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Constructing Ecological Networks Based on Ecosystem Services and Network Analysis in Chongqing, China

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Abstract: Ecological networks in mountainous regions are vital for enhancing ecosystem functionality and ensuring regional ecological stability, alleviating the contradiction between land use and ecological development in rapid urbanization. However, the complexity of mountains and the need to establish a connection between ecosystem services and human well-being present significant challenges in constructing ecological networks. This study proposes an idea that identifies and derives an optimal scenario for ecological networks, integrating insights from ecosystem services and network analysis. The aim of the ecological network is to improve and protect the ecosystem's stability while better guiding sustainable development in mountainous regions' urban and rural areas. This study uses qualitative evaluation methods and a graph theory model to obtain the ecological network's sources and links. The results indicate that (1) 58 important ecological source areas were identified, with a total area of 5746 km^2, mainly covered by woodland and water bodies. (2) An optimal and feasible scenario comprising 5 horizontal and 14 longitudinal corridors was established. Corridors rely primarily on the river system and mountains. (3) A total of 5 key ecological function areas and some ecological zones in important urban development areas were identified. Control measures for these ecological lands were proposed to enhance the effectiveness of ecosystem service construction. It can be concluded that identifying and deriving an optimal scenario of ecological networks in mountainous regions from the perspectives of ecosystem services and network analysis is feasible.

Keywords: mountain regions; importance of ecosystem services; ecological networks; network analysis; Chongqing

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1. Introduction

In the Anthropocene era, rapid urbanization has led to unprecedented human alterations of the Earth's land surface, posing a threat to ecosystem services supply and, ultimately, human well-being [1–4]. Mountain ecosystems, serving as critical sentinels of ecosystem services, support 22% of the world's population, providing a disproportionate measure of essential ecosystem services, such as freshwater, raw materials, climate regulation, and recreation [5–8]. However, due to unprecedented rates and magnitude of population growth, unsustainable development, and exploitation of resources, the pressure on natural ecosystems in mountain regions is becoming greater and greater, influencing their structure and function [9–11]. This pressure exacerbates landscape fragmentation and decreases landscape connectivity, altering the size, shape, spatial arrangement, and isolation of habitat patches, consequently influencing ecological processes such as soil flow, water, energy, and organisms across landscapes [12]. Consequently, the supply of

ecosystem services in mountain regions is increasingly jeopardized [13,14]. Ongoing research continues to emphasize the indispensable role of ecological networks in developing strategies to regulate specific ecological processes and increase landscape connectivity in vulnerable mountainous areas [15–18], thereby enhancing ecosystem functionality and ensuring regional ecological stability.

Ecological networks in mountain regions are composed of two main components: ecological sources and ecological corridors [19]. Ecological source areas are typically identified by selecting nature reserves, forest parks, scenic areas, wetlands, or core patches [20] or by generating them through land use simulation [21]. Another method involves estimating the value of natural ecosystems, which includes direct market valuation methods and stated preference methods, such as ecosystem functions [22] or value [23], ecosystem health [24], ecosystem service [25], and habitat quality evaluation [25]. Ecological corridors are identified through the connectivity model, such as the minimum cumulative resistance model [26,27], circuit theory [22,25], graph theory and network analysis [28,29], and morphologic spatial pattern analysis [18,30]. However, several authors have noted that further exploration is needed to understand non-utilitarian benefits, primarily provided by regulating and cultural services, as well as to determine the complete value of ecosystem services. Additionally, different valuation methods are necessary to match the broad diversity of values [31,32]. Non-monetary measures like ratings and rankings help address the mountains' complexity and integrate ecological and social issues [33]. Therefore, this study will incorporate ecosystem services using non-monetary approaches and network analysis to provide a more comprehensive and practical approach to establishing ecological networks in mountain regions.

Chongqing, historically renowned as a 'mountain city', has a distinctive ecology and geographical position within the Three Gorges Reservoir area. It stands out as one of China's and the world's most unique ecological zones, serving as a critical ecological barrier in the Yangtze River basin. However, rapid urbanization has triggered significant conflicts between development and ecological conservation, resulting in a continuous reduction in ecological space, escalating soil erosion, severe air and water pollution, and the disorderly layout of urban space [23]. Therefore, this study selects Chongqing as a representative region where the conflict between urban expansion and ecological environmental protection continues to intensify.

This study offers three contributions to the literature: (1) considering ecological functions, development sensitivity, and complexity in mountain regions. Most existing studies focus on ecosystem services using the value measurement method when exploring ecological network construction [34–36]. However, this study integrates ecosystem services using non-monetary approaches and ecological suitability together to evaluate ecological importance. Based on the two evaluation results, ecological networks can protect ecological spaces with high ecosystem service value and avoid the development of highly ecologically sensitive areas in mountain regions. (2) We utilize network analysis methods that are applicable to various spatial scales [37] to formulate ecological network scenarios from which optimal planning solutions are selected. (3) This study conducts a practical analysis of Chongqing using the proposed ecological network construction idea. Based on this ecological network, key ecological function areas and some ecological zones in Chongqing are identified. Furthermore, control measures for these ecological lands are proposed to enhance the effectiveness of ecosystem service construction in mountain regions.

This study aimed to (1) design an ecological network for Chongqing to improve ecosystem services, lighten natural disasters, ensure the region's ecological security, and preserve historical and cultural values in mountain regions and (2) propose an ecological network construction framework by analyzing the importance of ecosystem services using non-monetary measures integrated with network analysis to provide new insights into ecological construction in mountain regions affected by urbanization. The remainder of this paper is structured as follows: Firstly, ecological suitability analysis was conducted to establish an objective basis for ecological network construction. Next, ecosystem services

importance analysis was performed using non-monetary approaches to identify important ecological sources. Subsequently, graph theory was employed to simplify important ecological source areas as nodes for constructing ecological network scenarios, and network analysis was utilized to evaluate the structure, connectivity, and effectiveness of these scenarios. Finally, an optimal scenario was derived. Based on this, spatial control measures were proposed to protect key ecological function areas and key ecological zones within urban areas.

2. Materials and Methods

2.1. Study Area

Chongqing is the area under investigation in this study. Chongqing is located on the eastern edge of the Sichuan Basin, a transition zone between the Qinghai–Tibet Plateau and the middle and lower reaches of the Yangtze Plain, in West–Central China, between 28°10′ and 32°13′ N, 105°17′ and 110°11′ E. It comprises 38 administrative districts, including 24 districts and 14 counties, with an area of about 82,403 km^2 (Figure 1). Chongqing had a population of over 32 million in 2022. The urbanization rate was 70.96% in 2022.

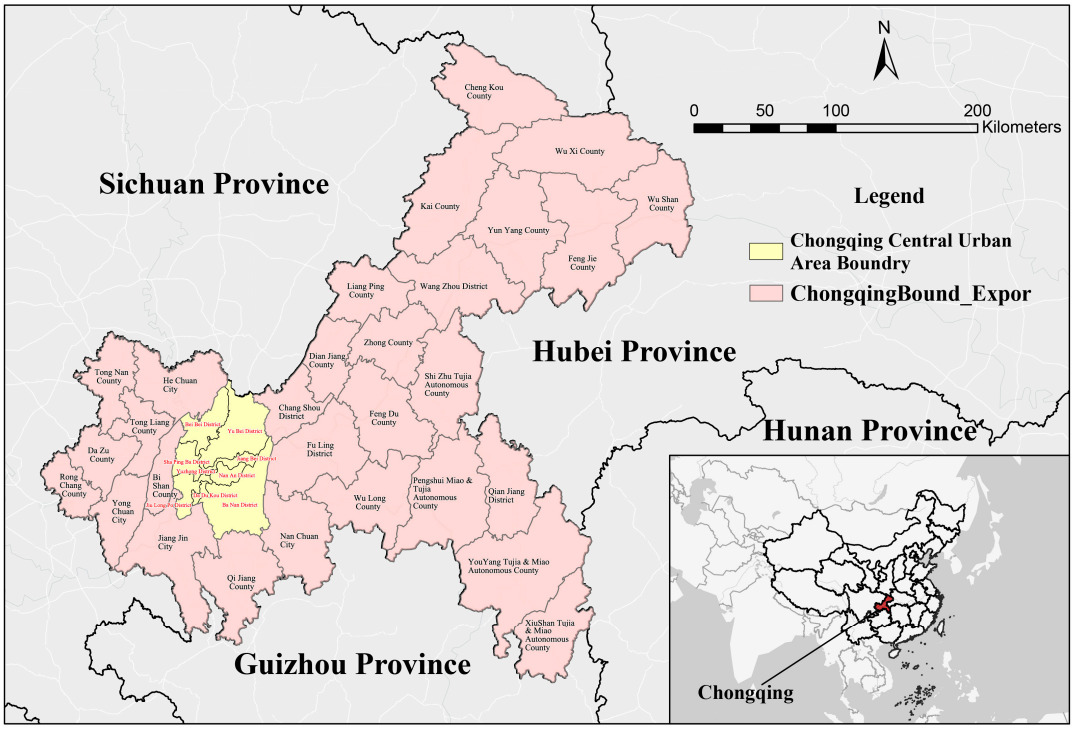


Figure 1. Location of the Chongqing area, China.

Chongqing boasts abundant forest vegetation, biodiversity, and cultural resources, contributing to its high capacity for ecosystem services (Figure 2). Chongqing has a subtropical humid monsoon climate characterized by an average annual temperature ranging from 16 to 18 °C, abundant rainfall of 1000–1450 mm annually, and frequent foggy days. Its topography is dominated by hills and mountainous terrain, covering 76% of the total area, with a forest coverage of 22.3%. Chongqing is recognized as one of China's 17 key biodiversity areas of global conservation importance. Chongqing's river systems, which are characteristic of mountainous regions, feature abundant rainfall, deep valleys, steep slopes, and large gradients, contributing significantly to soil erosion. Chongqing boasts numerous tourist attractions, including the Dazu Rock Carvings (World Heritage Site), the Wulong Karst (World Natural Heritage Site), and the Three Gorges. Moreover, the Three Gorges Reservoir area in Chongqing is an important water function area in China.

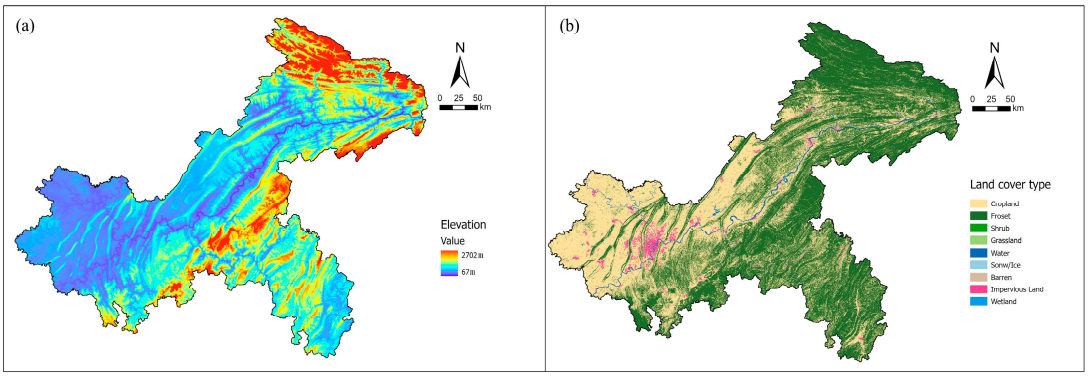


Figure 2. (**a**) The elevation in Chongqing; (**b**) The land cover type in Chongqing.

2.2. Data

The data used in this study are mainly related to ecological suitability and ecosystem services. Land use data were based on interpreting Landsat series satellite images in 2020. Environmental data include digital elevation model (DEM), slope data, and geological disaster data. Ecological functional land data include Nature Reserves, Forest Parks, Scenic areas, Cultural Heritage Sites, and other key ecological areas. NVDI data include Vegetation data and Forest Resources Category II. Water bodies data include rivers, lakes, and water resources. Biodiversity data include national first- and second-level key species and rare and endangered species. All data, including data derived from the sources above and relevant auxiliary data, were converted into raster format for spatial operations to facilitate spatial analysis. All geographic elements were processed according to the World Geodetic System (WGS) 1984 World Mercator projection coordinate system, with raster data of 30 × 30 accuracy (Table 1).

Table 1. Details of all data.

Data	Subdata	Year (s)	Spatial Resolution	Sources
Land use data	Land use	2020	30 m	https://earthexplorer.usgs.gov, accessed on 3 January 2020.
Environmental data	DEM, slope, geological disaster	2020	30 m	https://earthexplorer.usgs.gov, accessed on 3 January 2020.
Ecological functional land data	Nature Reserves, Forest Parks, Cultural Heritage Sites and Scenic Spots, Wetlands	2020	30 m	Chongqing Environmental Protection Bureau, Chongqing Forestry Bureau
NVDI data	Vegetation data	2020	30 m	Chongqing Forestry Bureau
	Forest Resources Category II	2020	30 m	Chongqing Forestry Bureau
Water bodies data	Rivers, lakes, and water sources	2020	30 m	Chongqing Water Resources Bureau
Biodiversity data	National protected animals and plants and endangered animals and plants	2020	30 m	Chongqing Environmental Protection Bureau
Soil erosion data	Soil erosion	2020	30 m	Chongqing Water Resources Bureau

2.3. Methods

In this study, the ecological network in Chongqing was established by coupled ecosystem services, including water conservation, soil conservation, biodiversity conservation,

and cultural ecosystem services, with network analysis to alleviate the contradiction between land use and ecological conservation in rapid urbanization. First, ecological suitability analysis was applied to comprehend the constraints and suitability under the ecological priority scenario in mountain regions. Second, the importance and spatial distribution of 4 types of ecosystem services were investigated via ecosystem services importance analysis using non-monetary approaches. Important ecological service areas were identified based on a comprehensive analysis of ecological suitability and an assessment of integrated ecosystem services. Important ecological source areas were simplified as nodes to construct ecological network scenarios with the graph theory. Ecological network scenarios' structure, connectivity, and effectiveness were assessed with network analysis. Finally, an optimal scenario was obtained. Control measures for key ecological spaces and construction strategies for crucial development areas were proposed. The technical pathway is described in Figure 3.

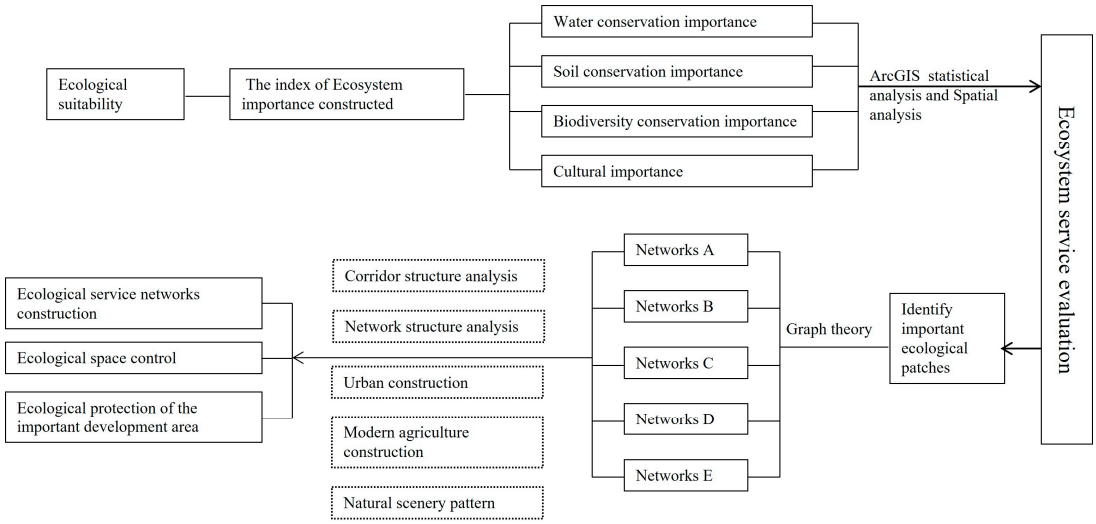


Figure 3. Technical pathway diagram.

2.3.1. Ecological Suitability Analysis

The ecologically suitable areas refer to the ecological elements and substances that significantly influence the overall ecological environment of a region [38]. These areas are challenging to restore if they become damaged. Therefore, this study lays the groundwork for identifying ecological source areas through ecological suitability analysis (Table 2). An ecological sensitivity analysis index system was developed based on previous studies [39–41] while also considering the resource characteristics of Chongqing. This study selects slope, altitude above sea level, lithological character, geological disaster, forest and green space, wetland, nature reserves, scenic spots, forest parks, enclave—nature and cultural reserves, etc., as evaluation indicators of ecological suitability. These indicators encompass considerations for soil and water conservation, biodiversity, and cultural aspects.

With reference to [39–41], each indicator is assigned a value ranging from 0 to 2 based on its importance to Chongqing's ecological security and socio-economic development. Based on a comprehensive understanding of the metropolitan area's ecological environment, the importance of each factor to the regional ecological service function, as well as its sensitivity to human impact and destruction, is comprehensively assessed. A judgment matrix is then constructed through pairwise comparisons, comparing the importance of each factor to the ecological environment. Subsequently, the largest eigenvector of the judgment matrix is calculated, and importance weights are assigned to each indicator. The evaluated results reflect the eco-environmental suitability of Chongqing's ecological networks.

Table 2. Suitability evaluation criteria of ecological land.

Ecological Factors	Classification	Evaluation Value	Weight
Slope	>48%	2	0.15
	25~48%	1	
	<25%	0	
Altitude above sea level	<196 m	0	0.10
	>500 m	1	
	196~500 m	2	
Lithological character	\ [1]	2	0.10
	Carbonate reservoir	1	
	Argillaceous and sandstone	0	
Geological disaster	Geological disaster spots or subsided areas, which are weighty disasters	2	0.15
	Active zone and potentially active zone,	1	
	Non-active zone	0	
Forest and green space	Urban forest space	2	0.10
	Urban green space	1	
	The area which is not forest or green space	0	
Wetland	500 m around medium reservoir	2	0.10
	Converge area of reservoir and water source, wetland isolation paddy field	1	
	Non-water source area	0	
Nature Reserves, Scenic Spots, Forest Park	National and Municipal Nature Reserves, Forest Parks, Cultural Heritage Sites, and Scenic Spots	2	0.12
	\	1	
	The area does not have a Nature Reserve, Forest Park, or Scenic Spot	0	
Enclave-Nature and Cultural Reserves	\	2	0.18
	Enclave—Nature and Cultural Reserve	1	
	Non-Nature, Enclave—Cultural Reserve	0	

[1] "\" means the content other than the options listed in the table.

2.3.2. Ecosystem Services Importance Analysis

Ecosystem services are important and serve as a comprehensive indicator that characterizes the regional-scale ecosystem structure and the significance of ecological functions [42]. Following an analysis of the natural and socio-economic conditions in Chongqing and adhering to regulations outlined by the Ministry of Environmental Protection of the People's Republic of China, we identified four primary ecosystem services: water conservation importance, soil conservation importance, biodiversity conservation importance, and cultural ecosystem importance. These services are pivotal in expressing the regional ecosystem's role in maintaining stability within the region and its surroundings.

Data for the year 2020 were collected and reassessed to ensure accuracy and relevance. A standardization process was implemented to enhance the comparability of ecosystem services' importance indicators, constraining resulting values from 0 to 1. The standardized values (X_1) were calculated using the following formula:

$$X_1 = (Xmax - Xmin)/(X - Xmin) \quad (1)$$

X_{min} and X_{max} represent the minimum and maximum values of the indicator data, respectively.

The importance of water conservation refers to assessing the level of water resource security and flood regulation within the research area [43]. An analysis of the importance of water conservation was conducted by considering the geographical features and the contribution of water resources to the study area. An analysis of the importance of water

conservation was conducted by considering the geographical features and the contribution of water resources to the study area. Based on previous studies [44,45] and the resource characteristics of Chongqing, this analysis considered features such as lakes, reservoir water collection areas, various water conservation forests, and water conservation buffer zones along rivers. The assessment results are categorized into four levels: extremely important, strongly important, moderately important, and slightly important (Table 3).

Table 3. Assessment levels of importance for water conservation.

Affected Targets		Types and Areas of Influence	Classification
River	The hydro-fluctuation-belt of the Three Gorges Reservoir of the main river (urban water sources, flood regulation)	1 km on both sides of the river 2 km on both sides of the river 3 km on both sides of the river	Extremely important Strongly important Moderately important
	Second-order stream (water sources, flood regulation)	200 m on both sides of the river 400 m on both sides of the river 600 m on both sides of the river	Extremely important Strongly important Moderately important
Lake, reservoir, water source protection area			Extremely important
Forest	Water conservation forest (water sources)	Evergreen and deciduous broad-leaved mixed forest, evergreen coniferous forest, evergreen broadleaved forest, mixed evergreen coniferous broad-leaved forest	Extremely important
		Deciduous broad-leaved forest, economic trees, mixed broadleaf—conifer forest	Strongly important
		Brush	Moderately important
Agricultural and other areas			Slightly important

The importance of soil conservation lies in assessing the impact of soil erosion on downstream rivers and water resources, primarily through a sensitivity analysis of soil erosion [46]. Firstly, soil erosion sensitivity in the study area was assessed through factor analysis, incorporating variables such as rainfall erosivity, soil erodibility, slope gradient and length, and land surface vegetation cover, as indicated by previous research. Secondly, the importance of soil protection, particularly for overlaying rivers, lakes, and water source elements, was analyzed based on a sensitivity analysis of soil erosion. The results were classified into four levels: extremely important, strongly important, moderately important, and slightly important, as detailed in Table 4.

Table 4. Assessment levels of soil conservation importance.

Affected Water Body	Sensitivity of Soil Erosion				
	Insensitive	Slightly Sensitive	Moderately Sensitive	Strongly Sensitive	Extremely Sensitive
The 1st- and 2nd-order rivers; The drinking water bodies of large and medium-sized cities	Slightly important	Strongly important	Extremely important	Extremely important	Extremely important
The 3rd-order rivers; The drinking water bodies of the towns	Slightly important	Moderately important	Strongly important	Strongly important	Extremely important
The 4th- and 5th-order rivers	Slightly important	Slightly important	Moderately important	Strongly important	Strongly important

The biodiversity conservation function refers to the role played by the ecosystem in maintaining genes, species, and ecosystem diversity [47]. The importance of biodiversity conservation was assessed using the evaluation method of biodiversity conservation importance in Kunming's research [48]. On the one hand, this study clarified the spatial distribution of species through relevant surveys and research on species listed in the List of Key Protected Wild Animals and Plants in Chongqing Municipality. Based on the classification of protected species, areas containing first- and second-class national protected animals, plants, and endangered species were determined to be extremely or strongly important. On the other hand, the importance of biodiversity conservation was assessed by categorizing various types of nature reserves at all levels. Referring to the 'Technical Guidelines for Evaluation of Resource and Environmental Carrying Capacity and Suitability of Territorial Spatial Development in Chongqing (for Trial Implementation)', three levels of importance (extreme, strong, and moderate) were assigned to national, provincial, and municipal ecological areas, respectively. Due to the ambiguity and complexity of documents and policies, we consulted experts on the importance of biodiversity conservation assessment. For example, the importance of the 'Four Mountains' nature reserve was assessed. In this way, the importance of biodiversity conservation in Chongqing was evaluated, as shown in Table 5.

Table 5. Assessment levels of biodiversity conservation importance.

Classification	Ecological Regions
Extremely important	The area of the first-class nationally protected animals and plants and endangered animals and plants. National Nature Reserves, Forest Parks, and Scenic Spots
Strongly important	The area of the second-class nationally protected animals and plants and endangered animals and plants. Provincial Nature Reserves, Forest Parks, and Scenic Spots. 'Four Mountains' Nature Reserve [1]
Moderately important	The area of other nationally and provincially protected animals and plants. County Nature Reserves, Forest Parks, and Scenic Spots
Slightly important	Other areas

[1] 'Four Mountains' Nature Reserve: In 2007, the Chongqing government introduced the 'Regulation of the Development and Construction Control of Chongqing Four Mountain Area', designating the ecological green spaces of Jinyun, Zhongliang, Tongluo, and Mingyue Mountains as the 'Four Mountains' Nature Reserve. Urban green spaces were also zoned to regulate constructive expansion and ensure protection.

The importance of a cultural ecosystem refers to ecologically functional land with significant national or provincial social and cultural values [49]. This study's natural and cultural heritage evaluation is comprehensive, drawing upon the Cultural Services Importance Assessment methods used in Harbin and Qingdao [34,50]. Therefore, the cultural ecosystem not only encompasses heritage listed in the World Natural and Cultural Heritage List but also includes various levels of Scenic Spots, Nature Reserves, National Forest Parks, and National and Municipal Historical and Cultural Cities, as well as Cultural Heritage Sites at the national and municipal levels, counting only once for those with dual or multiple roles. The results were classified into four levels: Extremely Important, Strongly Important, Moderately Important, and Slightly Important, as depicted in Table 6.

Table 6. Assessment levels of importance for cultural ecosystems.

Ecological Regions	Classification
National Nature Reserves, Forest Parks, and Scenic Spots	Extremely important
Special significance national conservative heritage unit. Municipal Nature Reserves, Forest Parks, and Scenic Spots	Strong important
Historical significance municipal conservative heritage units	Moderately important
Historical significance district Scenic Spots and district conservative heritage units	Slightly important

2.3.3. Identifying Ecological Source Areas

Important ecological source areas were identified through a comprehensive analysis of regional ecological conditions and an assessment of ecosystem services. The central position of each parcel within the regional ecosystem and the significance of ecological services were considered in this process. After evaluating the importance of water conservation, soil conservation, biodiversity conservation, and the cultural ecosystem, hierarchical maps were created to integrate the importance of individual ecosystem elements. These maps helped determine whether the importance of each grid unit's ecosystem was singular or composite. In cases of singular ecosystem importance areas, the importance of individual ecosystem factors was assessed based on their importance within the ecosystem. Conversely, the primary factors influencing ecosystem importance were identified using the maximum limiting factor method in composite ecosystem importance areas. The overall importance of the ecosystem was then determined based on the ecological significance of these primary factors.

$$EIF = Max\ (WF, SF, BF, CF) \quad (2)$$

EIF: Ecosystem importance;
WF: Importance of water conservation;
SF: Soil conservation importance;
BF: Importance of biodiversity conservation;
CF: Importance of cultural ecosystem.

After analyzing the comprehensive importance of ecosystem services and ecological suitability, we utilized regional comprehensive methods, dominant factor analysis, and species aggregation methods to identify and designate specific areas characterized by key ecosystem functions. Based on the comparison between Maryland's and Florida's ecological network practices [51,52], the threshold of ecological source areas is set at 200 hm^2 to support the ecological network construction on this study scale. Then, ecological source areas' boundaries are smoothed to eliminate little tendrils [51] so that ecological source areas can be finally identified.

2.3.4. Network Analysis

Graph theory and network analysis methodologies were employed to construct ecological networks. In graph theory, landscape elements are abstracted into a network structure. This study drew upon network analysis in Xiamen ecological network construction [53]. Patches are referred to as 'nodes', while corridors are identified as 'links and routes' [54]. Branch networks and circuit networks are used in graph theory to interpret the spatial pattern of networks [55]. Network structure analysis, which incorporates indicators illustrating the interrelationships of landscape elements, provides a method to aggregate patch and corridor analysis results [53]. The complexity of a network is measured by concepts such as network circuitry (α index), node/line ratio (β index), network connectivity (γ index), and cost ratio (Cr) [56] (Table 7).

Table 7. The calculation method and index meaning of α, β, γ index and cost ratio.

Index Type	Calculation Method	Index Meaning
α index	$\alpha = (L - V + 1)/(2V - 5)$	The network circuitry (α) is a degree which loops within a network. The α index ranges from 0 for no loops in the network to 1.0 for the maximum number of loops in the network [57].
β index	$\beta = L/V$	A network's node/line ratio ($\beta \leq 1$) presents a dendroid pattern. $\beta = 1$, the network presents a single loop. $\beta > 1$, the network presents more complex connectivity [57].
γ index	$\gamma = L/3(V - 2)$	The network connectivity (γ) index ranges from 0, representing no linking nodes, to 1.0, meaning all nodes are connected [57].

Table 7. *Cont.*

Index Type	Calculation Method	Index Meaning
Cost ratio	Cr = 1 − (numbers of corridors/length of corridors)	Measure different green spaces and network cost differences regarding the socio-economic realities and landscape environment [57].

L: refers to the number of corridors. V means the number of nodes.

2.3.5. Ecological Networks Delineation

In this study, the construction of ecological networks followed the landscape pattern of landscape ecology, adopting the 'patch-corridor-matrix' paradigm. Ecological source areas, exhibiting distinct appearances and properties from the surrounding environment while maintaining internal homogeneity, were classified as 'patches' [58]. Linear ecological source areas, such as rivers, mountains, forests, and forest belts, were regarded as 'corridors' [58]. In this study, nodes refer to any discrete non-linear patch, while links are linear elements [53]. A total of 58 important ecological service areas in Chongqing were selected as nodes. Network alternatives were generated based on the 58 nodes (Figure 4). Network A depicted a simple branched network, linking only central nodes, while Network B interconnected all 58 nodes. Network C consisted of two major circuits, while Network D represented a complex multi-circuit network reflecting optimal connectivity. During the formation process, obstacles to corridor development were considered and modified based on urban construction and agricultural development. Subsequently, ecological network types A-E were established. Finally, an optimal scenario for the ecological network in Chongqing was selected using parameters such as length, density, and number of corridors; α index; β index; γ index; and cost ratio.

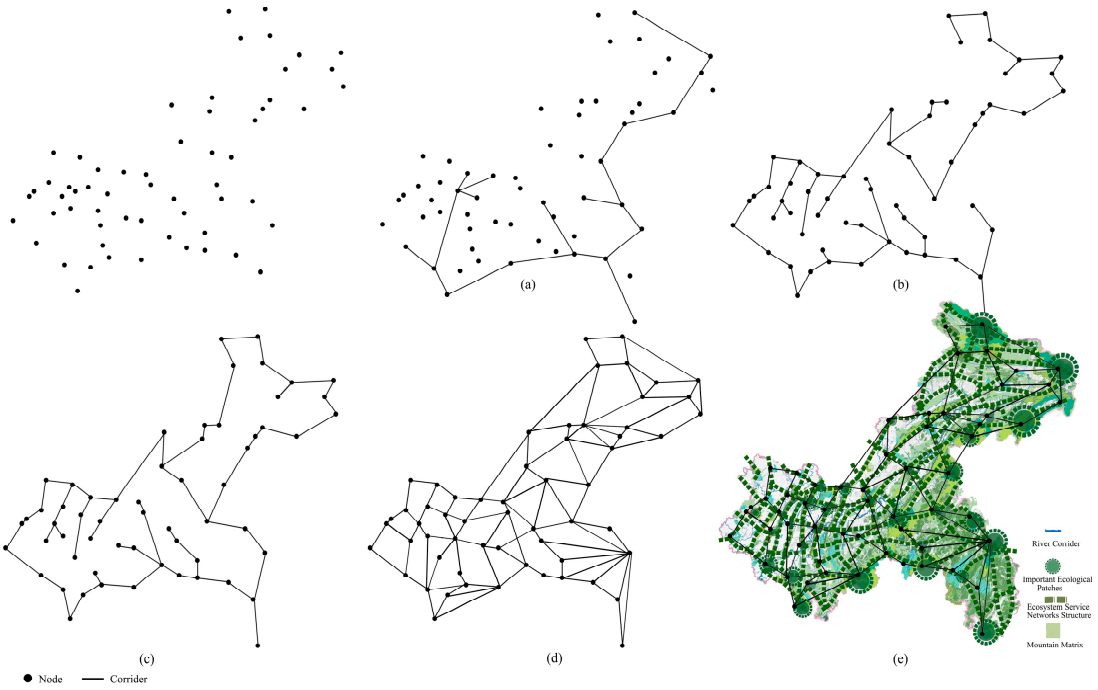


Figure 4. A total of 58 ecological patches were selected as nodes for ecological network planning. (**a**,**b**) Networks A and B represented branched networks; (**c**) Network C formed a single major circuit; (**d**) Network D depicted a complex multi-circuit network; (**e**) Network E illustrated an optimal and feasible scenario with the highest level of connectivity achievable within the constraints of the site conditions.

3. Results

3.1. Ecosystem Services Importance

The importance of water conservation is depicted in Figure 5a. Approximately 26.98% of the areas were classified as extremely important, primarily distributed along the riverside in a belt-like pattern, with a few scattered patches of extremely important areas. Areas classified as strongly important, accounting for 8.23%, are mainly found in water bodies and high-vegetation-covered mountainous regions. This is primarily attributed to the high forest coverage in high-altitude areas, where plant litter and roots contribute to soil structure improvement and enhanced water infiltration and retention capacity. Areas classified as extremely and strongly important for water conservation are primarily distributed within the ecological barrier zones inside the first layer of ridgelines on both sides of the Yangtze River and its major tributaries. These areas are crucial in maintaining reservoir water quality, reducing sedimentation, facilitating rainwater runoff, and regulating floodwaters. Additionally, the Three Gorges area, considered an important water source conservation area, has experienced adverse effects on ecosystem integrity and connectivity due to urban and town construction resulting from resettlement and relocation initiatives associated with the Three Gorges Project. Areas classified as slightly important for water conservation services, accounting for 46.09%, are mainly concentrated in urban development areas. This is primarily due to higher proportions of construction land in urban areas with dense populations and higher socio-economic status, resulting in lower water retention capacity.

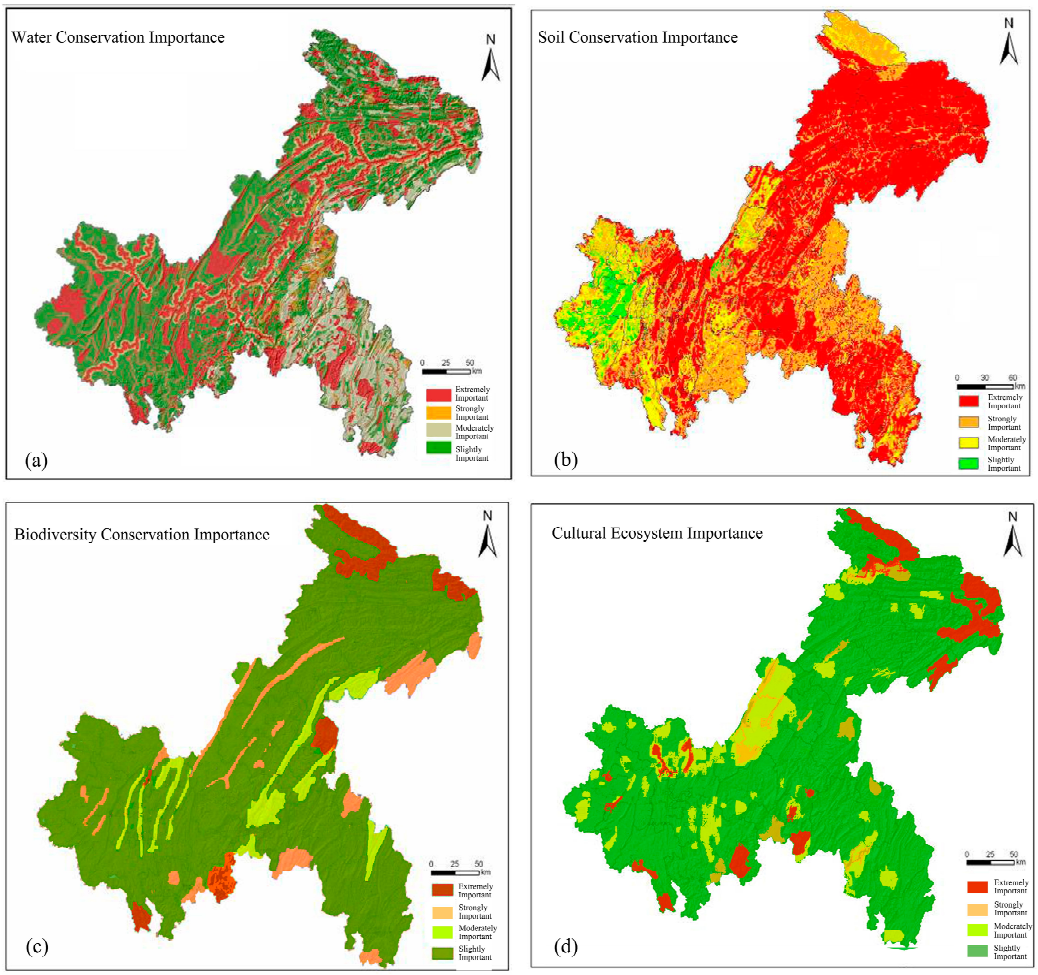


Figure 5. The assessment of ecosystem service. (**a**) Water conservation importance; (**b**) Soil conservation importance; (**c**) Biodiversity conservation importance; (**d**) Cultural ecosystem importance.

The importance of soil conservation is depicted in Figure 5b. Extremely important areas, comprising 53.5% of the study area, are primarily determined by the distribution characteristics of river hierarchy and soil erosion sensitivity. Chongqing Municipality is situated in the upper reaches of the Yangtze River, with the main stem traversing the entire territory from southwest to northeast. Within its borders are five major tributaries: the Jialing River, Qu River, Fu River, Wu River, and Daning River, along with hundreds of small- and medium-sized rivers. First- and second-order rivers cover a wide range, providing abundant water resources. Additionally, due to erosion caused by river scouring in most areas of the Three Gorges Reservoir area, soil erosion sensitivity is moderately sensitive. Rainfall in Chongqing is mainly concentrated in the northeastern Qinba Mountains and the southeastern Wuling Mountains, where soil erosion sensitivity is highly sensitive. Therefore, soil conservation of extreme importance is required in most areas of Chongqing Municipality. The spatial distribution of strongly important areas was found to be scattered, primarily encompassing Chengkou District in northeastern Chongqing, sections of Qianjiang District in southeastern Chongqing, segments of the Liangping–Dianjiang parallel ridges and valleys, and parts of the one-hour economic circle. Collectively, these regions accounted for 32.77% of the total area. In the hilly area of western Chongqing, which is characterized by hills, relatively flat terrain, and lower rainfall, soil erosion sensitivity is low. The rivers in this region are predominantly grade 3 rivers. Consequently, soil conservation importance was primarily rated as moderately to slightly important. The importance of soil conservation in urban development and construction areas in multi-center clusters is slight, mainly due to the relatively high level of regional urbanization and industrialization, the general hardening of the ground surface, and the lack of vegetation coverage.

The importance of biodiversity conservation is represented in Figure 5c. Approximately 81.54% of the areas were deemed slightly important, primarily distributed in urban clusters where human activities exert significant influence. These areas are characterized by high population density and intense production and living activities. These moderately important areas were mainly distributed in a strip in the central region of Chongqing. Around 6.58% of the areas were considered strongly important, with an irregular distribution in Chongqing's central and southeastern parts. The remaining 5.84% of areas marked as extremely important were mainly concentrated in nature reserves northeast and southeast of Chongqing. The strongly and extremely important areas are predominantly clustered in mountainous regions with high vegetation cover and away from urban built-up areas, primarily along the Yangtze and Jialing Rivers. These areas experience minimal human disturbance, possess excellent vegetation coverage, and maintain a high level of biodiversity.

The importance of the cultural ecosystem is depicted in Figure 5d. The area with extreme importance totaled 5056 km^2, accounting for 6.15% of the study area. Approximately 3.36% of the areas were classified as strongly important cultural services, while 8.48% were considered moderately important. The majority, comprising about 81.75% or 67,360 km^2, fell into the slightly important cultural services category. Areas with strongly important cultural services were primarily distributed across Chengkou District, Wuxi County, Wushan County, Wulong District, Wansheng, and Nanchuan District. Areas classified as moderately important and above accounted for 18.25% of Chongqing's total area. This observation correlates closely with Chongqing's robust economic development, high living standards, and income levels. The thriving urban development in the city stimulates the demand for cultural services, thereby enhancing the overall value of cultural services.

3.2. Ecological Source Area

This study first reclassifies the results of ecosystem services evaluation using a natural break classification method. The natural break values are obtained from the Jenk optimization method of statistics, which can minimize the sum of internal variances at all levels [59,60]. This study integrates ecosystem services and ecological suitability analysis results to obtain the spatial distribution of comprehensive ecosystem importance for

Chongqing. Using the natural breaks method, comprehensive ecosystem importance can be divided into four levels: extremely important, strongly important, moderately important, and slightly important areas. Overall, the distribution of ecosystem service importance is scattered, with various levels intertwined. However, areas less affected by human activities, such as mountainous regions, tend to exhibit higher importance than low-lying areas more heavily impacted by human activities. The strongly important area was the largest, accounting for 44.70%. The moderately important area accounted for 44.45%. The extremely important areas, accounting for 5.93%, are primarily located in the northeast region of Chongqing. The slightly important areas, accounting for 4.92%, are mainly distributed in the western region and Chongqing's urban districts and counties. These areas are dominated by low-value ecosystems, such as urban and agricultural lands, with limited coverage of water bodies, which cannot significantly enhance the overall importance of ecosystem services in the region (Figure 6).

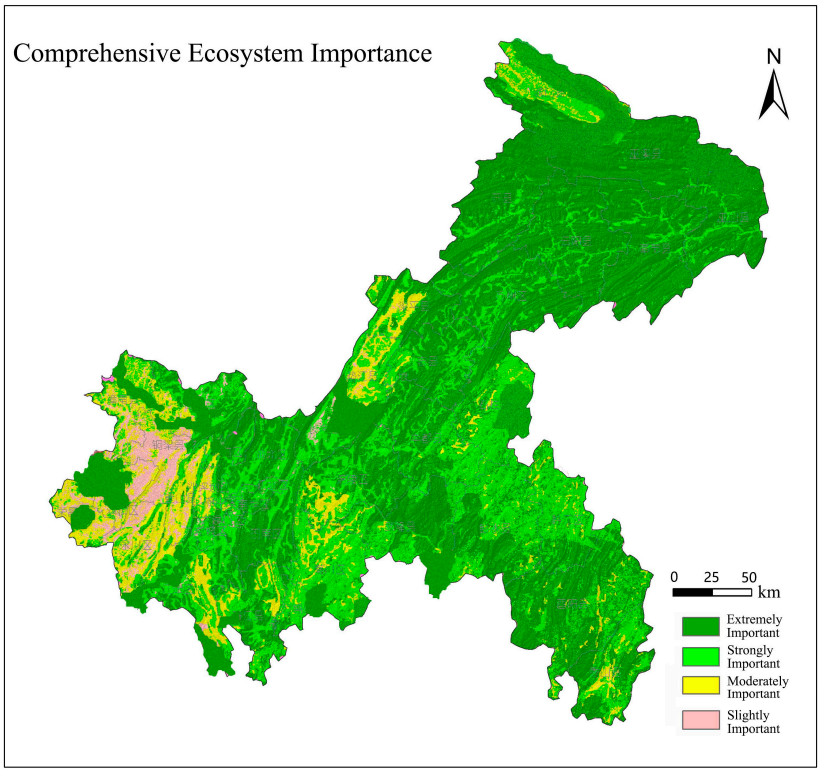


Figure 6. Comprehensive ecosystem importance.

Strongly and extremely important areas crucial for maintaining ecosystem security were extracted. After applying a threshold filter (200 hm^2) and boundary modification, 58 ecological source areas in Chongqing were identified (Figure 7). These areas are primarily characterized by woodland and water bodies. Figure 7 illustrates that the ecological source areas are mainly distributed in the northeast and southeast of Chongqing, as well as within the one-hour economic circle.

3.3. Network Delineation

This study uses the linkage pathway tool to simulate the line between nodes with the common network type in graph theory based on the identified important ecological source areas. Considering the specific mountain conditions of Chongqing, links were considered unfeasible if they were blocked, redundant due to diversion around unsuitable areas, or converged upon another node [53]. Links were considered insufficient if they did not meet the mountain–water landscape pattern in Chongqing. Network D–E was then tested to determine which links were feasible considering urban construction, agricultural

development, and the mountain–water landscape pattern [61]. Some corridors in the ecological networks were adjusted from straight lines to curves to circumvent these barriers. The remaining links were then depicted graphically as an optimal and feasible scenario, like Network E (Figure 8), representing the highest level of connectivity achievable within these constraints. Network E comprises 5 horizontal and 14 longitudinal corridors, connecting mountains, green spaces, water systems, Cultural Heritage Sites, and agricultural belts with high value in ecosystem services. This network can enhance ecological efficiency and facilitate the spread of ecosystem benefits across other patches. Circuit Network E within the Three Gorges Reservoir area provides habitat for marginal species, facilitates access to essential ecological flows, and hinders certain components, thus playing a vital role in ecological protection.

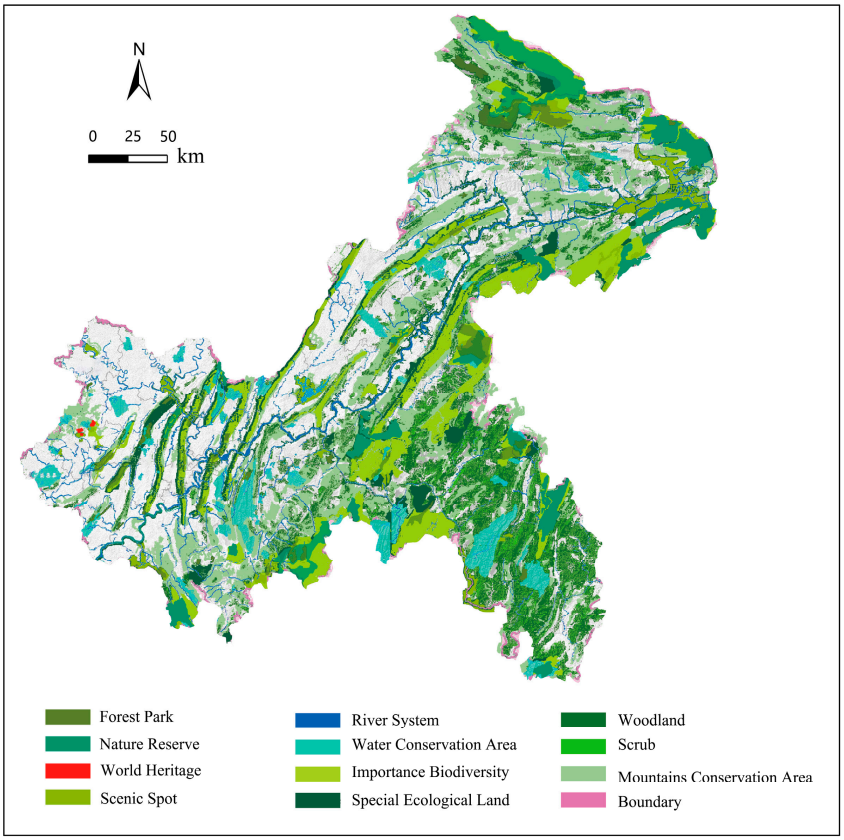


Figure 7. Important ecological source areas in Chongqing.

3.4. Ecological Networks Analysis

The results of corridor structure analysis for Networks A–E are represented in Tables 8 and 9. The rankings of the number of links (corridors) were E > D > C > B > A, and those of the length and density of corridors were D > E > C > B > A. These rankings indicate that Networks D and E exhibit higher complexity and connectivity. Network D was the most complex ecological network with the highest connectivity. However, its cost ratio was also higher than networks B, C, and E. Compared to Network D, Network E exhibited the same α index, β index, and γ index but with a significantly lower cost ratio. These results highlighted that Network E, with the highest circuitry and connectivity, also demonstrated relatively higher cost efficiency. Therefore, Network E can be considered an optimal scenario for the ecological network in Chongqing. It is more conducive to the flow of energy, logistics, and the movement of living creatures in the landscape, ultimately enhancing ecosystem services in Chongqing.

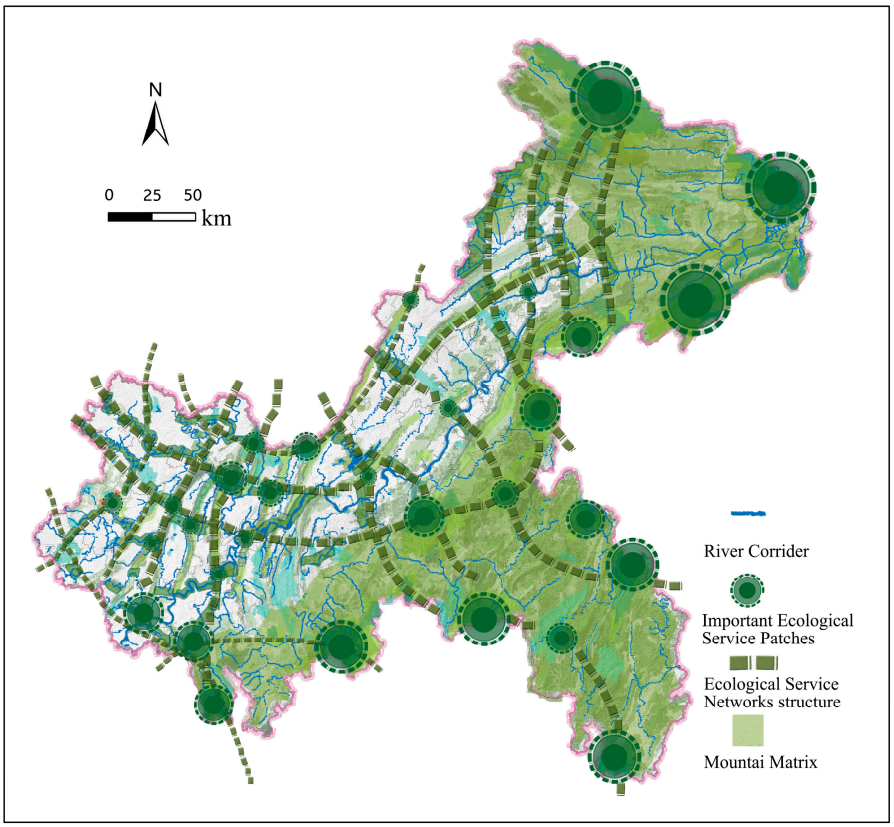


Figure 8. An optimal and feasible scenario (Network E).

Table 8. Structural characteristics of corridors analysis for Network A–E alternative scenarios.

Network	Corridor Number	Corridor Length(km)	Corridor Density (km × km^{-2})
A	21	1192.59	0.01447
B	58	2117.88	0.2570
C	60	2246.37	0.02726
D	74	3238.97	0.03930
E	74	3300.42	0.04010

Table 9. Indices of network structure analysis for the alternative scenarios of Networks A–E.

Network	Node	Corridor	α Index	β Index	γ Index	Cost Ratio
A	58	21	0	0.36	0.125	0.9824
B	58	58	0.00	1	0.345	0.6726
C	58	60	0.03	1.03	0.357	0.8733
D	58	74	0.15	1.26	0.44	0.8772
E	58	74	0.15	1.26	0.44	0.9776

4. Discussion

4.1. Advantages of Coupled Graph Theory and Network Analysis for Ecological Network Construction Based on Ecosystem Services

Protecting ecosystem services is significant in mountainous regions, benefiting those residing within these ecosystems and individuals living outside the mountain ranges [62]. In this study, we proposed a system for constructing ecological networks that integrates the importance of ecosystem services in Chongqing. The process involves the following steps: (1) defining goals and objectives, (2) analyzing ecological suitability, (3) assessing the importance of ecosystem services, (4) identifying ecological source areas, (5) delineating

networks using graph theory, and (6) analyzing ecological networks. This study can offer new insights into ecological construction in mountain regions affected by urbanization.

In recent years, scholars have increasingly focused on constructing ecological networks from the ecosystem services perspective. For instance, Bai et al. (2021) integrated ecosystem services and ecological sensitivity assessments to identify areas of high ecological importance in Harbin, utilizing a least-cost path model to ensure ecosystem stability [34]. Therefore, this study combined ecological suitability analysis and non-monetary ecosystem services importance evaluations to identify key ecological patches that offer vital ecosystem services and high-quality habitats. Compared to alternative methods, our approach emphasizes integrated geological disaster, cultural, and ecological values in mountain regions. Graph theory and network analysis were commonly used to construct ecological networks and investigate the structures of various network types and their optimization problems [59]. A total of 58 ecological source areas were simplified into 'graphs' and subjected to quantitative analysis to determine optimal scenarios for ecosystem services networks. Our study systematically analyzed the topological relationship between ecological land patches and corridors, considering urban construction and agricultural development in identifying the optimal ecological network plan. The sources and corridors screened on this basis could be more practicable, effective, and more likely to alleviate ecological fragmentation resulting from high urbanization and enhance ecosystem services in mountain regions.

4.2. Identifying Effective Ecological Source Areas That Take into Account Ecological Suitability and Ecosystem Services Importance

Identifying effective ecological sources is crucial for maintaining and enhancing ecological processes, mitigating landscape fragmentation, and optimizing resource allocation for effective ecological protection and management [63]. This study combined suitability analysis with ecological service importance analysis to identify ecological source areas. This method represents Chongqing's ecological base and is of far-reaching significance for improving ecosystem quality and maintaining ecosystem stability. Ecological suitability analysis is the foundation for constructing ecological networks in mountain regions [64]. In this paper, when analyzing the ecological adaptability of Chongqing City under the mountain ecological priority scenario focused on serving people, relevant research is referenced, and domain weights are assigned as follows: 0.15 for slopes, 0.15 for geological hazards, and 0.18 for Cultural Reserves. Additionally, Forests and Green Spaces, Wetlands, Nature Reserves, Scenic Spots, Forest Parks, Enclave—Nature, and Cultural Reserves were selected because they are more eco-sensitivity areas [34]. Therefore, this study further identifies ecological source areas through ecological suitability analysis.

Non-market valuation techniques used in ecosystem services evaluation consider ecosystem services within the complexity of mountains and integrate ecological and social issues [65,66]. Based on Chongqing's natural and socio-economic conditions, this study selected four major ecosystem services: biodiversity, soil, water, and culture. Cultural ecosystem services focus on indirect services that benefit mountain people, such as the aesthetic value of a place, the historical significance, and even emotional attachment to the site [67]. The indicators used in this study can represent the direct or indirect benefits people can obtain from ecosystem services [65,68]. Additionally, non-market valuation techniques pay more attention to the interconnections between ecosystem services, human well-being, and ecosystem services and the impact of human factors on ecosystem services [5]. This study can better combine the actual situation of Chongqing's mountain ecology, consider the complexity and importance of multiple mountain ecological services, and consider people's cultural and entertainment needs rather than purely theoretical operations.

4.3. Optimal Scenario for Ecological Networks Employing Graph Theory and Network Analysis

This study employed graph theory and network analysis to investigate the structure and optimization of various networks. This method can reveal the spatial distribution

pattern of things from a numerical perspective [63], compare constructed solutions, and determine the optimal solution and its feasibility. Consideration was given to the current status of urban development, modern agricultural construction, and the mountain–water landscape pattern. Existing studies only consider resistance factors [61]. However, this study not only includes resistance factors but also includes the mountain–water landscape pattern as supplementary factors. The reason for including this factor is that the mountain–water landscape pattern can affect the aesthetic of the mountain city. Based on these factors, an effective ecological Network E ensuring landscape connectivity is ultimately delineated. The methods employed in this study may be effective for landscape ecosystem conservation and space planning in mountainous areas, especially where the aesthetic value needs to be considered in urban construction.

4.4. Ecological Network Planning Measure Suggestions

To ensure the ecological security functions of ecosystem services in Chongqing, we identified five key ecological function areas through assessments of ecosystem service importance, land use conditions, and ecological suitability analysis. The selection criteria were derived from the assessment results of biodiversity conservation, soil conservation, and water conservation: Table 10 and Figure 9 list five key ecological function areas and their dominant and auxiliary functions. Beginning with the goal of curbing the trend of ecological degradation and enhancing the recovery of key ecological function areas, we proposed control measures for these ecological lands. Examples of these measures include the following: The Three Gorges Reservoir area primarily provides ecosystem services such as water conservation and biodiversity preservation, with flood regulation following closely. The ecological security of this area is crucial for ensuring the ecological safety of the middle and lower reaches of the Yangtze River. Therefore, priority should be placed on ecological environmental protection, particularly in the post-Three Gorges era. Tailored development of characteristic industries should be promoted, considering the capacity of local resources and the environment, with strategic and targeted approaches. It is essential to effectively protect the reservoir area's water environment and aquatic ecological security. This includes constructing ecological barriers around the Three Gorges Reservoir and strengthening comprehensive management of geological disasters, soil erosion, and desertification. Such measures are essential for maximizing the functions of the Three Gorges Project, including flood control, power generation, navigation, and the provision of clean freshwater resources, ensuring its long-term stable operation.

The Qinba Mountainous Area plays a crucial role in water conservation. Following the principle of prioritizing ecological environmental protection, efforts should focus on restoring and rebuilding the ecosystem of the mountainous subtropical evergreen broad-leaved forests to improve the fragile ecological environment. Emphasizing water conservation and biodiversity protection, optimizing the mountain regions' forest and grassland vegetation structure should be a priority. This entails gradually restoring the original vegetation system of evergreen broad-leaved forests, safeguarding and enhancing soil and water conservation functions, and preserving water sources in mountainous areas. The acceleration of the construction of ecological barriers and the establishment of ecological economic highlands in the Qinba Mountainous Area is essential. It should be based on the rational development and utilization of ecological resources, focusing on fostering the ecological industry chain. This approach will foster a characteristic regional pattern of ecological industry development and establish a mountainous ecological economic system centered around the circular economy.

Table 10. The dominant eco-function of the important ecological functional region in Chongqing.

Serial Number	Name of the Important Ecological Functional Region	The Dominant Eco-Function				
		Water Conservation	Soil Conservation	Biodiversity Conservation	Water Quality Safety	Flood Regulation
1	Three Gorges Reservoir: Important water conservation area	++	+	++	++	++
2	Qinba Mountain: Important water conservation area	++	+	++		
3	Wuling Mountain: Important biodiversity conservation area	++	++	++		
4	Jinfo Mountain: Important biodiversity conservation area	++	+	++		
5	'Four Mountains' in urban area: Important ecological protective screen	++	+	+	++	

'+' refers to the general importance of ecological function. '++' refers to the higher importance of ecological function.

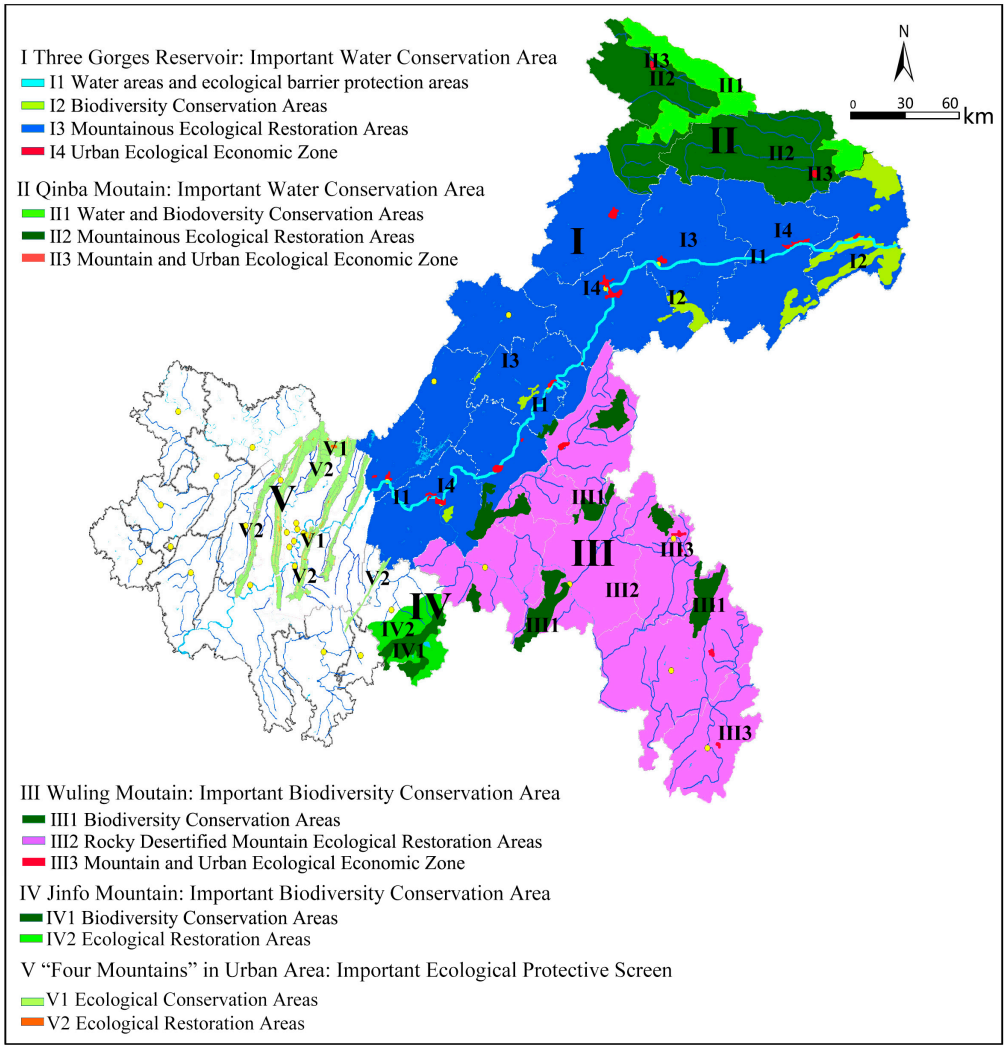


Figure 9. Protection, planning, and construction of key ecological functional areas in Chongqing.

Planners and managers should pay significant attention to human-transformed sites where anthropogenic threats arise, not limited to conservation areas [69]. Therefore, developing coordinated strategies that align urban and rural construction with significant ecological functional areas and formulate ecological space control strategies is crucial. Key ecological zones within urban areas should be integrated into urban systems' spatial protection framework to safeguard core regions' sustainable ecological service capacities. The management and control strategies of the Three Gorges Reservoir area are as follows: (1) due to its crucial role in water conservation, both urban and rural construction is directed toward safeguarding the water quality of the Three Gorges Reservoir. Measures are taken to strengthen control over pollution sources, with a particular focus on riparian zones. (2) Strategies are devised, which consider diverse riparian typologies, geological conditions, ecological environments, urban landscape demands, and coordination with geological disaster prevention. These strategies encompass plans for preservation, ecological restoration, sanitation, reservoir cleansing, and comprehensive shoreline environmental management. Implementing greening actions along the Yangtze River is prioritized within the area visible from the first layer of mountain ridges adjacent to the Three Gorges Reservoir. Guided by the 'Four Along' principle, national soil and water conservation and ecological environment construction projects are implemented along the peripheries of towns, reservoir areas, riverbanks, and major highways. (3) Particular emphasis is placed on developing characteristic industries compatible with the local environmental capacity. Adjustments and optimizations in industrial, urban, and population layouts are developed to guide industries toward moderate concentration in towns, industrial parks, and transportation hubs. The 'Wankaiyun' comprehensive industrial development zone is established as the largest comprehensive industrial base and commercial logistics center in the core area of the Three Gorges Reservoir. Dianjiang, Liangping, Fengdu, and Zhongxian, serving as nodes along transportation arteries and the Yangtze River, form two relatively dense axes of characteristic industrial development connected to the 'one-hour economic circle'. Wushan and Fengjie are designated as hubs for characteristic industrial development, focusing on ecological economic development, such as tourism, green agricultural and forest product processing, clean energy, and green building materials.

In the Qinba Mountainous Area, urban and rural construction should uphold the regional ecological integrity of the existing mountain and water spaces. Simultaneously, the rapid construction of the 'Qinba Mountainous Area Ecological Barrier and Ecological Economic Highlands' must preserve regional ecological continuity. Within urban areas, the 'Four Mountains' should be acknowledged as the ecological cornerstone of the region and given priority for protection. Urban development activities, especially within the controlled zones of the 'Four Mountains', must align with the requirements of ecological environmental protection, strictly controlling the scale and intensity of development. Emphasis should be placed on protecting natural mountains and mountainous forest ecosystems in their pristine state, as well as biodiversity conservation, maintaining the ecological integrity of existing mountain and water spaces, and ensuring regional ecological integrity and continuity. In the Wuling Mountainous Area, efforts should be made to promote afforestation and grassland restoration on sloping farmland, increase vegetation coverage, and prevent the expansion of rocky areas. It is essential to implement afforestation and grassland restoration for sloping farmland above 25°, to strengthen the ecological restoration of abandoned mines, to adjust industrial structure, and to optimize economic development models. It is a priority to establish green agricultural production bases, focus on the ecological industry chain, and form a regional characteristic ecological industry development pattern, along with rational guidance for population and industry concentration.

4.5. Limitations and Future Research

In the context of rapid urbanization, constructing ecological networks based on ecosystem services constitutes an important research direction that should be considered in mountain regions at present and in the future. Therefore, this study introduced the model

of ecosystem services' importance analysis using non-monetary approaches, which focused more on considering the complexity of mountain nature. This approach was coupled with graph theory and network analysis required for ecological network construction to depict an optimal and feasible scenario. Thus, an ecological network conforming to urban construction, agricultural development, and the mountain–water landscape pattern in Chongqing was established. Based on this, space control measures were presented to protect key ecological function areas and key ecological zones within urban areas. However, this study also suffers certain limitations. First, non-market valuation methods employed for ecosystem services are an empirical pattern measured at the expert's level. It depends on the choice of ecosystem services to include [70]. Therefore, the determination is subjective. However, this study adopts a natural break method, which can minimize the sum of internal variances, to rank the importance of ecological protection [59,60]. We also tried to reduce the individual subjectivity of the evaluation results by referring to existing research literature. The results align with Chongqing's mountainous areas' ecological conditions and urban development. Moreover, evaluating multiple services can elicit unexpected outcomes and trade-offs [71]. Compared with these methods [36,50,68,72,73], our method may ignore areas with higher comprehensive ecosystem service value obtained through the superposition method in a certain space. Our future research will explore and analyze the results of comprehensive ecosystem service value using the superposition method and the maximum limiting factor method. Second, there is a lack of consideration of spatial processes at the level of entire ecosystems, like local biotic and abiotic contributions and the flux through landscape networks. The meta-system approach to explore regional-scale ecological processes [74–76] is indeed the direction we need to strive for in the future. Finally, ecological corridors were not classified and graded in the ecological network generation. In the future, Chongqing's current land use status should be compared with the planned ecological corridors to identify construction corridors, potential corridors, and protected corridors to formulate ecological corridor construction strategies better.

5. Conclusions

In this study, we chose the Chongqing metropolitan area, where the conflict between urban expansion and ecological environmental protection continues to intensify, as a case study. Using the qualitative evaluation methods and graph theory model, this study constructed an ecological network from the perspectives of ecosystem services and network analysis. We presented space control measures to protect key ecological function areas and key ecological zones within urban areas. This is a new and feasible idea to identify the ecological source by considering multiple ecosystem services and obtain an optimal scenario in mountain regions. In this study, the following results were obtained:

(1) A total of 58 important ecological source areas were identified, with a total area of 5746 km^2, accounting for 79.15% of the total foreground area. They mainly exhibited a distribution trend of higher values in the central and southeastern parts and lower values in the northwest. The land use types largely include water bodies and woodlands.
(2) Using graph theory and network analysis methods, an optimal scenario was established, consisting of 5 horizontal corridors and 14 longitudinal corridors, connecting mountains, green spaces, water systems, and agricultural belts with high ecosystem services value.
(3) A total of 5 crucial ecological function areas and key ecological zones in important urban development areas were identified. Control measures for these ecological lands were proposed to enhance the effectiveness of ecological service construction and ensure the ecological security functions of ecosystem services in Chongqing.
(4) The results of the network structure analysis indicated that the constructed ecological network had strong integrity. This method has obvious applicability and reliability. This provides reliable ideas for constructing regional ecological security and building a bridge between the natural environment and human society in mountain regions.

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