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以栖息地修复为导向的湿地公园设计方法——以云南省保山市青华湿地为例

WETLAND PARK DESIGN FOR HABITAT RESTORATION —CASE STUDY ON THE QINGHUA WETLAND IN BAOSHAN, YUNNAN PROVINCE

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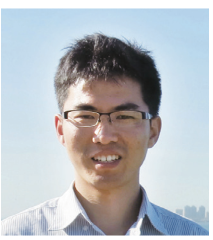

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摘要

湿地公园设计需要保护湿地的生态系统并进行科学修复，但在实践中，湿地修复的相关生态原理经常未能有效表达在设计方案中，导致湿地修复的生态效益——尤其是生物多样性及栖息地效益——并不显著。本文简述了水淹、肥力等影响湿地生态系统的主导因子，梳理了湿地生态系统修复的基本原理，采用了以湿地鸟类作为指示物种的湿地评价方法。基于多年实践，笔者总结了一套以栖息地修复为导向，以水文设计为基础的湿地公园规划设计方法，期望实现生态学基本原理在空间层面的转译，来指导景观设计师实现生态设计的有效落地。此方法包括7个步骤：目标物种选择及目标设定－生境类型设计及空间布局－地形营造－水位设计－植物群落构建－低干预的景观设计－预留让自然做功的空间。文中以云南省保山市青华湿地为例，介绍了在每一个步骤中落实以栖息地修复为导向的生态系统修复设计方法。

关键词

生态修复；湿地修复；栖息地修复；湿地公园设计；生物多样性；鸟类栖息地；青华海国家湿地公园

ABSTRACT

Wetland park design seeks to protect and restore the wetland ecosystems of sites through scientific approaches. However, in practice, the relevant ecological principles about wetland restoration are often not effectively understood or applied by landscape designers, resulting in compromised ecological benefits after the restoration, especially in biodiversity and habitat benefits. The authors highlighted the main causal factors in wetland—flooding and fertility—and adopted wetland birds as indicator species to simplify the evaluation method. Based on years of practice, the authors summarized a hydrology-based wetland design method for habitat restoration, aiming to translate ecological principles and research findings into design guidelines that can be easily understood and applied by landscape designers to spatial design. This design method includes 7 steps, namely 1) targeted species selection and goal setting; 2) design of habitat types and spatial arrangement; 3) landform design; 4) water level design; 5) plant community building; 6) landscape design with minimal intervention; and 7) spatial design for natural succession. The article then expanded each step using an illustrative design case, the Qinghua Wetland in Baoshan, Yunnan Province.

KEYWORDS

Ecological Restoration; Wetland Restoration; Habitat Restoration; Wetland Park Design; Biodiversity; Bird Habitat; Qinghuahai National Wetland Park

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1 引言

基于自然的解决方案（Nature-Based Solutions，以下简称NBS）理念于2002年被首次提出，后被世界银行在2008年《生物多样性、气候变化和适应：世界银行投资中基于自然的解决方案》[1]的报告中使用，现已受到世界范围的广泛关注。栖息地修复是NBS之一，主要目的是修复生态系统及保护物种多样性[2]。

基于多年的湿地公园设计实践经验，笔者认为湿地公园的主要设计目标是提升场地的生物多样性（即生态系统服务），并据此总结出了一套以水文修复为手段、以栖息地修复为导向的湿地公园设计方法。

景观设计师在方案设计时，需要相对量化的设计参数支持，包括水面积大小、水深、深水区—浅水区比例、植物群落中各种植物的占比等信息。然而，生态学者的现有研究成果通常为定性描述或统计分析，缺少空间尺度上的详细量化信息，导致这些研究成果对于实践的指导性不强。本文旨在探索一种将复杂的生态原理向景观设计师进行简明化、定量化的转译方式，从而更好地促进多专业融合，最大程度地提升湿地修复项目的生态效益。

2 湿地栖息地影响因子

在《湿地生态学：原理与保护》一书中，湿地生态学家保罗·凯迪详细总结了湿地设计的理论体系。凯迪将湿地的定义简化为：“水淹导致土壤以无氧过程为主，从而迫使生物（特别是有根植物）对水淹产生适应的生态系统”[3][4]。水淹是湿地产生的原因，其导致土壤氧气浓度下降，迫使生物必须同时耐受水淹的直接影响及无氧环境产生的次级影响[3]。凯迪认为影响湿地的因素主要为水淹、肥力、干扰、竞争、食植和埋藏[3][4]。2017年，凯迪又将湿地影响因子简化为5个，即水淹、肥力、干扰、竞争，及其他因子，其中水淹及肥力的影响最为显著[3]。这一理论对于湿地的可持续修复实践具有重要借鉴意义。

水淹因子主要包括水淹时长、水淹周期及水淹深度。凯迪发现根据水淹深度及水淹周期的不同，植物群落会有所不同，甚至25cm的水

1 Introduction

The concept of Nature-Based Solutions (NBS) was first proposed in 2002 and then referred in the Biodiversity, Climate Change and Adaptation: Nature-based Solution from the World Bank Portfolio 2008[1]. Now having attracted worldwide attention, NBS often leverage the methods of habitat restoration to restore ecosystems and protect biodiversity[2].

Upon years of wetland park design practices, the authors believe that wetland parks are mainly designed to enhance the sites' biodiversity, as an ecosystem services, and summarize the steps and techniques for wetland park design that aim to (re-)introduce habitats to the site with hydrological restoration approaches.

Quantitative references about the area of water body, water depth, ratio between deep and shallow areas, proportions of each plants in vegetation communities, etc. are needed for landscape design. However, most ecological studies are qualitative descriptions or statistical analyses that lack quantified spatial measurements. To facilitate cross-disciplinary integration and to maximize the ecological benefits of constructed / restored wetlands, this article renders complicated ecological principles and research findings into quantified measurements that can be easily understood and applied by landscape designers.

2 Causal Factors of Wetland Habitats

In *Wetland Ecology: Principles and Conservation*, wetland ecologist Paul Keddy expounded on the theories about wetland design and defined wetland as “an ecosystem that arises when inundation by water produces soils dominated by anaerobic processes, which, in turn, forces the biota, particularly rooted plants, to adapt to flooding”[3][4]. Water creates wetlands—“there is a cause (inundation by water), a proximate effect (reduction of oxygen levels in the soil), and a secondary effect (the biota must tolerate both the direct effects of flooding and the secondary effects of anaerobic conditions).”[3] According to Keddy, the conditions of wetlands are subject to several causal factors, including flooding (hydrology), fertility, disturbance, competition, herbivory, and burial[3][4]. In 2017, he further re-summarized these factors as flooding, fertility, disturbance, competition, and others, among which flooding and fertility are the most significant ones[3]. His theories are of remarkable references for the sustainable restoration of wetlands.

Flooding can be further measured by duration, cycle or pulse, and depth. Keddy found that varied flooding depths and pulses would result in different compositions or forms of plant

深变化也会对植物群落的物种组成产生很大影响。[4]在考虑水淹时长和水深时，要为不同的植物预留非淹没期，以便植物补充氧气。

肥力因子主要是指湿地中的营养物质含量，尤其是氮和磷的含量。氮含量是湿地植物生长的主要考量指标。一般来说，营养物质越多，生物量越大，但是植物的多样性会随之减少[4][5]。乔斯·T·A·费霍文等人发现适合植物生长的氮磷比例为14:1到16:1之间[6]，这与阿尔弗雷德·C·雷得费尔得于1934年提出的Redfield值一致，即浮游植物生长对碳、氮、磷的粒子数需求比例为106:16:1[7][8]。

其他各湿地影响因子均会对湿地设计及后期管理和维护产生较大影响，同样需要设计者予以重视[7]，基于篇幅，笔者不在此详细展开。同时，设计师也需要借鉴其他专业的相关研究成果——如滨岸带的成带现象[4]、底栖动物的密度及与水深的关系[9][10]、自然湿地及修复湿地的种子库物种密度等[4][5][9][10]——来指导自己的湿地设计实践。

3 以栖息地修复为导向的湿地生态系统设计

生态系统修复通常需要经历环境修复、修复管理、维护管理三个阶段，本文主要阐述如何通过以栖息地修复为导向的设计手段营造湿地生态系统的物理化学环境，以为后续的环境修复提供基础条件。

以栖息地修复为导向的湿地设计方法是一种基于生物视角的现代循证设计方法，其基本思路是根据地带性规律、生态演替及生态位原理选择适宜的湿地指示生物，构造种群适宜的栖息地系统，对水文、植被与生物进行同步修复，最终将生态系统修复到一定的功能水平。栖息地修复的目标是"建造一个由特定的植物物种组成，且能够为特定的动物物种提供生境的湿地"[3][4]。设计师通过研究场地特征及周边类似区域内的动植物物种，确定期望重新引入的物种，包括关键物种。但是，由于待修复的湿地往往是生态退化型湿地，因而修复目标可以场地的历史资料或周边的健康湿地案例为参照。在多数情况下，

communities—a 25-centimeter water depth change can lead to a considerable disparity.[4] Beside flooding duration and depth, wetland design needs to consider flood pulse to facilitate the aerenchyma of plants in non-flood days.

Fertility refers to the nutrient contents in wetlands, particularly the contents of nitrogen and phosphorus. The availability of nitrogen is commonly adopted to assess how suitable a wetland is for living creatures. Generally, the more the nutrients, the larger the biomass and the smaller the biodiversity will be[4][5]. Jos T. A. Verhoeven et al. found that the ideal nitrogen-phosphorus atom ratio for plant growth is between 14:1 and 16:1[6], consistent with the Redfield value proposed by Alfred C. Redfield in 1934, i.e. the atom ratio of carbon, nitrogen, and phosphorus for growth of phytoplankton is 106:16:1[7][8].

Other causal factors also exert measurable impact on wetland habitats and should be taken careful consideration in the design, post-management, and maintenance of wetlands[7]. Limited by length, this article will not go through the rest one by one. Designers can suitably adopt existing research findings from allied fields on, for example, the zonation along the shoreland[4], the relationship between the density of benthic animals and the water depth[9][10], as well as the species densities of seed banks in natural and restored wetlands[4][5][9][10].

3 Wetland Ecosystem Design for Habitat Restoration

Ecosystem restoration often goes through three stages: environmental restoration, restoration management, and maintenance. This article focuses on introducing the design methods to create the physicochemical conditions of wetland ecosystems for habitat restoration, also laying a foundation for follow-up environmental restoration.

The wetland design aiming to restore habitats can be considered a modern evidence-based and biology-support design approach. Appropriate biological indicators of wetlands are selected based on the zonation pattern, ecological succession, and ecological niche principles, which can indicate the suitability of a habitat system, support a symbiotic restoration of hydrology, vegetation, and biology, and eventually realize the delivery of ecosystem services. Precisely, the goal of habitat restoration is "to create a wetland dominated by specific plant species to provide habitat for specific animal species."[3][4] By studying the site characteristics and inventorying the flora and fauna of similar areas in the same region, landscape designers can decide the species to be introduced, including the key ones. However, most wetlands to be restored suffer from ecological

难以在短期内完全修复到历史或自然状态，比较现实的修复目标是建立一个具备自然系统要素的过渡生态系统[4]，再通过自然演替逐渐修复至近自然的生态系统。

评价生态修复是否成功，有指示物种法、指标体系法[11]、定量生态排序法及利用参照湿地进行类比等方法[4]。虽然指示物种在生态修复上是有效的衡量标准并已广泛被研究人员所接受，但指示物种的选择没有绝对的标准，应取决于实际的空间尺度[12]。在较小的空间尺度下（如池塘），植物和无脊椎动物可以起到指示作用；而在大空间尺度下（如自然保护区），较大生物体的指示作用更强；在介于两者之间的空间尺度下，鸟类则被证明能够对环境变化做出响应（出现频率、密度和繁殖率等对生态环境敏感），有着广泛的食性和适当的营养级水平，且鸟类便于通过鸟鸣进行识别和监测，是良好的生态系统修复评价指标，已被广泛用作河滨、湿地和陆地生境的指示物种[5]。

在设计阶段不需要，也不可能就每个影响因素进行设计，因此需要运用一种简化的、有代表性的设计方法。鉴于水淹为湿地的主要影响因子之一，笔者以水深为主要指标，并总结出了以栖息地修复为导向的7个重要设计步骤，分别是：1）目标物种选择及目标设定；2）生境类型设计及空间布局；3）地形营造；4）水位设计；5）植物群落构建；6）低干预的景观设计；7）预留自然做功空间。后文将以云南省保山市青华湿地为例，详细阐述这7个设计步骤。

4 设计案例：青华湿地生态修复设计

青华海国家湿地公园位于云南省保山市隆阳区，主要组成包括北庙湖、东河和青华海湿地三个组成部分（图1）。青华海湿地可分为西湖（61hm^2）、东湖（101hm^2）和青华湿地（313hm^2）三个部分（图2），其中西湖、东湖为已修复湿地，但人工化特点较为明显；青华湿地古时为湖泊湿地，20世纪50年代以来因围垦而不断萎缩，现状为低

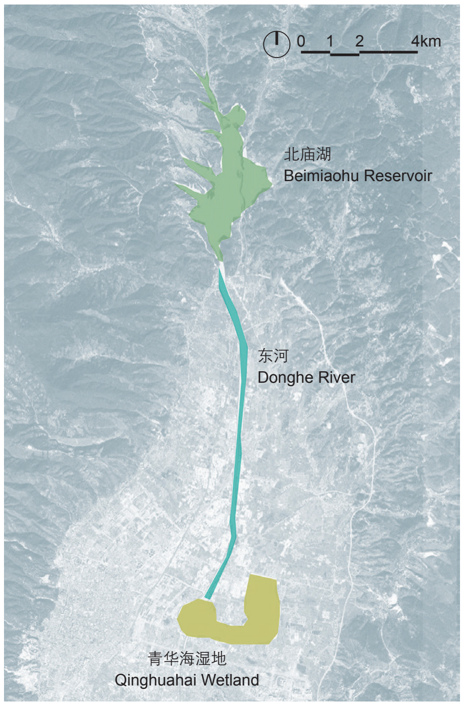
deterioration, and the restoration goals can be identified by referring to the site's historical records or other healthy wetlands nearby. It is hard to fully restore a natural or an exact habitat in history in a short period; habitat restoration can be realized by first creating an interim ecosystem composed of natural system elements[4] and then allowing for natural successions towards a "quasi-natural ecosystem."

The success of ecological restoration can be assessed with e.g. indicator species, indicator systems[11], quantitative ecological sequencing approach, and analogy methods[4]. Indicator species is the most widely adopted measurement to ecological restoration, and the species should be chosen upon the spatial scale of sites[12]. To smaller sites (e.g. ponds), plants and invertebrates can be used as the indicators; to larger sites (e.g. nature reserves), big creatures are more instructively indicative; and to medium-scale sites, birds are often selected as indicators for ecosystem restoration because they are sensitive to environmental changes (in occurrence, density, and reproduction rate, etc.), have diverse foraging with an appropriate nutrition level, and can be easily recognized and monitored by their twitter. Birds are used worldwide as indicator species to the restoration of riverain, wetland, and inland habitats[5].

At the design stage, it is neither necessary nor possible to respond to every factor. A simplified design method is needed. Taking water depth as the major consideration, as an demonstration, the authors come up with 7 steps of wetland design for habitat restorations, namely 1) targeted species selection and goal setting; 2) design of habitat types and spatial arrangement; 3) landform design; 4) water level design; 5) plant community building; 6) landscape design with minimal intervention; and 7) spatial design for natural succession. The article will expand each step combining with an illustrative design case, the Qinghua Wetland in Baoshan, Yunnan Province.

4 Illustrative Case: Ecological Restoration Design of the Qinghua Wetland

Located in the Longyang District of Baoshan, Yunnan, the Qinghuahai National Wetland Park is composed of the Beimiaohu Reservoir, Donghe River, and Qinghuahai Wetland (Fig. 1). The Qinghuahai Wetland consists of three wetlands, namely Xihu Wetland (61 hm^2), Donghu Wetland (101 hm^2), and Qinghua Wetland (313 hm^2) (Fig. 2), with the first two having finished the restoration with landscaped measures. The Qinghua Wetland used to be a lacustrine wetland and began to shrink due to the agricultural reclamation since the 1950s. It now is a low-lying farmland. This project aims to restore the



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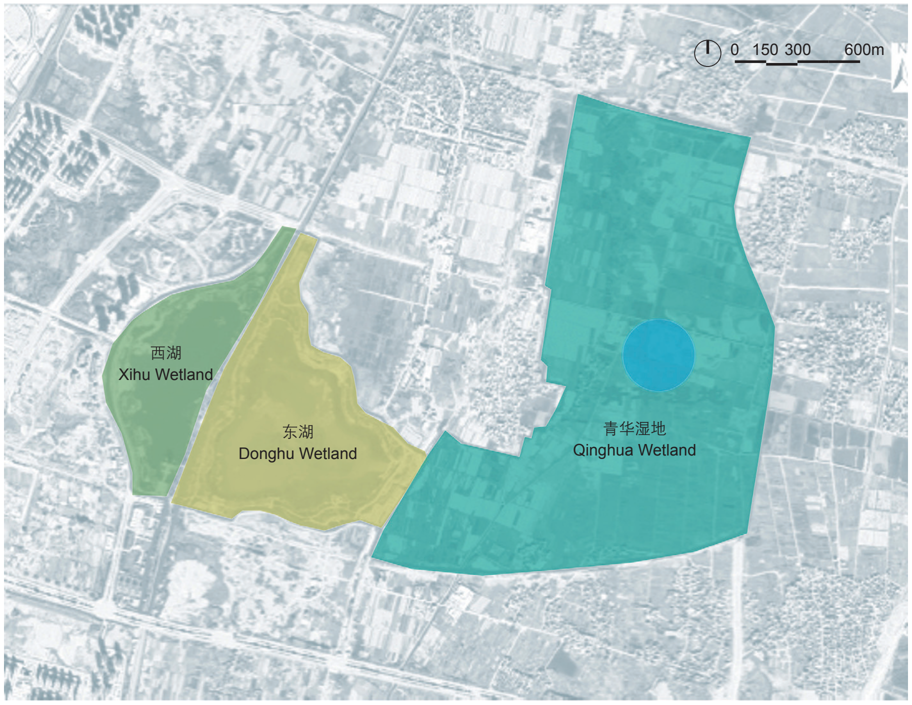

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1. 青华海国家湿地公园区位图
2. 青华湿地区位图

1. Site location of Qinghuahai National Wetland Park
2. Site location of Qinghua Wetland

洼农田。本项目的设计目标是修复区域内的湖泊湿地生态系统。本文将重点论述以栖息地为导向的前期方案设计过程。

4. 1 目标物种选择及目标设定

根据对云南西部其他湖泊湿地（如剑湖[13]、拉市海[13][14]、泸沽湖[15]和洱海[16]）及贵州的草海等湖泊湿地[17]的鸟类群落调查研究，该区域湿地鸟类总体上以雁鸭类（Anatidae）、鸊鷉类（Podicedidae）、秧鸡类（Rallidae）为主[18][19]。案例范围内的调研结果显示，记录到鸟类约170种，其中湿地鸟类55种，优势种类包括鸊鷉目和雁鸭目的各种野鸭、鹳形目的各种鹭鸟、鹤形目秧鸡科的白骨顶（*Fulica atra*）等，这与区域内其他湖泊湿地的鸟类群落情况一致。另外，每年春秋两季均有黑鹳（*Ciconia nigra*）、灰鹤（*Grus grus*）等大型珍稀候鸟迁徙经过保山盆地，远期的青华海湿地也将有望为这些珍稀物种提供良好的栖息地。因此，本次设计的指示物种需要涵盖雁鸭类、鸊鷉类、秧鸡类等游禽，鹭类涉禽，以及区域珍稀湿地候鸟。

本次设计最终选取了6种典型的湿地鸟类为指示物种（表1），分别是赤麻鸭（*Tadorna ferruginea*）、绿头鸭（*Anas platyrhynchos*）、小鸊鷉（*Podiceps ruficollis*）、白骨顶、白鹭（*Egretta garzetta*）和灰鹤。

lacustrine wetland ecosystem of the site. This article introduces the development of the design proposal for habitat restoration.

4.1 Targeted Species Selection and Goal Setting

Studies on the avian communities in other lacustrine wetlands in western Yunnan (e.g. the Jianhu Lake[13], Lashihai Lake[13][14], Lugu Lake[15], and Erhai Lake[16]), as well as the Caohai Lake in Guizhou[17], signpost that, on the whole, Anatidae, Podicedidae, and Rallidae birds are the dominant species in this region[18][19]. The site investigation inventoried nearly 170 bird species, 55 of which are wetland birds. The dominant species include birds of Podicedidae, Anatidea, and Ardeidae, and *Fulica atra*. This is similar with the bird communities of other lake wetlands. Also, large rare migratory birds such as *Ciconia nigra* and *Grus grus* pass through the Baoshan Basin in spring and fall, and the Qinghuahai National Wetland Park is expected to provide quality habitats for them. The indicator species in this project therefore need to include the swimming birds of Anatidae, Podicedidae, and Rallidae, the wading bird species of *Ardeidae*, and regional rare wetland bird species.

Finally, 6 targeted species are decided (Table 1): *Tadorna ferruginea*, *Anas platyrhynchos*, *Podiceps ruficollis*, *Fulica atra*, *Egretta garzetta*, and *Grus grus*. The designers carefully study the habitats requirements of each bird[20]~[26] to inform the design

设计团队分别对这些鸟类的栖息地进行了详细研究[20]~[26]，以为设计提供参数依据。

根据指示物种的栖息地偏好，再结合青华湿地历史资料，以及当地水资源总量、水环境条件、现状地形等要素，最终确定以近自然浅水草型湖泊湿地生态系统作为生态修复的总体目标，其典型特征为水深较浅，拥有丰富的挺水和沉水植物，可提供大量的开阔浅水和浅滩环境。

4.2 生境类型设计及空间布局

首先，根据目标物种确定核心栖息地类型及主导因素，并清晰界定或描述相关参数条件。例如，赤麻鸭、绿头鸭等游禽类候鸟栖息地的理想水深为1m左右，休憩环境偏向于在裸露泥滩、砾石滩、沙滩或草地开阔环境[10]；而白鹭等典型涉禽类则更喜好水深小于0.3m的浅沼，其筑巢环境偏好人类干扰较少的密林[23][27]（图3）。

其次，在典型栖息地规模方面，鉴于青华湿地修复后要为大量游禽类候鸟提供越冬栖息地，因而将超过50%的水域规划为浅水栖息地

with quantitative references.

By understanding the habitat preference of the indicator species, reviewing the historical data of Qinghua Wetland, and investigating the total water resources, water environment conditions, terrain conditions, etc., the designers determine to restore the wetland into a near-natural shallow macrophytic lake wetland ecosystem, which consists of shallow water bodies with diverse emergent and submerged plants, providing rich marshes and mudflats.

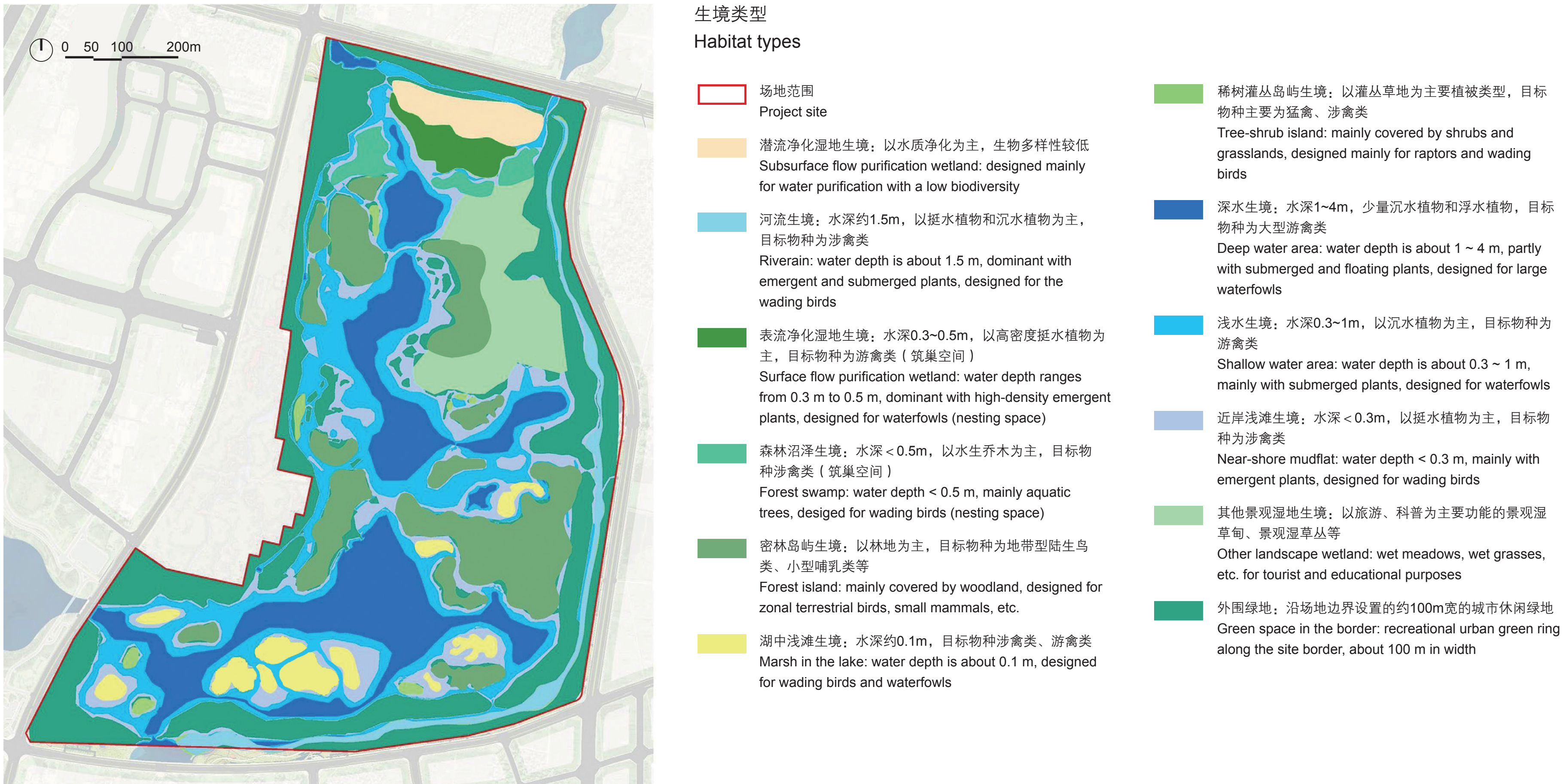
4.2 Design of Habitat Types and Spatial Arrangement

To begin with, the main habitat types and associated causal factors should be identified upon the targeted species, and clearly defined or described with parameters. For instance, for the habitats of waterfowls such as *Tadorna ferruginea* and *Anas platyrhynchos*, the ideal water depth is about 1 meter, in forms of uncovered mud banks, gravel banks, sand banks, grasslands, and other open water areas[10]; Wading birds such as *Egretta garzetta* prefer shallow marshes with a water depth less than 0.3 meter and often nestle in the forest swamps far from human intervention[23][27] (Fig. 3).

The restored Qinghua Wetland will provide overwintering habitats for many migratory waterfowls. Thus over 50% of the

表1：青华湿地公园生态修复设计案例选取的指示物种
Table 1: Indicator species for the ecological restoration of Qinghua Wetland

稀有程度 Rareness level	目标类群 Target species	指示物种 Indicator species	类型 Type		生境偏好 Habitat preference			设计指导意义 Design guidelines
					水深偏好 Water depth preference	植被偏好 Vegetation preference	筑巢环境偏好 Nesting preference	
区域常见湿地鸟类 Regional ordinary wetland bird	雁鸭类 Anatidae	赤麻鸭 *Tadorna ferruginea*	候鸟 Migrant	游禽 Waterfowl	0.5 ~ 2 m	莎草科植物，如光叶眼子菜（*Potamogeton lucens*） Sedges, e. g. *Potamogeton lucens*	沙洲或粘土性质的洞穴 Sandbank or clay caves	确定适宜的水深参数、重点栖息地类型、重点植被类型等 Offering quantitative references for the design of water depth, key habitat types, key vegetation types, etc.
		绿头鸭 *Anas platyrhynchos*	候鸟 Migrant	游禽 Waterfowl	0.5 ~ 1 m	河岸植被覆盖，茂密的挺水植物 Riverian areas covered with lush emergent plants	近水地面植被里，树桩或灌木丛中 Between vegetation near water bodies, in stumps, or in shrubs	
	䴙䴘类 Podicedidae	小䴙䴘 *Podiceps ruficollis*	留鸟 Resident	游禽 Waterfowl	0.5 ~ 1 m	挺水植物、藻类和沉水植物 emergent vegetation, algae, and submerged plants	挺水植被、淹没的树枝或灌木中 Between emergent plants, submerged branches or shrubs	
	秧鸡类 Rallidae	白骨顶 *Fulica atra*	候鸟 Migrant	游禽 Waterfowl	0.2 ~ 1.0 m	挺水植物和沉水植物 Emergent and submerged plants	挺水植物、灌木丛中，树桩或树杈上 Between emergent plants or shrubs, or on stumps or branches	
	鹭类 Ardeidae	白鹭 *Egretta garzetta*	留鸟 Resident	涉禽 Wading bird	0.1 ~ 0.15 m	裸滩 Uncovered beach	湿地周边林地 Forests near wetlants	
区域珍稀湿地鸟类 Regional rare wetland bird	鹤类 Gruidae	灰鹤 *Grus grus*	候鸟 Migrant	涉禽 Wading bird	≤ 0.5 m	莎草（*Cyperus rotundus*）和芦苇（*Phragmites australis*） *Cyperus rotundus* and *Phragmites australis*	干扰较小的沼泽、石楠丛、莎草草甸的水中 In less-disturbed marshes, heather bushes, or sedge meadows	



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（水深0.5~1.5m）；深水生境（水深1.5~4m）不超过总体水面的20%，以为大型游禽类提供栖息地[28]；而作为涉禽类的栖息地，近岸浅滩和浅沼栖息地占总水域面积的比例不低于25%，但在空间上呈现周期性变化。为了确定供湿地鸟类筑巢繁衍的岛屿生境的总体面积，设计综合考虑了填挖方量和生态功能需求等因素，并根据岛屿的大小分为草滩绿洲、稀树灌丛岛屿及密林岛屿。

再次，在栖息地的空间布局方面，设计模拟自然的湖泊湿地格局，设置了多样化的动植物生境空间。例如，近岸浅滩生境分布在岸线及岛屿岸线周边；选择不规则的岛屿形态，形成更多样的岛屿微生境。

4.3 地形营造

地形是湿地生态系统修复的空间载体，是植被空间分异的主要自

water area of the site is planned as shallow water habitats (0.5 ~ 1.5 m in water depth)[28], no more than 20% as deep water habitats (1.5 ~ 4 m in water depth), providing habitats for large swimming birds, and no less than 25% as the near-shore mudflats, marshes, and shallow swamps for wading birds, the layout of which will dynamically change along the flood pulse. To determine the total area of island habitats where birds can nestle and reproduce, the designers take into consideration the amount of cut-and-fill as well as ecological services; the island habitats are diversified as grass islets, tree-shrub islands, and forest islands by size.

In terms of the spatial layout of habitats, various flora and fauna habitats are designed that simulate the pattern of natural lacustrine wetlands. For instance, the near-shore mudflats are scattered along the land and island banks; irregular islands are designed to create diverse island micro-habitats.

4.3 Landform Design

Landform design is to create the physical spaces where the restoration of wetland ecosystem occurs, and landform is an

3. 青华湿地典型鸟类栖息地

3. Key habitats for birds in Qinghua Wetland

4. 青华湿地地形改造

4. Landform design scheme of Qinghua Wetland

然约束因子[3]。典型的湿地地形包括浅滩、湾型岸带、生境岛、开敞水面、急流带和滞水带等类型[29]。在地形设计的过程当中应当避免过于均一化，多样化的水底微地形可以丰富水深和水温分布的多样性，从而增强湿地生态系统的稳定性[3][4]。岛屿位置在综合考虑水土保持需求和保证最小填挖方量的前提下，尽量自然化地随机分布（图4，5）。

驳岸坡度是影响生物多样性的重要因素，应根据实际场地情况，设计尽可能多样化的自然驳岸。生态缓坡坡度设计缓于1:6；在部分空间充足的区段，岸线采用了1:16的坡度设计。

4.4 水位设计

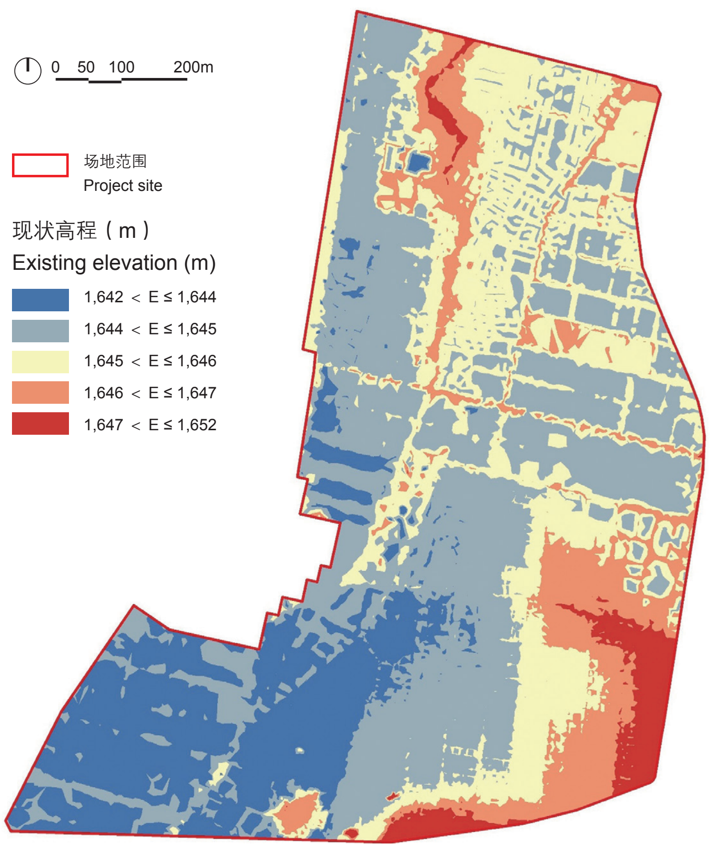
在湿地水位方面，项目团队重点考虑了短时间周期（约3~5天）内的水位变化和季节性水位变化。湿地枯水和丰水季节的水位变化幅度约为0.5m，具体水位可在公园运营后依据生态效益反馈进行调整。在夏季丰水期，湿地承担着排洪蓄涝的功能，水位上升使得大量的浅沼、浅水及深水栖息地要进行依次转换，在此期间不耐长时间水淹的植物

important natural constraint that defines the spatial distribution of plants[3]. Typically wetland landforms include mudflat, bay shore, island, open water area, torrent zone, and backwater zone[29]. Diverse landforms should be designed to increase the variety of water-depth and water-temperature zones, so as to enhance the stability of wetland ecosystem[3][4]. The islands and islets should be distributed randomly, combining with the needs for water-soil conservation and minimum cut-and-fill (Fig. 4, 5).

The gradient of bank slope impacts the biodiversity of a site drastically. Natural banks need to be diversified as much as possible upon site conditions. The gradient of ecological slopes should be no more than 1:6, or 1:16 to the cases with a sufficient area of flats.

4.4 Water Level Design

The designers make allowance for both the short-term (3 to 5 days) water level changes and seasonal water level changes. The water level of the site would drop about 0.5 m from the rainy season to the dry season, and, after the completion, adjustments will be needed according the actual water level changes for a better ecological performance. During summers (the rainy season), the wetland will function to store floods. The



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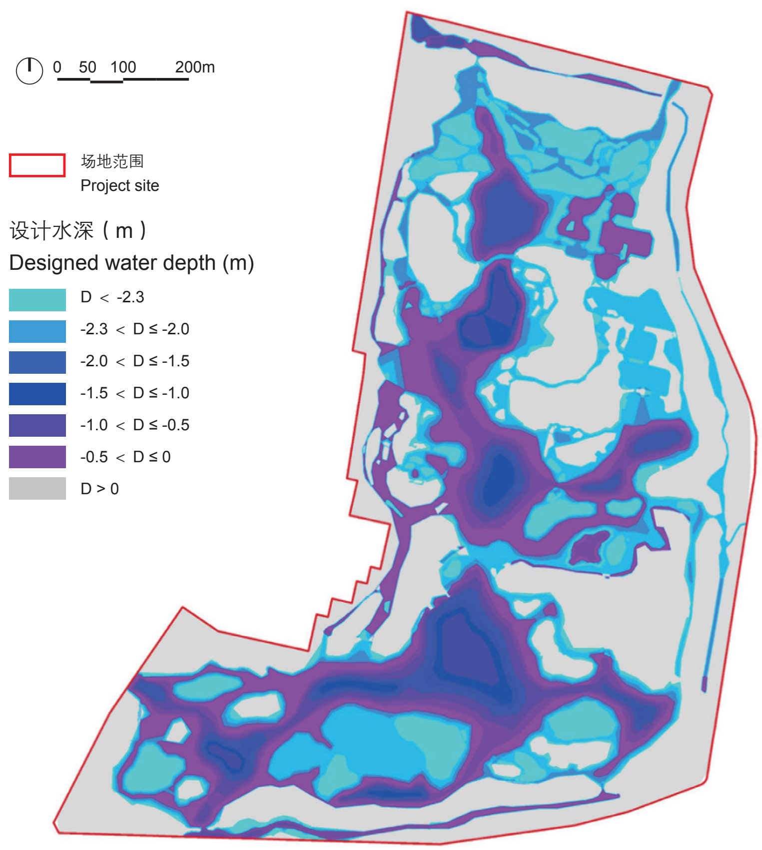

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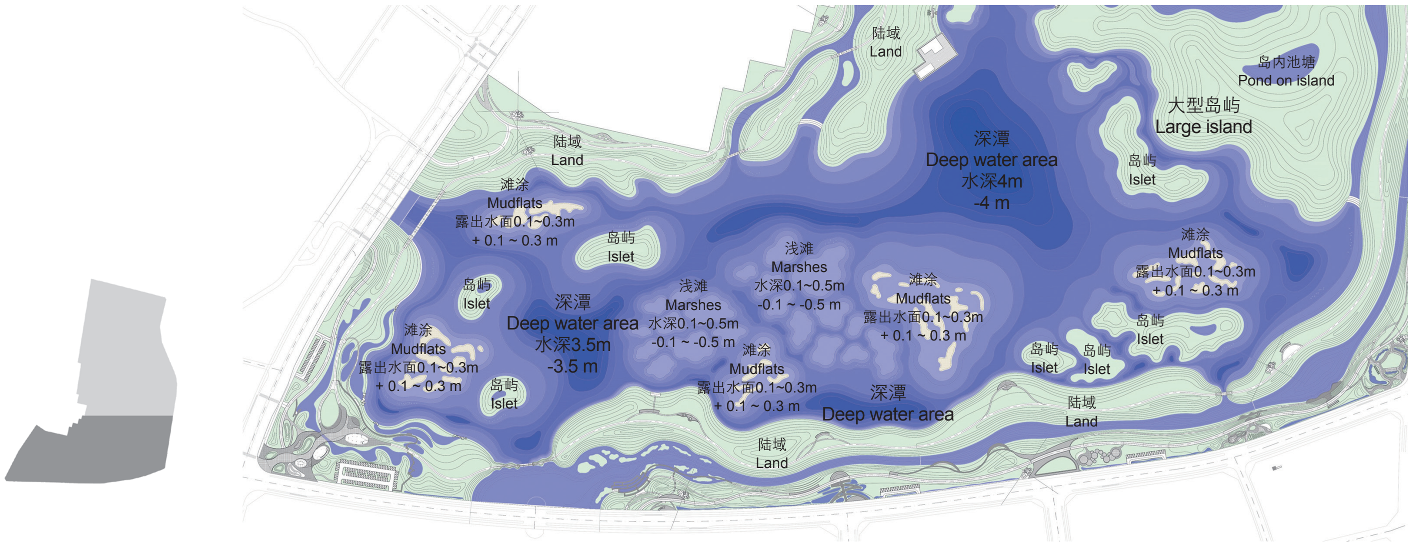

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5. 针对不同湿地鸟类生境偏好的微地形设计

5. Micro-topography design for the habitats of wetland birds according to their habitat preferences

种类也将被自然淘汰；通过水闸系统控制的水位变化，可实现短持续时间内周期性水位小幅度缓慢转换，水位下降时裸露出的滩涂将为涉禽鸟类提供良好的觅食空间，水位上升时浅水环境的增加则为游禽鸟类提供了更多的栖息地。

4.5 植物群落构建

据实际调查，目前整个青华海国家湿地公园区域内野生维管束植物约480种，这为规划设计提供了丰富的乡土植物资源库。参考地带性植被特征，设计师与生态学者共同设计了四大植被群落类型，分别是：1）大型岛屿上的滇西高原典型的半湿润常绿阔叶林，主要包括元江栲（*Castanopsis orthacantha*）群落、滇青冈（*Cyclobalanopsis glaucoides*）群落、滇石栎（*Lithocarpus dealbatus*）群落；2）中小型岛屿上的稀树草丛；3）滨水边缘的暖性湿草丛及地带性的湖泊湿地植物群落，主要包括四脉金茅（*Eulalia quadrinervis*）群落、刺芒野古草（*Arundinella setosa*）草丛群落、李氏禾（*Leersia hexandra*）—燕子花（*Iris laevigata*）群落、海南马塘（*Digitaria setigera*）—云南莎草（*Cyperus duclouxii*）群落、野菱（*Trapa incisa*）群落、菰（*Zizania latifolia*）群落、慈姑（*Sagittaria trifolia*）群落、菖蒲（*Acorus tatarinowii*）群落；4）湖岸密林（图6）。

在半湿润常绿阔叶林群落设计上，本项目选取地带性的顶级植物群落类型作为目标植物群落。在造林模式上，本项目使用了宫胁造林法[30]，即利用群落演替的自然规律实行高密度、多种类的造林方法。此法适用于以生态栖息地修复为目的的岛屿、半岛等区域。林地生态系

water level rise will turn the marshes and shallow water areas of the site into deep water zones, where the vegetation species that are not tolerant to long-time inundation will be eliminated. The water level can also be slightly adjusted with the system of reservoirs or dams for a short time period, when the emergent mudflats will serve as foraging places for wading birds, or the increase of submerged areas will augment the habitats for swimming birds.

4.5 Plant Community Building

Field investigations inventory nearly 480 native tracheophyte species across the whole area of the Qinghuahai National Wetland Park, which admirably informs the plant community design. By studying the attributes of zonal vegetation, the designers together with ecologists profile 4 major vegetation community types for the site, namely 1) the semi-humid evergreen broad-leaf forest typical to the Western Yunnan Plateau (for larger islands), including communities dominant by *Castanopsis orthacantha*, *Cyclobalanopsis glaucoides*, *Lithocarpus dealbatus*, etc.; 2) tree-shrub community (for smaller islands); 3) riverain warm wet grassland and zonal lacustrine wetland community, including communities of *Eulalia quadrinervis*, *Arundinella setosa*, *Leersia hexandra–Iris laevigata*, *Digitaria setigera–Cyperus duclouxii*, *Trapa incise*, *Zizania latifolia*, *Sagittaria trifolia*, and *Acorus tatarinowii*; and 4) lakeshore forest (Fig. 6).

For the semi-humid evergreen broad-leaf forest community, top zonal plant communities are chosen as the targeted communities of the site. The Miyawaki's ecological method to reforestation[30], i.e. high-density and high-diversity afforestation that leverages natural succession of vegetation community, is employed in islands and lakeshores. The energy flow, information flow, and material flow

统与湿地生态系统之间会产生各类的能量流、信息流、物质流，形成复合的生态系统。设计团队根据成带学原理，将湿地植物依据水深梯度依次分布——也就是说，湿地植物实际上在水位和水深设计条件确定之后，就已经确定了其大致的类型和空间布局。暖性湿草丛植被分布在季节性水淹的低洼地或滨水地带，这类草丛会存在相当长的时间（几年到数十年不等），从管理的角度可把它们看作永久植物群落。

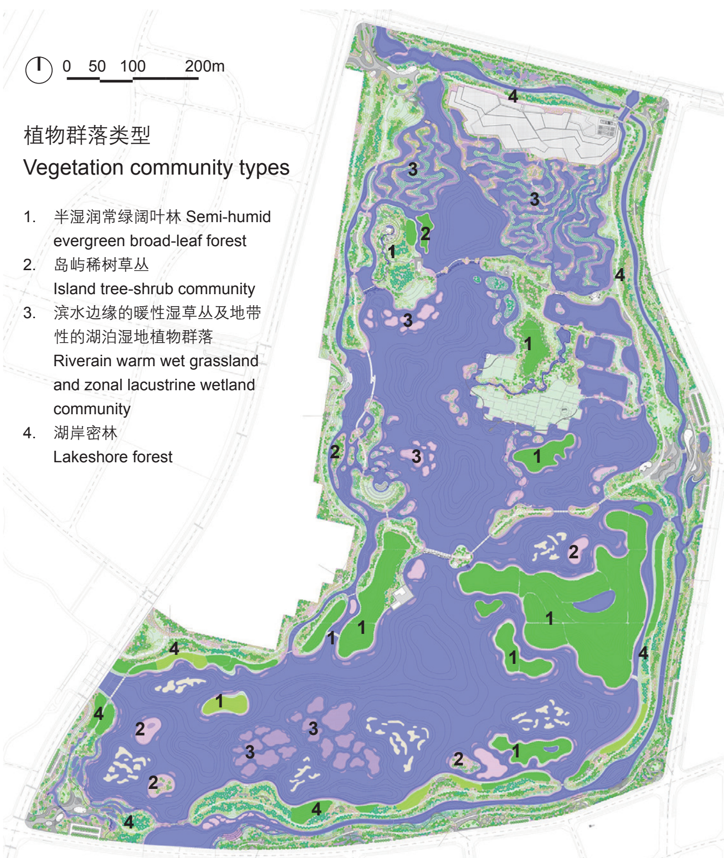
4.6 低干扰的景观设计

在以栖息地修复为导向的设计过程中，重点关注目标物种对人类干扰的敏感度，耐受距离是对干扰敏感度的一个量化指标。湿地鸟类对人类干扰的耐受距离分为警戒距离、惊飞距离、缓冲距离和安全距离，通常选择惊飞距离作为设计参数。惊飞距离越远，说明对人类干扰越敏感，如涉禽类惊飞距离一般为15m左右，游禽类惊飞距离一般为10m左右；而其他已经适应人类干扰的鸟类，如树麻雀（*Passer montanus*）、喜鹊（*Pica pica*）等，惊飞距离可以近至5m以内[31][32]。另

between the forest ecosystem and the wetland ecosystem will shape a compound ecosystem of the site. Following the zonation principle, the designers distribute the wetland plant communities by required water depth—actually, the plant community types and spatial distribution are roughly defined by the landform design. The warm wet grassland grows in the low-lying terrains, riverain areas, or lakeshores where season inundation occur. The grass will lastingly survive for several years or even decades, which thus can be regarded as perpetual plant communities.

4.6 Landscape Design with Minimal Intervention

Minimizing human intervention on the targeted species is prioritized during the habitat restoration process. Tolerance distance is a measurement of birds' sensitivity to intervention. For wetland birds, there are alerting distance, flush distance, buffer distance, and safety distance, and flush distance is mostly used as wetland design measurement. The longer the flush distance, the more sensitive to human intervention the birds are. For instance, the flush distance of wading birds is around 15 meters and 10 meters to swimming birds, while for the birds used to human interventions (e.g. *Passer montanus*, *Pica pica*) the flush distance is observed less than 5 meters[31][32]. Birds' flush



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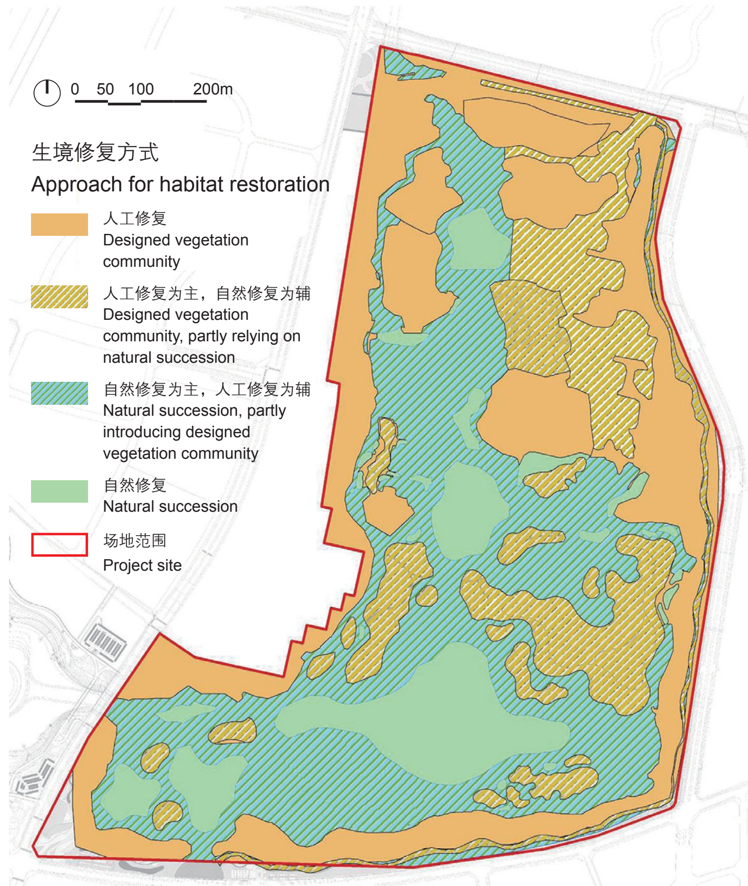

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6. 青华湿地植被群落类型
7. 青华湿地栖息地修复方式

6. Vegetation community types in Qinghua Wetland
7. Approaches for habitat restoration in Qinghua Wetland

外，鸟类的惊飞距离还与环境隐蔽程度、隔离程度、人为投食等因素有关[33][34]。在景观设施空间布局（包括主要园路、游船路线的布设）当中，参考目标物种的惊飞距离参数，设置距离核心栖息地的缓冲距离，减少湿地公园内游客对鸟类生境的干扰；岛屿栖息地由于水面的隔离性较强，鸟类的惊飞距离会相对变短，在景观游憩区域可采取小型岛屿的形式。在空间狭小的亲水步道边缘可增加植物遮蔽度，也可以减短惊飞距离，降低干扰程度。

4.7 预留让自然做功的空间

从零开始的自然做功一般需要相对较长的时间（参考湿地案例需要8年左右），利用表层土壤的种子库（包含了大量地表植被群落的种子、营养体等植物繁殖体）[4]，在预留的自然修复空间中，通过人工引入参考湿地的表层土壤，可以加快自然做功效率[4][35]。

此次设计采取了人工修复和自然修复相结合的措施（图7）。首先，预留自然修复空间，主要市民游憩区域以人工种植为主、自然修复为辅；在以生态栖息功能为主的生态修复区，则以自然修复为主、人工种植为辅。其次，在地形整理初期，收集表层土壤（表层20cm的土壤层）作为表层土壤种子库，以在生态系统修复空间中进行回用。

5 结语

湿地生态系统修复要求景观设计师将生态原理转化为恰当的设计语言。笔者在多年实践过程中致力于思考如何将生态学原理转化为景观设计语言，并总结出一套包含7个步骤的湿地公园设计方法，其核心指导思想是理解自然界的科学规律，并创造条件让自然做功。通过结合青华湿地生态系统修复设计案例，笔者对这一方法进行了具体说明。

为了评价生态修复的绩效，需要定期对项目中所选的影响因子（包括水深、水质、动植物种类及数量）进行监测，并制定适应性管理或调整措施。项目有望在3~8年后实现生态系统的近自然状态。LAF

distance sometimes changes because of the exposure and shield extent of the environment as well as human feeding[33][34]. In this case, landscape features and facilities (including the paths and boating routes) are arranged by staying away from the habitats of the targeted species that are far enough to protect the birds from visitors' interventions. Specifically, for the island habitats, water surfaces can act as barriers between birds and humans, so that the flush distance can be set relatively shorter than usual. Therefore, smaller islands or islets are encouraged typologies in sightseeing and recreational areas. Along the waterfront walkways, plants can be added as shields that shorten the flush distance and minimize human intervention.

4.7 Spatial Design for Natural Succession

In wetland restoration practices, natural succession often takes a long time (about 8 years in similar cases) to begin. The process can be accelerated if the design replaces seed banks from other wetlands in this region (which contain a large amount of propagules e.g. seeds and nutrients of ground vegetation)[4] into the topsoil of the site[4][35].

In this case, the design employs both restoration approaches of designed vegetation community and natural succession (Fig. 7). By reserving the space for natural restoration, the sightseeing zones introduce designed vegetation communities that partly allow for natural succession; for the ecological restoration areas (i.e. key habitats), natural succession is dominantly used, partly introducing designed vegetation communities. Also, in the land leveling stage, topsoil (about 20 cm in depth) is collected as a seed tank and replaced into the areas of ecosystem restoration.

5 Conclusion

The wetland ecosystem restoration requires landscape designers to translate related ecological principles into appropriate design languages, to which the authors have practiced for years. In this article, authors summarize 7 steps for wetland park design upon a comprehensive understanding on the laws of nature. This design method celebrates, leverages, and facilitates natural succession. This method is clearly illustrated with the ecosystem restoration design of Qinghua Wetland.

To evaluate the performance of ecological restoration, it is necessary to regularly monitor the impact factors (water depth, water quality, flora and fauna species and amount, etc.) and to make adaptive management or adjustment measures if needed. The ecosystem of the Qinghua Wetland is expected to restore back to a near-natural or "quasi-natural" state within 3 to 8 years. LAF

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