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Heavy metal contamination of road-deposited sediments in a medium size city of China

Wei Zhu · Bo Bian · Lei Li

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Abstract Road-deposited sediment (RDS) is an important environmental medium that affects the characteristics of heavy metals in stormwater runoff. 62 RDS samples were collected from four different land use types (commercial, residential, intense traffic and riverside park) in the Zhenjiang city of China. The samples were analysed for concentrations of five metals (Zn, Pb, Cu, Cr and Ni). The maximum mean concentrations of Zn, Pb, Cu, Cr and Ni from different land use types were 686, 589, 158, 129 and 125 mg/kg, respectively. The intense traffic area displayed the highest metal concentrations, whilst Zn, Cr, Ni and Cu did not show any discernible variations among the other three areas. Seven particle sizes were analysed separately for the heavy metal concentrations. In all studied areas, particles <63 μm have the highest metal concentrations: 926–1,188 mg/kg of Zn, 270–928 mg/kg of Pb, 150–220 mg/kg of Cu, 99–172 mg/kg of Cr and 96–147 mg/kg of Ni. The fine particle fraction (<63 μm) of the samples accounted for about 25–60% of the total metal loading; in contrast, the coarsest fraction (1,000–2,000 μm) only contributed 1–5%. The calculated ecological risk index shows that considerably high potential risks exist in the intense traffic area particularly due to high concentrations of Pb. These findings provide invaluable information for the development of appropriate management strategies to decrease non-point source contamination loading to the water environment in urban areas.

Keywords Road-deposited sediment · Land use type · Particle size distribution · Heavy metals loading · Ecological risk index

W. Zhu · B. Bian (✉)
College of Environmental Science and Engineering,
Hohai University,
1 Xikang Road,
Nanjing 210098, People's Republic of China
e-mail: bianbo1@163.com

W. Zhu
State Key Laboratory of Hydrology–Water Resources and Hydraulic Engineering, Hohai University,
Nanjing 210098, People's Republic of China

L. Li
Research Academy of Hohai University,
Nanjing 210098, People's Republic of China

Introduction

With China's rapid urban population growth and industrialisation, pollution of urban water bodies has become an increasingly serious problem, threatening the urban ecological environment. There has been an urgent need for effective pollution control. As the point source pollution is reduced, the contribution of non-point sources within and around the city is becoming an important issue (Buffleben et al. 2002). Urban stormwater runoff is now recognized as a major source of pollutants (Brezonik 2002). It is much more difficult to control the stormwater runoff pollution due to the random nature of the rainfall and uncertainty of the pollution source.

Urban stormwater runoff pollution results from washed off urban road-deposited sediments (RDS) during heavy rainfalls (Legret and Pagotto 1999; Sorme and Lagerkvist 2002), which contains very high levels of heavy metals and organics (Stone and Marsalek 1996; Kim et al. 1998; Yunker et al. 2002). These pollutants affect significantly the water quality of the receiving water bodies. Therefore, to effectively control the urban water body pollution, we need to determine the types and contents of the runoff pollutants, which in turn depend on the RDS pollutants composition and concentration in the areas.

An earlier study by Harrison et al. (1981) on the RDS in the London city indicated that the main RDS pollutants were Pb, Zn, Cu and Cd with concentrations up to 2,100, 539, 108 and 2.7 mg/kg respectively. Other researches also showed high contents of heavy metals in the RDS at the traffic intersection where vehicles are typically decelerated (Fergusson and Ryan 1984; Ellis and Revitt 1982). In particular, lead has been found to be the most detectable heavy metal in the RDS in busy traffic areas (Culbard et al. 1988; Leharne et al. 1992; Wong and Mak 1997). Further research shows that the RDS particle size, pollutants composition and concentration are related to the weather condition, traffic density and industrial condition as well as the closeness to soils (De Miguel et al. 1997; Droppo et al. 1998; Jiries et al. 2001; Kim et al. 1998; Wang et al. 1998). It also has been found that cities with larger populations tend to have higher RDS heavy metal concentrations (Charlesworth et al. 2003).

The RDS size distribution plays a critical role in urban stormwater management plans (Herngren et al. 2006). Adachi and Tainosho (2005) deals with relatively large particles of road sediments (50–2,830 μm). Some studies have indicated that the chemical composition of road sediments varies with grain sizes between 20 and 1,500 μm (Al-Rajhi et al. 1996) or between 63 and 2,000 μm (Sutherland 2003). Metal concentrations have been found to increase as the sediment particle size decreases; and the highest concentrations of Zn, Cu and Pb were associated with particle fractions <250 μm (Ellis and Revitt 1982; Sansalone and Buchberger 1997). The most important index of contamination for RDS is the mass loading of a trace element in a given grain size fraction. Loading combines trace metal concentration, on a grain size basis, with data on the mass percent. On average the finest fraction (<63 μm), accounted for 51±15% of the total labile Pb stored in RDSs in Palolo Valley. This can be compared to storage in the coarsest fraction (1,000–2,000 μm) which accounted for only 3±1.5% (Sutherland 2003). Some studies have indicated that a Pb loading of 30% is in the <63 μm fraction, 18% for the 125–250 μm fraction and 14% for the 250–500 μm fraction (Biggins and Harrison 1980).

Most previous RDS researches have been conducted in developed countries. Banerjee (2003) presented one of the few studies carried out in developing countries which typically have different types of industries and worse pollution conditions. The study showed that the contents of Cr, Ni and Cu were particularly high in the industrial areas with concentrations significantly exceeding the levels detected in developed countries. In China, Shi (1990) investigated surface sediments in the Chengdu city. The results showed that the Cu, Pb and Zn concentrations were particularly high in the intense traffic area and 70% of RDS particles were smaller than 360 μm. Previous researches also showed that the concentrations of heavy metals in the RDS vary considerably from city to city (Chon et al. 1995; Droppo et al. 1998; Wang et al. 1998; Jiries et al. 2001) depending on many factors such as the density of local industrial activities and technologies employed in these activities as well as local weather conditions (particularly wind patterns). Large differences in the level of RDS pollution exist among countries of different economic development level and cities of different sizes. In China, there are 70 cities with 1 to 2 million populations. To study the characteristics of the RDS pollution in these medium size cities has important implications for non-point source pollution control and management in China and perhaps other developing countries too.

The RDS research is often conducted at the city scale. A city commonly consists of areas of different land uses which exhibit their own characteristics; and these characteristics affect the distribution and pollution level of the urban RDS directly or indirectly. Currently there are no available data of trace metal concentrations in different grain size fractions of

RDS; and yet these data are important for the assessment of the potential toxic pollution of various road types in developing countries. Previous studies focused only on limited locations, particularly along major traffic roads and there is no extensive survey on general RDS conditions in urban riverside parks.

Given such a background, this investigation selects four urban areas in the Zhenjiang city (a typical medium size city in China) to study heavy metal pollutants in the RDS including Pb, Zn, Cu, Ni and Cr. The study aims to quantify heavy metal concentrations in particles with different grain size fractions and total concentrations, and to compute heavy metals loadings for each particle size fraction in the RDS. The results will help to determine the effects of particle sizes on the total pollution level in different urban areas.

Materials and methods

Study area and sampling locations

Zhenjiang, a city in the eastern China, is on the tip of the fertile Yangtze River delta. It is the place where the famous Yangtze River and Beijing–Hangzhou Grand Canal intersect (Fig. 1). The city has been developed with various industry, business and tourism sectors. It also has an important port in the navigation along the Yangtze River. The local annual mean temperature is 15.5°C. The annual precipitation is about 1,070 mm and the sunlight hour is 2,057.2 h. The Zhenjiang city is representative of medium size cities in the eastern China.

The city centre has developed commercial and residential areas, riverside parks, and a transportation

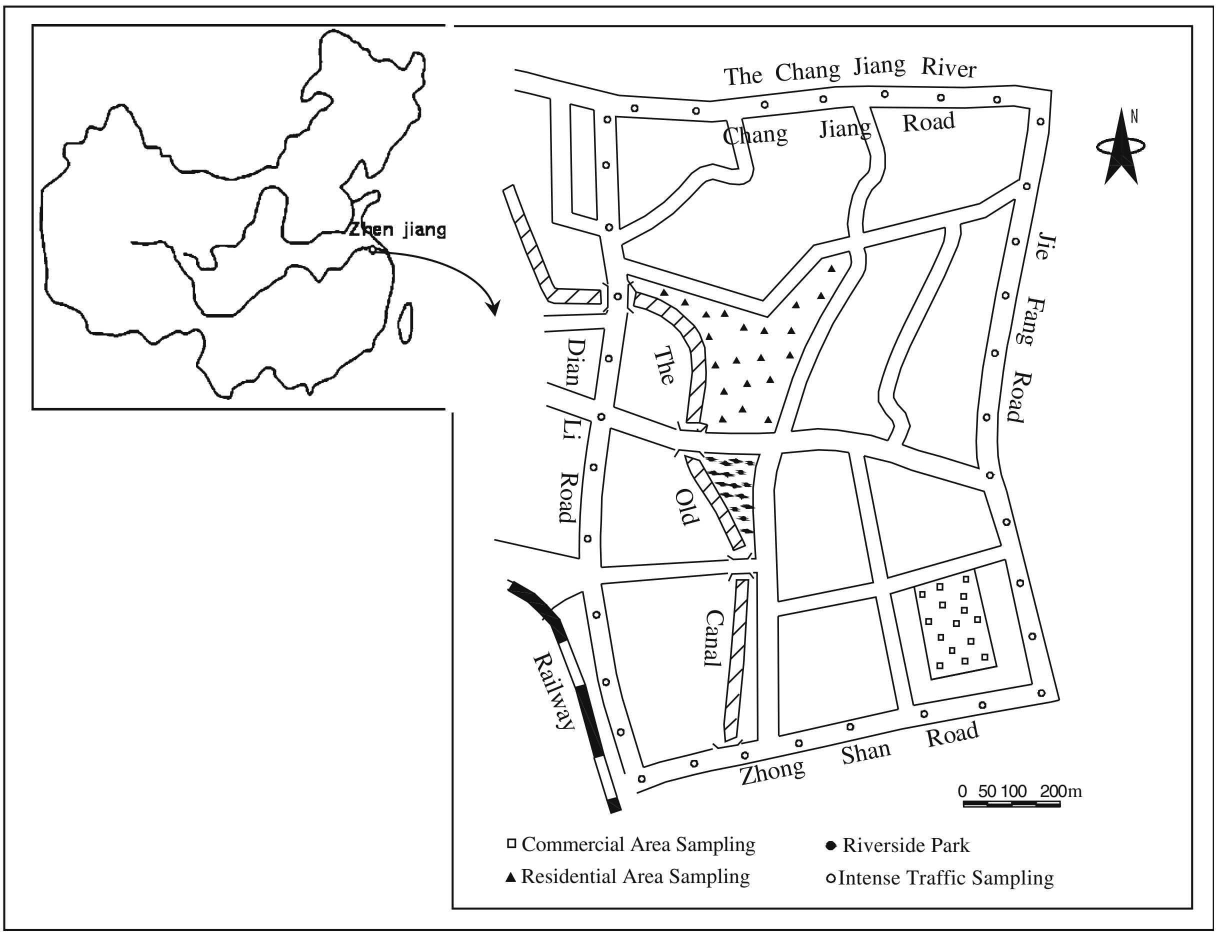

Fig. 1 Map of study areas and sampling locations

network. RDS samples were collected separately from these areas. The commercial area sampled is beside major roads, with a mean people influx of 2,561 persons per hour. An old residential area was also sampled, where the roads have been used as a temporary car park with a mean pedestrian influx of 651 persons per hour and a mean traffic density of 121 cars per hour and 306 motorcycles per hour. The riverside park sampled is in the old City adjacent to main urban transportation roads. Four major roads were also examined: Changjiang, Jiefang, Zhongshan and Dianli Road (Fig. 1). These four roads represent intense traffic areas and their mean traffic density is 1,438 vehicles per hours, 18.6% of which are large vehicles.

Sampling and analysis

Sample collection

A total of 62 samples were collected using a random sampling strategy at the sampling locations from March to May 2006. The sampling site is shown in Fig. 1. As mentioned above, the RDS samples were collected from four areas of different land uses in very early morning outside the road cleaning period: residential, commercial, intense traffic and park areas. The samples of road sediment that has accumulated in a gutter 1 and 2 days. The sampling points were located on the road within 1 m from the curb where the RDS containing lead and other heavy metals such as Cd and Zn tends to accumulate as a result of airborne redistribution by automobiles (Al-Rajhi et al. 1996; Tuner et al. 2001; Momani et al. 2002). Each sample, which weighed between 60 and 500 g, was collected from a 1 m^2 area using a clean plastic dustpan and a brush (Kim et al. 1998; Xie et al. 2000). The samples were stored separately in self-sealing plastic bags to avoid contamination and transported back to the laboratory for subsequent preparation and analysis. In the mean time, soil samples were collected from the suburb where was not relatively polluted by use of RDS sampling methodology to determine the background levels of heavy metals in soils from the surrounding areas.

Sample analysis

Particle-size analysis The samples were dried for 48 h at 105°C and then stored in a cool, dark place for further fractionation and analysis. The samples were sieved using a 2 mm nylon mesh to remove gravel-sized materials and large plant roots, and then screened into seven fractions. These fractions and their descriptive classifications (Folk 1974) are: 1,000–2,000 μm (very coarse sand), 500–1,000 μm (coarse sand), 250–500 μm (medium sand), 125–250 μm (fine sand), 63–125 μm (very fine sand), 54–63 μm (silt and clay) and <54 μm (clay). Materials of sizes greater than 2,000 μm were discarded. So particles coarser than 2,000 μm are of limited importance in transporting adsorbed metals in urban systems (Droppo et al. 1998; Sutherland and Tolosa 2000; Pagotto et al. 2001; Stone and Marsalek 1996) from both hydraulic and geochemical point of view. Then the different size fractions were weighed on the day of collection and then stored in a desiccator prior to chemical analysis.

Heavy metal concentration analysis A small portion of each sample (0.3 g) was placed in a polypropylene vessel (speed wave MWS-3+). A mixture of guaranteed reagent (6 ml of 90% HNO_3, 3 ml of 75% $HClO_4$ and 3 ml of 78% HF) was added to the vessel to digest the sample following the steps listed in Table 1. The residuals were redissolved in a plastic bottle with 10 ml HCL (1:1) and diluted to 25 ml of deionised water. Concentrations of Cu, Pb, Zn, Cr and Ni were determined by using an atomic absorption spectrophotometer. Approximately 5% of the samples were analysed as quality control/quality assurance measures internal and external standards, duplicate samples as well as metal-free de-ionized water were used in the analysis.

Organic matters analysis Based on the principle of classical potassium dichromate oxidation-outer heating, a method for the determination of organic matters in RDS samples by oxidation-reduction titration with furnace digestion was proposed.

Table 1 Operating conditions for microwave assisted pseudo-digestion

Step	Temperature (°C)	Pressure (Pa)	Time (min)	Power (w)
1	180	31	5	95
2	190	38	20	99
3	100	30	5	80
4	100	20	1	80
5	100	20	1	80

Heavy metal loading

To determine how particles of different grain sizes contributed to the overall contamination of the RDS, the pollution load percentage was computed for individual RDS sample by combining the concentration dada for the grain size fractions and their mass size percentages. The equation for GSF_{Load} (Loading on a Grain Size Fraction) values was adapted from Sutherland (2003):

$$GSF_{Load} = \frac{C_i \times GS_i}{\sum_{i=1}^{m} C_i \times GS_i}, \quad (1)$$

where C_i is the heavy metal concentration in an individual grain size fraction in mg/kg, GS_i is the mass percentage of that size fraction, and m is the total number of grain size fractions.

Assessment of the degree of heavy metal contamination

Potential ecological risk index (RI) was introduced to assess the contamination degree of RDS. The equation for calculating the RI was proposed by Hakanson (1980), according to the toxicity of heavy metals and response of the environment:

$$C_f^i = \frac{C^i}{C_n^i}, \quad (2a)$$

$$E_r^i = T_r^i \times C_f^i, \quad (2b)$$

$$RI = \sum E_r^i, \quad (2c)$$

where E_r^i is the monomial potential ecological risk factor, T_r^i is the metal toxic factor. Based on the standardized heavy metal toxic factor developed by Hakanson (1980), the order of level of heavy metal toxicity is Pb=Cu > Zn. The toxic factor for Pb and Cu is 5, and 1 for Zn. C_f^i is the metal pollution factor, C^i is the concentration of the metal in samples, and C_n^i is a reference value for the metal. In this study, C_n^i is taken to be the background values of pristine soils around the city. RI represents the sensitivity of the biological community to the toxic substance and illustrates the potential ecological risk caused by the overall contamination. Since the number of pollutants considered in this study is different from that of Hakanson (1980), adjustment of the factor standard was made as shown in Table 2.

Results and discussion

Particle-size distribution

The particle size is an important parameter for characterising the particle's behaviour. The samples were first analysed for the size fraction. The results are shows in Table 3. There is a decreasing trend in the mean grain size: riverside park > residential area > intense traffic area > commercial area. The mass percentages for particles smaller than 63 μm increase in sequence following the order of intense traffic area, commercial area, residential area and riverside park. However the mass percentages for particles larger than 63 μm show the opposite trend. The mass percentages of particles smaller than 250 μm in these four areas are 61.55, 75.10, 81.56 and 82.48%, respectively. Fine particles seem to account for the majority of RDS in the Zhenjiang city. The mass percentage ratio of the fine (<63 μm) to the coarse (500–2,000 μm) particles varies significantly from 1.2 to 7.2. In contrast, this ratio ranged between 1.3 and 3.8 in the study of Sutherland (2003).

Total metal concentrations of RDS

The mean concentrations of the five metals (Zn, Pb, Cu, Cr and Ni) in the RDS from the four study areas are shown in Fig. 2. It can be seen that Zn shows the highest mean concentration, 687 mg/kg; the highest mean concentrations of Pb, Cu, Cr and Ni are 589, 158, 129 and 125 mg/kg respectively. The highest

Table 2 Standards for C_i^f, E_i^r and RI

C_i^f	Pollution degree	E_i^r	RI	Pollution degree
<3	Clean	≤15	≤50	Low
1–3	Low	15–30	50–100	Moderate
3–6	Moderate	30–60	100–200	Considerable
6–9	Considerable	60–120	>200	High
>9	High	>120		Very high

Table 3 Mass percentages each size fraction of RDS from study areas

Area (μm)	Intense traffic	Commercial	Residential	Riverside park
<54	3.22±0.86	6.35±1.21	12.83±2.50	13.46±2.91
54–63	16.32±4.01	15.12±2.32	26.76±5.61	33.27±3.42
63–125	23.24±4.62	22.32±4.63	21.66±4.85	19.25±4.14
125–250	25.52±6.05	24.96±7.10	21.23±3.46	15.58±4.84
250–500	21.30±3.96	20.54±4.85	11.96±2.41	10.55±3.52
500–1,000	7.14±2.36	6.64±4.33	3.78±0.86	4.63±0.81
1,000–2,000	4.40±0.68	3.5±1.74	1.74±1.30	3.36±0.32

Values expressed as mean± standard deviation

mean metal concentrations occur in the intense traffic area. The variations in the mean metal concentrations of the RDS from the other three areas are less discernible. The ratios of the highest mean concentrations of the five metals (Zn, Pb, Cu, Cr and Ni) to the background metal levels of uncontaminated soils are approximately 6.8, 7.6, 5.3, 1.5 and 1.3 respectively. Based on the calculated standard deviations for the samples, the degree of RDS metal contamination shows a large spatial variation with serious contamination taking place locally. The order of the degree of contamination is the intense traffic area > riverside park > residential area > commercial area. The intense traffic area is characterised by high concentrations of both Zn and Pb while other areas exhibit only high concentrations of Zn.

One of the most important factors that can affect the concentrations of the metals is the land use (Wigington et al. 1983). There are large differences in concentrations of the heavy metal in RDS from different land uses. The common sources of heavy metals in the RDS have been identified: Pb comes mainly from vehicle emissions; Zn is mainly from the tire dust, brake dust, body rust and car tires; Cu, Cr and Ni are mainly from the dust of industrial raw materials; and Ni is related to the geological background (De Miguel et al. 1997; Alloway and Ayres 1997; Li et al. 2001; Yeung et al. 2003). This is why the Zn and Pb concentrations of RDS in the intense traffic areas are high. Moreover, the examined intense traffic area enclosed by four roads is the city's traffic lifeline; along the road, there are several heavily polluting industrial enterprises such as a titanium plant, batteries plant and dye plant. Industrial particulate materials produced by these enterprises will settle inevitably on the surface of the road. Those suspended particles in the air are washed down to the surface during rainfall events. Therefore, in these areas, the Cu, Cr and Ni concentrations of RDS are also high.

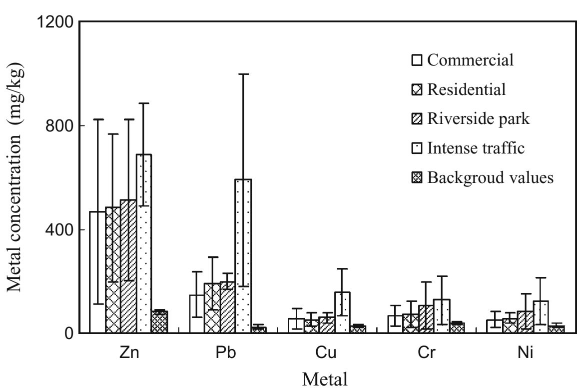

Fig. 2 Mean concentrations of RDS in different areas of Zhenjiang

The riverside park is located in the old urban area, adjacent to a busy traffic network. The residential area is also located in the old urban area, beside a small factory which processes waste materials. So, the clay and organic carbon contents of RDS in the riverside park are high. Metal concentration has been found to correlate with the clay and organic carbon contents (Haster and James 1994; Sansalone and Buchberger 1997; Singh et al. 1999). Therefore, the heavy metal concentrations in the riverside park are relatively high. The roads within the area are used for temporary parking and so relatively large levels of heavy metals are detected in this area. The commercial area located in the city centre is surrounded by a relatively good environment where large vehicles are not permitted to enter and few industrial pollution sources exist. The area is mainly affected by activities of pedestrians and shoppers. Therefore, the local heavy metal concentration is relatively low.

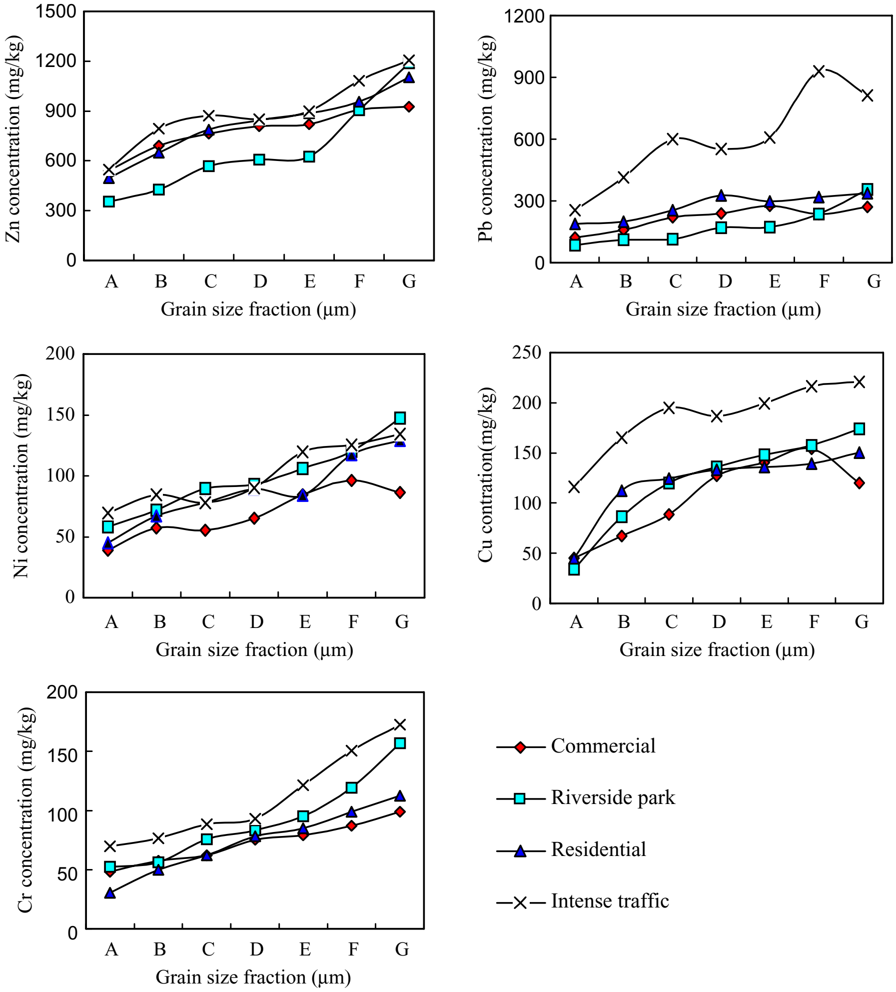

Fig. 3 Distribution of heavy metal concentration in the size-fractionated RDS where A, B, C, D, E, F and G are used to represent the 2,000–1,000, 1,000–500, 500–250, 250–125, 125–63, 63–54 and <54 µm size-fraction

Distribution of heavy metal concentrations in the various grain size fractions

The variations of heavy metal concentration with the size fractions are shown in the Fig. 3. It can be seen that the variation patterns of Zn, Pb, Cu, Cr and Ni in the four study areas are simila**.** The highest concentrations of Zn, Pb, Cu, Cr and Ni in the various size fractions occurred in the intense traffic area. Zn was the most abundant element in the various size fractions in all of the areas. With the exception of Cu in the commercial area, the highest concentrations were found in the particle size fraction within the range of 125–250 µm. Four elements were analysed in each particle size range and the highest concentrations were consistently found in the less than 63 µm size range. This can be attributed to the relatively high organic matter content in this size fraction in the four areas.

The variations of heavy metal contents with different particle size fractions (>63 µm) are characterised by an increasing trend of metal concentrations with decreasing particle size. The ratio of metal concentrations in fine particles to that in coarse particles is greater than 1. Such behaviour is usually attributed to the exponential increase in specific surface area (as the particle size decreases) (Horowitz 1991). The very high concentrations of Zn present in fine particles could be explained by the high Zn concentrations in tires (1,190–18,300 mg/kg) and dusts from brake pads (346–9,630 mg/kg). Copper concentrations are generally low in tires (1–3 mg/kg) but high in brake pad dusts (70–1,980 mg/kg with an average of 219.5 mg/kg) (J. M. Zanders). These vehicle sources tend to release fine particles, which is consistent with the higher metal concentrations in the fine particle fractions of RDS. Therefore, the metal concentrations of the fine particle fractions of RDS from the traffic areas are obviously higher than those in other areas.

Heavy metal loading

The metal loading of the whole sample and the contribution of each particle size fraction to this loading have been determined using the particle-size distribution (Table 3) and the metal concentration data (Fig. 3). The metal loading given by each particle size fraction from the four study areas is shown in Fig. 4. There are large differences in the metal loading percentages of different particle size fractions in the various land use areas. In both the parks and residential areas, the metal loading percentages (Zn, Pb, Cu, Cr and Ni) increase as the particle size decreases except for the finest size (<54 μm). The maximum loading percentage of the very coarse sand fraction (1,000–2,000 μm) accounts for only about 1% of the total loading. In the commercial and intense traffic areas, the maximum loading percentage occurred in the range of 125–250 μm. The loading percentage drops off as the particle size decreases further and the maximum loading of the coarsest size fraction (1,000–2,000 μm) accounts for only about 5% of the total loading. Therefore, the metal content of RDS is mainly stored in the fraction from 0 to 1,000 μm. These data support the conclusion by Stone and Marsalek (1996) that road sediments larger than 2,000 μm are of little importance in carrying and storing metals.

The metal load contributed by each particle size fraction is shown in Fig. 4. In the size 125~2,000 μm fraction, the metal load increases as the particle size decreases with the maximum load in the <63 μm fraction. The ratio of the metal load of the finest (less than 63 μm) particles to that of the coarsest (1,000–2,000 μm) particles varies greatly from area to area. For Zn, the highest ratio value is 14 in the residential area while the smallest value is 4 in the commercial areas. The largest Pb ratio is 19 in the residential areas and the smallest is 5 in the commercial areas. The

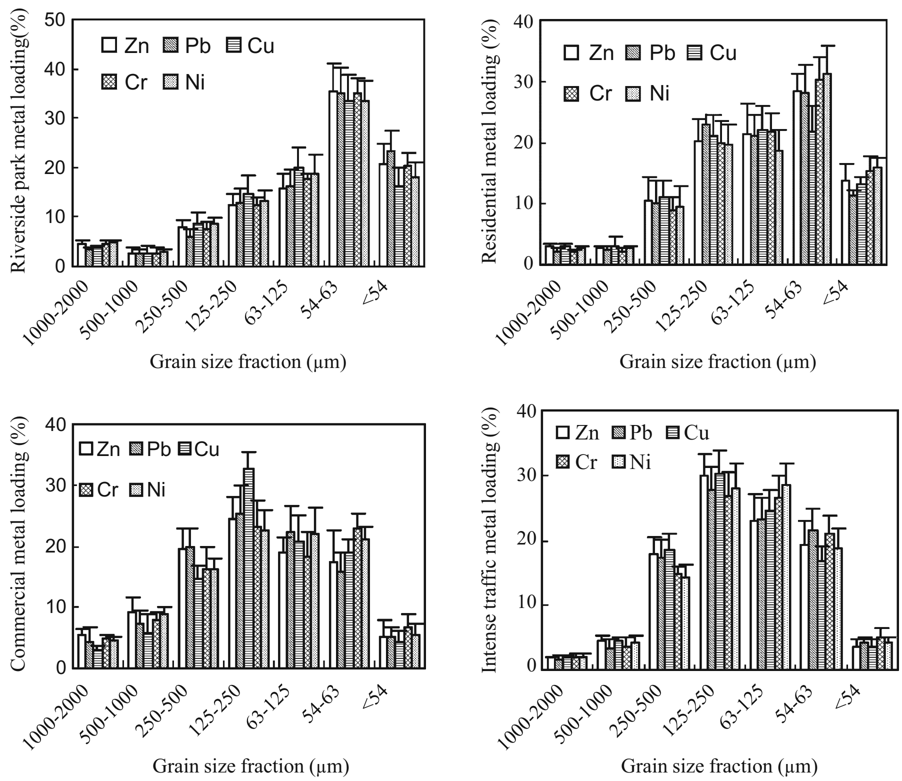

Fig. 4 The heavy metal loading for RDS from different areas in the Zhenjiang city

largest Cu ratio is 13 in the riverside park areas and the smallest is 8 in the commercial areas. The largest ratios for Cr and Ni are respectively 20 and 17 both in the residential areas while the smallest for both metals is 6 in the commercial area. To improve our understanding of the RDS contamination, the particle size distributions of RDS and metals concentrations in different particle size fractions ought to be considered in calculating the pollutant load. The overall metal contamination due to the load from each particle size fraction would provide a sound theoretical basis for effective control and management of urban stormwater runoff pollution.

Assessment of the degree of metal contamination

High concentrations of heavy metals in RDS enhances the importance of sediments as a direct source of potential toxins in the urban water environments. To better assess heavy metal contamination of RDS in the Zhenjiang city, Zn, Pb and Cu with significant environmental implications were selected as the main metals for quantifying the contamination degree. The results are shown in Table 4. According to Table 2 standards, it was found that the Zn concentration is above the medium contamination level in all the areas. The Cu contamination level is high in the intense traffic areas and is low in the other areas. The Pb contamination level is also considerably high in all areas according to the calculated monomial heavy metal pollution coefficient (C_f^i). To quantify the potential ecological risk of the three heavy metals in ˙Zhenjiang RDS ecological risk index, RI, is calculated as the sum of all four risk factors in ˙four areas, which describes the sensitivity of the biological areas to the toxic substances and illustrates the potential ecological risk caused by the overall pollution. The ecological risk index which accounts for the pollution caused by three heavy metals illustrate that the potential ecological risk of Zn is low; however, Pb poses a considerable potential risk to the local ecological system. The potential ecological risk of Cu is at a medium level especially in the intense traffic area. The intense traffic area is potentially posed considerably high risk. There is a sharp boundary at the intense traffic area where the RI values decrease from considerably high ecological risk in intense traffic to low ecological risk in commercial area. The ecological risk index, accounting for the pollution caused by three heavy metals illustrate that Pb, among the three heavy metals, poses the main risk to the urban ecological system in the Zhenjiang city.

Table 4 The heavy metal potential ecological risk indexes in RDS of each area of Zhenjiang city

Metal	Index	Commercial	Riverside park	Residential	Intense traffic
Zn	C_f^i	5.69	5.87	6.24	8.35
	E_r^i	5.69	5.87	6.24	8.35
Pb	C_f^i	6.02	7.83	8.09	23.95
	E_r^i	30.12	39.16	40.45	119.75
Cu	C_f^i	1.99	1.83	2.10	5.61
	E_r^i	9.94	9.15	10.52	28.04
RI		45.83	57.40	52.40	157.14

Concluding remarks

(1) Land use is one of the major factors contributing to the difference in the heavy metal concentration in the RDS. Among all the heavy metals, Zn shows the highest mean concentration of 687 mg/kg. The highest mean concentrations of Pb, Cu, Cr and Ni are 589, 158, 129 and 125 mg/kg respectively. The highest mean concentrations of metals occur in the intense traffic area. The variations in the mean concentrations of Zn, Pb, Cr, Ni and Cu in the RDS are less discernible in the other three areas.

(2) The important index of contamination for RDS is the ratio of the concentration of the fine particles to that of the coarse particles. In the study areas, such ratios are found to be larger than 1. So, especially the fine particle size is concerned. The metal concentration generally increases with decreasing particle sizes.

(3) There are large differences in the metal loading percentage of different particle size fractions among the samples from the study areas of different land uses. Overall, particles in the <63 μm fraction is dominant of the total metal loading. In contrast, the storage in the coarsest fraction (1,000–2,000 μm) accounts for small part of the total load.

(4) Zn and Pb show moderate to high levels of contamination. Cu shows high levels of contamination in the intense traffic areas and low levels

of contamination in the other areas. The calculated ecological risk index suggests that RDS at the intense traffic area pose a considerably high potential risk for the local biological community. The potential ecological risk due to Pb is particularly high.

(5) These findings will facilitate the characterization of contamination of RDS and are significant from an environmental management perspective, especially for the control of urban runoff contamination.

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