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立体生态景观的适应性重构——山地城市河流护岸草本植物群落生态种植

AN ADAPTIVE MULTI-LAYERED ECOLOGICAL LANDSCAPE: THE ECOLOGICAL PLANTING OF HERBACEOUS COMMUNITIES ON RIVER REVETMENTS IN MOUNTAINOUS CITY

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摘要

植物群落是为山地城市河岸景观提供固岸护岸、泥沙拦截、水体净化、生态缓冲、生物多样性保育及景观美化等复合生态功能的重要载体。山地城市水文过程复杂多变，对河岸景观中植物群落的结构、功能和生态过程形成逆境胁迫。研究基于重庆市九龙外滩河流护岸的修复实践，提出了以顺应水文特征的分带分段优化种植和多层拟自然野花草甸配置为主体的河岸草本植物群落生态种植技术框架，进而阐述了山地城市河流护岸草本植物景观的生态种植设计与实践的原则与模式，最后评估了草本植物群落所发挥的生态效益，发现草本群落能够应对夏季山地河流的陡涨陡落与高温干旱的交替作用，以及暴雨径流冲刷等复杂山地城市水文条件。研究可为长江干流河岸景观优化提供科学参考，为长江生态大保护与长江上游重要生态屏障建设提供实践应用范式。

关键词

草本植物群落；河流护岸；水文条件；生态种植；适应性；山地城市

ABSTRACT

Plant communities in mountainous cities play significant roles in revetment protection, sediment interception, water purification, ecological buffer, biodiversity conservation, and landscape quality improvement. Meanwhile, the local complex hydrologic conditions may pose adversity stress to the structure, function, and ecological process of these plant communities. This paper introduces the restoration practices of river revetments in the Jiulong Waitan section of Chongqing employing ecological planting strategies. First, a technical framework was proposed for the re-establishment of riparian herbaceous communities as the multi-layered semi-natural meadows that were planted by strips and zones upon hydrologic conditions. Second, principles and modes of these ecological planting practices were elaborated. Third, an evaluation on the communities' performance indicated that they could adapt to the complex hydrological conditions in mountainous cities, including sharp rise and fall of river level during summer floods, high temperature, and storm runoff. This study may provide a scientific reference for riverfront landscape optimization of the main stream of the Yangtze River, and a paradigm for the ecological conservation and the establishment of ecological barrier for the upper reaches.

KEYWORDS

Herbaceous Communities; River Revetment; Hydrologic Conditions; Ecological Planting; Adaptability; Mountainous Cities

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中国科学院成都生物研究所山地生态恢复与生物资源利用重点实验室生态恢复与生物多样性保育四川省重点实验室开放课题“川西地区野花草甸种质资源调查及应用设计研究”（编号：KXYSWS2001）

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1 引言

河岸景观是城市水陆相互作用的生态界面，既提供了泥沙拦截与过滤、水体净化、生态缓冲、生物生境供给等重要生态系统服务，也营建了可供游憩审美的滨水空间，形成“河流—河岸—城市”协同共生体。植物群落是城市河岸景观发挥上述生态系统服务，以及提升城市环境品质的重要基础[1][2]。当前，国内外河岸景观的研究应用主要集中于揭示河岸景观退化机制、优化护岸工程结构和更新水文调控技术等。近年来，城市河流护岸较多采用宾格石笼网、内嵌式生态格栅等工程措施，将硬质护岸工程与植被修复相结合，以保持河岸水土并构建可持续河岸景观系统[3]。然而，针对河岸植物群落种植设计的研究及应用较为薄弱，相关工作以植物种类单一和种植布局单调的绿化技术为主，导致河岸植被结构单调、物种贫乏且生态功能低下。

城市河岸景观系统的演变顺应了河流与城市水文的发展规律，能够适应区域水文特征是河岸植物群落维持生长和可持续的关键[4]。中国山地面积广阔，但河岸景观的研究应用多基于平原城市的水文特征开展，缺乏针对地貌多变、空间复杂的山地城市的河岸植被修复与景观优化的相关研究。对山地城市而言，一方面，夏季洪水陡涨陡落，水位高程变化差异大，河岸界面受影响较大[5]；另一方面，受城市建设导致的水文特征变化影响，城市的河岸水环境变得愈发脆弱，径流冲刷、水土流失与杂草入侵现象频发[6]。水文条件的年际变化或季节变化加剧了河岸植物群落结构和生态系统服务的不稳定，给河岸景观的修复与管理带来了严峻挑战。

如何顺应山地城市河岸景观中的复杂水文条件及时空变化规律，设计、营建并持续优化植物群落，是风景园林学科亟待解决的问题。基于此，本研究选取重庆市九龙外滩长江干流护岸景观作为河岸植物群落生态修复的研究对象。考虑到草本植物群落对强人工干扰的城市

1 Introduction

Riverfront landscapes serve as an ecological interface where land-water interactions occur in the city. They not only retain, filter, and purify water, cushion the impact on ecosystems, and provide habitats, but also shape the riverfront for citizens' leisure and recreational opportunities. A river-riverfront-city symbiosis thus comes into being. As a component of urban riverfront landscapes, plant communities play a significant role in delivering ecosystem services and improving urban environmental quality[1][2]. Most existing studies of riverfront landscapes focus on evidencing the degradation of riverfront landscapes, improving the structure of revetment projects, and showcasing new hydrologic regulation techniques. Many cities use gabions and the embedded ecological grids onto revetments to combine hard engineering techniques with plant restoration measures for water and soil conservation and a sustainable riverfront landscape system[3]. There are few of studies on riparian plant community that can guide related design practice, which sometimes is nothing more than greening with limited plant species and in a monotonous planting pattern, resulting in poor community structures, and low biodiversity and ecosystem services.

The evolution of urban riverfront landscapes needs to be in line with hydrologic laws to ensure the growth, adaptation, and sustainability of riparian plant communities[4]. China has a great amount of mountainous territory. Most studies on riverfront landscapes explore the hydrologic patterns in plain cities. Little research has targeted the restoration of riparian vegetation and the improvement of riverfront landscapes in mountainous cities with diverse complex landforms and urban spaces. The river levels in mountainous cities often sharply rise and fall during summer floods, causing significant impact on urban riverfronts[5]. At the same time, urban development would change a city's hydrologic pattern, often resulting in an increasingly vulnerable riverfront, severer water-soil loss, and exacerbated weed invasion[6]. Riparian plant communities are largely subject to the inter-annual or seasonal variation of hydrologic conditions, especially in the stability of community structure and the delivery of ecosystem services, posing grave challenges to the restoration and management of riverfront landscapes.

It is a pressing task for the professionals in Landscape Architecture to conceive, build, and continuously improve plant communities that can adapt to the complex hydrologic conditions and spatiotemporal changes of riverfront landscapes in mountainous cities. This paper elaborates the ecological

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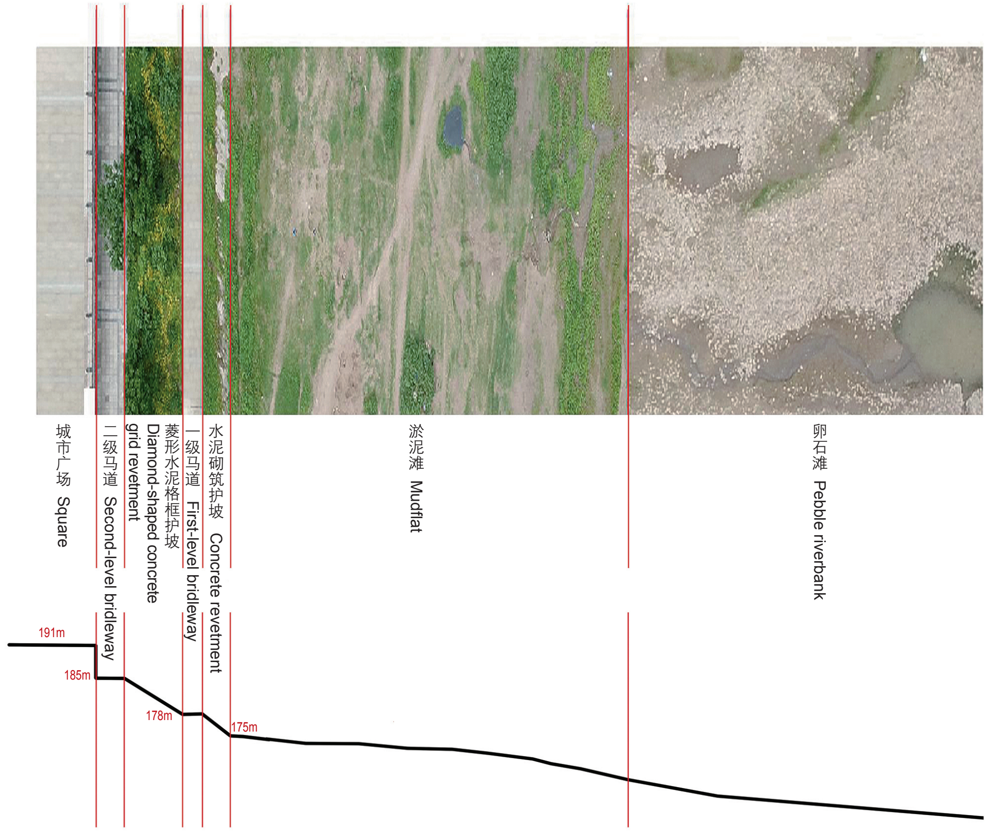

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1. 研究区域环境概况

1. Overview of the study area

生境具有较强的适应能力，且适宜种植于护岸工程的回填土壤中，研究探索了以草本植物群落为主体的立体生态景观的适应性重构途径，提出了可供相关实践参考的植被修复技术框架，并进行了生态效益评估。同时，研究区域是长江生态大保护、长江上游重要生态屏障的关键节点，研究成果可为长江上游地区“河流—河岸—城市”协同共生体的可持续营建提供科学指导。

2 研究区域

研究区域位于重庆市主城区长江干流左岸、九滨路下方的九龙外滩护岸（图1—1）。场地长约1 500m，内部人行交通以沿江修建的马道为主，一级马道高程为178m，二级马道高程为185m，一、二级马道之间由梯步连通，可为游客提供游憩空间。175~178m高程为完全硬化的水泥砌筑岸坡，175m高程以下为以泥沙和卵石为底质的河漫滩消落带区域（图1—2）。

实施草本植物群落生态种植的工程主体是位于178~185m高程之间的菱形水泥格框护坡（图2）。护坡坡度达30.3°，较为陡峭；菱形水泥格框内回填覆土的深度为20cm，回填土以下结构依次为卵石层（20cm深）、防水阻根卷材，以及夯土。菱形水泥格框护坡的回填土层较薄、土壤贫瘠，护坡植物种类单一。在护岸原有植被中，随水文

restoration of riparian plant communities of the revetment landscape along the Yangtze River in the Jiulong Waitan section of Chongqing, with a focus on forming a multi-layered ecological landscape through the restoration of herbaceous communities—herbaceous community is proven to have a strong adaptation to intensive human intervention and able to live in the backfill soil of urban revetments. This paper also proposes a restoration technical framework and associated evaluation methods to measure the ecological benefits after restoration. As the study site sits in a key eco-linkage and ecological barrier of the upper Yangtze River, the findings can offer scientific references for the sustainable construction of the river-riverfront-city symbiosis for the cities at the upper reaches of the Yangtze River.

2 Study Area

The study area covers the revetments at the left bank of the Yangtze River in the Jiulong Waitan section of Chongqing (Fig. 1-1), which protects the Jiubin Road for approximately 1,500 meters long. The paths within the site are mostly the bridleways built along the river. The elevation of the lower and the upper bridleways is 178 m and 185 m, respectively, which two are connected by stairs, offering recreational spaces

2. 菱形水泥格框护坡所在位置
3. 研究地块护岸修复前以葎草（*Humulus scandens*）为优势种的单优植物群落

2. Location of the diamond-shaped concrete grid revetment
3. *Humulus scandens* was the single dominant species in the revetment before restoration in the study area

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传播入侵扩散的葎草（*Humulus scandens*）占据竞争优势，并形成单优群落，同时伴生有鬼针草（*Bidens pilosa*）等恶性杂草。原有护岸植物景观效果单调，动植物栖息生境品质和生态系统结构完整性差，生物多样性低（图3）。本研究中生态种植所面临的不仅是山地河流夏季洪水淹没和暴雨径流冲刷的频繁胁迫，还有坡地汇水和快速排水的交替影响，因此护坡植物的选择、配置与种植难度极大。

3 山地城市河岸草本植物群落生态种植技术框架

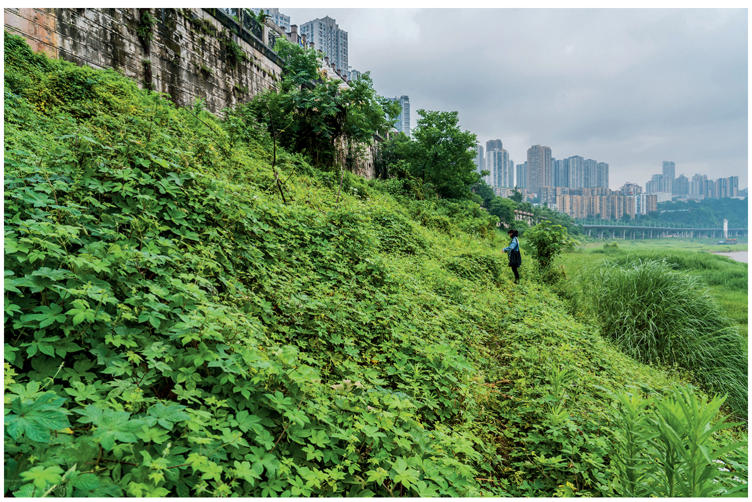
2018年初，研究团队启动九龙外滩护岸生态种植项目，综合考虑场地的生态和游憩需求，选择研究区域内长度约950m的一段菱形水泥格框护坡，进行草本植物群落生态种植；其余护岸未做任何处理，仍

for visitors. The revetment in elevation of 175 ~ 178 m is completely made of concrete, and that below 175 m is a hydro-fluctuation zone covered with sediments and pebbles (Fig. 1-2).

The diamond-shaped concrete grid revetment in elevation of 178 ~ 185 m is the main body for the ecological planting of herbaceous communities (Fig. 2). The gradient of the revetment is relatively steep (30.3°), and the depth of the backfill soil in the diamond-shaped concreted grid is 20 cm, with substrates including pebbles (20 cm in depth), waterproof coil coatings, and rammed earth, in order. The backfill soil is thin and infertile, which was often planted with monoculture or vegetation with rather low species diversity. Prior to implementation, the plant community on the revetment was dominated by *Humulus scandens* which was spread by river systems, accompanied with pernicious weeds such as *Bidens pilosa*; the quality of the overall landscape as well as the flora and fauna habitats was unenviable, with a deteriorated integrity of ecosystem structure and a low biodiversity (Fig. 3). The site suffers from frequent floods and storms in summer and faces the alternating challenges of fast drainage in the sloped catchment, which makes the ecological planting extremely difficult in species selection and placement.

3 Ecological Planting Technical Framework of Riparian Herbaceous Communities in Mountainous Cities

In early 2018, the research team, considering the ecological and recreational needs, started the ecological planting project for the site by introducing herbaceous communities to a 950-meter-long diamond-shaped concrete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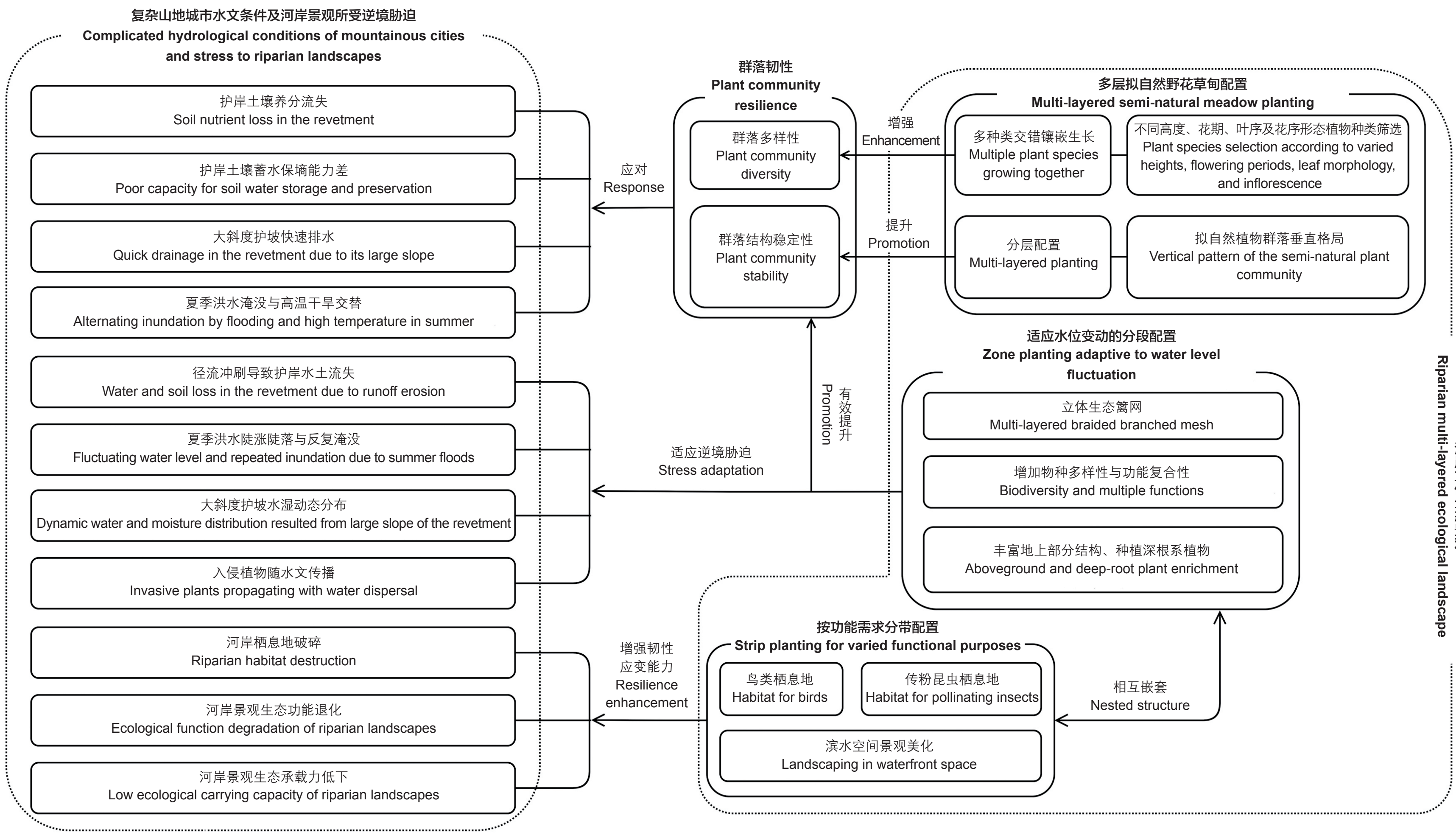

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4

由原有植被覆盖。实施生态种植的重点在于营建能够有效适应场地严苛环境挑战的草本植物群落。本研究提出以顺应水文特征的分带分段优化种植及多层拟自然野花草甸配置为主体的生态种植技术框架（图4）。

3. 1 顺应水文特征的分带分段优化种植

重庆市主城区长江护岸工程的防洪标准为100年一遇（洪水水位线为194.3m），研究区域的菱形水泥格框护坡最大高程（185.0m）低于主城区5年一遇设计洪水水位线（185.9m）。研究根据高程及历年夏季洪水水位变化记录，将护坡分为三个断面：低断面（178~181m）、中断面（181~183m）和高断面（183~185m）。同时，研究以2018年主城区所受的5年一遇夏季洪水影响为例，依据6~8月记录的水位变化（图5），发现夏季洪水反复淹没和冲刷是导致研究区域低断面植被覆盖率低、物种组成较为单一的重要因素；相较低断面，中断面较少受到夏季洪水侵蚀，同时相较高断面，其具有更丰富的水湿条件和更充足的光照，是种植草本植物并建立高丰度植物群落的理想护坡空间；高断面受夏季

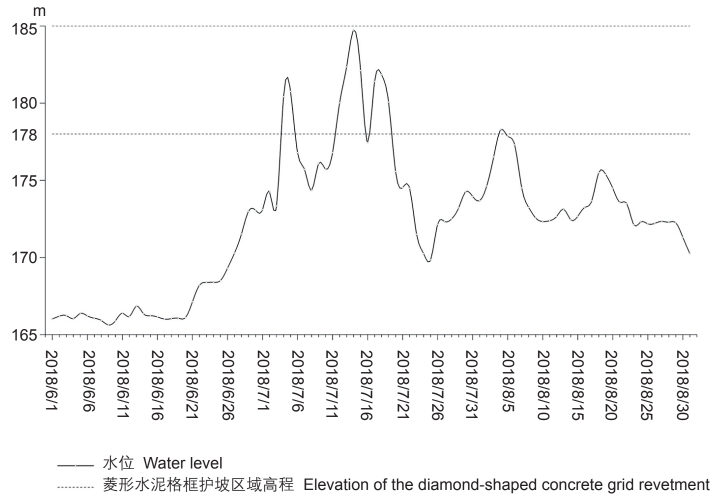
grid revetment. The rest of the revetment remained covered by the existing vegetation communities. The goal of this ecological planting was to establish herbaceous communities that can adapt to the harsh environmental challenges. This paper introduces a technical framework for the re-establishment of riparian herbaceous communities as the multi-layered semi-natural meadows that were planted by strips and zones upon hydrologic conditions (Fig. 4).

3.1 Strip-Zone Planting Based on Hydrologic Conditions

The revetment projects in downtown Chongqing are required to withstand 100-year flood events (the flood level being 194.3 m). The maximum elevation of the diamond-shaped concrete grid revetment in the study area (185.0 m) is even lower than the standard of 5-year flood events (185.9 m). Considering the historical flood levels in summer, the researchers divided the revetment into three sections by elevation: the lower section (178 ~ 181 m), the middle section (181 ~ 183m),

4. 山地城市河岸草本植物群落生态种植技术框架

4. Technical framework of ecological planting for riparian herbaceous communities in mountainous city



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5. 2018年6~8月研究地块内长江干流水位变化

5. Water level changes of the mainstream of the Yangtze River in the study site (from June to August, 2018)

洪水淹没影响频率最低，但由于上部界面缺乏植被拦截缓冲，该断面受到的暴雨径流冲刷更强，不利于水泥格框内回填土的固定。

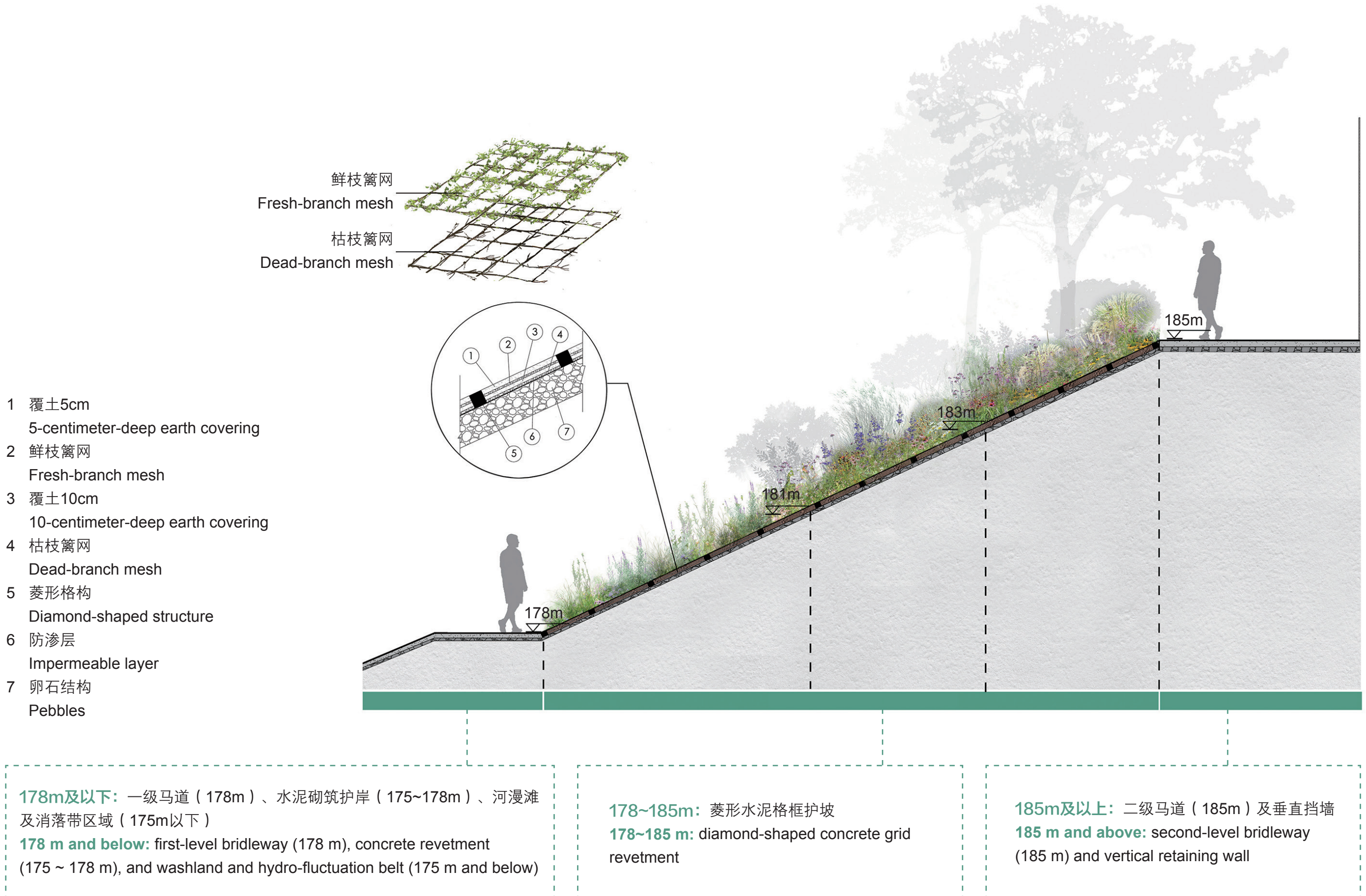
针对研究区域中运用的分带分段的种植模式，一方面，在菱形水泥格框护坡中按河岸景观生态功能需求，同时基于乡土物种考虑，分带构建草本植物景观：2018年5月，种植以观赏禾草为优势种的高草野花草甸带，营建具有自然野趣的草甸景观和小型鸟类庇护生境；2019年3月，种植以阔叶草本植物为优势种的阔叶野花草甸带，在实现丰富的植物色彩组合的同时维持区内传粉昆虫的蜜粉源（表1）。另一

and the upper section (183 ~ 185 m). At the same time, the research analyzed the site's water level data during June to August in 2018, a 5-year flood (Fig. 5), and found that 1) the low vegetation coverage and low species richness of the lower section mainly resulted from frequent summer flood inundations and flushes; 2) the elevation of the middle section advantaged it with less impact of floods and better humidity and light conditions, which made it a suitable place to establish herbaceous communities of a richer diversity; 3) the upper section, though suffering from the least impact by the floods, was heavily prone to rainwater runoffs due to the lack of vegetation barriers, which undermined the stability of the backfill soil.

The strip-zone planting strategy was adopted to meet the ecological needs of the riverfront landscape and to celebrate native species. Two major strips were built: in May 2018, a tall-grass meadow was planted to create a natural landscape and habitats for small birds; and in March 2019, a forb-rich meadow was planted to create a community that is of seasonal features and serves as a nectar and pollen source within the area (Table 1). At the same time, planting zones were planned to introduce a great variety of plants into the lower, middle, and upper sections, forming a nested system in spatial pattern and function, and creating a

表1：草本植物物种选择表
Table 1: Selected herbaceous plant species

亚层 Sublayer	草甸类别 Meadow type			
	高草野花草甸带 Tall-grass meadow		阔叶野花草甸带 Forb-rich meadow	
最低亚层 Lower sublayer	滨菊 *Leucanthemum vulgare*	耧斗菜 *Aquilegia viridiflora*	狗牙根 *Cynodon dactylon*	金叶石菖蒲 *Acorus gramineus*
	络石 *Trachelospermum jasminoides*	铁线蕨 *Adiantum capillus-veneris*		
	鸭跖草 *Commelina communis*			
中间亚层 Middle sublayer	八宝景天 *Sedum spectabile*	黑心菊 *Rudbeckia hirta*	八宝景天 *Sedum spectabile*	灯心草 *Juncus effusus*
	黄金菊 *Euryops pectinatus*	藿香蓟 *Ageratum conyzoides*	黑心菊 *Rudbeckia hirta*	藿香蓟 *Ageratum conyzoides*
	狼尾草 *Pennisetum alopecuroides*	美国薄荷 *Monarda didyma*	假龙头 *Physostegia virginiana*	蓝花鼠尾草 *Salvia farinacea*
	绵毛水苏 *Stachys lanata*	山桃草 *Gaura lindheimeri*	毛地黄 *Digitalis purpurea*	木茼蒿 *Argyranthemum frutescens*
	肾蕨 *Nephrolepis auriculata*	鼠尾草 *Salvia japonica*	千叶蓍 *Achillea millefolium*	山桃草 *Gaura lindheimeri*
	松果菊 *Echinacea purpurea*	萱草 *Hemerocallis fulva*	松果菊 *Echinacea purpurea*	细茎针茅 *Stipa tenuissima*
			萱草 *Hemerocallis fulva*	羽扇豆 *Lupinus micranthus*
			鸢尾 *Iris tectorum*	
最高亚层 Upper sublayer	蒲苇 *Cortaderia selloana*	千屈菜 *Lythrum salicaria*	柳叶马鞭草 *Verbena bonariensis*	墨西哥鼠尾草 *Salvia leucantha*
	细叶芒 *Miscanthus sinensis*		千屈菜 *Lythrum salicaria*	



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6. 顺应水文特征的分段优化种植模式图

6. Strip planting modes adaptive to local hydrological conditions

方面，针对低、中、高三个高程断面，实施分段植物群落配置，形成空间格局与功能的相互嵌套，从而营建具备生态适应性的草本植物群落景观。同时，为保护河流水生态安全与控制建设成本，本研究在实施生态种植前仅对菱形水泥格框护坡原有杂草植被进行了简单人工拔除，未施用除草剂对残留根系与土壤种子库进行灭活。

受夏季洪水侵蚀最为严重的低断面以耐淹固土为主要目标进行设计种植，混栽狗牙根（*Cynodon dactylon*）、千屈菜（*Lythrum salicaria*）与鸢尾（*Iris tectorum*）等乡土耐淹植物，并采用生物篱网技术稳定护坡土壤：在该断面的菱形水泥格框中取出深度为15cm的土壤，铺设桂花（*Osmanthus fragrans*）枯枝形成枯枝篱网；回填10cm深的土壤后，用耐水淹且自然分布于三峡库区消落带的秋华柳（*Salix variegata*）枝条编织成鲜枝篱网，放置于菱形水泥格框中，并在其上覆土（5cm深）（图6）。枯枝篱网与鲜枝篱网能够与种植在其中的草本植物根系交互盘结，形成

landscape of herbaceous communities that is of a strong ecological adaptability. Before the planting, the researchers manually removed the weeds in the diamond-shaped concrete grid revetment without the use of herbicides to protect the river ecosystems and also to reduce implementation cost.

Since the lower section is the most vulnerable to floods, submergence-tolerant native species such as *Cynodon dactylon*, *Lythrum salicaria*, and *Iris tectorum* were used. Braided branched mesh to increase soil stability was also introduced: a soil layer of 15 centimeters was taken out from the concrete grid and used withered branches of *Osmanthus fragrans* to form a protective net; a 10-centimeter-deep soil layer was filled back onto the net; then branches of *Salix variegata*, a native species widely spreading in the hydro-fluctuation zone of the Three Gorges Reservoir, were used to braid another layer of protective net, which was placed onto the grid and covered with a soil layer with a depth of 5 centimeters (Fig. 6). Both protective nets would be interwoven with the roots of herbaceous plants into a whole, forming a multi-layered compact bio-network

致密而坚韧的壤中立体生物网络，可有效增强护坡的抗冲刷能力，同时提高土壤孔隙度，形成复杂的地下生态结构，有利于稳固土壤，减少水土流失。

设计根据中断面的水湿变化特点和光照条件，选择了耐水湿且具备一定耐旱能力的草本植物进行混种，以增加植物群落的物种丰富度。在位于该断面的高草野花草甸带中稀疏混栽狼尾草（*Pennisetum alopecuroides*）、蒲苇（*Cortaderia selloana*）和细叶芒（*Miscanthus sinensis*）等地下茎发达的观赏禾草作为建群植物，可在保持水土的同时为鸟类提供良好的栖息地。阔叶野花草甸带则主要混种八宝景天（*Sedum spectabile*）、蓝花鼠尾草（*Salvia farinacea*）、柳叶马鞭草（*Verbena bonariensis*）、毛地黄（*Digitalis purpurea*）、松果菊（*Echinacea purpurea*）、萱草（*Hemerocallis fulva*）和鸢尾等花序明显、蜜粉源丰富且能覆盖不同开花期的阔叶草本植物，提升滨水公共空间景观品质，并为城市传粉昆虫提供生境走廊（图6）。通过对蜜蜂、蝴蝶等传粉昆虫和小型鸟类的生态保育，实现授粉及植物繁殖体传播，从而保障植物群落的多样性与自我维持功能[7]。

高断面存在径流冲刷强和土壤蓄水保墒能力差等问题，故而选择黑心菊（*Rudbeckia hirta*）、柳叶马鞭草、墨西哥鼠尾草（*Salvia leucantha*）、细叶芒等盖度较大且叶序高度各异的草本植物，形成层次丰富的植物群落，增强对降雨及径流的拦截能力（图6）。配置蒲苇、细叶芒、萱草等根系较深的物种加固护坡土壤，同时利用土壤深层水分，帮助高断面更显著地应对夏季高温干旱。

3.2 多层拟自然野花草甸配置

模拟自然植物群落并提高群落生物多样性与稳定性是河岸草本植物群落生态种植的核心目标。在河岸自然草甸系统中，多种草本植物镶嵌交错生长，不同花期、不同高度和不同叶序形态的植物种植可有效保证植被覆盖度和丰富的季相，同时保障群落的自我维持功能。

本研究提出多层拟自然野花草甸配置方法，通过模拟河岸自然草甸群落的水平格局与垂直结构，为高草野花草甸带与阔叶野花草甸带分别设计种植三个亚层：

that is much more resilient against flood inundation and flush, and helps increase soil porosity. By doing so, a well-designed underground eco-structure was formed which can effectively facilitate water-soil conservation.

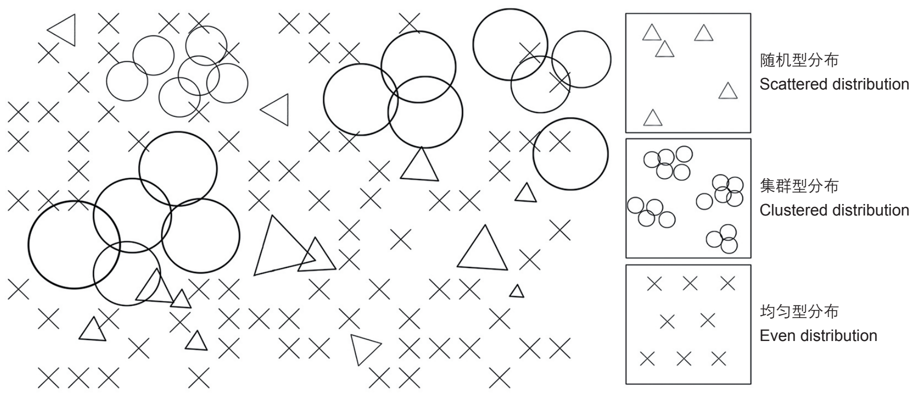
In the middle section, a wide range of wet- and drought-tolerant herbaceous species were in a sparse mixture according to the dynamic humidity changes and light conditions. For the tall-grass meadow, ornamental grasses with robust underground stems such as *Pennisetum alopecuroides*, *Cortaderia selloana*, and *Miscanthus sinensis* were used for water-soil conservation and habitat creation for birds. For the forb-rich meadow, species with distinctive inflorescences, rich nectar and pollen sources, and different flowering periods were used, including *Sedum spectabile*, *Salvia farinacea*, *Verbena bonariensis*, *Digitalis purpurea*, *Echinacea purpurea*, *Hemerocallis fulva*, and *Iris tectorum*. Such a palette can improve the riverfront landscape quality and provide habitat corridors for pollinators, e.g. bees, butterflies, and small birds (Fig. 6), which ensures the pollination and species spread that is critical to maintaining the biodiversity and self-sustaining ability of plant communities[7].

The planting in the upper section was challenged by heavy runoff and poor soil-moisture preservation. Plants of a larger spread and with different heights of phyllotaxis—including *Rudbeckia hirta*, *Verbena bonariensis*, *Salvia leucantha*, and *Miscanthus sinensis*—were introduced to form a complex-structured plant community with an improved capacity to retain rainwater (Fig. 6). The community was supplemented with deep-rooted species such as *Cortaderia selloana*, *Miscanthus sinensis*, and *Hemerocallis fulva* for a stronger soil stability in this section. Larger roots may access moisture held in deeper soil, so that the plant community could establish a higher tolerance to the heat and drought in summer.

3.2 Planting Design of Multi-Layered Semi-Natural Meadow

Generally, imitating natural plant communities and improving their biodiversity and stability is an essential goal of ecological planting of riparian herbaceous communities. In this case, the riparian meadows were structured out of a variety of herbaceous plants with different flowering periods, stem heights, and leaf morphology, which may form a greater vegetation cover and various landscape seasonalities, and guarantee the self-sustainability of the communities.

This study proposed a planting method to establish multi-layered semi-natural meadows, which simulated the horizontal pattern and vertical structure of natural riparian meadow communities, by designing three sublayers for each meadow.



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7. 多层拟自然野花草甸配置的水平种植模式图

7. Horizontal planting modes of the multi-layered semi-natural meadow

1）最低亚层选择滨菊（*Leucanthemum vulgare*）、狗牙根、金叶石菖蒲（*Acorus gramineus*）、耧斗菜（*Aquilegia viridiflora*）、络石（*Trachelospermum jasminoides*）、鸭跖草（*Commelina communis*）等耐半荫、叶序及花茎较矮、冠层面积较大和花期较早的植物，它们能够在更高亚层的遮盖下正常生长，保证了早春的植被覆盖度与春花表现。

2）配置设计的中间亚层具有最高的物种丰富度与种植密度，选择灯心草（*Juncus effusus*）、狼尾草、细茎针茅（*Stipa tenuissima*）等对变化的水文条件和强人工干扰具有良好抗性的观赏禾草，以及八宝景天、黄金菊（*Euryops pectinatus*）、黑心菊、藿香蓟（*Ageratum conyzoides*）、假龙头（*Physostegia virginiana*）、美国薄荷（*Monarda didyma*）、绵毛水苏（*Stachys lanata*）、蓝花鼠尾草、毛地黄、木茼蒿（*Argyranthemum frutescens*）、千叶蓍（*Achillea millefolium*）、山桃草（*Gaura lindheimeri*）、肾蕨（*Nephrolepis auriculata*）、鼠尾草（*Salvia japonica*）、松果菊、萱草、羽扇豆（*Lupinus micranthus*）、鸢尾等花期长、头状花序与总状花序色彩鲜艳的阔叶草本植物进行混种。

3）最高亚层的物种丰富度与种植密度应低于其他亚层，选择柳叶马鞭草、千屈菜等叶序量较少的品种从而为其他亚层提供更好的光照条件，同时选择墨西哥鼠尾草、蒲苇、细叶芒等抽薹开花时花茎较高的品种，形成拥有丰富景观层次的长花期野花草甸。

最高亚层植物呈随机型分布种植，中间亚层及最低亚层植物呈集群型或均匀型分布种植（图7），从而营建出与传统地被花坛景观或成团成块种植的花境景观有所区别的具有自然野趣的群落景观。

1) The lower sublayer consists of semi-shade-tolerant plants with shorter shoots, larger spread, and earlier flowering periods, such as *Leucanthemum vulgare*, *Cynodon dactylon*, *Acorus gramineus*, *Aquilegia viridiflora*, *Trachelospermum jasminoides*, and *Commelina communis*. These herbaceous species can grow under other sublayers consisting of taller plants and offer a flowering landscape in early spring.

2) The middle sublayer was designed with the richest variety of species in the highest density. Specially, ornamental grasses such as *Juncus effuses*, *Pennisetum alopecuroides*, and *Stipa tenuissima* are of good tolerance to the changing hydrological conditions and human disturbance, which were planted in a mixture with the forb species with long flowering periods, and multi-hued flower heads or racemes, including *Sedum spectabile*, *Euryops pectinatus*, *Rudbeckia hirta*, *Ageratum conyzoides*, *Phytostegia virginiana*, *Monarda didyma*, *Stachys lanata*, *Salvia farinacea*, *Digitalis purpurea*, *Argyranthemum frutescens*, *Achillea millefolium*, *Gaura lindheimeri*, *Nephrolepis auriculata*, *Salvia japonica*, *Echinacea purpurea*, *Hemerocallis fulva*, *Lupinus micranthus*, and *Iris tectorum*.

3) The species richness and planting density of the upper sublayer were relatively low, and less-leaf species were adopted (e.g. *Verbena bonariensis* and *Lythrum salicaria*) to leave more sunshine for the plants beneath them. Meanwhile, the species with higher flower shoots, such as *Salvia leucantha*, *Cortaderia selloana*, and *Miscanthus sinensis*, were selected to create a multi-layered architecture with longer period of flowering attractiveness.

The herbaceous species for the upper sublayer were scattered randomly, while those in the middle and lower sublayers were distributed in cluster or evenly (Fig. 7), creating a natural landscape of wildness that is different from the traditional ground-level flower beds or the flower borders with plants grown in clumps.

8. 高草野花草甸带景观

8. The strip landscape of tall-grass meadow

4 河岸草本植物群落生态效益评估

4.1 对山地城市复杂水文条件的适应性

研究区域内的高草野花草甸带自建立之后，曾多次经历由上游特大暴雨导致的洪峰过境。洪水期间，流速快、冲刷力强且含沙量高的浑浊江水反复冲刷和淹没草本植物群落（图8–1）。同时，重庆地区洪水过境与夏季高温时间高度重合，修复后的高草野花草甸带景观经历严酷逆境考验，具备了能够应对山地河流夏季陡涨陡落洪泛侵蚀与高温干旱交替的快速自我修复能力，同时也较好地适应了山地城市建成区汇水面径流的频繁冲刷与面源污染影响。原本结构单一、景观品质较差的河岸植物群落现已拥有错落有致的垂直分层和丰富的季相变化（图8–2），为市民提供了静谧舒适的江岸立体生态景观，并成为了水—陆生态系统间的过渡区域，加强了滨江绿地与河漫滩消落带之间的生态联系，同时为杂食性鸟类功能种团提供了重要庇护与栖息场所。

4 Ecological Benefit Evaluation of the Riparian Herbaceous Communities

4.1 Adaptability to Complex Hydrological Conditions in Mountainous Cities

After its establishment, the tall-grass meadow has experienced repeated peak floods caused by heavy rains, which heavily flushed and inundated the herbaceous communities by rushing water with intensive sediments (Fig. 8-1). Worse, the concurrent summer high temperature in Chongqing aggravates this adverse situation, from which, though, the restored tall-grass meadow survived due to its resilience to the alternating sharp rise and fall of the river level, erosion, and drought. This adaptability also worked when confronting the frequent heavy runoff and non-point source pollution in mountainous urban built-up areas. The riparian plant communities, previously with poor structure and landscape quality, now enjoys well-distributed vertical layers and rich seasonal changes (Fig. 8-2), providing citizens with a tranquil and comfortable multi-layered ecological landscape. This constructed zone supporting land-water interactions has also enhanced the ecological connection between riparian green space and hydro-fluctuation zone, and provided an important shelter and habitat for omnivorous bird species.

夏季洪水冲刷淹没
Inundation and flush caused by summer floods

2018年7月14日，水位达182.11m
Water level reached 182.11 m on July 14, 2018

2018年7月15日，水位达184.73m
Water level reached 184.73 m on July 15, 2018

高草野花草甸景观动态
The tall-grass meadow changing with time

2018年8月20日
August 20, 2018

2019年6月1日
June 1, 2019

2018年9月6日
September 6, 2018

2020年5月8日
May 8, 2020

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通过生态种植营建的阔叶野花草甸带也逐步适应了夏季暴雨高温的多重胁迫，自2019年至今连续两年繁花盛开，景观层次与色彩丰富且季相多变，使菱形水泥格框护坡区域呈现“绿化充分、生机盎然、蝶舞鸟鸣”的立体生态景观，实现了滨江公共空间景观的品质提升，为市民提供了共享的绿意空间（图9）。

经过生态种植营建的高草野花草甸和阔叶野花草甸采取粗放人工管护——每年12月刈割一次。两处草甸群落充分发挥了河岸水土保持、生物多样性保育、景观优化等生态系统服务，在主城区河岸区域成功建立了“河流—河岸—城市”整体生态基础设施，为区域生物多样性保育及水生态安全提供了保障。

4.2 河岸草本植物群落多样性与结构特征

2019年9月，团队在研究区域选取高草野花草甸、阔叶野花草甸与原有植被（对照组）三种草本植物群落开展定量调查。主要方法为在研究区域内设置样带，每种群落分别设置包含178~185m高程、宽度2m的三条样带，每条样带之间间隔约100m。根据高程梯度，每条样带分别在178~181m、181~183m和183~185m高程断面内设置三个样点。每个样点内随机选取三个不同高度的1m × 1m样方，记录样方中的草本植物种类、株数、植物高度及盖度等定量指标。

方差分析表明，高草野花草甸群落与阔叶野花草甸群落的样

The forb-rich meadow has also adapted to the alternating challenges of heavy rain and high temperature in summer, where the flowers have bloomed since 2019, forming rich landscape and colorful seasonal changes. The diamond-shaped concrete grid revetment thus presented a green, vital, and exuberant multi-layered ecological shared space for citizens with pleasant riverfront landscape (Fig. 9).

Being mowed once a year in December, the extensively managed tall-grass meadow and forb-rich meadow communities have played their full role in providing ecosystem services such as soil and water conservation, biodiversity conservation, and landscape optimization. A river-riverfront-city symbiosis of ecological infrastructure, thus, is established to enhance regional biodiversity and ecosystem security in the riverfront of Chongqing downtown area.

4.2 Diversity and Structural Characteristics of Riparian Herbaceous Communities

In September 2019, the study team selected three groups of herbaceous communities, i.e. the tall-grass meadow, forb-rich meadow, and untreated existing vegetation (as the control group) for a quantitative survey. First, three 2-meter-wide

9. 阔叶野花草甸带景观2019年与2020年的对比

9. Comparison of the forb-rich meadows in 2019 and 2020

2019年7月15日
July 15, 2019

2019年6月1日
June 1, 2019

2019年6月1日
June 1, 2019

2020年4月26日
April 26, 2020

2020年5月8日
May 8, 2020

2020年5月8日
May 8, 2020

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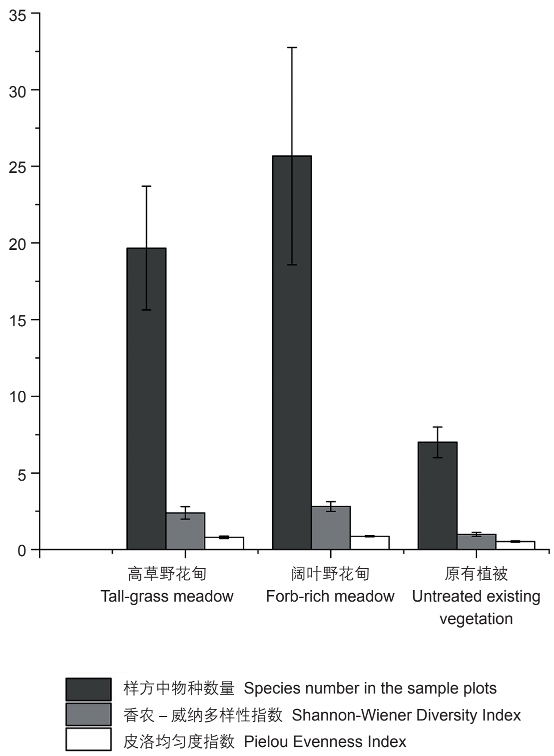
10. 草本植物群落多样性特征

10. Diversity characteristics of the herbaceous communities



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方中物种数量、香农—威纳（Shannon–Wiener）多样性指数及皮洛（Pielou）均匀度指数显著高于对照组植被（图10）。结果显示，本研究所采用的生态种植技术显著增加了研究区域内的草本植物群落的物种丰富度和群落多样性，有利于增加草本植物群落的稳定性和应对环境压力的自我调节功能，并提供更丰富的小型生境组合，从而促进生物多样性的恢复及保育[8][9]。结果表明，在空间格局上相互嵌套的分带与分段配置，以及多层拟自然配置技术，建立了对复杂山地城市水文条件具有良好适应能力的草本植物景观。

研究地块原本由大量葎草、鬼针草等恶性杂草覆盖，植被同时受水文传播、风力传播及人工干扰导致的杂草入侵影响。采样结果显示，修复后，高草野花草甸群落中种植的草本植物种类株数约占总株数的56.1%，盖度约占84.9%；阔叶野花草甸群落中种植的草本植物种类株数约占总株数的64.9%，盖度约占76.3%。该结果表明，通过生态种植的河岸草本植物群落能够适应高强度的杂草竞争胁迫，所选草本植物形成优势种群，生长迅速并逐渐占据大量群落生存空间，逐步向稳定和合理分布的格局发展，有利于景观的可持续发展。

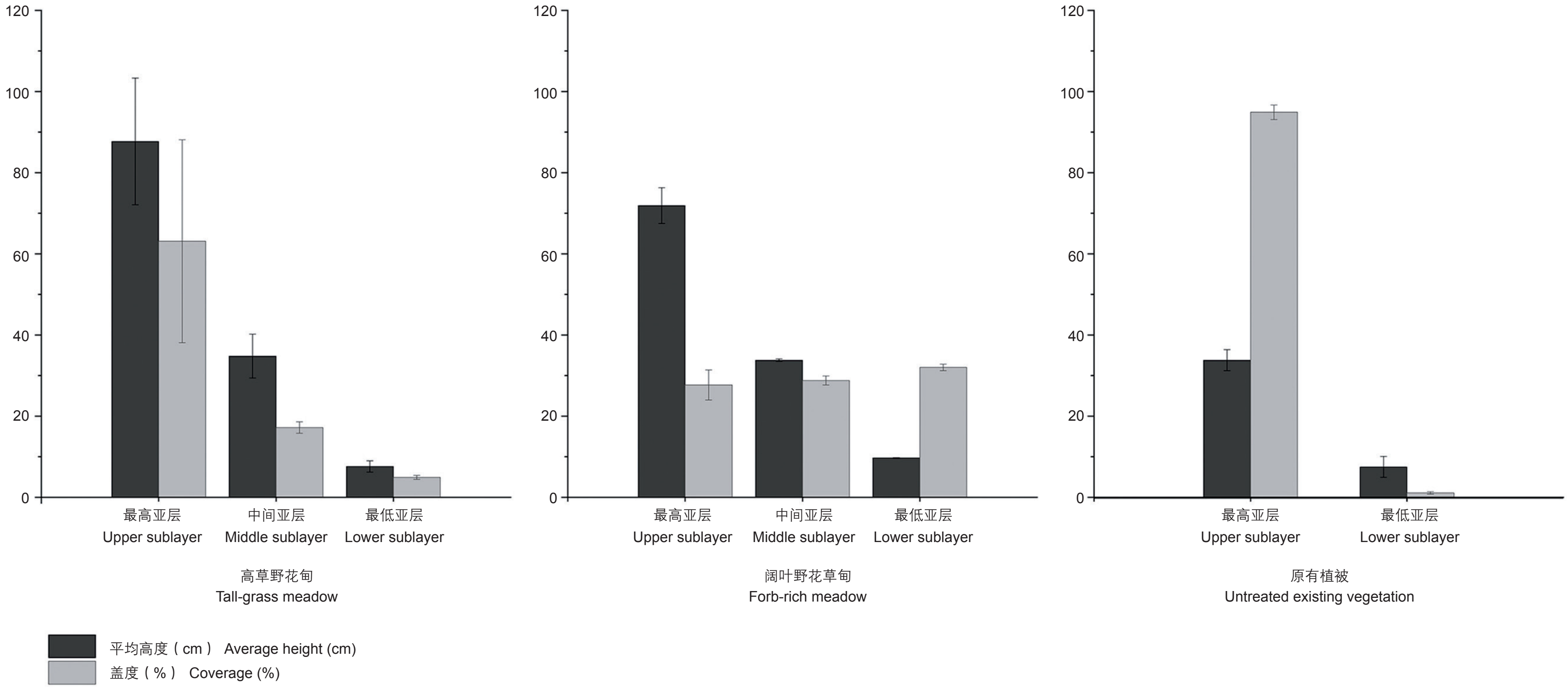
高草野花草甸群落三个亚层的高度分别为0~20cm、20~60cm和60~100cm；阔叶野花草甸群落三个亚层的高度分别为0~10cm、10~40cm和40~80cm；原有植被的葎草单优群落仅显示出两个亚层（0~10cm和10~40cm）（图11）。原有植被中最高亚层植物的盖度达90%以上，其中葎草盖度占最高亚层的94.9%，导致群落结构极为单一。通过优化草本植物群落结构多样性，能够增强其降水拦截与生物

sample plots were marked in each group, which were set from the elevation of 178 m to 185 m in the study area, with a distance of 100 m between replicates. Second, in each plot, three transects of different elevation range, i.e. 178 ~ 181 m, 181 ~ 183 m, and 183 ~ 185 m, were determined. Then three 1 m × 1 m quadrats in different elevations were selected at random from each transect to record the quantitative indicators, e.g., species, plant number, height of individuals, and percentage of cover.

ANOVA tests showed that the number of species, the Shannon-Wiener Diversity Index and the Pielou's Evenness Index in the quadrats of tall-grass meadow and forb-rich meadow communities were significantly higher than those in the control group (Fig. 10). The results proved the success of ecological planting in increasing species richness and community diversity in the study area, which could further make the herbaceous communities more stable and resilient against environmental challenges, while restoring and conserving the biodiversity by providing richer small-scale habitat assemblages[8][9]. The multi-layered semi-natural meadows planted by strips and zones have become a sustainable system with nested spatial patterns, which have sound adaptability to the complex hydrological conditions in mountainous cities.

The study site was originally dominated by a large number of pernicious weeds (e.g. *Humulus scandens* and *Bidens pilosa*) and affected by weed invasion caused by water or wind dispersal and human interference. According to the sampling results, after restoration, the number of individuals of the planted species in the tall-grass meadow community reached about 56.1% of the total, with a coverage of 84.9%. For the forb-rich meadow community, the number of individuals of the planted species accounted for 64.9% and a coverage of 76.3%. In this sense, the ecologically planted riparian herbaceous species dominated in intense competition with weeds. They gradually developed into a stable and rationally distributed pattern while occupying a large portion of the communities, which is conducive to the sustainable landscape development.

The heights of sublayers varied in the quadrats—0 ~ 20 cm, 20 ~ 60 cm, and 60 ~ 100 cm in the tall-grass meadow community; 0 ~ 10 cm, 10 ~ 40 cm, and 40 ~ 80 cm in the forb-rich meadow community; and 0 ~ 10 cm and 10 ~ 40 cm in the original community dominated by Humulus scandens (Fig. 11). The untreated existing community showed only two sublayers, while the upper sublayer plants covered over 90%, in which sublayer the *Humulus scandens*' coverage was about 94.9%, causing a low species diversity. Admittedly, the more diverse the herbaceous community' structure is, the better role it will play in rainfall interception and habitat provision[10]. In



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11. 草本植物群落垂直分层结构特征

11. Characteristics of the vertically layered herbaceous communities

生境供给功能[10]。高草野花草甸群落中蒲苇、细叶芒等高大的观赏禾草成为优势种，最高亚层盖度最高，以较矮的伴生种为主的中间亚层与最低亚层盖度依次降低。为使中间亚层与最低亚层植物接受更多光照，可以适当增加高草野花草甸带的刈割管护次数。阔叶野花草甸群落的中间亚层和最低亚层盖度高于最高亚层，符合分层种植设计目标，其中最高亚层植物植株叶序量少，为中间亚层植物提供了良好的光照条件，有利于中间亚层植物生长开花。

5 结语

本研究以适应夏季河流陡涨陡落造成的洪水侵蚀、高温干旱及暴雨径流冲刷等复杂山地城市水文条件和提供高效生态系统服务为目标，提出了河岸草本植物群落的生态种植技术框架，意在为长江干流

the tall-grass meadow community, ornamental grasses such as *Cortaderia selloana* and *Miscanthus sinensis* became dominant, where the upper sublayer covered the most, and the middle and lower sublayers composed mainly of shorter accompanying species witnessed a successive decrease in coverage. To provide a better light condition for plants in the two lower sublayers, the frequency of mowing the tall-grass meadow could be increased appropriately. In the forb-rich meadow community, the coverage of the middle and lower sublayers were higher than that of the upper sublayer, which satisfied the design goals of multi-layered planting. The less-leaf plants in the upper sublayer then provided greater light conditions for the middle sublayer plants to grow and flower.

5 Conclusion

This study proposed a technical framework of ecological planting of riparian herbaceous communities to realize their adaptation to the complex hydrological conditions in mountainous cities, including flood erosion caused by sharp rise and fall of river level during summer floods, high temperature, and storm runoff, while providing high-quality ecosystem services. This framework may also provide a scientific reference for riparian landscape optimization of the main stream of the

河岸景观优化提供科学参考，为长江生态大保护与长江上游重要生态屏障建设提供实践应用范式。

本文从功能构建、分带分段配置、适生种类筛选、拟自然分层的群落结构配置等方面进行了探索。生态种植实施后，研究区域原本结构单一、物种贫乏的护岸植被转化成为层次错落、色彩丰富和季相多变的立体生态景观，对山地城市复杂水文胁迫具有良好适应性和快速自我修复能力。

在今后的研究和实践中，需要进一步探究山地城市河岸草本植物群落在复杂水文胁迫、高强度人工干扰、种间竞争，以及水文条件的年际变化等多重影响下的环境适应机制。通过积累与分析多年群落数据，深入了解山地城市河岸草本植物景观中物种流、营养流及水文流等生态过程，可完善生态种植技术框架、优化可持续管护措施。**LAF**

Yangtze River and a paradigm for the ecological conservation and the establishment of ecological barrier for the upper reaches.

By ecological function enhancement, strip-zone planting based on hydrologic conditions, species selection, and structural arrangement of multi-layered semi-natural communities, this study created a multi-layered ecological landscape with colorful seasonal changes, which has displaced the poor-structured communities with low biodiversity communities. It could be adaptable and resilient to complex hydrological challenges in mountainous cities.

Further focus of research and practices may shift to exploring the environmental adaptation mechanism of the herbaceous communities in mountainous cities in response to complex hydrological challenges, intensive human interference, inter-species competition, and inter-annual hydrological changes. A longer-term analysis of the communities may also drive deeper understanding of the ecological processes of species flow, nutrient flow, and hydrological flow of riparian herbaceous landscape in mountainous cities, thereby iterating the ecological planting technical framework and optimizing sustainable management and protection measures. **LAF**

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