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Understanding aqueous trace metal characteristics from industrial sources in China

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Abstract

Trace metals are a group of toxic pollutants that can cause serious damage to ecosystems and humans. To determine the distribution characteristics of aqueous trace metal contamination and identify critical pollution sources, it is necessary to develop a detailed estimation of trace metal emissions. By considering emission-related factors in each industrial sector, we estimate that the emissions were approximately 2, 61 t, 2,684 t, 301 t and 309 t for mercury, cadmium, chromium, arsenic and lead, respectively, in 2010 in China. These values are much higher than those provided in annual statistical reports. Our research identified critical emissions sources, including Shandong, Henan, Jiangsu and Guangdong Provinces and Raw Chemical, Non-ferrous Smelting, Non-ferrous Mining and Metal Products industries. However, Shandong and Metal Products are ignored in 'The Twelfth 5-Year Plan for Complete Control of Trace Metal Pollution'. This research generally found that the allowable discharge levels had a significant impact on specific sectors. Total emissions are much lower than the maximum allowable under current Chinese emissions regulations but exceed limits recommended by Integrated Pollution Prevention and Control (European Union). Furthermore, our study found that many regions located along upstream reaches of the Yangtze River, like Sichuan Province, are sources of cross-boundary pollution.

Keywords: Arsenic; Cadmium; Chromium; Emission factor; Lead; Mercury

1. Introduction

Trace metals, such as mercury, cadmium, arsenic, lead and chromium, are a group of toxic pollutants that can cause serious damage to ecosystems and humans (Kim *et al.*, 2010; Babula *et al.*, 2008).

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Similar to persistent organic pollutants, some of the trace metals discharged into water are easily converted into more persistent and toxic compounds, which can cause global pollution via long-distance transport and bioaccumulation in the food chain (Nansai *et al.*, 2012). For example, mercury in water mainly exists as divalent Hg(II) (Hg^{2+}) and MeHg (Lin *et al.*, 2012). MeHg is readily assimilated by aquatic organisms and accumulates in fish, which are consumed by humans and may therefore pose health risks (Da Silva *et al.*, 2005). Thus, greater attention should be paid to trace metals emitted into water bodies.

Anthropogenic activities have been estimated to have major impacts on global biogeochemical cycles of most trace metals (Nriagu & Pacyna, 1988). The first global emission inventory for trace metals was made by Nriagu (1979), who used emission factors (EFs) of each source and estimated global trace metal emissions released into the atmosphere, water and soil. Trace metals discharged from anthropogenic sources have been widely reported (Environmental Protection Agency, 1997). Recent research demonstrated that approximately half of the mass of global metal cycles was mobilized by human activities (Rauch & Pacyna, 2009). For example, the largest source of atmospheric trace metals was stationary fossil fuel combustion, especially coal combustion (Pacyna & Pacyna, 2001; Wu *et al.*, 2006).

The atmosphere, water and soil are three media into which trace metals are released (Nriagu, 1979; Nriagu & Pacyna, 1988; Mielke & Reagan, 1998; Smedley & Kinniburgh, 2002). Nriagu & Pacyna (1988) generated a worldwide estimation of trace metals released into the air, water and soils (see Table S2 in the Supporting Information, available online at http://www.iwaponline.com/wp/017/071.pdf). Except for lead, more trace metals were emitted into water than into the atmosphere. To produce reliable estimations and develop EFs, several studies on trace metal emissions have been conducted in many parts of the world, including both developed and developing countries, and a wide range of elements have been estimated. Table S3 (online at http://www.iwaponline.com/wp/017/071.pdf) provides a list of published works and metals of interest in studies of emission to the atmosphere, water and soil in (a) Europe, (b) North America, (c) the Asia-Pacific region and (d) worldwide. Emissions in China and at the global scale are most likely two of the most extensively studied geographic scales.

China is an important trace metal manufacturing center (Pacyna *et al.*, 2006, 2010; Shetty *et al.*, 2008; Lin *et al.*, 2012). Wu *et al.* (2006) found that the average annual increase in the rate of total Hg emissions from anthropogenic sources from 1995 to 2003 in China was 2.9% y^{-1}. Tian *et al.* (2012) generated an integrated inventory of atmospheric antimony emissions in China for the years 2005–2009, including antimony emissions from 2,188 large point sources and area sources. However, Lin *et al.* (2012) showed that, thus far, studies on trace metals in Chinese water bodies have not been very systematic. Researchers have little knowledge about trace metal emissions to water bodies in China. The knowledge gap on trace metal emissions to water bodies in China includes two aspects: (a) the distribution of trace metal sources and the level of emissions and (b) how emission levels in China compare to those in other parts of the world (Covelli *et al.*, 2009).

The present research attempted to produce comprehensive, reliable results on aqueous trace metal emissions by identifying the emission distribution and the contributions of industrial sources. Based on the results, this research attempted to understand China's industrial emission levels and the policy implications of the findings on the sources of trace metals. A basic simulation model of trace metal production and trace metal emission is presented in Section 2. The simulation results of major industrial emitters and their spatial distribution are presented in Section 3, and a discussion of the policy implications of China's emission levels and source distributions is outlined in Section 4.

2. Methodology and data sources

2.1. Methodology

The EF method has been widely used to estimate trace metal emissions (Liang *et al.*, 2013). The EF method involves three main components: the EF; the economic output or mass transformation, transportation and consumption; and pollution control technologies. However, the EF method relies on large amounts of data, with more source data leading to more precise estimates (Fang *et al.*, 2013). Thus, a model based on EF (Nriagu & Pacyna, 1988; Nriagu, 1989; Nansai *et al.*, 2012; Tian *et al.*, 2012; Zhang *et al.*, 2012) and integrated with a pollution source census dataset has been developed to calculate the annual emissions of aqueous mercury, cadmium, arsenic, lead and chromium in China. Emissions were estimated using statistical data on industrial output value and specific EFs. The basic formula can be expressed as follows:

$$E = \sum_i \sum_j (G_{i,j} \cdot \mathrm{EF}_{\mathrm{ELE},i,j} \cdot (1 - P_{\mathrm{ELE},i,j}))$$

$$\mathrm{EF}_{\mathrm{ELE},j} = E_{0,j}/G_{0,j}$$

$$P_{\mathrm{ELE},j} = ((A_{0,j} - E_{0,j})/A_{0,j}) \times 100\%$$

where E is the national industrial emissions of aqueous trace metals in 2010; $G_{i,j}$ is the gross output value of industrial sector j, province i, 2010; $\mathrm{EF}_{\mathrm{ELE},i,j}$ is the factor of the pollutants released during the production activity of industrial sector j, province i; $P_{\mathrm{ELE},i,j}$ is the fraction of pollutants removed by existing pollution control device of industrial sector j, province i, and EF and P are all the national average of certain industrial sectors in China. $A_{0,j}$ is the amount of trace metals produced by industrial sector j, 2007; $E_{0,j}$ is the trace metals emissions of industrial sector j, 2007; ELE is the element; j is the industrial sector; and i is the province.

Using DecisionTools@Risk, the Monte Carlo stochastic simulation approach was employed to model probability distributions of key input parameters, and uncertainties estimated. EFs and removal fractions, are primarily from two sources: Pollution Source Census Database and National Statistical Database, which do not match well. A triangular distribution function is assumed for factor data for limited samples (Tian *et al.*, 2012; Liu *et al.*, 2013). Table S12 (available online at http://www.iwaponline.com/wp/017/071.pdf) summarizes the key characteristics of distribution function curves for EFs. The Monte Carlo sampling number was set as 10,000 (Lloyd & Ries, 2007).

2.2. Data sources

The national average EF and pollutants removal fraction by industrial sector were obtained from the pollution source census database 2007 (Editorial committee on First China Pollution Source Census, 2011), which has investigated all the pollution sources. National data from 39 industrial sectors in China were summed up. Factors of five trace metals were estimated as emissions by gross output value. The results for the EF and the fraction of pollutants removed are summarized in Tables S4 and S8, respectively (online at http://www.iwaponline.com/wp/017/071.pdf).

Data on provincial gross output by industrial sector in China in 2010 were collected from 30 local government statistical documents, such as the Beijing Statistical Yearbook (Beijing Municipal Bureau of Statistics and National Bureau of Statistics (NBS) Survey Office in Beijing, 2011). All industrial output values have been converted from current prices in 2010 to fixed prices in 2007.

Twelve sectors' (see Table S4) industrial output values in Henan and Liaoning Provinces were obtained by using a proportional allocation method according to the sectors' proportion of the national scale because factors for gross industrial output value in those sectors were not available. Information about Hong Kong, Macao and Taiwan were not available in the pollution source census database; thus, these regions were not included in our analysis or discussion.

3. Results

3.1. Sectoral characteristics of trace metals

3.1.1. Amount of trace metals produced by sector. The total amount of mercury, cadmium, chromium, arsenic and lead produced were approximately 35 t, 4,404 t, 15,748 t, 12,848 t and 7,133 t, respectively (see Table S5, available online at http://www.iwaponline.com/wp/017/071.pdf). Manufacture of raw chemical materials and chemical products (MRCM), smelting and pressing of non-ferrous metals (SPNM), mining and processing of non-ferrous metal ores (MPNM), manufacture of metal products (MMP) and manufacture of leather, fur, feather and related products (MLFF) were the leading producing sectors in China, as shown in Figure S1 (online at http://www.iwaponline.com/wp/017/071.pdf).

MMP (industrial sector abbreviations are defined in Table S1, online at http://www.iwaponline.com/wp/017/071.pdf) contributed 67.1% to the total production of chromium, MLFF contributed 16.0% and MTEQ contributed 5.3%. These three sectors comprise the majority of China's industrial production of aqueous chromium, accounting for nearly 90% of the total. Except for chromium, MRCM, SPNM and MPNM were the three highest producing sectors of trace metals. The three sectors together contributed 96.0% of the total production of mercury and contributed 99.6%, 98.3% and 93.3% to the total production of cadmium, arsenic and lead, respectively. The contribution from the remaining sectors was small. In this category, MRCM produced half of the total production of mercury, and SPNM produced over 90% of the total production of cadmium, approximately half of the total production of arsenic and over 70% of the total production of lead.

3.1.2. Amount of trace metal emissions by sector. The total amount of mercury, cadmium, chromium, arsenic and lead emissions were 2 t, 61 t, 2684 t, 301 t and 309 t, respectively (see Table S5). MRCM, SPNM, MPNM, MMP and MLFF were the leading emitting sectors in China. Aqueous trace metals from industrial sources are shown in Figure 1.

MMP contributed 66.8% of total chromium emissions, and MLFF contributed 28.5%. These two sectors comprise the majority of China's industrial chromium emissions to water bodies, accounting for nearly 96% of the total. Except for chromium, MRCM, SPNM and MPNM were the three highest emitting sectors. The three sectors together contributed 82.8% of the total mercury emissions and contributed 95.1%, 89.5% and 87.2% of the total cadmium, arsenic and lead emissions, respectively. The contribution from the remaining sectors was small. In this category, SPNM produced nearly 80% of the cadmium emissions and half of the lead emissions.

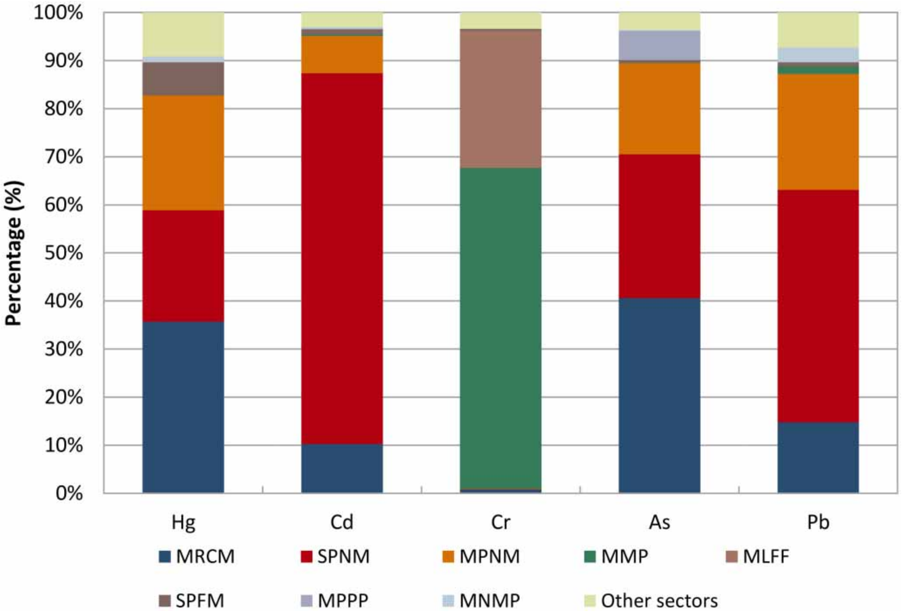

Fig. 1. Volume of trace metal emissions to water bodies by industrial sector in 2010 in China.

3.2. Regional distribution of trace metals

3.2.1. Regional amount of trace metals produced. There was remarkable unevenness at the provincial level in terms of the amount of trace metals produced, as shown in Table S6 (online at http://www.iwaponline.com/wp/017/071.pdf). Some provinces exhibited much higher production levels than the national average, such as the eastern and central provinces. Guangdong Province in southern China also had high production levels. Some provinces had much lower production than the national average, such as the western provinces (especially Tibet). The regional distribution of trace metals produced in industrial wastewater is shown in Figure S2 (online at http://www.iwaponline.com/wp/017/071.pdf).

Shandong, Jiangsu, Henan and Guangdong Provinces contributed much more of the trace metals in industrial wastewater than other provinces. The four provinces together contributed 44.8% of the total production of mercury and 39.3%, 47.3%, 42.9% and 40.8% of the total production of cadmium, chromium, arsenic and lead, respectively. The highest production of chromium, found in Guangdong, was estimated as 2,943 t in 2010. This province contributed 18.7% of the total industrial production of aqueous chromium. The highest production of mercury and lead, and the second highest for cadmium and arsenic, were found in Shandong; the levels were estimated to be nearly 5 t, 803 t, 467 t and 1,706 t for mercury, lead, cadmium and arsenic, respectively, in 2010, contributing 14.4%, 11.2%, 11.0% and 13.3% of the total, respectively. The highest production of cadmium and arsenic, and the second highest for mercury, chromium and lead, were found in Jiangsu, at approximately 487 t, 1,788 t, 5 t, 2,408 t and 781 t for cadmium, arsenic, mercury, chromium and lead, respectively, contributing 11.1%, 13.9%, 13.8%, 15.3% and 10.9% of the total, respectively.

In addition to the provinces listed above, Zhejiang, Hunan, Jiangxi, Liaoning, Inner Mongolia, Sichuan and Anhui had high production levels of one or two trace metals. Other provinces, such as

Tibet, Hainan, Ningxia, Heilongjiang, Xinjiang and others, accounted for less than 1% of the production of trace metals.

3.2.2. Regional amount of trace metal emissions. Similar to production, trace metal emissions varied dramatically by province, as shown in Table S6. Emissions in eastern and central provinces were much higher than those in the west, especially Tibet. In addition, Guangdong Province in southern China had high emissions. The regional distribution of trace metal emissions to water bodies is shown in Figure 2.

Shandong, Jiangsu, Henan and Guangdong Provinces are critical emitters of trace metals into water in China. These four provinces together contributed 43.1% of the total emission of mercury and contributed 39.8%, 46.7% 43.8% and 41.8% to the total emissions of cadmium, chromium, arsenic and lead, respectively. The highest emission of chromium, found in Guangdong, was estimated as 525 t in 2010. This province contributed 19.6% of the total industrial emission of aqueous chromium. The highest emissions of aqueous mercury, cadmium, arsenic and lead, found in Shandong, were estimated to be approximately 0.04 t, 7 t, 43 t and 38 t in 2010, respectively, contributing 13.6%, 11.0%, 14.3% and 12.2%, respectively, of the national industrial emissions. The province with the second highest emissions was Jiangsu Province for four pollutants (not including lead), followed by Henan Province for three pollutants (not including chromium or lead), and Guangdong Province for four pollutants (not including chromium).

In addition, Zhejiang, Hunan, Liaoning, Inner Mongolia, Sichuan, Anhui and Shanghai had high emissions for one or two pollutants. The contribution from other provinces, such as Tibet, Hainan, Ningxia, Heilongjiang, Beijing, Xinjiang and others, was less than 1% of the emission of any trace metals.

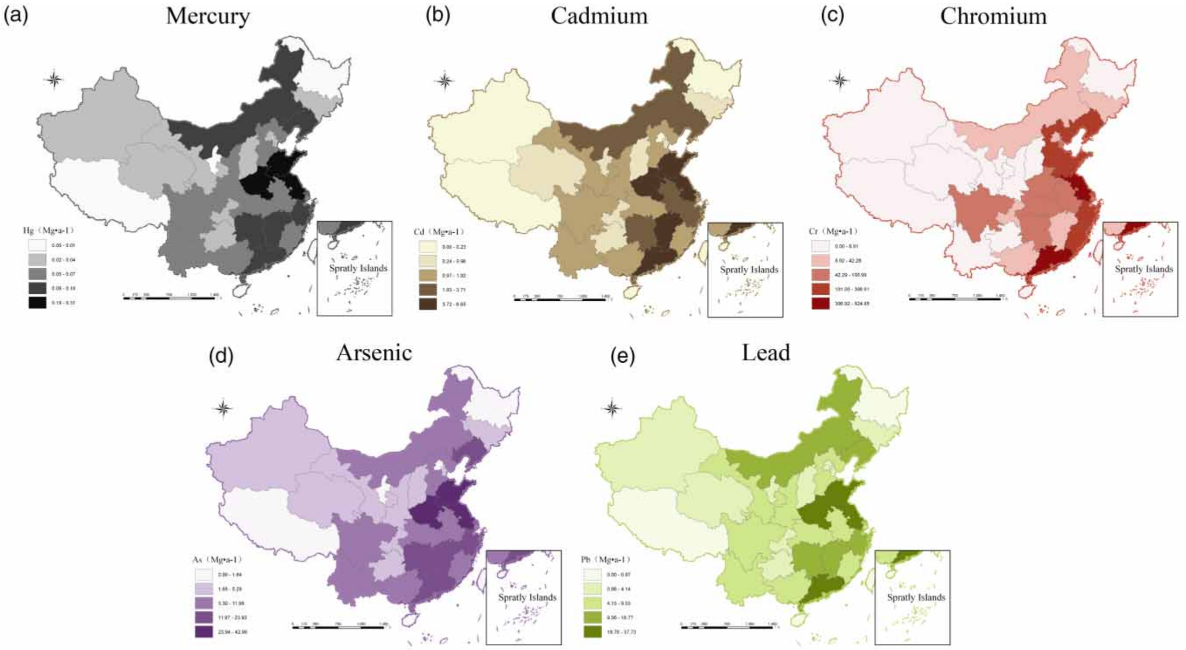

Fig. 2. Volume of trace metal emissions to water bodies by province in 2010 in China.

4. Discussion

4.1. Comparison to ex post data

Data from '2010 Annual Statistic Report on Environment in China' (Ministry of Environmental Protection of the People's Republic of China (ZHB), 2011) show that the emissions of trace metals were 1.05 t, 30.1 t, 54.8 t, 118.1 t and 140.8 t for mercury, cadmium, hexavalent chrome, arsenic and lead, respectively. These values were much lower than those found by the present research. Many provinces have no data included in the report, whereas the present research includes data from all provinces, including Tibet. At the provincial scale, Hunan is a major emitting province according to the report, contributing 49.8%, 43.3%, 49.9% and 22.9% of the emissions of mercury, cadmium, arsenic and lead, respectively. Hunan, Guangxi and Jiangxi Provinces together contributed 57.0%, 69.9%, 81.2% and 45.8% of the emissions of mercury, cadmium, arsenic and lead, respectively. According to the present research, however, the three provinces contributed only 11.2%, 15.5%, 11.8% and 14.0%, respectively, of the emissions of these metals. Four major emitting provinces were not included in the top five emitting provinces in the annual report. It is worth noting that Shandong and Jiangsu only contributed 0.2% of mercury emissions according to the report. At the sectoral scale, MRCM, SPNM and MPNM were the top three emitting sectors according to the report, together contributing 65.2%, 92.7%, 97.2% and 84.5% of the emissions of mercury, cadmium, arsenic and lead, respectively.

The differences between the results of the present study and those of the annual report can be mostly attributed to statistical scale and data acquisition mode. The present research investigated all industrial sources in China and summed them up by sector, whereas the annual report focused on 80,000 industrial enterprises above a designated size. Furthermore, observers randomly chose a sampling time on a day during the wet season or dry season or chose a result after multiple sampling, which may have had a great impact on the final results. In addition, data manipulation can occur in management products, especially in the annual report. The annual report is regarded as a baseline from which to base political assessments of total emissions reductions and the environmental responsibility of industries and local governments. Thus, the possibility of punishment, such as being dismissed from office, can create problems of bias in assessments of environmental issues. As a consequence, although the results provided in the annual report appear to be reasonable, they may reflect data manipulated by political concerns (see Table S7, online at http://www.iwaponline.com/wp/017/071.pdf).

4.2. Discharge levels

4.2.1. Comparison of levels with national standard. National average removal fractions for mercury, cadmium, chromium, arsenic and lead were 93.51%, 98.63%, 82.95%, 97.66% and 95.66%, respectively. The fraction of trace metals removed in 2010 are summarized in Tables S8 and S9 (online at http://www.iwaponline.com/wp/017/071.pdf). Existing wastewater discharge standards concerning trace metal emissions in China include the *Integrated Wastewater Discharge Standard*. Emissions of trace metals from industrial sources in 2010 were much lower than the maximum allowable amount based on the emission limit values above (see Table S10, online at http://www.iwaponline.com/wp/017/071.pdf) for both sectoral and provincial emissions.

In China, only two industrial sectors' removal rates are high for all trace metals, namely, the SPNM and MRCM sectors. Treatment technology in these two sectors is more advanced than it is in other sectors, and the specific industrial standard is stricter. Removal rates for chromium in 22 sectors were above average. Otherwise, only a few sectors were above the national average (two for cadmium; four for mercury, arsenic and lead), as shown in Figure 3. In addition, provinces and industrial sectors with extremely high emissions (e.g., Guangdong and SPNM) may make a large impact on national average removal rates. For example, low chromium removal efficiency in Guangdong Province and in the MMP industry lead to much lower values for chromium (82.95%), as shown in Figure 4.

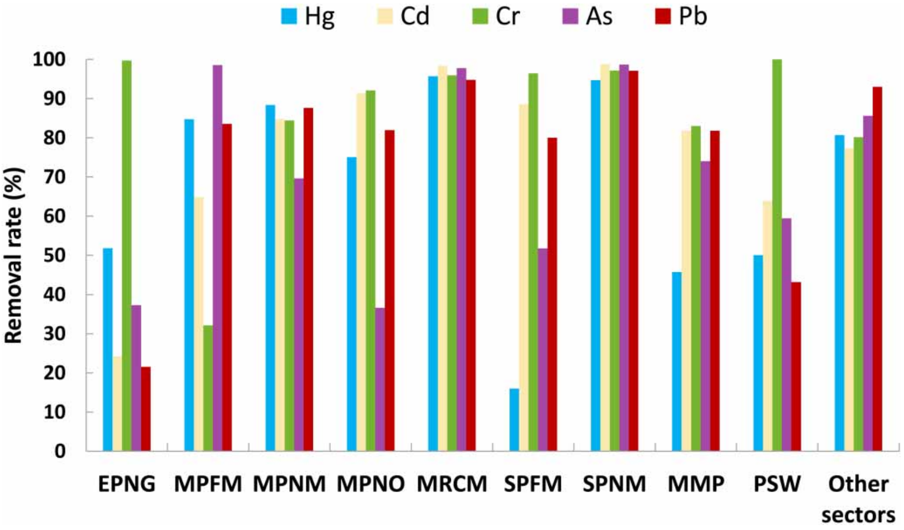

Fig. 3. National removal rate of trace metals by industrial sector in 2010 in China.

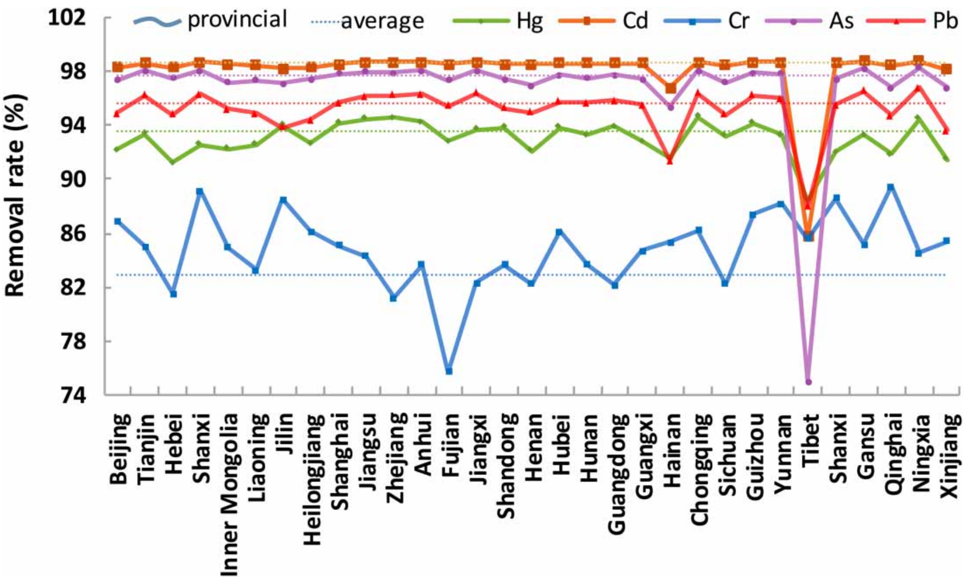

Fig. 4. Removal rate of trace metals by province in 2010 in China.

4.2.2. Comparison of levels with EU standard. Current emissions standards for trace metals in China are close to the early EU Directive (84/156/EEC, 83/513/EEC, in which the limit value for mercury and cadmium discharges is 0.05 mg L^{-1} and 0.2 mg L^{-1}, respectively). However, most of the Chinese standards are lower than the present European Directive. Compared with the above standards, trace metals discharged from certain sectors exceed the limits set forth in the best available techniques standards of the integrated pollution prevention and control (see Table S11, online at http://www.iwaponline.com/wp/017/071.pdf). MRCM, SPFNFM, MLFF and MMP are four major sectors in which emissions are much higher than the EU standard. Arsenic emissions from MRCM and SPFNFM were approximately 122 t and 90 t, respectively, whereas the limits under present EU standards are 51 t and 54 t, respectively. Lead emissions from SPFNFM were approximately 150 t, whereas the current EU standard is 109 t. Chromium emissions from MMP and MLFF were approximately 1,793 t and 765 t, respectively, whereas the current EU standards are 151 t and 112 t, respectively. The total amount of trace metal emissions at the national level does not exceed the national limit because several sectors, such as MFU, emit no or little trace metals and thus have a minimal contribution to the final average.

However, we found the environmental quality standards for trace metals in China to be close to those in developed countries. Therefore, a phenomenon called 'diluted emission' arises and affects the total amount of pollutants. To reduce emissions into water bodies, higher discharge standards, especially provincial standards and industry-specific standards, are urgently needed.

4.3. National pollution control plan

'The Twelfth 5-Year Plan for Complete Control of Trace Metal Pollution' (The Central People's Government of the People's Republic of China, 2011) considers these trace metals to be very important to pollution control. However, many regions and sectors are ignored in the plan.

4.3.1. Regional pollution control. The plan sets 14 provinces as major controlling regions. Approximately half of these provinces were among the top emitters of all trace metals according to the present research (depicted in the center of the large green circle in Figure 5). Some provinces listed in the plan are those that had the highest emissions of one trace metal according to our results (depicted in the intersection of the large circle at the center and the small circles around it in Figure 5). However, some provinces that had high emissions of certain metals (depicted in the disjointed section in Figure 5) are ignored in the plan. In the national plan, five provinces emitting high amounts of mercury into water are not included, including Shandong, Liaoning, Hebei, Shanghai and Anhui. In addition, three provinces emitting high levels of cadmium and lead, five provinces emitting high levels of arsenic and seven provinces emitting high levels of chromium are not included in the plan, including Shandong, Liaoning and Anhui, among others. It is worth noting that Shandong Province is not listed as a major controlling region in the plan even though it emits almost the largest amount of trace metals into water of all provinces. We also found that some major controlling regions included in the plan are ecologically vulnerable, including Gansu and Qinghai Provinces.

4.3.2. National industrial pollution control. The plan sets five industrial sectors as major controlling sources. These sectors are MPNM, SPNM, LSB, MLFF and MRCM. Only one of these sectors has exactly the same ranking according to its levels of trace metal emissions in the plan as in the present research (depicted in the center of the small blue circle in Figure 6). Some sectors listed in the controlling plan were found to be the highest emitters of one or two trace metals according to our results

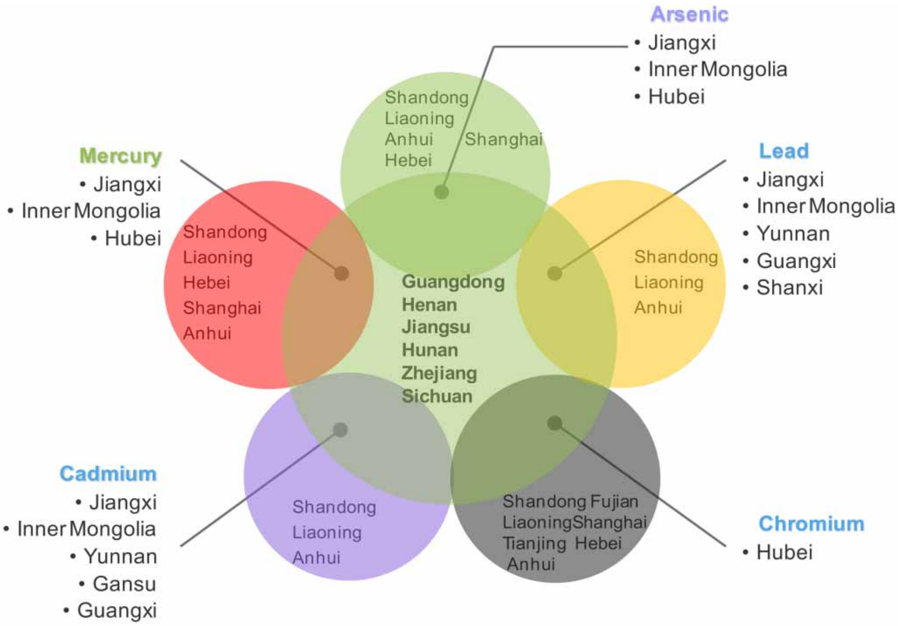

Fig. 5. Relationship between the trace metal pollution control plan and provincial assessments. Please refer to the online version of this paper to see this figure in color: http://www.iwaponline.com/wp/toc.htm.

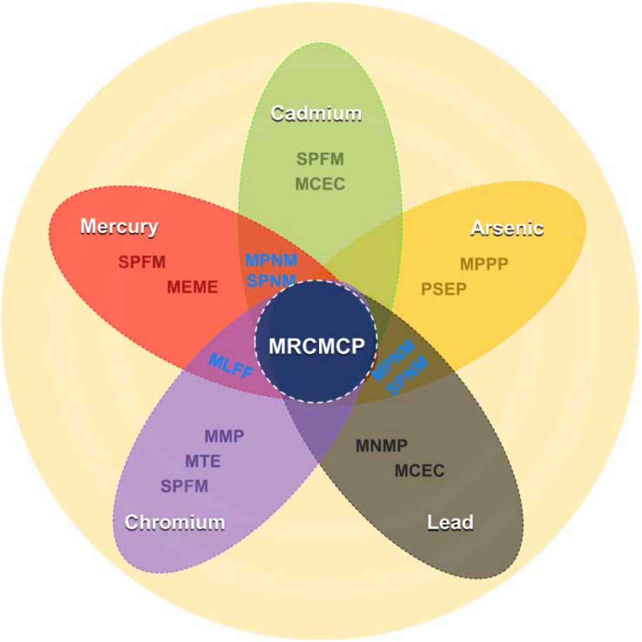

Fig. 6. Relationship between the trace metal pollution control plan and industrial sector assessments. Please refer to the online version of this paper to see this figure in color: http://www.iwaponline.com/wp/toc.htm.

(depicted in the intersection of the large ellipse with the blue font in Figure 6). However, some sectors that had high emissions of certain metals in the present study (depicted in the disjointed section of each ellipse in Figure 6) are ignored in the plan. In the national controlling plan, the SPFM and MEME industries, which emit high levels of mercury; the SPFM and MCEC industries, which emit high levels of cadmium; the MMP, MTEQ and SPFM industries, which emit high levels of chromium; the MPPP and PSEP industries, which emit high levels of arsenic; and the MNMP and MCEC industries, which emit high levels of lead into water, are not included. Note that the MMP industry, which emits almost 70% of the total chromium into water, is not listed as a major controlling source in the plan.

4.3.3. Cross-boundary pollution. In China, several studies have been conducted in the Yangtze River Delta and the Pearl River Delta because these areas are well developed and often have experienced severe pollution problems. Many surveys of trace metals in large river basins in China have been published (Ip *et al.*, 2007; Li & Zhang, 2010; Sun *et al.*, 2011). Bias might exist in studies because most research has focused the risks from downstream discharges. As found in our study, in Sichuan Province, where the basin-and-hill areas are established as Soil and Water Conservation Districts (with water environmental function managed at the watershed scale), the standards for pollutant emissions and concentrations were strict. In Sichuan Province, large amounts of chromium and arsenic (approximately 80 t and 10 t, respectively) were emitted into water, posing great potential risks to upstream areas of the Yangtze River. In Jiangxi Province, which is located upstream of the East River and the North River in the Pearl River watershed, large amounts of mercury, cadmium and arsenic (approximately 0.1 t, 5 t and 14 t, respectively) were emitted into water. Jiangsu, Guangdong and Shandong Provinces, which have high emissions, were established as highly concentrated residential districts (with water environmental function managed at the watershed scale). The standard for drinking water in cities and towns of the area required class II or class III standards. Stricter standards are needed for the total amount of pollutant emission concentrations.

Finally, we provided an accurate estimate of trace metals from industrial discharge. However, many sources and distributions are still unknown due to the lack of measurements, and more information on trace metal deposition (dry deposition and wet deposition via precipitation) in water bodies is needed. As soon as these data become available, a complete emission inventory will be constructed. Further research can then be conducted, including on-site measurements and human health risk assessments in critical regions.

4.4. Uncertainty analysis

Monte Carlo simulation is used to quantify the uncertainty in our trace metals emission estimates depending on available EFs distribution. Detailed information of EFs with corresponding statistical distributions can be found in the Supporting Information (available online at http://www.iwaponline.com/wp/017/071.pdf). The ranges of four trace metals emissions from industrial sectors and provinces in China with uncertainties are listed in Table 1. The overall uncertainties in our inventories are estimated at about −20–30%. The stochastic simulation approach made mean estimates larger than the approach treating emissions factors as point values, which exceeded 59%, 49%, 117% and 135% for mercury, cadmium, arsenic and lead, respectively. SPNM is estimated to have the smallest uncertainty for four metals due to relatively high data quality. In contrast, higher uncertainties can be observed in MF, MB and PTMW. The high uncertainties for these industrial processes mainly results from inadequate source information and the limited database in China. Owing to significant variation from one plant to another in emissions factors, and significant variation over time in the emissions factor for a specific

Table 1. Uncertainties of trace metal emissions in China, 2010[a].

	Total uncertainties			Uncertainties			Uncertainties	
Metal	Mean	Range	Sector	Mean	Range	Province	Mean	Range
Mercury	3.5	2.5–4.6 (−28%, 33%)	SPNM[b]	0.5	0.3–0.6 (−26%, 28%)	Gansu	0.04	0.03–0.05 (−22%, 24%)
Cadmium	90	64–121 (−29%, 34%)	SPNM	38	29–47 (−24%, 25%)	Shanxi	0.9	0.7–1.1 (−20%, 20%)
Arsenic	652	438–893 (−33%, 37%)	SPNM	64	48–79 (−24%, 24%)	Gansu	5.8	4.2–7.6 (−28%, 32%)
Lead	727	453–1,064 (−38%, 46%)	SPNM	100	75–125 (−25%, 25%)	Ningxia	1.5	1.1–1.8 (−23%, 25%)

[a] Emissions are given in tons per year. The percentages in parentheses indicate the 90% confidence interval around the central estimate.

[b] Industrial sector abbreviations are defined in Table S1 (available online at http://www.iwaponline.com/wp/017/071.pdf).

plant, adopting an average value of EFs for these industrial processes provides just a preliminary estimate and may lead to under- or overestimation of the trace metal emissions from some specific sources. For a more reliable estimation of trace metal emissions, long-term field testing, large scale monitoring and a fully industrial database in China should be considered.

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