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Identification and Graded Optimization of the Ecological Security Pattern in Zhengzhou, China

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Research Article

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Posted Date: November 25th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11734631/v1

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Additional Declarations: No competing interests reported.

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Declarations

Funding: This research received no external funding.

Abstract

The planning value of ecological security patterns lies in explaining the connections between ecological spaces and, based on this, prioritizing conservation and restoration efforts. Using Zhengzhou as a case study, this study combines morphological spatial pattern analysis, integrated resistance modeling, least-cost paths, and circuit theory to identify potential ecological corridors and local ecological pinchpoints. By integrating road networks and urban environments, the study conducts risk grading and further discusses its implications for landscape design and management. Results show that 48 ecological source areas form a city-wide network through 110 potential corridors. The western and southwestern regions are characterized by larger source areas and adjacent short connections; linear source areas in the north connect to the interior of the city in multiple directions; and some corridors in the middle and the east span larger gaps between source areas; The 64 candidate pinchpoints formed 10, 10, and 32 high-, medium-, and low-risk connected corridors, respectively, a further 58 corridors were not assigned a pinchpoint-based risk level. Although source areas in the western region are relatively large, connections with scattered source areas on the periphery still need to be strengthened. Connections in urban areas and at road intersections face more pronounced external disturbance. Based on these findings, the study proposes management approaches for core protection, isolated-patch connection, and linear connection, as well as conservation, restoration, and low-intervention measures commensurate with corridor risk levels. Existing planning and conservation practices at Beilong Lake are used to discuss coordination among the lake, riparian zones, roads, and public activities. Ecological security patterns thus link citywide conservation priorities to site design, enabling green space development, road renewal, and waterfront management to be organized around a shared ecological framework.

Keywords: ecological security pattern; landscape connectivity; circuit theory; corridor grading; ecological restoration; Zhengzhou

1 Introduction

The concept of ecological security patterns developed from landscape ecology's understanding of the relationship between spatial patterns and ecology. Kongjian Yu, founding dean of the College of Architecture and Landscape Architecture at Peking University, introduced landscape security patterns into planning analysis to safeguard key ecological processes, emphasizing the identification of locations important to these processes [1]. Subsequent, related research developed an approach based on spatial networks of ecological source areas and their connecting corridors, bringing patch conservation, landscape connectivity, and ecological restoration into a common spatial framework [2].

Recent research has placed greater emphasis on ecological thresholds, the coupling of patterns and processes, and the evaluation of conservation effectiveness, establishing ecological security patterns as an important strategy for reconciling ecosystem integrity with territorial spatial use [3].

Research on the relationship between ecological security patterns and urban environments has focused on three main aspects: maintaining ecological conditions, spatial connectivity, and multifunctionality [4].

Habitat maintenance concerns the retention and stability of ecological patches during urban expansion and emphasizes that source areas cannot be valued solely by their area at a single point in time or by ecological quality [5]. Spatial connectivity focuses links between isolated green spaces, rivers, lakes, wetlands, and natural areas on the urban periphery. A study in Wuhan incorporated urban–rural connectivity into pattern optimization [6], while a study in Haidian improved network connectivity through wetland stepping stones and supplementary corridors [7]. Research on

multifunctionality further explores the relationship between ecological conservation and public use. Studies have incorporated ecological and recreational functions into the ecological security pattern of Fuzhou and into the assessment of urban ecological spaces [8, 9]. Together, these research directions indicate that urban ecological conservation now extends beyond individual natural patches to holistic spatial networks by diverse functions and varying degrees of connectivity. Accordingly, research methods have evolved into a technical framework comprising source area identification, resistance surface construction, corridor extraction, and key node identification. Source areas can be identified through comprehensive evaluations based on ecosystem services, habitat quality, and ecological sensitivity [10, 11], or by employing morphological spatial pattern analysis (MSPA) to identify structural types such as core, edge, and bridge [12]; A study of Beijing's central urban area further combined MSPA, habitat quality, and connectivity to select source areas, thereby balancing form and function [13]. Resistance surfaces typically integrate land cover, topography, and human disturbance, with factor weightings tailored to the analysis subject and scale [14]. The Minimum Cumulative Resistance (MCR) model compares the distance-weighted costs of alternative paths to identify potential connections between source areas [15]. Circuit theory simulates current flow along multiple pathways through a landscape, helping identify local concentrations of flow [16]. Studies in the Changchun-Jilin-Tumen region and the Shanxi section of the Yellow River basin combined remotely sensed ecological quality with circuit analysis, extending the ways in which ecological assessment can inform the identification of connections [17, 18].

Research conclusions and planning outcomes can be broadly categorized into three categories: pattern diagnosis, conservation prioritization, and restoration optimization. Pattern diagnosis highlights spatial differences between source areas and corridors and identifies the impacts of land use and human activities through multi-temporal comparisons [19]. Conservation prioritization has expanded from the importance of individual factors to the overall effects of the network. Studies in Nanjing used scenarios of disturbance to nodes and corridors to identify strategic ecological spaces and changes in resilience [20, 21], while research in highly urbanized areas highlighted the conservation value of stepping stones with high centrality [22]. Comparisons of source area stability and network connectivity have revealed trade-offs between conservation objectives [23]. Restoration optimization includes barrier mitigation and stepping-stone supplementation [24], differentiated management based on landscape multifunctionality [25], and graded restoration measures that consider source areas, corridors, key nodes, and land use [26, 27]. Furthermore, multi-scenario evaluations have begun to assess the conservation effectiveness of landscape pattern designs [28], while multi-scale landscape network studies focus on inter-regional connections and local spatial synergy [29], facilitating the translation of research findings into concrete design actions.

Existing research provides a methodological foundation for constructing ecological security patterns. However, in specific urban applications, it remains necessary to clarify the correspondence between potential regional connections, locally constrained locations, and government management measures. Network models have limitations in representing connections, and species-oriented studies require validation against specific habitat requirements [30]. Topographic differences and source area selection may also change the relative importance of plains and mountainous areas [31].

Studies have already been conducted in the Zhengzhou metropolitan area using MSPA, MCR, and network structure analysis to identify ecological connections and node organization characteristics along the Yellow River [32]. Regional network identification nevertheless needs to be linked to conservation, connectivity, and use at individual sites. Zhengzhou includes mountainous areas, rivers, farmland, and urban transportation networks. It is therefore necessary

both to identify ecological connections and to determine which connections warrant priority protection and which locations are suitable for local verification. This study focuses on Zhengzhou's administrative area and follows a sequence of source area identification, resistance surface construction, and corridor extraction to identify potential ecological corridors and local pinchpoints. It examines graded management in relation to roads and urban spaces. The study analyzes the spatial organization of ecological areas at three levels—source areas, corridors, and the overall pattern—and proposes approaches to source area protection by type and corridor intervention by risk level. Beilong Lake is used to examine how citywide identification results can inform local spatial design, providing suggestions for ecological conservation across Zhengzhou and directions for further research.

2 Data and Methods

2.1 Study Area

The study covers the administrative area of Zhengzhou; its location and administrative divisions are shown in Figure 1. Zhengzhou, the capital of Henan Province, comprises six districts, five county-level cities, and one county, with a total area of approximately 7,567 km² [33] [34]. At the end of 2025, its permanent resident population was 13.138 million, and its urbanization rate was 81.52%. The ratio of the primary, secondary, and tertiary sectors was 1.2:36.6:62.2, with services and industry providing the main economic support [35]. Zhengzhou lies in the transition between mountainous terrain and plains. Mountains in the west and southwest, the Yellow River's banks in the north, and rivers throughout the municipality provide an important foundation for its ecological spaces. Agricultural production, urban development, and transportation infrastructure on the central and eastern plains jointly influence connectivity between patches.

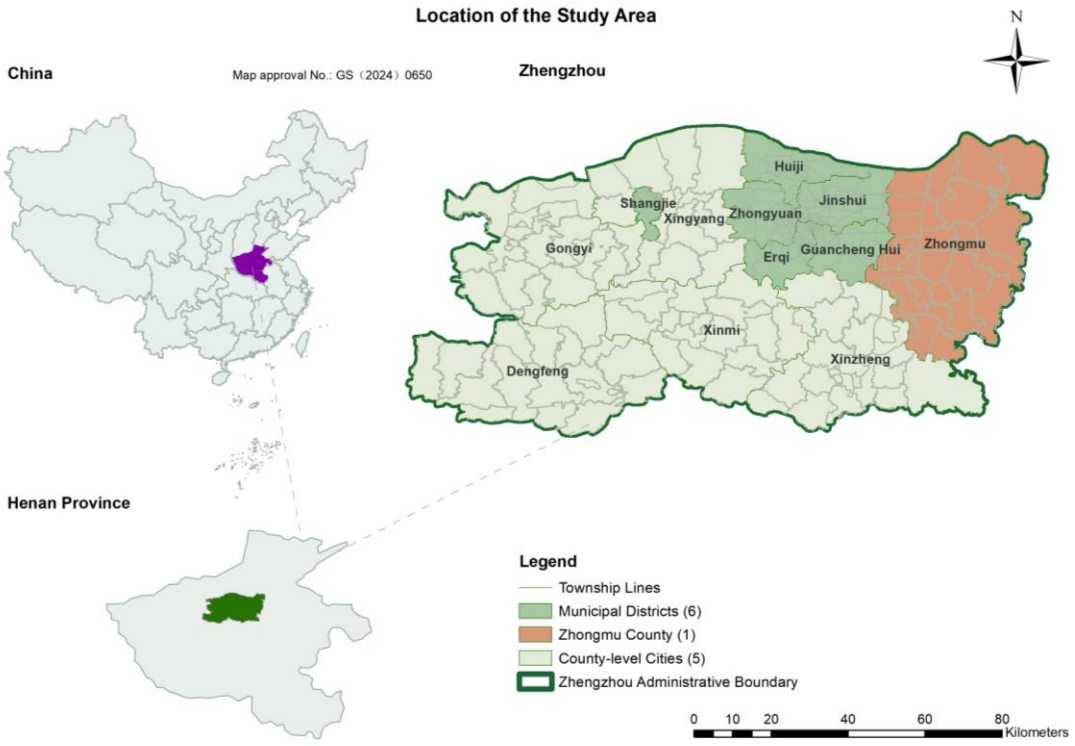


Figure 1. Location and administrative divisions of the study area.

The State Council's approval of the *Zhengzhou Territorial Space Master Plan (2021–2035)* calls for strengthening the Songshan ecological barrier, advancing the protection of the Yellow River's southern bank ecosystem, and enhancing spatial management of river and lake areas such as the Suoxu River and Jialu River [36]. The plan requires at least 547.02 km² within the ecological

conservation redline and limits the area within the urban development boundary to 2,074.69 km² by 2035. The municipality contains both relatively continuous habitats and scattered small ecological spaces, with connections influenced by patch distribution, topography, and development. Urban and agricultural land is interspersed among these spaces, forming the landscape through which ecological processes operate. This study addresses the local challenge of coordinating the protection of larger patches with connections to scattered peripheral spaces.

2.2 Data Sources and Processing

This study used land cover data, Digital Elevation Models (DEMs), Landsat remote sensing imagery, OpenStreetMap road data, as well as administrative boundaries and hydrological network datasets. Land cover data were obtained from the GlobeLand30 platform of the National Geomatics Center of China. The DEM was obtained from the Geospatial Data Cloud of the Computer Network Information Center, Chinese Academy of Sciences. Landsat imagery was provided by the U.S. Geological Survey (USGS) through EarthExplorer, and road data were provided by OpenStreetMap. Administrative boundaries and river network data were obtained from the National Geographic Information Resource Catalog Service System. Land cover data is used for MSPA classification and land cover characterization; the DEM data is used for elevation analysis and slope calculation; landsat imagery was used to derive the normalized difference vegetation index (NDVI) and characterize the spectral properties of vegetation. Major roads were selected by category for distance analysis. Administrative boundaries defined the study extent and were used to clip the data, while river network data provided the hydrological context. All spatial data were projected to WGS 1984 UTM Zone 50N. The ecological source areas, integrated resistance surface, least-cost paths, and local current results derived from these datasets provided the spatial basis for the ecological security pattern analysis. Planning and case materials were drawn from publicly available documents issued by the State Council and relevant departments in Zhengzhou and Zhengdong New District. These materials informed the study area background and the discussion of the Beilong Lake application.

2.3 Methods

2.3.1 Identification of Ecological Source Areas

Morphological spatial pattern analysis (MSPA) uses mathematical morphology to classify foreground ecological land into seven types: core, islet, edge, perforation, bridge, loop, and branch [12, 37]. Core areas consist of foreground pixels farther from the background than a specified edge width and can be represented by morphological erosion (Table 2). This expression describes only core area extraction; classification into all seven types requires the full MSPA procedure.

Land cover data were converted into a binary foreground–background image, and MSPA was used to extract morphological cores as candidate source areas. Area-based screening and vectorization yielded 48 ecological source areas, which served as nodes in the subsequent network analysis. Morphological cores represent the internal continuity of land cover. Recent studies have also combined MSPA with habitat quality or ecological indices to select source areas [13, 17]. The same source area boundaries were used in all analyses.

2.3.2 Construction of the Integrated Ecological Resistance Surface

Knaapen et al. proposed the minimum cumulative resistance model to incorporate both interpatch distance and the conditions of the intervening landscape into estimates of ecological isolation [15].

The minimum cumulative resistance (MCR) model combines movement distance with landscape resistance along the route. It compares candidate paths from a source area to a target location and determines the minimum cumulative cost (Table 2). A least-cost path (LCP), obtained

by backtracking across the resulting cost surface, locates a potential connection between source areas. In this study, LCPs were used to extract potential ecological corridors, and local current analysis was conducted within the corresponding corridor extents. Geometric path length describes spatial distance, whereas cumulative cost represents connectivity conditions arising from the combined effects of distance and resistance [14, 15].

Table 1. Ecological resistance factors, weights, classes, and assigned values

Resistance Type	Resistance Factor	Importance Coefficient	Classification	Resistance Value
Natural Conditions Impact (0.8674)	Land Use Type	0.3522	Forest Land (20)	1
			Grassland (30)	2
			Wetlands (50)	1
			Water bodies (60)	1
			Cropland (10)	3
			Artificial surfaces (80)	5
	NDVI	0.1892	[−0.398594, 0.079206]	5
			(0.079206, 0.272359]	4
			(0.272359, 0.419766]	3
			(0.419766, 0.592587]	2
			(0.592587, 0.902649]	1
	Elevation/m	0.1630	[28, 158]	1
			(158, 292]	2
			(292, 463]	3
			(463, 711]	4
			(711, 1476]	5
	Slope/(°)	0.1630	[0, 4.117571]	1
			(4.117571, 9.333160]	2
			(9.333160, 16.744788]	3
			(16.744788, 27.450472]	4
			(27.450472, 69.998703]	5
Human Activities Disturbance (0.1326)	Distance from Main Road Distance/m	0.1326	[0, 587.376428]	5
			(587.376428, 1483.898346]	4
			(1483.898346, 2658.651203]	3
			(2658.651203, 4297.122292]	2
			(4297.122292, 7883.209961]	1

Note: The importance coefficients are the four-decimal values used to calculate the integrated resistance surface and sum to 1. The values in parentheses for the natural conditions and human activities groups are the sums of the coefficients within each group and are shown only to indicate these groupings. The numbers in parentheses for land use types are GlobeLand30 codes. Values at shared boundaries between continuous-factor intervals are assigned to the preceding class. NDVI is converted so that higher vegetation cover corresponds to lower resistance. The thresholds and resistance values in the table are taken from the project's reclassification records.

Landscape resistance represents the relative cost of organism movement through different landscape environments, accounting for land cover, topography, vegetation, and proximity to

roads. Each factor is converted to resistance values and placed on a common scale, then multiplied by its corresponding weight and summed to produce a integrated ecological resistance surface. The analytic hierarchy process (AHP) is used to determine the weights, and the internal consistency of the pairwise comparison matrix is assessed using a consistency test [38]. Land cover and NDVI characterize the land surface and vegetation conditions, respectively; elevation and slope describe topographic differences; and distance to roads represents proximity to transport infrastructure. Resistance parameters should match the study scale and the subject of analysis [14]. Approaches to spatial heterogeneity in watershed studies also indicate the need to distinguish between topographic and human activity contexts [11, 18].

The weights were synthesized from the AHP weights for five common factors in four studies covering Fuzhou, the West Liaohe River Basin, Liaoning Province, and Chengmai County [8, 39, 40, 41]. The five-factor weights from each study were first normalized and then combined using an equally weighted geometric mean. The ratios of the combined weights were mapped to the Saaty scale to construct a 5 × 5 reciprocal pairwise comparison matrix, and the final weights were obtained from its principal eigenvector. The matrix had a maximum eigenvalue of 5.055431, a consistency index (CI) of 0.013858, a random index (RI) of 1.12, and a consistency ratio (CR) of 0.012373, below 0.10.

The AHP weights for the five factors are 0.352188 for land cover, 0.189213 for NDVI, 0.132650 for road proximity, 0.162974 for slope, and 0.162974 for elevation (Table 1).

2.3.3 Corridor Construction and Ecological Pinchpoint Identification

Linkage Mapper was used to extract least-cost paths between ecological source areas, and Pinchpoint Mapper was used for local current analysis. Circuit theory represents the landscape as a network of resistive elements, allowing simulated current to flow along multiple routes according to Ohm's law and current conservation (Table 2) [16]. In the local analysis, current density was calculated for adjacent pairs of source areas, with the maximum value retained for overlapping pixels to identify sections where current was relatively concentrated. Previous studies distinguish the roles of pinchpoints and barriers [42]; the features identified and classified in this study are candidate ecological pinchpoints.

Areas with high local current values were screened by area to identify candidate ecological pinchpoints. These were manually classified as high, medium, or low risk based on their spatial relationships with roads, urban areas, and ecological source areas. High risk mainly corresponds to locations where roads and urban areas intersect; medium risk mainly corresponds to areas surrounding core source areas and transition zones extending toward urban areas; and low risk mainly corresponds to linear areas on the municipal periphery. Here, risk denotes a relative planning assessment based on spatial location and external disturbance. The pinchpoints were spatially intersected with the least-cost paths. When a corridor intersected multiple pinchpoints, it was assigned the highest risk level among them; corridors with no intersections were left unclassified. Risk levels were assigned on the basis of actual spatial intersections, linking the local positions of pinchpoints to the overall connections provided by corridors.

The main methods and computational relationships are presented in Table 2. MSPA is used to identify the morphology of ecological source areas, MCR to calculate minimum cumulative costs and extract potential corridors, and circuit theory to analyze local current flow and pinchpoints. The weighted overlay of resistance factors provides the input for the MCR and circuit models.

Table 2. Main methods and computational relationships

Research Method	Purpose	Computational Relationship	Notation
MSPA (Core Extraction)	Identify morphological cores within the foreground	$Core_s = \{x \in F: d(x, F^c) > s\}$	F denotes the foreground and F^c the background; s is the edge width, d is distance, and x is a pixel. This equation expresses only the condition for core areas and does not replace the complete seven-class MSPA algorithm.
Minimum Cumulative Resistance (MCR)	Calculate minimum cumulative costs to support the extraction of potential corridors	$MCR_a(x) = \min_{P:a\to x} \sum_{\ell \in P} r_\ell d_\ell$	a is a source area, x is the target location, and P is a candidate path; $r\ell$ is the mean resistance of a path segment, and $d\ell$ is the distance traveled through it.
Circuit Theory	Simulate current flow along multiple paths and identify local ecological pinchpoints	$I_{uv} = \frac{V_u - V_v}{r_{uv}}$ $\sum_v I_{uv} = 0$	Vu and Vv are the potentials at adjacent nodes, ruv is the resistance of the connection, and Iuv is the edge current. Current is conserved at internal nodes, and current injection and withdrawal are specified for each pair of source areas.

3 Results

3.1 Ecological Source Area Identification

Morphological cores were extracted from land cover data using MSPA, and ecological source areas were selected by area. A total of 48 source areas were included in the network analysis (Figures 2 and 5). The source areas are generally dispersed, with clusters in the west and predominantly scattered linear and isolated patches in the north and south. The map shows that core areas are concentrated in the western and southwestern parts of the municipality, with a linear distribution near the northern boundary. The central and eastern interior is dominated by scattered small patches and narrow linear features. Perforations remain visible within larger core patches, whose outer edges and connecting features are relatively complex. The selected source areas retain these spatial differences: larger patches cluster in the central-western and southwestern regions, forming the main patch basis of the network; linear source areas in the north and larger patches at the northeastern end form another set of areas to be connected. Several small and medium-sized source areas remain along the southern edge and in the central part of the municipality, while source areas are relatively sparse in the southeast. This uneven distribution means that maintaining connections between adjacent western patches and establishing connections across larger gaps in the central and eastern regions involve different ecological conditions and challenges.

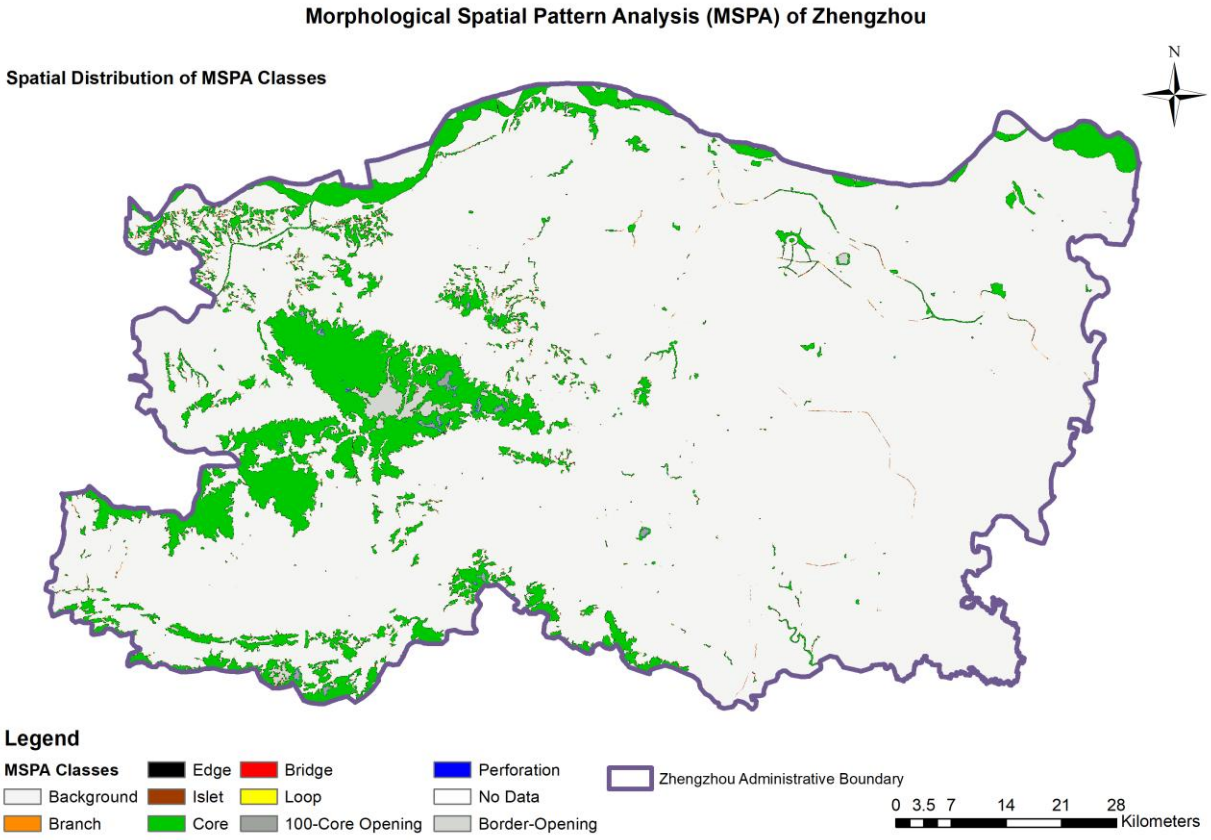


Figure 2. MSPA classification in Zhengzhou

Note: The network analysis includes 48 ecological source areas; MSPA classes represent landscape morphological structure.

3.2 Resistance Factors and the Integrated Resistance Surface

Land cover, topography, water systems, roads, and vegetation provide the environmental context for resistance analysis. Figure 3 presents the spatial distributions of the five reclassified resistance factors, with water systems included as background information for spatial interpretation. Artificial surfaces occupy higher proportions of Zhongyuan, Guancheng Hui, and Jinshui districts, and lower proportions of the county-level cities in the west and southwest. Elevation generally decreases from west to east, with higher elevations and steeper slopes concentrated in the central-western and southwestern regions and along the southern edge; the eastern terrain is relatively flat. Water bodies form a band along the northern boundary, while rivers and canals extend into the central and eastern regions and interweave with scattered water bodies. Roads are denser in the eastern part of the central region and in the southeast, and sparser in the western mountains. High NDVI values occur mainly in the central-western and southwestern regions and along the southern edge, while high and low values form a mosaic in the central and eastern regions. White areas indicate pixels with no data after cloud masking.

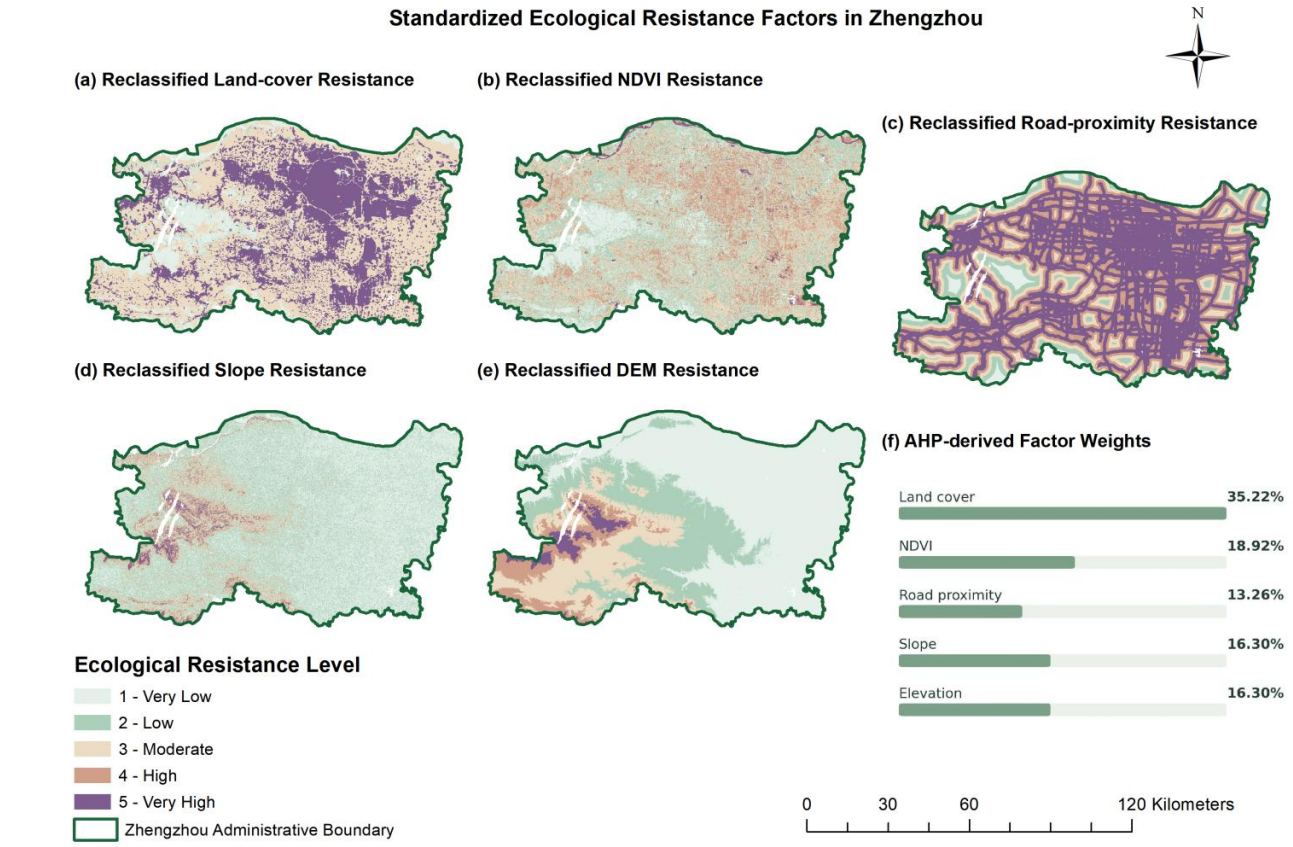
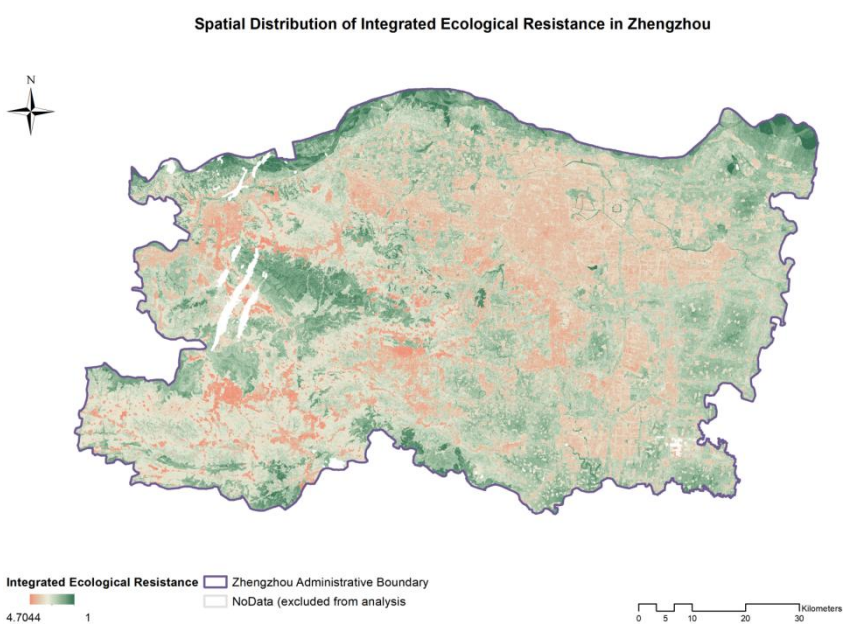


Figure 3. Spatial distributions of the ecological resistance factors in Zhengzhou



The integrated resistance surface was generated by converting the factors to resistance values and applying a weighted overlay; its spatial distribution is shown in Figure 4. The same resistance surface was used in subsequent corridor calculations to provide a consistent cost basis for identifying connections and analyzing pinchpoints. By combining the effects of the individual factors, integrated resistance provides a common spatial basis for comparing potential connections between source areas. Higher resistance is concentrated in urban areas in the central and eastern regions and in some developed areas in the west. Lower resistance is found mainly in the western and southwestern mountains and along rivers in the north. This contrast also reflects the different connectivity conditions in urban and road-dense areas and around western and peripheral source areas.

Figure 4. Integrated ecological resistance surface in Zhengzhou

3.3 Potential Corridor and Ecological Pinchpoint Identification

A total of 110 valid potential ecological corridors were identified, connecting 48 ecological source areas into an integrated network (Figure 5). The paths have a total length of 1,008.161 km and a median length of 5.570 km, with minimum and maximum lengths of 0.042 km and 67.428 km, respectively. The total length includes shared path segments. Short connections are concentrated around larger source areas in the west and southwest. Connections along northern rivers extend into the interior of the municipality, while some corridors in the central and eastern regions span larger gaps between source areas; coverage is relatively sparse in the southeast. Local current analysis and area-based screening identified 64 candidate ecological pinchpoints. These are concentrated along the northern edge and the southwestern–southern periphery, with localized clusters in the central and northeastern regions; some occur where source areas and corridors meet (Figure 6).

Manual interpretation classified 12, 12, and 40 pinchpoints as high, medium, and low risk, respectively (Figure 6). High-risk pinchpoints occur mainly along connections in the northwest, the northeastern interior, and the southern part of the central region. Medium-risk pinchpoints are more common along connections in the central-western and central regions, while low-risk pinchpoints occur mainly along the northern edge and the southwestern–southern periphery. Spatial intersection and assignment of the highest intersecting risk level classified 52 corridors, or 47.27% of all corridors: 10 as high risk, 10 as medium risk, and 32 as low risk. Another 58 remained unclassified (Figure 7). Corridors assigned high risk occur mainly in the northwest and the central and eastern regions, while those assigned low risk are more common along the northern edge and the southwestern periphery. Unclassified means only that a corridor did not intersect any candidate pinchpoint identified in this analysis.

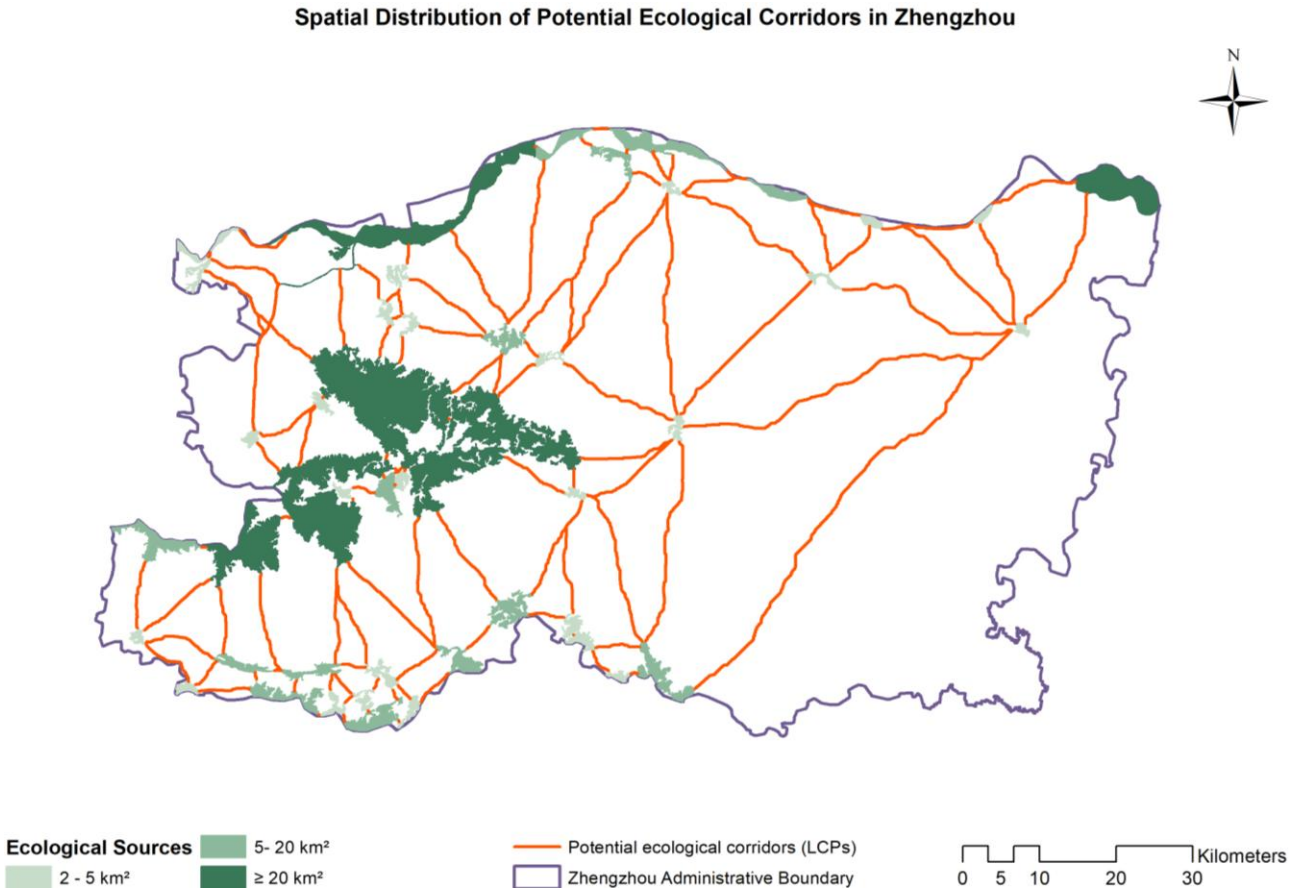


Figure 5. Spatial distribution of potential ecological corridors in Zhengzhou

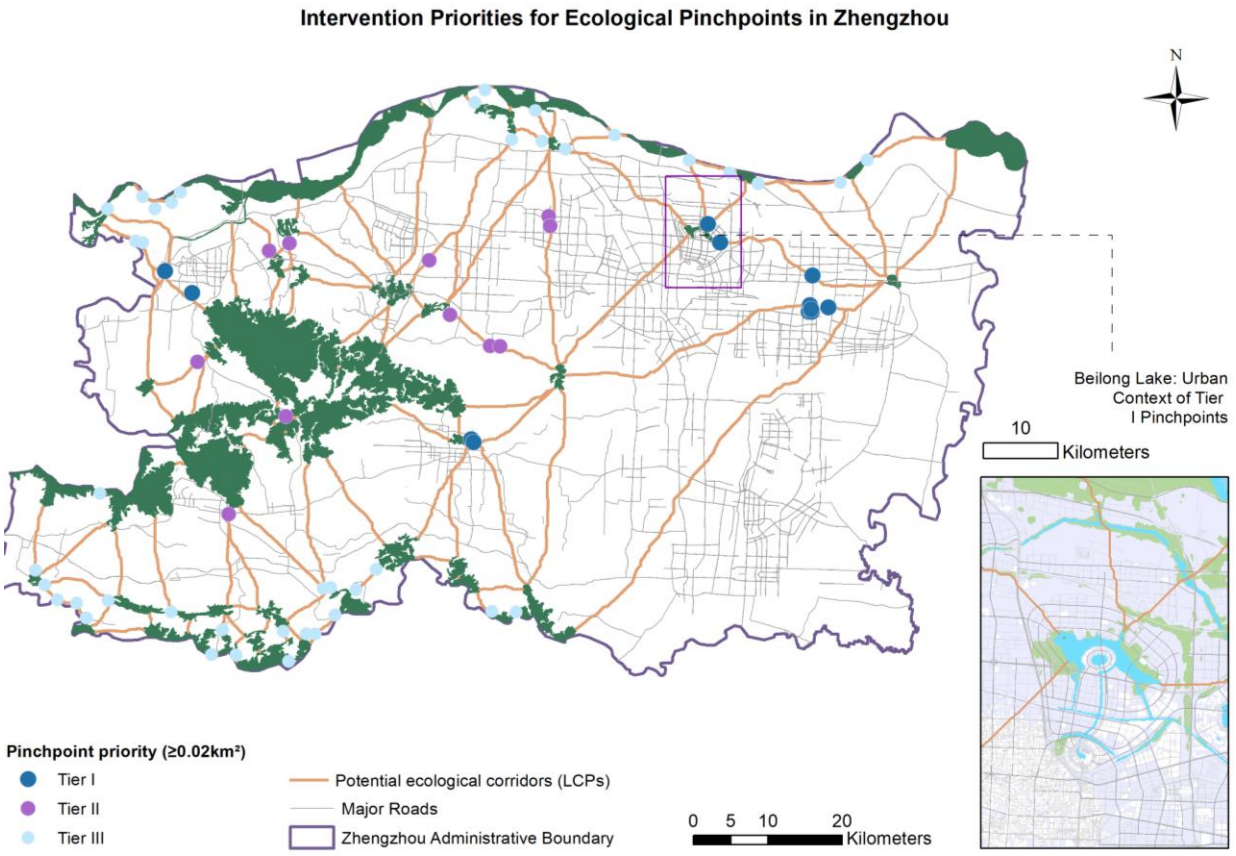


Figure 6. Risk classification of ecological pinchpoints

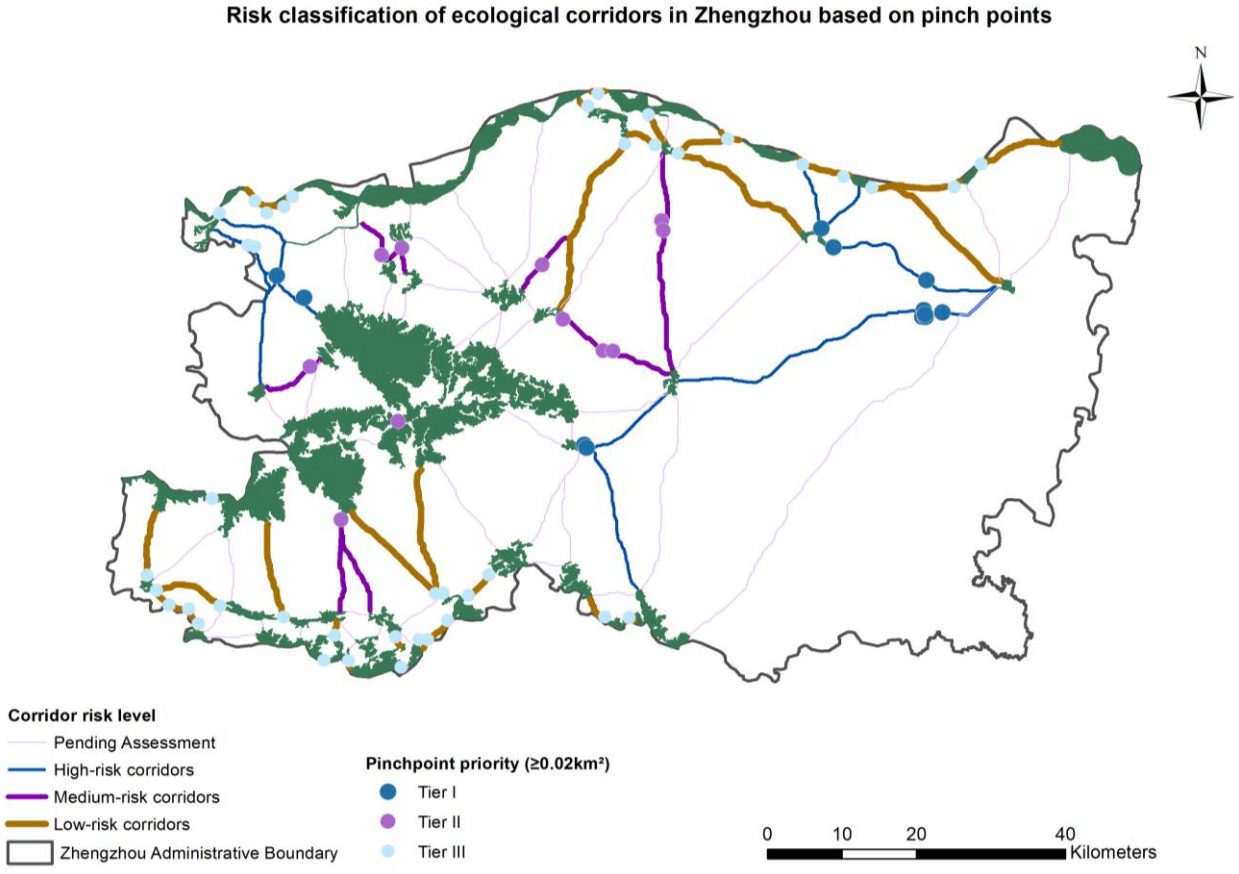


Figure 7. Pinchpoint-based risk classification of ecological corridors in Zhengzhou

Note: Each connection inherits the highest risk level among the pinchpoints it intersects. There are 10 high-risk, 10 medium-risk, 32 low-risk, and 58 unclassified corridors.

4 Discussion

4.1 From Patch Distribution to the Citywide Organization of Ecological Spaces

The most distinctive feature of Zhengzhou's ecological security pattern is a network formed by larger mountain patches, linear riparian spaces in the north, and dispersed ecological spaces in the central and eastern areas. Source areas are concentrated in the west and southwest, with many short connections between neighboring patches. Ecological spaces in the north extend along the boundary and connect to the interior of the municipality through multiple routes. In the central and eastern plains, connections span greater distances between source areas, and land use along these routes becomes more diverse. In terms of spatial organization, larger patches in the west form local clusters, whereas peripheral source areas are distributed as strips and scattered patches, with some spaces extending in north–south and east–west directions. The concentration of source area coverage alongside dispersed peripheral connections makes connectivity between larger patches and scattered source areas an issue that requires attention in pattern optimization.

High-risk corridor connections are concentrated around urban areas and at road crossings in the west. Medium-risk connections are more dispersed, while low-risk connections occur mainly along the northern and southwestern–southern periphery. The influence of roads and built-up areas varies with corridor location, so the risks associated with these connections need to be interpreted by considering pinchpoints, roads, and source area boundaries together. Differences in corridor length also imply differences in how spatially concentrated conservation tasks are. Short connections between adjacent source areas in the southwest cover a limited area but lie at the interface between two patches; their protection should consider both ends of the connection and the intervening gap. Longer corridors in the central and northeastern areas cross multiple parcels, with individual parks or local greening projects covering particular sections. For short connections, the area to be retained at the connecting interface should therefore be clearly defined. For longer corridors, it is necessary to check whether successive sections can connect and to prioritize clear gaps that affect the connection as a whole.

This relationship between source areas and corridors shows that ecological conservation concerns both area and location. Larger source areas form the basis of the network, while suitably located small and medium-sized patches may contribute to connections across several areas. Larger source areas in the west form local clusters but have relatively weak connections to scattered peripheral source areas. From a citywide spatial perspective, connections through these scattered source areas and adjacent linear spaces still need to be strengthened to reduce the isolation of larger source areas from their surroundings. In planning, Zhengzhou can retain spaces that provide connections in different directions, allowing continuous mountain areas, riparian green spaces, and small interior patches to contribute jointly to the network. Where connections cross multiple land-use units, each section has a role in maintaining continuity, and the treatment of local project boundaries should be coordinated with adjacent parcels.

4.2 Protection by Source Area Type and Restoration by Corridor Risk Level

Based on the spatial organization of source areas and corridors, this study distinguishes three types of source area management: core protection, isolated-patch connection, and linear connection. It also assigns protection and restoration measures according to the high, medium, and low risk levels of corridors (Figure 8). Different measures may therefore apply within the same risk level. Their selection depends jointly on existing habitats, land-use conditions, and conservation objectives, resulting in site-specific designs.

4.2.1 Source Area Protection by Type and Spatial Connectivity

Protection of source areas by type is based on the spatial morphology and connectivity functions of patches (Table 3). Core protection focuses on area and the integrity of internal habitats; isolated-patch connection focuses on linking dispersed peripheral patches; and linear connection focuses on riparian continuity and connections toward the interior of the municipality. Patch stability, network connectivity, and multifunctional management need to be considered together [23, 25]. Specific locations for retention and supplementation should be determined in relation to existing vegetation, land-use conditions, and potential connections [24], with coordinated restoration priorities for patch protection and linear connectivity [43].

Table 3. Type-based protection of ecological source areas and spatial design measures

Management type	Main spatial features	Protection and design measures
Core protection	Larger source areas in the west and southwest	Maintain patch area and internal habitat integrity; retain woodland and connections between adjacent patches; locate recreational facilities along existing roads and within existing activity spaces.
Isolated-patch connection	Dispersed peripheral source areas and potential connections in the central and eastern areas	Connect patches through existing green spaces, ditches, and forest strips; add small habitats at suitable locations; coordinate the locations retained or restored on adjacent parcels.
Linear connection	Riparian and other linear source areas	Retain continuous riparian zones and maintain connections toward the interior of the municipality; provide crossings and connections at interfaces with development; delineate public activity areas by section.

4.2.2 Risk-Based Corridor Restoration and Landscape Design

Corridor risk classification is used to prioritize local assessments and interventions (Table 4). High-risk sections require priority assessment of barriers caused by roads and development; medium-risk sections require local gaps to be filled; and low-risk sections require existing habitats to be maintained. Crossing arrangements should be determined according to the target taxa, surrounding habitats, and existing facilities [44]. The 58 unclassified corridors remain a separate management category and should not be considered low-risk. Specific measures within the same risk level still depend on site conditions, with implementation informed by baseline ecological conditions and restoration potential [26, 45].

Table 4. Risk-based restoration and spatial design measures for ecological corridors

Risk level	Corridor count	Main spatial features	Protection and design measures
High risk	10	Sections intersecting urban development and roads	Assess existing bridges, culverts, and passage spaces; restore vegetation connections at entrances, passages, and exits according to the barriers present; provide suitable crossing structures where necessary.
Medium risk	10	Local gaps and transition areas within existing connections	Retain continuous vegetation; restore connections across habitat gaps and land-use boundaries; coordinate source areas at both ends with transition spaces along the route.
Low risk	32	Connections along the northern and southwestern–southern periphery	Protect existing habitats and use low-intervention maintenance; allow natural recovery where conditions permit; coordinate ongoing maintenance of ditches, edge strips, and connections across parcels.

Risk level	Corridor count	Main spatial features	Protection and design measures
Unclassified	58	Corridors that do not intersect the candidate pinchpoints identified in this study	Retain unclassified status; conduct further assessments using surrounding land use, changes in development, and field surveys, rather than directly applying low-risk measures.

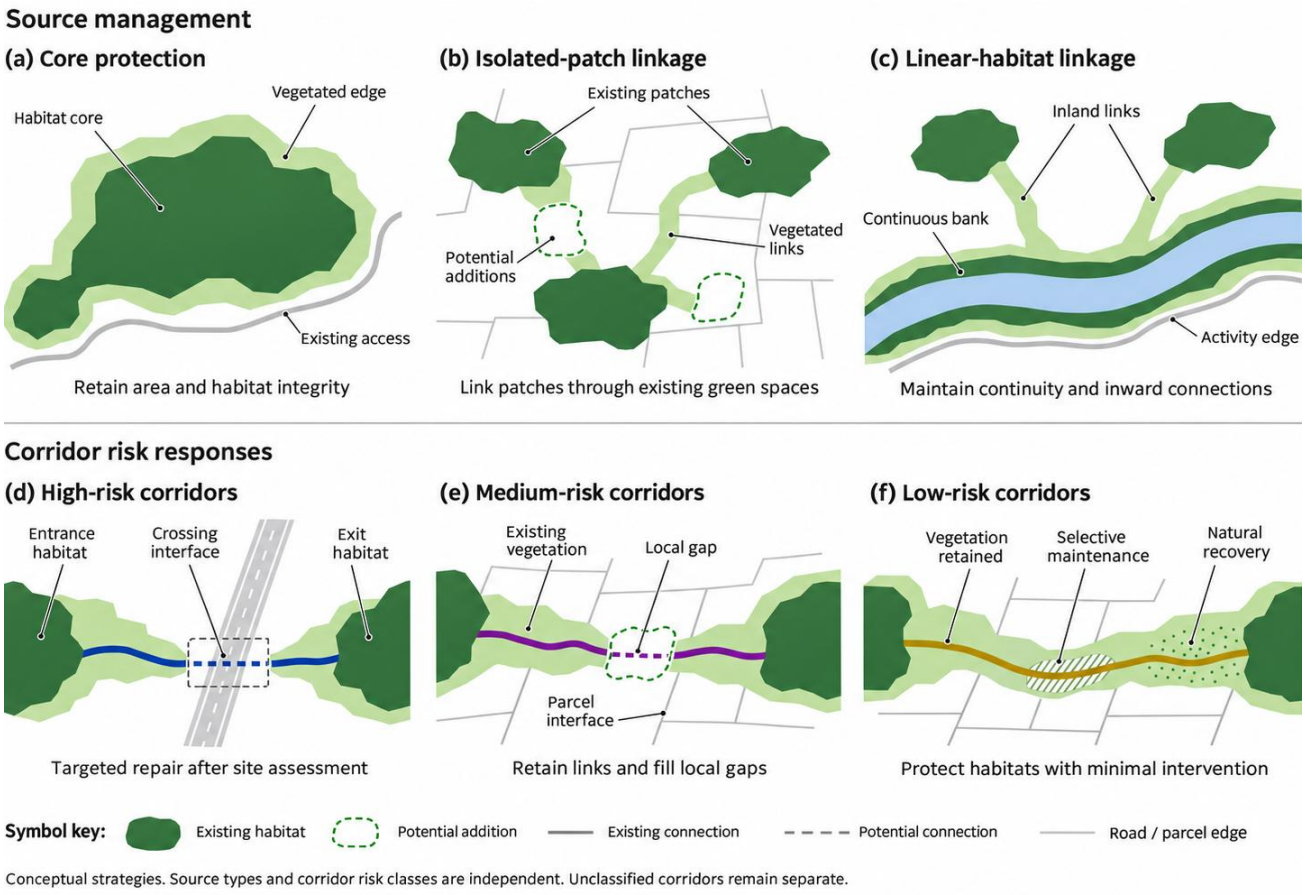


Figure 8. Schematic design for source area types and corridor risk levels

4.2.3 Local Application at Beilong Lake

Beilong Lake serves both wetland conservation and public recreation functions [46]. Drawing on the existing planning context [47] and the source area types and corridor risk levels discussed above, this study proposes three design units: wetland conservation, woodland connections west of the lake, and extension of waterfront green belts (Figure 9).

Unit A covers the northwestern part of the lake and its adjoining shoreline, focusing on habitat conservation and directing recreation away from sensitive habitats. Based on records of winter waterbird activity [48] and subsequent arrangements such as dedicated swan-watching routes [49], the proposed measures retain aquatic vegetation and suitable shallow-water habitats, establish a vegetated buffer on the landward side, and locate observation points and spaces for environmental education at the outer edge of the buffer. Routes should avoid actual nest sites during the breeding season, and visitor stops close to the water should be controlled along shoreline sections where birds congregate during the wintering season.

Unit B follows the woodland west of the lake toward the Forest Park, focusing on connecting dispersed green spaces and improving interfaces with roads. The birdwatching guide records routes through the woodland west of the lake and across Longhu Inner Ring West Road [48]. The proposed measures add patches of native trees, shrubs, and grasses to the existing woodland to

connect forest edges and roadside green belts. Road crossings should be prioritized for assessment. After overlaying the corridor and risk classification results, restoration measures should be determined according to the target taxa and existing crossing spaces, while light disturbance should be controlled.

Unit C follows the southern shore of Beilong Lake and connects to the Ruyi Canal, focusing on riparian continuity and the organization of public activities. In line with planned connections for daytime boat tours [50], the proposed measures retain continuous waterfront vegetation, add small habitats in suitable gaps, and connect nearby urban green spaces. Paths and spaces for stopping should be located on the urban side. Boat stops should be concentrated along existing service sections of the shoreline, avoiding habitat and breeding areas. The extent and timing of activities should be controlled in accordance with management requirements for the water area [51].

Future development at key locations could accommodate visitor arrivals and departures and provide public services. Zhengdong New District plans to undertake conceptual design for the Financial Island Transfer Center, West Commercial Park, East Canal Park, and the parcel west of the Investment Promotion Center [52]. This study proposes organizing environmental education displays and existing visitor routes around these nodes to reduce the dispersal of service facilities along habitat shorelines, so that future development is coordinated with conservation, connectivity, and activity zoning in the three units.

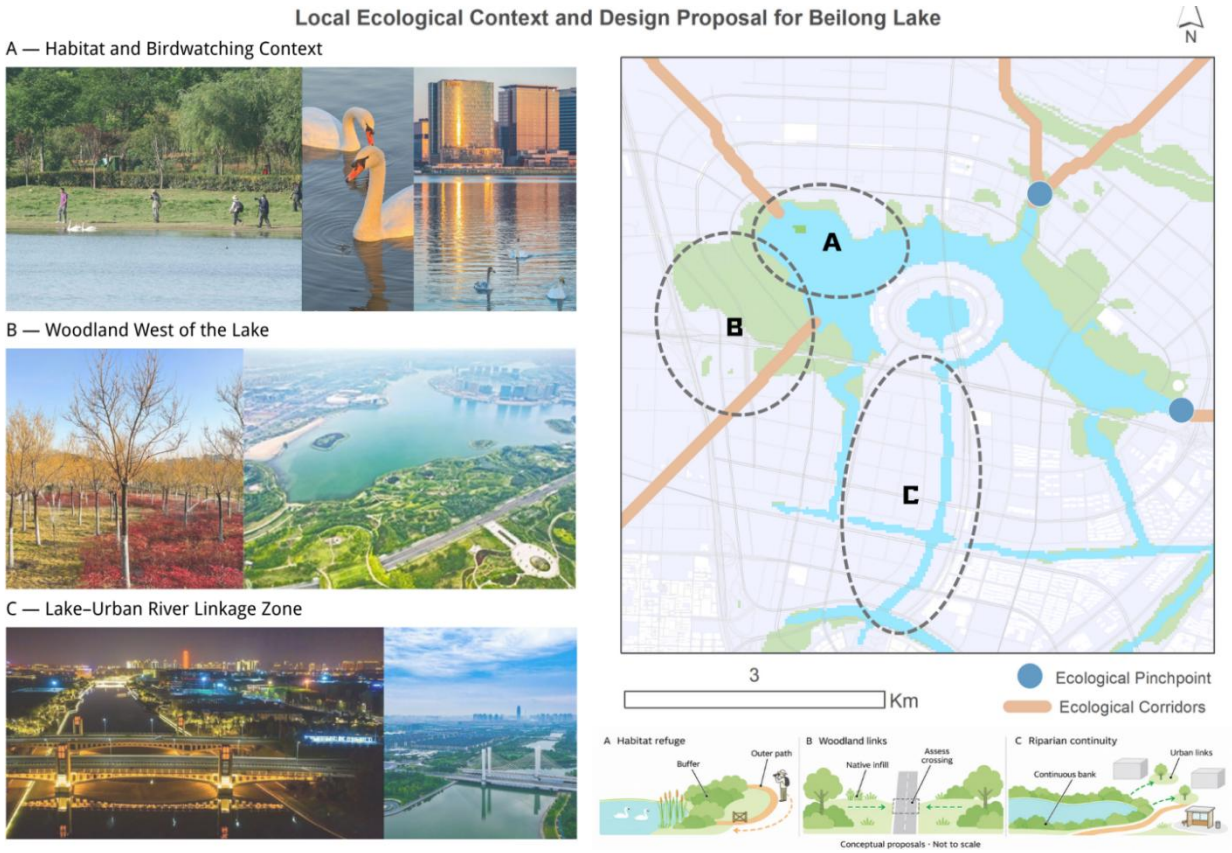


Figure 9. Local ecological connections and site design responses at Beilong Lake

Image sources (from left to right within each group): Group A: photographs by Ma Jian [53], Wang Yining [54], and Bian Ji [54]; Group B: photographs by the author and Li Xinhua [55]; Group C: both photographs by Zhang Wenju [56]. The GIS map on the right was prepared by the author.

5 Conclusions

By combining source area identification, integrated resistance, least-cost paths, and circuit analysis, this study identifies the spatial organization of Zhengzhou's ecological network and

directions for protection by priority level. The network comprises 48 source areas connected by 110 potential corridors, but connectivity between source areas varies spatially. Larger source areas cluster in the west and southwest, with many short connections between neighboring patches but relatively weak connections to scattered peripheral source areas. Linear source areas in the north connect to the interior of the municipality in several directions, while some corridors in the central and eastern areas span larger gaps between source areas. These findings show that the relative isolation of source areas reflects both scattered patch distributions and the continuity of their peripheral connecting spaces. Urban development and road crossings are external connection locations that require particular attention. Optimizing Zhengzhou's ecological security pattern should therefore protect larger source areas while strengthening connections between scattered peripheral source areas and linear ecological spaces. Mountain areas require the integrity of patches and their surrounding connections to be maintained; riparian areas require continuous riparian zones and inward-extending connections to be retained; and central and eastern areas require connections across parcels to be organized around existing ecological spaces.

The comparison of corridor priorities further shows that maintaining overall connectivity and protecting local pinchpoints are complementary tasks. The 64 candidate pinchpoints correspond to 52 corridors classified by pinchpoint association, including 10 each in Classes I and II. All five high-centrality corridors belong to the group left unclassified in the pinchpoint-based assessment. This difference shows that classification based solely on local pinchpoints cannot fully account for corridors that support important overall connections. Management by priority level therefore needs to consider both a corridor's role in network connectivity and local spatial constraints. Corridors that contribute more to overall connectivity should be retained over the long term. Conservation or improvement tasks for priority sections associated with pinchpoints should be determined according to existing conditions, while other connections should continue to support the network through routine maintenance. Assessments of importance and the selection of measures can thus jointly inform the allocation of conservation resources.

For local planning, this study proposes a way to link citywide ecological network identification, source area classification, and corridor risk classification to site-level protection, restoration, and ongoing management. Mountain margins, road crossings, waterfront transition zones, farmland margins, and urban green space interfaces provide specific locations for translating the citywide pattern into landscape design. Topography, land cover, use, and management conditions should inform vegetation retention, spatial connections, the organization of activities, and maintenance practices. Spaces with good continuity primarily require existing conditions to be maintained. Where connections are constrained, improvements should address identifiable site problems, integrating ecological network protection into routine development of parks, roads, waterfronts, and agricultural landscapes.

The Beilong Lake case provides a site-level discussion of how this approach can be applied. Existing plans, seasonal protection of species, and management of the water area provide a practical basis for coordinating open water, riparian zones, surrounding woodland, and public activities. Citywide network analysis also indicates that conservation of the lake area should consider its connections to surrounding ecological spaces. The planning implication is to translate the spatial relationships and connectivity characteristics of ecological spaces into differentiated conservation tasks, then apply these tasks to specific landscapes and ongoing management. This offers a reference for balancing regional ecological integrity with the quality of everyday spaces in areas encompassing mountains, riparian zones, and urban development needs.

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