Construction and optimisation of watershed scale ecological network: a case study of kuye river basin

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Introduction: Creating an ecological space network is essential for safeguarding the core structure of ecological space.

Methods: Morphological spatial pattern analysis was used to locate ecological sources in the Kuye River Basin. Using the least cumulative resistance model and gravity model, the resistance surface, ecological corridor, and ecological space management network are determined.

Results and discussion: The study revealed that in 2022, the predominant land use types in the Kuye River Basin were wood land and grassland, cultivated land, and construction land. MSPA model software identifies a substantial portion of the landscape pattern as consisting of core and marginal areas, which encompass 30324.05 hm^2 and 15088.24 hm^2. High ecological resistance surface factors dominate the socioeconomically vibrant zone and northern regions. Resistance values ranging from 0.02 to 0.87, and high and law resistance zones alternate. The minimal cumulative resistance approach found 171 ecological corridors. And gravity model using the interaction matrix of 19 primary ecological sources discovered 8 first-level ecological corridors with the highest interaction force. There are 137 core and 23 subsidiary ecological corridors with significant affects. Overlying the road factors and ecological corridors of national highways, provincial roads, railways, and high-speed roads creates a total of 38 ecological breakpoints, each characterized by specific barrier effects and legal ecological stability.

1 Introduction

The rapid progress of socio-economic development and irresponsible human actions in recent years have caused a variety of ecological degradation problems, resulting in significant changes in the ecological landscape (Lin et al., 2009). Reversing urban problems during urbanisation is difficult, and the ecosystem is under unprecedented stress (Yin et al., 2011; Chen et al., 2021). Ecological protection and restoration are global priorities (Farage et al., 2021). The Yellow River Basin (YRB), a major cultural center in China, is an ecological barrier and socio-economic region that provides vital

ecosystem services (Song et al., 2022). The basin's fragile ecological condition and major people-land conflict remain severe due to human activities and natural calamities (Chen et al., 2020; Yan et al., 2022).The Kuye River Basin, a significant Yellow River Basin tributary, is crucial to northern China's energy and ecological security. It oversees the national strategic goal of "high-quality development and ecological protection of the Yellow River Basin." And the city is resource-rich and resource-based. However, long-term economic activity is threatening the environment and ecosytem. Due to the rapid development of the mining industry and massive expansion of construction land, soil erosion, habitat fragmentation, and serious ecological problems have increased (Chen et al., 2022; Wei et al., 2022; Zeng et al., 2023). The "14th Five-Year Plan" of the Yellow River Basin is a crucial time to promote both superior growth and ecological conservation. How to identify ecological sources, build significant corridors, and restore and plan ecosystems under sustainable economic development in basin counties and cities is a research topic and scientific issue. These difficulties relate to Yellow River Basin ecological protection and high-quality development as national strategic needs.

In contrast, ecological networks were introduced in Europe in the 1980s as a scientific method of nature conservation and spatial planning to prevent regional patches from becoming isolated and maintain or restore natural ecosystem connectivity (Nie et al., 2021; Jin et al., 2022). Ecological networks, which include ecological springs and potential ecological corridors (Salviano et al., 2021), can efficiently improve connectivity between isolated patches in a region, facilitate material and energy movement, and improve network structure and function (Fath et al., 2007). The services of regional natural systems are significantly enhanced (Chen et al., 2011; Chen et al., 2017). Jongman et al. (2004) define an ecological network as a network of nature reserves with core areas, corridors, buffer zones and restoration areas. Landscape ecology principles are used to repair and preserve natural environments. Many scientists have since conducted considerable investigation from many aspects (Wang et al., 2022a; Wang et al., 2022b). Thus, ecological networks have expanded from habitat conservation to ecosystem integrity. These networks now incorporate landscape planning, greenway networks, and ecological environmental governance (Li et al., 2022; Wang et al., 2022b; Mao et al., 2023). Recently, research on ecological network design has moved towards a paradigm called "source extraction-resistance surface construction-corridor simulation." Logical ecological network development requires efficient resource extraction. Recently developed stratigies for identifying ecological sources are more objective than subjective ways like picking nature reserves or ecosystems. Morphological Spatial Pattern Analysis (MSPA) and the Patch Importance Index (dPC) from landscape graph theory are used in these methods. Using MSPA and dPC techniques can identify crucial patches that sustain landscape connectivity (Clerici and Vogt, 2013; Ordóñez-Gómez et al., 2015). These methods have helped construct urban ecological networks (Huang et al., 2021; Liu et al., 2023b) and forest conservation areas (Barbati et al., 2013; Wang et al., 2021). Researchers can realistically model organisms' environmental challenges by including geography, land use, roads, water, and human

activities. Using a holistic approach, we can better comprehend ecological interconnection and the connections between numerous ecological processes (Peng et al., 2018; Wang S. et al., 2022). Huang et al. (2021) examined Wuhan City ecological network development from environmental and socioeconomic perspectives. Many considerations were considered. They gained a better understanding of how natural processes such as habitat fragmentation and human actions like urbanization and infrastructure development affect ecological resilience by integrating these factors. This comprehensive research illuminates biological corridors' resilience to human-induced pressures and environmental changes. In addition, the Minimum Cumulative Resistance (MCR) model is now the most widely used approach to simulate ecological corridors. This quantitative analytical model measures ecological patches separation and identifies the best species migration path via space (Fu et al., 2024). When combined with gravity model, this model appropriatelt compares ecological corridor importance. It may also evaluate ecological corridor hierarchies between patches (Luo et al., 2023). However, it is important to emphasise that ecological network construction goes beyond MSPA and MCR (Yang et al., 2023). Other methods and models have also advanced the field (Li et al., 2017). The global spread of species has been predicted via species distribution models (SDMs). However, MSPA and MCR are still commonly utilized in ecological network research and construction (Xu et al., 2024). The combination of the two methods provides a more powerful, effective and comprehensive methodology for ecological network construction, making it the preferred option for both research and practical applications.

This research studies the Kuye River Basin and employs Morphological Spatial Pattern Analysis method to identify the significant ecological source sites. Scientifically combining patch importance, likely connectivity, and total connectivity index achieves this. And elevation, slope, land use type, road traffic, water system and natural and socio-economic characteristics were used to build resilient zones (Ma et al., 2011). The basin's ecological spatial network design was constructed by merging the gravity and MCR model, then identified and extracted the ecological corridors. Aims to explore the direction of ecological network optimisation to improve the overall biodiversity (Kumaraswamy and Udayakumar, 2011) of the watershed and ecosystem, taking into account the current phenomenon of rapid urbanisation. It does so by considering multiple perspectives and using scientific methods.

2 Study area

Originating in Zhashu Village, Chaideng Township, Dongsheng District, Ordos City, Inner Mongolia Autonomous Region, the Kuye River Basin (109° 28′-110° 45′E, 38° 22′-39° 50′N) is a tributary of the middle reaches of the Yellow River (Figure 1). With two tributaries from the Ulan Mulun River and the Niuchuan River, it is a principal tributary of the Yellow River. Primary stream covers 8,706 km² and 242 km long. The basin has diverse landforms, severe soil erosion, frequent

FIGURE 1
Overview of study area.
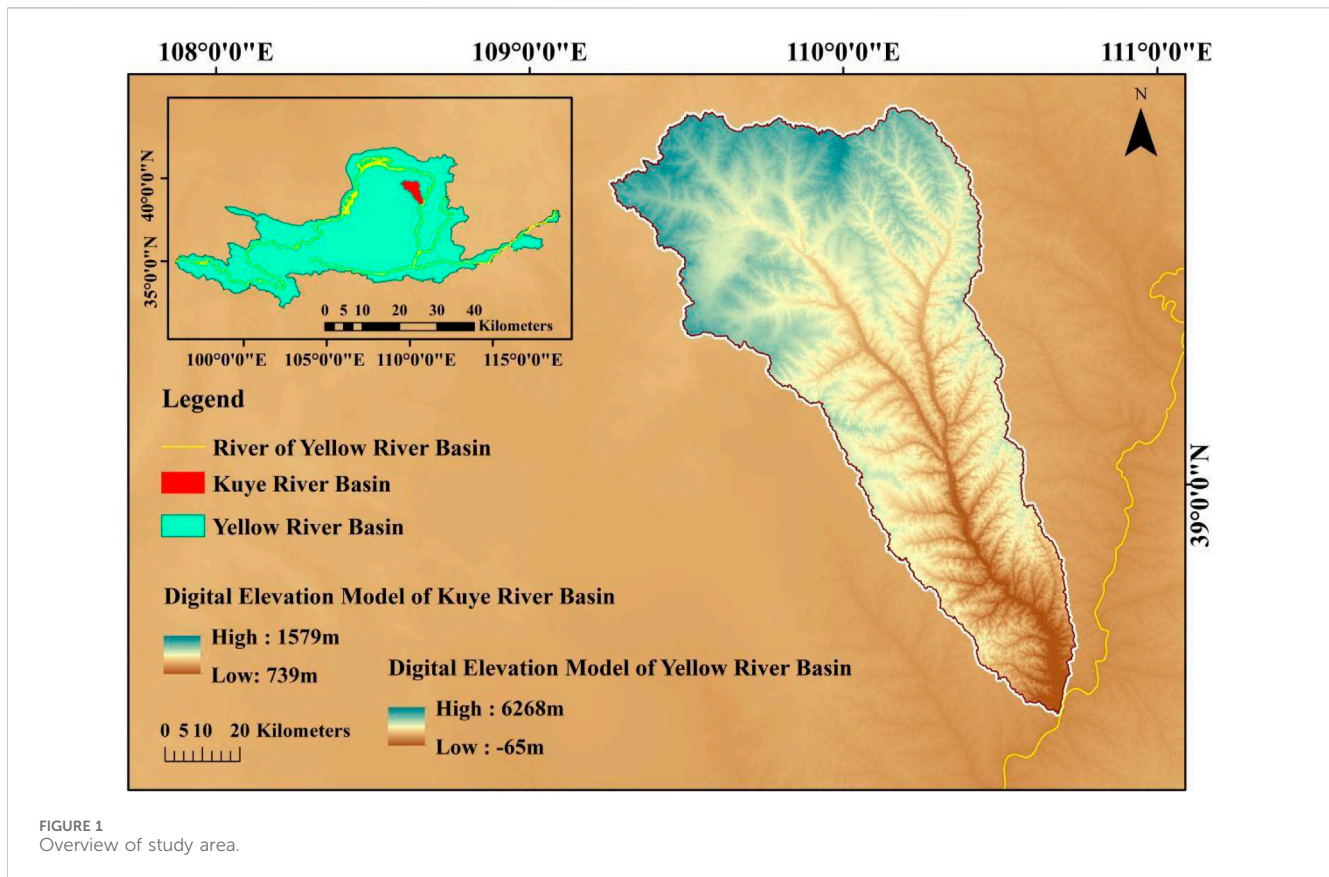
droughts, rainstorms, dust storms, and a large supply of coarse silt to the Yellow River. Shenfu Dongsheng super-large coalfield crosses across the basin, making it the heart of China's cross-cicurity "Shanxi-Shaanxi-Inner Mongolia energy and heavy chemical base" construction (Wei et al., 2023b). The acceleration of urbanization, industrial and mining development and construction, population, and predatory management has caused the significant conflict between people and land, soil erosion, the sharp decline in biodiversity, function, and value of ecosystem services, and ecological landscape fragmentation.

3 Data sources and research methods

3.1 Data sources

This study made use of digital elevation data, socioeconomic data, and images from remote sensing. More precisely, this encompasses the subsequent elements (Table 1).

3.2 Research method

3.2.1 Land use dynamic degree

The quantitative shift in land use types over a given time period, mostly reflecting regional variations in land use change rate and intensity, is called "land use dynamic degree" and has two categories: comprehensive and single (Li et al., 2022). Equation 1 calculate the dynamic degree of single land use, which shows the change rate of a land use type in a region over time (Liu et al., 2023a). The dynamic degree of land use (Equation 2) is used to assess land use transfer between categories during the study (Chen et al., 2022; Wei et al., 2023a). It can illustrate regional comprehensive land use change intensity and compare local and whole area change.

$$LUT^{now-before} = \frac{LUT^{now} - LUT^{before}}{LUT^{before} \times Time} \times 100\% \quad (1)$$

$$LUT^{synthesize} = \left[\frac{\sum_{i=1}^{n} \Delta LUT^{x-y}}{2\sum_{i=1}^{n} LUT^{x}} \right] \times \frac{1}{Time} \times 100\% \quad (2)$$

Where $LUT^{now-before}$ reflects the area of a land use type at the start and end of the study period, while LUT previous represents its dynamic degree. Time (study duration), $LUT^{synthesize}$ (land use dynamic degree), LUT^{x} (number of beginning land use types), ΔLUT^{x-y} (area of x-type land transformed to other land types) are all represented.

3.2.2 Morphological spatial pattern analysis

Morphological Spatial Patterning Analysis (MSPA) is a classification approach for raster image processing. Vogt et al. (2009), Soille and Vogt (2009) presented it using expansion, corrosion, and open/close arithmetic. It is distinguishes itself from existing identification approaches that merely choose ecological sources from patch regions or extract patches and corridors for connectivity analysis. It avoids subjective bias by

TABLE 1 Summary table of data sources.

	Data content	Source	Web address
1	Landsat TM 45 and Landsat 8 OLI_TIRS satellite remote sensing images	Geospatial Data Cloud	http://www.gscloud.cn
2	Examining the land use information of the research region in 2022 using photos from remote sensing. With a resolution of 30 m, the land use types are categorized into the following categories: cultivated land (including dry land), wood land (including land with trees, shrubbery, sparse forest land, other woodlands), grassland (including low coverage grassland, moderate coverage grassland, high coverage grassland), water area (including rivers and canals, lake, reservoir pond, bench land), construction land (including urban land, rural residential area, other construction land), and other land (including sandy land, saline-alkali land, wetland, bare land)	The Environment for Visualizing Images 5.3.1	https://envi.geoscene.cn/appstore/
3	Digital elevation model	Geospatial Data Cloud	http://www.gscloud.cn
4	The digital elevation model used to generate the slope data was produced using the ArcGIS software's ArcToolbox module, 3D Analyst Tools-Raster Surface-Slope	ArcGIS	http://www.arcgis.com/
5	Image preprocessing such as atmospheric correction, mosaic, cropping, and radiometric calibration are carried out using ENVI of Visualizing Images 5.3.1 program in order to produce the normalized difference vegetation index. The pixel dichotomy model is used to estimate the band, and the outliers are eliminated	The Environment for Visualizing Images 5.3.1	https://envi.geoscene.cn/appstore/
6	The water distance data is derived from Digital Elevation Model data and acquired through the hydrological analysis and Euclidean distance analysis modules of ArcGIS software	ArcGIS	http://www.arcgis.com/

TABLE 2 Landscape Types and Ecological Implications of morphological spatial pattern analysis.

Landscape type	Ecological implications
Edge	It is located at the edge of the core area and the transition area between the peripheral non-green landscape area, which can reduce the impact of the external environment and human disturbance
Branch	It is at the edge of the core area, and the transition area between the peripheral non-green landscape area, which can reduce the impact of the external environment and man-made disturbances, usually for the forest park, Large forest farms and other peripheral forest belts
Islet	Small patches that are independent of each other and have low connectivity are less likely to exchange material and energy with other patches. Most of them are small green spaces in urban or rural areas
Core	Can be used as a "source" for a variety of ecological processes, mostly in forest parks with large patch sizes, large forests, etc., which are important for the reproduction of species and the conservation of biodiversity
Loop	The internal channel of material and energy exchange in the same core area is the shortcut of material and energy exchange in the core area
Perforation	As a transitional region, it also has an edge effect, which exists between the core patch and its internal non-green space
Bridge in edge	Narrow areas connecting patches of different core areas and characterized by ecological corridors, mostly in the form of green belts, which are conducive to the migration of species and the connectivity of landscapes within the territory

treating each patch as a coherent unit when assessing landscape connectedness (Liu et al., 2023a).

For morphological spatial pattern analysis to determine the ecological source, we used ArcGIS software's ArcToolbox-Spatial anlyst-Reclass module. Foreground data was 2022 Kuye River Basin wood land usage (assignment 2). Background data—water, construction, grassland, agricultural, and other land uses—is used to generate binary grid 8-bit Tiff data (assignment 1). Guidos' eight-neighborhood image refining methodology was used to examine the binary data. The seven landscape features discovered background, edge, branch, islet, core, loop, perforation, and bridge in edge (Lu et al., 2017; Hong et al., 2023). To verify that the data accurately reflect the structural elements like corridors and core area (Table2).

3.2.3 Ecological source identification

Ecological source sites in the Kuye River Basin are important ecological and economic assets that must be protected (Lin et al., 2009; Han et al., 2023). Ecological source areas are tracts of land with diverse landscapes that provide important ecological functions. Offer vital ecological services. Keeps landscape ecosystem stable and intect. The ecological core is crucial to the ecosystem. Ecological advantages may spread to the surrounding ecosystem (Guan et al., 2023). Landscape connectedness is the extent to which natural areas in a region are linked. Ecological services and biodiversity depend on it (Mitchell et al., 2013). Overall connectivity (IIC), probable connectivity (PC) and patch importance (dI) can assess regional landscape connection and patch relevance. Landscape pattern and function assessment

and ecological source identification depend on these measures (Saura and Pascual-Hortal, 2007).

According to the United States Department of Agriculture (USDA) regulations (Bentrup, 2008), plants, birds and mammals need at least 5 hm^2 of suitable habitat in urban areas, as supported by relevant studies. Considering this law and the Kuye River Basin's urban growth characteristics, we choose core areas greater than 5 hm^2. We used the Confer software to evaluate landscape connectedness using IIC (Equation 3), PC (Equation 4) and dI indices (Equation 5). This evaluation helped us to rank the Kuye River Basin center areas' value. We then selected ecological source areas greater than 5 hm^2 for our investigation.

$$IIC = \frac{\sum_{a=1}^{n}\sum_{b=1}^{n}\frac{s_a \times s_b}{1+nl_{ab}}}{A_L^2} \qquad (3)$$

$$PC = \frac{\sum_{a=1}^{n}\sum_{b=1}^{n}p_{ab}^* \times s_a \times s_b}{A_L^2} \qquad (4)$$

$$dl = \frac{I - I_{remove}}{I} \times 100\% \qquad (5)$$

Where IIC is the overall connection index; PC is the probable connectivity index; and dl is the patch importance value. S_a and S_b are the areas of patches a and b; nl_{ab} is the number of links between them; A_L is the total area; and p^*_{ab} is the greatest probability of organisms propagating between a and b. I, IIC, PC, and I_{remove} is the value of the landscape connectivity index after removing the landscape connectivity index value after patch a.

3.2.4 Construction of ecological resistance surface

Ecological source sits in the Kuye River Basin are important ecological and economic assets that must be protected (Yang et al., 2024). The ease of navigating landscapes and the variety of landscapes between source locations might also affect landscape resistance (Peterman et al., 2014; Cao et al., 2022). Landscape resistance measures how easily organisms can move between landscape units (Liu et al., 2021). Due to the mountainous, ecological corridors need established in gradual slopes. Likewise, traffic primarily follows the river valley. In order to prevent the ecological corridors from being located on top of main roads, a road resistance factor is incorporated based on the types of land use. The Kuye River Basin is a typical resource-dependent city. However, long-term mining has severely affected the river's ecology. Rapid mining boom, substantial building, and increasing urbanization have put pressure on the Kuye River ecology. We chose seven elements to design a resistance surface for the research region based on the Kuye River Basin's natural and socio-economic development. Land use structure, digital elevation model, slope, vegetation cover, road, water, and population density are considerations (Figure 2).

Then determine the weight assigned to each resistance factor after selecting them based on Kuye River Basin. Each resistance element's influence must be assessed and quantified (Kang et al., 2021). The entropy value approach estimates indicator weights. Because it avoid unpredictability and guesswork, this strategy is better than subjective assignment. It also effectively addresses indicator variable overlap (Wang et al., 2014). Entropy was used to calculate the weights of the seven ecological landscape resistance variables. Combining the weights of seven indicators (raster data) in ArcGIS created an integrated resistance surface data. Land use structure, elevation, slope, vegetation cover, distance from roads, distance from water,

and population density are indications. The results are shown in Table 3.

(1) Standardisation of evaluation indicators

Standardizing the data first was necessary due to the indicator's different scales. Equation 6 standardised positive indications. Equation 7 standardised negatives. Resistance rises with positive indicator values. Resistance decreases as negetive indication value rises.

$$y_{ij} = \frac{x_{ij} - \min(x_{ij})}{\max(x_{ij}) - \min(x_{ij})} \qquad (6)$$

$$y_{ij} = \frac{\max(x_{ij}) - x_{ij}}{\max(x_{ij}) - \min(x_{ij})} \qquad (7)$$

Where y_{ij} denotes the standardised value of the ith grid cell of the jth evaluation indicator; x_{ij} denotes the original value of the ith grid cell of the jth evaluation indicator; $max(x_{ij})$ and $min(x_{ij})$ denote the maximum and minimum values of all grid cells of the jth evaluation indicator, respectively.

(2) Assignment of indicator weights

The indicator weight method (Zhang et al., 2020a) uses the entropy weight method in objective assignment to improve accuracy and objectivity while reducing subjectivity and uncertainty. First, calculate the entropy of m evaluation items and n evaluation indicators under the theory of entropy weight approach. Let p_{ij} (Equation 8) be the weight of the ith evaluated indication under the jth indicator and e_i (Equation 9) its entropy value.

$$P_{ij} = \frac{1 + X_{ij}}{\sum_{i=1}^{m}(1 + X_{ij})} \qquad (8)$$

$$e_i = \frac{-1}{\ln m}\sum_{i=1}^{m}P_{ij}\ln P_{ij} \qquad (9)$$

When $P_{ij} = 0$, $P_{ij}lnP_{ij} = 0$, after the entropy value of the indicator is determined, the entropy weight W_i of the ith indicator can be determined according to the Equation 10.

$$W_i = \frac{1 - e_i}{\sum_{i=1}^{m}(1 - e_i)} \qquad (10)$$

3.2.5 Ecological network construction
(1) Identification of ecological corridors

Ecological corridors, characterized by their varied ecological roles, play a crucial role in facilitating the life, mobility, and migration of various species. It creates and maintains corridors across fragmented habitats, allowing creatures to freely migrate (Wang and Zhang, 2005; Qin et al., 2024). It also links fragmented ecosystems to form a strong biological network. The Kuye River Basin maintains ecosystem structure and ecological processes. This creates a consistent basin ecological security pattern (Feng et al., 2023). This research uses the MCR model to demonstrate resistance over different terrains from the

FIGURE 2
(Continued).
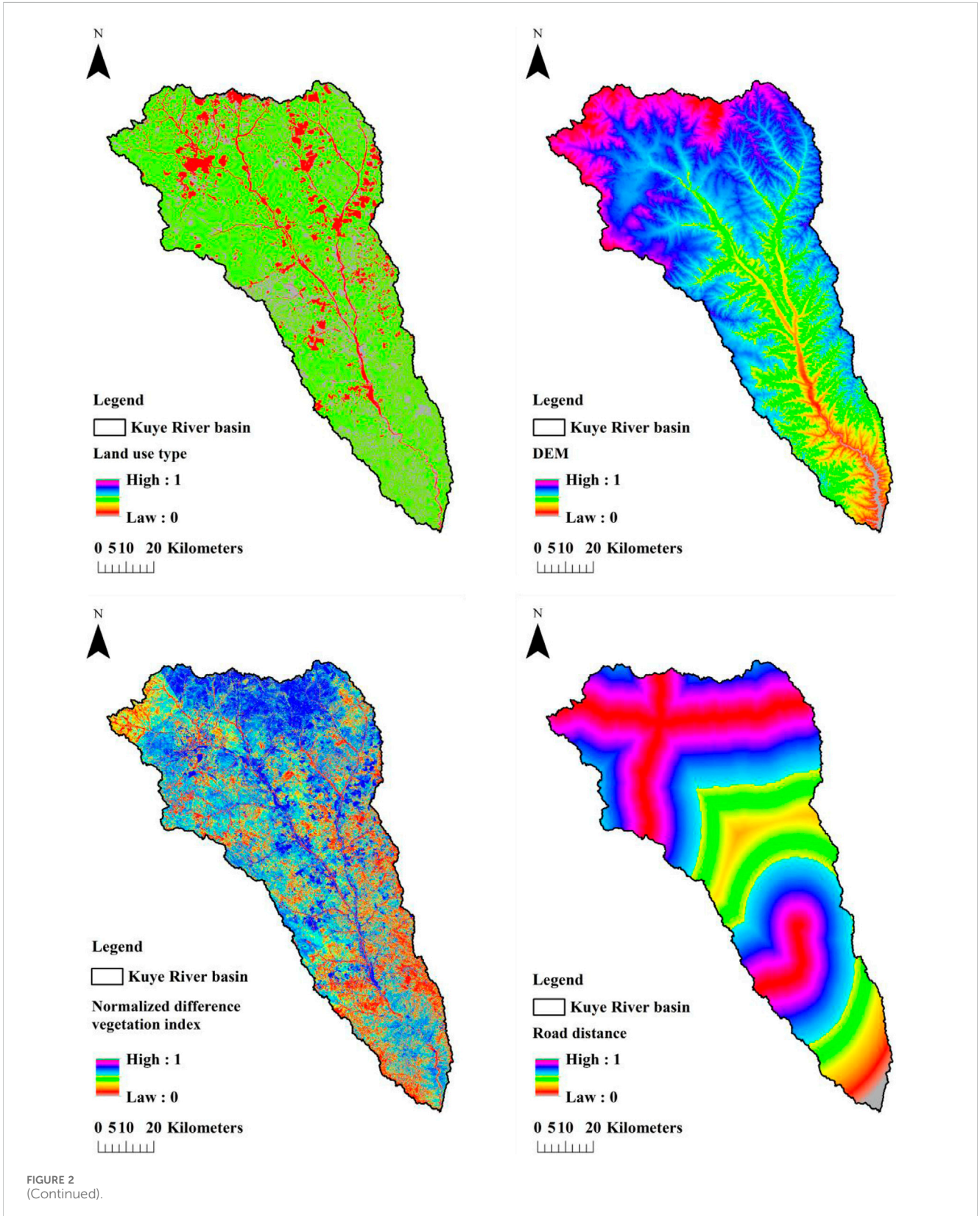
"source" to the objective (Equation 11). Research found the Kuye River Basin pathways with the least cumulative resistance between the main patches using this information.

$$MCR = fmin \sum_{j=m}^{i=n} \left(D_{ij} \times R_i \right) \qquad (11)$$

FIGURE 2
(Continued). Ecological resistance surface factor.
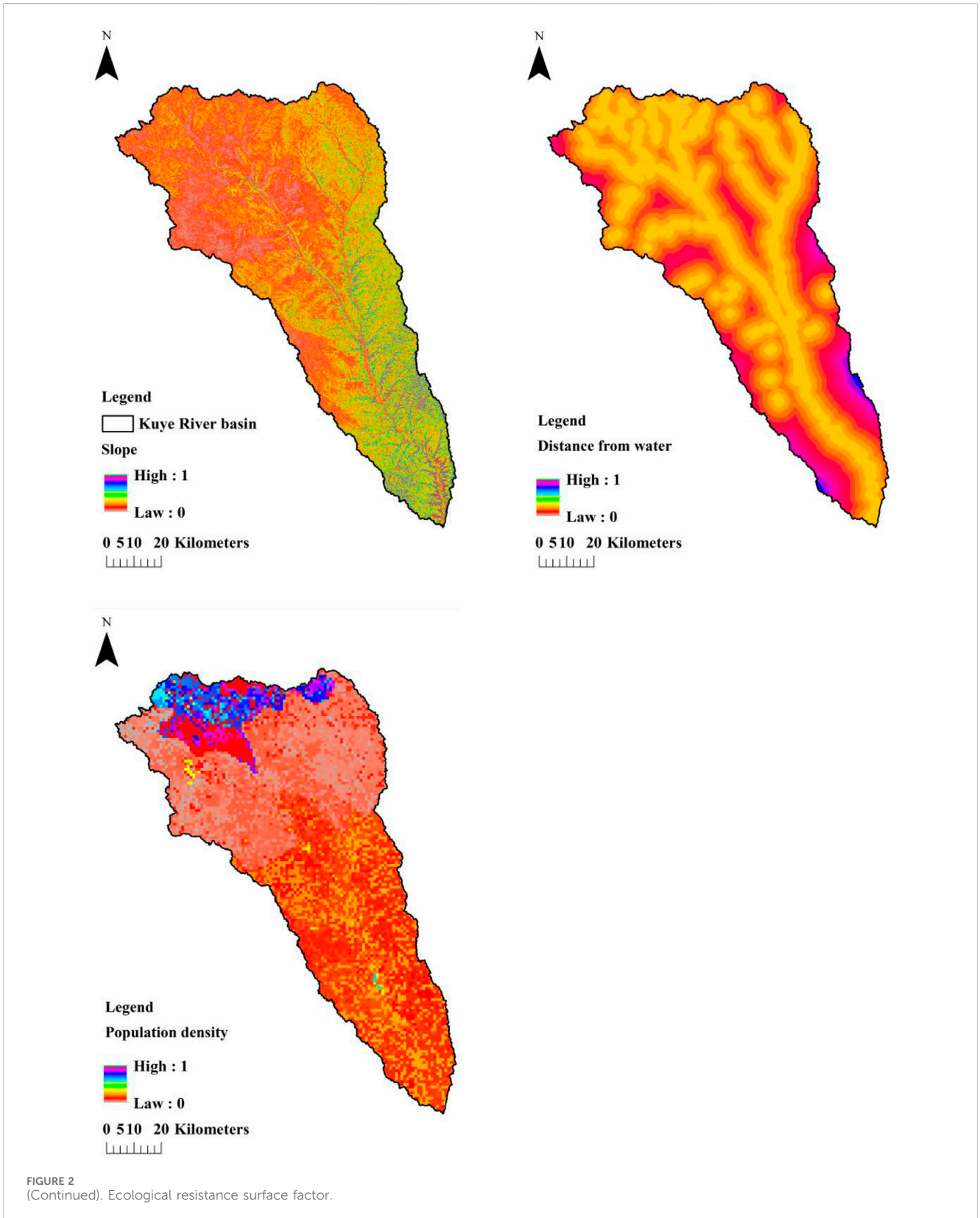
The formula expresses the positive association between a point's minimal resistance and its distance from all sources, as well as the features of the landscape base, by using an unknown monotonically increasing function, denoted by f. D_{ij} is the spatial distance of the base plane i of a landscape that the species travels across from source j to a specific place in space. m is the number of landscape units i, n is the number of ecological sources j. R_i is the landscape's resistance to a species' migration.

TABLE 3 Ecological resistance factors and weight settings.

First level indicator	Second level indicator	Indicator weight
Natural factors	digital elevation model	0.058
	slope	0.098
	distance from water	0.096
	Normalized Difference Vegetation Index	0.3
Socioeconomic factors	land use structure	0.237
	distance from roads	0.128
	population density	0.083

(2) Identification of crucial ecological corridors

The gravity model quantifies habitat patches interaction. This proves ecological corridors and emphasizes patche connection. In a given area, patches or corridors with higher quality habitats may make migration and dispersal easier and increase special survival (Zhang et al., 2020b; Zhang et al., 2023). By combining the gravity model and interaction matrix between the ecological source patches, the Kuye River Basins' ecological corridors may be identifies and each plate's relative quantified. The precise computation procedure is as follows (Equation 12):

$$G_{ij} = \frac{N_i N_j}{D^{ij}} = \frac{\left[\frac{1}{P} \times \ln(S_i)\right]\left[\frac{1}{p_j \times \ln(S_j)}\right]}{\left(\frac{L_{ij}}{L_{max}}\right)^2} = \frac{L_{max}^2 \ln(S_i \times S_j)}{L_{ij}^2 P_i P_j} \quad (12)$$

The force of interaction between patches i and j is represented by G_{ij}. N_i and N_j, indicate the weight values of two patches, while D_{ij} represents the standardized potential ecological resistance between patches i and j. The overall ecological resistance value between patches i and j is L_{ij}, the greatest is L_{max}, and patch i's is P_i. S_i is patch i's area, patch j's is P_j. S_j is patch j's area.

(3) Identification of ecological breakpoints

Ecological nodes in the landscape matrix help species spread (Chen et al., 2006). Previous ecological studies have called regions with considerable human activity and traffic "breakpoints". The occurrence of "fracture points" may fragment the watershed ecosystem, affecting biodiversity (Louder and Wyborn, 2020) and the functioning and value of ecosystem services. Thus, study analyzes the distribution map of the key transportation routes in the study region to estimate ecological breakpoints.

4 Results and analysis

4.1 Land use structure change

The essay highlights the strong correlation between land use change and social, economic, and ecological issues in the Kuye River Basin. Land use play a crucial role in altering both natural landscapes and human social contexts. The study found that the Kuye River Basin was

FIGURE 3
Spatial and temporal distribution of land use in Kuye River basin.
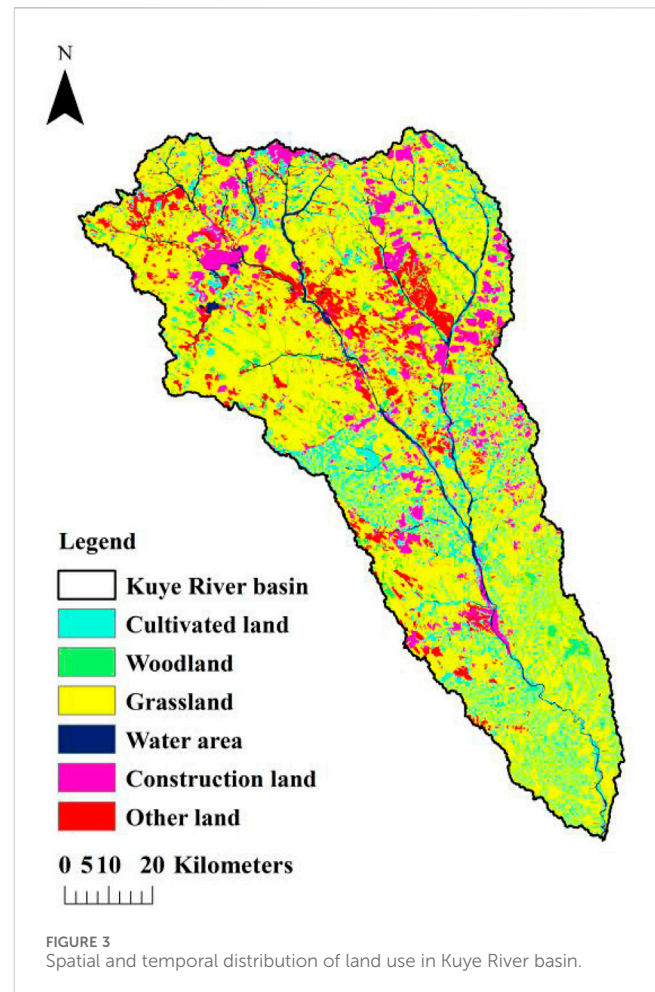
dominated by wood land and grassland, cultivated land, and construction land in 2022 (Figure 3). Which accounted for 85.37% of the region. The spatial distribution covers much of the basin, including the north, middle, and south sections. The basin has a distinct land use landscape pattern gue to higher idensity in the west of the northwestern and central parts This phenomena is mostly driven by social and environmental variables. The policy to turn farms into forests and ban mountain grazing has societal consequences (Xue, 2023). This has led to a significant increase of wood land and grassland. Additionally, large areas of steep slopes and wasteland in the basin have been transformed into wood land, leading to an enhancement in the hierarchy of the plant community (Lu et al., 2022). Furthermore, this suggests that wood land is the prevailing landscape types in the watershed. And, the policy of reforesting cultivated land has resulted it.

In addition, the Kuye River Basin serves as a significant mining region for Shenfu and other coal fields. The provision of residential land for coal miners is the main driver of other development land expansion. Other construction land has grown significantly due to the increase of production and living facilities, including transportation and supporting services (Pontius et al., 2008; Chen et al., 2022). Furthermore, urban land and rural settlements have grown due to socioeconomic growth and urbanization. Construction land is mostly in the central, northern, and northeastern watersheds.

4.2 Landscape pattern distribution characteristics

The ecological source areas maintain the research area's natural ecological environment and limit human expansion and construction. Based on the calculations made by the MSPA, calculated the Kuye River Basin's ecological source areas as 30,324.05 h m², 64.13% of biological landscape. Meaning basin's ecological space is dominated by big core patches (Figure 4).
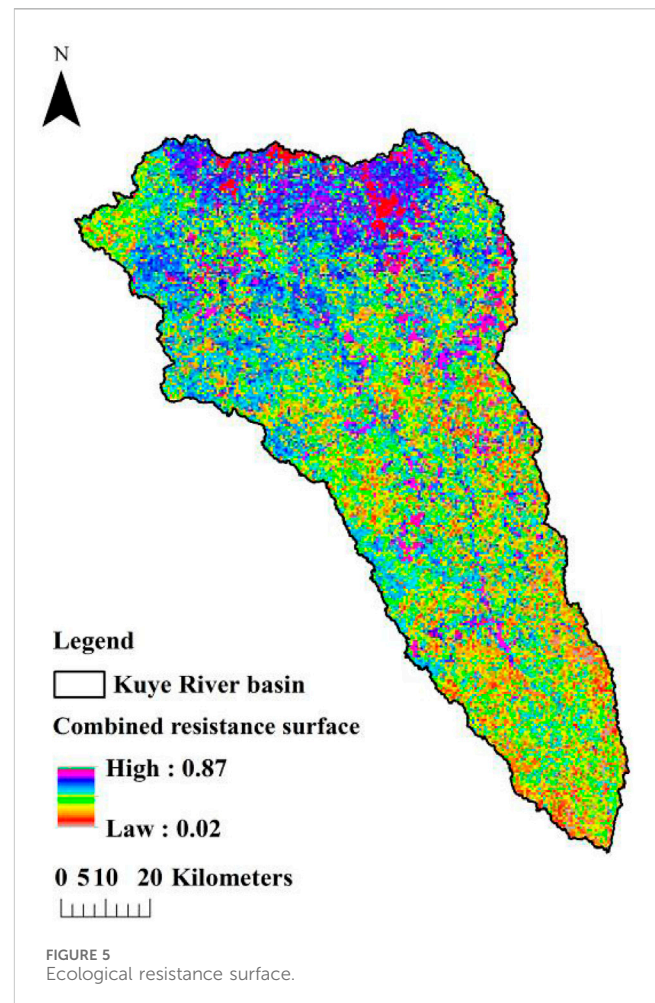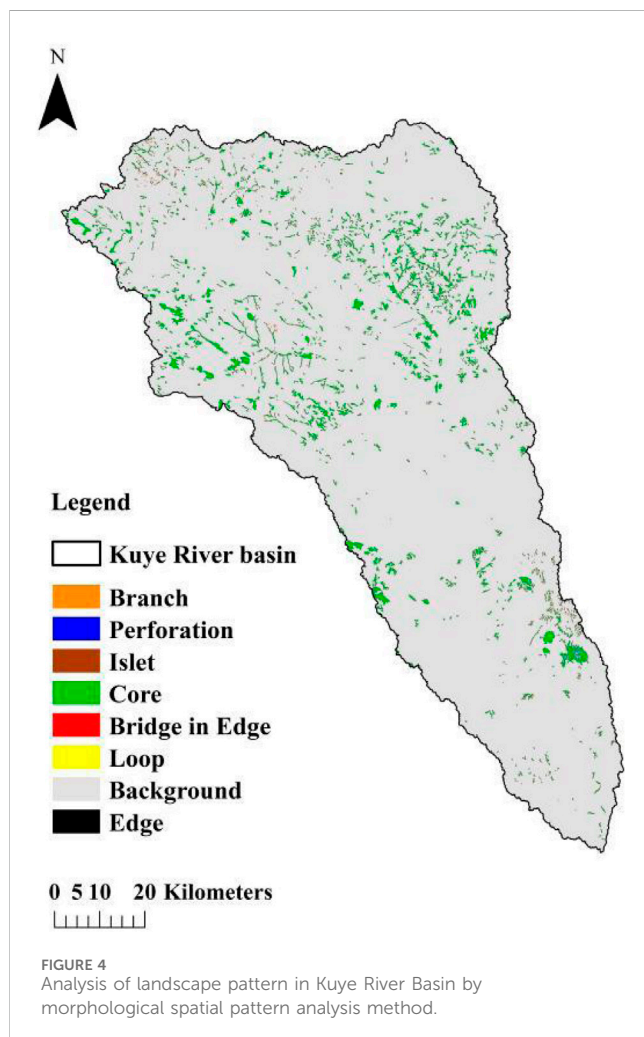
The primary region in the northern part is predominantly focused in the northwest. The northeast region has a low population density and poor terrain connectivity, which hampers species and materials mobility between core areas. The primary region in the southern part is mostly focused in the southeastern area. Mountains and rivers steep slopes and less human intervention are more common in the south section. The central region's main cities are along the Ulamurun River. As a resource-based metropolis, the Kuye River Basin focuses on long-term mining and the expansion of construction land have accelerated urbanization, largely due to human activity. The ceore region's thiness and division creating a "fracture zone" that affects north-south flow. Furthermore, the fringe zone, with the highest height and percentage, cover 31.91% of the landscape ecological area. The fringe zone protects the core area from the outer area, and its stability is essential.
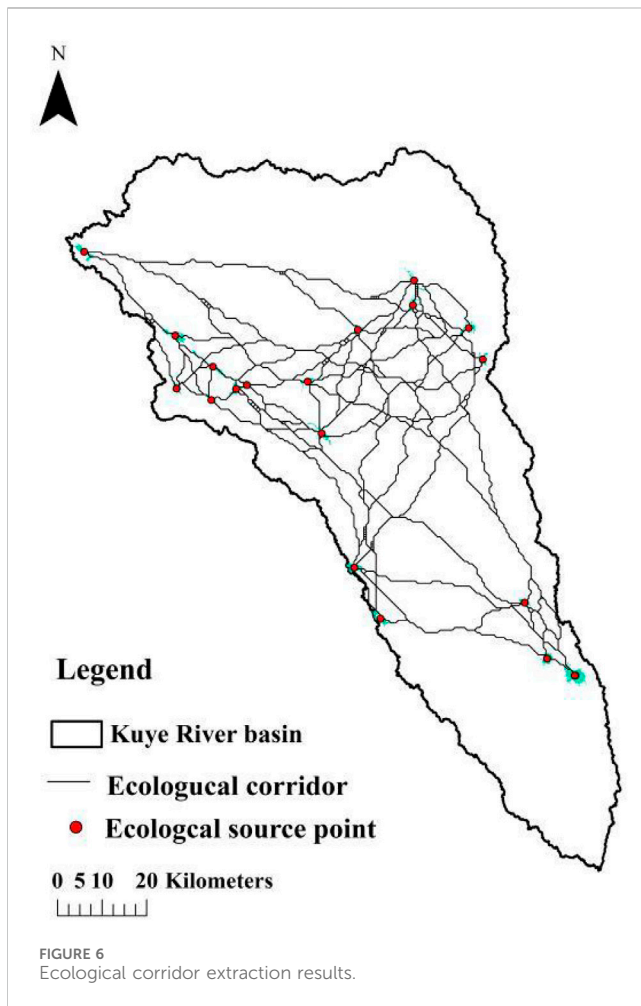
The edge effect influences the impact of external disturbances on the ecosystem and biodiversity (Squires, 2014), perhaps lessening their effects on the edge. Branch (known as Table 1), is a type of landscape that originates from a boundary of a watershed (either a marginal zone or pore) or a connecting portion (such as a bridging or loop channel). It is only connected to the boundary or connecting portion at one end. The main function of a branch is to facilitate the dispersal of species and the exchange of energy with peripheral landscapes. Branches are primarily found in the northern region of the basin. Furthermore, the bridge area comprise 1.05% of the entire foreground area. The interhange of material and energy between core patches in the study region is crucial. The edge is a boundary zone that sepatares the central region from the surrounding non-green environment. It spans an area of 15,088.24 h m². The edge effect may reduce the impact of external disruptions on the ecosystem and biodiversity.

4.3 Ecological network structure

4.3.1 Ecological network structure

Based on the comprehensive resistance surface depicted in Figure 5, the resistance values are dispersed throughout the rage of 0.02 to 0.87. And in the center, northern and northestern

FIGURE 4
Analysis of landscape pattern in Kuye River Basin by morphological spatial pattern analysis method.

FIGURE 5
Ecological resistance surface.

FIGURE 6
Ecological corridor extraction results.

resistance is high. The resistance elements indicates that this location is a vibrant socio-economic hub due to its high population density, broad road network, and abundant developed land. The low resistance zone is mostly situated in the south and has a sparse population, less human disturbance, extensive forest and grass covers, and higher elevation and slope. The MCR model identified ecological corridors based on ecological source and resistance surface. After removing redundant and overlapping corridors, 171 ecological corridors were found (Figure 6).

In general, the research site's center has better interconnectedness and more ecological corridors. The south region of the research area is economically underdeveloped due to its vast vegetation, concentrated biological resources, and low human density. Thus, natural corridors are short and sparse. Furthermore, the ecological corridors have cleaer topography and geomorphology, but their connectivity within the watershed system is inadequate.

4.3.2 Ecological corridors and crucial ecological corridors

Ecological corridor creation and management become more economical as source interaction force increases, as does species material-energy exchange. This work created 137 general, 23 second-level, and 11 first-level ecological corridors

(Table 4; Figure 7). Close proximity to ecological sources, which have minimal terrain resistance, facilitates organism mobility and material exchange. Next are ecological source sites 12 and 13, then 16 and 19, then 8 and 12, and finally 10, 13, and 11. We calculated the interaction force between Kuye River Basin biological source sites using the gravity model. Based on our investigation, ecological source site 9 and 12 have the strongest contact force. The two habitat patches between ecological corridors with stronger interaction forces have better environmental quality. Close proximity to ecological sources, which have minimal terrain resistance, facilitates organism mobility and material exchange. Next are ecological source sites 12 and 13, then 16 and 19, then 8 and 12, and finally 10, 13, and 11.

The distance between ecological source site 1 and 15, 16, 17, 18, and 19 limits circulation. It is difficult to link ecological source site 1 in ecological source sites 15, 16, 17, 18, 19 in the northwest. Connecting the north and south regions for material and energy exchange is required to ensure landscape connectedness of the study area. Hence, the corridor connecting patches 1 and 15–19 is important.
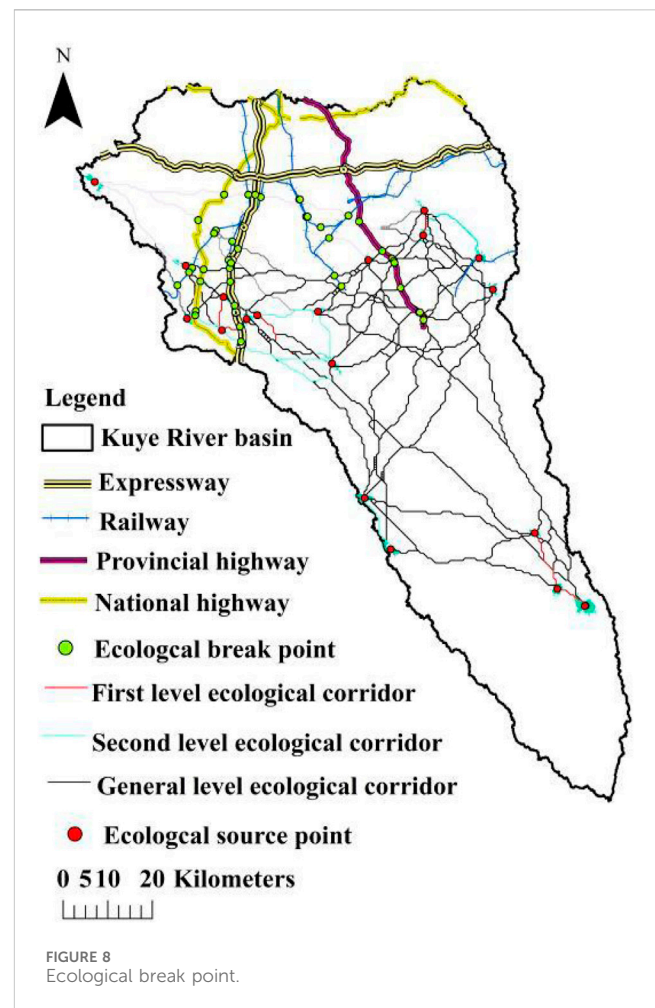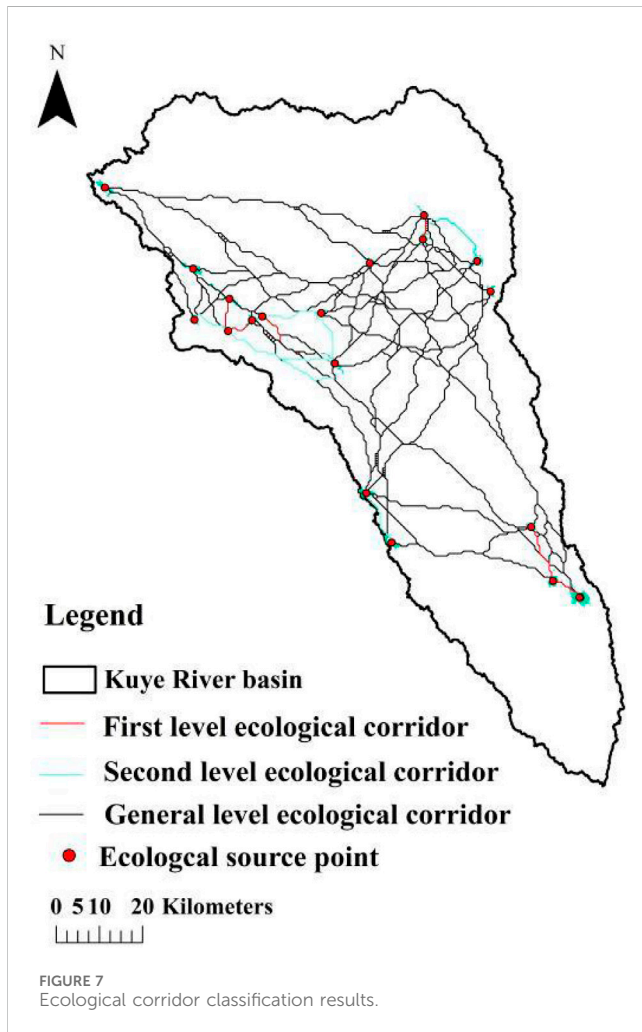
4.3.3 Ecological breakpoints

The presence of a traffic road network in the ecological corridor hinders biological migration and information exchange due to its tendency to promote fragmentation. ArcGIS' linkage mapper tools and data management features helped us find 38 biological breakpoints in the Kuye River Basin. The road layer and corridor layer of national, provincial, railway, and high-speed highways were overlaid (Figure 8). The ecological breakpoints were mostly in the north of the research area. The landscape resistance component showed flat topography, a large concentration of development land, a dense population, and a well-developed road network. This means the area is densely populated and full of human activity.

These biological breakpoints hindered the spread of ecological effects within the ecological corridor, and were strategic points that indicate the key areas of concern for ecological management.

5 Discussion

5.1 Land use structure and planning

An examination of the existing land use type indicates that the main key ecological areas predominantly concentrate in the center urban building land zone of the research area. Despite being few in number, these areas are of utmost ecological importance in the region, since they play a crucial role in maintaining overall resilience. It is crucial to prioritize the cultivation and advancement of ecological areas, such as forests and grasslands, in order to prevent excessive future growth.Urban construction land is highly vulnerable to external interruptions induced by human-made construction operations. It is advisable to establish urban development boundaries in a sensible manner, exercise scientific control over the amount of land used for construction, and apply methods to decrease human-caused disruptions.

TABLE 4 . The interaction force matrix of ecological source in Kuye River Basin under gravity model.

	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00	11.00	12.00	13.00	14.00	15.00	16.00	17.00	18.00	19.00
1.00	0.00	18.99	16.39	19.48	24.11	25.39	159.60	17.92	29.92	69.20	100.49	57.81	78.63	30.20	12.56	17.48	9.98	14.57	14.82
2.00		0.00	1,068.61	213.18	391.84	18.50	132.31	32.21	56.79	38.71	24.03	27.65	30.10	46.23	15.24	28.33	10.74	21.44	21.68
3.00			0.00	382.55	818.86	24.87	240.32	44.22	87.13	54.46	32.26	38.48	41.08	70.26	22.34	40.76	15.11	30.05	30.20
4.00				0.00	45.66	169.28	23.98	1,458.49	23.06	39.88	26.13	28.83	32.13	71.76	27.03	52.87	18.07	38.30	38.33
5.00					0.00	75.69	223.78	146.67	490.69	199.46	97.75	134.64	132.42	249.66	50.24	74.08	32.79	54.78	55.10
6.00						0.00	35.33	23.62	75.35	358.73	817.13	327.55	447.36	68.22	18.49	21.48	13.19	17.04	17.02
7.00							0.00	20.00	25.42	45.22	29.20	32.77	37.54	85.70	40.34	86.69	25.99	59.98	59.42
8.00								0.00	209.94	2,603.44	1941.51	2,898.02	2,187.14	170.18	34.58	36.55	23.29	28.30	28.05
9.00									0.00	434.94	405.27	9,450.33	1,457.06	216.97	31.17	30.11	19.87	22.82	22.45
10.00										0.00	151.09	346.65	269.32	870.78	59.02	50.90	35.03	37.61	37.94
11.00											0.00	33.00	819.18	116.86	29.87	32.40	20.30	25.36	25.22
12.00												0.00	2,987.52	201.30	31.82	31.38	20.53	23.90	23.55
13.00													0.00	200.81	40.05	39.92	25.82	30.63	30.26
14.00														0.00	98.86	65.22	49.25	45.69	43.78
15.00															0.00	91.38	251.58	68.93	62.59
16.00																0.00	183.10	2,978.49	1888.92
17.00																	0.00	128.06	109.86
18.00																		0.00	108.84
19.00																			0.00

FIGURE 7
Ecological corridor classification results.

FIGURE 8
Ecological break point.

5.2 Ecological networking and resistance surface construction

The ecological network was created by integrating different components of the ecosystem, with a particular focus on the watershed as the level of analysis. The Kuye River Basin ecological patch pattern indicated that ecological sources are mainly found in area with high biomass, gentle slopes, low topographic relief, infrequent soil erosion, and minimal geologic hazards. Conversely, human affected areas have fractured landscapes. The ecological patches exhibited a diminutive size and lacked adequate connectivity, resulting in an imbalanced spatial distribution of ecological sources. Wang et al. (2024) study of Erhai Lake Basin's ecological network supports this result, demonstrating the ecological benefits of ecological sources. In contrast, we did not select nature reserves, national parks, or a specific terrain as ecological sources. Instead, we employed the MSPA approach and conducted a landscape connectivity overlay analysis to enhance the scientific objectivity of extracting ecological sources.

This study is a significant advance above previous research. Most previous investigations assigned a score using expert scoring or land use categories. However, including the physical surroundings and human interference reduced subjectivity in this investigation. The elements are standardized and calculated using indicator-specific procedures. We ended up with separate weights. After creating the cost resistance surface, the minimal cost path value connecting ecological sources and other target sources is calculated to produce an ecologically acceptable biological circulation corridor. Reduces subjectivity and inaccuracies when determining resistance levels with this method. Resistance level determination is more objective and error-free with this method.

5.3 Ecological planning recommendations

Through our empirical investigation of the Kuye River Basin, we have found distinct nodes and corridors. These apparently inconsequential elements were demonstrated to be crucial to the network's robustness and efficiency. If these crucial areas experienced a malfunction, the network would be adversely affected. These nodes and corridors play a crucial role as biological hubs and connections, influencing the migration of species and the transmission of energy.

The study determined that future ecological protection and construction efforts should prioritize the planning, construction, and maintenance of natural vegetation protection zones alongside transportation roads. Additionally, it suggests the creation of three-dimensional ecological greenways at ecological breakpoints to facilitate the migration of biological species and the exchange of materials. It is crucial to focus on restoring ecological breakpoints and to consider implementing specific solutions such as underpasses, tunnels, flyovers, and other methods when constructing high-quality highways. To mitigate the hindrance of roads to species migration and ensure the unimpeded movement of organisms.

6 Conclusion

This study focused on the Kuye River Basin, which is the central area of China's "Jin-Shaan-Mongolia Energy and Heavy Chemical Industry Base" and has a highly fragmented ecological landscape. The research analyzed the land use structure and landscape ecological pattern, identified ecological source sites, constructed landscape ecological resistance surfaces (Ye et al., 2015), and extracted and analyzed ecological corridors for the migration of living organisms and species. Ultimately, we examined the ecological thresholds that impede the movement of living organisms and the transfer of materials. By conducting an impartial assessment, we have developed an ecological network for the Kuye River Basin. This network serves as a reliable and practical reference for landscape ecological planning in the Kuye River Basin and other basins that share similar natural and socio-economic characteristics.

Upon detailed investigation, we found an imbalanced spatial organization of the ecological network in the Kuye River Basin, stressing the need to increase internal intricacy. The Kuye River Basin' ecological security pattern must be optimized, especially in the north where human activities affect resource allocation. Hence, safeguarding crucial ecological resources, including 11 primary ecological corridors, 23 ecological corridors, and 137 general ecological corridors, as well as 38 ecological breaks in the economically advanced northern districts of the watershed, is essential for enhancing the efficiency of the watershed's ecological network and overall ecosystem services.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

YW: Writing–original draft. FQ: Writing–review and editing. LL: Writing–review and editing. XD: Writing–review and editing.

Funding

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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