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Grain size distribution of road-deposited sediment and its contribution to heavy metal pollution in urban runoff in Beijing, China

Hongtao Zhao, Xuyong Li*, Xiaomei Wang, Di Tian

State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Shuangqing Road 18, Beijing 100085, China

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ABSTRACT

Pollutant washoff from road-deposited sediment (RDS) is an increasing problem associated with the rapid urbanization of China that results in urban non-point source pollution. Here, we analyzed the RDS grain size distribution and its potential impact on heavy metal pollution in urban runoff from impervious surfaces of urban villages, colleges and residences, and main traffic roads in the Haidian District, Beijing, China. RDS with smaller grain size had a higher metal concentration. Specifically, particles with the smallest grain size (<44 μm) had the highest metal concentration in most areas (unit: mg/kg): Cd 0.28–1.31, Cr 57.9–154, Cu 68.1–142, Ni 25.8–78.0, Pb 73.1–222 and Zn 264–664. Particles with smaller grain size (<250 μm) contributed more than 80% of the total metal loads in RDS washoff, while suspended solids with a grain size <44 μm in runoff water accounted for greater than 70% of the metal mass in the total suspended solids (TSS). The heavy metal content in the TSS was 2.21–6.52% of that in the RDS. These findings will facilitate our understanding of the importance of RDS grain size distribution in heavy metal pollution caused by urban storm runoff.

1. Introduction

Due to China's rapid urban population growth and industrialization, urban runoff with contaminated road-deposited sediment (RDS) has become an increasingly serious problem [1]. RDS is an important environmental medium due to its atmospheric resuspension and because it is present in storm runoff [2]. RDS is the sink and source of metals and other contaminants on impervious surfaces in urban environments [3], and it often contains elevated concentrations of toxic metals [4]. During rainfall, RDS is transported into the receiving waters, where it has a marked effect on water quality and aquatic biota [5]. Urban storm runoff has been deemed one of the leading sources of water quality impairment for rivers, lakes and estuaries [6]. It is also well known that urban storm runoff is much more difficult to control due the random nature of rainfall and uncertainty of the pollution source [7].

The grain size distribution of RDS is a particularly important factor because it determines the mobility of the particles and their associated pollutant concentrations [8–10]. The behavior of RDS in runoff depends on its grain size distribution [11,12]. Furthermore, smaller particles have lower densities [1], greater surface area per volume unit and higher organic matter contents [13,14]. For most pollutants, higher concentrations are found on smaller RDS [15–17]. Street surfaces are both sources of urban runoff pollutants and pathways for the transport of pollutants [18]. Street sweepers play an important role in removing litter and debris, but are relatively ineffective at removing smaller particles [19]. Indeed, many studies have shown that the efficiency of conventional street sweeping decreases with grain size [20,21]. Hence, smaller particles remain after street sweeping and are incorporated into stormwater runoff [22].

The amount, particulate size and particulate mobility of RDS are critical to assessment of the role of RDS in heavy metal pollution in urban runoff. Most previous studies have focused on the pollutant distribution in different size RDS and the concentration or transport of pollutants in runoff water separately [7,23–26]. Few studies have investigated the grain size distribution in RDS and suspended solids in stormwater runoff simultaneously [8,27]. A previous study demonstrated the importance of grain size for modeling sediment-associated transport from urban road surfaces [2]. The results of these previous studies have indicated that there is clearly a need to link the amount and grain size distribution of RDS with suspended solids in stormwater runoff so that we can better understand how RDS affects heavy metal pollution through urban runoff.

Like most big cities, Beijing has experienced a rapid expansion of impervious surface due to the migration of people from rural to urban areas in the last decade. In this study, we measured the amount, particulate size, and particulate mobility of RDS and heavy metal concentrations in runoff water from impervious surfaces of different land uses in the Haidian District of Beijing. Specifically, the following aspects were addressed in this paper: (1) What is the critical grain size associated with heavy metal pollutants in RDS? (2)

* Corresponding author. Tel.: +86 10 62849428; fax: +86 10 62849428.
E-mail address: xyli@rcees.ac.cn (X. Li).

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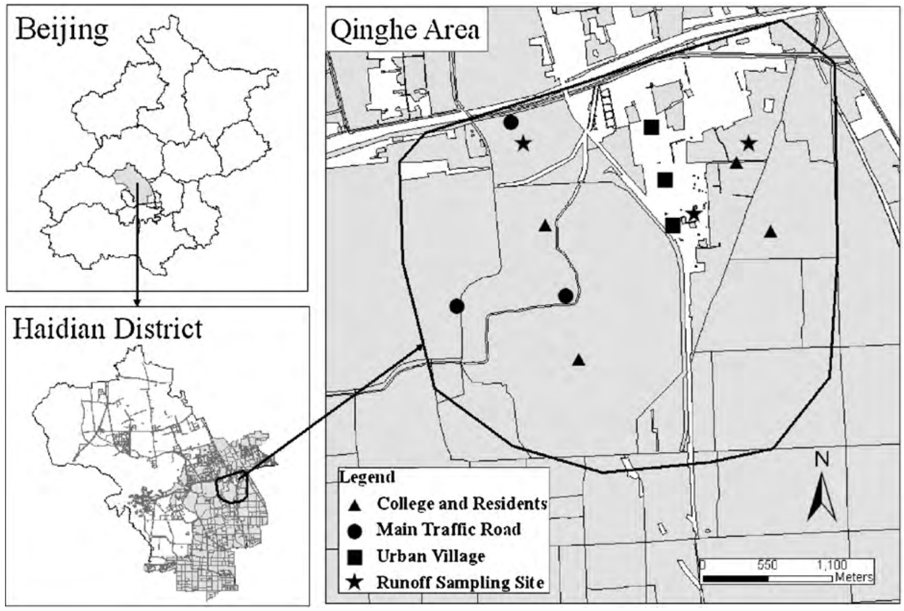

Fig. 1. Study area and sampling site locations in the Qinghe area of the Haidian District, Beijing, China.

How do the amount and grain size of RDS affect suspended solids and heavy metal concentrations in urban runoff? (3) What is the role of urban land use types in RDS and what is their contribution to heavy metal pollution in urban runoff?

2. Materials and methods

2.1. Study site description

Haidian, which is one of eight districts in the urban area of Beijing, China, is located in the northwest portion of the city. The mean annual temperature of Haidian is 14.0 °C and the average annual rainfall is 570 mm. The district has an area of 430 km^2, a population of 2.81 million and contains more than 80 higher education and 213 research institutions. In addition, most farm villages in the region are rapidly being converted into urban villages. Overall, colleges and residences, urban villages and main traffic roads are the three typical impervious land use types in Haidian District. The important factors affecting RDS amount and contaminant concentration of RDS in our study areas include impervious surface condition, street sweeping manner and frequency, and traffic intensity. Colleges and residences have relatively smooth and less damaged impervious surface, regularly daily hand-sweeping or mechanical sweeping, lower traffic intensity; urban villages have heavily damaged impervious surface, rarely street sweeping, and medium level of traffic intensity; main traffic roads have less damaged impervious surface, regularly daily mechanical sweeping, and higher traffic intensity. The streets in the region are hand-swept daily with straw brooms in the colleges and residences, with the exception of Tsinghua University, where the streets are swept with a mechanical sweeper. The roads in the urban villages are rarely swept, while mechanical sweepers are used to clean the main traffic roads. In our study area, runoff water finally enters the Qinghe River through the city rainfall drainage pipe system.

2.2. Sample collection and grain size fractionating

2.2.1. RDS sample collection and grain size fraction

We collected RDS samples using a domestic vacuum cleaner during June 9–10, 2009. The RDS sampling sites were distributed among the following land use types: three in urban village roads, four in residential and college avenues, and three on main traffic roads (Fig. 1). We had three duplicate sampling points at each sampling site. The sites on main traffic roads and college avenues were paved with asphalt, while the other sites were paved with concrete. Sampling area was from the central line to the curb of the road and the size of area was measured by the ruler. We measured total RDS mass weight at each sampling area. We took about 0.8–1.5 kg of RDS sample at each sampling point. Polyester sieves were used for grain size fractionation.

Samples were sorted into grain size fractions of <44, 44–62, 62–105, 105–149, 149–250, 250–450, 450–1000 and 1000–2000 μm. Heavy metals were analyzed for each grain size fraction. In the field of sedimentology, grain size <63 μm, 63–125 μm, 125–250 μm, 250–500 μm, 500–1000 μm, and 1000–2000 μm is typically referred to as silt and clay, very fine sand, fine sand, medium sand, coarse sand, and very coarse sand, respectively [2].

2.2.2. Runoff water sample collection

Runoff water samples were collected from three different land use impervious surfaces: Qianbajia (urban village), Xiangbaiqiqiao (main traffic road), and Jingshiyuan (residential and college avenues). In our study area, runoff water finally enters the Qinghe River through the city rainfall drainage pipe system. The samples were taken during two rainfall events, 27 mm rainfall for 1.8 h on June 16, 2009, and 44 mm rainfall for 2.9 h on June 18, 2009. We collected runoff water samples manually at each site at 5-min intervals during the first 15 min of the rainfall event; after that the samples were collected at 10-min intervals until there was no more runoff. We collected 12 and 19 water samples at each site during their two rain events on June 16 and 18, 2009, respectively. The runoff volume was measured using calibrated polythene barrels with a volume of 20 L for higher volumes and 5 L barrels for lower volumes during rainfall events. In addition, water samples were collected using plastic bottles and then analyzed in the laboratory within 5 days of the sampling date.

2.2.3. Estimation of heavy metal loads in RDS

To determine the contribution of particles with different grain sizes to the overall contamination of the RDS, we computed the pollutant load percentage for individual RDS samples. We considered