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《环境科学》征订启事(4061) 《环境科学》征稿简则(4132) 信息(4233, 4293, 4304)

海绵城市地块汇水区颗粒污染物的传输

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摘要: 目前我国海绵工程建设多集中在地块汇水区单元内开展, 通过多个低影响开发(LID)设施协同完成地表径流水质水量的调控, 但基于地块汇水区尺度下城市面源污染的产生和控制效果鲜有报道。本研究比较分析了不同硬化率地块汇水单元内的面源颗粒污染物晴天累积、降雨冲刷、地表径流及径流输出负荷状况。结果表明, 地块汇水单元内硬质路面是面源颗粒污染物贡献的最主要的下垫面类型, 中硬化率(61.1%)地块和高硬化率(73.6%)地块路面街尘累积量分别约占汇水区单元的88.4%(2.22~12.51 g·m⁻²)和90.1%(4.99~33.43 g·m⁻²), 对径流SS的输出贡献比率分别约为91.7%(0.97~7.34 g·m⁻²)和90.5%(0.92~18.77 g·m⁻²), 降雨径流SS污染负荷占比分别约为95.2%和83.1%, 经LID设施处理后输出径流污染负荷约为地表径流的24.0%和40.2%。硬质路面的街尘晴天累积及降雨冲刷以>150 μm为主, 地表径流及输出径流则以<50 μm粒径段为主, 同时地块不透水比例的增加, 细粒径(<105 μm)颗粒物的累积及冲刷分布增大(24.4%和106.4%), 而粒径<50 μm的颗粒物在路面径流中的分布减小(12.4%)。屋面的街尘累积、冲刷及降雨径流的粒径分布状况与硬质路面大致相似, 但中硬化率地块(>1000 μm)和高硬化率地块(250~450 μm、<45 μm)在3个粒径段范围的颗粒物累积和冲刷相较于路面街尘粒径分布明显增加(>1000 μm: 58.1%和108.5%; 250~450 μm: 72.9%和41.8%; <45 μm: 59.2%和64.8%)。以上结果揭示了颗粒污染物在地块汇水区尺度下的污染全过程(累积-冲刷-输出)分布及LID设施对地块整体SS污染负荷的控制效果, 可为地块汇水单元内LID设施工程绩效的科学评估提供重要参考。

关键词: 地块汇水区; 低影响开发; 街尘; 降雨径流; 粒径分布

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Transition of Particulate Pollutant in the Parcel-based Catchment of Sponge City

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Abstract: Most sponge city constructions in China are carried out in urban parcel-based catchments, and the quality and quantity of surface runoff can be controlled by several low impact development (LID) facilities. However, there are few reports on the generation and control of urban diffuse pollution. In this study, two areas with different hardening rates were compared to analyze the load conditions during the accumulation-wash-off-transport process of particulate pollutants. The results showed that the road surface in the catchment was the main underlying surface that the particulate pollutants contributed to. The road dust accumulation in the medium hardening rate (61.1%) and high hardening rate (73.6%) plots accounted for 88.4% (2.22-12.51 g·m⁻²) and 90.1% (4.99-33.43 g·m⁻²) of the catchment area unit, respectively. The contribution to the suspended solids (SS) load of runoff was 91.7% (0.97-7.34 g·m⁻²) and 90.5% (0.92-18.77 g·m⁻²), respectively. The SS load of road runoff accounted for approximately 95.2% and 83.1%, respectively. The pollution load (SS) after treatment by the LID facilities was approximately 24.0% and 40.2% of the surface runoff, respectively. The particle size distribution of road dust during the accumulation and wash-off processes was >150 μm, while that in surface and output runoff was <50 μm. With the increase in the impervious area, the distribution of finer particles (<105 μm) in the process of accumulation and wash-off increased (24.4%, 106.4%), while the distribution of particles <50 μm in road runoff decreased (12.4%). The particle size distribution of the accumulated, washed dust, and the rain runoff on the roof were roughly similar to those on the road. However, compared to the particle size distribution of road dust, in the accumulation and wash-off processes, the coarser particles (>1000 μm) of the medium hardening rate plot and the particles of size 250-450 μm and <45 μm of the high hardening rate plot increased significantly (>1000 μm: 58.1%, 108.5%; 250-450 μm: 72.9%, 41.8%; <45 μm: 59.2%, 64.8%). The results revealed the entire distribution process (accumulation—wash-off—transport) of particulate pollutants and the effect of LID facilities on the total SS pollution load of the catchment, which can provide an important reference for the scientific assessment of the project performance of LID installation in urban parcel-based catchments.

Key words: urban parcel-based catchment; low-impact development (LID); street dust; rainfall runoff; particle size distribution

随着点源污染控制措施的不断完善, 城市面源 污染作为第二大面污染源对城市水环境的影响越来越

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越突出^[1~3]. 同时, 由于我国城市化进程的不断推进, 城区快速增加的不透水面使得流域水文连接性增强, 导致更高的径流量和峰值流量, 进而携带更多的污染物造成受纳水体污染^[4,5]. 有研究表明, 径流污染源头控制是普遍认可的城市面源污染最有效的控制措施^[6,7].

低影响开发 (low-impact development, LID) 作为我国海绵城市建设中重要的技术手段, 从源头上利用渗透、滞留等措施可有效解决大概率小降雨事件带来的面源污染问题^[8~10]. LID 通过把传统的整个汇水区单元划分为几个子单元, 实现对整个汇水区的水文断接^[11]. 目前我国海绵城市改建工程的实质是以地块汇水区 (一般小于 0.5 km^2) 为单元采用不同 LID 设施实现城市地表径流污染调控. 以往对 LID 设施的研究多集中于简单的设施流入和流出的径流水质变化^[12~15], 而科学评估其工程绩效需建立在汇水区尺度上. 由于城市面源污染在 LID 建成区存在多介质-多路径-多过程的复杂性, 降雨过程中其汇排水关系较为复杂, 汇水区在不同降雨条件下甚至一场降雨不同时段内的划分波动较大, 实地监测的难度较大, 目前对其绩效评估多通过模型模拟来完成^[16~19]. 但是, 模拟的准确性需要以大量的实测数据为支撑, 然而目前基于地块汇水区尺度下的污染物全过程监测较少. 同时, 鉴于悬浮颗粒物 (SS) 与其他污染物存在一定的相关性^[20], 我国海绵城市评价标准也将 SS 作为径流污染控制指标^[21]. 因此, 开展基于地块汇水区尺度上的城市面源颗粒污染物在 LID 建

成区内的全过程监测是海绵城市建设的必要环节.

鉴于此, 以深圳市龙岗区海绵城市改建地块为例, 选取两个不同硬化率的示范点, 划定其汇水分区, 开展基于地块汇水区尺度污染全过程的观测. 集中关注地块不同下垫面的晴天街尘累积特征、降雨径流冲刷特征、地表径流污染特征及 LID 设施对径流水质的净化特征, 以期为地块 LID 设施改建工程的优化布置及科学评估地块汇水单元内的污染控制效果提供重要参考.

1 材料与方法

1.1 研究区概况

龙岗区位于深圳市东部, 为亚热带海洋性季风气候, 多年平均降雨量 $1\,933.3 \text{ mm}$. 本研究选取的两个代表监测点位于深圳龙岗区坪地街道, 排水体制皆为分流制排水体制. 中硬化率地块, 占地面积 $11\,142 \text{ m}^2$, 透水面积比率 38.9% , 建设的海绵设施主要包括雨水花园、高位花坛和透水铺装等, 屋面径流雨水主要通过高位花坛和雨水罐进行预处理; 路面径流经雨水花园、渗透渠等海绵设施处理后通过地下雨水管排入市政管网. 根据其地下管网的分布情况, 选取一小汇水区单元进行研究, 汇水区总面积为 $6\,513.95 \text{ m}^2$. 高硬化率地块, 总面积 $55\,676 \text{ m}^2$, 透水率 26.5% , 设有雨水花园、渗透渠和环保雨水口, 主要用于处理路面径流, 经其处理后最终通过雨水管排出. 研究选取的汇水区单元总面积 $9\,793.74 \text{ m}^2$ (图 1).



图 1 研究区概况示意

Fig. 1 Study area overview

1.2 样品采集与处理

为研究海绵城市示范区内面源污染状况及其控制效果, 于 2019 年 3~7 月开展实地观测工作. 结合地块汇水区地下雨水管网资料和现场踏勘, 实地观察不同降雨事件中径流发生路径, 确定一定降雨条件下的汇水边界, 从而在其相关节点进行水质水量

观测 (图 2). 样品的采集主要包括: 降雨前后的地表颗粒物及降雨事件发生时产生的地表径流和地下管网出流.

地表颗粒物样品: 地表颗粒物的采集包括路面和屋面. 于 2019 年 3~7 月观测的降雨前后在汇水单元内设一个 $1\text{ m} \times 3\text{ m}$ 的采样点, 使用戴森吸尘

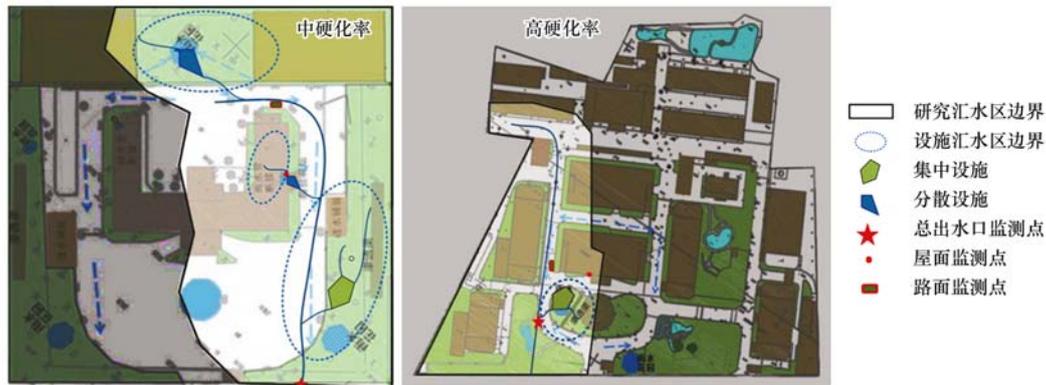


图2 径流监测点布置示意

Fig. 2 Layout of runoff sampling points

器采集样方内全部地表颗粒物样品,密封保存并记录.同时,为保证街尘样品具有代表性,样品采集结束后做好标记以避免重复采样.鉴于当地湿度较大,将所采集的街尘样品置于冷冻干燥机(FreeZone)内进行预处理,称重.取处理好的样品通过空气动力筛分仪(Retsch AS200 jet)筛分为: <20 、 $20 \sim 45$ 、 $45 \sim 63$ 、 $63 \sim 105$ 、 $105 \sim 150$ 、 $150 \sim 250$ 、 $250 \sim 450$ 、 $450 \sim 1\,000$ 和 $>1\,000 \mu\text{m}$ 这9个粒径段,并将筛分好的街尘样品称重并记录.

径流样品:地表径流样品的采集主要包括路面径流和屋面径流,降雨特征如表1所示.当硬质路面和雨水管有径流产生,即开始径流样品的采集工

作,初期15 min内的径流样品按照每间隔5 min采集一次,其后采样时间间隔根据径流情况增加为10 min、20 min、30 min或1 h直至径流结束.硬质路面监测点在采样的同时用容积法测定其流量,雨水管径流流量的监测使用水文综合测量仪(Starflow6526).屋面径流样品由于监测现场较为复杂,故采集其等时混合径流样品.同时,为观测降雨量,在采样点附近安装RG3-M型翻斗式雨量计(Onset Computer Corporation,美国HOBO).采集到的径流样品置于聚乙烯瓶中,测定其SS、TP、COD和TN浓度,并通过马尔文激光粒度仪(Mastersizer 2000)测定其粒径分布.

表1 降雨事件特征

Table 1 Basic characteristics of rainfall events

降雨日期 (年-月-日)	降雨量/mm	降雨历时/h	平均降雨强度 $/\text{mm}\cdot\text{h}^{-1}$	降雨时间间隔 $/\text{d}$
2019-03-09	5.2	1.2	4.5	1.3
2019-03-25	8.4	2.2	3.8	14.8
2019-04-14	1.4	0.5	3.1	1.9
2019-04-16	15.4	2.7	5.8	1.3
2019-04-18	10.4	2.2	4.8	2.2
2019-04-20	38.8	2.9	13.5	0.6
2019-04-27	30.4	1.9	16.4	7.0
2019-04-30	11.8	1.4	8.9	2.7
2019-05-07	16	2.5	6.3	0.6
2019-05-23	9.4	4.4	2.2	2.7
2019-05-26	11.6	1.3	8.8	0.2
2019-06-10	33.2	1.4	24.3	6
2019-06-11	21	10.8	3.5	0.3
2019-06-13	8.8	0.4	21.6	1.5

1.3 数据分析

为更好地表征一次降雨事件的径流污染程度,用场次径流污染平均浓度(event mean concentration, EMC)来表示一场降雨径流全过程排放的污染物平均浓度,场次降雨径流污染负荷表示一场降雨所形成的地表径流排放的污染物总量^[22,23].

2 结果与分析

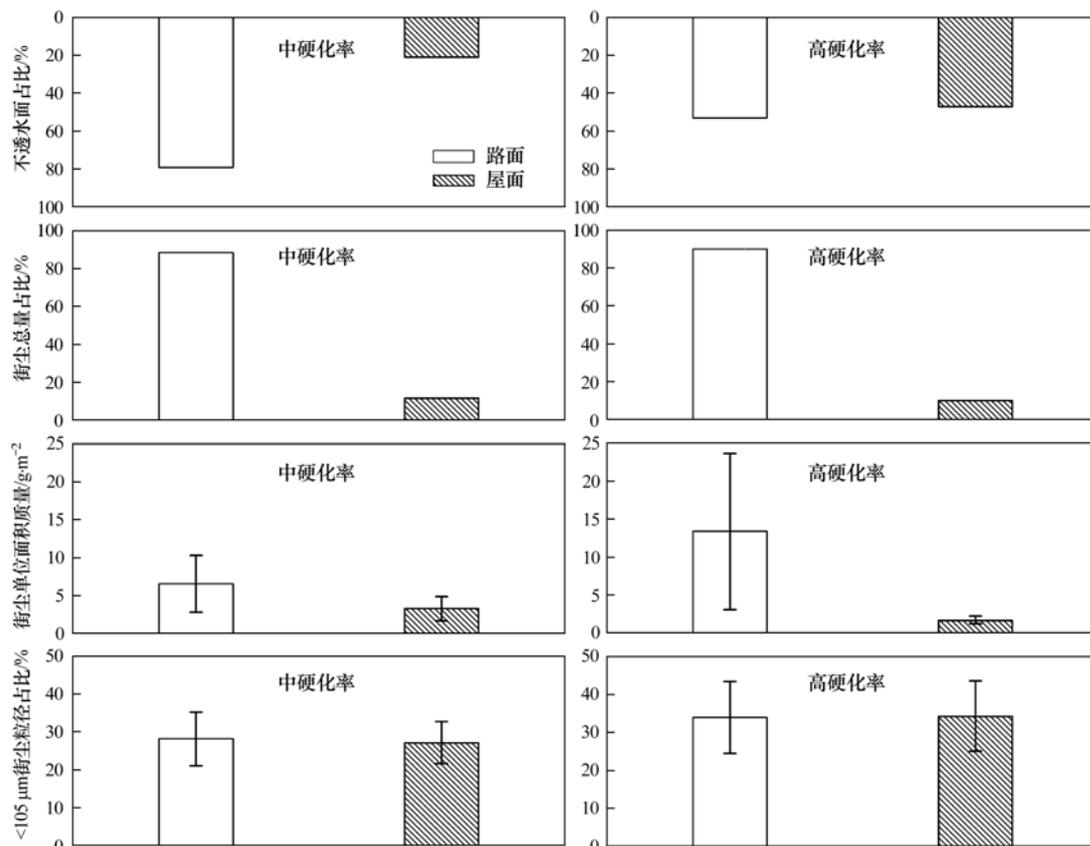
2.1 不同下垫面的街尘晴天静态累积及粒径分布特征

街尘是引发城市面源污染最广泛和最重要的污染载体^[24],明确其在不同下垫面上静态累积特征,量化不同下垫面污染源贡献比例,是开展海绵设施设计

的重要前提,将为有针对性控制地表径流污染提供重要依据.在中度硬化率(61.1%)地块(图3),路面、屋面占地块不透水面积比例分别为79.2%和20.8%,而两者贡献的街尘占地块街尘总量的88.4%和11.6%.高度硬化(73.6%)地块,路面对不透水面积贡献比分别是53.1%和46.9%,两者贡献的街尘占地块街尘总量的90.1%和9.9%.

对比两地块的两下垫面(路面和屋面)上街尘累积状况发现,路面上街尘单位面积质量受不透水率变化较为明显,在中硬化率和高硬化率地块分别

为 $2.22 \sim 12.51 \text{ g}\cdot\text{m}^{-2}$ 和 $4.99 \sim 33.43 \text{ g}\cdot\text{m}^{-2}$,平均单位面积质量增加约104.81%.同时,其粒径组成也发生相应的变化, $<105 \mu\text{m}$ 的街尘作为潜在冲刷及富集污染物较为显著的粒径范围^[25],在中硬化率和高硬化率地块街尘中的质量占比分别为18.4%~37.2%和25.3%~50.2%,平均增加24.4%.以上结果表明,高硬化率地块具有较高的潜在污染风险,且硬质路面为地块潜在污染源汇集的主要下垫面类型.因此,城区海绵设施改建过程中,需重点关注高硬化率地块及路面径流的处理.



不透水面占比是下垫面面积占地块不透水总面积的比例

图3 下垫面分布及街尘静态累积

Fig. 3 Distribution of underlying surface and static accumulation of street dust

2.2 降雨冲刷对面源颗粒污染物的影响

明确地块汇水区内不同下垫面的街尘输出总量及其粒径构成特征,可为海绵建设过程中LID设施的选择、布置及其日常运行维护提供重要的参考.由图4可知,中硬化率地块路面和屋面的街尘单位面积冲刷量分别为 $0.97 \sim 7.34 \text{ g}\cdot\text{m}^{-2}$ 和 $1.1 \sim 1.54 \text{ g}\cdot\text{m}^{-2}$,平均冲刷率48.9%和55.8%,而街尘冲刷总量约占地块冲刷总量的91.7%和8.3%.高硬化率地块路面和屋面的单位面积冲刷量分别为 $0.92 \sim 18.77 \text{ g}\cdot\text{m}^{-2}$ 和 $0.31 \sim 1.01 \text{ g}\cdot\text{m}^{-2}$,平均冲刷率38.8%和42.8%,冲刷总量约占整个地块的90.5%和9.5%.对于其冲刷街尘的粒径分布, $<105 \mu\text{m}$

街尘的单位面积冲刷率在两地块表现出较为明显的差异性.路面街尘在中硬化率和高硬化率地块的单位面积冲刷率分别为7.8%~38.3%和30.0%~55.1%,平均增加106.4%;而屋面街尘在两地块的单位面积冲刷率分别为5.9%~28.2%和30.5%~58.3%,平均增加160.2%.由此可见,降雨冲刷污染贡献绝大多数来源于硬质路面,并且高硬化率地块其冲刷小粒径街尘的占比相对较大.

2.3 径流SS污染特征及其差异性分析

城市面源污染产生的根本原因在于降雨冲刷地表颗粒污染物,使污染径流进入收纳水体而引发的水体水质污染^[26,27].SS对污染物吸附能力较强,是

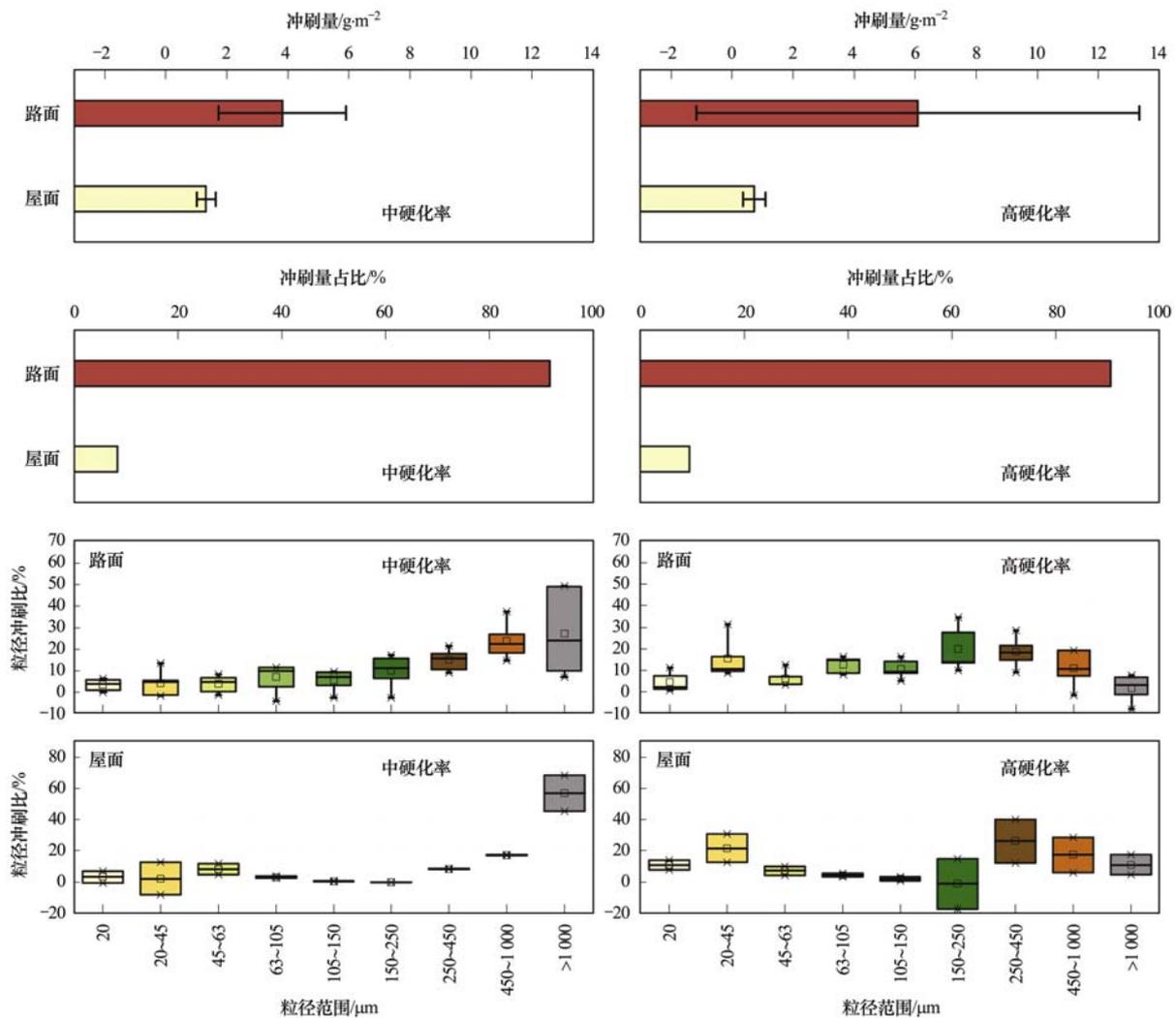


图4 街尘冲刷及粒径分布特征

Fig. 4 Wash-off and particle size distribution characteristics of street dust

径流中最主要的污染物之一^[28,29],也是我国评价海绵城市的重要指标^[21].因此,以径流中SS为导向,研究其污染及粒径分布特征,可为海绵城市的工程设计工作提供直接的数据参考.

如图5所示,中硬化率地块路面和屋面的径流SS污染负荷贡献比分别约为95.2%和4.8%;高硬化率地块路面与屋面的贡献比约为83.1%和16.9%.对径流粒径分布 D_{90} (样品累计粒度分布数达到90%时所对应的粒径)的分析来看,高硬化率地块路面径流的过程变化较为明显,在径流初期大颗粒即随地表径流进行迁移,同时在降雨强度较大的情况下其迁移能力明显高于中硬化率.由此可见,地块整体径流SS污染负荷主要源于硬质路面,且在高硬化率地块大粒径颗粒的迁移能力高于中硬化率地块.

2.4 径流SS输出特征分析

LID设施对径流具有调控作用,以往对设施的研究多集中于对单个及设施组合进出水口的径流变

化^[12~15].但是,目前我国海绵改建工程多基于地块尺度,因此科学评估其处理效果应建立在地块整体尺度上.如图6所示,中硬化率和高硬化率地块LID设施组合对SS总负荷的平均削减率分别为76.0%和59.9%.分析其差异性,高硬化率地块由于地表硬化程度较高、建筑物密集、透水地表集中分布等因素造成LID设施改建区域有限,设施所处的研究汇水区边界较大但其本身汇水区较小,降雨过程中仅部分径流可经LID设施处理净化,其余则直接经雨水管排入市政管网,从而导致其污染物负荷削减率较低.从其输出径流的粒径分布来看(图7和图8),管道出流皆以小粒径为主,大粒径颗粒体积分数占比有不同程度地下降特征,可见LID设施对地块径流粒径的去除依旧主要针对于大粒径颗粒($>200\mu\text{m}$)^[11,30].综上所述,LID设施的布置问题,不仅需考虑场地的适建性,还需关注整个服务汇水区内的径流外排特征,尽量保证绝大部分降雨径流经LID设施后排出.

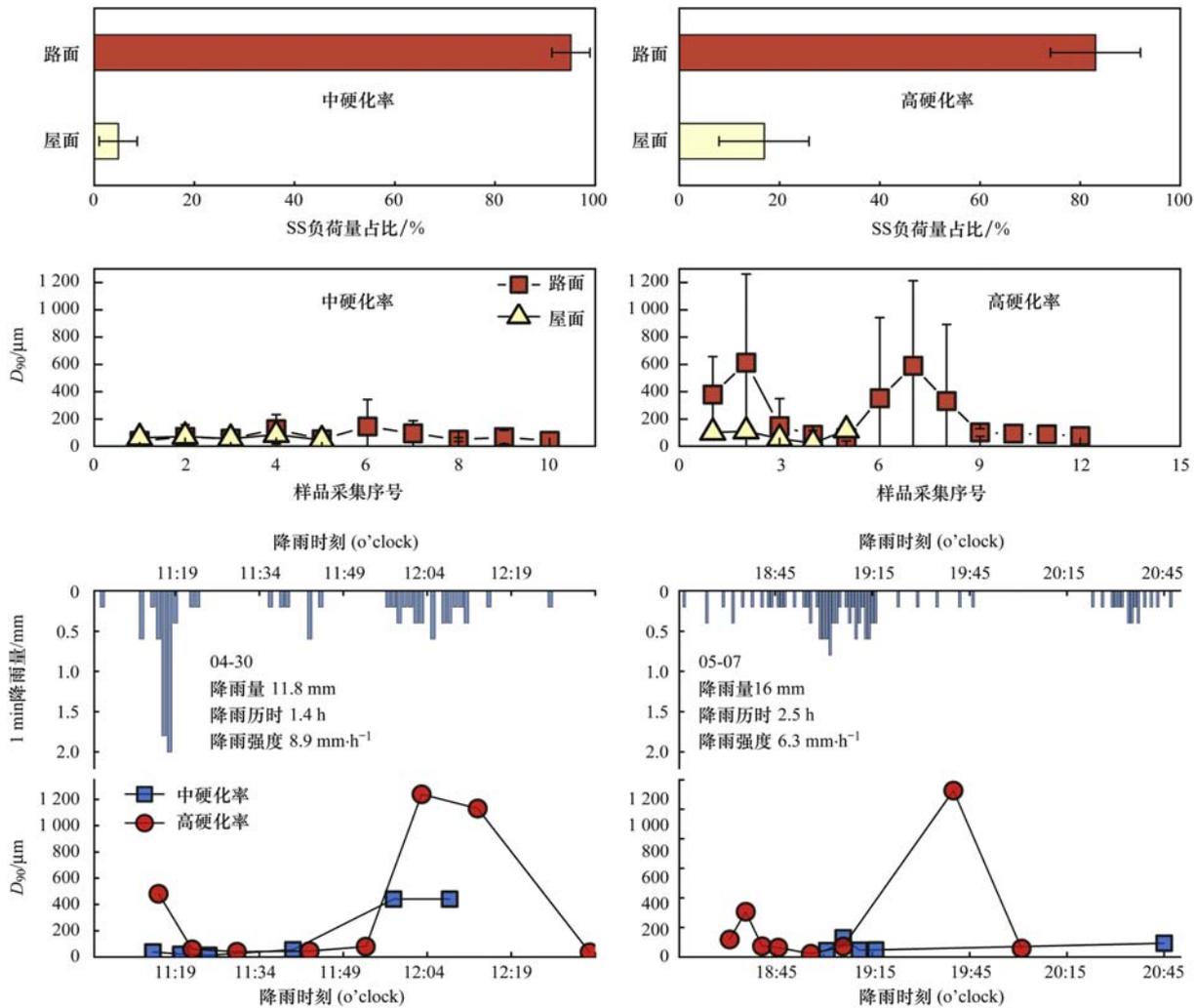


图5 地表径流 SS 负荷分布及其粒径变化过程

Fig. 5 SS load distribution and process of the particle size change in surface runoff

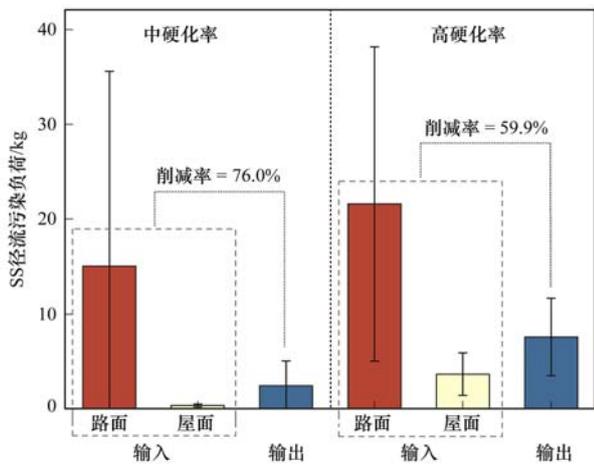


图6 径流 SS 污染负荷变化及其削减率

Fig. 6 Variations and reduction rates of SS load in runoff

3 讨论

3.1 颗粒物粒径全过程分析

粒径作为表征颗粒物行为的重要参数,可在一定程度上决定污染物的累积及迁移过程^[31].有研究

表明,污染物的富集、冲刷及 LID 设施的处理净化都对颗粒物粒径存在较强的选择性^[11,32,33].因此,颗粒物粒径作为污染物迁移的指示灯,关注 LID 建成区内全过程的粒径分布变化可进一步预估其潜在污染风险.本研究通过对比两地块颗粒物粒径全过程分析发现,其在晴天累积、降雨冲刷及 LID 设施净化过程中都表现出较为明显的差异性(图9).晴天累积颗粒物都以 > 150 μm 粒径段为主(中硬化率:路面 65.8%、屋面 69.5%;高硬化率:路面 55.6%、屋面 60.9%);而降雨冲刷颗粒物粒径分布在两地块差异性显著,以 > 150 μm 粒径段为例(中硬化率:路面 75.9%、屋面 82.4%;高硬化率:路面 51.0%、屋面 53.6%);降雨径流中颗粒物粒径分布受当地降雨特征影响,易被冲刷带走的大粒径颗粒在降雨过程中自由态向固定态的转变及雨滴等的侵蚀作用^[30,34,35],粒径分布则以 < 50 μm 粒径段为主(中硬化率:路面 87.2%、屋面 85.6%;高硬化率:路面 76.4%、屋面 79.7%);经 LID 设施处理后 < 50 μm

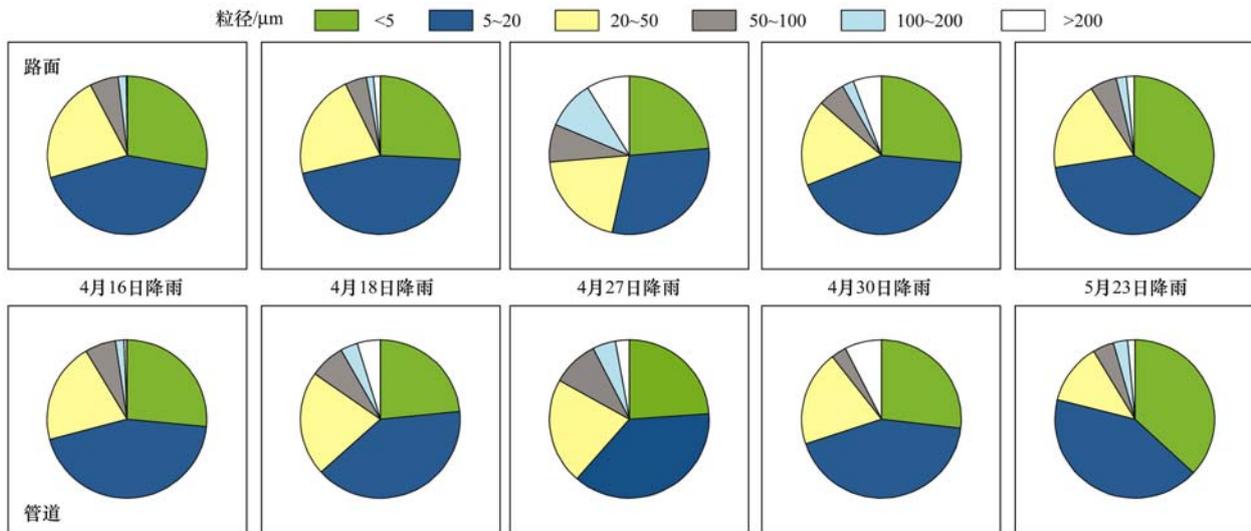


图 7 中硬化率地块径流颗粒物粒径分布

Fig. 7 Particle size distribution of runoff in medium hardening rate plot

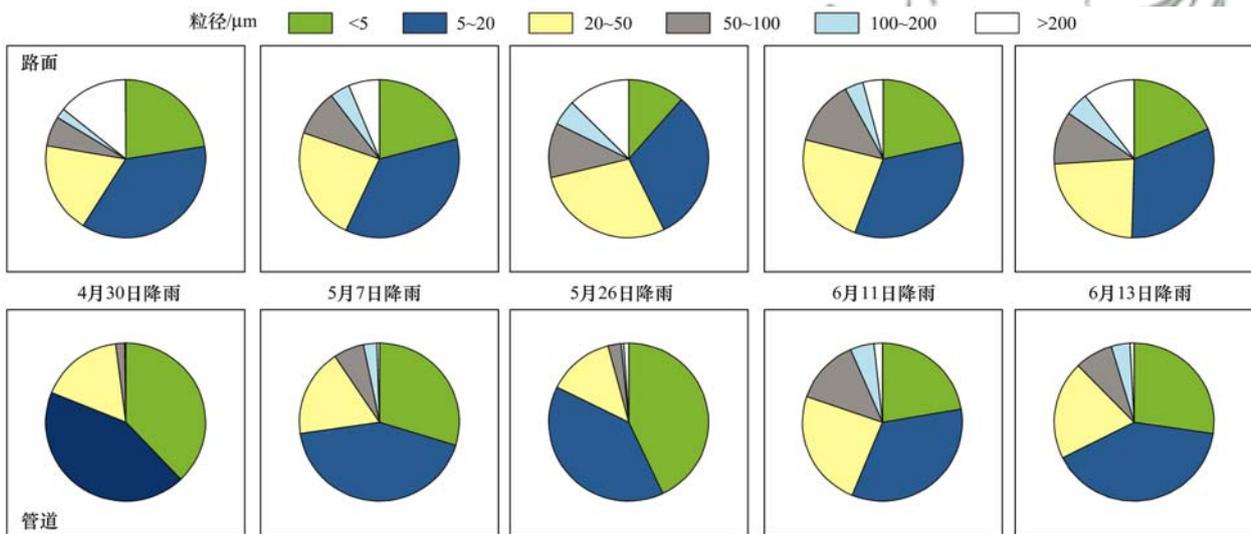


图 8 高硬化率地块径流颗粒物粒径分布

Fig. 8 Particle size distribution of runoff in high hardening rate plot

粒径段的颗粒物在中硬化率和高硬化率地块的占比分别为 88.0% 和 90.5%。同时,对比地块两不同下垫面,中硬化率地块屋面 >1 000 μm、高硬化率地块屋面 250 ~ 450 μm、<45 μm 粒径段颗粒物的累积及冲刷相较于路面明显增加 (>1 000 μm: 58.1%、108.5%; 250 ~ 450 μm: 72.9%、41.8%; <45 μm: 59.2%、64.8%)。显然,小粒径颗粒物的晴天累积及降雨冲刷在高硬化率地块占比较大,而在地表径流中,小粒径颗粒物在中硬化率地块的占比则高于高硬化率地块。分析其原因:中硬化率地块因车流量及人流量较少,对街尘的碾压程度较低,地块晴天累积的大粒径颗粒物较多且在雨滴的打击下易分解为细小颗粒物;而高硬化率地块碾压侵蚀程度较高,大粒径颗粒物的占比明显减少,加上其地面粗糙程度较小,降雨冲刷过程中地面对颗

粒物的滞留程度较低,颗粒物多直接随径流进入水体而雨滴溅蚀状况较少。同时,对比两地块径流水质状况(图 10),高硬化率地块地表径流污染程度整体高于中硬化率地块,说明因雨滴溅蚀产生的小粒径颗粒物所负载的污染物要少于直接冲刷进入径流的颗粒物。但是,鉴于大粒径颗粒物在晴天累积及降雨冲刷中占比较大,其对污染负荷的整体贡献尚不明确^[36]。因此,在后续研究中关注大粒径颗粒物在径流中的污染总负荷的贡献情况对控制面源污染至关重要。

3.2 颗粒污染物分布及“累积-冲刷-输送”特征

以城市各地块为单元,结合下垫面特征布置 LID 设施是目前我国海绵城市改建工程的重要趋势^[37,38],其 LID 设施的设置更为分散且设施的选择往往不局限于单个或单一设施。LID 设施将整个汇

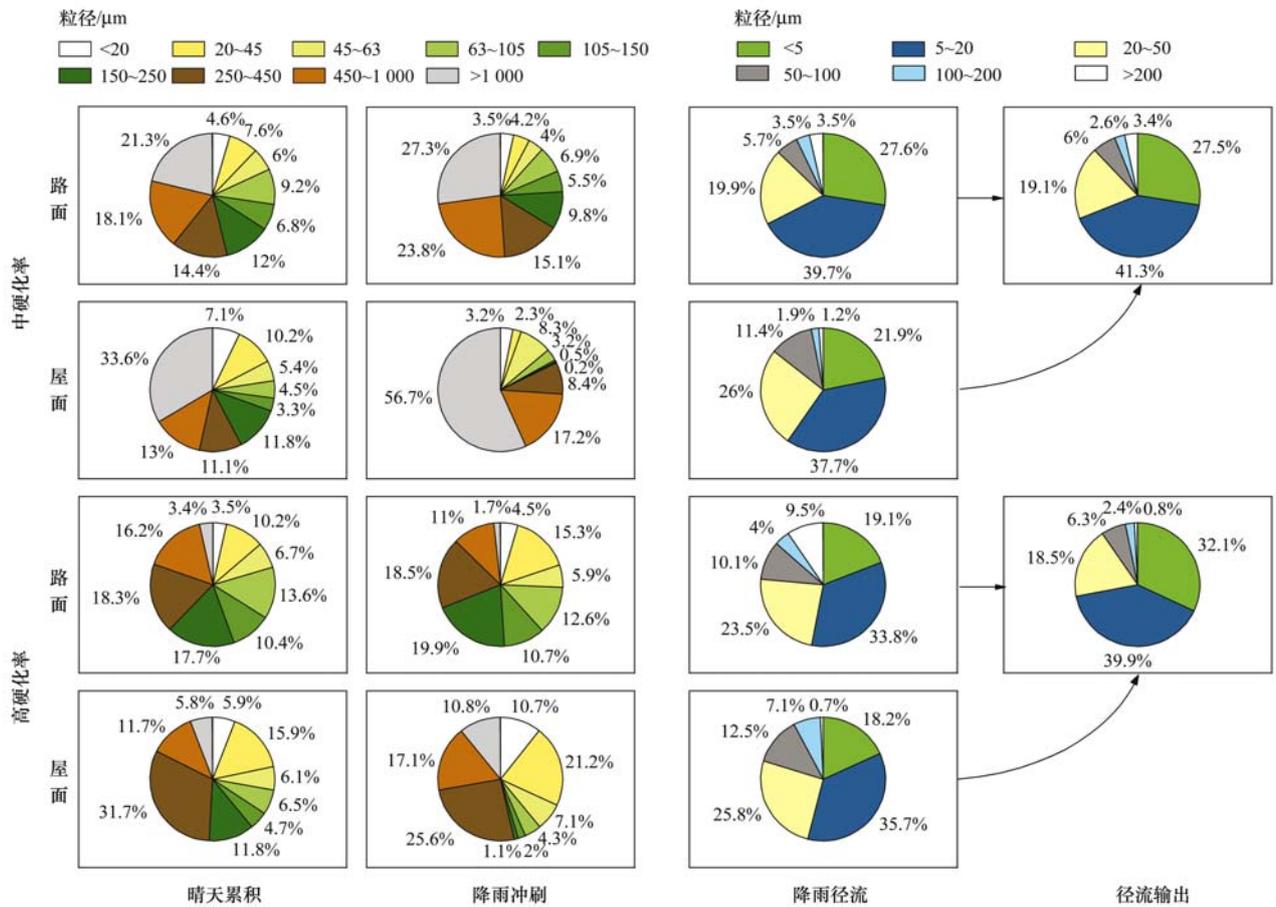


图 9 颗粒物粒径分布的全过程变化

Fig. 9 Changes in particle size distribution during the entire transport process

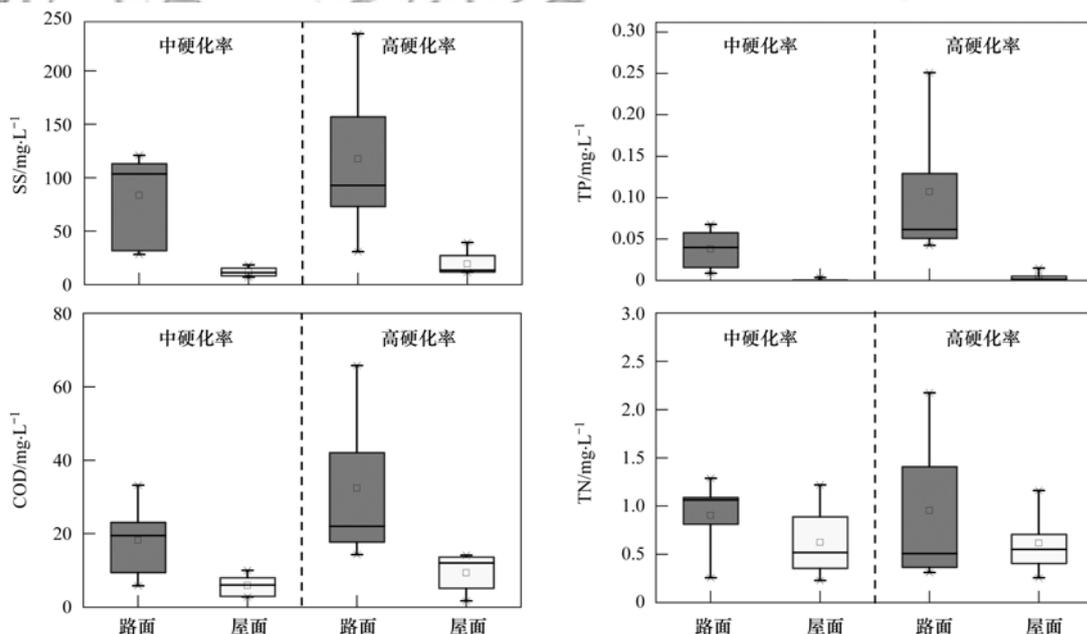


图 10 地表径流中污染物的 EMC

Fig. 10 Event mean concentrations of pollutants in surface runoff

水区单元划分为几个小汇水区,以往简单的 LID 设施进出水口径流水质变化特征研究不足以表征其对整个地块降雨径流的影响.同时,颗粒物作为污染物的重要载体,其在前期污染物累积、中期污染物传输

和后期污染物净化处理中起到重要作用^[39].因此,在地块汇水区整体尺度上量化颗粒污染物的累积-冲刷-输出负荷占比对后期 LID 设施的优化布置及其工程绩效的科学评估具有重要意义.本研究结

合地下雨水管网和地表高程数据划定汇水分区, 识别地块污染贡献主要下垫面类型并在关键汇排水节点上进行采样监测. 此次研究对比了不同硬化率地块(中硬化率:61.1%; 高硬化率:73.6%)晴天累积负荷分布(中硬化率:路面 88.4%、屋面 11.6%; 高硬化率:路面 90.1%、屋面 9.9%), 径流冲刷负荷分布(中硬化率:路面 91.7%、屋面 8.3%; 高硬化率:路面 90.5%、屋面 9.5%), 径流污染负荷分布(中硬化率:路面 95.2%、屋面 4.8%; 高硬化率:路面 83.1%、屋面 16.9%), 经 LID 排放污染负荷(中

硬化率:24.0%; 高硬化率:40.2%) 分布状况(图 11). 显然,路面为地块面源污染控制的主要下垫面类型,对于改建空间有限的地块需首先考虑路面径流处理设施的设置. 地块汇水区尺度 LID 对 SS 污染负荷削减约 60%,因地块本身改建空间有限,所有 LID 设施服务的汇水区范围小于研究区地块尺度汇水区,导致地表径流无法全部径流 LID 设施. 同时 LID 设施建设更为分散、汇水面积占地块整体比例更大的中硬化率地块,其削减效果优于高硬化率地块.

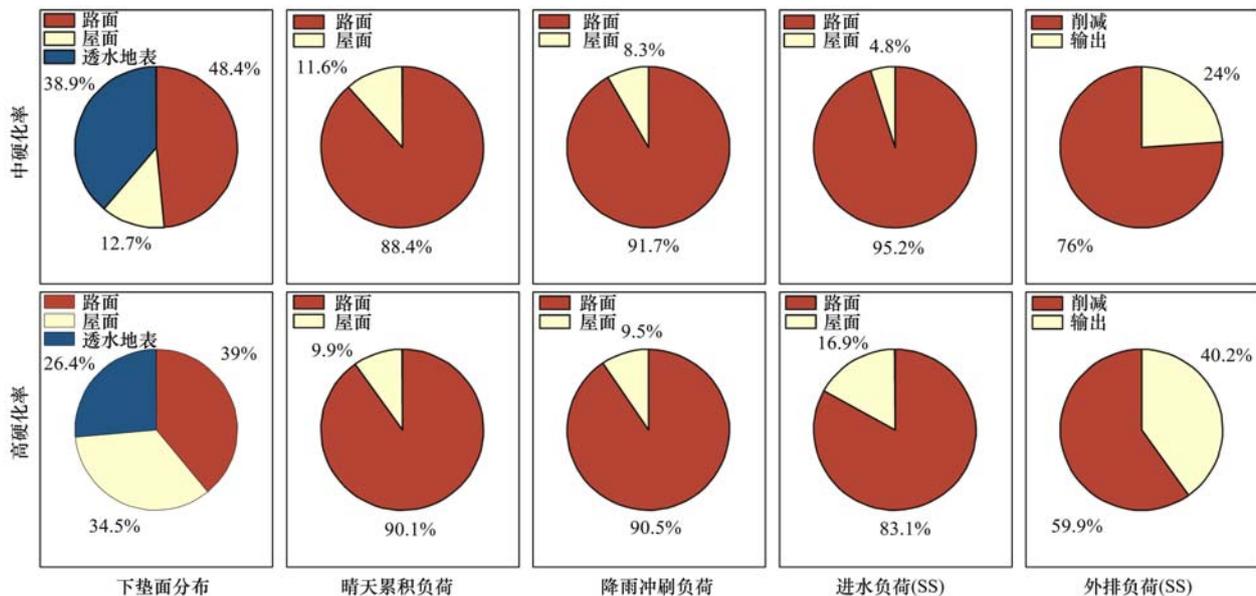


图 11 颗粒污染物负荷分布

Fig. 11 Distribution of particulate pollutant load

4 结论

(1) 地块汇水单元内路面为街尘富集的主要下垫面类型,其街尘累积量占地块街尘总量的 90% 左右. 地块不透水比例的增加,路面街尘单位面积累积量增加, < 105 μm 的街尘质量占比也有所增加.

(2) 受降雨径流影响,路面和屋面的街尘单位面积冲刷量分别约为 $4.95 \text{ g}\cdot\text{m}^{-2}$ 和 $1.02 \text{ g}\cdot\text{m}^{-2}$,路面街尘冲刷质量占比在整个地块汇水单元内可达到 90% 以上,小粒径 (< 105 μm) 颗粒物的单位面积冲刷率在高硬化率地块整体高于中硬化率地块.

(3) 地表径流 SS 污染负荷贡献主要源于硬质路面,其污染负荷贡献比例可达到 80% 以上. 经 LID 设施组合的净化作用,两地块汇水区整体 SS 污染负荷削减 76.0% (中硬化率) 和 59.9% (高硬化率).

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