

# Pollution and Ecological Risk Assessment of Potentially Toxic Elements in Road-Deposited Sediments Around the Active Smelting Industry of Korea

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## Research Article

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# Abstract

Potentially toxic elements (PTEs) were investigated in the different sizes of road deposited sediments (RDS) around the active smelting industry to understand their sources and to assess the pollution and ecological risk levels. The highest PTEs concentrations was shown near the raw materials import port and the smelting facilities. The fine particles of RDS showed extremely high PTEs concentrations. Zn has the highest mean concentration in the <63 mm particle size of RDS, followed by Pb>Cu>As>Cr>Ni>Cd>Hg. The PTEs concentrations of this study were the highest values compared to the soils around the smelter and the RDS in urban and industrial areas in the world. This indicates that these PTEs pollution in RDS were mainly attributed to the transportation of raw materials for the smelting industry. According to nemerow pollution index calculation, RDS at all sampling sites with particles of less than 250 mm was seriously polluted with PTEs. The ecological risk was also found to be very high in all RDS fractions and highly toxic elements such as Cd, Pb and Hg pose extremely risk. Given the total amounts PTEs in the road surface, it is necessary to apply RDS removal management plan to reduce the PTEs pollution.

# Introduction

Road infrastructure and transportation are important component of urban area and have enabled the rapid development of industrialization and urbanization. Road deposited sediments (RDS) are highly contaminated with potentially toxic elements (PTEs) by various traffic and industry related sources such as vehicular exhaust and non-exhaust sources, atmospheric deposition and surrounding soil erosion and spill of industrial raw materials during transportation<sup>1-6</sup>. Thus, roads are often a prominent point-source and non-point source of dissolved and sediment-associated PTEs<sup>6-10</sup>. The particle size distribution of RDS is a very important factor as it determines the behavior and mobility of the particles and shows the highest concentration of PTEs in fine particles<sup>11-13</sup>. Environmental concern related to RDS is that RDS containing high concentrations of PTEs on the road surface adversely affects the surrounding environments as well as human health<sup>14-16</sup>. The fine fraction of RDS are readily transported to the surrounding aquatic environments by stormwater runoff. Many studies reported that the fine particle (<44 mm<sup>17</sup>, <63mm<sup>18</sup>, <125 mm<sup>6</sup>) largely contributed of total suspended solids (TSS) load in stormwater runoff from urban and industrial areas. The finer RDS are also re-suspended by strong winds and the high-speed movement of the vehicles, therefore, PTEs bound to fine particles of RDS and surrounding soils can enter the human body via inhalation, ingestion and dermal absorption<sup>19-21</sup>. Our previous study reported that 14.3-15.8 g/m<sup>2</sup> (<63 mm) and 3.2-4.2 g/m<sup>2</sup> (>1000 mm) of RDS in urban area accumulate on the road surface in Korea<sup>22</sup>. On road surface, RDS are deposited of 11.7 g/m<sup>2</sup> in urban area<sup>17</sup> and 174.6 g/m<sup>2</sup> in industrial area<sup>6</sup>. Industrial areas are characterized by a higher accumulation of road dust than urban areas. In Korea, the amounts and concentrations of PTES in fine particle of RDS were much higher in industrial area than in urban areas<sup>5, 22-23</sup>. Given the total length of road, a huge amount of PTEs would have been accumulated in road surface. Of course, PTEs pollution in industrial RDS is subjected to the complex influence of traffic and industrial activities. Lanzerstorfer<sup>13</sup> reported that the PTEs concentrations in urban RDS can be used a useful indicator for environmental pollution. The potential sources of PTEs can be identified by evaluating the PTEs concentrations in RDS from different land use types and the elemental ratios of them<sup>11, 24-26</sup>. Although there are very few RDS studies in industrial areas

compared to urban areas, the study of PTEs concentration in RDS from the industrial area will make it possible to differentiate between transport and industrial activities. The objectives of this study are to: (1) evaluate the PTEs pollution levels of different RDS sizes in industrial area where the smelting industry is active; (2) identify the pollution sources of PTEs; (3) assess the potential ecological posed by PTEs.

## Materials And Methods

### Sampling and PTEs analysis.

Total of 14 RDS samples were collected from Onsan Industrial complex including several smelting facilities of Korea (Fig. 1) during December 2013 following a dry weather periods of about 10 days. The RDS were collected in four and more sub-sampling for each site using cordless vacuum cleaner (DC-35, Dyson Co., UK) with 0.5 m × 0.5 m space along the curb of road. After sampling, the samples were stored in a zipper bag and the vacuum cleaner was replaced or cleaned to avoid cross contamination. Each RDS sample were sieved individually using <63 mm, 63-125 mm, 125-250 mm, 250-500 mm, 500-1000 mm, >1000 mm<sup>27</sup> by using vibratory sieve shaker (Analysette 3 pro, Fritsch Co., Germany) with nylon sieves. Each fraction of RDS sample was weighted, pulverized (Pulverisette 6, Fritsch Co., Germany) and stored separately into pre-acid cleaned polyethylene bottle until metal analysis. About 0.1 g of each ground and homogenized RDS sample was weighted in Teflon digestion vessel added with high purity (Ultra-100 grade, Kanto Chemical, Japan) of HNO<sub>3</sub>, HF and HClO<sub>4</sub> on a hot plate at 180 °C for 24 h for total digestion. After evaporation and redissolution with 2% HNO<sub>3</sub>, heavy metals of Cr, Ni, Cu, Zn, As, Cd and Pb were analyzed using inductively coupled plasma mass spectrometry (ICP-MS, iCAP-Q, Thermo Scientific Co., Germany). Hg was determined using Hg analyzer (Hydra-C, Leeman Labs, USA) based on the USEPA 7473 method. The blanks and duplicate measurements were performed for quality control. Two types of certified reference materials for MESS-4 and PACS-3 (National Research Council, Canada) were used to check data accuracy. Recoveries ranged between 96.4% and 102.1% for MESS-4 and between 93.9% and 106.0% for PACS-3, respectively.

### Pollution level assessment.

The geo-accumulation index ( $I_{geo}$ ), proposed by Muller<sup>28</sup>, can be used to assess the pollution level of individual metal using the following equation:

$$I_{geo} = \log_2 (C_i / (1.5 \times B_i))$$

where  $C_i$  and  $B_i$  are the concentrations of RDS samples and the geochemical background values<sup>29</sup>, 1.5 is the background correction efficient.  $I_{geo}$  value were classified into seven categories<sup>28, 30</sup>.

The nemerow index ( $P_N$ ) are widely used to make a comprehensive evaluation of the pollution levels of heavy metals in soils and sediments<sup>31-35</sup> and was calculated using the following equation:

$$P_N = \sqrt{\frac{(\frac{1}{n} \sum_{i=1}^n PI_i^2) + (Max PI)^2}{2}}$$

where PI represent a single pollution index of metal  $i$ ,  $PI_i=C_i/S_i$ .  $C_i$  is the measured concentration of each metal  $i$ . The calculated results of  $P_N$  using the geological background value can be overestimated the magnitude of metal pollution<sup>36</sup>. Therefore, the soil quality guideline values were used in this study to better reflect the comprehensive pollution level of heavy metals in Korea.  $S_i$  is the soil pollution concern standard for road and factory site in Korea and its values (mg/kg) of  $Cr^{6+}$ , Ni, Cu, Zn, As, Cd, Pb and Hg were 40, 500, 2000, 2000, 200, 60, 700 and 20, respectively<sup>37</sup>. In case of Cr, in Korea soil quality guideline, the concentration of  $Cr^{6+}$  is recommended. Lazo<sup>38</sup> reported that the content of  $Cr^{6+}$  accounts for more than 90% of total Cr in the contaminated area. Therefore, the application of total Cr concentration instead of  $Cr^{6+}$  of this study did not significantly affect the results of pollution evaluation for eight metals using  $P_N$ . This index divides pollution into five grades<sup>39</sup>.

### Potential ecological risk assessment.

Potential ecological risk index (PER), proposed by Hakanson<sup>40</sup> can be used to assess the risk of eight metals based on their toxicity response using the following equations:

$$E_r^i = T_r^i \times (C_i/B_i)$$

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

where  $C_i$  and  $B_i$  were the same as those in  $I_{geo}$  calculation.  $E_r^i$  is the single factor ecological risk degree for PTEs.  $T_r^i$  is the toxic response factor for a single metal pollution (Hg=40, Cd=30, As=10, Cu=Ni=Pb=5, Cr=2, Zn=1)<sup>40-41</sup>.  $E_r^i$  were classified into five classes<sup>42</sup> and the PER value were classified into four classes<sup>40, 43</sup>. PASW statistics program (version 18) were used for the pearson's correlation analysis and hierarchical cluster analysis (HCA) to understand the relationship between metals and different size fractions of RDS.

**Table 1.** Minimum, maximum and mean values of PTEs in the different sizes of road-deposited sediments of this study.

Size		RDS	Cr	Ni	Cu	Zn	As	Cd	Pb	Hg
(mm)		g/m <sup>2</sup>	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
>1000	Min	4	51	26	71g	256	3	0.9	65	0.01
	Max	298	220	68	3212	3735	100	20.9	1685	27.9
	<b>Mean</b>	<b>104</b>	<b>120</b>	<b>46</b>	<b>623</b>	<b>623</b>	<b>46</b>	<b>6.3</b>	<b>470</b>	<b>2.5</b>
	SD	92	56	15	846	846	28	5.0	418	7.4
500~ 1000	Min	30	76	28	249	1177	10	2.0	209	0.1
	Max	688	2262	1156	7537	16579	187	45.9	4083	54.6
	<b>Mean</b>	<b>200</b>	<b>410</b>	<b>166</b>	<b>2243</b>	<b>7167</b>	<b>67</b>	<b>11.5</b>	<b>1483</b>	<b>4.5</b>
	SD	193	552	287	2016	5186	49	11.2	1107	14.4
250~ 500	Min	85	80	23	294	1518	25	2.2	240	0.1
	Max	1104	435	187	8477	20034	341	64.2	6264	62.4
	<b>Mean</b>	<b>373</b>	<b>249</b>	<b>111</b>	<b>2782</b>	<b>8646</b>	<b>92</b>	<b>18.8</b>	<b>2171</b>	<b>5.5</b>
	SD	330	107	50	2170	5708	85	16.9	1560	16.4
125~ 250	Min	72	100	23	284	1279	12	3.7	268	0.3
	Max	704	678	556	10875	26279	374	157.9	10311	69.6
	<b>Mean</b>	<b>272</b>	<b>285</b>	<b>147</b>	<b>2978</b>	<b>6743</b>	<b>141</b>	<b>38.0</b>	<b>3072</b>	<b>7.2</b>
	SD	223	138	127	2708	6135	110	39.4	2718	18.1
63~ 125	Min	53	199	54	348	2152	59	7.4	463	0.4
	Max	335	921	645	16511	112751	840	644.1	23536	46.4
	<b>Mean</b>	<b>138</b>	<b>476</b>	<b>222</b>	<b>5265</b>	<b>19620</b>	<b>330</b>	<b>128.7</b>	<b>7924</b>	<b>8.9</b>
	SD	94	217	153	4258	28085	204	162.6	6927	11.9
<63	Min	28	200	106	975	4400	110	17.6	1253	1.2
	Max	197	1416	1081	18873	166457	2721	975.6	44667	45.1
	<b>Mean</b>	<b>85</b>	<b>596</b>	<b>364</b>	<b>7071</b>	<b>34592</b>	<b>961</b>	<b>225.1</b>	<b>13561</b>	<b>17.0</b>
	SD	50	368	299	5552	44856	744	278.6	12438	13.2

## Results And Discussion

PTEs contents in different size of RDS.

The minimum, maximum and mean values of the total RDS amount and Cr, Ni, Cu, Zn, As, Cd, Pb and Hg concentrations are shown in Table 1. The Cu, Zn, As, Cd, Pb and Hg concentrations significantly increased with decreasing in particle size of RDS (Fig. 2). Mean PTE concentrations in the fine particle size (<63 mm) of RDS was 5.0 (Cr) ~ 55.5 (Zn) times higher than those in the large particle size (>1000 mm). The mean concentrations of RDS (63 mm) was highest for Zn at 34,592 mg/kg, followed by Pb (13,561) > Cu (7,071) > As (961) > Cr (596) > Ni (364) > Cd (225) > Hg (17). The Cr and Ni concentrations in the fine particle size (<63 mm) showed highest values at S6 site, but the highest concentrations for Cu, Zn, As, Cd were observed in S4 and S5 sites which the smelting facilities exist.

The study area, Onsan industrial complex, has concentrated non-ferrous metal production industry of Korea. There are many smelting facilities in operation that produces 1.2 Mt of nonferrous metals annually, including Cu, Zn, Cd and Pb. Garmash (1985)<sup>44</sup> found that nonferrous metal smelters are more contaminated with Zn, Pb and Cd in soils than iron smelters. There are a raw material import port and outdoor raw material storage for smelting industry on the north of S4 site. Raw materials are transported using a large truck. The highest PTEs concentrations were observed in all particle sizes of RDS around the smelting facilities, indicating that the anthropogenic source of these PTEs were attributed to the transportation of raw materials for the smelting industry. The high correlation between Cr and Ni was observed. RDS of this study is significantly correlated with among Cu, Zn, As, Cd and Pb. Hierarchical cluster analysis was also conducted to understand the relationship among the different size of RDS. The dendrogram of the different particle sizes of RDS show two cluster groups. Group 1 comprises two particle size fractions (<125 mm) with significant PTEs contamination. Group 2 corresponded to the particle size of < 125 mm with moderate PTEs contamination.

The PTEs concentrations of this study are higher than in those of RDS in urban area of Korea<sup>10, 22-23</sup>, indicating that RDS of industrial area are mainly influenced by industrial activities related to transportation of raw materials for smelting industry. In particular, the concentration of PTEs in the fine (<63 mm) size of RDS in this study were the highest values compared to the RDS in urban cities<sup>3, 22, 45-47</sup> and the soils around the smelter<sup>48-59</sup> in the world (Table 2).

**Table 2.** Comparison between the average PTEs concentrations (mg/kg) in the road-deposited sediment (<63 mm) and those in the other published data.

Cr	Ni	Cu	Zn	As	Cd	Pb	Hg	Sample types	References
596	364	7071	34592	961	225.1	13561	17.0	<63mm, RDS	This study
167	50	160	907	15.7	1.4	207	0.04	<63mm, RDS	Urban, Korea <sup>22</sup>
841	246	193	2982	16.0	2.1	221	0.21	<63mm, RDS	Industrial, Korea <sup>45</sup>
-	52.1	345	1271	-	2.3	223	-	<75mm RDS	Urban, Korea <sup>46</sup>
-	-	124	630	-	38	350	-	<63mm, RDS	Urban, Spain <sup>47</sup>
182	109	287	1829	-	0.9	456	-	<20mm, RDS	Motorway, Poland <sup>3</sup> (
-	-	78	1062	-	5.54	363	-	Top soil (0-30cm)	Pb/Zn smelter, Australia <sup>48</sup>
			11995		169	2340		Top soil	Pb/Zn smelter, Fracne <sup>49</sup>
		4011	1503	333		1503		Soil (10~30 cm)	Cu smelter, Poland <sup>50</sup>
	10.2	13.6	2175	81	14.8	545		Top soil (0-10cm)	Pb/Zn smelter, Poland <sup>51</sup>
		161	3630		54.5	1740		Top soil (0-15cm)	Pb/Zn smelter, UK <sup>52</sup>
227	247	666	5917		138	4892		Top soil (0-20cm)	Pb/Zn smelter, Bulgaria <sup>53</sup>
		118	2558	76	31.7	953	2.27	Top soil (0-20cm)	Pb/Zn smelter, China <sup>54</sup>
		39	597		22.1	992		Top soil (0-5cm)	Pb/Zn smelter, China <sup>55</sup>
30	8	1877	5666	112	31.5	1004	12.8	<63mm, Top soil	Cu/Pb/Zn smelter, Canada <sup>56</sup>
		100	1100	100	7.6	2600	0.85	Surface soil	Pb/Zn smelter, Kosove <sup>57</sup>
160	54	44	280	9.3	7.7	220	0.25	Top soil (0-5 cm)	Pb/Zn smelter, Macedonia <sup>58</sup>
		4470	2620	1450	96.7	4640		Top soil (0-1cm)	Cu/Pb smelter, Namibia <sup>59</sup>

### **Pollution assess in industrial RDS.**

Based on PTEs concentrations in different particle size of RDS, quantification of PTEs pollution was conducted using the  $I_{geo}$  and  $P_N$  indices. Comparison of mean  $I_{geo}$  values in different particle size of RDS is shown in Table 3. RDS in less than 63 mm had the highest  $I_{geo}$  value for all PTEs. The mean of  $I_{geo}$  values of PTEs for <63 mm size of RDS are arranged in the following order: Cd>Pb>Zn>Hg>Cu>As>Ni>Cr. The mean values of  $I_{geo}$  for Cr and Ni show that the large particle (>125 mm) is not polluted, but the fine particle (<125 mm) is characterized as medium to heavily pollution. The mean values of  $I_{geo}$  showed that the RDS less than 1000 mm have an extremely heavy pollution for Cu, Zn, Cd and Pb. For the case of As and Hg, the mean values of  $I_{geo}$  in RDS less than 125 mm exceeded 5 corresponding extremely heavy pollution and RDS larger than 500 mm had relatively low pollution levels.

The results of nemerow index ( $P_N$ ) showed that the mean values were in the descending order of less than 63 mm (23.2) > 63-125 mm (12.8) > 125-250 mm (5.8) > 250-500 mm (4.7) > 500-1000 mm (7.5) > above 1000 mm (2.2). As the RDS size decreased, the  $P_N$  value increases. For the RDS size less than 250 mm,  $P_N$  values are significantly exceeding 3 at all sampling sites, representing serious polluted with PTEs (Fig. 3). Fig. 4 shows the spatial distribution of  $P_N$  values in the different size of RDS. The high pollution degree of RDS (<125 mm) indicates that the fine particles of RDS are attached to the tires according to vehicle transport and spreads through the entire road surface.

### **Ecological risk assessmen in industrial RDS.**

The results of single factor ecological risk degree ( $E_r^i$ ) are presented in Table 4. The highest mean  $E_r^i$  value is observed for Cd (75,044) in <63 mm of RDS and the lowest  $E_r^i$  value are observed for Cr (2.6) in >1000 mm of RDS. Similar to the PTEs concentrations, the single ecological risk was higher as the particle size of RDS decreased. The mean of single factor ecological risk degree ( $E_r^i$ ) values of Cr and Ni in all particle size was less than 40, which indicated that Cr and Ni concentrations of RDS correspond to the low ecological risk level. The mean values of  $E_r^i$  of Cd were the highest among those of all PTEs for all sampling sites and ranged from 2,095 (>1000 mm) to 75,044 (<63 mm), indicating extremely potential risk levels ( $E_r^i$  >320). Hg has the second highest  $E_r^i$  values and exceed 320 in all particle sizes of RDS, showing extremely potential risk. For Cu and Pb, the mean of  $E_r^i$  values was also obtained extremely potential risk except for the large RDS size >1000 mm. Generally, the  $E_r^i$  values were ranked in the following order: Cd>Hg>Pb>Cu>As>Zn>Ni>Cr. The mean of PER values, the comprehensive ecological risk of eight PTEs, ranged from 4,434 (>1000 mm) to 96,435 (<63 mm) and the fine particle was 21.7 times higher that large particle. The PER values exceeded 600, indicating very high ecological risk for all studied sites and particle size of RDS except for >1000 mm at S11 site (Fig. 3).

### **PTEs loads in RDS on the road surface around the active smelting industry.**

The mean of RDS amount in road surface were 104 for >1000 mm, 200 for 500-1000 mm, 373 for 250-500 mm, 272 for 125-250 mm, 138 for 63-125 mm, 85 g/m<sup>2</sup> for <63 mm, respectively (Table 1). The amount of RDS with particle size of 250-500 mm was the most abundant in this study. We also calculated the PTEs loads and the contribution of each particle size fraction using GSF<sub>loading</sub> (Fig. 5). A significant amount of PTEs (21,872 mg/m<sup>2</sup>) has accumulated on the road surface in industrial area. The each PTEs load in industrial RDS was much higher than in urban RDS<sup>17</sup>. The order of the sum PTEs loading value in RDS for all measured PTEs was less than 63 mm (26.3%) > 250-500 mm (23.6%) > 63-125 mm (22.5%) > 125-250 mm (16.7%) > 500-1000 mm (9.6%) > above 1000 mm (1.3%). Among the eight PTEs, Zn had the highest GSF<sub>loading</sub> value per unit area (11,802 mg/m<sup>2</sup>) of road surface, in the order of Cu (4,984) > Pb (4,177) > Cr (370) > As (215) > Ni (169) > Cd (47) > Hg (4). Given the GSF<sub>loading</sub> and PTEs concentrations, particles of 250-500 mm showed the highest contribution for Cr, Ni, Cu and Zn, but the mean values of GSF<sub>loading</sub> were dominant in the <63 mm fraction for Zn, As, Cd and Hg.

The mean of PTEs loading in RDS has accumulated about 48.8% in the <125 mm fraction, which is readily washed from stormwater runoff and is difficult to remove by road cleaning. Jeong et al.<sup>6</sup> evaluated the particle size distribution in total suspended solids (TSS) of industrial runoff and found that <125 mm particle size in TSS ranged from 53.9% to 98.7%. The particle size of <125 mm RDS accounted for 35.1%, 37.1%, 40.6%, 43.1%, 59.8%, 62.9%, 53.7% and 63.2 of Cr, Ni, Cu, Zn, As, Cd, Pb and Hg in total RDS, respectively. Our previous study proposed that RDS make a significant contribution of PTEs pollution to total suspended particles in stormwater runoff at industrial areas<sup>6</sup>.

Road surface is pollution hotspot where enormous PTEs accumulate in RDS and transport to surrounding environments via stormwater runoff and wind. The curb is the most RDS-accumulated area on a road surface<sup>6, 60</sup>. Therefore, road and street sweeping technique is recognizes as being efficient and important tool to reduce stormwater and atmosphere pollution derived from the RDS<sup>61-63</sup>. Tobin and Brinkmann<sup>61</sup> reported that the rotary brush sweeper is more efficient than vacuum sweeper for large sediments in road, but vacuum sweeper can be effective in removing fine particles. Kim et al.<sup>62</sup> estimated the removal efficiency of RDS by sweeping with vacuum-assisted rotary brush sweeper in Korea. They found that the mean of reduction in the load of RDS and heavy metals of highway by sweeping was 61.1% and 48%, respectively. The removal of particles (>65 mm) are greatly improve the highway runoff quality by vacuum-related rotary brush sweeper of RDS, indicating that the sweeping is more efficient for large particles. Given the total length of entire road, the amount of RDS and PTEs concentrations on the road surface, huge amounts of PTEs can be accumulated in the RDS of industrial area. RDS had the highest concentrations of PTEs in fine particle that are difficult to remove by road sweeping. In Korea, RDS is periodically removed by various types of road cleaning vehicles in urban cities, but road cleaning is not performed in industrial areas. Our results show that road cleaning in industrial areas can remove enormous PTEs that affect the environments and human health. RDS management strategies for fine particles are required to reduce the PTEs pollution and the ecological environmental risk.

## Conclusions

RDS is highly polluted by various pollutants, especially PTEs, and has received much attention as one of important pollution sources in the terrestrial, coastal and atmospheric environments as well as human health problems. We studied the concentrations and loadings of PTEs in different particle sizes of RDS around the active smelting industry to figure out their pollution source and to assess the pollution and potential ecological risk levels. PTE concentration in RDS increased with decreasing in particle size and the fine size (<63 mm) of RDS was heavily polluted with PTEs. Mean metal concentrations (mg/kg) in the fine size (<63 mm) were on the order of Zn (34,592) > Pb (13,561) > Cu (7071) > As (961) > Cr (596) > Ni (364) > Cd (225) > Hg (17). These concentrations of PTEs in this study were the highest values compared to the soils around the smelter and the RDS in urban cities in the world. Our results indicate that the PTEs in RDS might be affected by the truck spills during raw materials transportation and re-scattering of accumulated RDS because of high pollution levels not only around the smelting facility but also on the entire road surface. Road surface around the smelter have a significant amount of RDS accumulated with mean of 21,678 mg/m<sup>2</sup> compared to urban areas. Cr, Ni, Cu, Zn, As, Cd, Pb and Hg were accumulated per unit area in amounts of 370, 169, 4984, 11802, 215, 47, 4177 and 4 mg/m<sup>2</sup> in the road surface of study area. The relative contributions of Zn, As, Cd, Pb and Hg in the fraction (<125 mm) that could transport to the surrounding environments via runoff and resuspension accounted for 39.6% (Zn), 57.9% (As), 63.8% (Cd), 52.3% (Pb) and 51.3% (Hg) of the total RDS. Given the amount of PTEs deposited in the road surface, it is necessary to apply RDS removal management plan to reduce the PTEs pollution.

## Declarations

### Data availability

All Data for this study are available from the corresponding author on request.

### Competing interests (mandatory)

The authors declare that they have no conflict of interest.

### Acknowledgements (optional)

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### Author contributions

H.J and K.R conceptualized, conducted the PTEs measurements, prepared all figures and tables and wrote original manuscript. J.C performed RDS sampling and reviewed the manuscript. All authors reviewed the manuscript.

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## Tables

Due to technical limitations, table 3,4 is only available as a download in the Supplemental Files section.

## Figures

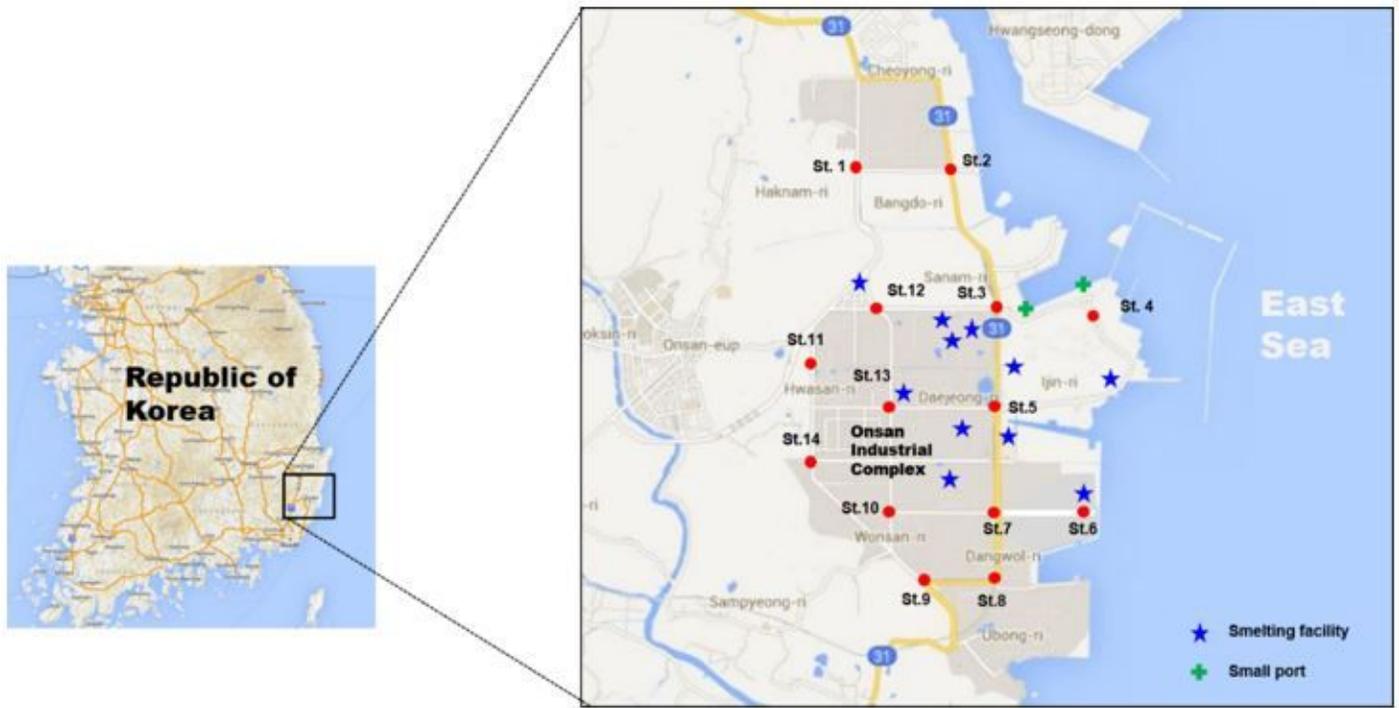


Figure 1

Locations of sampling sites for road-deposited sediments from Onsan industrial complex including the smelter of Korea. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

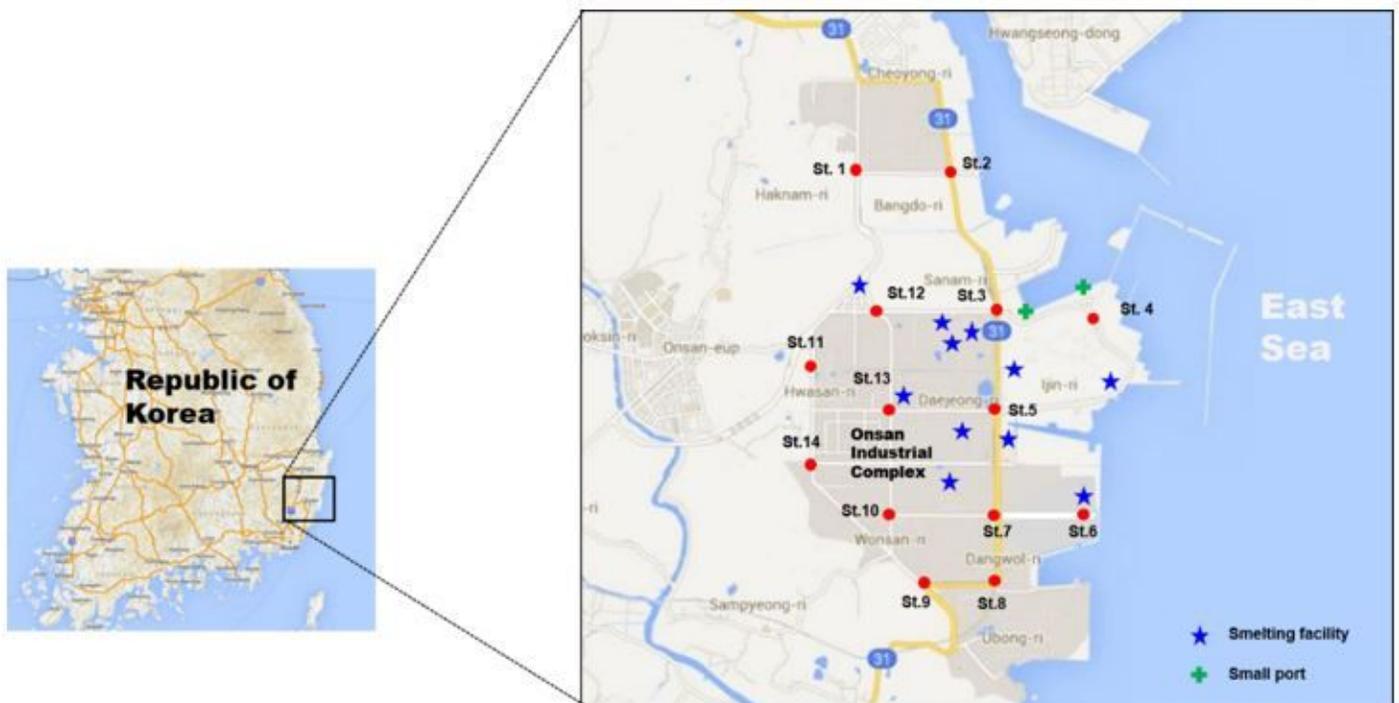
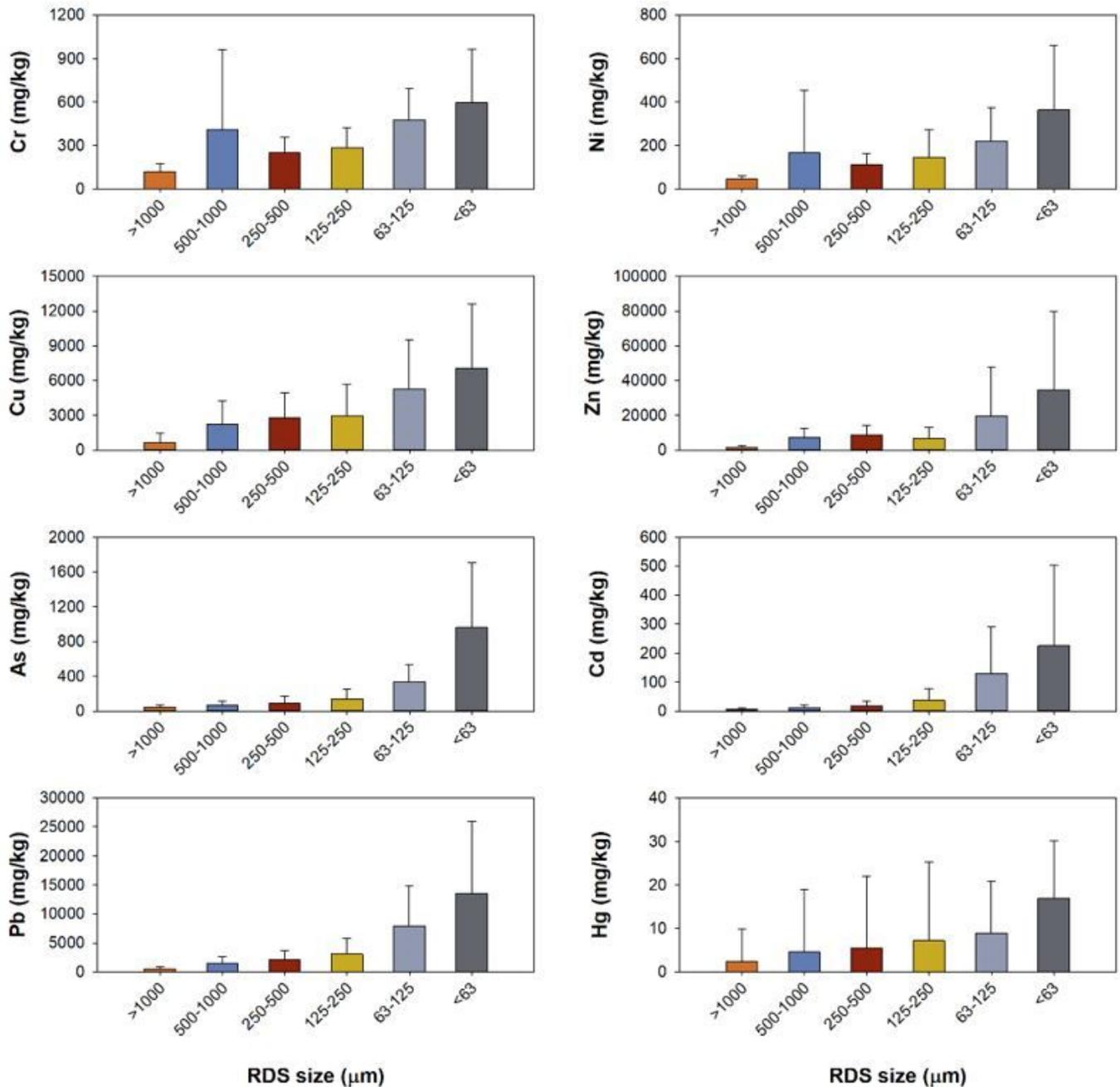


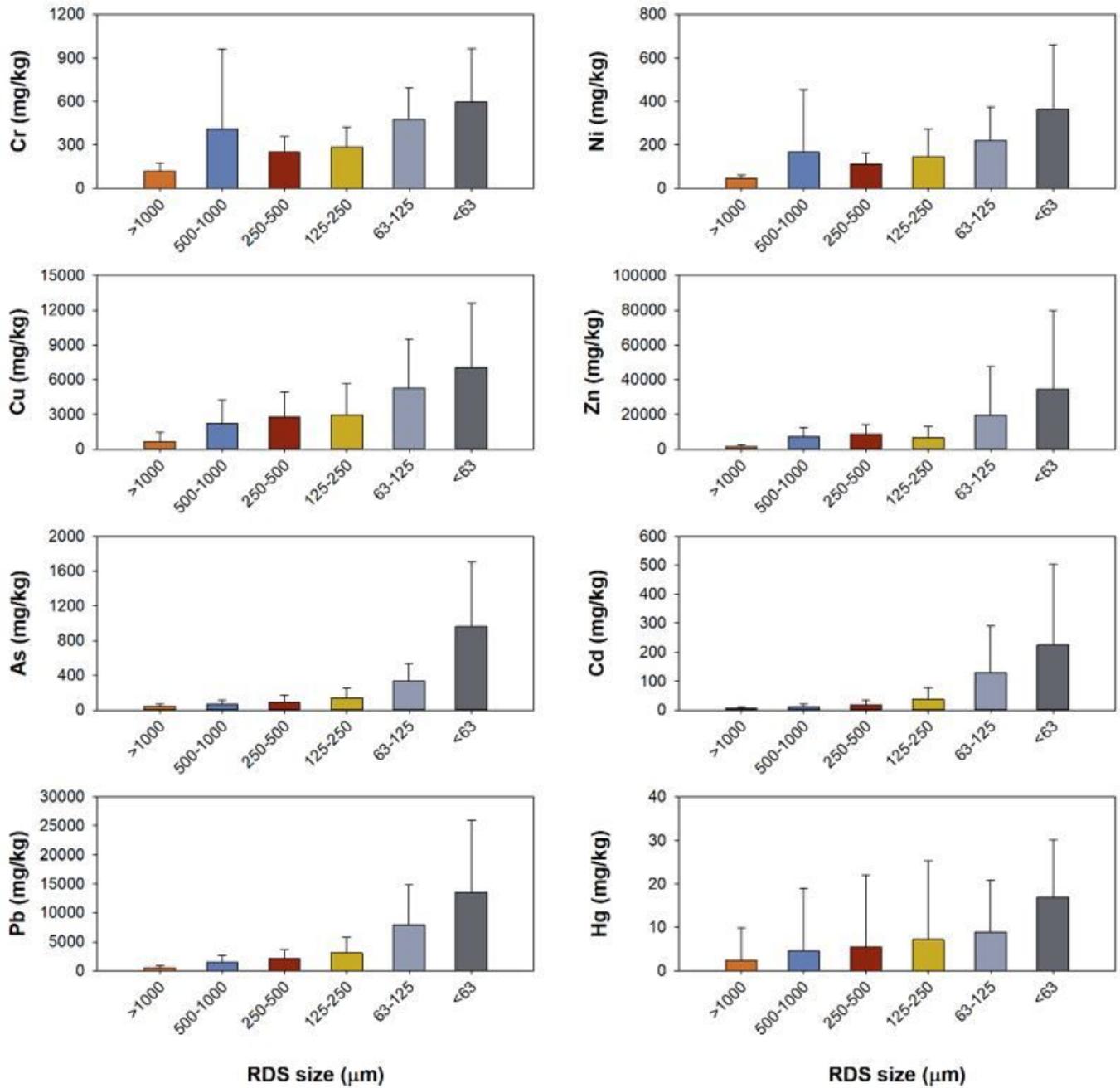
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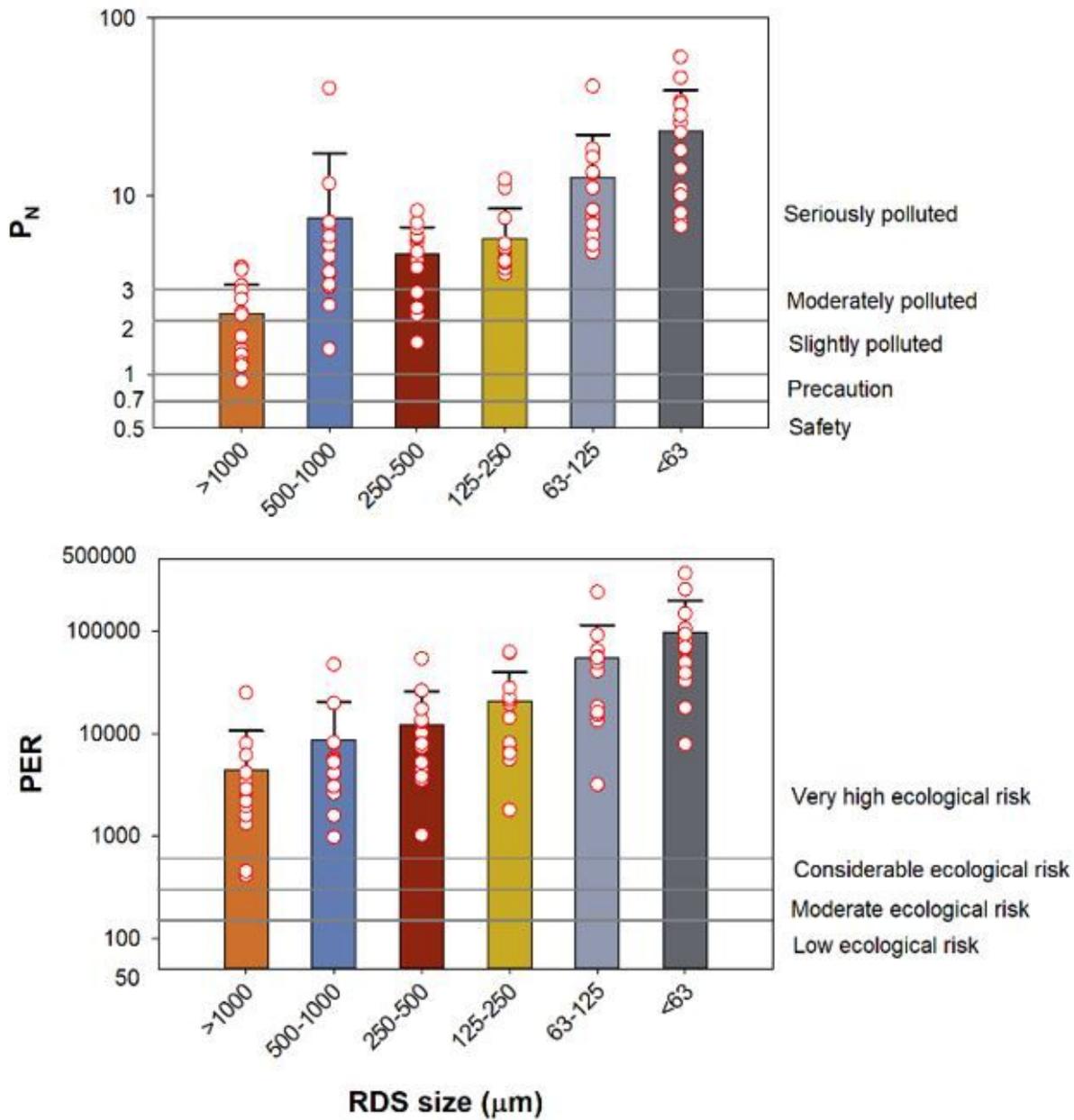
**Figure 2**

Comparison of mean PTEs concentrations (mg/kg) with standard deviation in the different sizes of road-deposited sediments of this study.



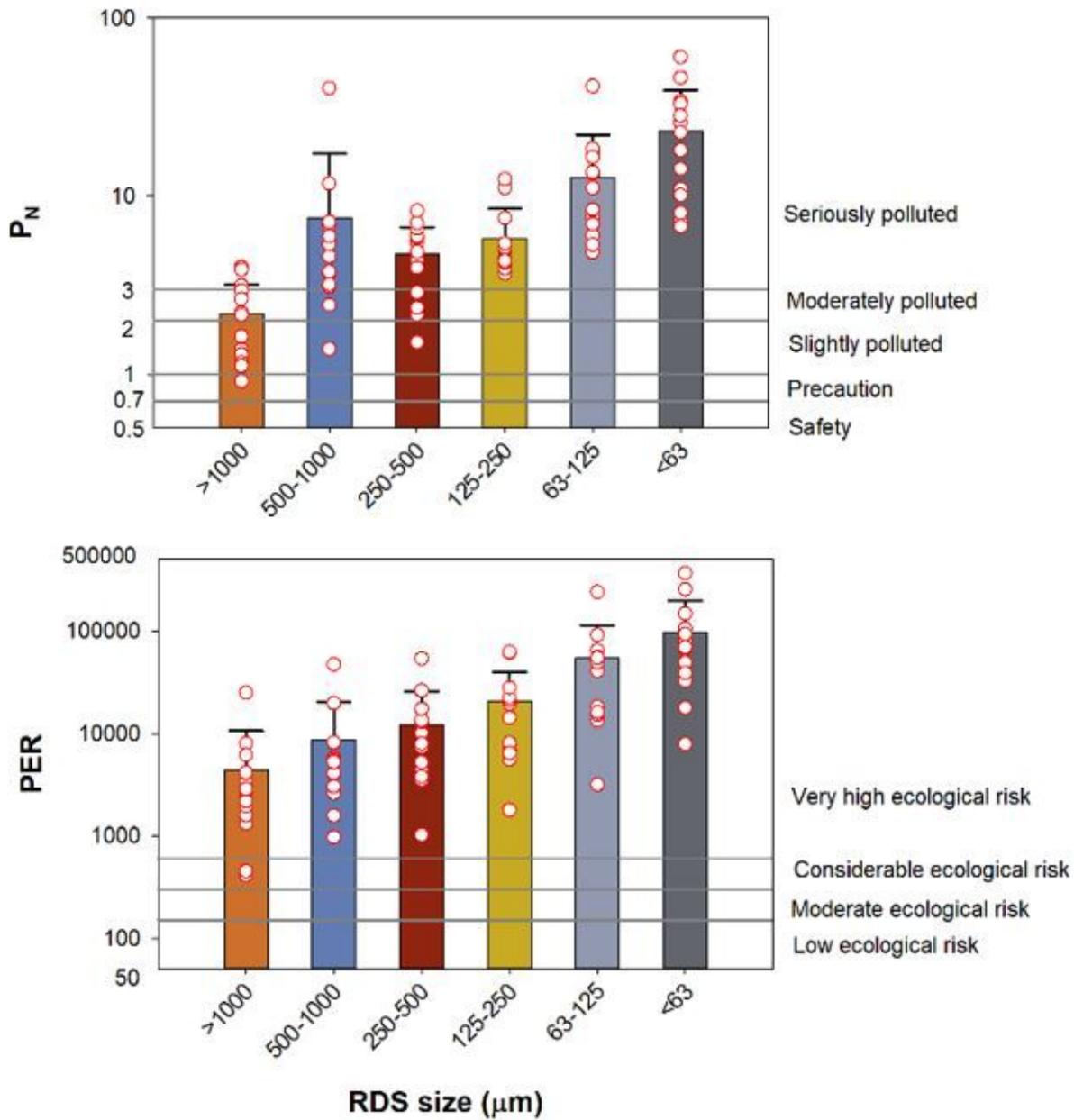
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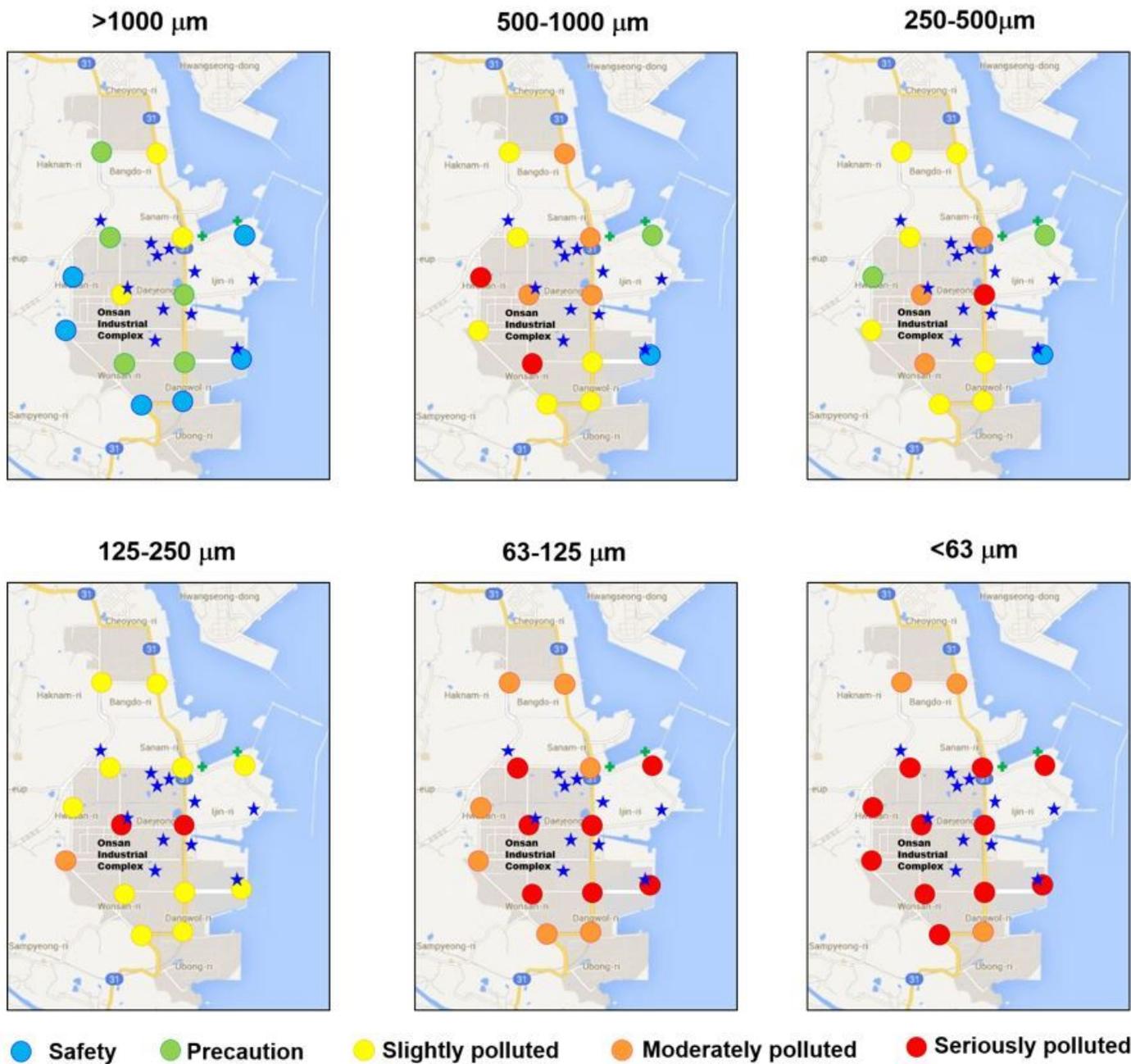
**Figure 3**

Comparison of nemerow index ( $P_N$ ) and potential ecological risk index (PER) of the difference sizes of road deposited sediments of this study.



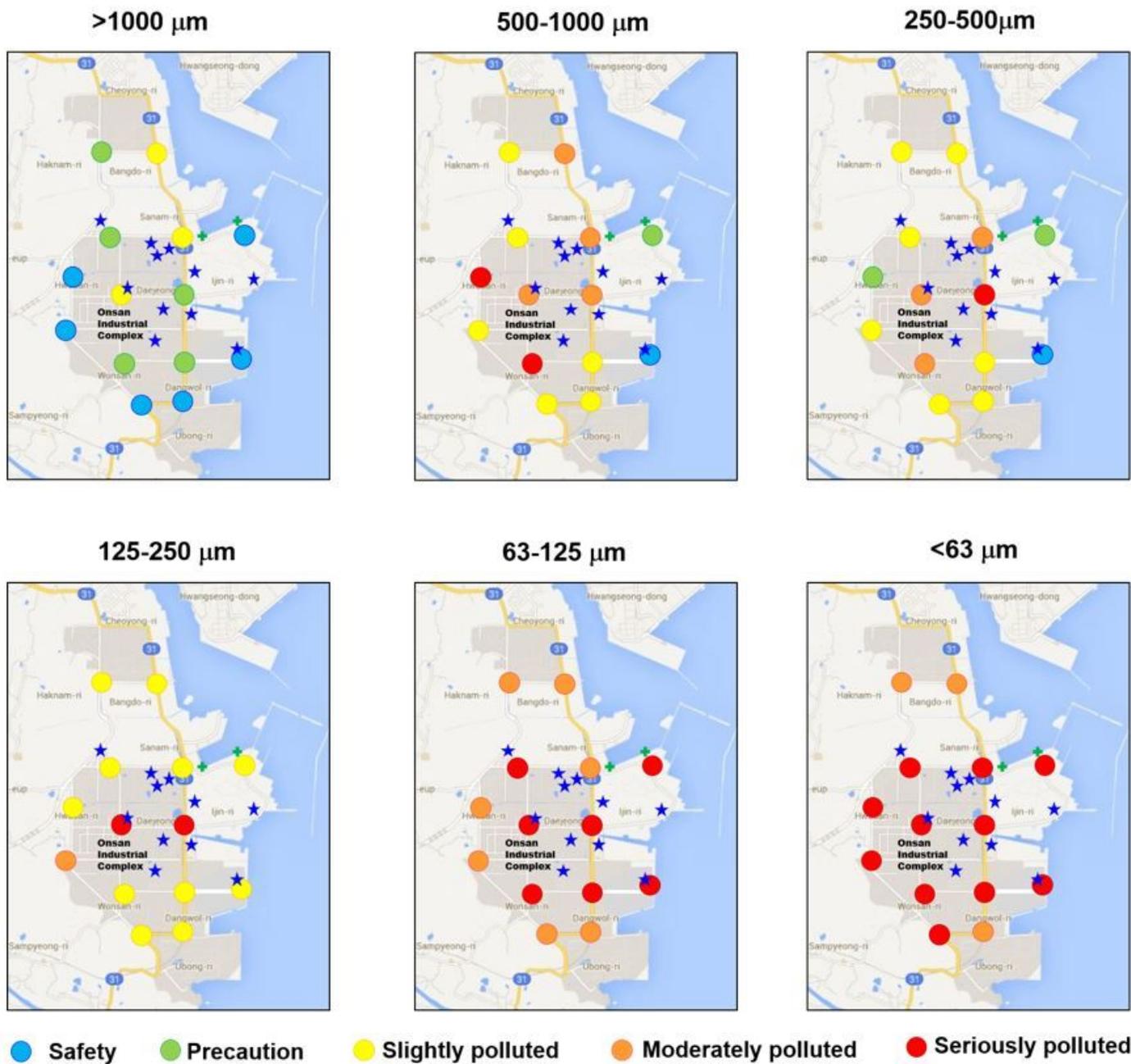
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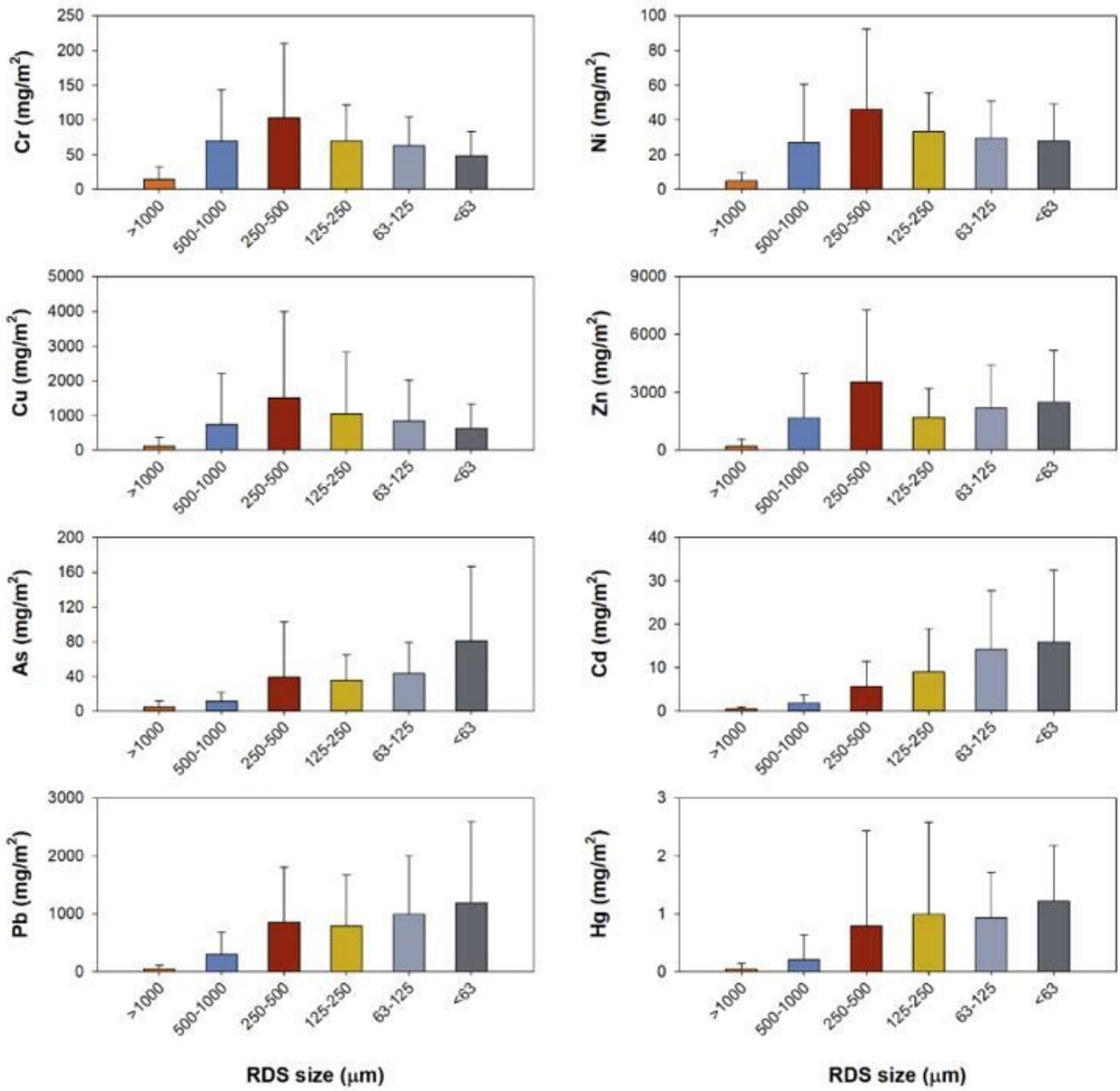
**Figure 4**

Spatial distribution of nemerow index (PN) values in the different sizes of road-deposited sediments. Blue star symbol means a smelting facility. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.



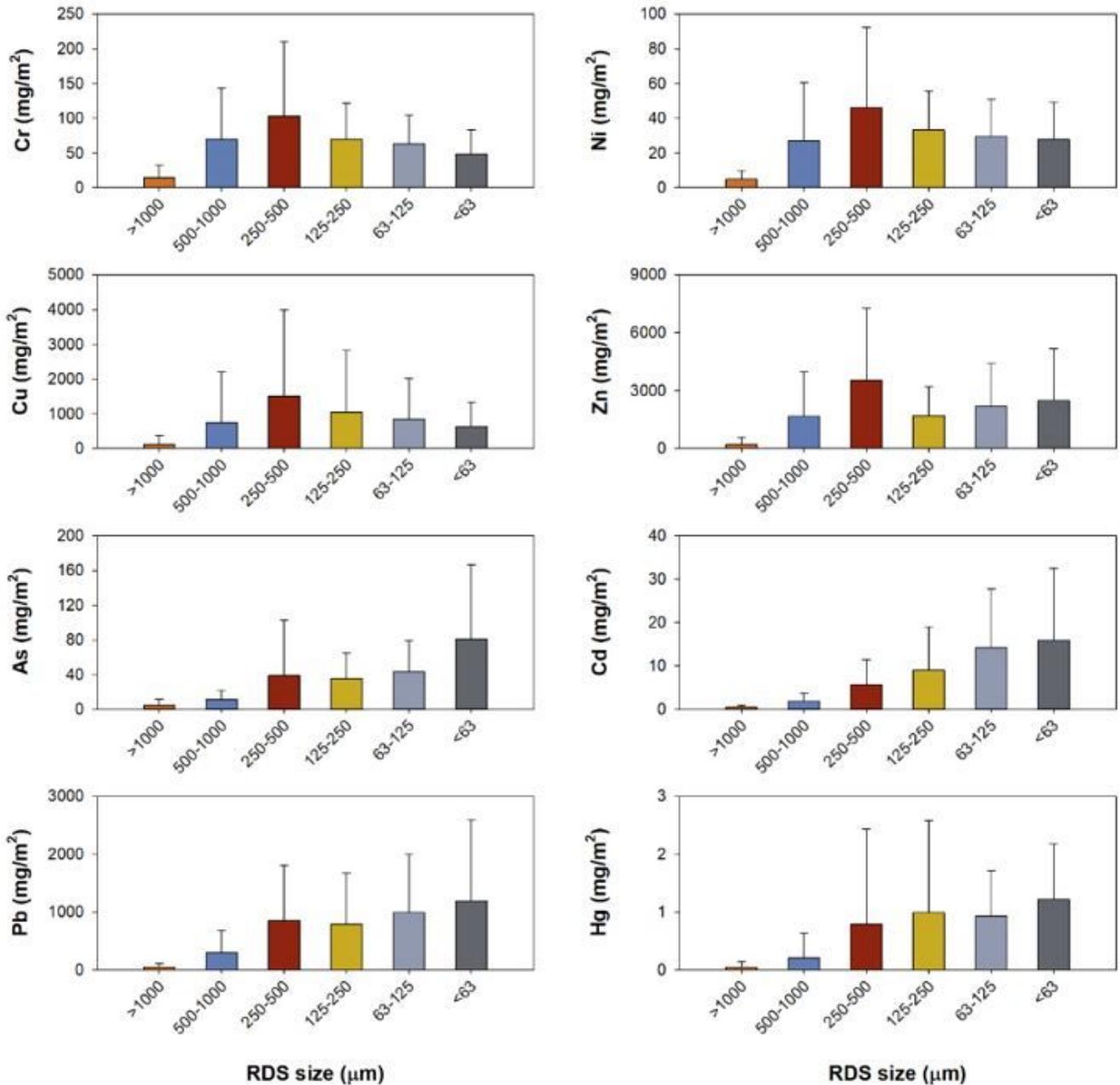
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**Figure 5**

Comparison of mean PTEs loads (mg/m<sup>2</sup>) with standard deviation in the different sizes of road-deposited sediments of this study.



**Figure 5**

Comparison of mean PTEs loads (mg/m<sup>2</sup>) with standard deviation in the different sizes of road-deposited sediments of this study.

## Supplementary Files

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