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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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
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.
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
Complicated hydrological conditions of mountainous cities and stress to riparian landscapes

1. Response & Resilience

- Soil nutrient loss in the revetment
- Poor capacity for soil water storage and preservation
- Quick drainage in the revetment due to its large slope
- Alternating inundation by flooding and high temperature in summer
- Fluctuating water level and repeated inundation due to summer floods
- Dynamic water and moisture distribution resulted from large slope of the revetment
- Invasive plants propagating with water dispersal
- Riparian habitat destruction
- Ecological function degradation of riparian landscapes
- Low ecological carrying capacity of riparian landscapes

2. Promotion & Multi-layered planting

- Multiple plant species growing together
- Plant species selection according to varied heights, flowering periods, leaf morphology, and inflorescence
- Multi-layered planting
- Vertical pattern of the semi-natural plant community
- Multi-layered semi-natural meadow planting

3. Strip-Zone Planting for varied functional purposes

- Habitat for birds
- Habitat for pollinating insects
- Aboveground and deep-root plant enrichment
- Nested structure

4. Riparian multi-layered ecological landscape

Enhancement of biodiversity and multiple functions

4.1 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 – 183 m), and the upper section (183 – 185 m).

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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
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

| Sublayer | Meadow type | Species |
|----------|-------------|---------|
| Lower    | Tall-grass meadow | Leucanthemum vulgare, Aquilegia viridiflora, Cynodon dactylon, Acorus gramineus |
| Middle   | Forb-rich meadow | Sedum spectabile, Euphorbia polychroma, Physostegia virginiana, Digitalis purpurea, Achillea millefolium |
| Upper    | Nymphoides auriculata, Echinacea purpurea, Lythrum salicaria, Lupinus micranthus |

Table 1: Selected herbaceous plant species
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.
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.

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.
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.
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.
通过生态植被建设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）。

经过生态植被建设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方数、植物种类数、植物高度及盖度等存在显著差异。
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. 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. In
生境供给功能。高草野花甸中，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甸的刈割管护次数。阔叶野花甸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
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