CONSTRUCTION OF ECOLOGICAL SECURITY PATTERNS IN HILLY CITIES BASED ON MORPHOLOGICAL SPATIAL PATTERN ANALYSIS AND MINIMUM CUMULATIVE RESISTANCE MODELS: A CASE STUDY OF GANZHOU, CHINA

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Abstract. Ganzhou was a typical hilly city and serves as an important ecological security barrier in southern China. The conflict between economic development and environmental protection necessitates the scientific construction of an ecological security pattern to ensure sustainable development. This study aims to improve and restore the ecosystem functions by constructing such a pattern through "ecological sources identification – resistance surface construction – ecological corridors extraction," utilizing ecosystem service value, Morphological Spatial Pattern Analysis (MSPA), the Minimum Cumulative Resistance (MCR) model, and gravity model. The results showed that: (1) A total of 17 ecological sources were identified, covering an area of 4104.2 km², accounting for approximately 10.4% of Ganzhou's total area. High-resistance surface was primarily located in the urban built-up areas of Ganzhou. The MCR model identified 33 ecological corridors, with a total length of 2220.1 km, and further analysis using gravity model identified 18 important ecological corridors, with a total length of 1471.9 km. (2) The study proposed an ecological security pattern scheme of "Three Barriers, Three Sources, Three Zones, Multiple Corridors" to optimize the spatial layout of Ganzhou's ecological elements, ensuring sustainable development for the city.
Keywords: *ecological source, resistance surface, ecological corridor, gravity model, ecological services importance assessment*

Introduction

With the rapid development of urbanization, high-intensity human activities and unreasonable land use have increasingly damaged urban ecosystems, and resulted in a series of severe ecological and environmental problems, such as prominent human-land conflicts, reduced biodiversity and soil erosion (Cetin et al., 2019; Ding et al., 2022; Mooney et al., 2013; Tang et al., 2018). Consequently, urban ecological security patterns have gradually become a research hotspot (Cook, 2002; Guan et al., 2024; Qiao et al., 2023; Yilmaz et al., 2016). The International Institute for Applied Systems Analysis first proposed the concept of ecological security in 1989. Since then, numerous scholars have expanded upon the concept of ecological security patterns (Yu, 1999; Costanza, 2012; Ma et al., 2004). In general, an ecological security pattern refers to the state of an ecosystem within a certain spatial scope that, through the protection and restoration of the ecological environment, can resist external disturbances and maintain its structural and functional stability (Peng et al., 2018a). The methods for constructing ecological security patterns are diverse, with the most common frameworks being based on either the "pattern-process-function" approach or the "source-resistance-corridor" approach (Su et al., 2013; Zhai et al., 2024). Currently, the latter approach become a commonly used method for identifying conservation and enhancing connectivity and management of these areas at the regional scale (Wang and Pan, 2019; Cheng et al., 2024; Zhang et al., 2024a).

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Addressing urban ecological security issues is a crucial prerequisite for achieving regional ecological security, and constructing urban ecological security patterns is an effective method of maintaining urban ecological security (Dai et al., 2021; Gong et al., 2023). However, existing research on urban ecological security pattern construction has certain limitations, primarily manifesting in the following aspects: (1) Different types of urban ecosystems have unique urban ecological security issues. Current research predominantly focuses on the ecological security of delta cities, resource-based cities, and arid region cities, with relatively scarce studies on the ecological security patterns of hilly cities (Peng et al., 2017; Yang et al., 2024; Hua et al., 2024). (2) The selection of ecological sources, the construction of resistance surface, and the identification of ecological corridors in most studies are relatively simplistic, often overlooking the impact of spatial heterogeneity of key ecosystem services in hilly cities (Li et al., 2011; Li et al., 2007). Therefore, this study aims to address the aforementioned issues by further optimizing and improving the identification of ecological sources, the construction of resistance surface, and the identification of ecological corridors, thereby making the construction of ecological security patterns of hilly cities more reasonable.

Ganzhou is located in the southern part of Jiangxi Province, China. It serves as the headwaters of the Gan River in the Yangtze River Basin and the Dong River and Bei River in the Pearl River Basin. It acts as a strategic gateway for integration into the Guangdong-Hong Kong-Macao Greater Bay Area, being the direct hinterland for inland development connected to the Bay Area. The topography of the city is predominantly mountainous and hilly, comprising 80.98% of its total area, making it a typical hilly city (Xu et al., 2019). Ganzhou is situated at the convergence of the Nanling Mountains, Wuyi Mountains, and Luoxiao Mountains, making it a critical area for biodiversity conservation and an important ecological security barrier in southern China. Notably, Ganzhou has the largest tungsten reserves and the second-largest rare earth reserves in China, earning it the titles of “World Tungsten Capital” and “Kingdom of Rare Earths.” It serves as a national base for the rare metals industry and advanced manufacturing. However, in 2022, Ganzhou had a resident population of 8.98 million, with per capita GDP of 50,400 RMB, ranking last among the 11 prefecture-level cities in Jiangxi province (Ganzhou Municipal Bureau of Statistics, 2023). The conflict between socio-economic development and environmental protection constraints persists.

The goal of ecological environment protection in Ganzhou is to build a “High-quality development demonstration zone for old revolutionary areas” and a model of “Beautiful China” with significantly enhanced ecological security barrier functions in southern China (Ganzhou Municipal Bureau of Natural Resources, 2024). However, two issues still require further exploration: On one hand, Ganzhou, as a hilly city, has the majority of its population concentrated in the red soil basin, which covers only 17% of the city’s total land area. This results in prominent human-land conflicts, severe soil erosion, and significant challenges in ecological restoration, sewage treatment, and slag disposal. On the other hand, current constructions of ecological security patterns mainly focus on economically developed eastern regions and ecologically significant western regions in China (Zhang et al., 2024b; Li et al., 2023), with insufficient research on central regions.

Based on this, this paper takes the typical hilly city of Ganzhou as a case study. Firstly, it identifies ecological sources from the perspectives of ecosystem structure and function. Secondly, it constructs resistance surface using land use types, elevation, and slope, further refining resistance surface with nighttime light data. Finally, it utilizes the

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MCR model to extract corridors among ecological sources and employs the gravity model to effectively identify important ecological corridors within the ecosystem. This paper also explores optimization suggestions and practical implementation paths for the ecological security pattern in hilly cities, aiming to achieve coordinated development and symbiotic integration of ecological service provision and socioeconomic activities in hilly cities. This research provides a reference for the construction of ecological security patterns in hilly cities.

Materials and methods

Study area and data

Study area

Ganzhou is located in the upper reaches of the Gan River in southern Jiangxi Province, China (*Fig. 1*). It lies between latitudes 24°29′ to 27°09′ N and longitudes 113°54′ to 116°38′ E. The total area of Ganzhou is 39,379.64 km^2, accounting for 23.6% of the total area of Jiangxi Province. The geomorphology of Ganzhou is predominantly mountainous and hilly and the average elevation across the city ranges between 300 and 500 m. Located on the southern edge of the mid-subtropical zone, Ganzhou experiences a subtropical monsoon climate characterized by prevailing winter and summer monsoons, concentrated rainfall in spring and summer, distinct seasons, mild temperatures, abundant heat, ample rainfall, short periods of extreme heat and cold, and a long frost-free period. The average annual precipitation in Ganzhou is 1568.75 mm, and the average annual temperature is 19.3°C (Zhen et al., 2021).

Data sources

The data used in this study include net primary productivity (NPP) of vegetation, digital elevation model (DEM), monthly average temperature, monthly average precipitation, soil texture, land use data, and nighttime light data. Detailed data sources are listed in *Table 1*.

Table 1. *Main data used in the study*

Data type	Data sources	Data accuracy	Year
Net primary productivity (NPP) of vegetation	National Tibetan Plateau Data Center (https://data.tpdc.ac.cn/)	500 m	2021-2023
Digital elevation model (DEM)	Geospatial Data Cloud (https://www.gscloud.cn/)	30 m	2024
Monthly mean temperature	National Tibetan Plateau Data Center (https://data.tpdc.ac.cn/)	1 km	2020-2022
Monthly mean precipitation	National Tibetan Plateau Data Center (https://data.tpdc.ac.cn/)	1 km	2020-2022
Soil texture (content of sand, silt, clay)	National Tibetan Plateau Data Center (https://data.tpdc.ac.cn/)	1 km	2009
Land use	Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (https://www.resdc.cn/)	30 m	2020
Night light data	National Tibetan Plateau Data Center (https://data.tpdc.ac.cn/)	500 m	2018-2020

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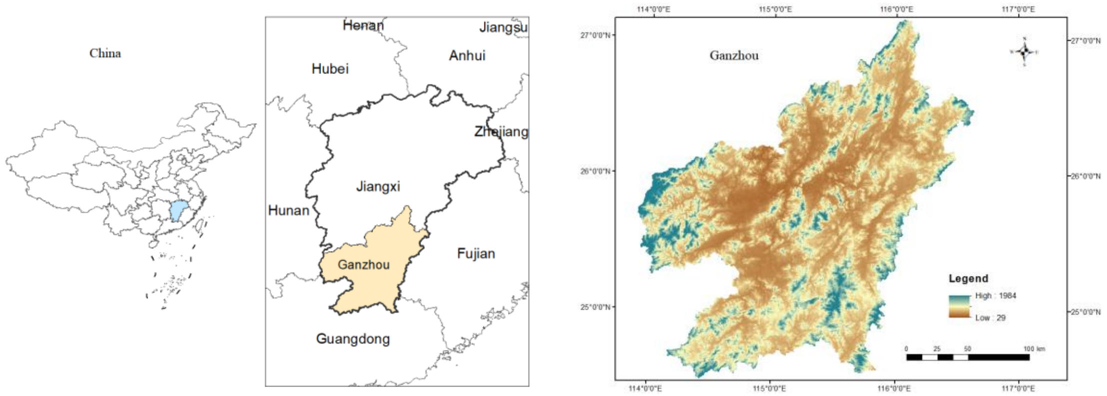

Figure 1. *Location of the study area*

Methods

Identification of ecological sources

Ecological Sources are key regions within ecological networks that possess high ecological functions and value, typically characterized by rich biodiversity and stable ecological environments. They provide species, energy, and material resources to other areas, playing a crucial role in maintaining ecosystem functions and biodiversity. In ecological corridors, ecological sources serve as both starting and ending points, connecting through corridors to support the migration of flora and fauna and maintain ecosystem stability. Ecological sources are vital area for species survival and migration, and they hold significant importance in preserving regional ecological security patterns (Liu et al., 2021a). Therefore, accurately identifying ecological sources is essential for constructing ecological security frameworks (Zhang et al., 2017).

Ecological services importance assessment

Ecological services refer to the various benefits that humans derive from ecosystems, including maintaining natural environmental conditions and utilities essential for human survival (Zhao, 2013; Li et al., 2024). The capacity of ecological services reflects the health status of the ecological environment. Based on the characteristics of Ganzhou, this study selects water conservation, soil conservation, and biodiversity protection as three ecological service indicators. The evaluation utilizes the Net Primary Productivity (NPP) quantitative indicator method provided in the “Technical Guidelines for Ecological Protection Red Lines” (2015 edition) (Ministry of Environmental Protection of China, 2015). The NPP quantitative indicator method uses NPP data combined with relevant data for evaluation (Zhang et al., 2016; Carreño et al., 2012; Barral and Oscar, 2012). Five methods are involved in the evaluation, the methods are as follows:

(1) Calculation method of water conservation service capacity index

The water conservation service of ecosystems is primarily manifested through functions such as vegetation interception of precipitation, enhanced soil infiltration, evaporation inhibition, and surface runoff mitigation (Zhou et al., 2018). The specific formula for calculating the WR index is as follows (*Eq. 1*):

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$$WR = NPP_{mean} \times F_{sic} \times F_{pre} \times (1 - F_{slo}) \quad \text{(Eq.1)}$$

where WR is water conservation service capacity index; NPP_{mean} is average annual Net Primary Productivity; F_{sic} is soil infiltration capacity factor; F_{pre} is precipitation factor; F_{slo} is slope factor.

(2) Calculation method of soil conservation service capacity index

Soil conservation service of ecosystems reduces soil erosion caused by water through its structure and processes, primarily manifested in the ability of vegetation roots to fix soil and reduce surface soil loss into gullies due to precipitation (Wu et al., 2022). The specific formula for calculating the S_{pro} index is as follows (*Eq. 2*):

$$S_{pro} = NPP_{mean} \times (1-K) \times (1-F_{Slo}) \quad \text{(Eq.2)}$$

where S_{pro} is soil conservation service capacity index; F_{Slo} is slope factor; K is soil erodibility factor.

(3) Calculation method of biodiversity protection service capacity index

The ecosystem's biodiversity protection service primarily includes functions such as the generation and maintenance of biodiversity, climate regulation, mitigation of floods and droughts, dispersion of seeds and pollen, control of pests, and purification of soil environments (Liquete et al., 2016). Net Primary Productivity, due to its capacity to directly reflect vegetation productivity, is widely used as a core indicator of biodiversity and habitat quality. By revealing the growth status and productivity levels of plants within ecosystems, NPP indirectly reflects the health of habitats and the richness of biodiversity. Although various indicators can describe ecological functions from different perspectives, there is currently no single indicator that more effectively represents habitat quality than NPP, making it indispensable in ecosystem health assessment. The specific formula for calculating the S_{bio} index is as follows (*Eq. 3*):

$$S_{bio} = NPP_{mean} \times F_{pre} \times F_{tem} \times (1-F_{alt}) \quad \text{(Eq.3)}$$

where S_{bio} is biodiversity protection service capacity index; F_{tem} is temperature factor; F_{pre} is precipitation factor; F_{alt} is elevation factor.

(4) Calculation method of comprehensive ecosystem service capacity index

To assess the importance of comprehensive ecosystem services (IESI), we calculate the Comprehensive Ecosystem Service Capacity Index. In evaluating ecosystem services in mountainous cities, water conservation, soil retention, and biodiversity are weighted equally, primarily due to their interdependence in maintaining ecological stability and supporting sustainable development. The diversity requirements and complex environment of mountainous ecosystems make these services essential for ecological balance. Equal weighting ensures that each service is fairly assessed, preventing an overemphasis on any single function. Equal weight was applied for the three capacity indices in this study. The specific calculation formula is as follows (*Eq. 4*):

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$$IESI = WR + S_{pro} + S_{bio} \quad \text{(Eq.4)}$$

where IESI is comprehensive ecosystem service capacity index; WR is water conservation service capacity index; S_{pro} is soil conservation service capacity index; S_{bio} is biodiversity protection service capacity index.

(5) Classification of ecological service importance levels

Using the quantiles method, both the three single-factor ecological service and integrated ecological service indicators were classification into five levels: insignificant; marginally important; moderately important; highly important; critically important (Ministry of Environmental Protection of China, 2015).

Morphological spatial pattern analysis

MSPA is a method proposed by Vogt et al. in 2007 for classifying binary raster images based on mathematical morphology principles (Vogt et al., 2007; Halimulati et al., 2021). This approach identifies spatial topological relationships between target pixel sets and structural elements, categorizing them into seven types: core, islet, perforation, edge, bridge, loop, and branch. MSPA is widely employed in Environmental Protection Agency (EPA) identification and network studies (Hernando et al., 2017). MSPA is noted for its simplicity and efficiency, capable of rapidly identifying landscape types without being constrained by research scale. This study selected highly human-disturbed croplands and urban areas as background, with forests, grasslands, shrublands, wetlands, and water bodies as foreground elements. Using the software of Guidos Tool Box 2.6, with an edge width set at 30 m, calculations were conducted using the default eight-neighbor analysis method (Cheng et al., 2020). This analysis identified seven landscape types in Ganzhou, subsequently, core areas were identified as potential ecological sources (Liu et al., 2021a).

Ecological sources should meet standards of ecological function, biodiversity, and size, prioritizing regions with significant ecological function and rich biodiversity. Larger ecological sources have greater ecological carrying capacity, reduced edge effects, and facilitate species migration and gene flow, enhancing ecological connectivity. The size of ecological sources should be adjusted based on the total study area to ensure the balance and optimal functionality of the ecological network, supporting biodiversity and ecological stability. Accordingly, this study selects areas over 100 km^2 as ecological sources. The ecological sources are extracted using the ecological service importance levels and the MSPA method. Areas of moderate and higher importance are selected for overlay analysis with potential ecological sources. Core patches overlapping in areas greater than 100 km^2 are extracted as ecological sources.

Construction and correction of resistance surface

The Resistance surface is a spatial model used to describe the resistance levels imposed by various land surface characteristics (such as land use types, vegetation types, and topography) on species migration and ecological processes within an ecological network. Resistance values are typically based on factors such as human activities, habitat fragmentation, and environmental conditions, with higher values indicating greater impediments to the movement of flora and fauna. When constructing the resistance surface, Geographic Information System (GIS) technology is employed to

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integrate resistance values from different regions, resulting in a comprehensive model. The construction of the resistance surface and the calibration of resistance values are critical components in studying biological migration and dispersal, as the impacts of natural conditions and human activities on species migration can vary significantly. Research indicates that the migration and dispersal of species between ecological sources are hindered by land cover status and human activities (Liu et al., 2021b).

This study selects three natural factors: land use type, elevation, and slope to obtain the basic resistance surface. Relevant research provides a basis for classification and assignment (*Table 2;* Li et al., 2024; Wang et al., 2022). However, different land cover types impose varying hindrances on ecological processes and the circulation of ecological factors across spatial scales. The method of assigning resistance coefficients based on land cover types partially neglects the differences in land use practices and intensities within the same land cover type, thereby making it challenging to accurately represent spatial variations in actual resistance (Peng et al., 2018b). Nighttime light data serves as a comprehensive indicator of human activity intensity (Li et al., 2022). To weaken the influence of subjective assignment, the interference of human activities on the flow and transmission of ecological elements is represented by nighttime light data, and the ecological comprehensive resistance surface is corrected (Liu et al., 2021b), aiming to enhance the accuracy and validity of corridor simulations. The formula is as follows (*Eq. 5*):

$$R^{*} = \frac{TLI_{\mathrm{i}}}{TLI_{\mathrm{a}}} \times R_{0} \tag{Eq.5}$$

where R^{*} is the modified grid resistance coefficient; TLI_i is the night light intensity value of grid i; TLI_a is the average night light intensity value of land type a; R_0 is the basic resistance value of grid i.

Table 2. *Basic ecological resistance factor from land use and DEM*

Resistance factor	Classification	Resistance value	Weight	Resistance factor	Classification	Resistance value	Weight
Land use type	Woodland	1	0.5	Slope (°)	< 5	1	0.25
	Shrubland	10			5-10	10	
	Grassland	30			10-20	50	
	Wetland	50			20-30	75	
	Water Bodies	75			> 30	100	
	Cultivated land	90		Elevation (m)	< 100	1	0.25
	Construction land	100			100-300	10	
					300-500	50	
					500-800	75	
					> 800	100	

Extraction of ecological corridors

Ecological corridors serve as crucial pathways for ecological elements to flow and transfer between ecological sources (Mao et al., 2020), carrying significant functions in maintaining ecosystem functioning and ensuring regional ecological security (Peng et al., 2017). These corridors, characterized by low resistance, effectively connect fragmented habitat patches, thereby promoting continuity and flux of ecological flows and processes within the region (Wang et al., 2022). Ecological corridors are considered pivotal areas likely to enhance and improve biodiversity connectivity inn ecological restoration (Ni et al., 2020). By facilitating exchange and migration among biological populations, ecological corridors provide essential support for the stability and health of ecosystems.

The Minimum Cumulative Resistance (MCR) model and the gravity model are applied in research to identify and extract ecological corridors.

Minimum cumulative resistance model

The MCR model, derived from the research of Knaapen et al. (1992) and modified by Yu (1999), simulates the minimum cumulative resistance required for species and ecological functional migration, identifying effective ecological corridors. By integrating ArcGIS cost path tools, the MCR model calculates resistance values based on land use, topography, and other ecological factors, extracting the lowest resistance paths between ecological sources to form low-cost potential ecological corridors. Compared to other methods, the MCR model more accurately simulates and quantifies the minimum cost paths of species, energy, and information (Wei et al., 2022; Peng et al., 2018b). To ensure the suitability, migration success rate, and effectiveness of ecological connectivity, corridor exclusion criteria include resistance values exceeding a threshold, overly long paths, and lack of spatial or functional continuity. Therefore, this study adopts the MCR model to construct potential ecological corridors using ArcGIS, with computational methods in *Equation 6* (Li et al., 2024).

$$MCR = f \min \sum_{j=n}^{i=m} (D_{ij} \times R_i) \tag{Eq.6}$$

In the equation, MCR represents the minimum cumulative resistance for species to disperse from one ecological source to another; D_{ij} denotes the spatial distance from ecological source j to landscape unit i; R_i corresponds to the adjusted ecological resistance coefficient for landscape unit i.

Gravity model

The gravity model, originating from physics, describes the attraction between two objects and is widely applied in ecology and geography to analyze interactions between regions. The gravity model is a method used to construct interaction matrices between ecological sources, quantifying the relative importance of potential ecological corridors. This model evaluates the significance of corridors based on the magnitude of interactions between source and target sites. Research indicates that stronger interactions lead to tighter connections between ecological sources, enhancing the frequency of ecological element movement and exchange. Consequently, higher levels of ecological corridors importance are associated with these interactions (Li et al., 2024; Kong and Yin, 2008). Therefore, the gravity model effectively identifies critical ecological corridors within ecosystems, thereby enhancing ecological security frameworks and facilitating the flow and maintenance of ecological elements. The calculation method for the gravity model is described by *Equation 7* (Liu et al., 2021a).

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$$G_{ij} = \frac{L_{max}^2 \ln(S_i S_j)}{L_{ij}^2 P_i P_j} \tag{Eq.7}$$

In the equation, G_{ij} represents the interaction strength between patch i and patch j; P_i and P_j denote the resistance values of patch i and patch j respectively; S_i and S_j represent the areas of patch i and patch j respectively; L_{ij} denotes the cumulative resistance value of the potential ecological corridors between patch i and patch j; L_{max} is the maximum cumulative resistance value among all potential ecological corridors in the study area.

Results

Identification of ecological sources

Assessment of ecological service importance

The importance levels of water conservation, soil conservation, and biodiversity protection generally exhibit a pattern of higher importance in the southeast and lower importance in the northwest (*Fig. 2*). The integrated ecological service importance levels derived from the equal-weight combination of these three factors also show a similar spatial distribution pattern. As the results show in *Table 3*, the integrated ecological service importance level was dominated by marginally important zone. Moderate to critical importance zone are predominantly located in the eastern and southern parts of the study area, totaling 22,822.64 km^2. The western and northern parts, characterized by intensive agricultural and built-up areas heavily influenced by human activities, exhibit lower levels of ecological service importance, primarily categorized as insignificant or marginally important zone, with respective areas of 7,814.17 km^2 and 8,265.41 km^2.

Morphological spatial pattern analysis

Based on the MSPA analysis results, the study area was classified into seven ecological landscape types, namely core areas, perforations, edge areas, islets, loop areas, bridge areas, and branches (Chen et al., 2021). These ecological landscapes cover a total area of approximately 23,568.9 km^2.

As the results show in *Table 4* and *Figure 3*, core areas occupy the largest area, approximately 16,438.85 km^2, which accounts for 69.75% of the total ecological landscape area. Islet landscapes are sparsely distributed in the study area, covering about 3.59% of the total area. Perforation and edge areas serve as transition zones between core areas and non-ecological landscapes, with areas amounting to 3.22% and 7.85% of the total ecological landscape area, respectively. Loop areas, bridge areas, and branches function as connections between different ecological landscapes. Loop areas serve as corridors for species migration, covering 2.35% of the total area. Bridge areas connect different core areas and are relatively large in size, accounting for approximately 9.91% of the total ecological landscape area. Branches connect core areas with other ecological landscapes, occupying 3.33% of the total area.

Overall, the extensive bridge areas indicate relatively smooth flow and transfer of ecological elements between core areas and other ecological landscapes, suggesting good ecological connectivity.

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Table 3. *Area of ecosystem service importance level*

Ecosystem service	**Statistics**	**Insignificant zone**	**Marginally important zone**	**Moderately important zone**	**Highly important zone**	**Critically important zone**
Water conservation service	Range	0-0.033	0.033-0.06	0.06-0.105	0.105-0.16	0.16-0.639
	Area (km^2)	16645.29	10224.5	7334.32	2856.94	1919.67
Soil conservation service	Range	0-0.009	0.009-0.116	0.006-0.142	0.142-0.184	0.184-0.592
	Area (km^2)	7679.99	17298.86	9855.89	3979.44	408.83
Biodiversity conservation service	Range	0-0.006	0.006-0.01	0.01-0.134	0.134-0.221	0.221-0.526
	Area (km^2)	10458.31	13742.81	7113.64	4289.87	3514.87
Ecosystem integration service	Range	0-0.08	0.08-0.134	0.134-0.198	0.198-0.285	0.285-0.46
	Area (km^2)	9655.21	15537	7750.29	3922.25	2007.84

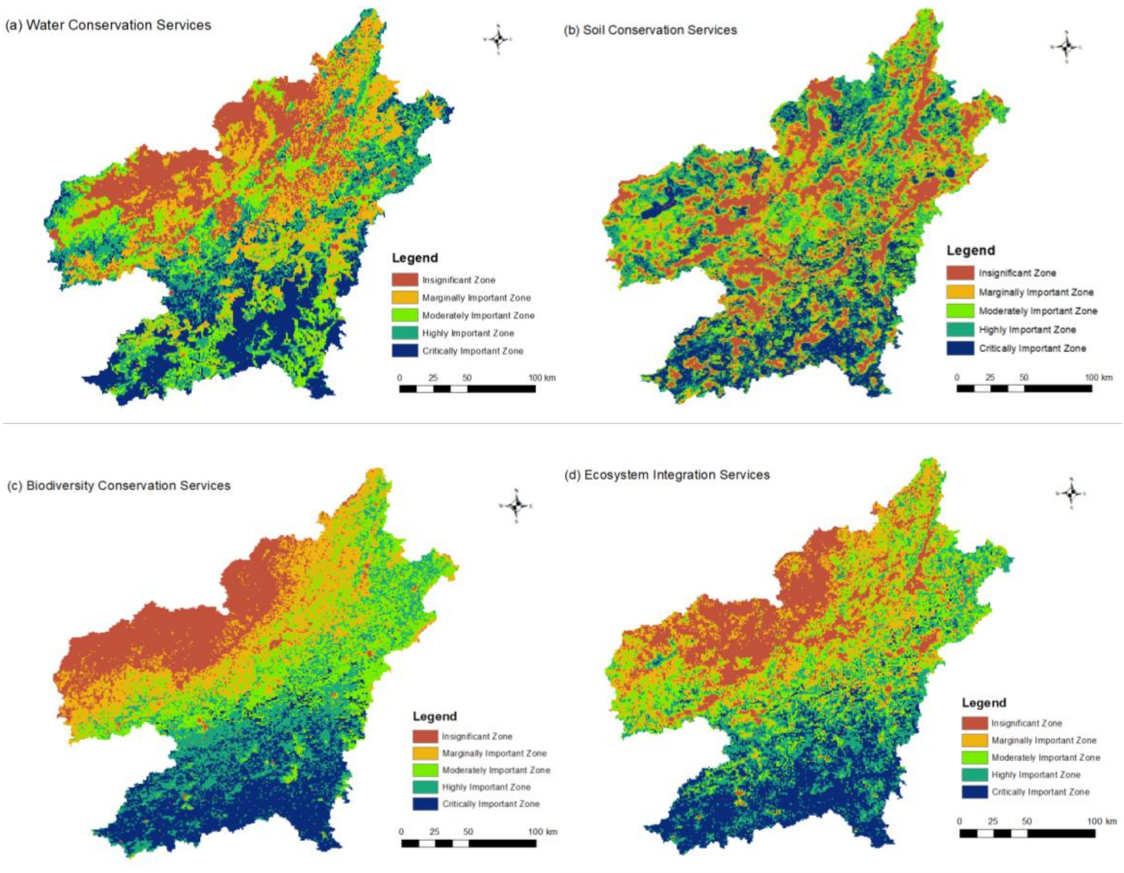

Figure 2. *Spatial distribution of ecosystem service importance level*

Table 4. *Statistics of ecological landscape types*

Statistics	**Core**	**Islet**	**Perforation**	**Edge**	**Loop**	**Bridge**	**Branch**	**Total**
Area (km^2)	16438.85	845.34	757.99	1851.16	554.45	2335.72	785.39	23568.9
Proportion	69.75%	3.59%	3.22%	7.85%	2.35%	9.91%	3.33%	100%

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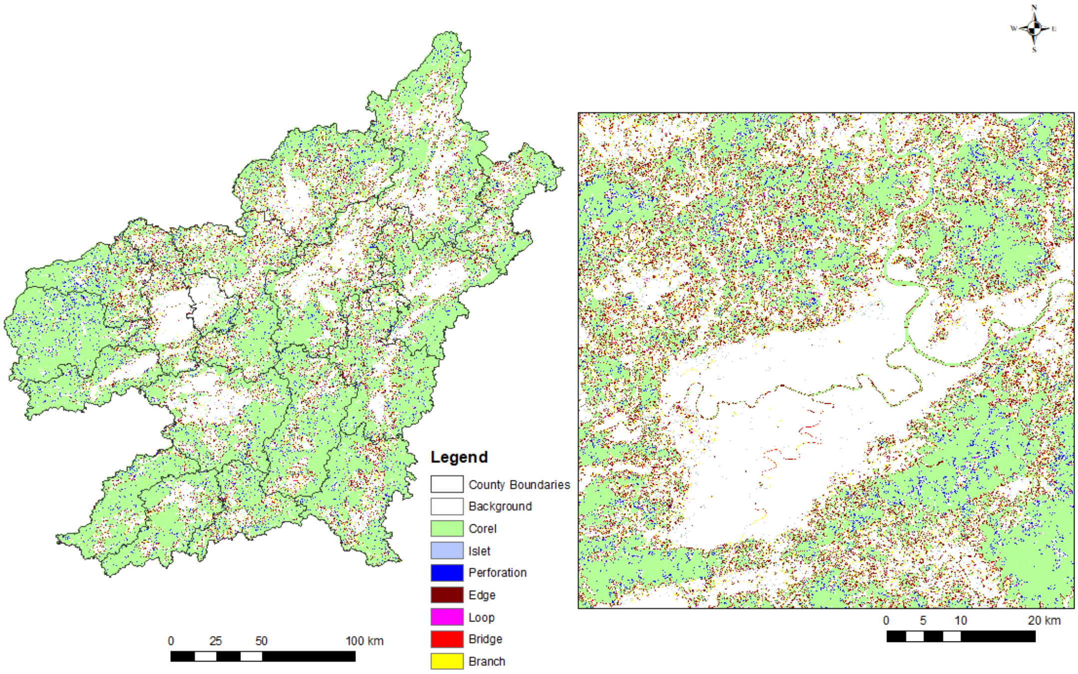

Figure 3. *Spatial distribution of ecological landscape types based on mspa method*

Extraction of ecological sources

This study examines the overlap between the core areas identified through MSPA and regions of medium or higher comprehensive ecosystem service importance. The patches which larger than 100 km² within these overlapping regions were selected as ecological sources. The total area of these ecological sources is 4104.21 km², accounting for approximately 24.97% of the core areas.

As seen in *Figure 4* and *Table 5*, these large ecological sources primarily encompass national geological parks, forest parks, and nature reserves in Ganzhou city. The number of the largest ecological source was no.11, located in Chongyi and Dayu county. Meiguan National Forest Park was inside the no.11. These areas are primarily located in the northeastern part of Ganzhou (Ningdu, Shicheng), the southern part (Anyuan, Huichang, Xunwu, Longnan, Quannan), and the southwestern part (Chongyi, Dayu), which are regions of high ecological demand, concentrated along the edges of various counties or at the borders between neighboring counties. This distribution is closely related to the topography of Ganzhou, which is characterized as a hilly and mountainous city with 80.98% of its area being hills and mountains, and only 17% being basins. The basins constitute the urban built-up areas.

In the eastern, central, and northwestern parts of Ganzhou, such as Zhanggong District, Nankang District, Xingguo County, the land is predominantly used for construction and agriculture, resulting in higher human activity intensity and fewer, more scattered ecological sources.

Ecological resistance surface construction

Resistance factors play a critical role in regional ecological security assessments. For instance, land use types directly influence the exchange of materials and information within and between ecological sources. Elevation variations affect the utilization and

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distribution of land resources, while different slopes influence the distribution and connectivity of biological habitats.

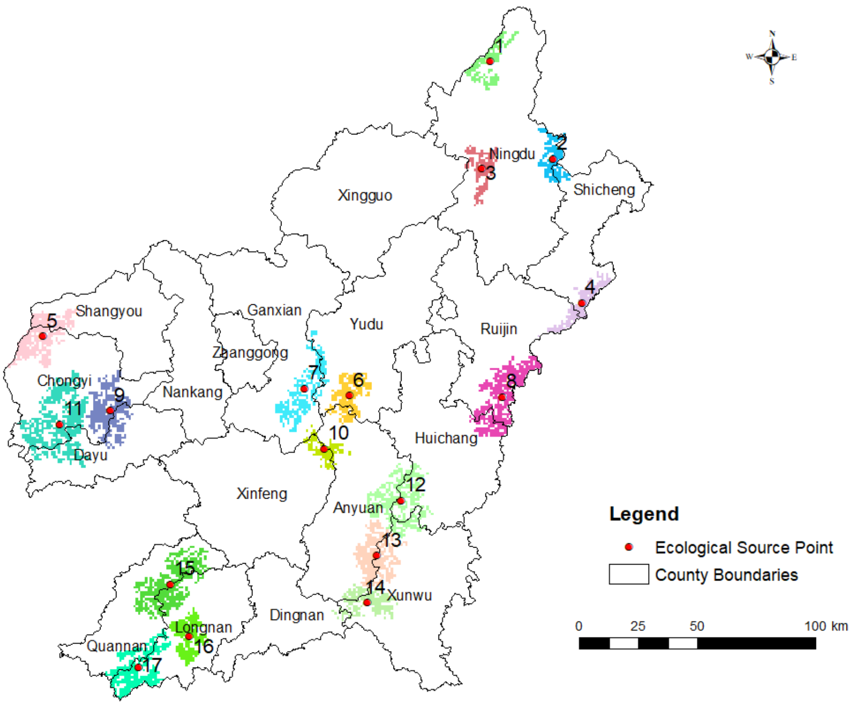

Figure 4. *Spatial distribution of ecological sources*

Table 5. *Basic characteristics of ecological sources*

Ecological sources No.	Area (km^2)	Location and key ecological area
1	137.92	Ningdu county
2	138.93	Ningdu & Shicheng county
3	127.51	Ningdu county, Cuiweifeng National Forest Park
4	144.78	Shicheng & Ruijin county, Shicheng National Geopark
5	279.48	Shangyou & Chongyi county, Wuzhifeng National Forest Park and Qiyunshan National Nature Reserve
6	192.00	Yudu & Anyuan county
7	245.04	Yudu & Ganxian county
8	353.59	Ruijin & Huichang county, Huichangshan National Forest Park
9	268.87	Chongyi & Dayu county, Yangmingshan National Forest Park and Ganzhou Yangminghu National Forest Park
10	107.96	Xinfeng & Anyuan county
11	466.94	Chongyi & Dayu county, Meiguan National Forest Park
12	343.02	Anyuan, Huichang & Xunwu county
13	292.64	Anyuan & Xunwu county, Sanbaishan National Forest Park
14	174.73	Anyuan & Xunwu county
15	385.86	Quannan & Longnan county
16	176.15	Longnan county
17	268.80	Quannan & Longnan county, Jiulianshan National Forest Park and Jiulianshan National Nature Reserve

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In this study, land use types, elevation, and slope data were utilized, combined with field surveys, to construct a base resistance surface. Using nighttime light data for adjustment, an ecological resistance surface was generated and classified into five levels: high resistance, moderate-high resistance, medium resistance, moderate-low resistance, and low resistance. A comparison between pre-revision and post-revision was showed in *Figure 5*, the portion of moderate-low resistance was improve and the revised resistance surface better reflects the conditions of a hilly and mountainous city. This indicates that the correction using nighttime light data more comprehensively considers the impact of human activities on ecological processes and more precisely assesses the disturbance levels affecting species migration.

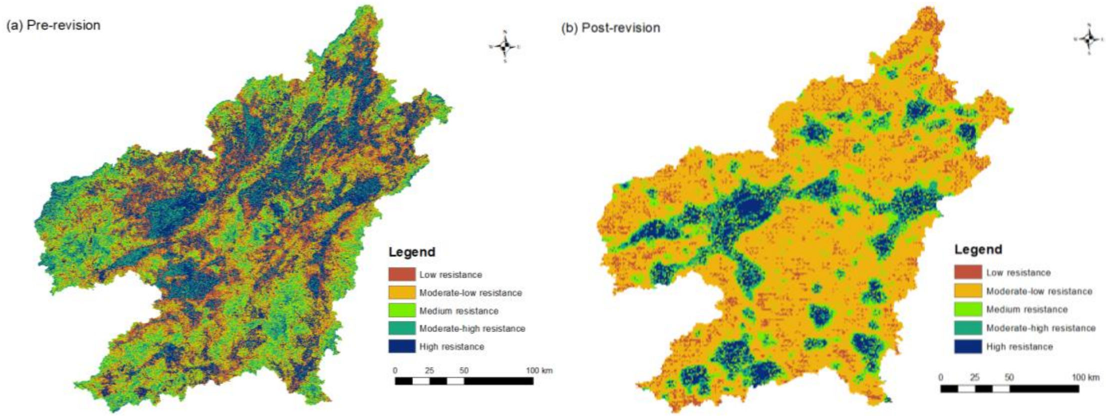

Figure 5. *Spatial distribution of resistance surface*

Extraction of ecological corridors and construction of ecological network

The MCR model was utilized to extract potential ecological corridors in the study area, identifying a total of 105 corridors. After removing duplicate and invalid paths, 33 ecological corridors were finalized, with a total length of 2220.1 km. Using the gravity model to calculate the interaction force matrix between ecological sources (*Table 6*), it was found that the interactions between sources 7 and 10, 6 and 7, 10 and 12, 12 and 13, 13 and 14 were the strongest, mainly distributed in the southeastern part of the study area. This indicates strong interactions and correlations between ecological sources in this region, with minimal resistance to the exchange of ecosystem material and energy flows, thus maximizing the potential for species migration. Therefore, the construction and protection of ecological corridors between these sources should be prioritized.

The study selected corridors with interaction forces greater than 100 as significant corridors, totaling 26. After removing duplicate paths, 18 significant ecological corridors were identified, with a total length of 1471.9 km (*Fig. 6.*). These important ecological corridors are distributed in a chain-like pattern within the study area. Due to higher altitudes and geographical separation by rivers, ecological sources #2 and #15 did not form ecological corridors. With larger ecological resistance coefficients, the interactions between ecological sources increased accordingly. Important ecological corridors span east, west, south, and north, with various woodlands being crucial components of these corridors. These significant corridors are vital for ensuring regional ecological security, providing essential migration pathways for species between ecological sources.

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Table 6. *Interaction matrix of ecological sources based on gravity model*

Source No.	1	3	4	5	6	7	8	9	10	11	12	13	14	16	17
1		661.7	484.7	94.5	55.2	43.2	20.4	3.7	67.9	7.5	26.6	34.4	36.8	6.0	5.8
3			587.4	47.0	29.7	23.5	10.3	1.6	37.8	3.4	14.6	18.6	19.4	2.9	2.9
4				118.2	84.0	67.0	28.5	4.2	108.7	8.5	41.9	52.6	54.7	7.9	8.2
5					33.1	25.4	13.3	16.6	38.9	38.8	15.5	20.5	22.5	4.1	3.8
6						1781.2	116.5	4.5	33.4	366.2	494.9	450.8	384.6	23.2	35.5
7							101.3	4.1	8929.2	6.3	776.6	585.2	722.2	24.0	45.5
8								1.8	182.7	2.9	111.1	116.5	80.4	7.6	9.2
9									6.1	155.6	2.3	3.1	3.9	0.7	0.7
10										9.4	2718.8	1511.5	1519.5	15.4	78.5
11											3.5	4.8	6.1	1.2	1.2
12												3120.9	443.1	12.9	23.2
13													1399.2	16.9	28.6
14														22.4	40.1
16															19.0
17															

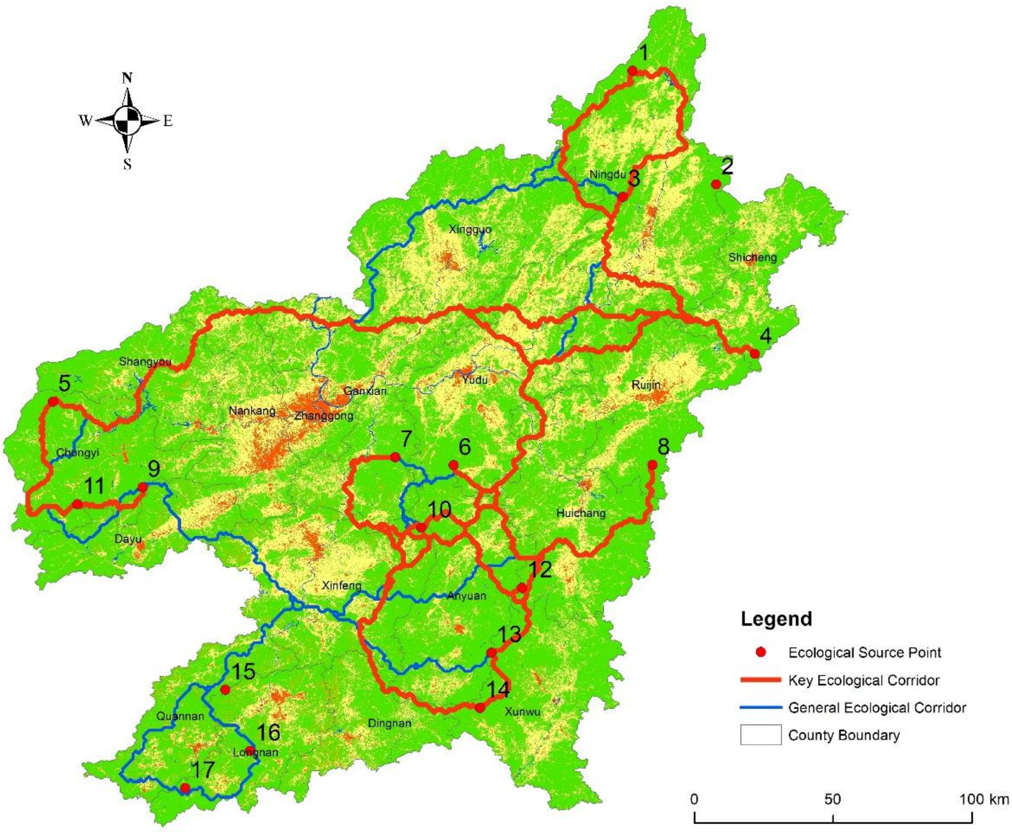

Figure 6. *Spatial distribution of ecological corridors*

Discussion

Policy implications of ecological management zoning

In Ganzhou, ecological sources primarily concentrate in peripheral regions with high habitat quality, while the central areas consist mostly of scattered small basins with dense populations, largely non-ecological zones (Zhang et al., 2024c). Therefore, this study utilizes the spatial distribution characteristics of natural ecological background, ecological sources, and corridors to establish an ecological security pattern. At a macro level, comprehensive planning and layout of ecological elements are proposed, presenting the optimized strategy of "Three Barriers, Three Sources, Three Zones, Multiple Corridors" for ecological security pattern showed in *Figure 7*, aiming to provide insights for ecological conservation and restoration efforts in Ganzhou.

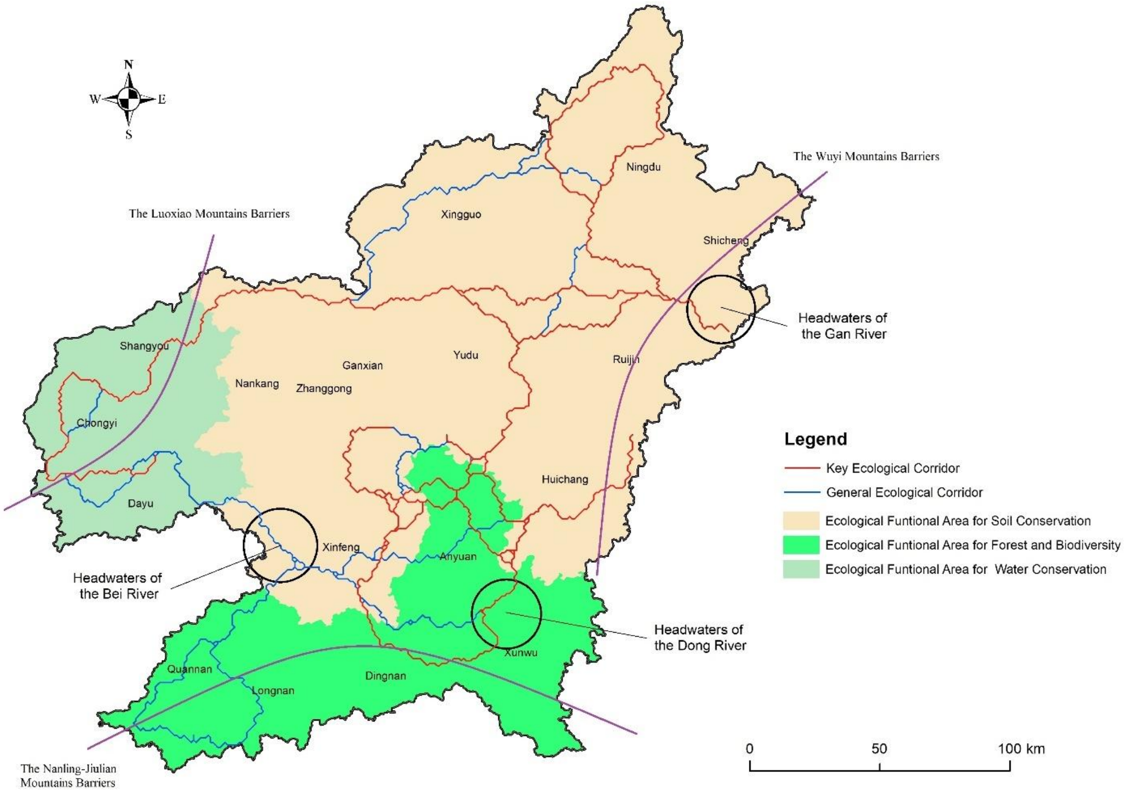

Figure 7. *The optimized strategy of "Three Barriers, Three Sources, Three Zones, Multiple Corridors"*

Three barriers

The "Three Barriers" refers to the three major mountain barrier systems: the Luoxiao Mountains, the Nanling-Jiuling Mountains, and the Wuyi Mountains. The Luoxiao Mountains serve as the watershed and source region for the Ganjiang and Xiangjiang Rivers. In the part of Ganzhou, it is called Zhuguang Mountain, which is the southern section of the Luoxiao Mountains. Qiyunshan National Nature Reserve is a key national ecological functional area, characterized by a relatively sparse population, predominantly mountainous terrain, high elevations, steep slopes, high forest coverage, and abundant biological resources. It is also rich in tungsten resources, being a major production area for tungsten and tungsten smelting products in China.

The Nanling Mountains, running east-west across southern China, serve as the watershed between the Pearl River and Yangtze River systems. Jiulianshan National Forest Park is located on the northern slopes of Jiulian Mountain, in the southwestern part of Longnan City at the border between Jiangxi and Guangdong provinces. This

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park is the core part of the eastern Nanling region, boasting rich wildlife resources and forest tourism landscapes, and maintaining the fragile ecological balance and sustainable socio-economic development of the Nanling area.

The Wuyi Mountains refer to the mountain system running north-south between Fujian and Jiangxi provinces, belonging to the northeastern extension of the Nanling Mountains within the Neo-Cathaysian geological unit. These mountains, oriented in a north-northeast direction, stretch along the Jiangxi-Fujian border, extending northeast to the Xianxia Range between Zhejiang and Jiangxi and southwest to the Jiulian Mountains at the Jiangxi-Guangdong border.

The terrain of Ganzhou is generally high in the south and low in the north, with the Luoxiao, Nanling-Jiuling, and Wuyi mountain systems forming the ecological highlands of Ganzhou. It is crucial to strengthen forest conservation and ecological restoration in protected areas to firmly establish the southern ecological barrier.

Three sources

The “Three Sources” refer to the headwaters of the Gan River, Dong River, and Bei River. The Gan River National Nature Reserve, located in Hengjiang Town, Shicheng County, Ganzhou, encompasses an area of 16,100.85 ha. The primary conservation target of this reserve is the mid-subtropical evergreen broadleaf forest ecosystem, classified as a forest ecological type nature reserve. The Dong River originates from Yajiabo Mountain in Sanbiao Township, Xunwu County. The river flows from northeast to southwest in Guangdong Province, eventually entering the Pearl River Delta at Shilong Town, Dongguan City. The basin includes two large reservoirs, Xinfengjiang Reservoir and Fengshuba Reservoir, as well as the Dongshen Water Supply Project, which supplies water to Hong Kong. The Bei River originates from a water point in Xiaomaoshan Mountain, Xinfeng County. Its main stream flows through Nanxiong City, Shixing County, Shaoguan City, Yingde City, and Qingyuan City, connecting with the Xijiang River at Sixianjiao in Sanshui District, Foshan City, before merging into the Pearl River Delta at Xiaohu Island in Huangge Town, Nansha District, Guangzhou City.

The “Three Sources” are of significant importance for the quality of drinking water supply in Jiangxi Province, the Pearl River Delta, and Hong Kong. Comprehensive protection measures must be implemented to protect the ecological environment of the Gan, Dong, and Bei River sources, ensuring clean and safe water sources and promoting sustainable regional development. These measures include forest and vegetation protection, water source protection, pollution control, cross-regional cooperation, and ecological compensation.

Three zones

The “Three Zones” refer to the ecological functional areas for water source conservation, soil conservation, and forest and biodiversity in Ganzhou. Water source conservation ecological function zone is located in the western part of Ganzhou, including Danyu County, Shangyou County, and Chongyi County. The intensity of soil erosion is mainly mild, with water erosion being the primary type. The dominant ecological function is water source conservation. Measures including forest protection and restoration, as well as water quality monitoring should be applied in the zone.

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Soil conservation ecological function zone is located in the central-eastern and northern parts of Ganzhou, including Zhanggong District, Ganxian District, Xinfeng County, Ningdu County, Yudu County, Xingguo County, Huichang County, Shicheng County, Ruijin City, and Nankang District, totaling 10 counties (cities, districts). The area is primarily hilly, with soil types mainly consisting of paddy soil and red soil. Forest types are predominantly single-species, with a focus on Pinus massoniana plantations, and forest quality is low. The soil and water conservation capacity is relatively low, with widespread landslides and severe soil erosion, mainly due to water erosion. The dominant ecological function is soil conservation, and measures including soil erosion control and forest management should be applied in the zone.

Forest and biodiversity ecological function zone is located in the southern part of Ganzhou, including Anyuan County, Longnan County, Dingnan County, Quannan County, and Xunwu County, totaling 5 counties. Soil erosion is relatively severe, with water erosion as the primary type. The dominant ecological functions are biodiversity and soil conservation. The ecological protection measures for this area should include biodiversity conservation and habitat restoration (Shen et al., 2023).

Multiple corridors

The term “Multiple Corridors” refers to the 33 ecological corridors proposed in this paper. The existing ecological corridors traverse Ganzhou in all directions (east, west, south, north) and connect all ecological sources except for source areas 2 and 15. Various types of forest land are important components of these ecological corridors. Ecological corridors are central to ensuring regional ecological security and provide essential migration pathways among ecological sources.

To maintain the ecological functions of these corridors and ensure they play a central role in regional ecological security, measures such as strengthening forest resource protection and management, restoring degraded areas, protecting habitats, and conducting ecological monitoring and assessment should be implemented.

Limitations and prospects

Firstly, the analysis of the temporal evolution of the ecological security pattern in Ganzhou could been conducted in further study. Existing studies have focused on predicting the temporal evolution of regional ecological sources and corridors under different scenarios (Nie et al., 2022, 2023). The use of the temporal dimension allows the construction of future scenarios and the assessment of patterns of ecological security under different scenarios. Future scenario simulations can include “natural evolution scenarios,” “low intervention scenarios” and “high intervention scenarios.” Analysis of these scenarios allows prediction of possible future ecological patterns and helps to identify which strategies are most conducive to ecological security.

Secondly, more indicators could be added to the assessment of the importance of ecosystem services to increase the objectivity and comprehensiveness of the assessment. In this study, the value of key ecosystem services in Ganzhou is evaluated using the NPP quantitative index method. The interference of human socioeconomic activities on ecological sources within the urban ecosystem and the impact of landscape connectivity at different scales on ecological processes is not sufficiently emphasized (Wu et al., 2019). Incorporating social, economic, and natural elements into the evaluation model would facilitate a more accurate assessment of the importance of ecosystem services (Lin et al., 2023).

Lastly, the identification of ecological sources in city needs further refinement. This study selects patches larger than 100 km^2 within overlapping areas as ecological sources. However, it neglects important urban green landscapes such as national wetland parks. Urban green spaces play an important role in enhancing urban ecosystem services, mitigating the urban heat island effect, and improving air quality. However, traditional ecological security pattern analysis may not adequately capture small-scale urban green spaces. Future research should accurately integrate urban green spaces into the ecological security pattern model using high-resolution remote sensing imagery and unmanned aerial vehicle technology. Refined classification algorithms can be used to identify different types of green spaces and quantify their ecological contributions, providing a basis for urban green space planning and optimization of ecological security patterns.

Addressing these limitations will enable a more comprehensive and accurate assessment of the ecological security pattern in Ganzhou, providing a stronger scientific basis for regional ecological protection and management decisions.

Conclusion

Ganzhou, as a typical region of mountainous and hilly urban areas, boasts high habitat quality but is environmentally fragile and sensitive, urgently requiring targeted protection and restoration. This study identifies ecological sources through comprehensive ecosystem service valuation and MSPA analysis. We constructed resistance surface based on land use types, elevation, and slope, and corrected them using nighttime light data. The MCR model was employed to extract corridors between ecological sources, while the gravity model identified critical ecological corridors. The research findings are as follows:

(1) The areas of moderate and above importance for comprehensive ecosystem service value in Ganzhou are predominantly situated in the eastern and southern regions of the study area, encompassing a total area of 22,822.64 km^2. The core area, as determined by the MSPA analysis method, is approximately 16,438.85 km^2. By overlaying areas of moderate and above importance in comprehensive ecosystem services with core area patches larger than 100 km^2, 17 ecological sources were identified, covering a total area of 4,104.21 km^2. These areas essentially encompass the significant national geological parks, nature reserves, and forest parks in Ganzhou. The high-resistance surface, corrected using nighttime light data, are mainly distributed in the central urban areas of Ganzhou, with particular concentration in the Gankang Basin, Xinfeng Basin, and Ruixingyu Basin. The MCR model identified 33 ecological corridors, with a total length of 2,220.1 km. Through the gravity model, 18 critical ecological corridors were determined, with a total length of 1,471.9 km. These ecological corridors effectively connect all the ecological sources, thereby constructing the ecological security pattern of Ganzhou.

(2) By optimizing the spatial distribution of ecological elements in Ganzhou, we propose an ecological security pattern optimization plan characterized by “Three Barriers, Three Sources, Three Zones, Multiple Corridors” as the foundational framework for the sustainable development of Ganzhou. The primary strategies for achieving ecological security in Ganzhou include enhancing the barrier functions of the three major mountain ranges, improving the ecological compensation mechanisms for water sources, and strengthening river and wetland protection to achieve integrated

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ecosystem conservation. Furthermore, the comprehensive restoration of ecosystem sensitivity will be pursued through measures such as controlling soil erosion and landslide management within watersheds, as well as implementing ecological protection and restoration of watershed mines. To ensure the security of ecosystem biodiversity, a biodiversity network will be established, and biodiversity monitoring activities will be conducted.

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