跨越界面的生态设计
——重庆市三峡库区澎溪河河／库岸带生态系统修复
Ecological Design Across Interface:
Ecosystem Restoration of Pengxi River/Reservoir in Three Gorges Reservoir Area, Chongqing

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摘要

河岸带是典型的生态交错区，是联系陆地和水生生态系统的重要界面，环境胁迫最易富集，河流自然调节也最为活跃，故而也是河流与景观环境耦合的核心部位。然而，水坝的建设及因此形成的水库的运行调节方式使得多数河段单一的河岸界面变成河／库交替的界面，由此对流域水文及水环境，以及流域整体生态系统产生巨大影响。本文在探讨河岸带界面概念、界面生态特征的基础上，提出了河／库岸带界面生态设计策略及基本技术框架，并以重庆市三峡库区澎溪河流域为例，探讨了河／库岸带界面生态系统修复设计实践。该项目从综合要素设计、结构设计、功能设计与过程设计4个方面，进行了适应水位变化的河／库岸界面生态系统修复设计与实践研究。生态绩效分析结果表明，修复后的乌杨坝河／库岸界面生态系统生境类型多样性增加明显，生物多样性提升效果显著，植物群落适应水位变化能力强，对面源污染具有明显的净化功能，实现了界面生态修复与滨水空间景观建设和优化协同共生。该项目是河／库岸带界面生态系统修复设计和实践的创新探索，其设计策略及模式可应用于受水位调节影响的河／库岸带生态系统修复。

关键词

生态设计；生态系统修复；河／库岸带生态界面；澎溪河流域；三峡库区；季节性水位变化

ABSTRACT

Riparian zone is a typical ecotone that connects terrestrial and aquatic ecosystems. At the same time, environmental stress magnifies here and the natural regulation of rivers is extremely active. In other words, the most dynamic and vibrant interactions between rivers and landscapes occur in riparian zones. However, the construction of dams and the operation of reservoirs have turned many riparian zones into river/reservoir alternation interfaces, influenced the shaping of hydrological and water environment, and the basin ecosystem as well. By introducing the definition and ecological characteristics of river/reservoir interface, this paper proposes the strategies and technical framework for the ecological design of river/reservoir interface. By studying the ecosystem restoration project of river/reservoir interface of Pengxi River in Three Gorges Reservoir Area of Chongqing, which emphasizes the comprehensive element design, structural design, functional design, and process design, this paper aims to provide a reference for related research and practice on river ecosystem restoration. The results of ecological performance analysis showed that the restored ecosystem of the Wuyangba river/reservoir interface has an obvious increase in habitat type diversity and biodiversity, a strong ability of plant communities to adapt to seasonal water level fluctuation, and an improvement in purifying non-point source pollution. The project demonstrates the coordination and symbiosis of interface ecological restoration and waterfront landscape construction and optimization. The project offers an innovative effort in exploring ecosystem restoration design and practice of river/reservoir interfaces. The design strategies and framework can be a reference for other ecosystem restoration cases that are affected by water level fluctuation in river/reservoir interfaces.

KEYWORDS

Ecological Design; Ecosystem Restoration; River/Reservoir Ecological Interface; Pengxi River Basin; Three Gorges Reservoir Area; Seasonal Water Level Fluctuation

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1 引言

“界面”（Interface）概念源于物理学，是指物质相与相的分界面[1]，具有显著的几何性和可视性，起着过滤、选择和调控等作用。20世纪六七十年代，物理学家与生态学家、生理学家合作提出了生物与环境间“界面”的概念，并应用到植被和大气环境关系的研究中[2]~[4]。1988年马世骏提出界面生态学是生态学的分支学科，并指出了界面生态学的发展趋势[5]。界面生态学研究在农林业和景观生态学领域开展较多，熊文愈等人在1986年对陆生植物地上部分的“生态界面”进行了定义，并用湍流运动方程组研究了生态界面流体的热力—动力学特性[6]。1993年，王信理等人以茶园为研究对象，揭示了生态边界层的结构特征和变化规律[7]。韩士杰等人指出森林界面就是森林与环境作用的层面，并论述了森林界面的生态结构及功能[8]。王红梅等人综述了景观生态界面的研究，认为生态界面作为景观镶嵌体结构和功能的组成成分，通过控制生态流来反映景观镶嵌体中元素（斑块）之间的相互作用[9]~[11]。

然而，目前鲜有对于陆地与河湖水体之间的水陆生态界面的研究。事实上，在河流与环境介质间存在着关系密切、作用活跃的范围，这个范围就是河流与不同环境介质（包括固相、液相、生物相）之间形成的界面层。河岸带是集水区陆域与河流水体间的界面，在河流生态系统健康维持中发挥着重要的生态服务功能[12]。罗伯特·J·奈曼等人对作为水陆界面的河岸进行了生态学综述[13]，认为河岸带的物种及生态过程多样，界面生态多样性与洪水格局、独特的生态过程、海拔变化，以及高地对河流走廊的影响有关，由此产生的动态界面环境支持着各种生活史策略、生物地化循环和速率，以及适应广泛时空尺度上干扰机制的生物及其种群。爱德华多·冈萨雷斯等人认为河岸带是沿内陆线性水道水生和陆地系统之间的界面[14]，尽管在河流系统中只占较为狭小的空间，但却在景观中发挥着巨大的生态作用，作者同时总结了影响河岸带的主要问题及其当前面临的管理挑战。根据一项近期研究，在全世界约有超过三分之二的大河已无法自由流淌，有超过3 700座大坝正在建设中[15]；这些水坝的建设及由此形成的水库的运行调节方式使得多数河段单一的河岸界面变成河/库交替的界面，由此对流域水文及水环境，以及流域整体生态系统产生很大的影响。既有研究多关注河岸带对面源污染的防控[16]、河岸带植物群落结构及多样性[17][18]、河岸带植物群落修复对自然洪水格局的响应[19]、河岸

1 Introduction

In the field of Physics, interface exists between material phase and phase, and features significant geometry and visibility, with filtering, screening, and regulation functions[1]. In the 1960s and 1970s, physicists worked with ecologists and physiologists and proposed the concept “interface” between the biology and the environment, which was applied to study the relationship between vegetation and atmospheric environment[2]~[4]. In 1988, Ma Shijun claimed that Interface Ecology is a subfield of Ecology, and pointed out its development trends[5]. Interface Ecology research is mostly made in such fields as Agriculture, Forestry, and Landscape Ecology. Xiong Wenyu et al. defined the concept “ecological interface” for terrestrial plants aboveground in 1986, and studied the thermodynamic and dynamic characteristics of ecological interface fluids with turbulent motion equations[6]. In 1993, Wang Xinli et al. studied the structural characteristics and evolution patterns of ecological interface with a focus on tea plants[7]. Han Shijie et al. pointed out that forest interface is the surface where the forest and the environment interact, and described the ecological structure and function of the forest interface[8]. Wang Hongmei et al. made a literature review of the studies on the ecological interface of landscapes, and pointed out that, as a structural and function component of landscape mosaic, ecological interfaces reflect the interaction between elements (patches) in landscape mosaic by controlling the ecological flow[9]~[11].

Yet, little research has been made on the land–water interface. In nature, rivers and environmental media closely interact, and the interface covers the solid phase, liquid phase, and biological phase. In a catchment area, the riparian zone is the interface between water and land, and provides essential ecological services to maintain the health of the river ecosystem[12]. Holding such an idea, Robert J. Naiman et al. made an ecological review on river banks[13], and pointed out that riparian zones have a high variety in species and ecological processes and the causal factors to the eco-diversity of interfaces include flood pattern, specific ecological process, altitude gradient, and the impact of highland on river corridor. Such dynamic interfaces support various life history strategies, biogeochemical cycle and rate, and organisms and their populations that adapt to the disturbance mechanism at a wide temporal–spatial scale. Edwardo González et al. defined riparian zone as the interface between the aquatic system and the terrestrial system along inland linear waterway[14], which covers only a relatively small area in the river system while being vital to the landscape. The study also summarized the major issues and challenges in the management of riparian zones. Recent research reveals that over two-thirds of the greatest rivers in the world are losing their natural flowing patterns, and more than 3,700 dams are under construction[15]. The construction of dams and the operation of reservoirs have turned many riparian zones into river/reservoir alternation interfaces, influenced the shaping of hydrological and water environment, and the basin ecosystem as well. Most existing research focuses on its role in the prevention and control of non-point source pollution[16], the structure and diversity of plant communities[17][18], the impact of plant community

带景观风貌[20]等，但这些研究对河岸带作为水陆界面的生态特征及功能关注较少，尤其对筑坝蓄水影响下天然河岸成为河／库岸带交替生态界面（下文简称“河／库岸带界面”）后的变化、修复技术及调控机理的研究很少。本文在探讨河岸带界面概念、界面生态特征的基础上，提出了河／库岸带界面生态设计策略及基本技术框架，并以重庆市三峡库区澎溪河流域为例，探讨了河／库岸带界面生态系统修复设计实践，以期为相关流域生态系统修复研究与实践提供参考。

2 河岸带界面总体特征与变化

2.1 河岸带界面概念及特征

河岸带是典型的生态交错区，是联系陆地和水生生态系统的重要界面，环境胁迫最易富集，河流自然调节也最为活跃，故而也是河流与景观环境耦合的核心部位。下文将从界面物理特征、生态特征、生态功能及生态过程等方面梳理河岸带界面的总体特征。

2.1.1 物理特征

河岸带界面类型及其物理特征与河岸带生态系统的结构及功能密切关联，是河岸带界面生态设计和修复的重要依据。河岸带界面的物理特征可概括为界面宽度、界面底质、界面坡度、界面起伏度等方面。河岸带界面宽度与河流分级有关，按照Strahler河流分级法[21]，河流级别越高，河岸带界面宽度越大。界面底质与河岸植物生长密切相关，可为动物提供不同性质的活动基底；按底质类型可划分为岩石、砾石、卵石、沙质、土质等河岸带界面类型。河岸带界面坡度与河岸稳定性相关，界面坡度也与河流纵向梯度上的河水作用及动力学相关；按坡度可划分为缓平、陡坡、陡峭、垂直等河岸带界面类型；通常，河流在向下游流动过程中，冲刷岸较为陡峭，淤积岸较为缓平。河岸带起伏度决定了界面中观和微观尺度的空间环境异质性，与生境类型的多样性密切相关。此外，按人类活动干扰情况可分为城镇、乡村、自然、荒野等河岸带界面类型。

2.1.2 生态特征

河岸带的生态特征可由土壤、植被等可指示水陆相互作用的因素来表征。河岸带具有明显的四维结构特征，即纵向（上游—下游）、横向（河床—河漫滩）、垂向（河川径流—地下水）和时间（随时间

restoration on natural flood pattern[19], riparian landscapes[20], etc. But less research is conducted to explore ecological characteristics and functions of riparian zone as the water–land interface, especially the absence on the ecological impact of dams on river/reservoir alternation interfaces (“river/reservoir interface” hereafter), and related restoration techniques and regulation mechanisms. By introducing the definition and ecological characteristics of river/reservoir interface, this paper proposes the strategies and technical framework for the ecological design of river/reservoir interface. By studying the ecosystem restoration design of river/reservoir interface of Pengxi River in Three Gorges Reservoir Area of Chongqing, this paper aims to provide a reference for related research and practice on river ecosystem restoration.

2 Characteristics of River/Reservoir Interfaces

2.1 Definition and Characteristics of River/Reservoir Interface

Riparian zone is a typical ecotone that connects terrestrial and aquatic ecosystems. At the same time, environmental stress magnifies here and the natural regulation of rivers is extremely active. In other words, the most dynamic and vibrant interactions between rivers and landscapes occur in riparian zones. This paper summarizes the characteristics of river/reservoir interface in such aspects as physics, ecology, ecological functions, and ecological processes.

2.1.1 Physical Characteristics

The types of river/reservoir interfaces and corresponding physical characteristics are in close relation with the structure and functions of the riparian ecosystem, which are the basis of ecological design and restoration. The physical characteristics of river/reservoir interface are often measured by width, sediment, slope gradient, and undulation. Interface width defines the river classification: According to the Strahler river classification method[21], the higher the grade, the greater the interface width. Interface sediment—rock, gravel, pebble, sandy, soil, etc.—defines the growth of plants and the habitats for wild animals. Slope gradient matters the stability of river banks and is affected by the vertical dynamics of the river. By slope gradient, river/reservoir interface can be divided into gentle slope, steep slope, sharp slope, and vertical slope. Generally, as the rivers flow downstream, scouring bank is steep and silting bank is gentle and flat. Interface undulation determines the spatial heterogeneity of the interface at the meso- or micro-scale, as well as the diversity of habitats. In addition, the interfaces can be categorized as town, rural, natural, and wilderness interfaces according the level of human interventions.

2.1.2 Ecological Characteristics

The ecological characteristics of river/reservoir interfaces can be measured by factors that indicate water–land interactions, such as soil and vegetation. The structure of a river/reservoir interface can be studied in four dimensions:

而变化的河岸形态及河岸生物群落演替）4个维度。河岸带界面生态特征与界面生境梯度紧密相连，特定河段的河岸带生物群落组成决定了河岸带界面的垂直空间结构（主要受高程、水分、地形梯度影响）与水平镶嵌结构（主要受地形梯度影响）。

2.1.3 生态功能

河岸带界面为河流提供遮荫、维持边岸稳定性、为河流生物提供有机质、过滤地表径流等生态功能。河岸带界面是所在流域系统中的重要廊道，动植物可以沿河在上下游迁移。作为水陆界面，进入或跨越河流的物质、能量及有机体被河岸带界面所拦截、过滤或调控[22]。河岸带界面也是河流营养物来源和河流食物网的能量来源，以及物种源（基因库）和野生动植物的重要栖息地[23][24]，具有汇（Sink）的功能，即汇集来自周围景观的有机体、能量及物质。

2.1.4 生态过程

河岸带界面生态功能与界面生态过程联系密切。河岸带界面生态过程指营养物质循环、能量流动、水文过程及其相互关系，具体包括跨越界面的地表水文流、营养物质流和物种流。

2.2 河／库岸带界面特征变化

由于河流梯级水坝建设及水库运行的人为调节方式，在自然洪水节律的基础上，河／库岸带界面特征已发生明显变化。大多数河流水库基于发电及防洪需要，在自然汛期后进行反季节水位调节，即冬季蓄水淹没，夏季出露。这种水位调节使得原来生存的生物物种难以适应冬季淹没的逆境，河／库岸带界面原有的地表径流拦截净化、库岸稳定、生物多样性保护等功能衰退，对流域水文过程及水环境，以及流域整体生态系统产生负面影响。因此，需要针对受到人工调节影响的河／库岸带界面的具体水位变化进行综合修复设计。

3 河／库岸带界面生态设计策略及技术框架

3.1 河／库岸带界面生态设计策略

针对受反季节水位调节影响的河／库岸带界面的生态特征变化，以及相关生态功能衰退问题，本文创新性地提出适用于河／库岸带界面生态设计的“NMSRMC策略”。

longitudinal (upstream–downstream), horizontal (riverbed–floodplain), vertical (river runoff–groundwater), and temporal (changes in riparian morphology and community succession). The ecological characteristics are in close relation with the gradient of interface habitats. The composition of flora-fauna communities in a particular river reach determines the interface's vertical spatial structure (subject to elevation, moisture, and topographic gradients) and horizontal mosaic structure (subject to topographic gradient mainly).

2.1.3 Ecological Functions

River/reservoir interface functions vitally to the river ecosystem services, such as offering shade for the river, maintaining the stability of banks, providing organic matters for aquatic species, and filtering runoffs. River/reservoir interfaces are also critical corridors for animals migration and plants spread between upstream and downstream, which intercept, filter or regulate the materials, energy, and organisms that enter or cross the river[22]. Besides, river/reservoir interface is also the nutrient and energy source, the species source (gene bank), and key habitats for wildlife to the river system[23][24]—it functions as sinks that gather organisms, energy, and matters from the environment.

2.1.4 Ecological Processes

Closely related with the ecological processes of river/reservoir interface, its ecological functions include nutrient cycle, energy flow, hydrological process, and the interactions among them, especially runoffs, nutrient and gene flows, etc. across the interface.

2.2 Seasonal Changes of River/Reservoir Interfaces Subject to Human Regulation

Dam construction along rivers and human regulation over reservoirs dramatically changed the natural flood pattern of rivers and the seasonal ecology of river/reservoir interfaces. For power and flood control purposes, most reservoirs retain water during winter and discharge it during summer. Such a water-level regulation made existing animal habitats and vegetation communities inundated in winter, damaging the interface ecosystem services such as runoff interception and purification, reservoir–river stabilization, and biodiversity conservation, and the hydrological process, water environment, and the larger basin ecosystem. Therefore, the specific water-level changes under human regulation are fundamental to each restoration design case of river/reservoir interfaces.

3 Strategies and Technical Framework for the Ecological Design of River/Reservoir Interface

3.1 Strategies for the Ecological Design of River/Reservoir Interface

In response to the ecological changes between seasons of river/reservoir interfaces, and to the degradation of ecological functions, this paper innovatively come up with the NMSRMC Strategies for the ecological design of river/reservoir interfaces.

1）N——基于自然的解决方案（nature-based solutions）：通过保护、管理和修复自然生态系统，以应对环境变化的挑战。充分了解天然河岸带界面生态特征、河／库岸带界面变化趋势，强调基于自然的解决方案在河／库岸带界面生态修复与调控中的应用。

2）M——多功能设计（multi-function design）：针对反季节水位调节导致下河／库岸带界面生态功能衰退状况，强调界面过滤、拦截、屏障、营建生境等多功能设计。

3）S——自然的自我设计（self-design of nature）：重视以洪水、风力／水／动物传播等自然动力过程为推动力的河／库岸带界面的自我设计能力。

4）R——再野化设计（rewilding design）：通过生态系统修复重塑自然过程。再野化不仅仅是河／库岸带形态上自然野趣的再现，更是河／库岸带食物网营养关系的全面建立，以及生态过程的修复。

5）M——多维空间设计（multi-dimensional spatial design）：受水位调节影响的河／库岸带界面是一个具有季节性变化的多维空间。遵循从上游到下游，以及深水区—浅水区—河／库岸带—过渡高地—高地的生态梯度变化，重建多空间维度、多景观层次、多生态序列的河／库岸带景观。

6）C——协同共生设计（collaborative design）：河／库岸带界面生态设计应遵循协同共生这一基本原则，使界面内所有要素形成相对稳定的协同共生系统。

3.2 河／库岸带界面生态设计技术框架

遵循界面生态设计策略，以要素—结构—功能—过程为逻辑思路，提出河／库岸带界面生态设计的基本技术框架（图1）。该框架强调环境要素与生物要素之间的协同共生，以及植物与动物的协同设计；通过结构设计，满足河／库岸带界面的多功能需求，从而维持河／库岸带界面的生态健康。

4 河／库岸带界面生态设计与实践：澎溪河流域河／库岸带生态修复

4.1 研究区域环境概况

重庆市澎溪河地处三峡库区腹心区域，发源于重庆市大巴山南坡的雪宝山，是三峡水库长江干流左岸的一级支流，受三峡水库蓄水影响显著（图2）。澎溪河多年平均流量102.81m^3/s[25]，干流在城区以上称为东河，主要支流包括南河、普里河和白夹溪。研究区域乌杨坝河岸带区域位于南河与东河汇合口的下游、澎溪河左岸，长约2km，平均宽度为200m，以丘陵低山地貌为主。研究区域属亚热带湿润季风气候，多年平均气温18.5℃，多年平均降水量1 385mm[26]。该区域冬季在

1) N—Nature-based solutions: Protect, manage, and restore natural ecosystems in response to the interface's environmental changes by understanding seasonal ecological characteristics and changes of the river/reservoir interface and promoting the application of nature-based solutions in the ecological restoration and regulation.

2) M—Multi-function design: Focus on the multi-function design, including filtering, interception, barrier, and habitat creation, to restore the interface's ecological functions.

3) S—Self-design of nature: Emphasize the self-design of nature and natural dynamic processes, such as flood process and seed spread via wind/water/animals.

4) R—Rewilding design: Remodel the natural processes through ecosystem restoration. Rewilding, instead of reintroducing historical natural wild scenes of the river/reservoir interface, is about the establishment of the trophic levels of regional food web, and the restoration of ecological processes.

5) M—Multi-dimensional spatial design: Subject to water-level regulation, the river/reservoir interface becomes a space with seasonal changes in multiple dimension. With respect to the ecological gradients from upstream to downstream, and from deep water areas, shallow water areas, rivers/reservoir, to transitional uplands and highlands, the restoration design is to form a multi-dimensional, multi-level, and multi-succession landscape for the river/reservoir interface.

6) C—Collaborative design: The ecological design of the river/reservoir interface should work with the natural laws of symbiosis and harmonize all kinds of natural elements, thus building a stable ecosystem.

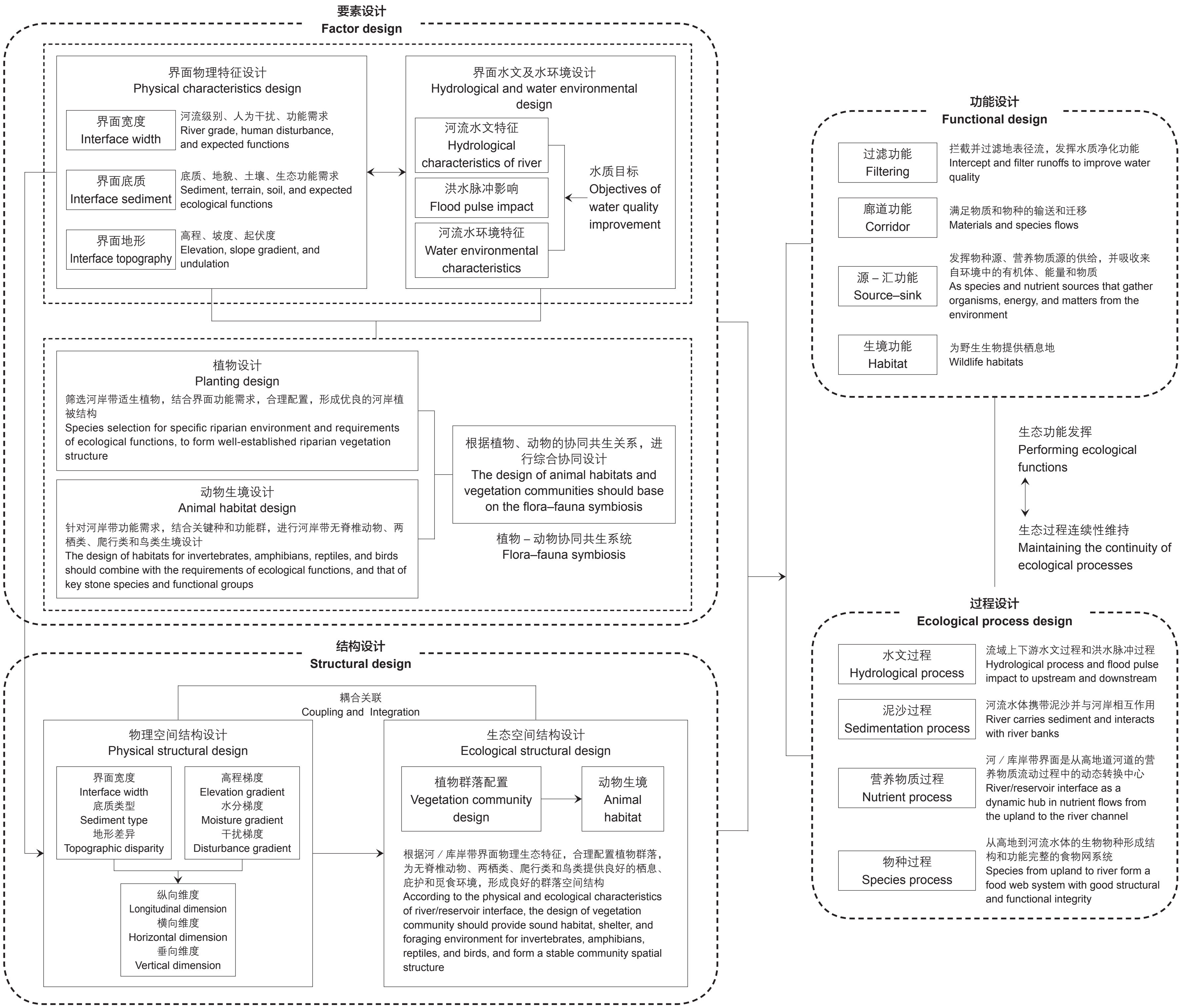
3.2 Technical Framework for the Ecological Design of River/Reservoir Interface

In line with above strategies and the workflow of "element–structure–function–process," a technical framework for the ecological design of river/reservoir interface is proposed (Fig. 1). The framework highlights the synergy between various environmental and biological elements, and flora–fauna symbiosis. The structural design of the river/reservoir interface should meet related multi-functional needs, so that to maintain the ecological health of the interface.

4 Case Study of Ecological Design of River/Reservoir Interface: Ecological Restoration of the River/Reservoir Interface in Pengxi River Reach

4.1 Background of the Study Area

Located in the core area of Three Gorges Reservoir, Pengxi River in Chongqing is originated from Xuebao Mountain on the southern slope of Ta-pa Mountains in Chongqing. It is a primary tributary in the north of Yangtze River and is significantly affected by the water-level regulation of the reservoir (Fig. 2). The annual average volume of the river is 102.81 m^3/s[25]. Its mainstream (named Donghe River) runs north of the urban area of the city, and its main tributaries include Nanhe River, Puli River, and Baijiaxi Stream. The research selected the Wuyangba River riparian zone, located at the lower reaches of the confluence of Nanhe River and Donghe River and on the left bank of Pengxi River, as the study area, where hilly topography dominates,



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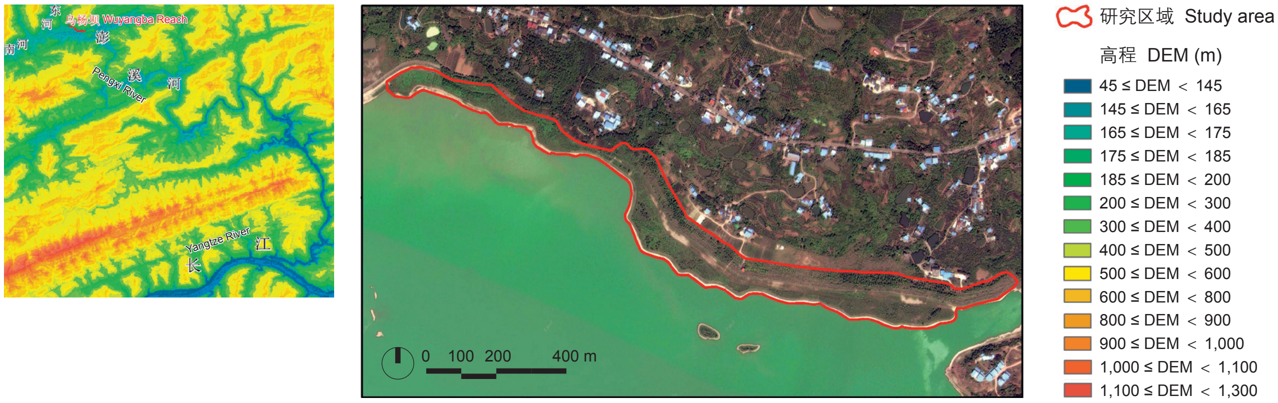
1. 河／库岸带界面生态设计技术框架
1. Technical framework for the ecological design of river/reservoir interface



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2. 研究区域地理位置

2. Location map of the study area

三峡水库高水位时为人工湖库（汉丰湖），而夏季低水位时为河，是典型的河—库交替区域，具有季节性水位变动：三峡水库蓄水后，每年汛后10月份，澎溪河水位逐步升高至175m，并维持到一月初；其后随着三峡水库放水，水位逐步下降，五月末降至最低水位145m。因此乌杨坝河段岸带区域也是典型的河/库岸带界面。

三峡水库蓄水前，澎溪河乌杨坝段河岸宽缓，河漫滩发育较好，底质以细沙和卵石为主，但因长期无序挖沙采石，河岸带原生地貌、基底结构及植被遭受严重破坏[27]。受三峡水库蓄水影响，原145m高程以下的河岸带被淹没；由于水位周期性涨落，植物种类单一、群落结构简单；因城市建设及防洪护岸需要，175~185m高程已建成完全硬化的护坡（图3）。

2012年乌杨坝下游建成了水位调节坝，同年笔者所在的研究团队基于界面生态设计策略和技术框架，完成了乌杨坝河/库岸带生态系统修复设计，第二年根据设计完成了地形和物理结构施工，第三年完成了植物栽种和群落配置。2017年之前，研究区域河段水位每年夏季最低水位为145m，冬季水位为175m；2017年水位调节坝正式下闸蓄水，每年夏季维持170.28m水位，冬季水位仍为175m。

4.2 综合要素设计

4.2.1 地形设计

乌杨坝河/库岸带175m高程是一个坡度转折点，175m以下是季节性水位波动区，175~185m区域是坡度约为40° 的护坡。本研究在维持

2 km in length and 200 m in width at average. It has a subtropical humid monsoon climate, with an annual average temperature of 18.5°C and an annual average precipitation of 1,385 mm[26]. This is a typical river–reservoir alternate zone with seasonal water level change—a natural river in summer while an artificial reservoir (Hanfeng Lake) in winter when Three Gorges Reservoir remains a high water level: After the impoundment of Three Gorges Reservoir and the flood season each year, the river's water level increasingly rises up to 175 m from October to the beginning of January; till to the end of May, water level gradually drops to 145 m. Therefore, the riparian zone of Wuyangba is a typical river/reservoir interface.

Before the construction of Three Gorges Reservoir, the Wuyangba reach had a wide, gentle bank and well-formed floodplain, and its sediment mainly composed of fine sand and pebbles. However, due to long-term unplanned excavation, the original terrain, topographic structure, and vegetation of the riparian zone are seriously damaged[27]. After the impoundment of the reservoir, the riparian zone below the elevation of 145 m was submerged. The periodic fluctuation of water level leads to the decrease of biodiversity and plant community structure, and a fully hardened revetment was built from 175 m to 185 m in elevation, for the requirements of urban construction and flood control (Fig. 3).

In 2012, a dam was built in the lower reaches of Wuyangba; in the same year, the research team completed the ecosystem restoration design of Wuyangba river/reservoir riparian zone based on above strategies and technical framework. The topography and physical structure construction for the ecological restoration was implemented in the second year, followed by the implementation of planting design in the third year. In 2017, the dam was formally put into use, and the low water level in the study area in summer rises from was 145 m to 170.28 m, and that in winter remains 175 m.

4.2 Integrated Design of All Kinds of Elements

4.2.1 Topographical Design

On the riparian bank in the study area, there is an environmental and terrain disparity in the elevation upper and lower than 175 m: the area below 175 m is subject to the seasonal fluctuation of water level, while the area at 175 m to 185 m

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原有蜿蜒岸线的基础上，进行河／库岸带界面复合地形格局设计：

1）145~165m高程带保留原微地貌形态，保留采掘坑，作为高水位时期水下丰富的地形结构；不进行植物种植，以自然修复的草本植物为主。

2）173m高程处有一处因人工挖掘破坏形成的较陡边坡，出于边坡稳定及扩展缓平岸带宽度的需求，将165~173m高程带设计为坡率1:3的缓平岸带，同时保持岸坡表面的微地形起伏。

3）173~175m高程带根据季节性水位变化，结合水生无脊椎动物、鱼类、水鸟觅食和产卵，候鸟觅食的生境需求，设计宽5m的线性凹道，以及洼地、浅塘等水文地貌结构。

4）通过破除硬质化护坡，在175~185m高程护坡上设计起伏的微地貌结构，形成乔—灌—草相结合的多层群落结构（图4）。

4.2.2 底质设计

除了河／库岸带界面稳定性外，界面底质设计还应综合考虑通过不同高程、不同类型底质设计，增加基底环境异质性，并与生物群落有机结合，形成适应水位变化的河／库岸带界面基底结构。

1）145~165m高程带保留原有砂石、黏土交混的底质，以利于植物群落的自然修复和水生无脊椎动物生存。

2）165~173m高程带内的平缓岸缘采用块石抛石护岸，形成多孔隙

is a revetment with a slope of about 40°. On the basis of maintaining the natural meandering shoreline, an integrated topographic design for the river/reservoir interface was carried out:

1) In 145~165 m elevation belt, existing micro-topography and excavation pits were retained to enrich the underwater topographic structure when inundated; With no additional planting design, natural vegetation (dominated by herbs) restoration process is allowed.

2) Since there is a relatively steep slope at 173 m elevation, shaped by manual excavation, the 165 ~ 173 m elevation belt was constructed into a gentle slope ratio of 1:3 for a better slope stability and a wider and flatter riparian zone, while reserving the existing micro undulations of the terrain.

3) In 173 ~ 175 m elevation belt, a hydro-geomorphic structure was carefully designed featuring a 5-metre-width swale, pits, and shallow ponds, with consideration of both the seasonal water level change and habitat requirements (aquatic invertebrates, fish, waterfowls for foraging and spawning; migratory birds for foraging).

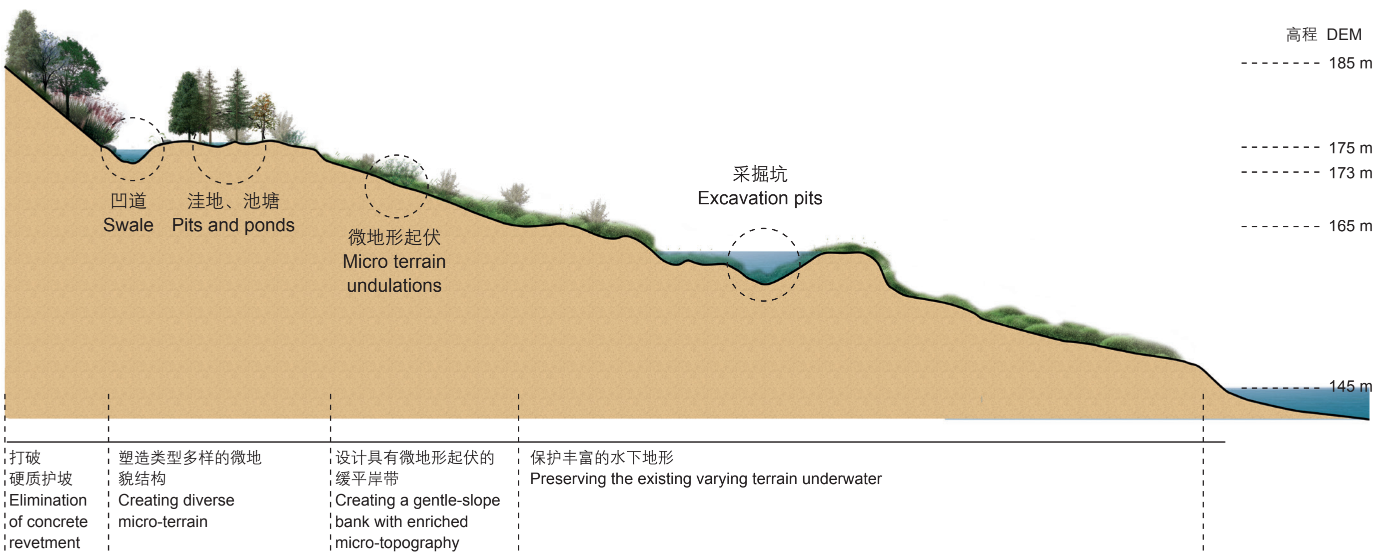
4) The existing concrete revetment of 175 ~ 185 m elevation belt was eliminated, then a mixed tree–shrub–grass community structure was established after the alternation of the micro topography (Fig. 4).

4.2.2 Sediment Design

In addition to the stability of the river/reservoir interface, sediment design should also consider terrain changes in elevation and the disparity in sediment, increase the heterogeneity of the substrate environment, and meet the requirements of for habitat creation, to form a healthy substrate structure of river/reservoir interface that adapts to water level changes.

1) In 145 ~ 165 m elevation belt, existing mixed sediment of sand, gravels, and clay was retained that can facilitate the natural restoration of plant communities and the habitat creation for aquatic invertebrates.

2) In 165 ~ 173 m elevation belt, the gentle sloped riparian was protected by



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3. 三峡水库蓄水前乌杨坝河岸状况（摄于2010年）
4. 乌杨坝河／库岸带界面复合地形格局设计

3. The Wuyangba Reach before the impoundment of the reservoir (taken in 2010)
4. Integrated topographic design for the study area

水岸，为鱼类及虾蟹类水生无脊椎动物提供栖居空间；其余区域选取砂卵石（或碎石土）分层碾压回填，其上铺设壤土，为灌丛和草本植物的修复提供条件。

3）173~175m高程带选取砂卵石分层碾压回填，再铺设壤土，为林泽带的种植提供生长基底；线性凹道两侧均用大块石抛石护岸，形成多孔隙水岸。

4）175~185m高程带破除硬质护坡后，回填夯实后铺设壤土，为乔—灌—草复层混交植物群落提供着生基底。

4.2.3 与水文变化相适应的种植设计

如何适应水位波动及复杂的水文变化，是乌杨坝界面生态设计的难点。本研究将高程与水文节律及水位波动相结合，无论是夏季的河流还是冬季的湖库，保证乌杨坝河／库岸带界面生态设计在纵向上不阻挡水文流，同时通过凹道设计保证横向上多流路水文形态的存在。

1）145~165m高程带植物以自然修复为主；

2）165~173m高程带稀疏种植耐水淹灌木、自然修复草本植物；

3）173~175m高程带种植混交林泽，林泽带内设计林窗、凹道、洼地、浅塘等水文地貌结构，后期依靠自然传播形成高草草本群落；

4）鉴于175m是消落带的最上缘，受潜水影响，水文环境较为潮湿，因此在175~176m高程带稀疏种植芭茅（*Miscanthus floridulus*），以在175~185m高程带的前缘形成缓冲带，同时也有助于丰富植物群落层次结构。

5）176~185m高程带设计乔—灌—草复层混交植物群落。

4.2.4 生物要素设计

本研究将植物物种筛选、配置、群落营建及多样化动物生境设计有机融为一体，根据高程、地形、水文变化，提出了地形—底质—生物协同设计系统和植物—昆虫—鸟类协同设计系统（图5）。设计重点在于运用耐受季节性水淹的和陆生的植物物种，建立强健的植物群落结构；再通过不同高程的生境设计吸引鸟类（包括林鸟和草丛鸟）、鱼类和水生昆虫，从而丰富乌杨坝河／库岸带界面的生物多样性。

植物筛选是河／库岸带界面生态修复的关键。鉴于水位呈周期性变化，不同高程的淹水深度、时间及频率均不同，这对植物群落的组成和分布格局等具有重要影响。165~173m高程带稀疏种植耐水淹的秋

rubbles to form a porous interface, which provides habitats for aquatic invertebrates such as fish, shrimps, and crabs. The remaining area was compacted and backfilled with layered sandy cobble (or gravel soil), and loam on top to facilitate the restoration of shrubs and herbs.

3) In 173 ~ 175 m elevation belt, sand and pebbles were used for layered compaction and backfill, and then loam was laid to improve the plant growth of the wetland woods belt. Both sides of the swale were protected by large stones, creating porous habitats on the bank.

4) In 175 ~ 185 m elevation belt, after the clearing up the existing concrete revetment, loam was laid after backfill and compaction, to ensure the healthy growth of the tree–shrub–grass community.

4.2.3 Vegetation Design Adaptive to Hydrological Changes

A challenging task to this river/reservoir interface ecological design was how to make the landscape adaptive to the seasonal water level fluctuations and the complex hydrological changes. In this project, elevation gradient, hydrological pattern, and water level fluctuation were studied as a whole to ensure the free flow of water—whether as a river in summer or reservoir in winter—and the design of the additional swale improve local hydrological pattern.

1) In 145 ~ 165 m elevation belt, natural succession of vegetation community is allowed;

2) In 165 ~ 173 m elevation belt, flood-tolerance shrubs were sparsely planted with the natural succession of herb species;

3) In 173 ~ 175 m elevation belt, the designed forest gaps, swale, pits, and shallows ponds in the wetland woods enrich the hydro-geomorphic structure, and tall-grass communities would be established via natural spread;

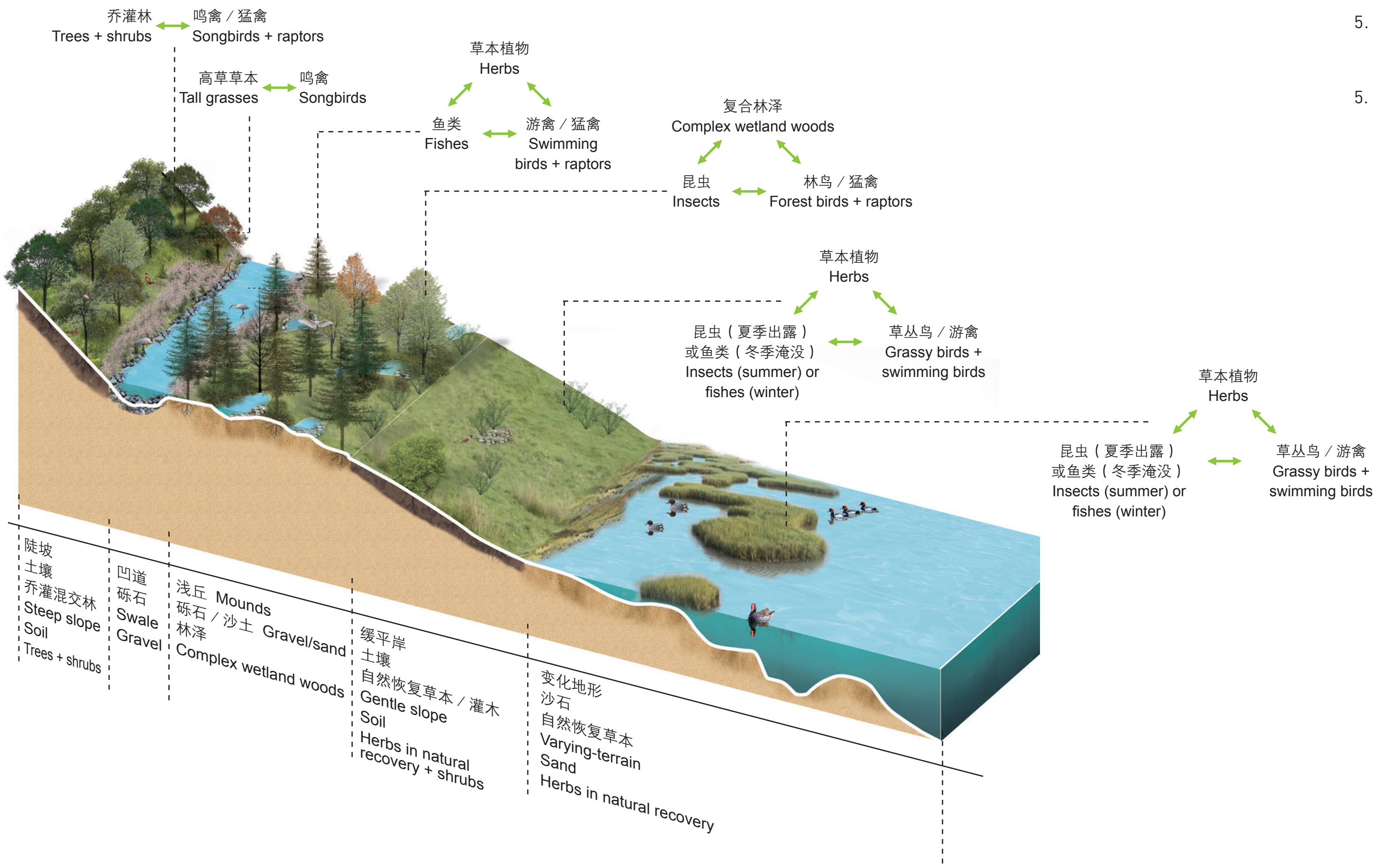
4) Since the upper edge of the hydro-fluctuation zone remains at 175 m in elevation, where the hydrological environment is relatively complex, *Miscanthus floridulus* was sparsely planted in the 175 ~ 176 m elevation belt to serve as a buffer that would also improve the hierarchical structure of designed plant communities.

5) In 175 ~ 185 m elevation belt, a mixed tree–shrub–grass community was formed.

4.2.4 Flora–Fauna Symbiosis Design

In this project, species selection, configuration, community construction of vegetation were integrated with the construction of diversified habitats for wild animals. Based on elevation, topographic, and hydrological conditions, a collaborative design of topography–sediment–organism and plants–insect–bird symbiosis design were proposed (Fig. 5). The design aimed to increase biodiversity of the river/reservoir interface by forming a vibrant vegetation community structure consists of flood-tolerance and terrestrial plants, homing creatures such as birds (including forest birds and grassy birds), fish, and aquatic insects at different elevation belts with various habitats.

Vegetation species selection is key to the ecological restoration of river/reservoir interface. As the inundation depth, duration, and frequency of each elevation belt in



5. 乌杨坝河 / 库岸带界面植物—昆虫—鸟类协同设计模式

5. Collaborative design of plants-insects-birds for the study area

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华柳（*Salix variegata*）等灌木，173~175m高程带种植耐水淹的乔木如池杉（*Taxodium distichum*）、落羽杉（*Taxodium distichum*）、中山杉（*Taxodium* ‘*zhongshanshan*’）、乌桕（*Triadica sebifera*）、杨树（*Populus simonii* var. *przewalskii*）、垂柳（*Salix babylonica*）等，并稀疏种植秋华柳、小梾木（*Cornus quinquenervis*）等耐水淹灌木，草本植物自然修复，由此形成乔—灌—草复层混交林泽带，冬季淹没水中，夏季出露（图6）。

在河岸带界面生态系统中，植物群落为鸟类提供栖息和庇护场所，以及食物来源；鸟类则承担着为河岸植物传播繁殖体的任务。通过植物与鸟类长期协同进化[28]，可形成稳定的河岸带界面生态系统。在从水到陆的生境梯度上，与高程、水位、地形和植物群落相呼应，在水域、滨水环境、河岸草地和灌丛，和河岸林生存的鸟类（包括游禽、涉禽、鸣禽、陆禽、攀禽、猛禽）与其所相应的植物形成复合格局。同样，在不同高程、水位、地形复合格局中，植物、昆虫、鸟类也形成协同共生关系，从而提高了河 / 库岸带界面的生物多样性。

4.3 结构设计

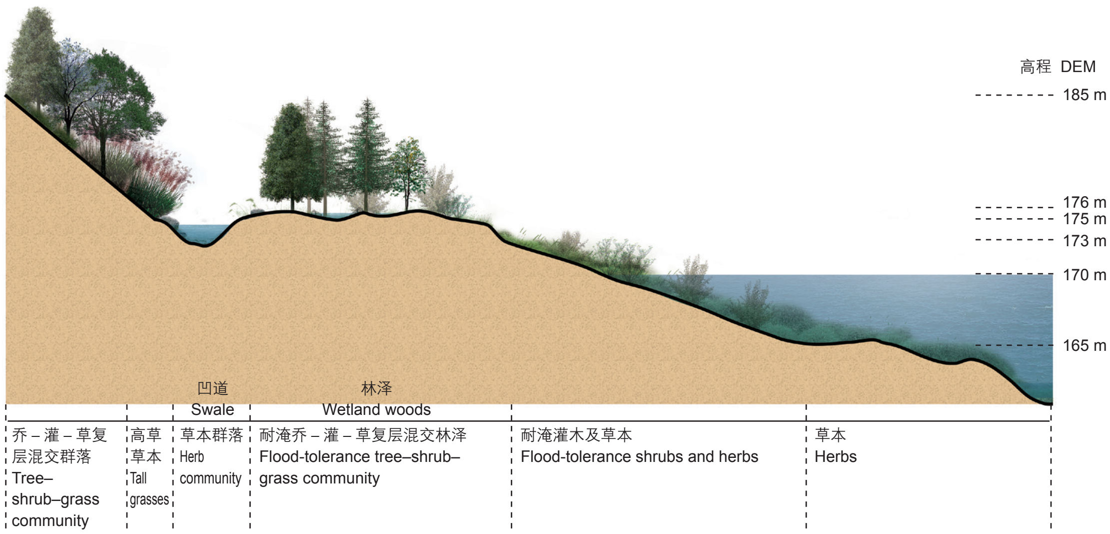
研究区域长约2km，从上游到下游不同断面河 / 库岸带宽度存在差异，因此本研究根据高程、地形、底质特征和水位变动，将植物群落

different seasons vary, the composition and distribution pattern of plant communities adopted varied planting schemes. In 165 ~ 173 m elevation belt, flood-tolerance shrubs (e.g., *Salix variegata*) were sparsely planted. In 173 ~ 175 m elevation belt, flood-tolerance trees (e.g., *Taxodium distichum*, *Taxodium distichum*, *Taxodium* ‘zhongshanshan’, *Triadica sebifera*, *Populus simonii* var. *przewalskii*, *Salix babylonica*) and sparsely planted shrubs (e.g., *Salix variegata*, *Cornus quinquenervis*) were combined with herb species easy to enter natural recovery, thus forming a multi-layered forest, submerged in winter and exposed in summer (Fig. 6).

In riparian ecosystems, plant communities provide birds with habitats, shelters, and foods, in return, birds help the plants with seed spread. Through long-term co-evolution as such[28], a stable riparian ecosystem can be established. The habitats for birds—swimming birds, wading birds, songbirds, terrestrial birds, climber birds, raptors, etc.—were carefully designed according to the elevation gradient, water level, topography, and plant communities, to form a complicated landscape consisting of the river channel, waterfront, riparian grasslands and shrubs, and riparian forests, from the water to the land. Similarly, the variety of plant communities and animal habitats created in such an organic, nested system will form a symbiosis between plants, insects, and birds, thereby increasing the biodiversity of the river/reservoir interface.

4.3 Structural Design

The study area is about 2 km in length, but the width of the riparian zone varies from upstream to downstream. Taking elevation gradient, topography and sediment



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6. 乌杨坝河／库岸带界面不同水位时期的植物群落模式图

6. Diagrams of the plant communities at different water levels

设计为多带多功能缓冲系统：173m高程以下为草本植被带；173~175m高程带为复合林泽带；175~176m高程带为滨水高草草本带；176~185m高程带为乔—灌—草复合混交植被带。在各高程带内，结合地形设计各种小微结构（如林窗、凹道、洼地、浅水塘），增加环境空间异质性，为不同种类的动物提供栖息环境；根据具体断面地形、底质变化，对各断面植被带宽度做出适应性调整，形成植物群落的水平镶嵌结构；为提升群落多样性以及群落结构稳定性，在复合林泽带和乔—灌—草复合混交植被带采取多种类植物交错镶嵌生长的种植策略，形成拟自然植物群落的多层垂直分布格局。

4.4 功能与过程设计

本研究重点针对乌杨坝河／库岸带的主要功能及生态过程进行设计，主要包括以下4个方面：

1）污染净化及雨洪控制。跨越界面的营养物质流是河／库水体的有机物来源，但同时也是外源性污染输入。通过多带多功能缓冲系统的设计和构建，形成一个净化水体污染的植被结构界面，在发挥拦截、净化地表径流作用的同时，还具备蓄、滞、缓、渗等雨洪控制功能。

2）河／库岸带界面稳定及水土保持。研究区域受水文流向及水位波动的影响，在坡度大的区段容易产生水土流失。通过建立具有复合基底和植物群落的生态缓冲结构，发挥稳定河／库岸带和保持水土的功能。

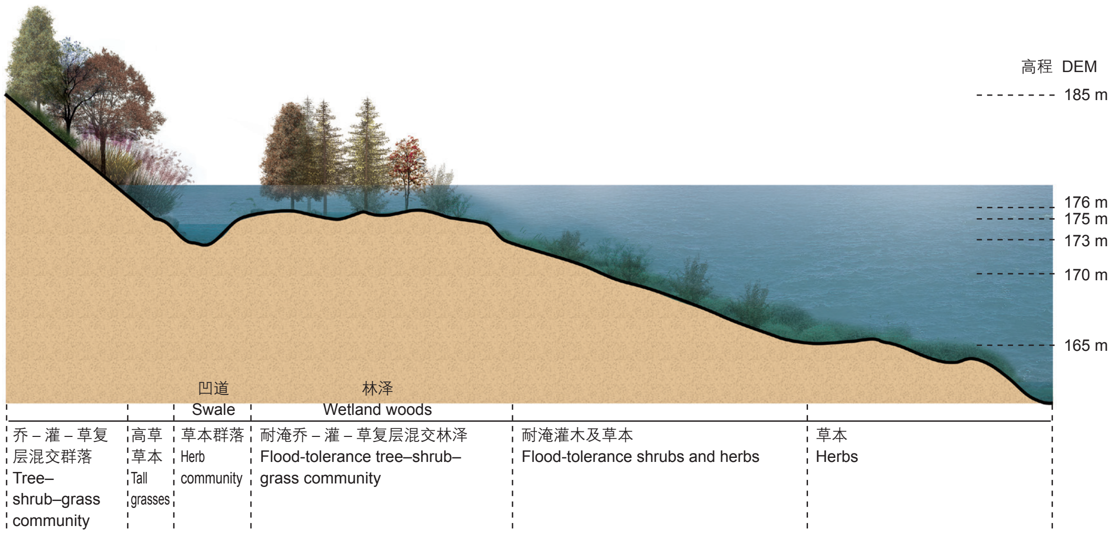
characteristics, and water level changes into account, the plant communities were designed to work as a multi-band, multi-functional buffer system, namely 1) the band of herbs (below 173 m); 2) the band of forest and swamps (173 ~ 175 m); 3) the band of riparian tall grasses (175 ~ 176 m); and 4) the band of hybrid tree–shrub–grass communities (176 ~ 185 m). In each band, various micro terrain structures (e.g. forest gaps, swale, pits, shallow ponds) were designed to increase the spatial heterogeneity and create conditions to habitat creation for different animal species. The width of each band was adjusted to increase the local adaptability according to specific topography and sediment situations, forming a horizontal mosaic structure of plant communities. To improve the diversity of vegetation communities and the stability of community structures, and to form multi-layered quasi-natural plant communities, a nested planting design was adopted in the band of forest and swamps and of mixed tree–shrub–grass communities.

4.4 Ecological Function and Process Design

The ecological functions and processes of river/reservoir interface in the study area were restored in the following four aspects:

1) Pollution purification and stormwater control. Nutrients flowing across the interface provide organic matters to the river/reservoir, but also bring pollutants into the water. Through the design and construction of the multi-band, multi-functional buffer system, a vegetation-based interface that purifies water pollution and facilitates stormwater control was formed: it intercepts and cleanses runoffs on the site and help enhance the barrier system's capacity in stormwater storage, detention, mitigation, and infiltration.

2) River/reservoir interface stabilization and water and soil conservation. Impacted by hydrological flows and water level fluctuations, the study area is prone to soil erosion in sections with steeper slopes. The adaptively designed buffer system with a composite substrate and plant communities can enhance its ability in river/reservoir interface stabilization, and water and soil conservation.



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3）生物多样性提升。物种流是河／库岸带界面连接陆域高地与河／库水体的重要生态过程，通过分段、分区、分层复合生境梯度设计，创造多种环境要素的空间组合，提高生境类型多样性，满足多样物种的栖息需求，达到提升生物多样性目标。

4）景观优化。通过对河／库岸带界面的立体结构设计、不同层次和季相色彩植物群落配置，以及不同季节鸟类的活动，形成具有动态美感的河／库岸带界面景观。

5 河／库岸带界面生态修复绩效评估

基于自然的解决方案，乌杨坝河／库岸带界面生态系统修复于2014年初完成。研究区域在基本没有人工管理措施的情况下，完全经由自然的自我设计和调控，目前正在经历一个明显的再野化过程，河／库岸带界面生态系统正在发挥着良好的生态效益（图7，8）。

5.1 生物多样性提升效果显著

研究区域种植的耐水淹乔、灌木历经多年季节性水位变动，存活状况良好，群落结构稳定，生物多样性提升明显（图9）。于2020年夏季进行的调查表明，没有进行修复的乌杨坝下游河／库岸带共有62种植物；而研究区域目前共有维管植物114种，其中草本植物有92种。

地形—底质—植物—动物的协同修复产生了明显效果，不同生境空间的形成，为涉禽、游禽、鸣禽等不同生态位的鸟类营造了栖

3) Biodiversity increase. Species flow between the highland and the water body is an important ecological process of the river/reservoir interface. The integrated design of habitats spectrum through the careful integration of segments, elevation bands, and layers created a resilient spatial system consisting of multiple environmental factors, which increases habitat diversity, and meeting the inhabiting requirements of diverse wild animals, thus achieving realizing the increase of biodiversity.

4) Landscape improvement. Considering the vertical landscape effect, the configuration of planting design on each layer, and the communities' seasonal sceneries, as well as bird behaviors in different seasons, a dynamic, attractive landscape would be formed for the river/reservoir interface.

5 Performance Evaluation of the Ecological Restoration of River/Reservoir Interface

By employing nature-based solutions, the ecosystem restoration of Wuyangba river/reservoir interface was completed in early 2014. With little human maintenance, natural succession and restoration has occurred on the study area, obviously undergoing a rewilding process, which improves the ecological benefits of the ecosystem of the river/reservoir interface (Fig. 7, 8).

5.1 Significant Increase in Biodiversity

The flood-tolerant trees and shrubs planted in the study area have withstood well through years of water level fluctuations. Plant community structure demonstrates its stability of community structure and the obvious increase in biodiversity (Fig. 9). A site survey in the summer of 2020 found that there are 114 species of vascular plants (including 92 herb species) in the study area, and that in the lower Wuyangba reach was 62, where no restoration measure was implemented.

The collaboratively ecological restoration of topography, sediment, plant community, and animal habitat has already seen success in the establishment of


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息、觅食乃至繁殖的生境，提高了鸟类多样性（表1）。区域内观察到的鸟类超过130种，其中湿地鸟类超过50%。随着水位的季节性变化，在研究区域，冬季高水位时期以鸭科（Anatidae）鸟类为主，主要有绿头鸭（*Anas platyrhynchos*）和罗纹鸭（*Mareca falcata*）等；春季水位下降，形成大片浅水和漫滩生境，在此区域分布的鸟类以鹡鸰科（Motacillidae）、鹭科（Ardeidae）及鹬类（Scolopacidae）为主；夏季低水位时期，草本植物生长旺盛，以植食性鸟类为主，如金翅雀（*Chloris sinica*）、麻雀（*Passer montanus*）等，也有一些食虫鸟类在此觅食，如黑卷尾（*Dicrurus macrocercus*）、棕背伯劳（*Lanius schach*）等。乌杨坝河 / 库岸带界面生态修复完成后，由于生境质量及食物条件优良，观察到的在此繁殖的鸟类日益增多，包括国家一级保护野生动物一种——中华秋沙鸭（*Mergus squamatus*）；国家二级保护野生动物7种——鹗（*Pandion haliaetus*）、普通鵟（*Buteo japonicus*）、白秋沙鸭（*Mergellus albellus*）、花脸鸭（*Sibirionetta formosa*）、鸳鸯（*Aix galericulata*）、黑颈䴙䴘（*Podiceps nigricollis*）和蓝喉歌鸲（*Luscinia svecica*）。

various habitats for wading birds, swimming birds, and songbirds in different niches, increasing avian biodiversity (Table 1). In the study area, more than 130 species of birds are observed, of which more than 50% are wetland birds. With the seasonal variation of water level, Anatidae species (mainly *Anas platyrhynchos* and *Mareca falcata*) are the dominated in winter (high water level). When water level drops in spring, a large area of shallow water bodies and floodplains emerge, where the dominated bird species are Motacillidae, Ardeidae, and Scolopacidae. In summer, water level drops the most and herbs grow vigorously, where dominated birds are mainly herbivorous species (e.g., *Chloris sinica*, *Passer montanus*), with a few of insectivorous species (e.g., *Dicrurus macrocercus*, *Lanius schach*). Since the ecologically restored Wuyangba river/reservoir interface has witnessed an improvement in habitats and foods, there is an increase in the number of bird species observed breeding here, including one species of national first class protected wildlife in China—*Mergus squamatus*, 7 species of national secondary protected wildlife—*Pandion haliaetus*, *Buteo japonicus*, *Mergellus albellus*, *Sibirionetta formosa*, *Aix galericulata*, *Podiceps nigricollis*, and *Luscinia svecica*.

7. 乌杨坝河 / 库岸带界面多带多功能缓冲系统（2017年7月拍摄）
8. 乌杨坝河 / 库岸带界面生态系统在经历再野化过程（2017年7月拍摄）
9. 不同水位时期乌杨坝河 / 库岸景观（左图摄于2018年11月，右图摄于2020年7月）

7. A multi-band, multi-functional buffer system (taken in July 2017)
8. The ecosystem of the river/reservoir interface has witnessed a rewilding process (taken in July, 2017)
9. Riparian landscapes at different water levels. Photos in the left were taken in November, 2018; and July, 2020 for the right.


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表1：乌杨坝河／库岸带生态界面植物—鸟类复合格局
Table 1: Plant community–bird symbiosis in the Wuyangba river/reservoir interface

高程 Elevation	生境梯度带 Habitat belt	目标植物群落－鸟类 Target vegetation community–avian species	优势植物 Dominant plant species	主要鸟类 Main avian species
≤173m	草本植物修复带 Restored grass belt	草本植物－游禽 Herbs–swimming birds	狗牙根（*Cynodon dactylon*）、牛鞭草（*Hemarthria altissima*）、红蓼（*Polygonum orientale*）、苍耳（*Xanthium sibiricum*）等 *Cynodon dactylon*, *Hemarthria altissima*, *Polygonum orientale*, *Xanthium sibiricum*, etc.	绿头鸭（*Anas platyrhynchos*）、绿翅鸭（*Anas crecca*）、针尾鸭（*Anas acuta*）、赤膀鸭（*Mareca strepera*）、赤颈鸭（*Mareca penelope*）、罗纹鸭（*Mareca falcata*）、红头潜鸭（*Aythya ferina*）、白秋沙鸭（*Mergellus albellus*）、金翅雀（*Chloris sinica*）、麻雀（*Passer montanus*）、纯色山鹪莺（*Prinia inornata*）、黑卷尾（*Dicrurus macrocercus*）等 *Anas platyrhynchos*, *Anas crecca*, *Anas acuta*, *Mareca strepera*, *Mareca Penelope*, *Mareca falcate*, *Aythya ferina*, *Mergellus albellus*, *Chloris sinica*, *Passer montanus*, *Prinia inornata*, *Dicrurus macrocercus*, etc.
173~175m	凹道（夏季为浅滩、冬季为明水面） Swale (shallows in summer and inundated in winter)	草本植物－涉禽+游禽 Herbs–wading birds and swimming birds	狗牙根、合萌（*Aeschynomene indica*）、芦苇（*Phragmites australis*）等 *Cynodon dactylon*, *Aeschynomene indica*, *Phragmites australis*, etc.	白鹭（*Egretta garzetta*）、池鹭（*Ardeola bacchus*）、斑嘴鸭（*Anas zonorhyncha*）、绿头鸭、绿翅鸭、骨顶鸡（*Fulica atra*）、黑水鸡（*Gallinula chloropus*）、棕头鸦雀（*Sinosuthora webbiana*）、白颊噪鹛（*Pterorhinus sannio*）等 *Egretta garzetta*, *Ardeola bacchus*, *Anas zonorhyncha*, *Anas platyrhynchos*, *Anas crecca*, *Fulica atra*, *Gallinula chloropus*, *Sinosuthora webbiana*, *Pterorhinus sannio*, etc.
	复合林泽带 Complex wetland woods belt	乔+灌+草－涉禽、猛禽 Tress, shrubs, and grasses–wading birds and raptors	池杉、落羽杉、乌桕、杨树、中山杉、牛鞭草、狗牙根、野大豆（*Glycine soja*）等 *Taxodium distichum*, *Taxodium distichum*, *Triadica sebifera*, *Populus simonii var. przewalskii*, *Taxodium hybrid*, *Hemarthria altissima*, *Cynodon dactylon*, *Glycine soja*, etc.	白鹭、苍鹭（*Ardea cinerea*）、普通鵟（*Buteo japonicus*）、普通鸬鹚（*Phalacrocorax carbo*）、乌鸫（*Turdus mandarinus*）、白颊噪鹛（*Pterorhinus sannio*）、黑枕黄鹂（*Oriolus chinensis*）、棕背伯劳（*Lanius schach*）等 *Egretta garzetta*, *Ardea cinerea*, *Buteo japonicas*, *Phalacrocorax carbo*, *Turdus mandarinus*, *Pterorhinus sannio*, *Oriolus chinensis*, *Lanius schach*, etc.
175~176m	临水高草草本带 Riverine tall-grass belt	高草草本+草本植物－鸣禽 Tall grasses and grasses–songbirds	芭茅（*Miscanthus floridulus*）、草木犀（*Miscanthus officinalis*）等 *Miscanthus floridulus*, *Miscanthus officinalis*, etc.	山麻雀（*Passer cinnamomeus*）、麻雀（*Passer montanus*）、金翅雀（*Chloris sinica*）、纯色山鹪莺（*Prinia inornata*）、棕颈钩嘴鹛（*Pomatorhinus ruficollis*）、棕头鸦雀（*Sinosuthora webbiana*）、白颊噪鹛（*Pterorhinus sannio*）等 *Passer cinnamomeus*, *Passer montanus*, *Chloris sinica*, *Prinia inornata*, *Pomatorhinus ruficollis*, *Sinosuthora webbiana*, *Pterorhinus sannio*, etc.
176~185m	复合混交植被带 Mixed vegetation belt	乔+灌+草－鸣禽+猛禽 Tress, shrubs, and grasses–songbirds and raptors	天竺桂（*Cinnamomum japonicum*）、枫香树（*Liquidambar formosana*）、栾树（*Koelreuteria paniculata*）、乌桕、黄荆（*Vitex negundo*）、马桑（*Coriaria nepalensis*）、构树（*Broussonetia papyrifera*）、白茅（*Imperata cylindrica*）、乌蔹莓（*Cayratia japonica*）等 *Cinnamomum japonicum*, *Liquidambar formosana*, *Koelreuteria paniculata*, *Triadica sebifera*, *Vitex negundo*, *Coriaria nepalensis*, *Broussonetia papyrifera*, *Imperata cylindrical*, *Cayratia japonica*, etc.	棕背伯劳（*Lanius schach*）、北红尾鸲（*Phoenicurus auroreus*）、红胁蓝尾鸲（*Tarsiger cyanurus*）、红头长尾山雀（*Aegithalos concinnus*）、远东山雀（*Parus minor*）、雀鹰（*Accipiter nisus*）、普通鵟、红嘴蓝鹊（*Urocissa erythroryncha*）、噪鹃（*Eudynamys scolopaceus*）、灰胸竹鸡（*Bambusicola thoracicus*）、雉鸡（*Phasianus colchicus*）等 *Lanius schach*, *Phoenicurus auroreus*, *Tarsiger cyanurus*, *Aegithalos concinnu*, *Parus minor*, *Accipiter nisus*, *Buteo japonica*, *Urocissa erythroryncha*, *Eudynamys scolopaceus*, *Bambusicola thoracicus*, *Phasianus colchicus*, etc.

5.2 植物适应水位变化能力强

无论是乔木、灌木，还是草本植物，经过7年冬季水淹的考验，植物的生长形态、繁殖状况、物候变化等均表现出对季节性水位变化的良好适应（图10），特别是乌桕在林泽乔木群落下层形成明显的更新苗层（图11）。

5.3 地表径流面源污染净化能力提升

2015年6~9月，研究团队先后4次在降雨期间收集修复后的河／库岸带坡顶与坡麓径流水样，每次采样选取三个重复采样点。水质监测

5.2 Enhanced Adaptability of Vegetation Communities to Water Level Changes

Going through the test of flooding in winter for seven years, vegetation in the study area, whether trees, shrubs, or herbs, has shown a strong adaptation to seasonal water level changes in growth morphology, reproduction, and phenology (Fig. 10). For example, *Triadica sebifera* has regenerated and formed a regeneration seedling layer under the wetland woods belt (Fig. 11).

5.3 Improvement of Purification Capacity of Non-Point Source Pollution via Runoffs

To evaluate the restoration performance of the site, from June to September, 2015, the research team collected runoff water samples from the top and foot


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分析表明，实施生态修复后，地表径流总氮（TN）、总磷（TP）的削减率分别达到37%和30%，而在乌杨坝未实施生态修复的对照区内，两项指标仅为13%和3%，由此可见，河 / 库岸带界面生态系统修复有效削减了入河 / 库污染负荷。此外，通过对地表径流的阻滞、吸纳等作用，修复后乌杨坝河 / 库岸带界面也发挥了较好的雨洪控制功能。

6 结论

作为水陆之间的生态界面，基于界面过滤、净化、生物多样性保护等生态服务功能的优化提升，河 / 库岸带界面生态设计应遵循从要素—结构—功能—过程的逻辑思路，强调生态要素设计与空间结构设计的有机融合，奠定界面生态功能的基础，满足河 / 库岸带界面的多功能需求；通过生态功能与过程的耦合设计，维持界面生态系统健康。

如何应对不断变化的环境，加强流域生态系统整体保护，是河 / 库岸带生态系统修复设计必须考虑的，而界面生态设计策略给这种适应性提供了可能。三峡库区澎溪河流域乌杨坝河 / 库岸带生态系统修


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of the river/reservoir riparian zone during rainfall for four times at three same sampling sites. Analyses of water quality showed that after ecological restoration, the reduction rates of total nitrogen (TN) and total phosphorus (TP) in runoffs reached 37% and 30% respectively—those in the adjacent area in the Wuyangba reach where no ecological restoration measures was implemented, were only 13% and 3% respectively. The effectiveness of the restored river/reservoir interface in reducing the pollutants into the river/reservoir is proven. In addition, through runoff detention and infiltration, the river/reservoir interface serve better in stormwater control.

6 Conclusions

As the ecological interface between land and waters, to enhance such ecological service functions such filtering, purification and biodiversity protection, the ecological design of river/reservoir interfaces where land and water ecologies interact, should follow workflow of "element–structure–function–process," and emphasize the integrated design of ecological elements and physical structures, so as to lay the foundation for the ecological functions of the interface and meet the needs to support its multiple functions. In addition, The ecological restoration also highlights the coupling design of ecological functions and processes to maintain the long-term health of the ecosystem.

The changing environment and the protection of the river ecosystem must be taken into consideration in the ecological restoration of the river/reservoir interface, which can be realized through a series of adaptive design strategies. The ecosystem restoration case of the river/reservoir interface in Wuyangba reach of Pengxi River in Three Gorges Reservoir Area displays that the expansion of interface space and

10. 冬季高水位期的耐水淹乔木（左图摄于2018年12月，右图摄于2020年12月）
11. 乌桕在林泽乔木群落下层形成明显的更新苗层。

10. The flood-tolerance trees inundated in winter (high water level). The photo in the left was taken in December, 2018, and the right is two years later.
11. *Triadica sebifera* has regenerated and formed a regeneration seedling layer under the wetland woods belt.

复案例的经验告诉我们，应充分考虑界面生态空间的拓展，优化界面生态结构，而不仅仅是单纯的植物栽种及群落构建。针对河／库岸带污染拦截净化、生物多样性保护等主要生态功能，应将河／库岸带界面物理结构、生态结构进行综合设计与应用，其中基于自然的解决方案是河／库岸带生态系统修复设计的重要途径。

乌杨坝河／库岸带生态系统修复研究仅仅是界面生态设计的初步探索，其设计策略及模式可应用于受水位调节影响的河／库岸带生态系统修复。在今后的研究中，应进一步探索河／库岸带界面生态组成要素的相互作用机理、界面物理结构与生态结构的耦合机制，研发适应流域环境变化和可持续发展需求的河／库岸带界面生态设计的系统方法和关键技术，开展适应"山—水—林—田—湖—草"生命共同体功能需求及流域多时空尺度环境变化的河／库岸带界面生态结构与功能协同的设计调控机理和方法体系研究。**LAF**

the optimization of ecological structure—rather than simply growing plants and building plant communities—is a critical part to ecological restoration. To improve the ecological functions such as pollutants cleansing and biodiversity protection, the physical structure and ecological structure of the river/reservoir interface should be designed as a whole, where natural-based solutions are employed as technique approaches.

The ecosystem restoration case of river/reservoir interface studied in this paper is only a preliminary effort, and design strategies and framework can be a reference for other ecosystem restoration cases that are affected by water level fluctuation in river/reservoir interfaces. More research is expected to study the interaction mechanism among the ecological elements, as well as the coupling mechanism of physical structure and ecological structure, of the river/reservoir interface. Related methodologies and key techniques of adaptation responding to the changes of the river/reservoir interface at the watershed scale and the needs of sustainability are expected. Studies on the design and regulation mechanism and associated methodologies are encouraged to coordinate the ecological structures and functions of the river/reservoir interface, thus promoting the overall improvement of the "mountain–water–forest–field–lake–grass" ecosystems, and addressing environmental issues at multiple temporal–spatial scales. **LAF**

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