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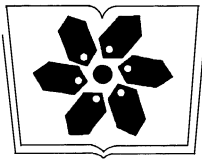
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封面图说: 永兴岛海滩植被——永兴岛是中国西沙群岛的主岛,也是西沙群岛及南海诸岛中最大的岛屿。国务院 2012 年 6 月批准设立的地级三沙市,管辖西沙群岛、中沙群岛、南沙群岛的岛礁及其海域,三沙市人民政府就驻西沙永兴岛。永兴岛岛上自然植被密布,野生植物有 148 种,占西沙野生植物总数的 89%,主要树种有草海桐(羊角树)、麻枫桐、野枇杷、海棠树和椰树等。其中草海桐也称为羊角树,是多年生常绿亚灌木植物,它们总是喜欢倚在珊瑚礁岸或是与其他滨海植物聚生于海岸沙滩,为典型的滨海植物。

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街尘与城市降雨径流污染的关系综述

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摘要:街尘是引起城市面源污染分布最为广泛、最重要的污染物载体,街尘及其负载的污染物与降雨冲刷相关过程的全面认识,对有效控制城市地表径流污染有着重要的意义。针对全球快速城市化背景下街尘及其降雨冲刷污染的研究现状,阐明了街尘及其降雨冲刷污染的不足与难点,并对未来研究方向的突破性给予展望。

关键词:街尘;降雨-冲刷过程;面源污染;粒径

Research progress on the relationship of pollutants between road-deposited sediments and its washoff

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Abstract: Road-deposited sediment (RDS) on impervious surfaces is an important carrier of contaminants. The road surface is a sink and source of metals and other contaminants in urban environments. During rainfall, RDS is transported to receiving waters, where it has a marked effect on water quality and aquatic biota. Because of rapid global urbanization, urban surface runoff containing contaminated RDS is becoming an increasingly serious environmental problem. Understanding the relationship between the RDS contribution and its washoff process is essential for controlling urban runoff pollution. Most previous studies have investigated contaminants in RDS and runoff separately. But the following aspects remain unclear: 1) The variety of RDS and its associated contaminants along urban-rural gradients. An urban-rural gradient pattern is common in the context of rapid urbanization in China. It strongly affects land use zoning, the proportion of impervious surfaces, traffic density, energy consumption, street cleaning methods and spatial distribution of manufacturing facilities. However, most studies have been conducted in central urban areas of larger cities, and few have investigated RDS variety and associated contaminants along urban-rural gradients. 2) The RDS washoff process from road surfaces. Because of the difficulty of using natural rainfall events to investigate rigorous RDS washoff processes, washoff is the least understood among the three processes (RDS buildup, washoff and transport) preceding material entry into receiving waters. 3) The quantitative relationship of contaminants between RDS and runoff. Previous studies have suggested that RDS and washoff particles have either an exponential, rating curve, or other relationship. The relationship depends on a range of parameters,

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such as surface characteristics, rainfall intensity and duration, RDS grain sizes, land use, and others. However, it is unclear how grain size composition influences the relationship of pollutants between RDS and washoff particles.

This paper represents a breakthrough in the study of these questions in the following aspects: 1) How RDS from an urban-rural gradient affects the relationship of contaminants in washoff particles. The quantity, grain size, and particle mobility of RDS are critical for assessing the role of RDS and its associated contaminants in urban runoff. Indeed, the urban-rural environmental gradient has an important influence on RDS quantity and grain size distribution. 2) The RDS washoff process from the road surface using rainfall simulation. Simulated rainfall has provided greater flexibility and control of fundamental rainfall parameters, such as intensity and duration. Thus, rainfall simulation for different-sized RDS particles in surface runoff can be used to provide insight into how the urban gradient affects the potential washoff load and ratio of pollutants associated with RDS. 3) The RDS grain size distribution is an important factor in determining the mobility of particles and their associated pollutant concentrations. Grain size composition is also a critical factor to establish the relationship between RDS and washoff particles, because surface washoff selectively transports RDS of particular grain sizes. The washoff percentage of each RDS size fraction (F_w) varies with RDS grain size, with smaller grain sizes associated with higher values of F_w . Washoff particles have higher proportions of smaller grain sizes than those in RDS.

Key Words: road-deposited sediment; rainfall-runoff process; diffused pollution; grain size

我国 90% 以上城市水体污染严重,其中城市径流污染是造成水环境恶化的重要原因之一^[1]。由于城市地表径流污染具有随机性、集中排放、冲击负荷大、源头监测难、控制难度大等特点,已引起人们的高度重视。目前我国城市化进程正快速推进,增加了不透水地表的比例,加大了地表产流量。城市人类活动强度增大导致地表累积污染物数量和种类急剧增加,造成城市地表径流污染程度加重,水体污染的贡献份额也有逐步升高的趋势^[2-4]。街尘是引起城市面源污染的分布最广泛、最重要的污染载体^[5-6],加深街尘及其负载的污染物与降雨冲刷相关过程的全面认识,对有效控制城市地表径流污染、改善城市水环境质量有着重要的意义。

街尘是一个来源复杂的污染物混合物,与大气污染和水体环境污染密切相关^[7]。当前道路地表街尘受到汽车尾气、轮胎磨损、工业生产活动、道路老化、大气沉降、融雪剂等污染,从而易富集有毒污染物尤其是重金属^[8]。街尘易随降雨冲刷迁移,形成地表径流污染^[8-9]。有研究表明,城市地表径流是重金属进入地表水体的重要途径,城市道路径流贡献了重金属总污染负荷 35%—75%^[10-11]。嘉兴市街尘的研究表明,街尘中的重金属和多环芳烃含量分别是该地区城市土壤背景值的 1.5—4.5 倍和 5—10 倍^[12]。街尘的累积规律、粒径分布、污染物组成、冲刷迁移行为、清扫去除等因素,及其这些因素与降雨-径流过程的联系成为当前关注的热点^[10,13]。

鉴于此,加强街尘及其降雨冲刷的研究对于水环境保护意义重大。然而,有关街尘及其降雨径流污染关系的认识还不够全面,研究还不够深入,本文系统性总结了街尘及其降雨径流关系的国内外研究进展,分析目前研究中存在的不足,并提出街尘及其降雨径流关系的几个研究方向。

1 街尘及其降雨冲刷污染的研究现状

1.1 街尘污染的研究现状

街尘(或街土)最初是指那些街道表面上可以被冲刷或清扫掉的尘土,英文名称为“street dust and dirt”^[14]。街尘是一个来源复杂的各种污染物的混合物,与大气污染和水体环境污染密切相关^[7]。街尘是由大气沉降、城市交通、建筑、工业等各种面源所产成的颗粒物质在风力、水力及重力作用下,沉积在城市地表形成^[5,15]。街尘的累积规律、粒径分布、污染物组成、冲刷迁移行为、清扫去除等与降雨-径流有关的污染问题成为当前关注的热点^[10,13]。街尘的颗粒组成与天气状况、交通密度、工业状况以及与土壤的接近程度等有关。街尘的重金属污染研究逐渐受到关注^[9],当前道路地表街尘受到汽车尾气、轮胎磨损、工业生产活动、道路老化、大气沉降、融雪剂等污染,从而易富集有毒污染物尤其是重金属^[8]。街尘中重金属具有长期性、隐匿性、

不可逆性及不可降解性,因此开展街尘中重金属污染状况的研究对降雨径流污染控制与治理有着重要意义。

随着降雨径流污染研究的深入,街尘作为城市地表径流污染的“源”日益受到重视。目前关于街尘污染的研究主要集中在三大方面:(1)街尘采样方法的改进。目前街尘样品采集方法主要有两大类:毛刷或笤帚清扫法和干式或湿式真空采样法^[16]。前者易造成小粒径街尘在采集过程中损失过高,后者采集精确度高,能够为准确研究街尘动态模拟、粒径组成及污染特征提供保障^[17]。国外研究中大多采用干式或湿式真空采样法^[11,18-19],国内研究主要是采用毛刷或笤帚清扫,不过近年来国内研究者也逐渐采用家庭用真空吸尘器采集街尘样品^[12,20]。(2)街尘的累积过程模拟及影响因素分析。街尘累积量和粒径组成变化受晴天累积天数、交通流量、土地利用类型、道路清扫方式、风力等因素影响^[4]。街尘的定量模拟主要为时间累积模型,主要有指数方程、幂方程或者其他方程^[19,21-22]。国内学者都对这面进行了相关研究并取得了一定进展^[23-24]。总的来看,街尘污染的形成可描述为“晴天累积和雨天冲刷”的反复过程。(3)街尘化学污染物调查、形态分级、时空分异、判源分析等^[7,25]。这些研究主要集中在大中型城市如上海、西安、北京、镇江、宝鸡等的中心城区等开展的,针对重金属、多环芳烃等典型面源污染物^[5,15]。总之,我国诸多城市中心区进行了街尘重金属污染的研究,取得很多有价值的成果^[5-6]。

然而,我国特殊城乡环境差异决定着城乡环境梯度下街尘及其降雨冲刷的重金属污染分布可能存在较大差异,其分异特征则鲜有研究报道。文中城乡环境梯度是指由于人口、能源、下垫面特征、交通、管理等因素造成的城市、乡镇和村庄在一定的空间上或时间上环境差异特征。城乡环境梯度决定了一定空间内人类活动类型、污染源的数量及强度、水文改变程度、环境管理水平等众多因素^[26-28]。目前我国城市街尘中重金属污染的研究集中在了大中型城市中心城区,对小城镇和农村村庄缺乏深入研究,造成了在我国城乡环境梯度尺度下街尘中重金属污染的认识还不足。

1.2 降雨径流污染的研究现状

国内外学者对降雨径流污染的研究主要是基于自然降雨条件下开展的,主要集中在以下三大方面:(1)降雨径流污染时空分布及影响因素分析。主要分析了土地利用类型、晴天累积天数、降雨特征、季节变化等因素对降雨径流时空部分的影响^[29-30]。(2)径流污染过程与机制。主要研究了径流过程中污染物的固液分配、基于降雨事件的初期冲刷(径流污染物累积曲线与径流流量累积之间的关系)、基于降雨季节的初期冲刷(季节性变化与径流污染排放特征的关系)等^[31-33]。国内对降雨径流时空分布与污染过程的研究主要在中大型城市中心城区如武汉、成都、西安、北京、上海、重庆、成都、杭州、长沙等开展^[3,34-40]。(3)街尘降雨冲刷模型及预测。降雨冲刷是地表径流污染的诱因,是街尘地表径流负荷产生的动力和输移条件,是地表径流污染产生过程中的至关重要环节^[41-42]。粒径决定着街尘颗粒在径流中可移动性^[13,43],街尘对地表径流污染的贡献取决于被径流冲刷进入水体的那部分粒径的街尘所负载的污染物,而不是所有粒径所负载的污染物。目前大多数研究表明在一般降雨事件中粒径 $<100\ \mu\text{m}$ 的街尘是径流中颗粒物的最主要组成部分。但主要城市面源污染模型包括复杂机理模型如暴雨模型(STORM)、雨水管理模型(SWMM)多采用采用指数冲刷方程,没有充分考虑街尘粒径组成比例的变化可能给街尘降雨冲刷带来的影响,造成对降雨径流冲刷挟带的街尘不能进行准确模拟^[44]。

由于集成 GIS 操作平台,国内外在降雨径流污染模型方面的研究已经取得了很大的进展^[45-47]。同时,由于城市地表径流具有间歇性、随机性、突发性等特点,使得预测和模拟面源污染具有一定的难度^[27,48]。20 世纪 80 年代起,国内一些城市如成都、苏州、北京等地借鉴国外研究城市径流的办法发展了我国城市径流污染的研究方法^[24,48-50]。街尘在城市环境中具有分布范围广、取样方便、代表性强。如果能建立静态街尘与动态径流的冲刷定量关系,将由街尘定量反演径流污染提供新思路,然而国内外有关这方面的研究尚处于起步阶段^[7,51]。

总之,国内外有关街尘与城市地表径流的重金属污染研究都取得了很大的进展,但由于国内外地表径流污染的研究多是基于自然降雨条件下集中在大中型城市的中心城区开展的,存在较多的不可控因素,同时缺

乏对街尘的降雨径流的人工控制实验的深入研究,阻碍了对城乡环境梯度下街尘及其降雨冲刷污染差异认识和对街尘与径流污染的定量关系深入理解。

2 街尘及其降雨冲刷污染的研究不足

2.1 对我国城乡二元结构和快速城市化背景下的街尘及对径流污染还缺乏完整的认识

城市化程度决定了一定空间内人类活动类型、污染源数量及强度、水文改变程度、环境管理水平等众多因素^[27-28],这些必然在城市各种污染物的载体和地表径流污染物的主要来源“街尘”上有所响应。在我国城乡二元经济结构下,街尘与不透水地表径流污染物在城乡环境梯度上必然有所响应。相比小城镇或者农村村庄,大城市中心城区往往人口密度大,人类各种生产和生活得到了集中和加强,增加了街尘和径流污染的强度和数量,不透水面面积与比例高增加了降雨径流的冲刷和挟带能力,增加了污染负荷的输出能力^[26]。但同时由于中心城区往往具有较高道路清扫水平又削减污染负荷的输出能力。目前我国城市街尘和地表径流的研究集中在了大中型城市,对小城镇和农村村中尚缺乏深入研究,造成了在我国城乡环境梯度尺度下街尘和径流污染的认知还不足。

2.2 对街尘冲刷过程中存在的迁移转化机制还不清楚

降雨冲刷过程是联系静态街尘和动态径流重要环节,由于城市地表径流污染形成过程的不确定性和自然降雨条件的不可控性,造成了研究街尘降雨冲刷是城市面源污染形成过程三个环节(累积、冲刷、传输)中最困难的^[42]。由于国内外对地表径流污染的研究主要是基于自然降雨条件下开展的^[4,12,40],存在较多的不可控因素,当前有关研究主要集中在街尘的累积过程和径流污染传输过程,同时缺乏对街尘的降雨径流的人工控制实验的深入研究,造成了对街尘冲刷过程研究较少,冲刷过程中的机理尚不明确。

2.3 静态街尘与动态径流的冲刷定量关系尚待深入研究

要定量估算一定时段内面源污染负荷量,最基本的方法是监测所有降水过程的径流水质,但受客观条件限制,显然这是不可能的。同时,由于城市地表径流污染具有发生随机、来源和排放点不固定、污染负荷的时间和空间变化幅度大、监测、控制和处理困难且复杂等特点,使得预测和模拟面源污染具有一定的难度^[27-28]。街尘在城市环境中具有分布范围广、取样方便、代表性强。如果能建立静态街尘与动态径流的冲刷定量关系,将由街尘定量反演径流污染提供新思路。国内外有关这方面的研究尚处于起步阶段,常静等提出了“城市地表灰尘-降雨径流”的系统概念,强调了不透水地面的累积和冲刷是污染物迁移转化的关键过程。赵洪涛等先后在北京市海淀区和通过野外街尘采样和径流观测,初步估算了街尘的定量冲刷比例^[52],但是从静态街尘到动态径流的冲刷定量关系尚有许多机理不清楚,如缺乏粒径对街尘冲刷率的定量关系表述;街尘与径流冲刷颗粒物之间污染物浓度与量的关系。

3 街尘及其降雨径流污染关系研究突破的新方向

3.1 城乡环境梯度差异对街尘及其降雨径流污染关系的影响

目前已有研究多集中在大中型城市中心城区,而没有考虑城乡梯度的差异性。然而,人口密度、土地利用类型、交通流量、化石能源消耗、道路清扫方式、卫生习惯等都存在明显的城乡环境梯度^[53-56],这些梯度变化影响到街尘的单位面积质量、粒径组成、重金属污染水平和赋存形态、街尘潜在降雨冲刷污染能力等^[52,57]。城乡一体化的大城市如北京在行政设置上分为中心城区、郊区城区(区县)、乡镇城区、农村村庄以及特殊的城中村,体现了城乡环境梯度,给人们提供了一个很好的研究对象。以北京市为例,探索我国这种具有典型城乡环境梯度的大中型城市的街尘及其降雨径流污染的关系,对于水环境污染源头控制和城乡分层次治理具有积极意义,将是街尘及其降雨径流关系研究的新方向。研究中的重点和难点问题包括城乡环境梯度如何影响街尘粒径组成、单位面积数量、输入和输出机制?城乡环境梯度如何影响街尘中重金属浓度、形态和来源?城乡环境梯度如何影响街尘及其负载重金属负荷及其对径流污染的潜在输出能力?

3.2 街尘及其负载的污染物径流冲刷行为研究

现有的研究多关注街尘或者降雨冲刷本身,对街尘与降雨冲刷污染之间的关系认识相对不足,尤其关于

不同降雨特征与不同街尘粒径组成交互影响下的降雨冲刷则鲜有报道。利用人工控制试验来模拟街尘冲刷则避免了自然降雨条件的不可控因素和不确定性,目前在街尘冲刷行为与下垫面粗糙度、降雨特征、颗粒传输距离、径流颗粒物粒径分布等方面研究的人工控制模拟都取得较大的进展^[41,58-59]。这些成果的取得为开展街尘及其负载污染物径流冲刷行为研究提供了基础,可围绕污染物在冲刷过程中的固液分配与粒径的交互影响;街尘中不同形态污染在径流冲刷过程中的吸附解析过程等展开突破性研究。

3.3 以粒径从静态街尘到动态径流的定量关系作为定量降雨冲刷污染的关键

有关粒径在街尘和径流污染中的关键作用正备受关注,然而多数研究集中在街尘与径流中粒径分布、及其污染物的关系等,对街尘中被降雨冲刷进入径流的那部分粒径的定量化研究至今鲜有报道。由于街尘是不同粒径颗粒物的组合体,因此,基于降雨事件特征的分粒径研究街尘对径流污染定量贡献,将由街尘直接定量反演径流污染有着重要意义。粒径在某种程度上决定着街尘颗粒的可移动性和潜在的污染效应^[60]。粒径大小影响着街尘在不同的水文水力条件下再移动和再传输的能力。由于城市地表径流具有颗粒物传输的特征,径流中的污染物如某些重金属和多环芳烃等赋存于不同粒径的径流悬浮物上变成颗粒态污染物,从而产生粒径分布对径流污染物的浓度、形态的重要影响^[43]。街尘对地表径流污染负荷的贡献取决于被径流冲刷进入水体的那部分粒径的街尘所负载的污染物负荷,而不是所有粒径所负载的污染物负荷,因此分粒径研究街尘对径流污染负荷的贡献,对由街尘直接定量反演径流污染负荷有着重要意义。然而,目前应用在 SWMM (雨水管理模型)、STORM (储存处理与溢流模型)、HSPF (水文模拟程序) 等城市径流模型的冲刷方程多是从径流量和水质两者关系的角度出发建立的或不能表征粒径组成比例的变化,因此不能很好描述“定量冲刷关键因子”粒径的作用。因此,对粒径从静态街尘到动态径流的关键作用的认识不足。加强粒径对街尘迁移行为和污染贡献影响的研究,从而建立基于粒径的冲刷方程,将能够为城市地表径流污染模型应用提供准确的参数信息。

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