Construction of Ecological Safety Network and Identification of Key Areas for Ecological Restoration in Resource-Based Cities-Take the Liuzhi Special Zone in Guizhou Province as an example

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Abstract

Constructing an ecological safety network is an effective measure to coordinate ecological protection and economic development in resource-based cities. Taking Liuzhi Special Zone as an example, the study adopts MSPA, ecological protection red line, and other multi-factor superposition to identify ecological source areas, integrates human and natural environmental impacts to construct resistance surfaces, and applies the circuit theory to extract ecological corridors and ecological nodes, which provides a comprehensive framework for building an ecological safety network. The results showed that 17 ecological sources (371.51 km^2) and 33 ecological corridors (163.92 km) constitute the ecological safety network in the study area, and 22 ecological pinch points (2.80 km) and 25 ecological obstacles (6.81 km) are the key areas for ecological protection and restoration in the study area. The results show that the ecological source areas are concentrated in the western and southern parts of the study area, adjacent to the mining area, which are strongly disturbed by human activities. The first- and second-level ecological sources are concentrated in clastic rock areas such as clay rock, sandstone, and siliceous rock in the west of the study area. The third-level ecological source is scattered in the southern region, dominated by dolomite, limestone, and other carbonate rocks. Ecological corridors connect discrete ecological sources in series. The first- and second-level ecological corridors are mainly distributed in the western part of the study area. The road networks and land types on both sides of the corridors are staggered, and geological disasters are dense. Based on regional characteristics, this paper proposes feasible ecological restoration strategies, which can provide scientific reference for the spatial layout of ecological security protection and ecological restoration measures in resource-based cities.

Keywords

Ecological security network; Circuit theory; MSPA; Ecological restoration; Resource-based city.

1. INTRODUCTION

Coal and carbon are the mainstay of China's energy structure, supporting rapid social and economic development while inevitably damaging the ecological environment [1]. High-intensity mining activities cause great disturbance to the supply and demand of ecosystem services, affecting the structural and functional integrity of ecosystems and thus threatening regional ecological security [2, 3]. Liuzhi Special Zone is a typical coal mining resource-based city; along with the extraction of mineral resources, while promoting rapid economic and social development, the ecological degradation problem has become more and more obvious, to a

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certain extent, impeding the sustainable development of the regional economy and environmental security [4], and urgently need to pay great attention to it.

The construction of an ecological safety network has been upgraded to one of the three major strategies for ecological restoration of land space [5, 6] and has become an effective means to maintain regional ecological security [7, 8]. The construction of an ecological security network emphasizes the effective connection between ecological sources and corridors at the landscape level, and the research framework of 'identification of ecological sources - construction of resistance surfaces - extraction of ecological corridors' has been formed [9]. As the most critical first step, ecological source identification includes direct and indirect identification [10]. Direct identification mostly takes scenic areas or nature reserves as ecological source sites, but this method neglects the functionality and structure of ecological source sites [11]. Indirect identification includes morphological spatial analysis method (MSPA), ecosystem service evaluation, etc., which effectively compensates for the shortcomings of direct identification methods [12]. Among them, the morphological spatial pattern analysis method (MSPA) can identify the areas that play an important role in landscape connectivity in the study area from the image element level, accurately judge the type and structure of the landscape, and often combine with landscape connectivity evaluation to scientifically screen the range of ecological source sites [13]. The construction of resistance surface mostly adopts comprehensive indicators combined with expert opinions to assign values, and uses soil loss equations and other corrections [14]. Ecological corridor extraction mostly uses the MCR model, gravity model, ant colony model, and circuit theory [15]. Circuit theory simulates the random migration and diffusion of species between source sites by using the characteristics of random current traveling in the resistive surface and intuitively responds to the relative importance of ecological corridors through the magnitude of cumulative current and identifies the location to extract the most reasonable corridor width, which makes up for the shortcomings of other models that are difficult to simulate the ecological flow [16, 17].

As a demonstration area for sustainable development of resource-based cities in Guizhou Province, the rapid economic growth of coal mines in Liuzhi Special Administrative Region has caused ecological degradation problems such as landscape fragmentation and impacts on biodiversity, leading to the effects on the coordination between economic development and ecological sustainability, and the construction of ecological safety networks is urgently needed to promote the sustainable development of the ecological environment. Given this, this study integrates the Morphological Spatial Analysis Method (MSPA), ecological protection red line, the scope of nature reserves, landscape connectivity analysis, and circuit theory to construct an ecological safety network and identify key points for ecological restoration, to provide support for maintaining the ecological safety of Liuzhi Special Zone and even the Beipanjiang River Basin, as well as providing references to the spatial layout for the protection of ecological safety and ecological restoration measures of the resource-based city.

2. MATERIALS AND METHODS

2.1. Overview of the study area

Liuzhi Special Zone is located in the Wumeng Mountain area in the western part of Guizhou Province, with a total area of 1799.48 km^2, and has the largest coal base south of the Yangtze River in China. It has a subtropical humid monsoon climate, with an average annual temperature of 15.6℃ and an average precipitation of 1474.6 mm per year. The district is widely distributed with Late Paleozoic Carboniferous to Mesozoic Jurassic strata. Its lithology is dominated by carbonate rocks such as greywacke, biotite greywacke, dolomitic greywacke, and other carbonate rocks. There are clays, quartz sandstones, siltstone sandstones, coal-bearing seams, and other crushed rocks, and the Emei Mountain basalt is widely distributed. The population

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density is 260 people/km^2, and ecological zones such as the Sheep Place River National Wetland Park are significant in stabilizing the supply of ecosystem services in the watershed. However, affected by the characteristics of karst terrain and geomorphology and the combination of strata and lithologies, disasters such as landslides, avalanches, and mudslides are prone to occur, and ecological problems such as soil erosion and reduction of biodiversity are highlighted (Fig. 1).

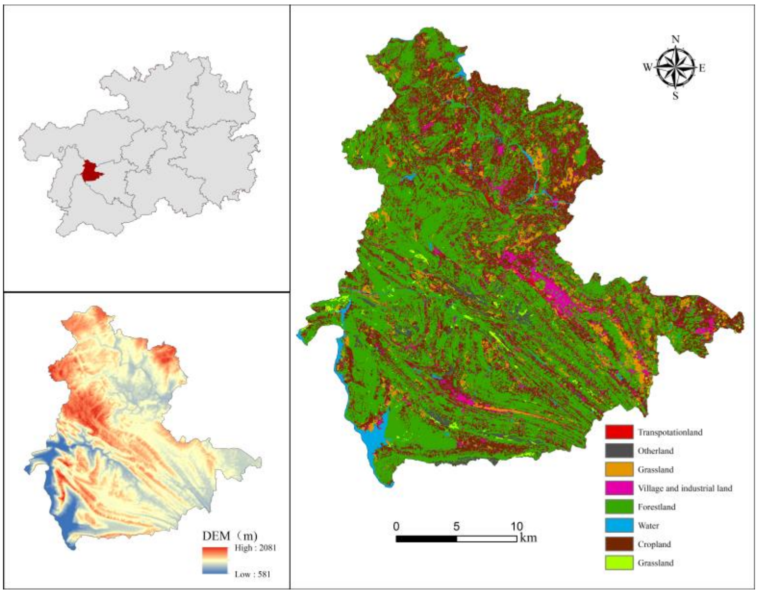

Fig. 1 Geographical location and land use type distribution of the study area

2.2. Data Sources

The data needed for the study include (1) 2020 data on land use, lithology, geo-disaster, ecological protection red line, and nature reserve, sourced from the State Key Laboratory of Karst Mountain Ecology and Environment of Guizhou Province. (2) Elevation DEM data for extracting watershed slope and terrain undulation, sourced from the Geospatial Data Cloud Platform. (3) Road network data are sourced from the Open Street Map website.

2.3. Research method

2.3.1 Ecological source identification

Ecological source land is the habitat for species survival and migration and the basis for constructing ecological networks [18]. Using Guidos Toolbox software, land types with high ecosystem service value and weak anthropogenic interference, such as forest land, grassland, and water as foreground, and land types with strong anthropogenic interference, such as industrial and mining land and transport land as background, seven types of landscape types were identified by using eight-neighborhood analysis for MSAP analysis [19]. Among them, the core area is the patch with better habitat quality, larger area, and high disturbance resistance, which can be used as the ecological source area [20]. This paper superimposes the environmental protection red line to avoid omitting the source areas implemented into the national land spatial planning. It refers to the existing studies to set the area threshold to screen the source area range [21].

Landscape connectivity represents the degree of patency or obstruction of species' activities between ecological sources, and environmental sources with higher connectivity are more favorable for maintaining regional ecosystem service functions and species diversity conservation [22]. PC is the best indicator for analyzing landscape connectivity [23], with a value range of 0-1, and the higher value range represents better landscape connectivity [24]. Considering that more than 20 species of terrestrial organisms, such as yellow muntjac, civet, mountain hare, wild boar, etc., are mainly distributed in the study area, the migration threshold

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was set to 5000 m. The probability of connectivity was set to 0.5 to analyze the importance of each ecological source site in maintaining landscape connectivity through the value domain of PC and dPC. See equations (1-2).

$$\mathrm{PC} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} a_i a_j a_{ij}}{S} \quad (1)$$

where n represents the number of landscape patches; a_i and a_j represent the areas of patch i and patch j, respectively; p_{ij} represents the maximum probability of a species flowing through all paths between patch i and patch j, and s is the total landscape area.

$$\mathrm{dPC} = \frac{PC - PC_{remove}}{PC} \times 100\% \quad (2)$$

where the variable PC represents the connectivity index of any landscape; PC_{remove} represents the final value domain of landscape connectivity after excluding a patch.

2.3.2 Resistance Surface Construction

To seek suitable habitats for survival activities, species randomly wander between different ecological sources, and their migration and dispersal processes must overcome certain resistance [25]. Based on the environmental situation of the watershed, integrating the impacts of human activities and the natural environment, the land use type, elevation, slope, vegetation cover, distance from the river, distance from the road, and distance from the mining area were selected as the resistance factors, and the resistance was assigned with a value of 1-5, with the larger value representing the greater resistance. At the same time, the hierarchical analysis method AHP combined with the expert opinion was used to determine the weights of each resistance factor (Table 1). Considering the serious fragmentation of surface vegetation, high degree of exposed bedrock, serious ecological degradation problems such as rock desertification and soil erosion, and the high intensity of mining activities in the region, the indexes of rock desertification, soil erosion, and geological disaster were selected to correct the resistance surface.

2.3.3 Ecological corridor extraction

The ecological corridor is an important linear landscape element in the landscape pattern, which connects environmental source areas, provides species migration sites, maintains biodiversity, and guarantees the safety of biological flows [26]. Based on the ecological source and ecological source resistance surface results, the circuit theory was applied to extract ecological corridors [27]; see Equation (3). Meanwhile, the Centrality Mapper module of the Circuitscape 4.0 tool was used to calculate the flow centrality of ecological corridors to judge the importance of different environmental corridors in maintaining ecological network connectivity.

$$\mathrm{I} = \frac{V}{R_{eff}} \quad (3)$$

where I and V are the currents and currents and voltages at both ends of the conductor, and R_{eff} is the effective resistance.

2.3.4 Ecological node identification

Ecological nodes are the key points that guarantee or hinder the smooth circulation of species between ecological sources based on the circuit theory proposed by McRae et al. They are also ecologically fragile points with poor resistance to external disturbances, and systematic protection and holistic restoration of the ecological nodes is an effective measure to improve the connectivity of landscapes and to guarantee ecological security [28]. The ecological nodes identified in this study include ecological pinch points and ecological obstacle points. Ecological pinch points are the necessary route for species migration and dispersal; identified in the Pinchpoint Mapper module under the Linkage Mapper 3.0 tool, the probability of a species

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passing through the area is equal to the current density of the current passing through the area, and the area with high value of current density is the ecological pinch point area, and removing or destroying these areas will affect the ecological security of the area, which is the key area for ecological protection [29]. Ecological pinch points are key areas that impede the circulation of species between ecological sources, run in Barrier Mapper under Linkage Mapper 3.0 tool, according to the size of the image resolution, based on a certain search radius of the moving window method of obtaining, calculating the cumulative current recovery value after the removal of the pinch point, the larger the recovery value represents that the area of the obstruction of the species activities, the higher the level of the region, systematic restoration of these areas can improve regional landscape connectivity and guarantee ecological circulation [30].

Table 1. Ecological resistance factor assignment and weight

Drag factor	Subclass	Resistance value	Weights
Land use type	Woodland	1	0.35
	Grassland	1	
	Other sites	2	
	Garden area	2	
	Arable land	3	
	Land for Water and Water Facilities	3	
	Transport Facilities	4	
	Urban villages and industrial and mining sites	5	
Elevation(m)	581～1043	1	0.1
	1043～1032	2	
	1032～1447	3	
	1447～1658	4	
	1658～2081	5	
Slope(°)	0～10	1	0.1
	10～18	2	
	18～28	3	
	28～39	4	
	>39	5	
Distance from road(m)	30～500	1	0.25
	0～888	2	
	888～2271	3	
	2271～4049	4	
	>4049	5	
Distance to mining area(m)	0～1190	1	0.25
	1190～2828	2	
	2828～4564	3	
	4564～7194	4	
	>7194	5	

3. RESULT ANALYSIS

3.1. Ecological source area determination

The results of the identification of ecological source sites in the Liuzhi Special Zone based on MSPA analysis are shown in Fig. 2, in which the core area is 540.73 km^2, accounting for 30.05% of the total area of the watershed, and the overall degree of fragmentation is high. Combined with the ecological protection red line and the scope of nature reserves, 17 ecological source

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areas were finally identified, with a total area of 371.51 km², accounting for about 20.64% of the watershed area, including wetlands, forests, waters, and other ecological patches.

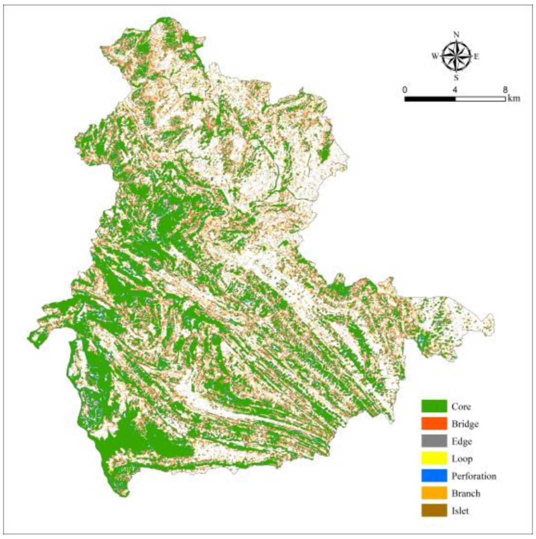

Fig.2 Landscape type map and area based on MSPA analysis

To avoid too much fragmentation of source sites, 17 patches with dPC>1 were finally screened as ecological source sites and divided into importance in this study based on the results of landscape connectivity analysis (Table 2) (Fig. 3).

Table 2. Index of the importance of ecological source

Number	Area (hm^2)	Exponents	
		dIIC	dPC
1	155.89	78.91	82.73
2	72.83	29.7	39.11
3	27.24	11.80	19.71
4	21.78	29.33	45.12
5	12.93	4.50	9.33
6	11.82	2.97	5.51
7	10.42	21.12	30.16
8	9.19	2.65	2.94
9	7.88	2.23	5.19
10	7.12	2.81	15.83
11	5.8	0.10	1.11
12	5.49	2.00	7.19
13	5.31	1.25	1.90
14	5.19	0.09	1.16
15	4.4	0.90	1.12
16	4.15	1.37	1.88
17	4.08	1.96	1.31

Regarding spatial distribution, the ecological sources are concentrated in the western and southern parts of the study area. In the western part of the study area, sandstone, claystone,

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and other debris rocks are widely distributed, the accumulation of debris weathering products is thick, and the impermeable layer of debris rocks is developed, with abundant surface runoff, which is conducive to the growth of plants. At the same time, the area is distributed with Emeishan basalt, the development of a thick red soil layer, and rich in a variety of micronutrients needed for plant growth and vegetation development, so the ecological source of concentrated and continuous and high importance of the distribution of the Sheyi River National Wetland Park. In the southern part of the study area, tuff, dolomitic tuff, and other carbonate rocks are widely distributed, with thin, weathered crusts, little clay residue, a high degree of exposed bedrock, poor water-holding capacity of the soil, and serious erosion, so only a small number of ecological sources are distributed in the area of clastic rocks, and their importance is relatively low. The basalt distribution area of Emei Mountain is large, coal mining resources are abundant, and many mining areas are adjacent to ecological source areas, causing interference and damage to the stability of the ecosystem and the connectivity of the source areas.

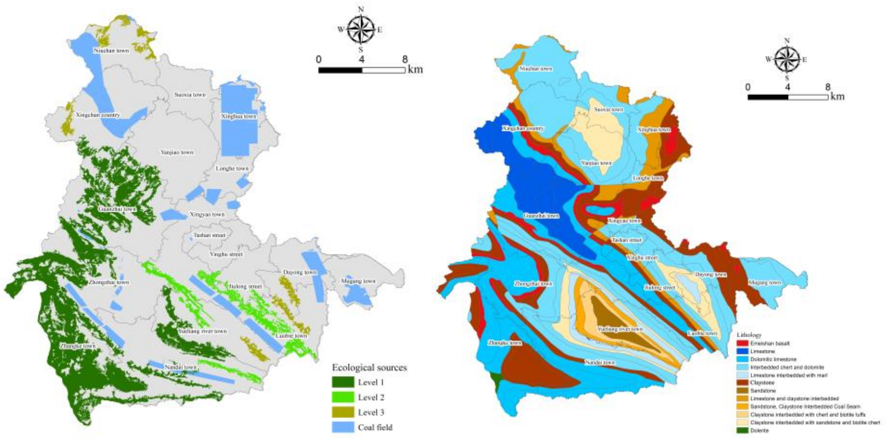

Fig.3 Ecological source area and regional lithology spatial distribution

3.2. Ecological corridor extraction

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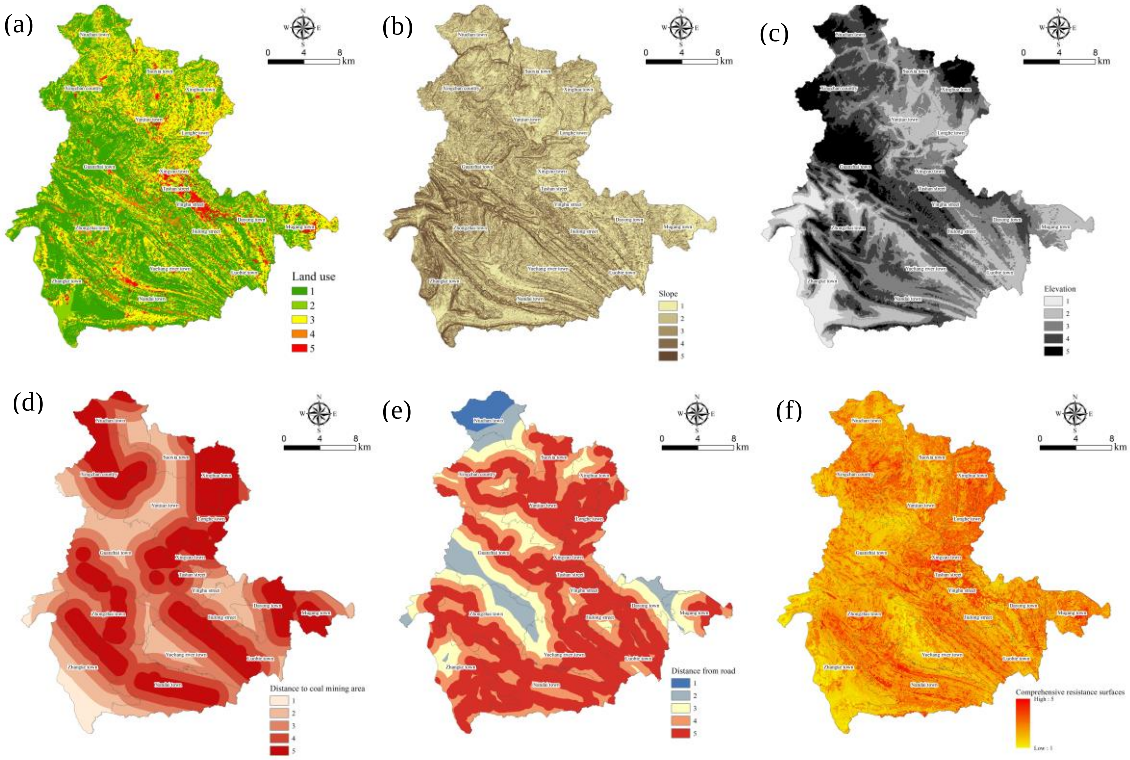

Fig.4 Ecological resistance factor classification and integrated resistance surfaces. (a) is the land-use resistance surface; (b) is the slope resistance surface; (c) is the elevation resistance surface; (d) is the distance to coal mining area; (e) is the distanee from road; (f) Comprehensive ecological resistance surface.

The results show that the study area's spatial distribution of resistance values significantly differs (Figure 5). The high resistance area is concentrated in the northern part of the study area near Xinhua Town, Longhe Town, and other mining areas. The land use types are mainly transport land, towns and villages, and industrial and mining land with strong anthropogenic interference, with large terrain undulation and concentrated distribution of geological hazard sites, so the obstacles for species to pass through the area are higher. At the same time, the large area of exposed bedrock in the carbonate rock area, coupled with the fragmented layout of the road network and land use types, coerced the migration and dispersal of species. The low-resistance area is concentrated in Guanzhai Town and Shekou Town in the western part of the study area, and the land use type is mainly woodland and grassland with weak anthropogenic interference. The terrain in this area is flat, and the vegetation cover is large and concentrated, so the obstacles for the species to pass through this area are low.

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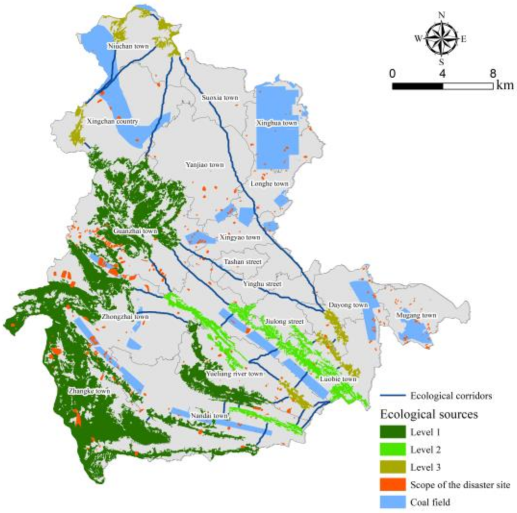

Fig. 6 Spatial distribution characteristics of ecological corridors.

Thirty-three ecological corridors (163.92 km) were extracted from the study area, connecting the discretely distributed source sites in a spider web around the periphery of the environmental source sites (Fig. 6). The road network density in the study area is high. High-resistance areas such as mining and residential areas cause habitat fragmentation, and the ecological corridors show obvious zigzagging and narrowing characteristics. The flow centrality of ecological corridors was divided from high to low using the natural breakpoint method, and nine extremely important ecological corridors, 13 important ecological corridors, and 11 general ecological corridors were obtained. Among them, the important environmental corridors are concentrated in the western part of the study area. The land use types on both sides of the corridors are mainly transport land, urban villages, and industrial and mining land. In contrast, the range of landslides, avalanches, and other geohazards and threats are highly concentrated on both sides of the corridors, indicating a risk of fragmentation of this part of the corridors while bearing the activities of the species.

3.3. Ecological Restoration Critical Areas and Restoration Strategies

3.3.1 Ecological pinch

The current density of the ecological corridor in the study area was gradually strengthened from blue to red, and the red area was the ecological pinch point area, which was the priority area for ecological protection. The current densities of ecological pinch points were superimposed with the ecological resistance surfaces and divided into 4 levels using the natural breakpoint method, and the highest level was extracted as the ecological pinch point areas in this study (Fig. 7). The results showed that a total of 22 ecological pinch point areas (2.80 km) were extracted from the study area in the form of narrow strips. Among them, the proportion of pinch points distributed on the primary and secondary ecological corridors was as high as 85%. The current land use in the pinch points is mainly forest, grassland, small ponds and wetlands, with a small amount of contiguous cultivated land, traffic station land and other areas with strong human interference, and the concentration of mines on both sides of the pinch point areas, with strong interference from human activities (Table 3).

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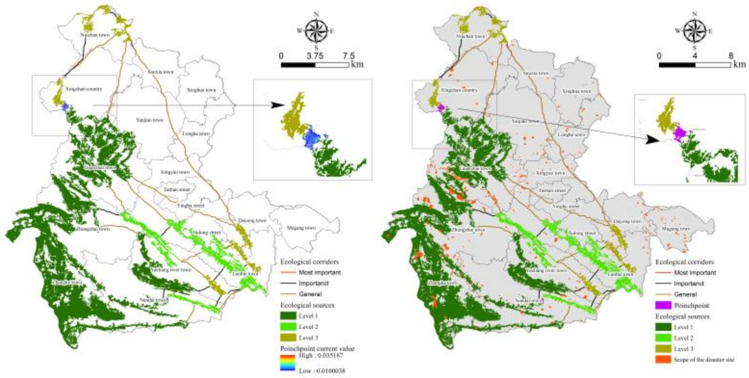

Fig. 7 Ecological pinch points current and its spatial distribution

Table 3. Distribution of ecological pinch-points area in Liuzhi

Townships	Quantities	Distribution location	Area (hm²)	Land use type
Guanzhai township	1	Duoque villages	5.22	Cropland, woodland, grassland
Jiulong Street	1	Hewan Community	3.24	Cultivated land, forest land, water and water facility land, garden land
Langdai township	2	Anle villages	8.09	Cultivated land, grassland, waters and water facilities land
	1	Banshitian village	9.58	
	1	Huajiao village	2.44	
	1	Tiaohuapo village	3.47	
Longhe township	2	Hongqi village	8.06	Grassland, woodland, garden
	1	Lianhe village	0.23	
	4	Linchang village	11.10	
	1	Yongfeng village	8.64	
Lubie Buyei Ethnicity and Yi Township	1	Matou village	6.48	Cropland, forest land
Tashan Street	1	Gaofen village	13.90	Grassland, Waters and Water Facilities Land
	1	Xinyao village	0.14	
Xinchang township	1	Gana village	1.89	Garden, woodland, grassland
	2	Lianglukou village	31.59	
	1	Luolong village	0.83	
Xinjiao town	3	Lianhe village	2.05	Cultivated land, forest land, water and water facility land, garden land
	1	Lianmeng village	0.10	
	1	Qiaoliang village	9.99	
	1	Yatang village	4.66	
Yanjiao town	1	Caoyuan village	11.43	Woodland, grassland
	2	Jingxin village	2.70	
	1	Liubao village	0.02	
Moon River Yi Buyi Miao Township	1	Mufatian village	14.56	Water and water facility land, grassland, forest land
	1	Zhiliu village	12.78	
	2	Zhongzai village	22.47	

About pinch point areas, the functional restoration and ecological management of woodlands and wetlands should be strengthened. For areas where the over-exploitation and utilization of forests, wetlands, and other resources have reduced the extent of rare animal and plant habitats, measures such as vegetation restoration and wildlife habitat restoration should be taken. At the same time, long-term sequence monitoring of groundwater level, surface water, vegetation, and

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geological disasters in mining areas should be strengthened, emphasis should be placed on soil and water conservation, and the scientific layout and optimization of production space, living space, and ecological space should be carried out, to maintain the stability of environmental pinch point areas.

3.3.2 Ecological barrier site

The current density of ecological obstacle points was superimposed with the ecological resistance surface and graded. The highest level was selected as the water's environmental obstacle point area (Fig. 8). The results showed that 25 ecological obstacle areas (6.81 km) were extracted. The ecological obstacle areas distributed in the primary and secondary environmental corridors accounted for 65%. The current land use of the ecological obstacle sites is mainly urban villages, industrial and mining land, contiguous cultivated land, and large residential communities (Table 4), which covers a large area and has a fragmented layout, with a high degree of fragmentation of habitats, and the restoration of these areas can maintain the safety of ecological corridors and improve the ability of ecosystems to withstand external risks.

Table 4. Distribution of ecological pinch-points area in Liuzhi

Towns and villages	Quantity	Distribution position	Area（hm^2）	Land use type
Dayong town	1	Liangshuijing Village	1.08	Urban villages and industrial and mining land, arable land
Guanzhai town	1	Bazi village	0.59	Towns and villages and industrial and mining land, arable land, transport land
	1	Gouwa village	2.07	
	1	Shele village	1.38	
	1	Xiamawong village	0.55	
Jiulong street	3	Boao village	4.12	Transport land, arable land
	1	Chuantong village	0.79	
Langdai town	1	Tianba village	6.27	Town and village i.e. industrial and mining land, Transport land
	2	Toutang village	14.70	
Lubie Buyei ethnicity and Yi township	1	Chuandong village	0.22	Arable land, towns and villages and industrial and mining land
	1	Changzai village	1.17	
Niuchang Miao and Yi township	2	Daqin village	7.40	Land for gardening, transport
	3	Jianyan village	7.20	
	3	Qianzhong village	3.28	
Sokha Miao, Yi and Hui nation Townships	1	Daqin village	2.16	Parkland, towns and villages and industrial and mining land
	1	Pinzai village	1.06	
Xinchang township	2	Songba village	84.35	Transport land, arable land
	2	Xinzai village	5.04	
	2	Xiongjing village	24.09	
Moon River Yi, Buyi and Miao Townships	1	Lanba village	2.25	Arable land
Zhongzai Miao, Yi and Hui nation Townships	1	Xinchang village	2.07	Arable land, towns and villages and industrial and mining land

The stability of the distribution area of the ecological barrier sites is under stress by mining activities, geological hazard bodies, etc. To ensure the normal migration of species and regional environmental security. Optimize the traffic network layout, reserve natural mountains as animal migration corridors, or scientifically layout culverts to reduce the impact of traffic development on species migration. At the same time, the rational layout of coal mining planning, the implementation of clean production in the coal mining industry, the development of corresponding ecological protection measures and the establishment of a perfect disaster monitoring system, the implementation of environmental restoration of resource-oriented cities and the construction of green mines, and the maintenance of ecological network connectivity.

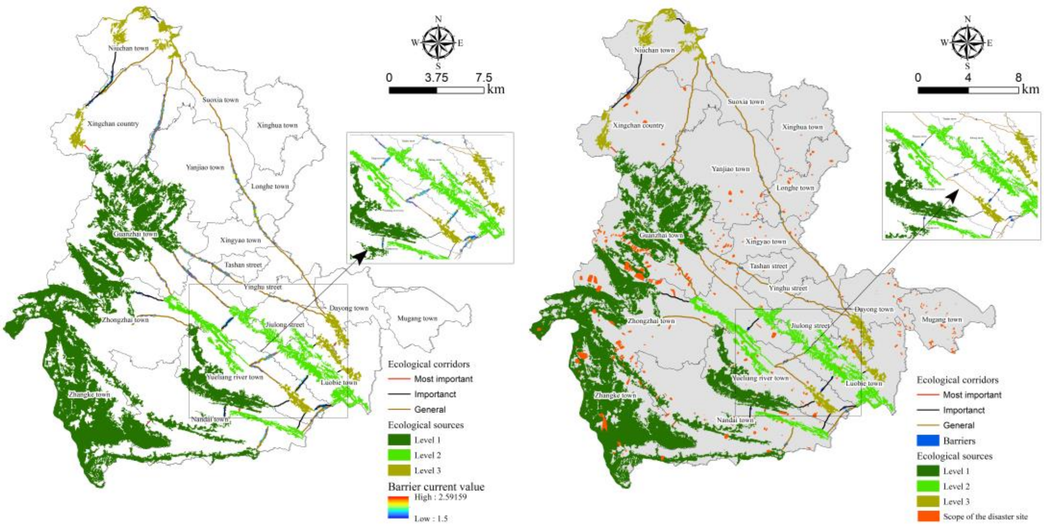

Fig. 8 Ecological barriers current and its spatial distribution

4. DISCUSSION

Although this study provides scientific references for the construction of ecological safety network and ecological restoration planning layout in resource cities, the following deficiencies still exist: in the identification of ecological source sites, the landscape connectivity analysis needs to set the distance threshold between the source sites, while the diffusion distance of different species is limited, due to the rich variety of terrestrial and aquatic organisms in the study area, it is not possible to migrate the distance of each species, and there is no clear standard for the landscape distance threshold at home and abroad. There is no clear standard for the landscape distance threshold, so the study integrated the existing results and the regional ecological background and finally chose 5000 m as the landscape distance threshold based on field research. The probability of connectivity was set to 0.5. When extracting the ecological pinch points and ecological obstacle points using the circuit theory, it is necessary to put a threshold for the width of the ecological corridors. The threshold selection affects the cumulative current value of the pinch and obstacle points. Still, it does not affect the spatial distribution and location, indicating that the solution to these key points is impossible. The ecological corridors' location means that solving these key points' ecological problems is an effective way to maintain ecological security. Considering the fragile ecosystems in the study area and the limited budget for ecological restoration, combined with the local urban development plan, 2000 m is finally chosen as the threshold value of the ecological corridor for extracting ecological pinch points and ecological obstacle points.

5. CONCLUSION

Taking the resource-oriented city Liuzhi Special Zone as an example, the study adopts MSPA, ecological red line, and other multi-factor superposition to identify the ecological source, integrates human and natural environmental impacts to construct the resistance surface, and applies the circuit theory to extract the environmental corridor and ecological nodes, providing a comprehensive environmental safety network construction method. The research results of this paper are as follows:

(1) The 17 ecological sources (371.51 km^2) in the study area were concentrated in the west and south of the region, adjacent to mining areas, and were strongly disturbed by human activities. The first- and second-level ecological sources are concentrated in clastic rock areas such as clay rock, sandstone, and siliceous rock in the west of the study area. The third-level ecological source is scattered in the southern region, dominated by dolomite, limestone, and other carbonate rocks. Ecological corridors connect discrete ecological sources in series.

(2) Thirty-three ecological corridors (163.92 km) were extracted according to the circuit theory to ring the source area in a spider web connecting the discrete distribution of environmental sources in the watershed. The primary and secondary ecological corridors were mainly distributed in the western part of the study area. The road networks and land use types on both sides of the corridors were staggered and intensively damaged.

(3) Twenty-two ecological pinch points and 25 ecological barrier points were selected as environmental protection and restoration areas.

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