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# 不同降雨条件下植被对绿色屋顶径流调控效益影响

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**摘要:** 植被是绿色屋顶的重要组成部分, 可通过截留雨水和蒸散耗水等过程影响绿色屋顶的径流调控效益. 本文基于太阳花 (*Portulaca grandiflora*)、佛甲草 (*Sedum lineare*)、高羊茅 (*Festuca elata*) 和无植被等 4 种植被覆盖类型绿色屋顶 2017 年雨季 26 场降雨径流过程的监测数据, 从径流和洪峰削减、产流和峰现时间延迟四方面定量分析植被在不同降雨条件下对绿色屋顶径流调控效益的影响. 结果表明, 绿色屋顶径流削减率与降雨量呈显著负相关 ( $P < 0.01$ ), 降雨量  $< 10$  mm 时, 绿色屋顶径流削减率等于或接近 100%; 降雨量超过 30 mm, 所有绿色屋顶的径流削减率降低到 70% 以下; 当降雨量达到监测期内最大的 81.4 mm 时, 各绿色屋顶径流削减率都低于 55%. 植被覆盖类型对绿色屋顶径流调控效益的影响随降雨条件而改变, 大雨条件下不同植被覆盖类型绿色屋顶的径流削减率差异最大, 中雨和暴雨条件下次之, 小雨条件下因各绿色屋顶几乎都不产流而无明显差异. 在中雨、大雨和暴雨条件下, 有植被覆盖绿色屋顶的径流削减率、洪峰削减率、产流和峰现时间延迟等 4 个指标都明显优于无植被覆盖的绿色屋顶. 株高和单位面积地上生物量最高的太阳花绿色屋顶的径流调控效益优于佛甲草绿色屋顶.

**关键词:** 绿色屋顶; 降雨; 植被; 径流/洪峰削减; 产流/峰现延迟

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## Impacts of Vegetation on Hydrological Performances of Green Roofs Under Different Rainfall Conditions

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**Abstract:** Vegetation is an important component of green roofs and may affect their hydrological performance through the processes of rainwater interception and evapotranspiration. Based on the rainfall-runoff observations of green roofs with four types of vegetation covers (*Portulaca grandiflora*, *Sedum lineare*, *Festuca elata*, and bare substrate) located in Beijing during 26 rainfall events from April to October 2017, the impacts of vegetation cover on the hydrological performance of green roofs were investigated using runoff and peak discharge reduction rates and time-delay of runoff generation and peak discharge as indices. For the 12 green roofs, there was a significantly negative correlation ( $P < 0.01$ ) between runoff reduction rate and rainfall event volume. For low rainfall ( $< 10$  mm), the runoff reduction rates of all the green roofs were equal or close to 100%. When the rainfall volume increased to about 30 mm, the runoff reduction rates dropped to below 70%. For the heaviest rainfall event during the observation period (81.4 mm), the runoff reduction rates of all the green roofs were less than 55%. The impacts of vegetation on the hydrological performance of green roofs changed with rainfall conditions. The differences between runoff reduction rates of green roofs with different types of vegetation cover were largest for the heavy rainfall events. For the moderate rainstorm events, the differences were slightly lower. For light rainfall events, however, no significant differences were observed among the runoff reduction rates of green roofs with different types of vegetation cover, as little runoff was generated. Vegetation cover could enhance the hydrological performance of green roofs, as the runoff and peak discharge reduction rates and time-delay of runoff generation and peak discharge of green roofs covered with vegetation were all better than those of the bare substrate for all the groups of rainfall events except the light rainfall. Vegetation-covered green roofs with *P. grandiflora* performed the best, as the average height and aboveground biomass per unit area of *P. grandiflora* were the largest.

**Key words:** green roof; rainfall; vegetation; runoff reduction; peak discharge mitigation

近年来, 绿色屋顶作为低影响开发 (LID) 和海绵城市建设的重要措施之一, 在许多国家和地区的城市建设中得到推广应用<sup>[1]</sup>. 相对于其他 LID 和海绵城市建设措施, 绿色屋顶的优势在于其不仅具有调控径流, 减少建筑热负荷, 为野生动物提供栖息地, 减少噪声和空气污染等生态功能<sup>[2~7]</sup>, 而且无需额外用地. 因此, 绿色屋顶在土地资源紧张且内涝积水严重、生态环境脆弱的城镇区域具有广泛的

应用前景. 绿色屋顶的结构从上到下一般包括植被层、基质层、过滤层、排水层和阻根防水层等<sup>[8,9]</sup>. 筒式 (粗放型) 绿色屋顶基质层厚度较薄, 对屋顶结

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构的承重能力要求、造价和养护成本都较低<sup>[4]</sup>,较复式绿色屋顶更为广泛地用于城市生态建设<sup>[10~14]</sup>.

植被层可通过自身形态特征提供观赏价值<sup>[15]</sup>,是绿色屋顶最重要的审美价值来源.植被也可为无脊椎动物和鸟类群落提供栖息地,改善屋顶生态环境<sup>[4,16,17]</sup>.绿色屋顶植被能通过蒸散发过程和高表层反射率起到良好的降温 and 热阻作用,缓解城市热岛效应<sup>[18]</sup>.而屋顶干燥、光强、风大、夏季高温和冬季寒冷的环境条件,使大多数植物难以在此存活.景天科植物因为独特的景天酸代谢过程<sup>[19]</sup>和叶肉储水功能<sup>[20]</sup>,具有极强的适应能力,成为世界上使用最广泛的屋顶绿化植物.非肉质植物如禾本科草本则需要一定灌溉才能在屋顶生长<sup>[21]</sup>.

绿色屋顶的径流调控功能主要通过滞留雨水来实现<sup>[22]</sup>,其雨水滞留能力主要由植被层截留雨水和基质层吸持雨水而形成<sup>[9]</sup>.基质层对雨水的吸持能力在绿色屋顶径流调控过程中起主要作用<sup>[23~25]</sup>.植被通过蒸散发耗水可维持基质层的雨水吸持能力,进而显著提高绿色屋顶径流削减效益<sup>[25]</sup>.植被的配置类型<sup>[26]</sup>和覆盖度<sup>[27]</sup>等特征决定了绿色屋顶植被层的雨水截留能力,因而也会影响绿色屋顶的径流调控效益.而在气候条件、基质类型和厚度等多种因素影响下<sup>[8,23,28~30]</sup>,植被对绿色屋顶径流调控过程的影响十分复杂,是目前绿色屋顶研究领域的国际前沿,而国内尚缺乏该方面的研究.

本文基于对北京市4种不同植被覆盖和3种生长基质类型绿色屋顶在2017年雨季的植被生长特征、降雨、基质层水分和径流过程的监测,定量分析植被对绿色屋顶径流调控效益的影响.根据降雨量大小对26场降雨进行分类,分析植被在不同降雨条件下对绿色屋顶径流调控效益的影响,并结合植物的生长特征和基质层水分的变化过程解析不同植被覆盖类型绿色屋顶径流调控效益存在差异的原因,以为绿色屋顶的植被配置及径流调控效益评估提供科学参考.

## 1 材料与方法

### 1.1 实验设计

本实验的绿色屋顶建于北京市海淀区北京林业大学林业楼楼顶.气候类型为北温带半湿润大陆性季风气候.1951~2013年年均降水量584 mm,全年降水的80%集中在夏季6、7、8月<sup>[31]</sup>.

实验设计12个1 m×1 m的不同生长基质和植被类型的绿色屋顶(图1).绿色屋顶从上向下依次

为植被层、生长基质层、过滤层、排水层和防水保护层.植被层种植佛甲草、太阳花、高羊茅并设置无植被对照组.实验过程中,佛甲草和太阳花生长状况良好,高羊茅因不适合屋顶干旱高温环境而大面积枯萎、死亡.基质层有改良土、田园土和轻质生长基质(轻质基)3种类型,厚度均为10 cm.改良土由轻砂壤土、腐殖土、珍珠岩、蛭石按比例混合而成,容重为 $0.63 \text{ g}\cdot\text{cm}^{-3}$ ,孔隙度为61.26%,饱和导水率为 $250 \text{ mm}\cdot\text{h}^{-1}$ ;田园土容重为 $1.13 \text{ g}\cdot\text{cm}^{-3}$ ,孔隙度为48.35%,饱和导水率为 $77 \text{ mm}\cdot\text{h}^{-1}$ ;轻质基由浮石、草炭土、沸石、碎木屑按比例混合而成,容重为 $0.55 \text{ g}\cdot\text{cm}^{-3}$ ,孔隙度为57.58%,饱和导水率为 $267 \text{ mm}\cdot\text{h}^{-1}$ .过滤层为 $300\sim400 \text{ g}\cdot\text{m}^{-2}$ 聚酯无纺布,排水层由厚度为10 cm直径约为30 mm陶粒组成,防水层为TPO防水卷材.

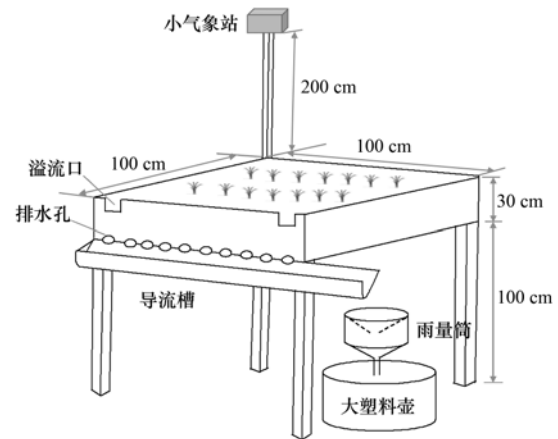


图1 绿色屋顶实验示意

Fig. 1 Structural diagram of the experimental devices

降雨过程由架设于绿色屋顶上方2 m的HOBO U30自动小气象站监测.基质层水分采用HOBO S-SMC-M005土壤水分传感器监测,径流过程采用雨量分辨率为1 mm的自记式雨量计监测.监测径流的雨量计下放置250 L塑料桶,用以承接绿色屋顶径流.每场降雨结束后,根据塑料桶内收集的径流总量检验和校核雨量计的测量结果,保证径流数据的可靠性.

基于张建军等<sup>[32]</sup>的测定方法,采集 $400 \text{ cm}^2$ 样方内植被的地上部分,置于 $65^\circ\text{C}$ 烘箱内烘干至恒重后称重,作为该植物的地上生物量.于实验装置内随机选取10个点,利用皮尺测定高度,取平均值作为该植物的株高.植被覆盖度利用照相法测定,监测期内定期修剪植物.

### 1.2 径流调控效益评价指标

经测定,林业楼顶防水油毛毡表面的雨水滞蓄

能力为 1.0 mm 左右, 即当降雨量大于 1 mm 时, 超出部分转化为径流. 设场降雨量为  $P$ , 当  $P \leq 1$  mm 时, 普通屋顶与绿色屋顶均不产流, 可认为绿色屋顶的径流削减率为 100%;  $P > 1$  mm 时, 普通屋顶产生的径流量为  $P - 1$ , 绿色屋顶的产流量为  $R$ , 皆以 mm 计. 相对于普通屋顶, 绿色屋顶的径流削减率( $D_r$ )可由式(1)计算:

$$D_r = \frac{(P - 1) - R}{(P - 1)} \times 100\% \quad (1)$$

绿色屋顶的洪峰削减率( $D_{pr}$ )可由下式计算:

$$D_{pr} = \frac{I_{\max} - D_p}{I_{\max}} \times 100\% \quad (2)$$

式中,  $I_{\max}$  为场降雨最大 5 min 雨强,  $\text{mm} \cdot \text{min}^{-1}$ ;  $D_p$  为绿色屋顶场降雨单位面积的洪峰流量,  $\text{mm} \cdot \text{min}^{-1}$ .

本研究以绿色屋顶开始产流时间与普通屋顶开始产流时间的差值为产流延迟时间, 以绿色屋顶径流峰值时间与降雨强度峰值时间的差值为峰现延迟时间, 分别衡量绿色屋顶对产流和峰现时间的延迟效益.

2 结果与分析

2.1 降雨特征与分类

参照 Voyde 等的研究<sup>[33]</sup>, 本文将前后两个间隔不超过 6 h 的降雨时段视为同一场降雨. 2017 年 5 ~ 10 月共监测到 26 场降雨, 其中大于 10 mm 的降雨有 13 场, 其降雨特征如表 1. 根据《降水等级标准》(GB/T 28592-2012), 将监测期内场降雨按照降雨量大小分为小雨(0.1 ~ 9.9 mm)、中雨(10 ~ 24.9 mm)、大雨(25 ~ 49.9 mm)、暴雨(50 ~ 99.9 mm)这 4 种类型. 实验期最大降雨为 7 月 15 日的暴雨, 历时 520 min, 降雨量为 81.4 mm, 最大雨强为 2.76  $\text{mm} \cdot \text{min}^{-1}$ . 持续时间最长的降雨为 6 月 22 日的暴雨, 历时 1 325 min, 降雨量为 63 mm, 最大雨强为 0.84  $\text{mm} \cdot \text{min}^{-1}$ .

2.2 降雨条件对绿色屋顶径流调控效益的影响

降雨量对不同植被类型绿色屋顶径流削减效益的影响见图 2. 以改良土为例[图 2(a)], 佛甲草、太阳花和无植被绿色屋顶的径流削减率都与降雨量显著负相关( $r_{\text{佛甲草}} = -0.861$ ,  $r_{\text{太阳花}} = -0.793$ ,  $r_{\text{无植被}} = -0.819$ ;  $P < 0.01$ ). 降雨量 < 10 mm 时, 3 种植被覆盖类型绿色屋顶的径流削减率都等于或接近 100%; 中雨时, 3 种绿色屋顶径流削减率大都在 70% ~ 100% 之间; 大雨时, 3 种绿色屋顶径流削减

率降到 45% ~ 70% 之间; 实验期间仅有两场暴雨, 3 种植被覆盖类型绿色屋顶的径流削减率在 42% ~ 62% 之间. 绿色屋顶的径流削减效益源于其具有一定的雨水滞留能力, 当降雨量超过绿色屋顶的最大雨水滞留能力时, 才会产生径流<sup>[22,34]</sup>. 雨量较小时雨水会被绿色屋顶全部吸持, 径流削减率可达到或接近 100%. 当降雨超出绿色屋顶最大雨水滞留能力时, 多余的雨水将转化为径流, 且径流量会随着降雨量增加而增加, 因此绿色屋顶径流削减率会随着降雨量的增加而减小. 田园土和轻质基绿色屋顶的径流削减率也与降雨量显著负相关[图 2(b) 和图 2(c)].

表 1 实验期内场降雨(>10 mm)特征

Table 1 Characteristics of rainfall events (> 10 mm)

| during the experimental period |            |              |                                             |
|--------------------------------|------------|--------------|---------------------------------------------|
| 日期<br>(月-日)                    | 降雨量<br>/mm | 降雨历时<br>/min | 最大雨强<br>/ $\text{mm} \cdot \text{min}^{-1}$ |
| 06-13                          | 12.4       | 210          | 0.48                                        |
| 06-22                          | 63.0       | 1 325        | 0.84                                        |
| 07-04                          | 18.8       | 300          | 0.36                                        |
| 07-06                          | 43.6       | 775          | 1.16                                        |
| 07-07                          | 17.6       | 130          | 0.6                                         |
| 07-15                          | 81.4       | 520          | 2.76                                        |
| 07-18                          | 10.6       | 320          | 0.28                                        |
| 07-21                          | 29.8       | 330          | 1.16                                        |
| 08-08                          | 10.2       | 45           | 0.64                                        |
| 08-12                          | 26.2       | 355          | 0.84                                        |
| 08-22                          | 44.2       | 940          | 0.44                                        |
| 08-27                          | 22.8       | 915          | 0.12                                        |

如图 3, 随着降雨量增大, 9 个绿色屋顶的洪峰削减率都呈下降趋势. 然而, 洪峰削减率与降雨量的相关关系并不显著. 场降雨的最大雨强与洪峰削减率也无显著相关关系. 原因较为复杂, 当最大雨强出现在绿色屋顶产流前, 此时绿色屋顶无径流亦无洪峰出现, 洪峰削减率为 100%. 而当最大雨强出现在绿色屋顶产流开始后, 绿色屋顶因为其植被的截留、基质层的下渗和过滤排水层的缓释作用仍能削减洪峰流量, 但洪峰削减量的大小还要由最大雨强、基质层下渗性能、排水层粗糙程度以及汇流路径长度等影响因素决定<sup>[22,35~37]</sup>. 由于降雨量、降雨强度、降雨间歇期天数等参数的随机性, 且不同植被和生长基质类型绿色屋顶的雨水滞留能力在每场降雨开始前并不相同<sup>[38]</sup>, 因此, 绿色屋顶的洪峰削减效益与场降雨量和最大雨强并未表现出显著相关关系.

2.3 植物生长特性分析

本实验过程中高羊茅因不适应屋顶环境大面积

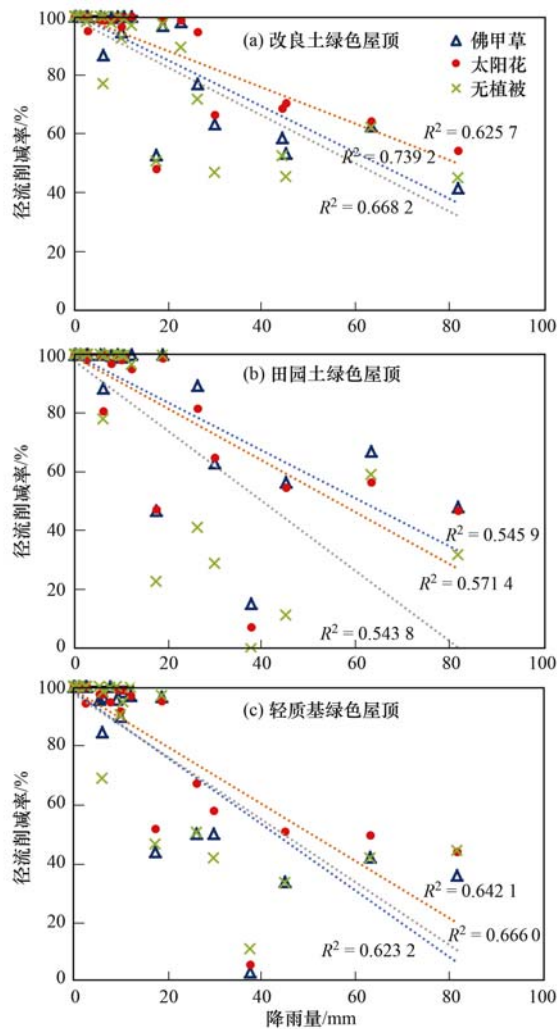


图2 降雨量对绿色屋顶径流削减率的影响

Fig. 2 Impacts of rainfall volume on runoff reduction rates of green roofs

死亡,而佛甲草和太阳花生长良好,其生长特征见表2. 佛甲草和太阳花的覆盖度在移栽一个月后均达到100%,太阳花的平均株高为26 cm,是佛甲草的2.6倍. 太阳花的地上生物量为 $1\,543\text{ g}\cdot\text{m}^{-2}$ ,也接近佛甲草的2倍. 太阳花的最大雨水截留量为 $1\,083\text{ g}\cdot\text{m}^{-2}$ ,高于佛甲草的 $833\text{ g}\cdot\text{m}^{-2}$ . 说明草本植物的茎叶具有降水截留作用,且这种作用会随着植被的株高、覆盖度和生物量的增大而逐渐增大<sup>[25,39]</sup>. 根据水量平衡原理,在降雨量和基质储水量相同情况下,植物截留量越大,绿色屋顶径流越小. 因此,在相同的基质层配置情况下,太阳花绿色屋顶的最大雨水滞留能力高于佛甲草绿色屋顶,且二者的雨水滞留能力都高于无植被的对照组.

2.4 植被类型对径流调控效益的影响

由于降雨条件对绿色屋顶径流调控效益的影响较大,且小雨条件下几乎所有绿色屋顶都未产生径流,本文分别从中雨、大雨、暴雨这3种降雨类型中各选取一场代表性降雨分析植被对绿色屋顶径流调控效益的影响. 图4显示了3种基质类型不同植被覆盖的绿色屋顶在8月8日中雨(10.2 mm)条件下的径流过程. 如图4(a),改良土基质的太阳花、佛甲草和无植被覆盖绿色屋顶分别产流0.31、0.47和0.65 L,径流削减率分别为96.6%、94.9%和92.9%,差异并不明显. 无植被的绿色屋顶并未表现出明显产流延迟效益,有植被的绿色屋顶在降雨开始5 min后产流. 太阳花绿色屋顶洪峰削减效益最强,洪峰流量仅为 $0.025\text{ L}\cdot\text{min}^{-1}$ ,洪峰流量削减率达到96.1%;佛甲草绿色屋顶的洪峰流量为

表2 植物生长特性

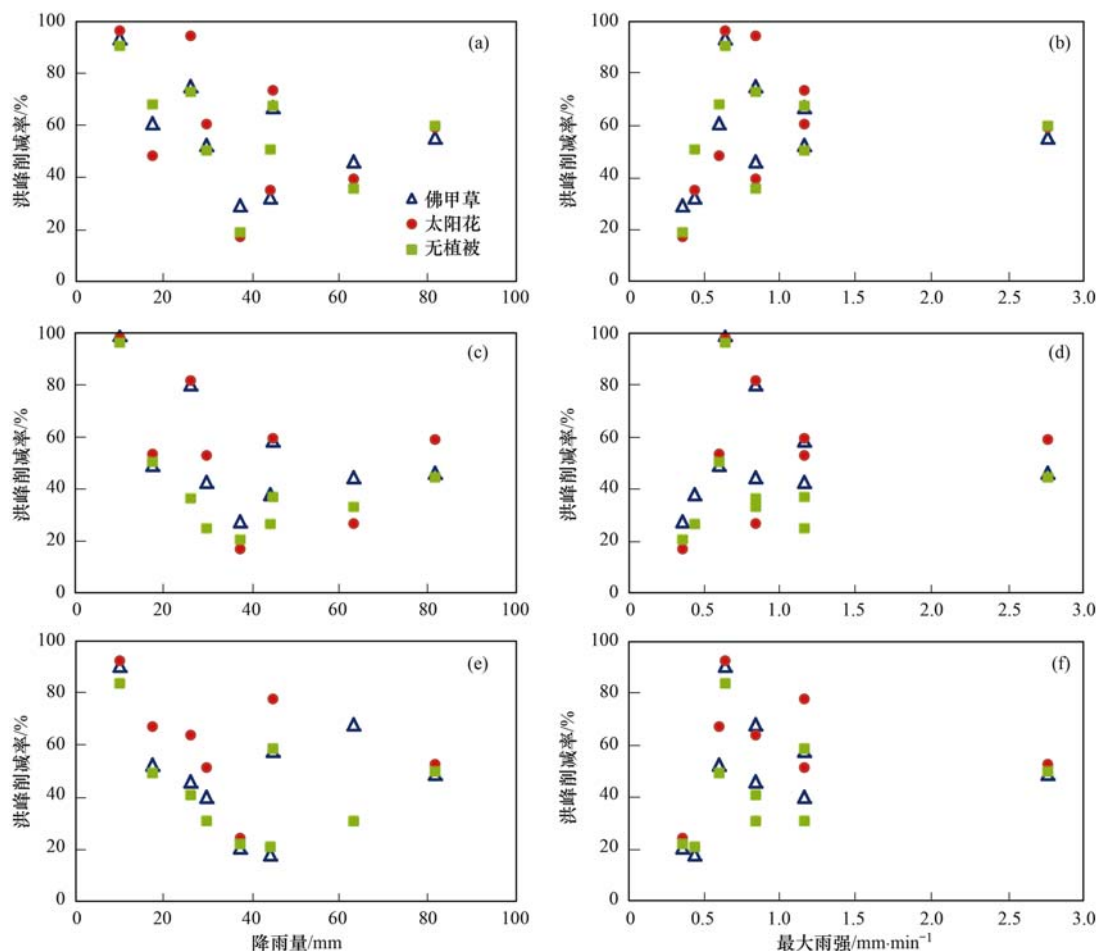
Table 2 Growth characteristics of experimental vegetation

| 植被类型                             | 平均株高<br>/cm | 覆盖度<br>/% | 地上生物量<br>/ $\text{g}\cdot\text{m}^{-2}$ | 最大截留量<br>/ $\text{g}\cdot\text{m}^{-2}$ |
|----------------------------------|-------------|-----------|-----------------------------------------|-----------------------------------------|
| 太阳花 <i>Portulaca grandiflora</i> | 26          | 100       | 1 543                                   | 1 083                                   |
| 佛甲草 <i>Sedum lineare</i>         | 10          | 100       | 873                                     | 833                                     |

$0.043\text{ L}\cdot\text{min}^{-1}$ ,洪峰削减率为93.2%;无植被覆盖绿色屋顶出现了相对最高的洪峰流量 $0.062\text{ L}\cdot\text{min}^{-1}$ ,洪峰削减率为90.3%. 相比普通屋面,太阳花、佛甲草和无植被的绿色屋顶都有5 min的峰现时间延迟效益. 不同植被类型的田园土和轻质基绿色屋顶[如图4(b)和4(c)]表现出的径流调控规律与改良土绿色屋顶相似,有植被的绿色屋顶径流调控各指标都略优于无植被的绿色屋顶.

在7月6日大雨(43.6 mm)条件下,不同植被覆盖类型的绿色屋顶呈现出差异明显的径流响应过

程(图5). 如图5(a),改良土基质的所有绿色屋顶在降雨开始30 min后同时产流,相比普通屋顶的产流开始时间延迟10 min. 太阳花、佛甲草和无植被覆盖绿色屋顶的径流量分别为12.8、20.4和23.9 L. 太阳花绿色屋顶表现出最强的径流削减功能,径流削减率为69.9%,佛甲草和无植被绿色屋顶的径流削减率分别为52%和44%. 大雨下3种绿色屋顶的径流削减效益大小排序仍与中雨条件下一致,但径流削减率之间的差值增大. 相比普通屋顶,无植被绿色屋顶的径流洪峰在最大雨强5 min



(a)、(b)改良土绿色屋顶;(c)、(d)田园土绿色屋顶;(e)、(f)轻质基绿色屋顶

图3 降雨量及最大雨强与绿色屋顶洪峰削减率之间关系

Fig. 3 Correlation between rainfall, maximum rain intensity, and peak discharge reduction rates

后出现,而两种植被覆盖绿色屋顶的径流洪峰出现在最大雨强4 h之后,表现出良好的峰现延迟效益.佛甲草屋顶与无植被屋顶的洪峰削减效益差别不大,分别为66.9%与67.7%.太阳花的洪峰削减率最高,为73.3%.田园土基质和轻质生长基的绿色屋顶其径流调控效益在大雨条件下受植被的影响规律与改良土基质的绿色屋顶基本一致[图5(b)和5(c)].

在7月15日的暴雨(81.4 mm)条件下,太阳花、佛甲草和无植被覆盖绿色屋顶的径流过程比较相似(图6).当生长基质为改良土时[如图6(a)],3种绿色屋顶都表现出了良好的产流延迟效益,分别为140、140和135 min.3种绿色屋顶的产流量分别为36.8、46.8和45.4 L,径流削减率分别为54.2%、41.7%和43.5%.虽然太阳花仍表现出最强的径流削减效益,但三者径流削减率之间的差值比之大雨条件有所减小.相比普通屋顶的洪峰流 $2.76 \text{ L} \cdot \text{min}^{-1}$ ,太阳花、佛甲草、无植被绿色屋顶

的洪峰削减效益分别为59.1%、52.4%和50.6%,分别推迟洪峰15、10和5 min.暴雨条件下,植被对绿色屋顶径流调控效益的影响在3种基质中呈现相似规律.如图6(c),轻质基绿色屋顶在暴雨条件下并未受到植被的较大影响,可能的原因是轻质基的透水性最好( $267 \text{ mm} \cdot \text{h}^{-1}$ ),加之暴雨的雨量较大和雨强较高,植被在降雨过程中的截留和降雨间歇期的蒸散发过程对绿色屋顶径流调控的影响不能突显.

图7显示了3种植被覆盖类型绿色屋顶在4种不同降雨类型下平均径流削减率差值的变化特征.小雨时,绿色屋顶都能滞留几乎全部雨水,因此不同植被覆盖类型绿色屋顶径流削减率之间的差值接近为0.当降雨量( $P$ )大于两种植被覆盖类型绿色屋顶中雨水滞留能力较小者的雨水滞留能力( $R_1$ )同时又不超过雨水滞留能力较大者的雨水滞留能力( $R_2$ )时(即 $R_1 < P \leq R_2$ ),雨水滞留能力较大者的径流削减率将保持为100%,而雨水滞留能力较小者

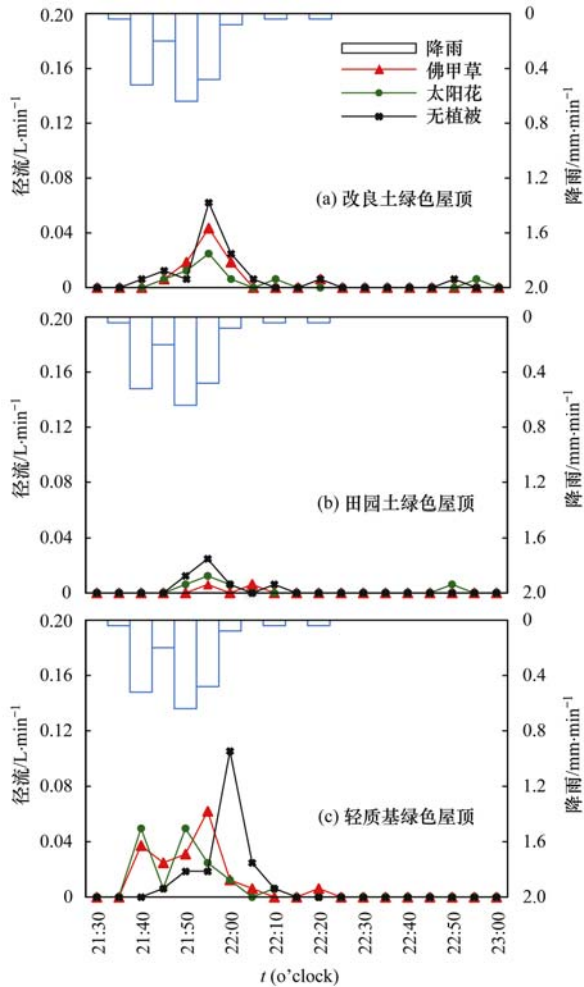


图4 不同植被类型绿色屋顶对8月8日中雨的径流响应

Fig. 4 Hydrographs of green roofs with different vegetation cover during the "8.8" rain event

的径流削减率会随着降雨量的增加而不断降低,因此二者径流削减率的差异也会随着降雨量的增加而增大,直至降雨量超过雨水滞留能力较大者的雨水滞留能力(即 $P > R_2$ )。当 $P > R_2 > R_1$ 时,两种不同植被覆盖类型绿色屋顶的径流削减率之差又开始随着降雨量的增加而减小。

### 3 讨论

绿色屋顶的径流调控效益主要通过其雨水滞留过程实现<sup>[6,22]</sup>。在降雨过程中,绿色屋顶通过植被截留、生长基质吸持等作用滞留雨水<sup>[40]</sup>。降雨结束后,滞留的雨水通过植被层和基质层的蒸散发过程返回到大气中<sup>[9,40,41]</sup>,绿色屋顶雨水滞留能力逐渐恢复<sup>[9,42,43]</sup>。植被雨水截留能力的差异是导致降雨过程中不同植被覆盖类型绿色屋顶径流调控效益存在差异的重要原因之一。此外,植被层的蒸散发过程会加快绿色屋顶滞留雨水的消耗。因此,有植被

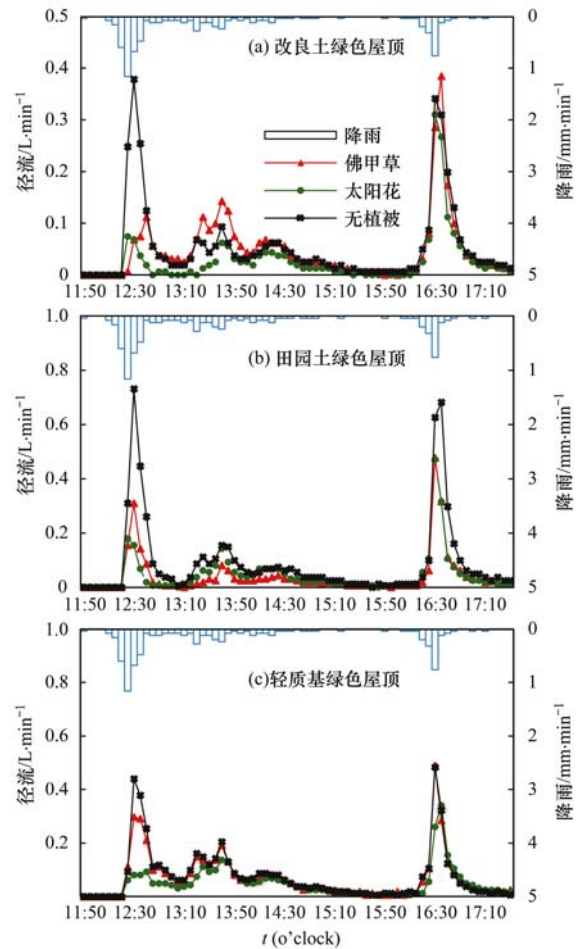


图5 不同植被类型绿色屋顶对7月6日大雨的径流响应

Fig. 5 Hydrographs of green roofs with different vegetation cover during the "7.6" rain event

覆盖绿色屋顶基质层的雨水吸持能力在降雨间歇期内能够更快地得到恢复。不同植被类型的蒸散发规律存在差异,进而影响绿色屋顶的径流调控效益。

本实验对改良土绿色屋顶基质含水量监测显示,在7月15日暴雨开始前1 h,太阳花、佛甲草和无植被绿色屋顶其基质含水量分别为6.1%、12.8%和17.6%。在基质厚度和类型相同、气候条件一致的情况下,基质前期含水量的高低反映了不同植被覆盖类型绿色屋顶雨水滞留能力恢复得快慢。太阳花绿色屋顶基质层含水量低于佛甲草绿色屋顶,说明太阳花的蒸散发耗水速率更大,这与二者的株高和生物量的差异相一致(表2)。有植被覆盖绿色屋顶的基质层含水量都低于无植被覆盖绿色屋顶,说明植被的存在加快了绿色屋顶滞留雨水的消耗,促进绿色屋顶雨水滞留能力的快速恢复。植被层雨水截留量受降雨量、降雨强度、风速以及植被生长特征等因素影响而变化。绿色屋顶的蒸散发

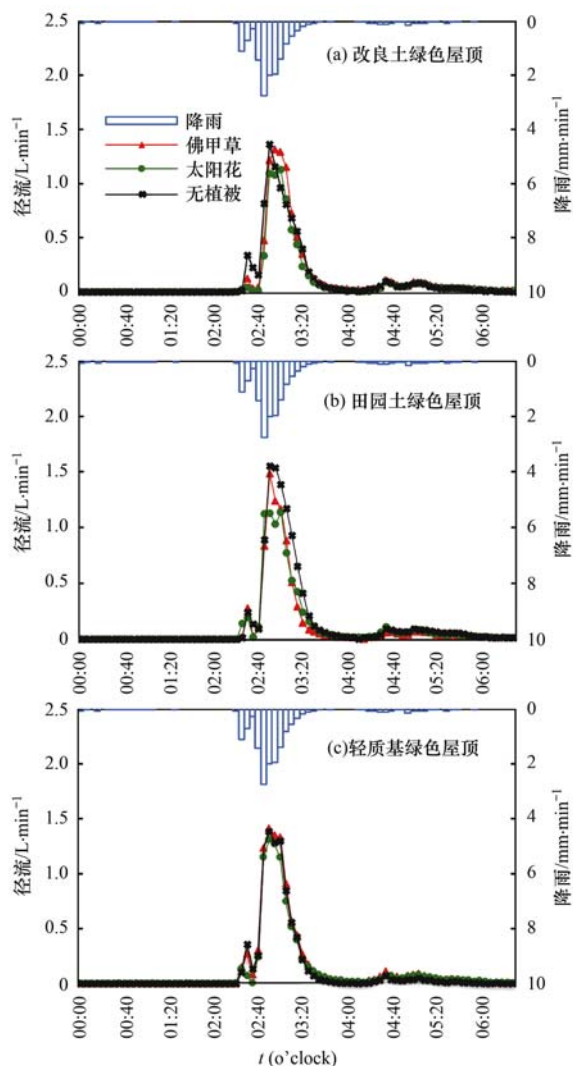


图6 不同植被类型绿色屋顶对7月15日暴雨的径流响应

Fig. 6 Hydrographs of green roofs with different vegetation cover during the "7.15" rain event

也随降雨间歇期的时间、温度、风速、太阳辐射、湿度等变化而变化, 每场降雨之前同一绿色屋顶蒸发过程耗水量不同. 因此植被层的截留量以及间歇期的蒸发对径流削减效益的贡献率在不同场次的降雨中变化较大, 本实验佛甲草绿色屋顶中植被截留量对径流削减效益的贡献率范围为 28.48% ~ 100%, 太阳花的植被截留量对径流削减效益的贡献率范围为 23.12% ~ 100%. 除雨水截留和蒸发过程外, 植被也可以通过根系的作用改变基质层的孔隙状况和透水性能等物理性质从而改变绿色屋顶基质层的透水性和持水能力<sup>[44]</sup>.

综合前文所选3场降雨的洪峰削减规律, 场降雨的降雨量和降雨强度的时程分布会对绿色屋顶洪峰削减效益产生重要影响. 除此之外, 基质层前期含水量<sup>[38]</sup>, 基质层的下渗性能<sup>[37]</sup>、排水系统汇流

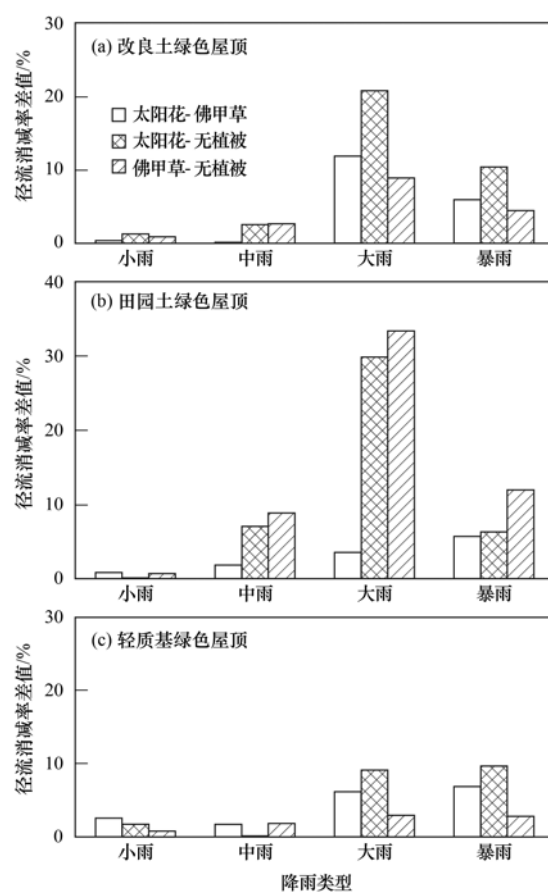


图7 不同降雨类型下各绿色屋顶间径流削减率均差

Fig. 7 Average differences in runoff reduction rates of green roofs during different types of rainfall events

时间和其材料的粗糙程度可能都会影响绿色屋顶的洪峰削减和峰现延迟效益<sup>[36]</sup>. 绿色屋顶径流削减效益随着降雨量的增大而减小, 在暴雨条件下径流削减效益相对较低. 因此, 在应对暴雨形成的城市内涝问题时, 绿色屋顶需配合其他 LID 或海绵措施综合应用才能起到较好的径流调控效果.

高羊茅在灌溉条件下生长良好, 但停止灌溉后无法在屋顶环境下存活. 说明在无灌溉条件下, 高羊茅不适于北京或气候条件类似区域的绿色屋顶建设. 但高羊茅枯萎后形成的枯草层, 也可提高绿色屋顶雨水滞留能力. 8月22日大雨中, 高羊茅枯草层覆盖的轻质基绿色屋顶滞留了 47.7% 的雨水, 高于无植被覆盖的轻质基绿色屋顶 (43.6%). 7月15日暴雨中, 高羊茅枯草覆盖的田园土绿色屋顶的雨水滞留率为 36.9%, 也高于无植被覆盖的田园土绿色屋顶 (33.0%). 此外, 田园土仅为实验对照, 由于其容重高、饱和导水率低以及可能的雨水径流污染风险等原因, 一般不宜直接作为绿色屋顶基质.

## 4 结论

(1)绿色屋顶径流削减率与降雨量呈显著负相关. 降雨量小于 10 mm 时, 不同基质和植被覆盖类型的绿色屋顶几乎都不产流; 降雨量超过 30 mm, 所有绿色屋顶的径流削减率降低到 70% 以下; 当降雨量达到监测期内最大的 81.4 mm 时, 各绿色屋顶径流削减率都低于 55%.

(2)植被通过雨水截留和蒸散发耗水等过程提升绿色屋顶的径流调控效益, 有植被覆盖绿色屋顶的径流削减率、洪峰削减率、产流和峰现时间延迟等 4 个径流调控效益指标都明显优于无植被覆盖的绿色屋顶.

(3)太阳花的株高和单位面积地上生物量高于佛甲草, 植被层截留量大、蒸散耗水速率快, 因而太阳花绿色屋顶的径流调控效益优于佛甲草绿色屋顶.

(4)植被覆盖类型对绿色屋顶径流调控效益的影响会随着降雨条件而改变, 大雨条件下不同植被覆盖类型绿色屋顶的径流削减率差异最大, 中雨和暴雨条件下次之, 小雨条件下因各绿色屋顶几乎都不产流而基本没有差异.

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