

Article

Ecological Network Optimization in Highly Urbanized Areas: Achieving Connectivity Between Natural and Human Activity Spaces—A Case Study of Guangzhou

Zhi Li ^{1,2,*}, Yifeng Wang ^{1,†} and Gengyuan Liu ³ 

¹ School of Architecture and Urban Planning, Guangdong University of Technology, Guangzhou 510090, China; wangyifeng1@mails.gdut.edu.cn

² Frontier Interdisciplinary Institute of Resources and Environment, Beijing Normal University, Zhuhai 519087, China

³ State Key Laboratory of Regional Environment and Sustainability, School of Environment, Beijing Normal University, Beijing 100875, China

* Correspondence: china-lizhi@gdut.edu.cn

† These authors contributed equally to this work.

Abstract

The insufficient connectivity between human activity spaces and the natural environment impairs ecosystem connectivity and leads to the gradual compression of the natural environment by human activity spaces. In highly urbanized areas, human activity spaces and natural environments are often disconnected, yet few existing ecological network studies have actively incorporated human activity spaces into the an optimization framework to promote their integration with natural ecosystems. Taking Guangzhou as a case study, this research integrates MSPA-InVEST (the Morphological Spatial Pattern Analysis—Integrated Valuation of Ecosystem Services and Trade-offs model), landscape connectivity assessment, the MCR model (Minimum Cumulative Resistance model), and the gravity model to identify ecological sources and potential corridors. It innovatively introduces enterprise kernel density to add planned sources and planned corridors, thereby developing an ecological network optimization scheme that achieves spatial integration between human activity spaces and the natural environment. The results identified 38 ecological sources (total area ~2907.65 km², accounting for 39.07% of the study area) and 46 basic ecological corridors, showing a spatial pattern of “dense in the north, sparse in the central-south”. The addition of 7 planned sources and 22 planned corridors increased the network’s closure, connectivity, and linkage rate by 115.38%, 24.79%, and 23.26%, respectively, with the overall connectivity reaching 0.53. The spatial pattern shifted from an uneven distribution to a “north–south linkage and full coverage” layout. The optimized ecological network effectively connects the major ecological source areas in Guangzhou and, in combination with natural corridors such as rivers, forms a comprehensive ecological security pattern of “mountains–water–forests–city”, thereby constructing a comprehensive ecological network framework for highly urbanized areas. This method takes into account both ecological integrity and economic spatial demands, providing a scientific reference for the construction of ecological networks and the optimization of territorial space in high-density megacities, with the ultimate goal of integrating human activity spaces with natural ecosystems and fostering sustainable development.



Academic Editor: Salvador García-Ayllón Veintimilla

Received: 21 April 2026

Revised: 24 May 2026

Accepted: 18 June 2026

Published: 16 July 2026

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Keywords: ecological source area; ecological corridor; ecological network; planning corridor; Guangzhou

1. Introduction

The survival and development of humanity hinge on the maintenance of biodiversity and the continuous provision of ecosystem services [1]. In recent years, the rapid urbanization process in China has triggered significant ecological stress effects [2]. Under the combined influence of urban construction land expansion and high-intensity human activities, natural habitats have been largely lost and show a trend of fragmentation [3,4]. This not only exerts immense pressure on the quality of regional human settlements but also undermines the overall development resilience of urban–rural systems [5]. Achieving a dynamic balance between economic and social development and ecological protection, and constructing a sustainable development path for harmonious coexistence between humans and nature have become critical priorities for promoting high-quality economic development [6,7]. Establishing an ecological security pattern not only aids in systematically assessing ecosystem service functions and revealing the spatial distribution of ecologically fragile areas but also provides a key path for resolving the dilemma between ecological protection and economic development [8,9]. Therefore, building ecological networks has become an important means of maintaining ecosystem connectivity, which is of great significance for ensuring ecosystem service functions and promoting regional ecological balance [10].

Existing research often adopts a technical framework of “source area identification–resistance surface construction–corridor extraction–ecological network optimization” [11]. Corridor extraction primarily utilizes the minimum cumulative resistance model (63.3%) and circuit theory (32.3%) [12]. In terms of ecological source area identification, large natural patches are often directly selected [13], or extraction is carried out based on assessment methods such as ecosystem services [14] and habitat quality [15,16]. Resistance surface construction commonly employs a method that combines land type assignment with nighttime light data correction. Specifically, based on setting basic ecological resistance coefficients according to land use types, the VIIRS/DNB nighttime light index is used to characterize human activity intensity and then correct the resistance values of each grid cell [17].

However, current research primarily focuses on the construction of ecological networks, while the supporting aspects such as the planning and design of landscape elements, network effectiveness evaluation, landscape pattern optimization, and application of results remain relatively weak. This may lead to the constructed ecological security pattern failing to achieve the expected effect [18]. Furthermore, the ecological consequences of human economic activities are often simplified as a single resistance factor, making it difficult to effectively integrate economic activity spaces into the existing analytical framework of ecological networks in areas with high urban development intensity. This results in an uneven spatial distribution of ecological networks, hinders the realization of harmonious coexistence between humans and nature, and further exacerbates habitat degradation, weakening the capacity of ecological sources to mitigate the negative effects of high-intensity construction areas on the environment [19]. In the process of ecological network optimization, this study incorporates high-intensity human activity spaces into the construction of the ecological network. Unlike previous studies that regarded such spaces as areas with negative ecological impacts and thus avoided them, this study integrates them as part of ecological network optimization.

This study addresses the following research questions: How can the ecological network be optimized to achieve spatial integration between human activity spaces and natural ecosystems? In highly urbanized areas, the lack of necessary spatial connections between human activity spaces and natural ecosystems not only weakens the connectivity of regional ecosystems but also puts the natural environment at risk of being progressively compressed

by human activity spaces. Guangzhou is located in the heart of the Guangdong–Hong Kong–Macao Greater Bay Area and is one of China’s most open and economically dynamic regions, characterized by robust economic momentum. Due to the continuous expansion of urban construction, ecological source areas have been significantly occupied and eroded, and there are almost no continuous ecological corridors within the built-up area. A series of ecological crises, such as frequent urban flooding, intensified heat island effect, and sharp decline in biodiversity, have become increasingly prominent [20]. Therefore, conducting research on the construction of Guangzhou’s ecological network has important practical significance and urgency. At the same time, it can also provide a reference for the study of ecological spatial patterns in other megacities and high-density construction areas. Based on this, this paper uses the MSPA-InVEST model to identify high-quality habitat core patches and determines ecological source areas through landscape connectivity evaluation. Furthermore, it utilizes the minimum cumulative resistance (MCR) model and gravity model to construct an ecological network, while coupling enterprise distribution density and high-habitat-quality patches and adding planned source areas and planned corridors, ultimately forming an ecological network system that balances the dual goals of ecological protection and economic development. This study aims to achieve spatial integration of human activity spaces and natural environments. Using Guangzhou as a case study, we seek to provide a scientific foundation for constructing ecological security patterns in highly urbanized areas, ultimately fostering regional sustainable development.

This research advances existing methodologies in two key ways. First, it introduces the enterprise kernel density to quantitatively characterize human activity intensity through kernel density analysis, thereby proactively incorporating economic spatial demands. Second, rather than passively identifying existing ecological elements, this framework proactively integrates planned sources and corridors. Through this proactive intervention, effective integration between human activity spaces and natural ecosystems is achieved in highly urbanized areas, thereby helping to promote sustainable development.

2. Materials and Methods

2.1. Overview of the Study Area

Guangzhou is located between 112°57′ E and 114°03′ E, and 22°26′ N to 23°56′ N, as shown in Figure 1. It encompasses 11 districts, namely Conghua, Zengcheng, Huadu, Baiyun, Huangpu, Tianhe, Yuexiu, Liwan, Haizhu, Panyu, and Nansha, with a total area of 7434.40 km². It has a marine subtropical monsoon climate, with an annual average temperature ranging from 21.5 °C to 22.2 °C, and an annual average precipitation exceeding 1800 mm [21]. As a megacity, Guangzhou is characterized by its vast territory, large population, rapid renewal and development, diverse land types, frequent surface changes, and abundant resources [22]. Building an ecological network at the regional scale has become a key approach for Guangzhou to implement its sustainable development strategy.

2.2. Data Sources

The main data used in this study include the following: the 2020 land use data with a spatial resolution of 30 m, provided by the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences (<https://www.resdc.cn>) (accessed on 10 July 2025). Landscape types (e.g., water bodies, forestland, cropland, and grassland) were extracted using GIS reclassification tools. Habitat quality was then assessed using the InVEST model. The ALOS PALSAR DEM data at 12.5 m resolution for 2011 (<https://earth.esa.int/eogateway>) (accessed on 10 July 2025) were processed using the slope and relief amplitude tools in GIS to extract slope and relief amplitude data. The 2023 road and railway data from OpenStreetMap (<https://openstreetmap.maps.arcgis.com/home/index.html>)

(accessed on 10 July 2025) were used to construct the resistance surface. The 2019 enterprise data of Guangdong Province, obtained from the Resource and Environment Science Data Platform (<https://www.resdc.cn>) (accessed on 10 July 2025), were used for kernel density analysis. All raster data were processed with GIS projection, and the projection coordinate system was WGS_1984_UTM_Zone_50N.

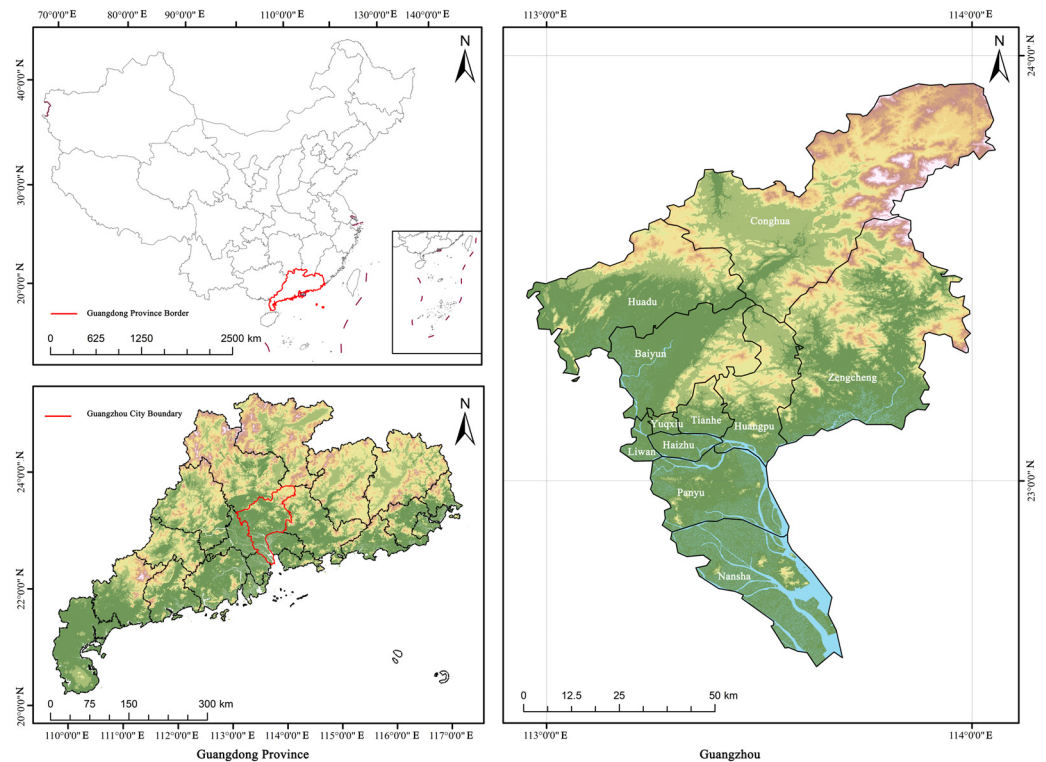


Figure 1. Study area.

2.3. Research Methodology

The specific steps of the research method workflow in this paper are shown in Figure 2.

2.3.1. Ecological Source Area Identification

The identification of ecological source areas is a crucial prerequisite for constructing ecological networks. By utilizing landscape element analysis, MSPA and InVEST models are employed to simulate the spatial distribution of habitat quality. Subsequently, ecological patches are extracted from high-quality core areas to constitute regional ecological source areas, thereby preventing misjudgments or omissions of source areas due to reliance on a single method. In this paper, forest land, grassland, reservoirs, ponds, and lakes are designated as foreground elements, while other land types are set as the background, creating a binary image. Based on the Guidos Toolbox platform, landscape elements are extracted using the eight-neighborhood analysis algorithm. Utilizing the habitat quality assessment module of the InVEST model, cultivated land, urban land, rural residential land, water bodies, and unused land are identified as the primary threat factors to habitat degradation. By combining the weights of threat sources with their spatial impact ranges, the degree and quality of regional habitat degradation are assessed. The relevant parameters involved in the model are primarily determined based on the InVEST model usage guide, existing literature, and expert experience [23–25]. Specific settings are outlined in Tables 1 and 2. The effective range of ecological patches is determined by the overall connectivity of functionally connected patches. Patches with high connectivity can sustain a larger number of biological populations [26]. To quantify this characteristic, Conefor 2.6 software

is employed in this study to analyze the connectivity strength among various landscape patches [27].

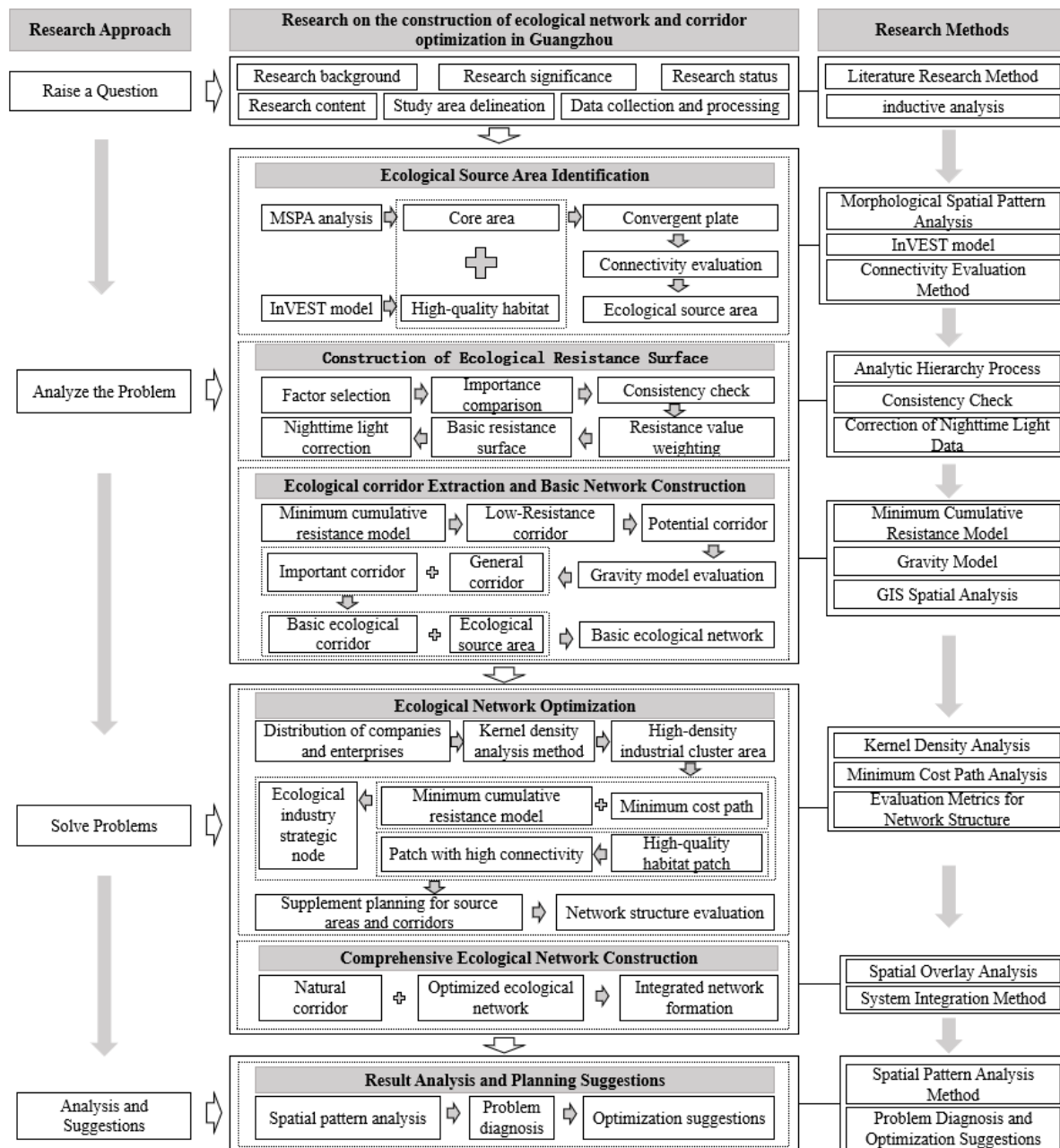


Figure 2. Technical route.

Table 1. Threat source, its maximum impact distance, weight, and attenuation type.

Threat Factor	Maximum Impact Distance (km)	Weight	Attenuation Type
Cultivated land	1	0.6	Linear decay
Countryside	2	0.4	Linear decay
Town	5	0.8	Exponential decay
Waters	3	0.1	Exponential decay
Unutilized land	1.5	0.5	Linear decay

Table 2. Assessment of habitat suitability and its relative sensitivity to different threat sources.

Type	Habitat Suitability	Cultivated Land	Town	Countryside	Waters	Unutilized Land
Paddy field	0.3	0	0.4	0.5	0.3	0.4
Dry land	0.2	0	0.3	0.4	0.1	0.3
Woodland	0.9	0.3	0.5	0.6	0.7	0.2
Shrubland	0.8	0.2	0.4	0.5	0.6	0.2
Sparsely wooded land	0.6	0.2	0.3	0.4	0.5	0.1
Other Woodlands	0.5	0.3	0.4	0.5	0.6	0.2
High-coverage grassland	0.8	0.5	0.3	0.3	0.3	0.6
Medium-coverage Grassland	0.7	0.4	0.3	0.3	0.3	0.5
River	0.7	0.1	0.7	0.8	0	0.2
Reservoirs, Ponds	1	0.1	0.7	0.7	0	0.2
Mudflat	1	0.1	0.7	0.9	0.5	0.2
Floodplain	1	0.1	0.7	0.9	0.4	0.2
Urban land	0	0	0	0	0	0.1
Rural residential Land	0	0	0	0	0	0.1
Land designated for public Transportation Construction	0	0	0	0	0	0.1

2.3.2. Resistance Surface Construction

The ease of species migration is jointly influenced by natural background and human disturbance, with different factors exerting varying directions of influence. Existing research has confirmed that the combination of landscape pattern and topography can alter the effectiveness of transmission of matter, energy, and information in a region. As the distance from roads increases, the gravitational force of urban expansion weakens, making species migration easier. The closer to water bodies, the higher the ecological mobility, which is more conducive to the expansion of ecological source areas. In constructing the ecological resistance surface, this study referred to relevant research [28–31] and selected five resistance indicators: landscape type, slope, topographic relief, distance to transportation routes, and distance to water bodies. The distance from transportation routes indicator was further subdivided into two sub-indicators: distance from railways and distance from roads. During the assignment process, spatial differences in habitat suitability under different landscape and topographic conditions were comprehensively considered, and distance decay laws were incorporated to grade and assign values to each factor. Based on this, a resistance factor discrimination matrix was constructed by referring to existing research results, and a consistency check was conducted to ensure the scientificity and rationality of the matrix.

The Analytic Hierarchy Process (AHP) can be utilized to determine the weight values of resistance factors in Guangzhou. As a multi-objective decision-making model, this method enables quantitative analysis by comprehensively considering the ecological significance of various factors. By converting expert experience into weight values, this method combines systematicness and operability, providing a scientific basis for constructing resistance surfaces.

(1) Construction of hierarchical model and judgment matrix

After a comprehensive and in-depth analysis of the impact of various relevant factors in the Guangzhou region, a hierarchical structure model was constructed from top to bottom based on the correlation of these factors. In this model, each level is closely connected, and based on both expert experience and relevant literature research [32,33], each resistance

factor is scored. Then, a judgment matrix was constructed by comparing each indicator pair (see Table 3) [34], with the formula as follows:

$$r_{ij} = \frac{1}{r_{ji}}$$

In the formula, r_{ij} represents the comparison result of the relative importance between factor i and factor j . Based on the aforementioned theories and standards, a judgment matrix for each evaluation factor of Guangzhou has been established. Details are provided in Table 4.

(2) Consistency check and calculation of factor weight values

In the process of calculating weights using the AHP, conducting a consistency check is a crucial step. This check aims to evaluate the consistency of the weight calculation results, that is, to calculate the value of the Consistency Ratio (CR). The formula is as follows:

$$CR = \frac{CI}{RI}$$

In the formula, $CI = (\text{maximum characteristic root} - n) / (n - 1)$. When $CR < 0.1$, the judgment matrix passes the consistency check, indicating that the weight calculation results are consistent; conversely, if $CR \geq 0.1$, the consistency of the judgment matrix is poor, and it is necessary to readjust the factor parameters and perform analysis again.

Table 3. Criteria for constructing the factor importance judgment matrix.

Scale r_{ij}	Meaning
1	r_i and r_j are of equal importance
3	r_i is slightly more important than r_j , and the reverse is 1/3
5	r_i is significantly more important than r_j , and the reverse is 1/5
7	r_i is more important than r_j , and the converse is 1/7
9	r_i is extremely important compared to r_j , and the converse is 1/9
2,4,6,8	The middle value between the two neighboring judgments mentioned above

Table 4. Evaluation factor judgment matrix of resistance surface.

Evaluation Factor	Landscape Type	Slope	Undulation	Distance from the Road	Distance from Water Bodies
Landscape type	1	9	8	5	3
Slope	1/9	1	1/2	1/7	1/8
Undulation	1/8	2	1	1/6	1/7
Distance to transportation routes	1/5	7	6	1	1/3
Distance to water bodies	1/3	8	7	3	1

In this study, based on the constructed judgment matrix, the calculation yielded a CI of 0.09071 and an RI of 1.12, leading to a CR of 0.08099, which is less than 0.1. This indicates that the judgment matrix meets the consistency check requirements, and the resulting weights are consistent. The final determined weight values for each evaluation factor are shown in Table 5.

Table 5. Assigning resistance factors.

Resistance Factor	Weight	Indicator	Resistance Coefficient	Resistance Factor	Weight	Indicator	Resistance Coefficient
Landscape type	0.42	Woodland, Wetland	1	Undulation (m)	0.08	16~38	10
		Rivers, Lakes	5			38~75	50
		Reservoirs, Ponds	10			75~128	75
		Arable land, Garden land, Grassland	15			128~243	100
		Urban green Space	20	Distance to roads (m)	0.2	>500	1
		Countryside	30			400~500	10
		Railway, Highway	60			250~400	50
		Town	80			150~250	75
		Mining and Industrial	100	Distance to transportation routes	0.2	0~150	100
		Bare ground	50			>1000	1
Slope (°)	0.05	0~3	1	Distance to railways (m)	0.25	500~1000	40
		3~6	10			200~500	75
		6~13	50			0~200	100
		13~23	75	Distance to water bodies (m)	0.25	<800	1
		23~67	100			800~1500	10
Undulation (m)	0.08	0~16	1			1500~2000	80
						>2000	100

After completing the aforementioned assessments, all resistance factors were imported into ArcGIS 10.8 and processed to categorize them into different resistance values. Based on the calculated weight values, the single-factor raster data was weighted and overlapped in ArcToolbox, ultimately yielding the resistance surface evaluation results for Guangzhou City. The specific formula is as follows:

$$W = \sum_{i=1}^n a_i x_i$$

In the formula, a_i represents the weight coefficient corresponding to the i -th ecological sensitivity evaluation index, while x_i represents the i -th ecological sensitivity evaluation index.

Previous studies have proven that nighttime light data can comprehensively reflect the intensity of human activities [35]; therefore, this paper applies it to the correction of the resistance surface [36], thereby enhancing the accuracy and rationality of corridor simulation. The formula is as follows:

$$R^* = \frac{TLL_i}{TLL_a} \times R_o$$

In the formula: R^* represents the corrected grid resistance coefficient; TLL_i is the nighttime light intensity value of grid i ; TLL_a is the average nighttime light intensity value of land type a (obtained by calculating the arithmetic mean of nighttime light values for all rasters within that land type); and R_o is the basic resistance value of grid i .

2.3.3. Ecological Corridor Extraction

An ecological corridor is essentially a low-resistance ecological connection zone that ensures the spatial continuity and smoothness of ecological processes such as material circulation and energy flow by connecting isolated habitat patches. Based on the minimum cumulative resistance (MCR) model combined with the cost path tool of ArcGIS, this study defines potential ecological corridors by simulating the minimum cumulative resistance paths linking ecological source areas. On this basis, the gravity model [37] is introduced to quantitatively assess the spatial interaction intensity between source patches, thereby identifying corridors that play a key role in maintaining regional ecological connectivity.

3. Results and Analysis

3.1. Ecological Source Area

3.1.1. Landscape Analysis Based on MSPA

Based on the MSPA method, the binary image is divided into seven non-overlapping landscape categories: Core, Islet, Loop, Bridge, Perforation, Edge, and Branch. After analyzing forest land, grassland, reservoirs, ponds, and lakes as foreground elements, it is found that among the seven types of landscapes mentioned above, the Core area occupies the largest area, accounting for 90.2%, primarily consisting of forest land, which is mostly distributed in the northern Conghua District, the periphery of Zengcheng District, the northern part of Huadu District, and Baiyun Mountain in the central part. In the core areas of Panyu District and the southern part of Huadu District, the number and size of patches are small, showing sporadic patchy aggregation. The Edge area, second only to the Core area in area, accounts for 7.4%, serving as a transition between the Core area and non-ecological landscapes, exhibiting edge effects. The Perforation area accounts for 1.6%, indicating the presence of some “holes” within the Core area, such as small patches of bare land or buildings among the forests, suggesting signs of internal fragmentation in some Core areas. Other landscape types account for a relatively small proportion. In summary, although Guangzhou has large patches of Core area, their spatial distribution is uneven, with a significant proportion of Edge area, indicating a notable squeezing effect of urban expansion on ecological landscapes. The proportion of Bridge area is limited, as Bridge areas are narrow corridors connecting different Core areas. The extremely low proportion of Bridge area implies that there is almost no interconnection between Core areas. The low proportion of Loop and Branch indicates the lack of effective linear connecting structures within and at the edges of patches. The perforation area accounts for 1.6%, indicating signs of internal fragmentation in some Core areas. Furthermore, Islets are completely isolated small patches. Although their small proportion is beneficial, indicating that there are not many completely isolated fragments, combined with the lack of Bridge area, it highlights the direct disconnection between large patches.

3.1.2. Habitat Quality

The suitability of the ecological environment is often gauged by habitat quality. This study quantitatively assesses the habitat quality of Guangzhou based on the habitat quality module in the InVEST model, with the calculation formula as follows [38]:

$$Q_{ij} = H_{ij} \times \left(1 - \frac{D_{ij}^2}{D_{ij}^2 + K^2}\right)$$

In the formula, Q_{ij} represents the habitat quality index of grid i within land use type j ; H_{ij} represents the habitat quality suitability of grid i in land use type j ; D_{ij} represents the level of stress experienced by grid i in land use type j ; and K represents the half-saturation parameter.

Based on the InVEST model, the habitat quality in Guangzhou was assessed. With the aid of ArcGIS's natural breakpoint method, the habitat quality was categorized into high-quality habitat (0.8–1), medium-quality habitat (0.3–0.8), and low-quality habitat (0–0.3). From a spatial distribution perspective, the habitat quality in Guangzhou exhibits a pattern of “high in the north and south, low in the center.” Among them, high-quality habitat accounts for 38.7% and shows significant spatial agglomeration; medium-quality habitat, mostly adjacent to forests and rivers, accounts for 13.5%. Due to the continuous expansion of surrounding development and construction activities, there is a hidden risk of habitat degradation in this area; low-quality habitat is clustered in the urban core, along railways and highways, and in areas with high development intensity around them. Due to rapid economic development, strong human activity interference, and a high proportion of construction land in these areas, the original natural ecosystem has been severely damaged. From a spatial structure perspective, there is a lack of gradual ecological buffering between high-quality and low-quality habitats, and local fragmentation issues are prominent. For example, at the junction of Baiyun District and Huadu District, high-quality patches are isolated within a low-quality matrix. This “islandization” pattern is prone to external interference affecting core habitats, posing a hidden risk of quality decline.

3.1.3. Identification and Evaluation of Habitat Sources

Based on the assessment results of the MSPA-InVEST model, high-quality habitat patches were extracted using the natural breaks method and merged with core area patches. Patches with an area of not less than 1 km² were selected as the analysis objects. The connectivity index of each patch was calculated using Conefor software. Referring to existing studies [39,40], patches with a dPC (potential connectivity change index) value greater than 0.2 were identified as ecological source areas. According to the natural breaks method, areas greater than 26, (3, 26), and (0.2, 3) were classified as core source areas, important source areas, and general source areas, respectively. From the perspective of spatial pattern, the overall ecological source distribution in the study area is extremely uneven, with dense distribution in the north and complete absence in the south. Core ecological source areas are distributed in the northeast region, important source areas are distributed in the north, central, and eastern parts, and source areas are also concentrated in the north. There are no ecological patches meeting the connectivity threshold in the south. This indicates that the habitat quality and landscape connectivity in the southern part of the study area are generally poor, and the ecological space is highly fragmented, with great potential for ecological restoration and source area cultivation.

3.2. Resistance Surface Evaluation

Based on Table 5, the resistance factor was calculated to obtain the resistance surface (Figure 3 left), and the ecological resistance surface was formed through nighttime light

correction (Figure 3 right). It was divided into high resistance (>307), relatively high resistance (123~307), relatively low resistance (41~123), and low resistance (0~41) using the natural break method. The results showed that areas with high and relatively high resistance accounted for 7.13% of the total area, mainly concentrated in the central districts of Yuexiu, Tianhe, Liwan, Haizhu, and Huangpu, as well as the central parts of Huadu District and Panyu District. These areas have intensive development and construction activities, strong human disturbance, and significantly compressed expansion space for ecological sources, which further creates significant obstacles to the connectivity among ecological source regions. The low-resistance areas accounted for 70.02%, distributed in woodlands, grasslands, and other areas less affected by humans. The relatively low-resistance areas accounted for 22.85%, mainly adjacent to road systems. The isolation effect of the road network weakens the interconnection between ecological sources, which directly leads to a lack of smooth transition between high- and low-resistance areas in some regions, resulting in narrow ecological transition zones.

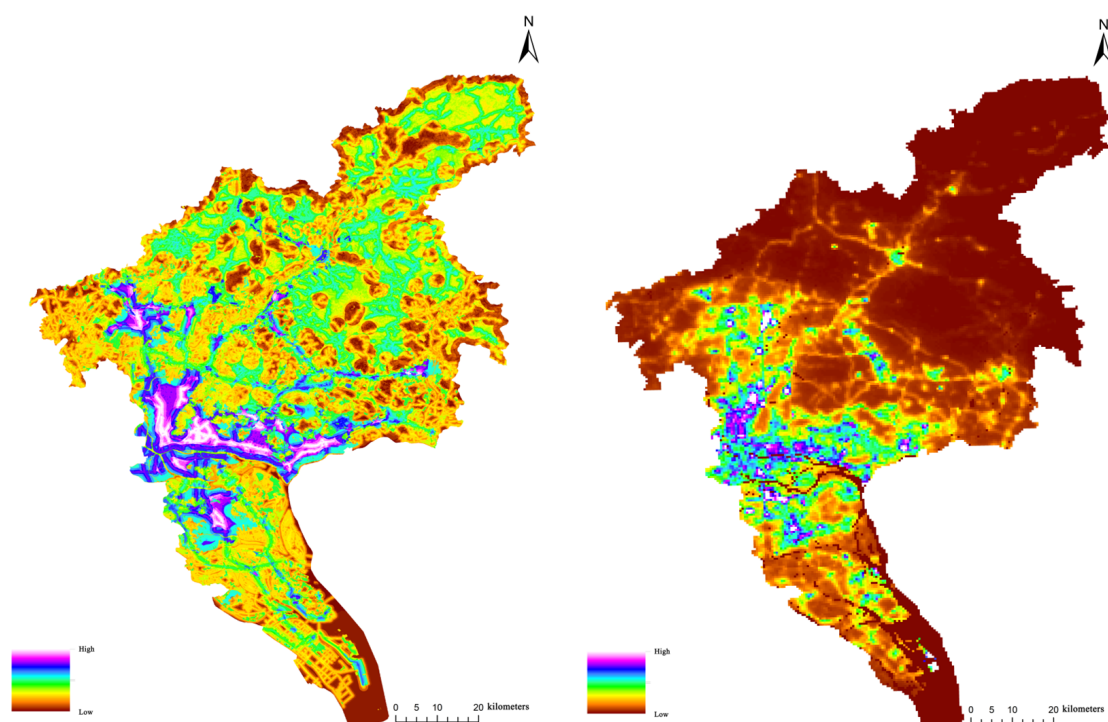


Figure 3. Resistance surface: basic resistance surface (left) and corrected resistance surface (right).

3.3. Ecological Network Construction

3.3.1. Gravity Model

The gravity model can be used to quantify the interaction force between ecological source areas and target patches, and this interaction force is positively correlated with the ecological importance of the corridor. By calculating the interaction strength between different combinations of source areas, corridors that play a crucial role in the diffusion of ecological flows can be effectively identified. This study utilizes this model to screen potential ecological corridors and extract important ecological corridors with strong interaction forces. The specific calculation formula is as follows [41]:

$$G_{ij} = \frac{N_i N_j}{D_{ij}^2} = \frac{\left(\frac{\ln(S_i)}{P_i}\right) \times \left(\frac{\ln(S_j)}{P_j}\right)}{\left(\frac{L_{ij}}{L_{\max}}\right)^2} = \frac{L_{\max}^2 \ln(S_i) \ln(S_j)}{L_{ij}^2 P_i P_j}$$

In the formula, G_{ij} represents the interaction force between core patches i and j . The magnitude of this value reflects the priority of potential ecological corridors between ecological source areas and serves as the weight value of the patches. D_{ij} is the standardized value of the potential corridor resistance between patches i and j . P_i is the resistance value of the patch, and L_{ij} is the cumulative resistance value of the corridor between patches i and j . L_{max} is the maximum value of the cumulative resistance of all corridors in the study area.

3.3.2. Corridor Extraction

Based on the MCR model, a total of 741 potential ecological corridors were extracted. These corridors are densely intertwined in space, with a significant overlap or similar direction of many paths, indicating a high degree of redundancy in the corridor network. To optimize the network structure, it is necessary to filter corridors based on their importance and substitutability. This study employed a gravity model to quantitatively evaluate the corridors. And based on relevant research [42], corridors with a gravity value greater than 1 and a low overlap rate between corridors were ultimately selected as basic ecological corridors. Here, corridors with a low overlap rate refer to those that, after spatial merging processing, do not significantly overlap with each other; where overlaps are obvious, those overlapping portions are merged. As a result, a total of 46 basic ecological corridors (Figure 4), including three important corridors, were identified.

Key corridors serve as the core backbone for maintaining regional ecological security patterns, playing a crucial role in connecting various ecological source areas and ensuring the basic migration needs of species. Specifically, Source Area No.1 is connected to Source Area No. 15 and Source Area No. 9 through key corridors, and similarly, Source Area No. 9 is also linked to Source Area No. 15 via a key corridor. This region is densely populated with grasslands and cultivated land, and has a relatively low density of railway networks, thus experiencing minimal interference from urban construction and transportation. This provides a low-resistance passage environment for species movement. Additionally, the large area of ecological source areas in this region, coupled with overall low ecological resistance values and superior ecological foundation conditions, has attracted a multitude of key corridors, forming a core connected area with high ecological value, thereby ensuring the stability of the ecosystem in this region.

General corridors effectively connect the ecological source areas in the western, central, and northern regions, forming a coherent network covering the northern part of Guangzhou City, ensuring the overall connectivity of ecological flows between regions. Although Source Area No.4 in Wangzi Mountain Forest Park is not directly connected by important corridors with high gravity values, it achieves functional ecological connectivity in this area through general corridors, supporting the exchange of material, energy, and information with various source areas. Overall, general corridors constitute the main framework of the ecological network in the northern part of Guangzhou City, playing a key structural supporting role in maintaining the stability of the regional ecological pattern.

Overall, the existing ecological corridors constitute the basic ecological network of Guangzhou, connecting most of the ecological source areas, supporting material exchange, energy flow, and information transmission between these areas, and providing key passageways for ecological flows. However, there is a significant imbalance in the spatial distribution of corridors. Important corridors are concentrated in the eastern part of Guangzhou and have a relatively limited distribution range. Most connections between source areas are undertaken by general corridors, presenting a pattern of “corridors highly concentrated in the north, with uneven distribution across the entire region.” In addition, the core source area No. 24 in Baiyun District and Tianhe District in the central part, as well as some general source areas, are still isolated due to the high urbanization of the

central urban area and have not been integrated into the overall network. Due to the barrier of large areas of urban construction land between the west and central ecological source areas, there is a lack of directly connected corridors. The overall ecological network is not perfect, so from the perspective of ecosystem stability, the supporting capacity of the current ecological network still needs to be improved. Based on ecosystem stability, it is necessary to balance landscape characteristics and economic development needs by adding ecological corridors in the southern part of Guangzhou to optimize the network structure, promote the organic connection between ecological space and economic development space, and systematically integrate and enhance regional ecological service functions.

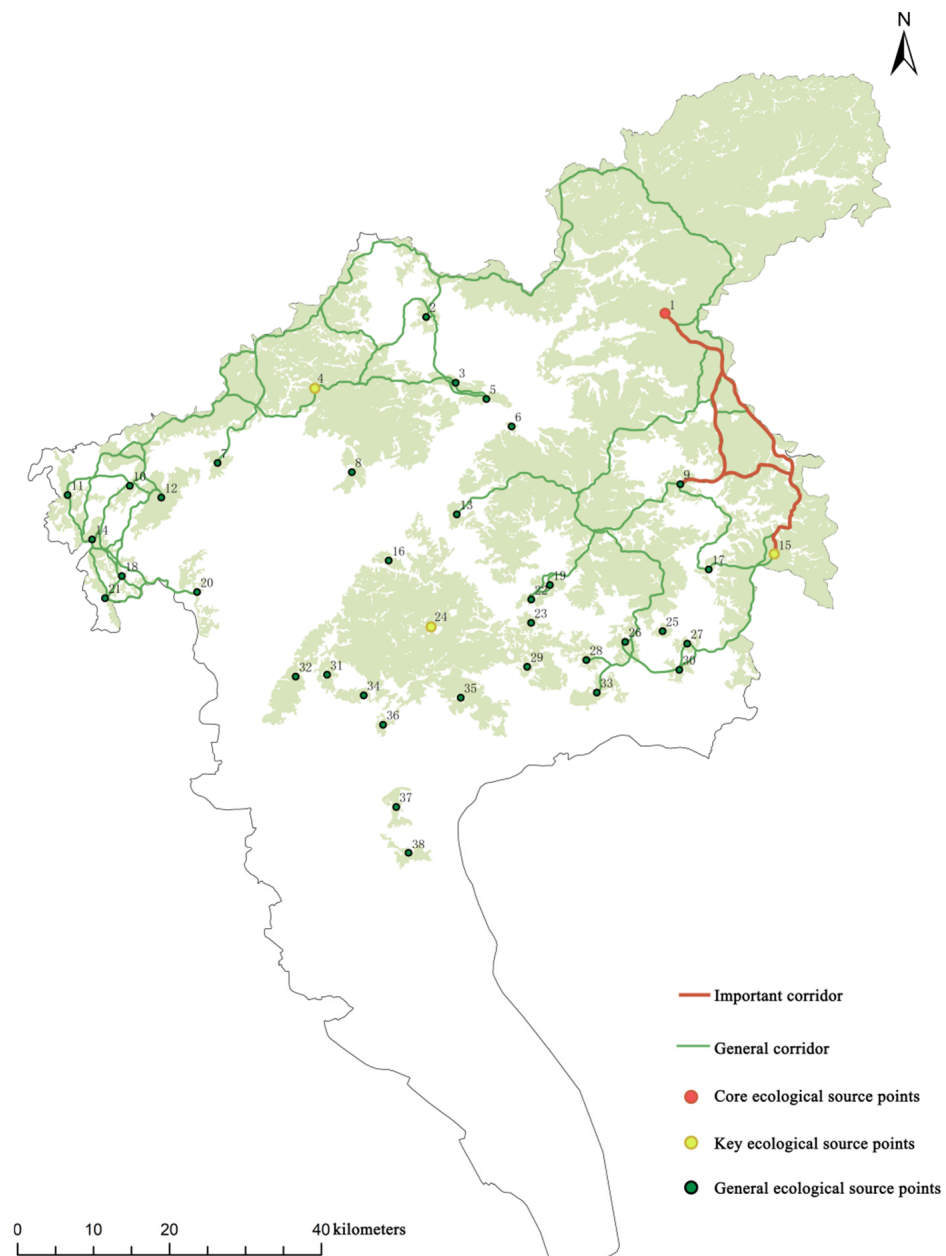


Figure 4. Basic ecological corridor.

3.4. Ecological Network Optimization

In the Guangdong–Hong Kong–Macao Greater Bay Area, Guangzhou ranks among the top in terms of urbanization level and is a typical region with a high concentration of population and industry. The overlay of old factories left over from the early industri-

alization period and dense construction space has led to prominent issues of landscape fragmentation. Especially in the southern region, there is a large distribution of land for transportation infrastructure and urban construction, which urgently requires the improvement of supporting environmental infrastructure to further optimize the regional ecological network structure.

Due to the high level of urbanization in the central region, the No. 24 core source area lacks corridors connecting it to other source areas. By analyzing the spatial distribution of companies and enterprises in the southern part of Guangzhou using the ArcGIS kernel density analysis method (Figure 5a), it was found that high-density agglomeration areas are primarily located in Yuexiu District, Liwan District, Tianhe District, Panyu District, Haizhu District, and Baiyun District. Among these, Tianhe District and Haizhu District exhibit the most significant agglomeration of enterprises, forming the core industrial area of Guangzhou and exhibiting a spatial pattern of radiation and diffusion towards surrounding areas. The kernel density was categorized into five classes using the natural breakpoints method: low, lower, medium, higher, and high density. In the northern part of Baiyun District, where the enterprise kernel density is relatively low, we extracted the least-cost path between the western and central source areas and selected the intersections of this path with the low-kernel-density zone as planned source sites, while removing points that are too close to each other. This approach minimizes disturbance to human activity areas while promoting connectivity between the western and central source areas. In the central region, where the enterprise kernel density is high and north–south connectivity among source areas is severely blocked, we extracted the intersections between the least-cost paths and the high-kernel-density zones, also removing points that are too close to each other. This similarly enhances north–south connectivity while minimizing modifications to high-density development areas. Finally, three sites were selected as the planned source areas in the central region. (Figure 5b).

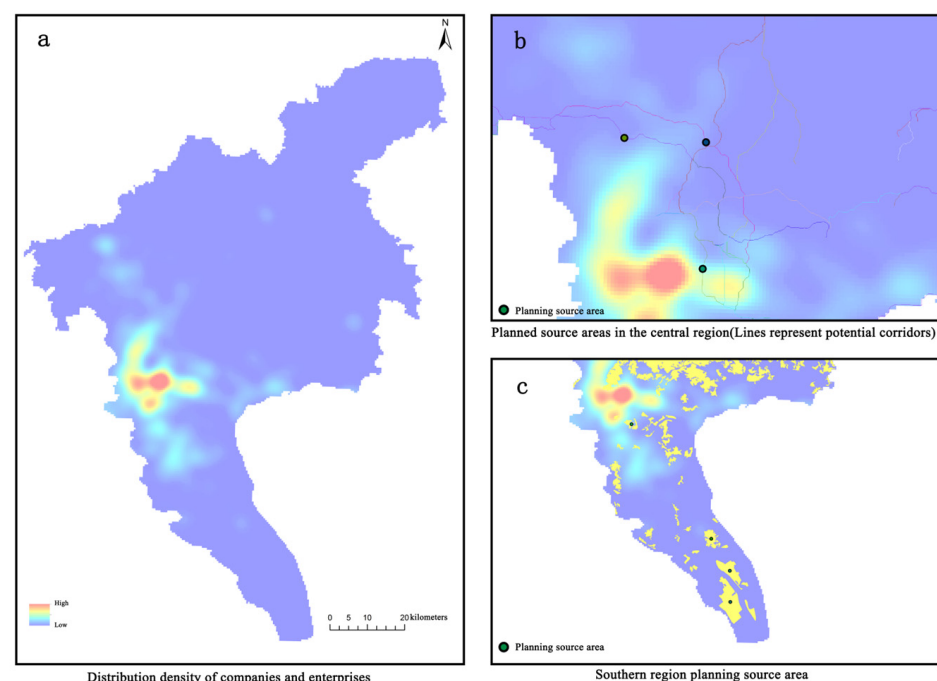


Figure 5. Planned source extraction. (a) Distribution density of companies and enterprises; (b) Planned source areas in the central region (Lines represent potential corridors); (c) Southern region planning source area.

The southern region lacks habitat source areas. In the InVEST habitat quality assessment, although there are some patches with high habitat quality in southern Guangzhou, due to the interference of high-intensity human development activities, their connectivity among patches is low in the Conefor analysis, and they are not identified as ecological source areas. Notably, although the overall connectivity of the southern patches is low, some patches still have a connectivity value (dPC) greater than 0.1, making them relatively better-connected among the southern patches; selecting them as planned source areas can achieve better ecological connectivity. Based on this, in subsequent planning, potential patches with low enterprise density, an area greater than 1 km², and a dPC greater than 0.1 were comprehensively selected as planned ecological source areas. Points that were relatively close in distance were eliminated, and four source area patches were determined (Figure 5c).

Ultimately, 7 nodes were retained, and a total of 22 corridors were added according to the minimum cumulative resistance model (Figure 6). The optimized ecological network effectively enhanced the spatial connectivity between various source areas. The important source area No. 24 in the central region was connected to surrounding source areas through planned source areas and corridors, ensuring the connectivity of various regions in the north. The south was connected to the north through planned source areas and corridors along the Pearl River, which not only protected isolated high-habitat patches in the southern region from the impact of environmental degradation in the surrounding areas but also strengthened the connectivity between high-habitat quality patches, thereby improving the overall ecological environment quality of the southern region. The planned corridors were generally distributed along rivers, reservoirs, and ponds, with some traversing areas with low urban road network density, achieving the minimization of human activity interference and the maximization of patch connectivity. The ecological network's closure, connectivity, and connectivity rate have been significantly improved compared to the previous ecological network (Table 6). Both the number of loops and the average connectivity of nodes in the network structure have increased, transforming the original uneven distribution pattern into a spatial form covering the entire Guangzhou area. Planned corridors complemented the existing ecological network. They promoted the smooth movement of ecological elements across the north–south axis. This optimization shifted the ecological security pattern from a localized configuration toward north–south linkage and full coverage.

Table 6. Network index before and after optimization.

Network Index	Network Closure (α)	Network Connectivity (β)	Network Connectivity Rate (γ)
Basic network (before optimization)	0.13	1.21	0.43
Planning network (after optimization)	0.28	1.51	0.53
Rate of change (%)	115.38	24.79	23.26

Note: $\alpha = (L - V + 1)/(2V - 5)$; $\beta = L/V$; $\gamma = L/[3(V - 2)]$. L is the number of corridors and V is the number of nodes.

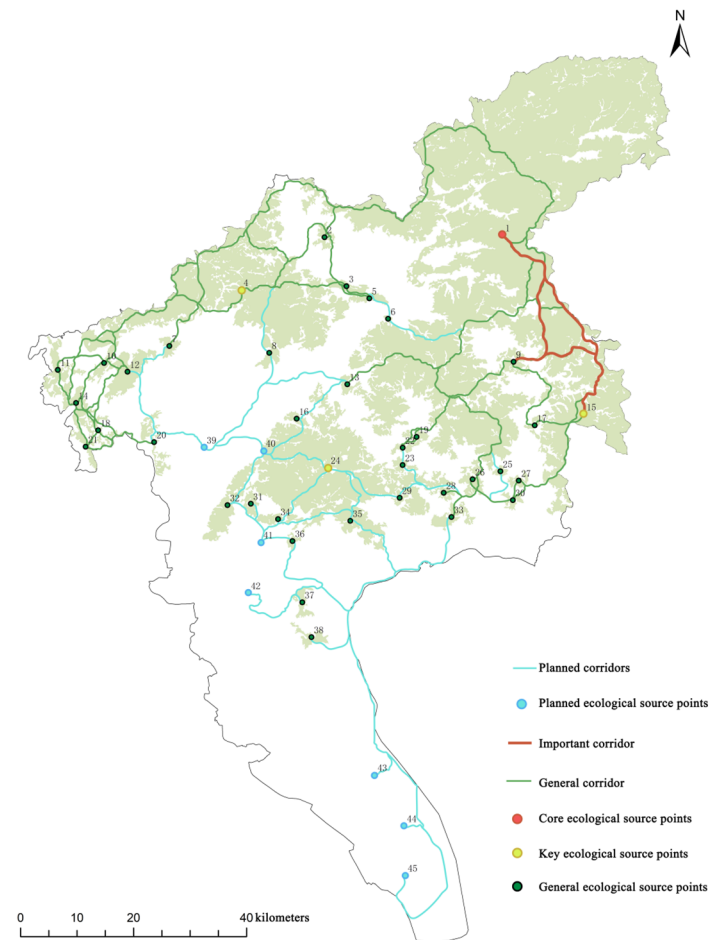


Figure 6. Planned corridor.

4. Discussion

The total area of ecological sources in Guangzhou is approximately 2907.65 km², accounting for 39.07% of the city's total area. The land use type is mainly forest land, indicating that forest land is a key component in maintaining regional ecological stability. Ecological sources are mainly distributed in Conghua District, the outskirts of Zengcheng District, the eastern and northern parts of Huadu District, and the mountainous and hilly areas in the central part of Guangzhou. These areas are characterized by rugged terrain, low population density, and a small proportion of built-up land, which has allowed natural habitats to remain intact. In contrast, in areas with higher urbanization levels such as Yuexiu, Tianhe, and Huangpu Districts, ecological sources are sparsely distributed, reflecting the fragmentation and squeezing effects of intensive urban construction on habitats. In the southern region, large-scale ecological sources have not been formed due to low patch connectivity, which is closely related to the region's historical rapid industrialization and expansion of transportation networks.

The agglomeration density of companies and enterprises in Guangzhou exhibits a gradient pattern decreasing from the central urban area to the peripheral regions. High-density agglomeration areas are mainly concentrated in Yuexiu, Liwan, Tianhe, Panyu, Haizhu, and Baiyun Districts, with Tianhe and Haizhu forming the core industrial area. This distribution pattern leads to two ecological consequences: first, it hinders ecological connectivity between the northern, western, and southern parts of Guangzhou; second, it leaves the core ecological sources in the central region relatively isolated, making it difficult to form

effective connections with surrounding sources. This indicates that corridor construction in industrial agglomeration areas must be a key focus in ecological network optimization.

After optimization, the network closure, connectivity, and connectivity rate increased by 115.38%, 24.79%, and 23.26%, respectively, with the connectivity rate reaching 0.53. The network structure has transformed from the original pattern of “dense in the north, sparse in the central-south” to a “north–south linkage” pattern covering the entire Guangzhou territory. From an ecological perspective, the substantial increase in closure indicates that the network has shifted from an approximately tree-like structure to a network structure with multiple loops, meaning that species dispersal has more alternative pathways, and the network’s ability to withstand local disturbances is expected to be enhanced.

According to the findings from ecological network construction, the following ecological optimization suggestions are proposed: (1) For patches with potential habitat degradation risks, mainly including high-habitat patches surrounded by low-habitat patches and high-habitat patches in the south, it is recommended to combine ecological functional zoning, strengthen the maintenance of internal ecological substrates and the protection of peripheral corridors, and prevent the expansion of low-quality patches. (2) For areas in central Guangzhou with dense urban construction land and high road network density, it is recommended to strengthen the construction of green infrastructure such as pocket parks and road shelterbelts, with native plants as the mainstay and vertical greening as a supplement, to build an ecological connectivity corridor running through the north and south, effectively alleviate the barrier effect between nature and human activity space. (3) The construction of planned source areas in the south is a key link in optimizing the ecological network. The selected source areas themselves have high habitat quality and good ecological foundations. Subsequent construction should focus on building a corridor system connecting various planned source areas, enhancing ecological connectivity between them, and achieving systematic improvement from “point” to “network”. (4) The corridors between the northern and western source areas also require attention. Optimizing corridor structure and function and strengthening ecological connectivity between the source areas may help enhance the overall stability and anti-interference ability of the ecological network. It should be noted that the above recommendations are derived from the high-resistance areas and corridor gaps identified by the model, combined with general principles of landscape ecology. This study did not directly test the empirical effects of green infrastructure (e.g., pocket parks and road shelterbelts) on ecosystem stability. Their actual ecological benefits need to be verified through post-implementation monitoring and evaluation in future planning.

The ecological network constructed in this paper does not fully incorporate urban green spaces, due to the spatial resolution limitations of land use data. Green spaces within urban construction land and other small-scale green spaces have not been effectively identified. In the next step, it is planned to combine high-precision data to construct an ecological corridor framework in the downtown area, further enhancing the ecological connectivity in the north–south direction of Guangzhou and promoting harmonious coexistence between humans and nature. As a proxy for human disturbance, nighttime lights have the advantage of being spatially continuous, objective, and easily accessible, which can mitigate the subjectivity inherent in traditional resistance surface assignment. However, their limitation lies in primarily reflecting nocturnal activities, and the high-light-intensity areas may have varying meanings of resistance for different species, leading to potential proxy biases. In the future, optimization can be achieved by integrating multi-source data with species characteristics. Furthermore, this paper focuses on the construction of the terrestrial ecological network and has not yet achieved land–sea coordination. As a coastal city, Guangzhou is home to typical shoreline types such as mangroves, wetlands, and oyster

reefs, which play an important ecological role in the habitat and reproduction of aquatic organisms and cannot be ignored. Future research should explore methods for constructing ecological networks in the context of land–sea integration, conducting refined analysis on key nodes in coastal areas to enhance the practical relevance and guiding significance of research results.

5. Conclusions

The main contribution of this study lies in proposing a method that actively incorporates human activity spaces into ecological network optimization, breaking through the limitation of traditional studies that treat high-intensity development areas as zones to be avoided. By introducing the enterprise kernel density index as a spatial constraint factor for planned source site selection, and without significantly interfering with existing development spaces, we selected and added planned sources and corridors, increasing the ecological network connectivity rate to 0.53 and achieving a pattern transformation from “dense in the north, sparse in the central-south” to “north–south linkage and full coverage.” Combined with natural corridors such as rivers, this forms a comprehensive “mountains–water–forests–city” ecological security pattern. This framework provides a replicable and transferable ecological network optimization pathway for high-density megacities, enhancing regional ecological connectivity while minimizing impacts on economic development spaces, thus contributing to sustainable development. It offers a reference for territorial spatial planning and ecological restoration, thereby achieving the goal of promoting spatial integration between human activity spaces and natural ecosystems.

Author Contributions: Conceptualization, Y.W.; Methodology, Z.L. and Y.W.; Validation, Z.L., Y.W. and G.L.; Formal analysis, Y.W.; Investigation, Y.W.; Resources, Z.L.; Data curation, Y.W.; Writing – original draft, Z.L. and Y.W.; Writing – review & editing, Z.L., Y.W. and G.L.; Visualization, Z.L. and Y.W.; Supervision, G.L.; Project administration, Z.L.; Funding acquisition, Z.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by The Asian Development Bank’s Knowledge Service Technical Assistance Project, titled “Research on Strategies and Policy Frameworks for Coastal Ecological Conservation and Restoration in Highly Urbanized Areas,” Project No.: TA10216-PRC, and the APC was funded by Research on Ecological Protection and Restoration Strategies and Policies of Coastal Zones in Guangdong’s Highly Urbanized Areas Inception Mission and the Key Projects of National Natural Science Foundation of China (No. 52430003).

Institutional Review Board Statement: Not Applicable.

Informed Consent Statement: Not Applicable.

Data Availability Statement: The original research findings presented in this paper have been included in the article. For further inquiries, please contact the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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