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Index models to evaluate the potential metal pollution contribution from washoff of road-deposited sediment

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ABSTRACT

The proper evaluation of pollutant strength and loads associated with road-deposited sediment (RDS) is crucial for controlling diffuse pollution in urban areas. A new index model, which combines source and transport factors and is called the RDS index, was developed using RDS characteristics (e.g., the amount, grain size, mobility, and metal concentrations) and used in a case study in the Beijing region. The observed and weighted RDS characteristics along an urban–rural gradient, which included central urban (UCA), urban village (UVA), central suburban county (CSA), rural town (RTA), and rural village (RVA) areas, were used to calculate the RDS index for the pollutant load ($RDS_{index,load}$) and the pollutant strength ($RDS_{index,strength}$). Our results demonstrated that the $RDS_{index,load}$ and $RDS_{index,strength}$ values both changed significantly along the urban–rural gradient. $RDS_{index,strength}$ increased along the urban–rural gradient and the $RDS_{index,load}$ value along the main roads decreased in the order RVA > UCA > CSA > RTA. The method offers a new way of assessing metal pollution in RDS and provides an important scientific basis for controlling pollution caused by RDS washoff.

1. Introduction

As point sources of pollution in China and many other countries decrease, urban runoff containing contaminated road-deposited sediment (RDS) is becoming an increasingly serious problem (Zhu et al., 2008; Zhao et al., 2010). RDS from impervious surfaces is an important carrier of contaminants, often containing metals at elevated concentrations (Aryal et al., 2009; Xiang et al., 2010). Large amounts of pollutants, such as nutrients, metals, and hydrocarbons, are usually transported in RDS washoff (Sartor and Boyd, 1972; Huber and Dickinson, 1988; Al-Khashman, 2007). Quantifying the relationship between RDS and washoff particles in urban runoff could provide a new method for estimating the pollution load that a waterway receives (Herngren et al.,

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2005; Zhao et al., 2011). A range of diffuse pollution models for urban areas have been proposed, including STORM, HSPF, DR3M-QUAL, SWMM, and SLAMM, and they have been used to estimate pollutant loads in runoff (Egodawatta et al., 2007; Wang et al., 2011). Despite the fact that the models mentioned above are widely used to estimate diffuse pollution sources in urban areas, they generally require substantial amounts of parameterization and calibration data (Shaw et al., 2006). Consequently, there is a need for improved runoff pollution estimates.

Identifying and prioritizing critical source areas could greatly improve the efficiency of RDS washoff pollution controls. Index models have been widely used for identifying diffuse critical source areas of phosphorus (P) on farms, and are less likely than other models to be constrained by a lack of input data (Heathwaite et al., 2005; Sharpley et al., 2008). Index models allow critical source areas to be identified by quantifying the relative pollution risk (e.g., as a probability) as opposed to the actual pollutant loading, because it is difficult to quantify transport factors (Buczko and Kuchenbuch, 2007; Buchanan et al., 2013). The index models mentioned above were initially devised for diffuse pollution in agricultural areas, and no index model has yet been specifically designed for diffuse pollution in urban areas that can be used to identify critical source areas of urban runoff. Characterizing RDS (e.g., the amount, grain sizes, associated metals, and mobility) can make it possible to identify critical source areas of urban runoff. A risk index (called RI_{RDS}) that combines RDS characteristics with a potential ecological risk index (*RI*) was developed by Zhao and Li (2013). The RI_{RDS} can be used to evaluate the amount of pollution present per unit area, but not the total pollution load. There is a clear need for the development of new simple but effective index models that use RDS characteristics to quantify or semi-quantify urban pollutant loadings.

The urban, suburban, and rural areas in and near large cities in China are generally divided into areas classed as urban districts, suburban county areas, rural townships, rural villages, and urban villages (Zhao et al., 2011). Previous studies have shown that RDS characteristics (including the amount of RDS present, its grain size distribution, metals associated with it, and its mobility) vary significantly along urban–rural gradients (Zhao et al., 2011). It is important to be able to evaluate the metal load associated with RDS correctly along urban–rural gradients, and developing such an ability will improve our understanding of the risks posed by heavy metal pollution in RDS being transported into urban water. The RDS characteristics mentioned above are critical to the assessment and evaluation of the role of RDS in metal pollution in urban runoff (Zhao and Li, 2013). However, there is still no index model available for identifying critical source areas of pollutants associated with RDS. Quantifying pollutant loadings will assist managers to focus remediation actions on decreasing RDS washoff into water bodies.

In this study, we aimed to 1) determine the source and transport factors for heavy metals in RDS using observed and weighted RDS characteristics in a multiplicative index, and 2) combine a number of functions for evaluating the pollution load and strength into one RDS index.

2. Materials and methods

2.1. *Study area and RDS sampling*

In general, big cities in China are divided by the government into urban, suburban, and rural areas, and the classifications used are urban district, suburban county, rural township, rural village, and urban village. We collected RDS samples from areas that were typical of each of these administrative divisions within the Beijing metropolitan region. The Beijing metropolitan region includes 16 administrative sub-divisions, which are county-level units that are governed directly by the municipality. There are six such districts in the urban area, and ten (eight districts and two counties) in the suburban area. The whole region can be divided into urban, suburban, and rural areas. In suburban and rural areas, each county consists of a group of towns, and each town consists of a group of villages. We chose five sampling areas along an urban–suburban–rural gradient, including a central urban area (UCA), an urban village area (UVA), a central suburban county area (CSA), a rural town area (RTA), and a rural village area (RVA). In general, the population density, traffic density, energy consumption, and frequency of road sweeping all decrease moving along the urban–rural gradient. Roads in the UCA and CSA generally have relatively smooth and undamaged impervious surfaces, and are regularly (daily) mechanically swept, whereas roads in the RTA, RVA, and UVA generally have very damaged surfaces, and are rarely swept.

RDS samples were collected using a domestic vacuum cleaner (Philips FC8264; Philips, Amsterdam, Netherlands) between 2 and 10 September 2009, following a period of about two weeks of dry weather. Three sampling sites were selected in each of the study areas. An unspecified area at each site was vacuumed from the central road marking to the curb until a reasonable amount of RDS was collected, then the size of the area sampled was measured with a ruler. Each RDS sample was weighed with an electronic balance, and sample masses of 0.8–1.5 kg were found to have been collected at each site. The mass of RDS per unit area was calculated by dividing the RDS mass collected by the size of the sampling area, and it ranged from 2 to 570 g/m^2 for all of the samples that were collected. The amount of RDS collected at a site was generally larger in the RTA, RVA, and UVA than in the UCA and CSA. The samples were separated into the grain size fractions <44, 44–62, 62–105, 105–149, 149–250, 250–450, 450–1000, and >1000 μm using polyester sieves.

2.2. *Analytical methods and quality control*

Metals were measured after the RDS samples had been digested with a mixture of HF and $HClO_4$ on a hotplate (Tessier et al., 1979). All solutions were stored at 4 °C until they were analyzed. The Cr, Cu, Ni, Pb, and Zn concentrations were determined using an Elan 6000 inductively coupled plasma-optical emission spectroscopy instrument (Perkin–Elmer, Waltham, MA, USA). Certified geochemical soil reference materials (CRMs) GSS-1 and GSS-2 were also analyzed to provide quality assurance and quality control (QA/QC) information. No RDS CRMs are available, but using soil CRMs has