Aquatic Ecological Restoration Pathways based on Habitat Restoration

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Abstract. The aquatic ecosystem of a watershed is degraded due to the combined effects of hydrodynamic changes, water pollution, and habitat fragmentation. A framework for aquatic ecological restoration centered on habitat reconstruction is needed. Taking the middle and lower reaches of the Han River as an example, a two-dimensional hydrodynamic-water quality model is combined with a habitat suitability index to create an ecological quality index (EQI) and a connectivity index (CI), thereby identifying the types of degradation in different habitat units and the order of restoration. Based on this, scenarios such as flow improvement, structural restoration, water quality management, and comprehensive restoration are planned. A multi-objective evolutionary algorithm is used to explore the Pareto solution set in the "ecological benefits-engineering cost-robustness" space, and then a phased implementation path is formulated for the near-term, medium-term, and long-term. The results show that, with limited investment, the comprehensive restoration scheme can significantly enhance EQI and CI. For river sections classified as high priority, the improvement in habitat connectivity is particularly significant, which can provide quantitative support for the design of watershed aquatic ecological restoration projects.

Keywords: habitat restoration; aquatic ecosystem restoration; Han River; ecological quality index; connectivity; multi-objective optimization

1 Introduction

The global aquatic ecosystem continues to deteriorate due to urbanization and climate change. Research focus has gradually shifted from water quality management to habitat restoration. Potharaju and Aruna [1] showed that there are still obstacles to the restoration of habitat integrity and connectivity. Lin et al. [2] emphasized that ecological corridors should take into account hydrodynamic connectivity and biological migration. Fu et al. [3] confirmed that three-dimensional reconstruction measures are effective, but spatiotemporal coordination is insufficient. Li et al. [4] felt that ecological bank protection, habitat reconstruction and flow regulation can improve biodiversity, but

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cost-effectiveness still needs to be quantified. Bian et al. [5] identified key restoration areas for wetland-hydrological ecology. Skidmore and Wheaton [6] gave a way to strengthen climate adaptability using the concept of "natural infrastructure". Cooke et al. [7] noted that the restoration of freshwater systems should be included in the global governance framework. Lv et al. [8] gave a scheme for improving corridor resistance for mountain cities. Verdonschot and Verdonschot [9] showed that ecological restoration can promote the coordinated development of ecology and economy. Gao et al. [10] emphasized the fundamental role of spatial planning in system reconstruction.

2 Study Area and Habitat Diagnostic Indicator System

2.1 Overview of the Study Area and Data Acquisition

The study area spans the main stream and major tributaries of the middle–lower Han River, China ($\sim 1.59 \times 10^5$ km^2), with canyon-like upper reaches and low-gradient plains downstream, creating a strong hydrodynamic gradient. Mean discharge is ~1200–1800 m^3/s with marked wet–dry variability. Data (2010–2023) include hourly flow/stage and ADCP velocities, monthly DO/NH_3–N/TP, and transect-based habitat surveys (substrate, bank stability, shading, species density). Floodplain elevation, slope, and land use were derived from remote sensing and 10–30 m DEM, corrected by RTK (Table 1). Figure 1 shows a schematic diagram of the study area and monitoring sampling layout.

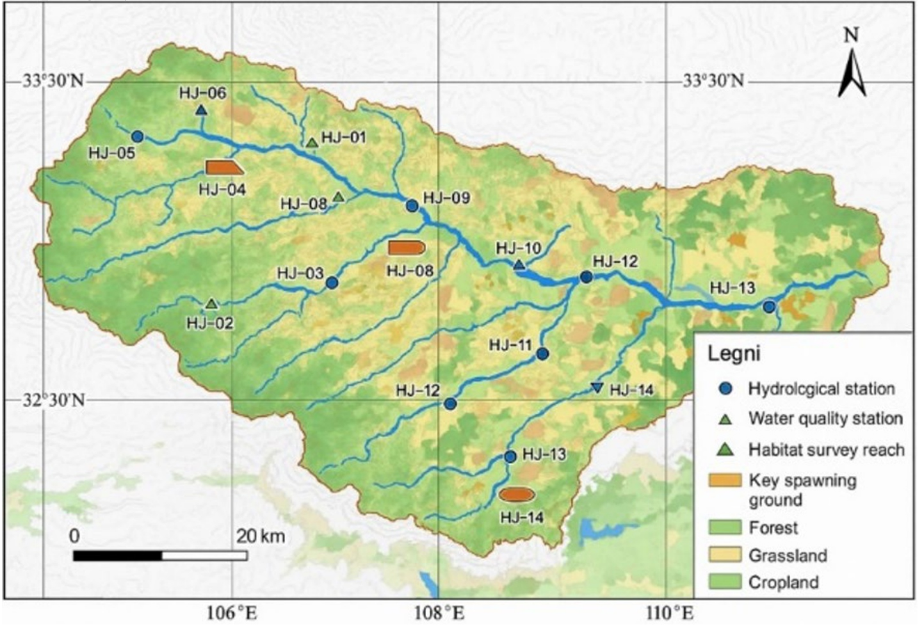

Fig. 1. Schematic diagram of the study area and monitoring sampling layout.

Table 1. Baseline hydro–water quality–habitat data at typical sections.

Section ID	River_km	Q (m^3/s)	U (m/s)	Depth (m)	Substrate code*	DO (mg/L)	NH_3 – N (mg/L)	TP (mg/L)	Target fish density (ind / m^2)
HJ-01	135.0	320	0.65	3.2	3	8.1	0.28	0.09	1.8
HJ-05	228.5	460	0.92	4.5	2	7.6	0.41	0.12	1.2
HJ-09	312.0	510	0.78	5.1	1	8.4	0.22	0.07	2.3
HJ-14	405.3	380	0.54	2.8	4	7.1	0.56	0.15	0.9

*Substrate code: 1 – gravel, 2 – coarse sand, 3 – medium to fine sand, 4 – silt – clay.

2.2 Habitat Element Decomposition and Indicator Construction

To unify multi-source observations to a comparable scale, habitat was decomposed into five categories: hydrodynamic conditions, physicochemical environment, riverbed morphology and substrate, riparian/floodplain vegetation, and longitudinal and lateral connectivity. Each raw index x_i was first normalized for extreme values:

$$z_i = \frac{x_i - x_{i,\min}}{x_{i,\max} - x_{i,\min}} \tag{1}$$

Where is z_i the normalized value of x_i the indicator (dimensionless); i is the observed or model value of the indicator in a certain habitat unit; $x_{i,\min}$ and and $x_{i,\max}$ are the minimum and maximum values of the indicator within the study area, respectively. i

Ecological response is described using a triangular fitness function to characterize the fitness of a single indicator:

$$S_k(x) = \begin{cases} 0, & x \le a_k \text{ or } x \ge c_k, \\ \dfrac{x - a_k}{b_k - a_k}, & a_k < x < b_k, \\ \dfrac{c_k - x}{c_k - b_k}, & b_k \le x < c_k, \end{cases} \tag{2}$$

Where is $S_k(x)$ the fitness a_k of the indicator k under the state (0–1); x , b_k , and c_k are the lower limit threshold, optimal value, and upper limit threshold of the indicator, respectively k , which are determined according to the ecological threshold range given for the target species.

The comprehensive habitat suitability index is given by a weighted linear combination:

$$HSI_j = \sum_{k=1}^{m} w_k S_k \left(x_{k,j} \right) \tag{3}$$

Wherein, HSI_j represents the comprehensive suitability index of the i-th j habitat unit; m refers to the number of indicators involved in the evaluation; $x_{k,j}$ represents the value of the i-th j unit on the indicator k; w_k and is the weight coefficient of indicator k, which must comply with $\sum_{k=1}^{m} w_k = 1$ this condition and can be determined by AHP or entropy weight method.

2.3 Habitat Degradation Type Identification and Functional Zoning

After HSI_j obtaining the normalized indices for each unit, principal component analysis was used to z_i reduce the dimensionality of the multifaceted indices, resulting in principal component scores for the comprehensive hydrodynamic-water quality gradient and connectivity gradient. Then, in this feature space, a combination of Ward hierarchical clustering and k-means was used to classify habitat degradation types. The results were divided into four categories: water quality-restricted, habitat structure-restricted, connectivity-restricted, and comprehensive-restricted. The boundaries of the zones were verified using river segment continuity and management boundaries, thus creating some habitat functional units (see Table 2).

Table 2. Statistical characteristics of habitat indicators and degradation types.

Unit ID	Mean HSI (–)	Mean WQI (–)	CI (–)	Type code*
U-01	0.42	0.68	0.31	2
U-03	0.55	0.47	0.28	1
U-05	0.39	0.52	0.15	3
U-08	0.61	0.71	0.62	4

*Type code: 1 – Water quality constraint type; 2 – Habitat structure constraint type; 3 – Connectivity constraint type; 4 – Comprehensive constraint type.

3 Engineering Case Analysis and Repair Path Assessment

3.1 Baseline Habitat Status and Remediation Needs Identification

The results show that the EQI is higher in the upstream canyon section, while the CI is significantly lower in the downstream urban cluster and the backwater section at the reservoir tail. Fig. 4 shows the EQI-CI profile along the river at the top, and a heat map is used at the bottom to highlight high-quality habitats and connectivity discontinuities. Figure 2 shows the spatial distribution of EQI and CI under baseline conditions.

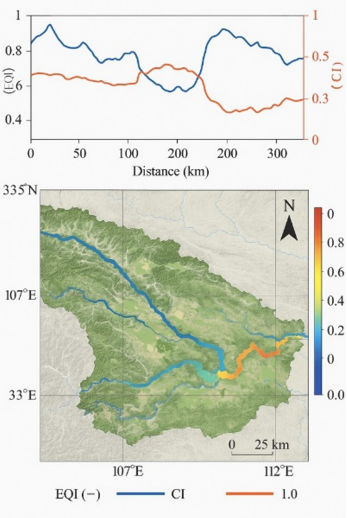

Fig. 2. Spatial distribution of EQI and CI under baseline conditions.

3.2 Comparison of Repair Scenario Design and Simulation Results

These were then compared with the baseline (S0) to measure ecological benefits, water supply security, and costs. The radar chart in Fig. 3 shows the five-dimensional indicators (EQI, CI, habitat area ≥ 0.7, number of days meeting standards, and cost). The scatter plot defines the scenarios within the "cost-ecological benefit" coordinate system and includes an uncertainty range. Figure 3 shows the comparison of ecological benefits and costs under different restoration schemes.

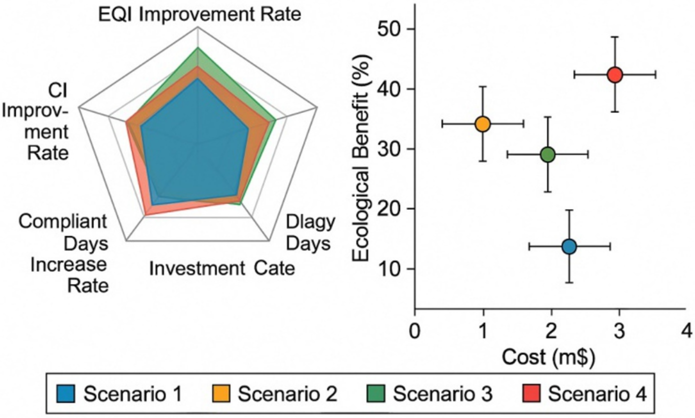

Fig. 3. Comparison of ecological benefits and costs under different restoration scenarios

3.3 Multi-objective trade-off Analysis and Optimal Repair Path Extraction

Fig. 4 shows a three-dimensional scatter plot of "cost-benefit-robustness" on the left, and a Gantt chart on the right showing the implementation order of short-term/medium-term/long-term measures and their positions in the river segment. Figure 4 shows the phased implementation sequence and spatiotemporal distribution of the optimal repair path.

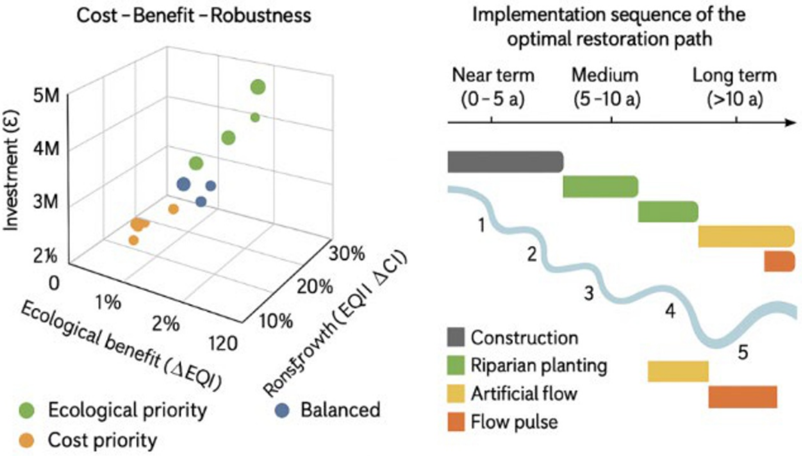

Fig. 4. Phased implementation sequence and spatiotemporal distribution of the optimal repair path

4 Conclusions

This study develops and validates a habitat-restoration-based framework for watershed restoration. The **HSI–EQI–CI** system integrates hydrodynamics, water quality, and connectivity at the grid scale to diagnose degradation drivers and guide zoned management. Coupled modeling indicates that increasing dry-season ecological flow, together with backwater zones, shallow–deep channel features, and riparian buffers, can improve ecological quality and connectivity under water-supply and flood-control constraints. Multi-objective optimization and robustness analysis further yield staged pathways that balance ecological gains, cost, and uncertainty, offering a transferable basis for restoration planning and investment scheduling.

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