways (Ljung et al., 2005; Acosta et al., 2009). Besides, many residential buildings in China were close to streets. The inhabitants are frequently exposed to street dust. Pollutant metals are usually non-degradable and there is no known homeostasis mechanism for them. Thus, any high levels of heavy metals will threaten biological life (Tong and Lam, 2000). They may accumulate in the fatty tissues of our body and affect our central nervous system, or they may be deposited in our circulatory system and disrupt the normal functioning of our internal organs, or they may act as cofactors in other diseases (Nriagu, 1988). Therefore, it is important to identify the origin and distribution of heavy metals in street dust, and estimate population heavy metal exposure via street dust in smelting district. There were many recent investigations on

---

[*] Corresponding author. Weishan Road 3195#, Changchun City, China, 130012. Tel.: +86 431 85542232 (o); fax: +86 431 85542298.
E-mail addresses: zhengnalzz@hotmail.com, zhengnalzz@neigae.ac.cn (N. Zheng).

0048-9697/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.scitotenv.2009.10.075

heavy metals in street dust reported in developed countries (Madany et al., 1994; Arslan, 2001; Sezgin et al., 2003; Ahmed and Ishiga, 2006; Hogervorst et al., 2007; Hur et al., 2007), but few had been done in China, especially in the smelting district.

The objectives of the present study were to determine the spatial distributions of Hg, Pb, Cd, Zn and Cu in the street dust in Huludao city; and to estimate population health risk due to heavy metal exposure to street dust according to Hazard Indexes (HIs) and cancer risk.

2. Materials and methods

2.1. The site of investigation — Huludao city, China

Huludao city (40°56′N, 120°28′E) is in Liaoning province in the northeast of China (Fig. 1). The climate of Huludao is a typical continental monsoon with an annual average temperature of 8.7 °C and an average annual rainfall of 590 mm. The primary wind direction is from northeast to southwest. The industrial district spans over 180 km^2 with the urban population of approximately 200,000 in 2007. HZP is situated at the southeast of Huludao city, near Liaodong Gulf (Fig. 1). During smelting process, Hg, Pb, Cd, Zn and Cu are emitted into the environment in large quantities through atmospheric deposition, solid waste emissions, sludge applications, and wastewater irrigation. About 260 t of mercury was emitted into the atmosphere from HZP in the decade from 1980 to 1990 (Dong, 1988). The industrial area of Huludao was selected in the present study to investigate heavy metal contamination.

2.2. Sample collection

The sampling grid is shown in Fig. 1, and 35 street dust sampling sites around the main streets were selected in Huludao city, including heavy and low traffic density areas, commercial areas, and residential districts. Sampling was undertaken over three consecutive days, in the summer after a dry spell of weather. Approximately 500 g street dust composite samples were collected using polyethylene brush on impervious surface (road, pavement, and gutter) within a 1-m^2 radius circles around each sampling site. All collected dust samples were stored in sealed polyethylene bags, labeled and then transported to the laboratory.

2.3. Preparation for the analysis

Street dust is operationally defined in this study as the particles of outdoor urban material with diameters below 100 µm. They are easily resuspended and can be inhaled through the nose or mouth during breathing (as opposed to bigger particles which move mainly by “saltation” and “creep”) (Nicholson, 1988; Sehmel, 1980; De Miguel et al., 2007). The equations used as sampling criteria for the inhalable fraction (IF) of particulate matter are applicable up to aerodynamic diameters less than or equal to 100 µm. There is evidence that the size range of inhalable particles with systemic toxicity that could pose a health risk should be extended even further (Kennedy and Hinds, 2002).

All the samples were dried at room temperature for 5 days, and then sieved through a 1.0 mm mesh nylon sieve to remove refuse and small stones. After samples were carefully homogenized and sieved through 100 µm, and the fraction below 100 µm was reduced by repeated quartering until a 0.5 g sample was obtained. 0.25 g dust samples were digested using the method of H_2SO_4-HNO_3-V_2O_5 (GB/T 17136-1997) in order to determine the concentration of total Hg in samples and blanks by cold vapour AAS. Another 0.25 g samples were digested using the method of $HClO_4$-HNO_3-HF (GB/T 17138, 17141-1997) to determine Pb, Cd, Zn and Cu concentrations by inductively coupled plasma mass spectroscopy, ICP-MS (Thermo Fisher). The accuracy and precision of the analytical method (accuracies within ±10%) was estimated by analyzing a soil Standard Reference Material (GBW 07405(GSS-5)).

2.4. Risk assessment model

Residential exposure of heavy metals to the street dust can occur via three main paths: (a) direct ingestion of substrate particles (D_{ing}); (b) inhalation of resuspended particles through mouth and nose (D_{inh}); and (c) dermal absorption of trace elements in particles adhered to exposed skin (D_{dermal}), or through inhalation of vapours (D_{vapour}). The dose received through each of the three paths was calculated using Eqs. (1)–(3) (USEPA, 1996, 1989). Hg exposure can also occur via inhalation of vapour, which can be expressed by Eq. (4). For carcinogens, the lifetime average daily dose (LADD) for Cd inhalation exposure route was used in the assessment of cancer risk (USEPA, 1996, 2001).

$$D_{\text{ing}} = C \times \frac{IngR \times EF \times ED}{BW \times AT} \times 10^{-6} \tag{1}$$

$$D_{\text{inh}} = C \times \frac{InhR \times EF \times ED}{PEF \times BW \times AT} \tag{2}$$

$$D_{\text{dermal}} = C \times \frac{SL \times SA \times ABS \times EF \times ED}{BW \times AT} \times 10^{-6} \tag{3}$$

$$D_{\text{vapour}} = C \times \frac{InhR \times EF \times ED}{VF \times BW \times AT} \tag{4}$$

$$LADD = \frac{C \times EF}{AT \times PEF} \times \left(\frac{InhR_{\text{child}} \times ED_{\text{child}}}{BW_{\text{child}}} + \frac{InhR_{\text{adult}} \times ED_{\text{adult}}}{BW_{\text{adult}}} \right). \tag{5}$$

IngR: ingestion rate, in this study, 200 mg day^{-1} for children and 100 mg day^{-1} for adults (USEPA, 2001). InhR: inhalation rate, in this study, 7.6 m^3 day^{-1} for children and 20 m^3 day^{-1} for adults (Van den Berg, 1995). EF: exposure frequency, in this study, 180 day year^{-1} (Ferreira-Baptista and De Miguel, 2005). ED: exposure duration, in this study, 6 years for children and 24 years for adults (USEPA, 2001). SA: exposed skin area; in this study, 2800 cm^2 for children and 5700 cm^2 for adults (USEPA, 2001). SL: skin adherence factor, in this study, 0.2 mg cm^{-2} h^{-1} for children and 0.7 mg cm^{-2} h^{-1} for adults (USEPA, 2001). ABS: dermal absorption factor (unitless), in this study, 0.001 for all elements. PEF: particle emission factor, in this study, 1.36×10^9 m^3 kg^{-1} (USEPA, 2001). VF: volatilization factor, in this study, for elemental Hg, 32675.6 m^3 kg^{-1} (USEPA, 2001). BW: average body weight; in this study, 15 kg for children and 70 kg for adults (USEPA, 1989). AT: averaging time; for non-carcinogens, ED × 365 days; for carcinogens, $70 \times 365 = 25{,}550$ days.

C (exposure-point concentration, mg/kg) in Eqs. (1)–(5), combined with the values for the exposure factors shown above, is considered to yield an estimate of the “reasonable maximum exposure” (USEPA, 1989), which is the upper limit of the 95% confidence interval for the mean. Since the concentration of most elements in the street dust samples has an approximate log-normal distribution, the 95% upper confidence limit (UCL) was calculated as shown in Eq. (6) (USEPA, 1996). Calculation of the exposure-point concentration term for log-transformed data:

$$C_{95\%\ \text{UCL}} = \exp\left\{ \overline{X} + 0.5 \times s^2 + \frac{s \times H}{\sqrt{n-1}} \right\} \tag{6}$$

where $\overline{X}$ is the arithmetic mean of the log-transformed data, s the standard deviation of the log-transformed data, H the H-statistic (Gilbert, 1987) and n the number of samples.

According to EPA's guideline on risk assessment, we have separate discussions for carcinogenic and noncarcinogenic effects because the methods used are different for these two modes of chemical toxicity.

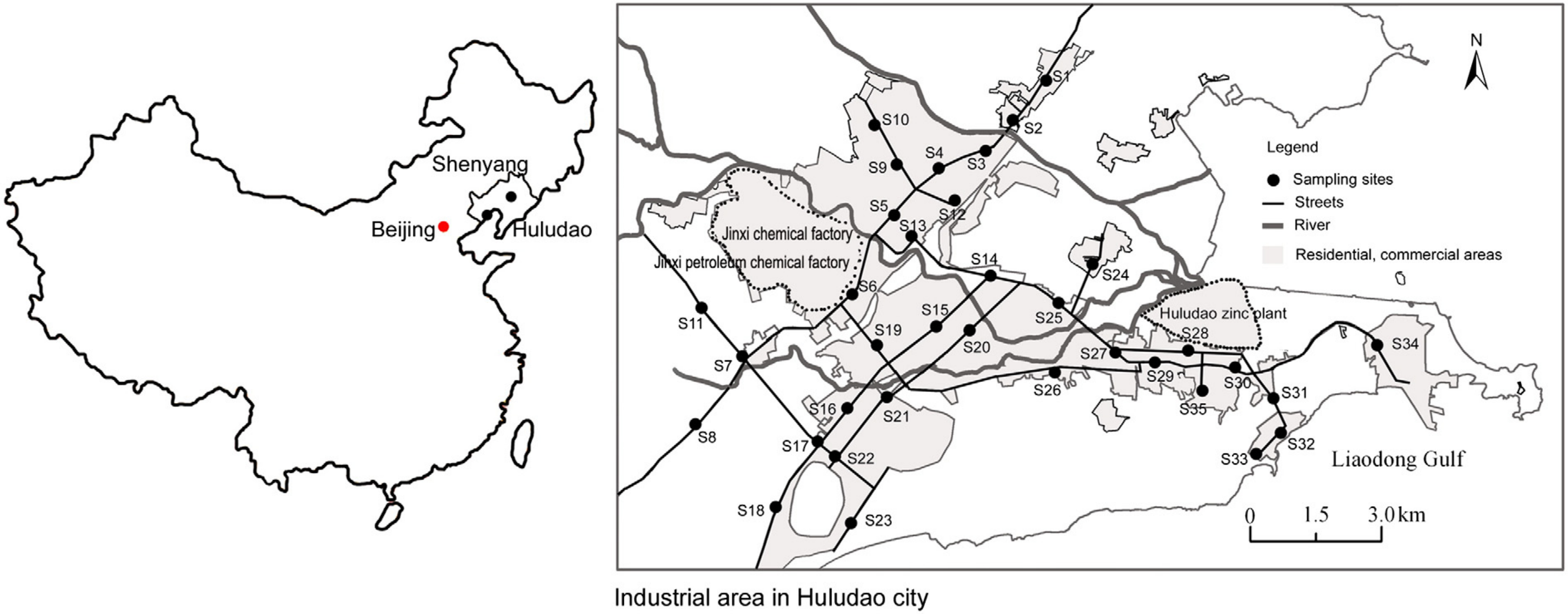

Fig. 1. Location map of study area.

Table 1
Heavy metals in street dust from industrial area of Huludao City (mg kg^{-1}).

Ions	Mean	Median	Min	Max	StDev	Skewness	Kurtosis	Background in soil*	EF
Hg	1.222	0.612	0.119	5.212	1.40	1.585	1.631	0.037	33.1
Pb	533.2	235.4	96.71	3903	815.4	3.374	11.58	21.6	24.7
Cd	72.84	19.72	5.559	726.2	159.9	3.482	11.84	0.108	674
Zn	5271	1374	517.8	79869	13403	5.034	27.49	63.5	83
Cu	264.4	161.6	58.02	1532	286.3	2.985	10.23	19.8	13.3

* China National Environmental Monitoring Center.

In this study, quantified risk or Hazard Indexes for both carcinogenic and noncarcinogenic effects was applied to each exposure pathway in the analysis. The doses thus calculated for each element and exposure pathway are subsequently divided by the corresponding reference dose to yield a hazard quotient (HQ), whereas for carcinogens the dose is multiplied by the corresponding slope factor to produce an estimate of cancer risk. Hazard index (HI) is equal to the sum of HQ. The approach assumes that the magnitude of the adverse effect is proportional to the sum of the ratios of the simultaneous subthreshold exposure to acceptable exposure for each chemical (US Environmental Protection Agency, 1989). If the value of HI is less than one, it is believed that there is no significant risk of non-carcinogenic effects. If HI exceeds one, then there is a chance that non-carcinogenic effects may occur, with a probability which tends to increase as the value of HI increases (USEPA, 2001). In this study, Hazard Index methods and cancer risk methods were used to assess population health risk of heavy metal exposure to street dust in Huludao city.

3. Results and discussion

3.1. Heavy metals in street dust

3.1.1. Heavy metal contents in street dust

All heavy metal contents in street dust have approximately log-normal distributions. Their concentrations are listed in Table 1. The maximum Hg, Pb, Cd, Zn and Cu concentrations in the street dust, which occur near HZP, are respectively 5.212, 3903, 726.2, 79,869, and 1532 mg kg^{-1}, and they are 141, 181, 6724, 1257 and 77.4 times as high as the background values in soil (China National Environmental Monitoring Center, 1990). In relative term, Cd is the biggest contributor to heavy metal contamination. Although the absolute heavy metal concentrations in the street dust decrease in the order of Zn>Pb>Cu>Cd>Hg, the enrichment factors (EF, i.e., the ratio of current to background concentration) of heavy metals decrease in the order of Cd>Zn>Hg>Pb>Cu. The average contents of heavy metals in the street dust were higher than those of other cities which were affected by traffic density and population, but similar to those of cities contaminated by zinc smelting (Table 2).

3.1.2. Spatial distribution of heavy metals in street dust

Spatial distributions of heavy metal concentrations in the street dust in Huludao city were separately shown (Fig. 2). The trends for Pb, Cd, Zn, and Cu are similar with higher concentrations near HZP. Pb, Cd, Zn, and Cu contents in street dust correlate linearly with each other (Table 3). We believe that heavy metal emission from HZP is the main source of heavy metal contamination in Huludao city.

Only part of the Hg spatial distribution is similar to that for other heavy metals of Pb, Cd, Zn, and Cu. This suggests that, besides HZP, there are other pollution sources which give relatively large contributions of Hg to the street dust. We know that Wuli River through Huludao was contaminated by Hg from chlor-alkali production prior to 1998, when the use of mercury cathodes was terminated. As a result, the soil along Wuli River had been contaminated by Hg (Zheng et al., 2007a,b). It is generally accepted that the two main sources of street dust, and consequently of the trace elements found therein, are deposition of previously suspended particles (atmosphere aerosol) and displaced urban soil (Ferreira-Baptista and De Miguel, 2005; Han et al., 2007). Soil particles is easily resuspended back into the atmosphere aerosol, to which it contributes a significant amount of trace elements (Maxwell and Nelson, 1978), or precipitation washes it away, becoming an important component of the suspended and dissolved solids in street run-off and in receiving water bodies (Vermette et al., 1991). Therefore, the contaminated soil is an important Hg pollution source to street dust in S14 and S25 sampling sites. Meanwhile, the street around Longbei Mountain (at site S18) is the third hot spot for Hg due to its hypsography.

Pb, Cd, Zn, and Cu concentrations in the street dust decrease with distance from HZP. Feng et al. (2006) used an exponential equation to fit such spatial variation of heavy metal contents. We have also used exponential equation to fit the spatial variations of heavy metal concentrations with the distance as shown in Fig. 3. The curves and the parameter were listed in Table 4, respectively. The fits to Pb, Cd, Zn and Cu concentrations with distance from the pollution source are relatively good, but not for Hg. The Pb, Cd, Zn, Cu contents decrease exponentially with distance from HZP, and drop rapidly within 2 km. It further proves that atmospheric deposit is the main source of heavy metals in the street dust. Hg, on the other hand, has multiple sources which make contributions to street dust.

Table 2
Heavy metal contents in street dust of different cities (mg kg^{-1}).

Location	Factor	Hg	Pb	Cd	Zn	Cu	Literature
Huludao, China	Zinc smelting	1.222	533	72.84	5271	264	In this study
He Zhang, China (soil)	Zinc smelting	–	9000	43	11,000	–	Bi et al. (2006)
Shenyang, China	Traffic density	–	106	4.35	334	81.3	Li et al. (2008)
Dhaka, Bangladesh	Traffic density	–	54	–	169	105	Ahmed and Ishiga (2006)
Birmingham, UK	Traffic density	–	48.0	1.62	534	466	Charlesworth et al. (2003)
Oslo	Traffic density	–	180	1.4	412	123	De Miguel et al. (1997)
Kara Industrial Estate, Jordan	Industrial pollution	–	11.2	–	13.1	11.3	Al-Khashman (2004)

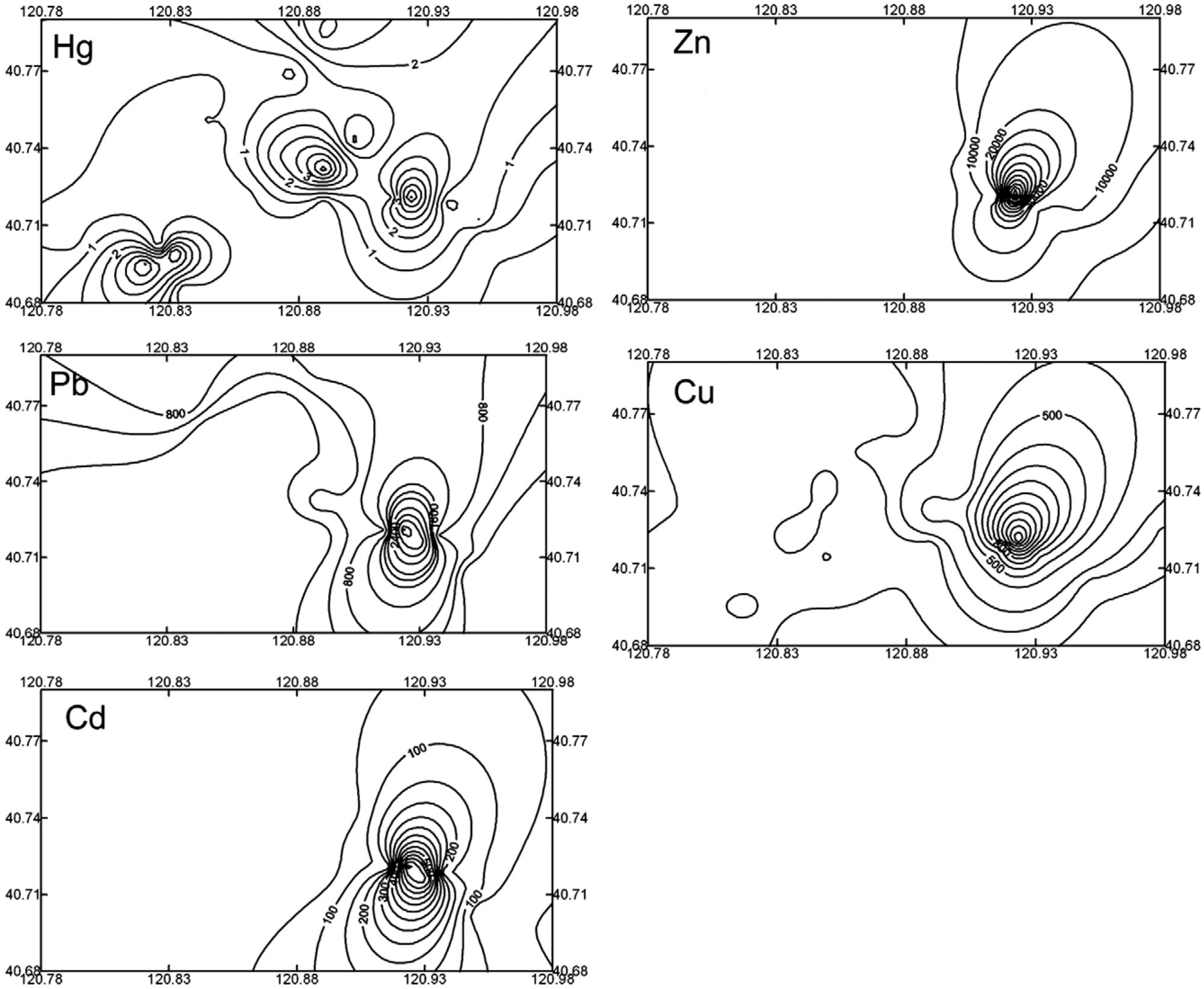

Fig. 2. Heavy metals spatial distribution in street and staircase dust (mg kg^{-1}).

3.1.3. Heavy metal contamination in different use scenarios

The geometrical means of heavy metal contents in the street dust of different use scenarios were calculated (Table 5). HZP appears to the most seriously contaminated site, followed by service station. But each heavy metal in street dust of other sites is in the same order of magnitude, significantly lower than that of HZP and service station. Pb, Cd and Zn contents near HZP are 10 times as high as other sampling sites, and 3–5 times for Hg and Cu. Except sites near HZP, heavy metal contents in the street dust from other sites are much higher than those of other cities, such as Shenyang. Huludao city is near Shenyang city (Fig. 1), and they have similar climate characteristics and geographical location. The main roads of Shenyang city are marked by high traffic and heavy commercial vehicles subjected to frequent stop-and-go situations (Ren et al., 2006). Moreover, the population of Shenyang city is higher than Huludao city. However, heavy metal contents in the street dust of Huludao city are significantly higher than those of Shenyang city, even excluding the data near HZP. This suggests that the major contribution to street dust in Huludao city is from atmospheric deposition originated from HZP, and traffic density and population make relatively insignificant contributions to the overall heavy metal contamination.

Table 3
Correlation coefficients between heavy metals in street dust.

	Hg	Pb	Cd	Zn	Cu
Hg	1	0.625	0.566	0.537	0.603
Pb		1	0.869	0.809	0.825
Cd			1	0.828	0.810
Zn				1	0.965
Cu					1

Significance to 0.01%, $n = 38$.

Piron-Frenet et al. (1994) found a correlation between traffic density and heavy metal deposited in roadside soil. Moreover, there was a relationship between population and heavy metal contents in the street dust (Charlesworth et al., 2003). In fact, this is not the case for Huludao, where the mean concentrations of heavy metals in the street dust are much higher than those of other cities with similar size of population (Tables 2 and 5). Moreover, there seems to be no obvious correlation between traffic density and heavy metals contents for the street dust. In smelting district, heavy metal contamination in the street dust due to smelting activities poses much higher risk than that from the automobiles.

3.2. Health risk assessment of heavy metal exposure to street dust

The relative toxicity values used in the analysis were taken from the US Department of Energy's RAIS compilation (U.S. Department of

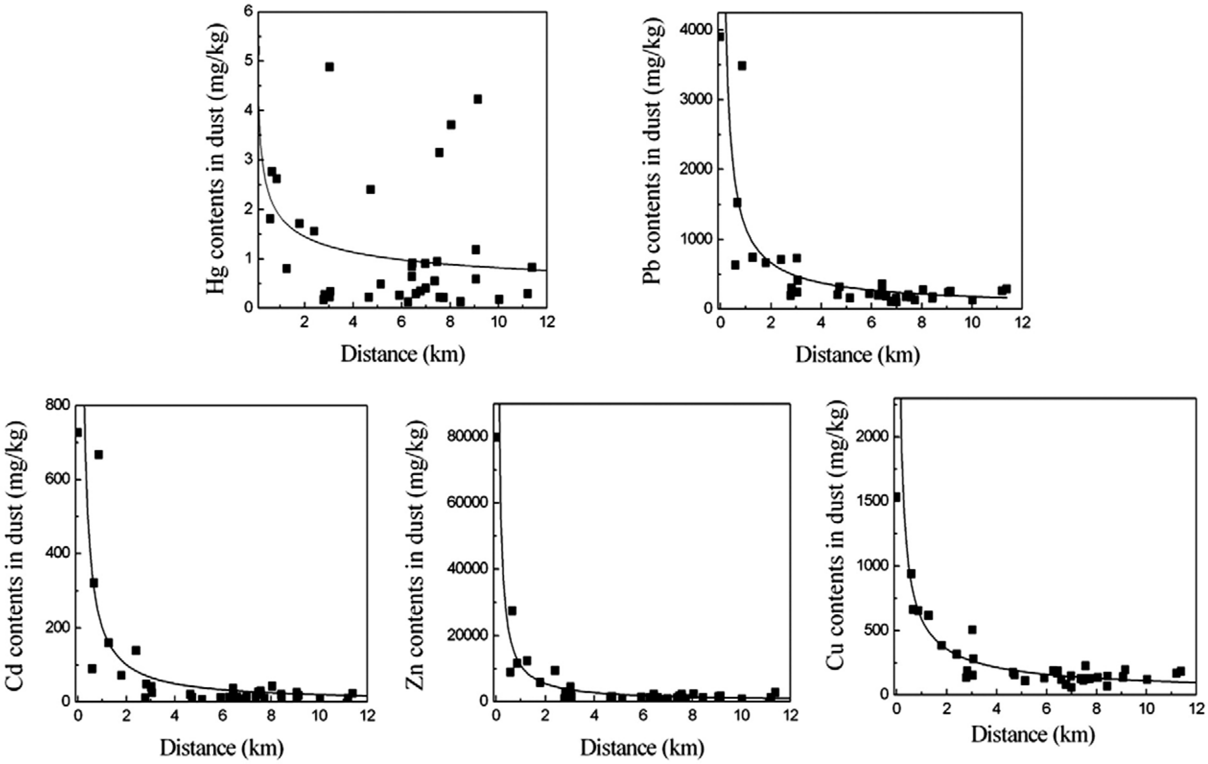

Fig. 3. Exponential variety of heavy metal contents with distance.

Energy, 2004). Reference doses for Pb have been taken from the WHO's (1993) Guidelines for Drinking Water Quality. Intake rates and particle emission and volatilization factors for street dust can be approximated by those developed for soil. Inhalation-specific toxicity data are available only for Cd. For the other four elements included in the risk analysis, the toxicity values considered for the inhalation route are the corresponding oral reference doses and slope factors, with the assumption that, after inhalation, the absorption of the particle-bound toxicants will result in similar health effects as if the particles had been ingested (Van den Berg, 1995; Naturvårdsverket, 1996; De Miguel et al., 2007).

Table 4
Estimated exponential equation of heavy metals in street dust.

Heavy metals	$y = a\,x^{b}$	R^2	Sampling number
Hg	$y = 1.8615x^{-0.3561}$	0.0798	35
Pb	$y = 1169x^{-0.8171}$	0.4672	35
Cd	$y = 203.7x^{-1.0151}$	0.4675	35
Zn	$y = 11089x^{-1.0117}$	0.6938	35
Cu	$y = 592.1x^{-0.7299}$	0.8623	35

For noncancer effect, in the case for children, ingestion of dust particles appears to be the route of exposure to street dust that results in a health risk for Pb, Cd, Zn and Cu, followed by dermal contact (Table 6). Similar results were obtained by Ferreira-Baptista and De Miguel (2005) in a study of exposure to heavy metals in street dust. HQ (noncancer risk) due to inhalation of dust particles is 2–4 orders of magnitude lower than the other two exposure pathways, and it is unlikely that this exposure route would pose a higher risk than ingestion. Therefore, inhalation of resuspended particles through the mouth and nose is almost negligible compared with the other routes of exposure. However, inhalation of Hg vapour as the fourth exposure pathway to street dust is significant, accounting for the main exposure in the street dust of Huludao city.

HIs for Hg, Pb, Cd, Zn and Cu to children decrease in the order of Pb>Cd>Hg>Zn>Cu. Regarding noncancer effects, Pb exhibit Hazard Indexes larger than safe level (1), which if contacted by children in large enough doses can trigger neurological and developmental disorders (Ferreira-Baptista and De Miguel, 2005). The children in Huludao city are also experiencing the potential health risk from Pb exposure from street dust. Though, HI for Cd (0.6) is lower than the safe level (1), Cd is a cumulative toxic metal and the kidney is the main target for Cd toxicity (De Burbure et al., 2003). So Cd exposure to the street dust in Huludao

Table 5
Heavy metal contents in different use scenarios.

Location	Hg	Pb	Cd	Zn	Cu
HZP	2.011 (1.530)[a]	1156 (1252)	176.6 (250.0)	15714 (28289)	729.1 (399.6)
Shopping center	0.797 (0.812)	188.2 (72.85)	12.68 (7.559)	1148 (362.5)	141.6 (29.50)
Residential area	0.358 (0.153)	196.7 (98.71)	29.52 (18.80)	1650 (1267)	136.4 (81.25)
Schools	0.709 (1.661)	257.0 (270.9)	19.41 (47.09)	1579 (3217)	163.3 (155.8)
Service station	1.143 (0.889)	890.6 (125.3)	28.92 (15.23)	2093 (532.1)	224.4 (112.1)
Suburb	0.242 (0.290)	214.3 (56.58)	17.80 (11.26)	1490 (732.7)	135.0 (44.29)

[a] Geometrical mean (standard deviation).

Table 6
Hazard quotient and risk for each element and exposure pathway.

mg/kg	Hg	Pb	Cd noncanc.	Cd canc.	Zn	Cu
C (95% UCL)	1.628	565.91	73.19	73.19	4966	286.3
Oral RfD	3.00E−04	3.50E−03	1.00E−03		3.00E−01	4.00E−02
Dermal RfD	2.10E−05	5.25E−04	1.00E−05		6.00E−02	1.20E−02
Inhal. RfD	8.57E−05					
Inhale. SF				6.3E+00		
Child						
HQ_{ing}	3.57E−02	1.06E+00	4.81E−01		1.09E−01	4.71E−02
HQ_{inh}	9.97E−07	2.97E−05	1.34E−05	2.36E−08	3.04E−06	1.31E−06
HQ_{dermal}	1.43E−03	1.98E−02	1.35E−01		1.52E−03	4.39E−04
HQ_{vapour}	1.45E−01					
$HI=\sum HQ_i$	1.82E−01	1.08E+00	6.16E−01		1.11E−01	4.75E−02
Cancer risk				2.36E−08		
Adult						
HQ_{ing}	3.82E−03	1.14E−01	5.16E−02		1.17E−02	5.04E−03
HQ_{inh}	5.62E−07	1.68E−05	7.58E−06	2.36E−08	1.72E−06	7.41E−07
HQ_{dermal}	2.18E−03	3.03E−02	2.06E−01		2.33E−03	6.71E−04
HQ_{vapour}	8.19E−02					
$HI=\sum HQ_i$	8.79E−02	1.44E−01	2.58E−01		1.40E−02	5.71E−03
Cancer risk				2.36E−08		

cannot be overlooked, and its ecological and health implications need further detailed investigations. Hg and Zn show HI larger than 0.1. Hg is the only element for which inhalation (of vapours) seems to pose the highest risk due to significant vapour pressure of Hg at ambient temperature (Meza-Figueroa et al., 2007). Moreover, especially high exposures to inorganic mercury may result in damage to the gastrointestinal tract, the nervous system, and the kidneys (Ye et al., 2009; Cheng et al., 2009). The potential health risk from Cu is the least. The most sensitive subpopulation is the young children, because of their hand-to-mouth activity, whereby contaminated dust can be readily ingested (Meza-Figueroa et al., 2007). Therefore, the exposure of the street dust to children could exhibit more potential health risk.

Compared to children, adult health risk due to heavy metal exposure from street dust is lower. The ingestion of dust particles appears to be the route of exposure to street dust that results in a health risk for Hg, Pb, Zn and Cu, followed by dermal contact. But HI for Cd through ingestion of dust particles is lower than dermal contact. Moreover, adult health risk due to dermal contact as the route of exposure to street dust is higher than children. HIs for Hg, Pb, Cd, Zn and Cu to adults decrease in the order of Cd>Pb>Hg>Zn>Cu. Pb and Cd exhibit HI larger than 0.1, and Cd potential health risk is higher than Pb. HIs for Hg, Pb, Cd, Zn and Cu on street dust exposure to adults in Huludao city are lower than 1, indicating that there is little adverse health risk due to street dust. However, heavy metals could be accumulated in body for a long time, and especially the noncancer adverse effects of Cd, Pb and Hg to the tissues of adults are quite serious.

For cancer risk, the only carcinogen risk for inhalation exposure modes was considered in the model, and the aggregate risk is calculated by Eq. (6). In Huludao city, cancer risk of Cd due to street dust exposure is low.

4. Conclusions

Thirty-five street dust sampling sites were selected to investigate heavy metals in the street dust contamination due to metal smelting in the industrial district of Huludao city. Spatial distributions of Hg, Pb, Cd, Zn and Cu in the street dust in Huludao city were elucidated. The trends for Hg, Pb, Cd, Zn, and Cu are similar with higher concentrations trending HZP. The exponential equation fits quite well for the variations of Pb, Cd, Zn and Cu contents with distance pollution sources, but not for Hg. The atmospheric deposition due to metals smelting from HZP is the main source of pollution to the street dust. Traffic density and population make slight contribution to heavy metal contamination.

The risk assessment to population exposure to street dust in the industrial area of Huludao city is affected by a significant degree of uncertainty. Now, in developing countries, especially, in China, reports and investigations on the estimates of toxicity values and exposure parameters are scanty. In order to estimate the health risk clearly, there is a need for further research of street dust exposure parameters and transport factors that would help reduce the uncertainties associated with the risk calculations. In Huludao city, the exposure pathway which results in the highest levels of risk for children and adults exposed to street dust is ingestion, and Pb and Cd are regarded as the most possible culprits to health risks.

Acknowledgements

The authors would like to acknowledge the support of the National Natural Science Foundation of China (No. 40803021), the Science Innovation Program of the Chinese Academy of Sciences (No. KZCX2-YW-QN306 and KZCX2-YW-309), President Award Science Foundation of Chinese Academy of Sciences (No. 08B3061) and Youth Doctor Foundation of Northeast Institute of Geography and Agricultural Ecology (No. 08H2101). We would like to thank Prof. Keh-Jim Dunn for his help to this paper.

References

Acosta JA, Cano AF, Arocena JM, Debela F, Martínez- Martínez S. Distribution of metals in soil particle size fractions and its implication to risk assessment of playground in Murcia City (Spain). Geoderma 2009;149:101–9.

Ahmed F, Ishiga H. Trace metal concentrations in street dusts of Dhaka city, Bangladesh. Atmos Environ 2006;40:3835–44.

Al-Khashman OA. Heavy metal distribution in dust, street dust and soils from the work place in Karak Industrial Estate, Jordan. Atmos Environ 2004;38:6803–12.

Arslan H. Heavy metals in street dust in Bursa, Turkey. J Trace Microprobe Tech 2001;19:439–45.

Bi X, Feng X, Yang Y, Qiu G, Li G, Li F, et al. Environmental contamination of heavy metals from zinc smelting areas in Hezhang county, western Guizhou, China. Environ Int 2006;32:883–90.

Charlesworth S, Everett M, McCarthy R, Ordóñez A, De Miguel E. A comparative study of heavy metal concentration and distribution in deposited street dusts in a large and a small urban area: Birmingham and Coventry, West Midlands, UK. Environ Int 2003;29:563–73.

Cheng JP, Gao LL, Zhao WC, Liu XJ, Sakamoto M, Wang WH. Mercury levels in fisherman and their household members in Zhoushan, China: impact of public health. Sci Total Environ 2009;407:2625–30.

China National Environmental Monitoring Center. Soil element background value in China. Beijing: China Environmental Science Press; 1990. p. 329. in Chinese.

De Burbure C, Buchet JP, Bernard A, Leroyer A, Nisse C, Haguenoer JM, et al. Biomarkers of renal effects in children and adults with low environmental exposure to heavy metals. J Toxicol Environ Health 2003;66:783–98.

De Miguel E, Llamas JF, Chacon E, Berg T, Larssen S, Royset O, et al. Origin and patterns of distribution of trace elements in street dust: unleaded petrol and urban lead. Atmos Environ 1997;31:2733–40.

De Miguel E, Iribarren I, Chacón E, Ordoňez A, Charlesworth S. Risk-based evaluation of the exposure of children to trace elements in playgrounds in Madrid (Spain). Chemosphere 2007;66:505–13.

Dong F. Hg removing from a zinc roaster acid plant. Vitriolic Acid Ind 1988;5:18–22 in Chinese.

Feng XB, Li GH, Qiu GL. A preliminary study on mercury contamination to the environment from artisanal zinc smelting using indigenous methods in Hezhang County, Guizhou, China: Part 2. Mercury contaminations to soil and crop. Sci Total Environ 2006;368:47–55.

Ferreira-Baptista L, De Miguel E. Geochemistry and risk assessment of street dust in Luanda, Angola: a tropical urban environment. Atmos Environ 2005;38:4501–12.

Gibson MG, Farmer JG. Multi-step chemical extraction of heavy metals from urban soils. Environ Pollut 1986;B 11:117–35.

Gilbert RO. Statistical Methods for Environmental Pollution Monitoring. New York: Van Nostrand Reinhold; 1987. p. 177–85.

Han L, Zhuang G, Cheng S, Wang Y, Li J. Characteristics of re-suspended road dust and its impact on the atmospheric environment in Beijing. Atmos Environ 2007;41:7485–99.

Harrison RM, Laxen DPH, Wilson SJ. Chemical association of lead, cadmium, copper, and zinc in street dust and roadside soil. Environ Sci Tech 1981;15:1378–83.

Hogervorst J, Plusquin M, Vangronsveld J, Nawrot T, Cuypers A, Hecke EV, et al. House dust as possible route of environmental exposure to cadmium and lead in the adult general population. Environ Res 2007;103:30–7.

Hur SD, Cunde X, Hong S, Barbante C, Gabrielli P, Lee K, et al. Seasonal patterns of heavy metal deposition to the snow on Lambert Glacier basin, East Antarctica. Atmos Environ 2007;41:8567–78.

Kennedy NJ, Hinds WC. Inhalability of large solid particles. J Aerosol Sci 2002;33:237–55.

Li C, Li FY, Zhang Y, Liu TW, Hou W. Spatial distribution characteristics of heavy metals in street dust in Shenyang city. Ecology Environ 2008;17:560–4.

Li XD, Poon C, Liu PS. Heavy metal contamination of urban soils and street dusts in Hong Kong. Appl Geochem 2001;16:1361–8.

Ljung K, Selinus O, Otabbong E. Metals in soils of children's urban environments in the small northern European city of Uppsala. Sci Total Environ 2005;366:749–59.

Madany IM, Akhter MS. Al Jowder OA. The correlations between heavy metals in residential indoor dust and outdoor street dust in Bahrain. Environ Int 1994;20:483–92.

Maxwell CM, Nelson DW. Development of lead emission factor for reentrained dust from paved roadways. The 71st Annual Meeting of the Air Pollution Control Association, Houston, Texas; 1978. p. 25–30.

Meza-Figueroa D, De la O-Villanueva M, De la Parra ML. Heavy metal distribution in dust from elementary schools in Hermosillo, Sonora, México. Atmos Environ 2007;41:276–88.

Naturvårdsverket. Development of generic guideline values. Model and data used for generic guideline values for contaminated soils in Sweden. Report 4639. Stockholm, Sweden; 1996.

Nicholson KW. A review of particle resuspension. Atmos Environ 1988;22:2639–51.

Niragu JO, Pacyna JM. Quantitative assessment of worldwide contamination of air, water and soils by trace meals. Nature 1988;333:134–9.

Nriagu JO. A silent epidemic of environmental metal poisoning? Environ Pollut 1988;50:139–61.

Pacyna EG, Pacyna JM. Global emission of mercury from anthropogenic sources in 1995. Water Air Soil Pollut 2002;137:149–65.

Piron-Frenet M, Bureau F, Pineau A. Lead accumulation in surface roadside soil: its relationship to traffic density and meteorological parameters. Sci Total Environ 1994;144:297–304.

Ren HM, Wang JD, Zhang XL. Assessment of soil lead exposure in children in Shenyang, China. Environ Pollut 2006;144:327–35.

Sehmel GA. Particle resuspension: a review. Environ Int 1980;4:107–27.

Sezgin N, Ozcan HK, Demir G, Nemlioglu S, Bayat C. Determination of heavy metal concentrations in street dusts in Istanbul E-5 highway. Environ Int 2003;29:979–85.

Thornton I. Metal contamination of soils in urban areas. In: Bullock P, Gregory PJ, editors. Soils in the Urban Environment. Blackwell; 1991. p. 47–75.

Tong STY, Lam KC. Home sweet home? A case study of household dust contamination in Hong Kong. Sci Total Environ 2000;256:115–23.

U.S. Department of Energy. RAIS: Risk Assessment Information System; 2004.

USEPA. Risk Assessment Guidance for Superfund, vol. I: Human Health Evaluation Manual. EPA/540/1-89/002. Office of Soild Waste and Emergency Response; 1989.

USEPA. Soil Screening Guidance: Technical Background Document. EPA/540/R-95/128. Office of Soild Waste and Emergency Response; 1996.

USEPA. Supplemental Guidance for Developing Soil Screening Levels for Superfund Sites. OSWER 9355.4-24. Office of Soild Waste and Emergency Response; 2001.

WHO. Guidelines for Drinking Water Quality. Recommendations, second ed, vol. I. Geneva: WHO; 1993.

Van den Berg R. Human exposure to soil contamination: a qualitative and quantitative analysis towards proposals for human toxicological intervention values. RIVM Report no. 725201011. Bilthoven, The Netherlands: National Institute of Public Health and Environmental Protection (RIVM); 1995.

Vermette SJ, Irvine KN, Drake JJ. Temporal variability of the elemental composition in urban street dust. Environ Monit Assess 1991;18:69–77.

Ye XB, Qian HJ, Xu PC, Zhu L, Longnecker M, Fu H. Nephrotoxicity, neurotoxicity, and mercury exposure among children with and without dental amalgam fillings. Int J Hyg Environ Health 2009;212:378–386.

Zheng N, Wang QC, Liang ZZ, Zheng DM. Distribution, combined contamination and risk assessment of heavy metals to sediment from freshwater rivers in Huludao City, Northeast of China. Environ Pollut 2007a;154:135–42.

Zheng N, Wang QC, Zhang XW, Zheng DM. Population health risk due to dietary intake of heavy metals in smelting area of Huludao City, China. Sci Total Environ 2007b;387:96-104.