Research on Wetland Landscape Design Strategies Based on Eco-Hydrological Restoration

Gong Jingzheng Hebei Academy of Fine Arts

ABSTRACT

Wetlands, known as the "kidneys of the Earth," play irreplaceable roles in maintaining ecological security, purifying water quality, regulating climate, and flood/drought mitigation. However, with accelerating anthropogenic activities, wetland ecosystems face severe threats and damages, including water pollution, biodiversity loss, and degradation. This study constructs a "vegetation-topography-hydrology" three-dimensional collaborative restoration model and employs SWMM simulation and AHP analysis to identify key regulatory parameters for wetland landscape design. Results show that optimized design enhances water purification efficiency by 35% and increases the biodiversity index by 1.8 times. The proposed landscape hydrological regulation technology provides a quantitative solution for wetland ecological restoration. This paper systematically analyzes the characteristics and functions of wetland ecosystems, elaborates on the principles and methods of wetland landscape design strategies based on eco-hydrological restoration, and discusses practical applications through case studies. Findings demonstrate that this strategy effectively improves water quality, enhances biodiversity, and strengthens ecosystem stability and resilience, offering novel thoughts and approaches for wetland conservation and sustainable development.

Keywords: Eco-Hydrological Restoration; Wetland Landscape; Landscape Hydrological Model; Analytic Hierarchy Process (AHP); Ecosystem Services

1. Introduction

Wetlands, as one of the Earth’s most vital ecosystems, exhibit unique natural attributes and multifunctional values. They purify water, regulate climate, mitigate floods/droughts, and provide habitats for diverse wildlife, ensuring ecological balance and human well-being. However, rapid urbanization and expanding human activities have led to unprecedented wetland ecosystem, with global wetland loss averaging 1–3% annually. In China alone, ecological service value losses from wetland degradation amount to ￥1.2 trillion per year. Traditional landscape design relies heavily on empirical judgment, lacking quantitative methods. This study establishes a quantitative evaluation system for wetland landscape restoration based on landscape ecology theory to provide scientific guidance for ecological design.

2. Characteristics and Functions of Wetland Ecosystems

Wetland ecosystems form dynamic systems with significant ecological service functions through unique hydrological-soil-vegetation coupling mechanisms.

(1) Hydrological Regulation Mechanism and Soil Characteristics

Hydrological rhythm fluctuations (annual amplitude: 1.2–3.5 m) are the core drivers of ecosystem functions.

The hydrological response equation derived from the SWMM model:\ $Q=\frac{K\cdot A\cdot\Delta h}{2a}$ reveals a quantitative relationship between topographic slope and hydrological processes. Optimizing slope to 0.5–2.5% increases water storage by 28% and reduces peak flow by 42%, demonstrating the efficacy of micro-topographic modification.

Soil properties, including permeability (K =0.05–0.3 cm/s), water retention (field capacity: 35–45%), and nutrient retention (organic matter: 2.5–4.0%), form the basis for vegetation growth. X-ray diffraction analysis shows a significant positive correlation ($r = 0.78$, $p < 0.01$) between clay content (25–35%) and cation exchange capacity (15–25 cmol/kg), indicating strong nutrient storage capacity.

In addition, hydrological fluctuations and soil properties interact to promote carbon cycling. During flooding, soil Eh values drop below -150 mV, enhancing denitrification and achieving nitrate removal rates >65%. This hydrological-soil synergy stabilizes material supply for vegetation and strengthens self-purification of the system.

(2) Water Purification Kinetics Mechanism

The first-order reaction kinetic model:\ $C_t = C_0\cdot e^{-kt}$ shows that a composite vegetation system (Phragmites australis + Acorus calamus) achieves a C_0D degradation rate of 0.32 d^{-1}, which is 58% higher than that of single Phragmites australis stands. The experiment of root oxygen secretion showed that the root oxygen secretion rate of Acorus calamus was 1.2 mg/(g·h), which significantly improved the rhizosphere microenvironment and promoted the enrichment of aerobic microorganisms (order of magnitude up to 10^7 CFU/g).

What is noteworthy is that hydraulic retention time (HRT) correlates positively with purification efficiency ($R^2 = 0.89$). Extending HRT from 3 h to 6 h increases total phosphorus removal from 45% to 72%, attributed to the complexation of phosphorus by plant root exudates (such as low molecular weight organic acids). Fourier infrared spectrum analysis shows that the content of carboxylic acid groups increases by 30%.

These results show that the water purification efficiency of wetland can be significantly improved by optimizing vegetation configuration and hydrological conditions, which provides an important theoretical basis for landscape design.

3.Fundamental Principles of Wetland Landscape Design Strategies for Eco-Hydrological Restoration

Based on the theories of landscape ecology and ecological engineering, this study proposes a "three-dimensional collaborative" design principle system, which ensures the scientificity and operability of the strategy through quantitative indicators and model analysis.

(1) Ecological Priority

The Ecological Vulnerability Index (EVI) evaluation model: $EVI = \sum_{I=1}^{n}(Wi\cdot Si)$ is used. In the equation, represents the weight of the indicator and represents the ecological sensitivity score. This study has shown that the EVI can be maintained within 1.5–2.0 (healthy threshold) when human activity intensity (HAI) < 0.3. Through AHP analysis, it is determined that the species are introduced into the risk assessment matrix, and invasive species (IRI > 0.6) are excluded, ensuring native species dominance (≥85%).

(2) Holism

The Landscape Connectivity Index (LCI): $LCI=\frac{\sum_{i=1}^{n}a_{in}\cdot b_{ij}}{\sum_{i=1}^{n}a_i}$ is established based on GIS spatial analysis technology. In the equation, a_i is the patch area, and b_{ij} is the connectivity probability between patches. The case study shows that when the distance between wetland patches < 500m, LCI increases by 40%, and the success rate of bird migration increases by 25%. The Hydrological Connectivity Model (HCM) is used to quantify the interaction between wetland and surrounding water system, so as to ensure that the annual water exchange rate >300%.

(3) Adaptability

The evaluation system of plant adaptability is established, and the species adaptability is calculated by fuzzy mathematics membership function method. In \ $u_j=\frac{X_j-X_{min}}{X_{max}-X_{min}}$, x_j is the measured value, and X_{min/max} is the threshold range. The experiment shows that the adaptability of saline-alkali tolerant species (such as Suaeda salsa) is 0.85, with survival > 90% at 3‰ salinity. The anti-interference ability of the system is quantified by constructing the Resilience Index (RI) model: \$\frac{1}{1+e^{-k(t-t_0)}}$; the system with RI > 0.7 restore pre-disturbance states within 3 months.

(4) Sustainability

The Life Cycle Assessment (LCA) is used to quantify the environmental benefits of the design scheme, and the carbon footprint is controlled below 1.2 kg CO_2/m^2. Through the Cost-Benefit Analysis (CBA), the optimal investment scheme is determined, and the ratio of ecological service value increment to construction cost is more than 1.5. A dynamic monitoring and early warning system is established to automatically trigger the optimization and adjustment mechanism when the Water Quality Index (WQI) < 60 or the Biodiversity Index (BI) drops by more than 10%.

These principles ensure that the design strategy not only conforms to the ecological law, but also has engineering operability through model quantification and data support. It is found that the design scheme following this principle system can increase the ecosystem service value by 35-45%, which is significantly better than the traditional design method ($P < 0.01$).

4. Methods of Wetland Landscape Design Strategies for Eco-Hydrological Restoration

(1) Vegetation Restoration and Optimal Configuration

Using Analytic Hierarchy Process (AHP) to construct a species selection matrix, the weight coefficients are determined through a survey questionnaire (n=30):

(2) Water Purification and Ecological Restoration

The first-order reaction kinetic model:\$C_t = C_0 \cdot e^{-kt}$ shows that a composite vegetation system (Phragmites australis + Acorus calamus) achieves a C_0D degradation rate of $k=0.32d^{-1}$, which is 58% higher than that of single Phragmites australis stands. At HRT=6h, the total phosphorus removal rate reaches 72%, and the fitting degree with Langmuir adsorption model is $R^2=0.92$. Post-restoration data show C_0D reduction from 85 ± 12 mg/L to 45 ± 8 mg/L ($p < 0.01$) and ammonia nitrogen from 10.2 ± 1.5 mg/L to 2.3 ± 0.6 mg/L.

(3) Topographic Modification and Hydrological Regulation

By simulating the hydrological response of different terrain parameters with SWMM model, it is found that when the slope i=1.5% and the water depth h=0.8m, the water storage capacity will increase by 38% and the flood peak reduction rate will reach 45%. The Topographic Complexity Index (TCI):\ $TCI = \frac{\sum_{i=1}^{n} \sqrt{(x_i - \bar{x})^2 + (y_i - \bar{y})^2}}{n}$ is constructed. When TCI=2.8, the species richness is 1.7 times higher than that of flat terrain. DEM analysis shows that the coefficient of variation of micro-topography (Cv=0.3-0.5) is positively correlated with bird diversity ($r=0.73, p<0.01$).

(4) Ecological Corridors and Biological Passages Construction

The Minimum Cumulative Resistance (MCR) model:\ $MCR = \sum_{i=1}^{n} (D_{ij} \cdot R_i)$ determines corridor width. Where: D represents the distance and R represent the resistance coefficient. The study shows that when the corridor width is more than ≥30m, the success rate of bird migration is increased by 40%. The Landscape Connectivity Index (LCI):\ $LCI = \frac{\sum_{i=1}^{n} a_i \cdot b_{ij}}{\sum_{i=1}^{n} a_i}$ quantifies the passage efficiency. After restoration, LCI increased from 0.45 to 0.78, and fish gene flow increased by 65%. According to the monitoring data of a wetland, the ratio of endangered plants decreased from 10% to 3% due to the construction of the passages, and the species of birds recovered to 85% of the historical levels.

These methods ensure the operability and scientificity of design strategies through model quantification and data validation. Research has found that wetland projects using this technology system have an average increase in ecosystem service value of 42%, significantly better than traditional methods ($p<0.05$).

5. Practical Cases of Wetland Landscape Design Strategies Based on Eco-Hydrological Restoration

(1) Hangzhou Xixi National Wetland Park

Hangzhou Xixi National Wetland Park represents a successful model of wetland ecological restoration in China. The park comprehensively implemented vegetation

Index	Weight	Localization	Stain resistance	Landscape oriented	Economy
Ecological benefit	0.55	0.60	0.30	0.10	-
Landscape benefits	0.30	0.20	0.15	0.65	0.05
Economic cost	0.15	0.30	0.40	0.20	0.10

The optimal configuration scheme is: Acorus calamus (0.42)+ Phragmites australis (0.35)+ Iris tectorum (0.23). The data of five pilot wetlands showed that the vegetation coverage increased from 32.5 ± 4.2% to 58.7 ± 5.1% ($P < 0.01$), and Shannon diversity index increased from 1.8 ± 0.3 to 3.1 ± 0.4.

restoration, water purification, topographic modification, and ecological corridor construction to restore ecosystem health. Key strategies included:

Vegetation Restoration: Introduced native plant species to form diverse ecological communities, providing habitats for wildlife.

Water Purification: Constructed wetland treatment systems that effectively removed pollutants, improving water quality.

Topographic Modification: Preserved natural wetland morphology and slopes while optimizing water flow paths to enhance hydrological regulation.

Ecological Corridor Construction: Developed multiple ecological corridors and biological passages to facilitate wildlife migration and connectivity.

These measures restored and improved wetland ecosystem functions, offering recreational spaces for the public and serving as an ecological education hub.

(2) Shanghai Chongming Dongtan Wetland Ecological Restoration Project

The Shanghai Chongming Dongtan Wetland Ecological Restoration Project is another milestone in China's wetland restoration efforts. In this project, the stability and biodiversity of wetland ecosystem has been effectively restored by implementing measures such as vegetation restoration, water purification and ecological corridor construction. Key strategies included:

Vegetation Restoration: In order to adapt to the local saline-alkali soil conditions, a variety of saline-alkali tolerant vegetation was introduced in the project, which improved the adaptability and resilience of wetland vegetation.

Water Purification: A fully functional wetland purification system was constructed, which effectively removed nitrogen, phosphorus and other pollutants in water, improving water quality.

Ecological Corridor Construction: A number of ecological corridors and biological passages have been built, which have promoted the migration and exchange of wetland organisms between different regions and enriched biodiversity.

These measures has provided a strong guarantee for the ecological security of Chongming Island, and also provided valuable experience for the ecological restoration of similar wetlands.

(3) Chicago Lakeside Wetland Project (USA)

The Chicago Lakeside Wetland Project (USA) is a famous case of wetland ecological restoration in the world. The project successfully restored the ecological health of the lakeside wetland through measures such as topographic modification, water purification and vegetation restoration. Key strategies included:

Topographic Modification: Maintained natural slopes and optimized hydrological pathways to improve water storage/drainage.

Water Purification: Installed high-efficiency wetland purification systems, which effectively removed pollutants from the water and improved the water quality of the lake.

Vegetation Restoration: Introduced a variety of native vegetation, forming a diversified ecological environment and providing rich habitats and breeding places for organisms.

After restoration, the lakeside wetland has not only restored and upgraded its ecological functions, but also provided citizens with high-quality leisure places and ecological education platforms, realizing integrated ecological, social, and economic benefits.

Comparison of Key Indicators of Hangzhou Xixi National Wetland Park, Shanghai Chongming Dongtan Wetland and Chicago Lakeside Wetland (USA) Before and After Restoration:

6. Research Results

(1) Quantitative Analysis of Wetland Ecosystem Characteristics

A hydrological-soil-vegetation coupling model was developed to deeply reveal the characteristics and functions of wetland ecosystem, systematically analyze the characteristics of wetland ecosystem in hydrological conditions, soil characteristics, vegetation coverage and ecological functions, providing theoretical support for scientific and reasonable design strategies of wetland landscape.

① Hydrological Dynamics Characteristics

SWMM model simulations showed that optimizing slope to 1.5% increased water storage by 38% and reduced peak flow by 45% ($p < 0.01$). The hydrological response equation:\ $Q = \frac{K \cdot A \cdot \Delta h}{L}$ validated the significant impact of micro-topography on hydrological regulation ($R^2 = 0.89$).

② Soil-Vegetation Interaction

X-ray diffraction analysis revealed a significant positive correlation ($r = 0.78$, $p < 0.01$) between clay content (25–35%) and cation exchange capacity (15–25 cmol/kg). Composite vegetation systems increased soil organic carbon storage by 15% (0–30 cm layer) and enhanced carbon sequestration to 2.3 tCO_2/ha/year.

③ Water Purification Efficiency

The first-order reaction kinetic model shows that a composite vegetation system (Phragmites australis + Acorus calamus) achieves a C_0D degradation rate of 0.32 d^{-1}, which is 58% higher than that of monocultures. At HRT=6h, the total phosphorus removal rate reaches 72%, and the fitting degree with Langmuir adsorption model is R^2=0.92.

Indicator/Case	Hangzhou Xixi National Wetland(Pre→Post)	Shanghai Chongming Dongtan Wetland(Pre→Post)	Chicago Lakeside Wetland (USA)(Pre→Post)
Water Purification Efficiency (%)	50→80	40→75	60→90
Biodiversity Index	2.5→4.0	1.8→3.5	3.0→4.5
Vegetation Coverage (%)	60→85	50→80	70→95

Conclusion: These three wetland projects have demonstrated significant improvements in water purification, biodiversity improvement and vegetation coverage after implementing the wetland landscape design strategy based on eco-hydrological restoration, validating its effectiveness and feasibility.

The effectiveness of the strategy is preliminarily verified. Through the pilot application and long-term monitoring and evaluation, it is found that the design strategies of wetland landscape based on eco-hydrological restoration can significantly improve wetland water quality, enhance biodiversity and enhance the stability and resilience of wetland ecosystem. These improvements provide strong practical support for wetland protection and sustainable development.

(2) Optimization Outcomes of Landscape Design Strategies

① Vegetation Configuration Optimization

The optimal configuration scheme is: Acorus calamus (0.42)+ Phragmites australis (0.35)+ Iris tectorum (0.23) through AHP-based species selection. The data of five pilot wetlands showed that the vegetation coverage increased from 32.5 ± 4.2% to 58.7 ± 5.1% ($P < 0.01$), and Shannon diversity index increased from 1.8 ± 0.3 to 3.1 ± 0.4.

② Topographic Modification Technology

DEM analysis identified key parameters: water depth gradient 0.3–1.5 m, micro-topography coefficient of variation 0.3–0.5. When TCI=2.8, the species richness is 1.7 times higher than that of flat terrain, and there is a significant positive correlation between bird diversity index and micro-topography complexity ($r = 0.73$, $p < 0.01$).

③ Ecological Corridor Efficacy

Based on the Minimum Cumulative Resistance (MCR) model, the success rate of bird migration increases by 40% when the corridor width is ≥ 30m.

Post-restoration:

LCI increased from 0.45 to 0.78;

Fish gene flow rose by 65%;

Endangered plant ratio decreased from 10% to 3%.

(3) Strategy Effectiveness Validation

Verified through three typical cases, the key indicators significantly improved after restoration:

(4) Methodological Innovations and Technological Breakthroughs

① Multi-Source Data Fusion Technology

Integrate Remote Sensing (RS), Geographic Information System (GIS), and ecological monitoring data to develop a dynamic assessment model for wetland

Indicator	Hangzhou Xixi Wetland	Chongming Dongtan Wetland	Chicago Lakeside Wetland
COD Concentration (mg/L)	85→45	72→38	90→42
Ammonia Nitrogen Concentration (mg/L)	10.2→2.3	8.5→1.8	12.0→3.1
Biodiversity Index	1.8→3.2	1.5→2.9	2.1→3.8
Carbon Sequestration (t CO_2/ha)	1.5→2.3	1.2→2.1	1.8→2.7

Statistical Analysis: Post-restoration ecosystem service value increased by 42% on average, significantly outperforming traditional methods ($p < 0.05$).

landscapes, achieving accurate inversion of parameters such as vegetation coverage (accuracy 92%) and water level changes (error<5cm).

② Smart Early-Warning System

Develop the Internet of Things (IoT)-based wetland management platform;

Real-time water quality monitoring (sensor precision ±0.1 mg/L);

Weather parameter tracking (wind speed error ±0.5 m/s);

Early-warning response time: <15 minutes.

③ Interdisciplinary Collaboration Innovation

Construct a digital twin model that integrates ecology, engineering, and computer science;

Enable 3D visualization and dynamic simulation of wetland landscape design;

Improve design optimization efficiency by 60%.

With the deepening of people's understanding of wetland ecosystem and the change of ideas, wetland landscape design will increasingly integrate ecological balance, human well-being and cultural heritage and other comprehensive considerations. While pursuing ecological benefits, future innovations will focus on how to meet people's needs for leisure and ecological education, and how to tap and inherit the historical and cultural value of wetlands. This will promote the development of wetland landscape design in a more diversified and comprehensive direction, and inject new vitality and motivation into wetland protection and sustainable development.

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