THE ECOLOGICAL NETWORK CONSTRUCTION IN CHINA WANYUAN BY ASSIGNING DIFFERENT RESISTANCE SURFACES

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Abstract. Constructing an ecological network can help mitigate the habitat fragmentation caused by urban expansion, as well as facilitate the survival and migration of species, which is beneficial for biodiversity conservation. We selected Wanyuan, China, for our study, and three different comprehensive resistance surfaces were generated by applying the analytic hierarchy process (AHP), the entropy method (EM), and the spatial principal component analysis (SPCA). Based on these three comprehensive resistance surfaces, three ecological networks were constructed. Then, the ecological networks were quantitatively evaluated to provide a more reasonable theoretical method for the construction of ecological networks in Wanyuan. Meanwhile, the differences between different resistance weighting methods in ecological network construction were discussed. The results indicated that: (1) It was more reasonable to use the SPCA to construct an ecological network in Wanyuan. (2) The weight values generated by the three methods differed significantly. The highest proportion of the AHP was land cover type, consistent with previous research results. However, the weights generated by the SPCA and the EM differed from previous research results. (3) Although the weight proportions of the three methods differed, the distribution areas of high and low values of the three comprehensive resistance surfaces were roughly the same.
Keywords: *resistance surfaces, the analytic hierarchy process, the entropy method, the spatial principal component analysis, ecological network*

Introduction

Urbanization has brought convenience to human lives, but also resulted in the loss and fragmentation of ecological habitats, which poses a serious threat to the diversity of biological populations. To safeguard biodiversity as much as possible in the urbanization process, scholars have suggested linking the fragmented ecological habitats with ecological corridors, creating a spatially integrated ecological network (Bascompte, 2010). The ecological network can reduce the negative impacts of urban expansion on habitat fragmentation, and provide conditions for the survival and migration of species, which contributes to biodiversity conservation (Shi et al., 2020). The framework for ecological network construction consists of four steps: “source identification-resistance surface construction-corridor identification-node extraction.” The resistance surface is an essential element of the ecological network construction,

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which reflects the difficulty level of species migration and diffusion or the functioning of a certain ecological process. It affects the rationality and effectiveness of the ecological network considerably.

The resistance surface is formed by selecting resistance factors and assigning weights to them. Resistance factors usually include land cover type, elevation, slope, road, water, settlement and other factors that influence the biological migration and diffusion. To determine the weights of resistance factors is the key to ensure evaluating results rationally. There are two methods for assigning the weights of resistance factors: subjective weighting method and objective weighting method. The former is to determine the indicator weights by combining professional knowledge and expert experience, usually using the AHP. The latter to is to assign weights to resistance factors according to the statistical information they reflect, commonly using the EM and the SPCA.

The AHP is a multi-objective decision analysis method that integrates quantitative and qualitative aspects (Saaty et al., 1985). This method determines weights by comparing two resistance factors pairwise, constructing a judgment matrix using a 1~9 scale method, and analyzing the intrinsic influence among factors. This method quantifies and mathematizes the thinking process of the expert. The AHP has a high subjectivity of weights, and may cause a large discrepancy between the results and the reality if the resistance factors are not adequately analyzed and studied. The SPCA reduces the dimensionality of multiple resistance factors and converts them into a few comprehensive variables, namely principal components. This method can simplify the system structure, while preserving as much information as possible from the original variables. This method can overcome the influence of subjective factors, but its effect is poor if the correlation degree among resistance factors is low (Abdi et al., 2010). The EM is a weighting method that applies the difference-driven principle, which implies that the more dispersed the resistance factor is, the more influential the indicator is on the comprehensive evaluation (Wei et al., 2022) The EM can eliminate the interference of human factors and could reflect the information contained in the indicator data fully and accurately, but it might overlook the importance of the indicator itself and fail to reduce the dimension of the evaluation indicators (Boucheron et al., 2013). The three methods have their own strengths and weaknesses in the construction of the resistance surface, and the choice of the resistance factor weight determination method depends on different research conditions and research areas.

To evaluate the rationality and effectiveness of ecological networks, researchers often use network analysis and landscape connectivity analysis. In other words, researchers usually employ multiple indices to analyze the characteristics of ecological networks and assess the rationality of their network structure. Network analysis evaluates the connectivity and effectiveness of the internal structure of ecological networks (Nie et al., 2021), while landscape connectivity analysis reflects the continuity of the overall function of the landscape. Landscape connectivity analysis also measures the functional characteristics of ecological networks, which are crucial for the world’s biodiversity conservation work (Saura et al., 2010). By integrating these two analyses, researchers can quantitatively examine the structural and functional aspects of ecological networks, which enhances the theoretical and practical significance of their construction (Nelson et al., 2009).

Wanyuan is a key zone for ecological function and water conservation in the upper reaches of the Yangtze River, with a vital ecological location. It plays a significant role in building the ecological barrier in the upper reaches of the Yangtze River and maintaining the ecological security of the Yangtze River basin. We selected Wanyuan as the study area and couples the morphological spatial pattern analysis (MSPA) and habitat quality model to identify potential source areas. We also chose important source areas based on landscape connectivity indices. Based on the AHP, the EM and the SPCA, three comprehensive resistance surfaces were generated, and the minimum cumulative resistance model (MCR) and circuit theory were used to extract ecological corridors, stepping stones and ecological barriers, and constructed three ecological networks. Through network analysis and landscape connectivity analysis, the rationality and effectiveness of the constructed ecological networks were evaluated, and a more reasonable theoretical method was provided for the construction of ecological networks in Wanyuan. At the same time, the most important anthropogenic factors of habitat isolation were explored, to provide scientific reference for the construction of ecological security pattern in Wanyuan.

Material and methods

The study area

Wanyuan is located in the northeastern border of Sichuan Province and the northeastern part of Dazhou City (31°39′–32°20′N, 107°28′–108°31′W) (*Fig. 1*). It lies on the watershed of the Jialing River and the Han River, in the hinterland of the middle section of the Daba Mountains. It is a national Qinba Biodiversity Main Functional Area, a national restricted development zone and an important ecological functional area, and one of the 20 key counties in the province for forest, grassland and wetland ecological barriers, with a high forest coverage rate of 63.7%. The city covers an area of 4065 km^2, with undulating peaks, rivers and mountains tilting from northeast to southwest. The city enjoys convenient transportation, as it is the main gateway to and from Sichuan in the north. Several major transportation lines, such as Xiangyu Railway, Baomao Expressway, National Highway 210 and 347, run through the city. However, due to the influence of topography and landforms, most human activities are concentrated in the valley areas. Therefore, most transportation and urban settlements are located along the rivers.

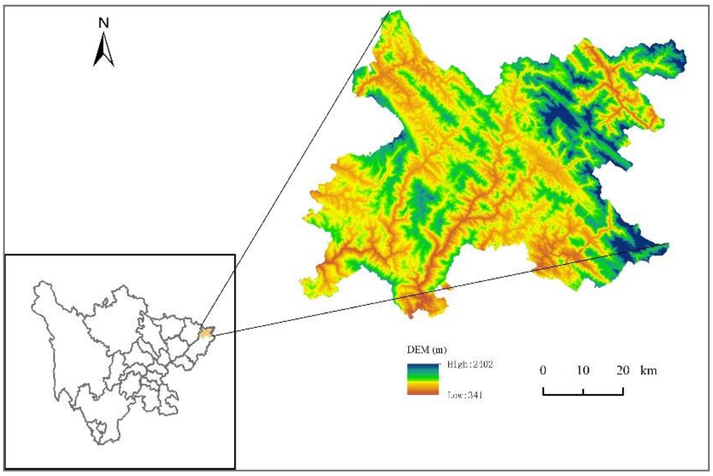

Figure 1. *Location and traffic map of the study area and DEM*

Data

This study uses the following main data sources: the land use vector data of Wanyuan in 2019, which includes 41 land cover types. These types are reclassified into 21 categories based on the current situation of Wanyuan and research needs (*Fig. 2*). Moreover, the digital elevation model (DEM), Normalized Difference Vegetation Index (NDVI), nature reserves, ecological protection red lines, rivers, roads and other data are obtained from the departments as Wanyuan City Natural Resources Bureau.

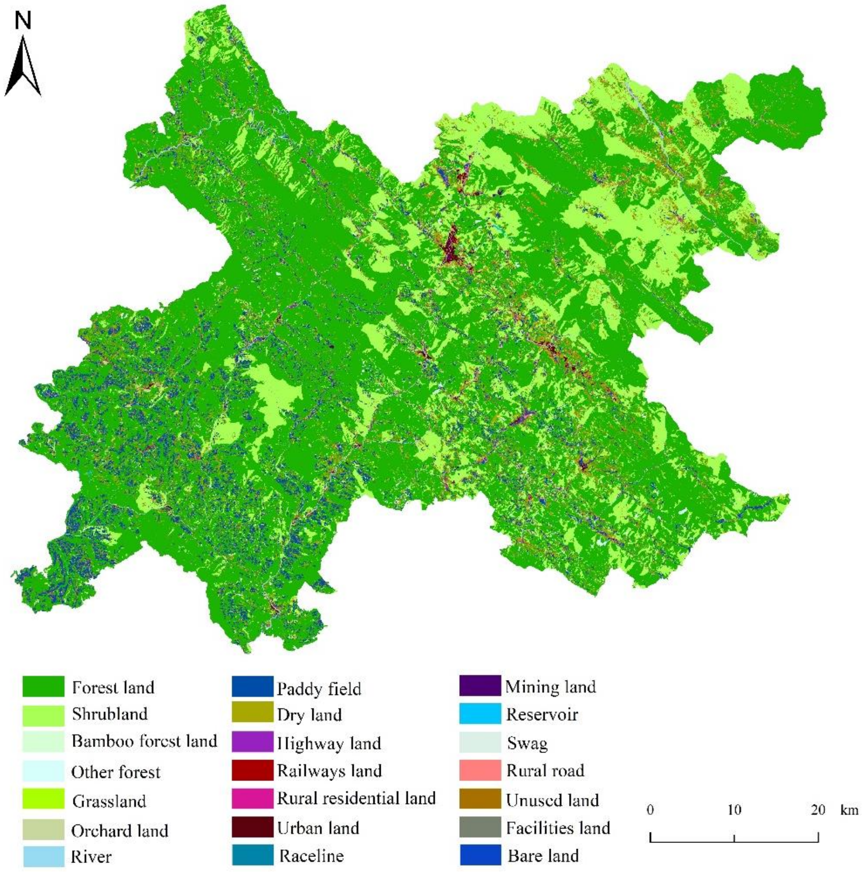

***Figure 2.** Spatial distribution of land cover type*

Methodology

Morphological spatial pattern analysis （MSPA）

We used Guidos Toolbox software to conduct MSPA of Wanyua, taking forest land as the foreground and the other land use types as the background. The analysis results are summarized in *Table 1*.

Habitat quality model

Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) is a suite of models that can evaluate the quantity and economic value of ecosystem services, and support ecosystem management and decision-making (Nelson et al., 2009). It quantifies ecosystem services in a transparent way, helping to improve the efficiency and rationality of natural resource decisions (Sharp et al., 2016). Based on the InVEST user manual, we used the Habitat Quality function, and consulted the existing domestic and foreign related studies (Li et al., 2021; Lin et al., 2018; Theobald et al., 2011; Wu et al., 2013) and the opinions of ecological experts, to select 21 habitat types and 6 threat factors, as well as the determination of determining the habitat suitability index (*Tables 2* and *3*). We then obtained the habitat quality index.

Table 1. *Characteristics of each landscape type*

Landscape type	Area (km^2)	Percentage in forest area (%)	Percentage in the study area (%)
Core	2526.32	75.9	62.3
Islet	19.22	0.6	0.5
Perforation	147.18	5.3	4.4
Edge	285.73	11.2	9.2
Bridge	149.82	2.7	2.2
Loop	100.59	1.3	1.1
Branch	99.04	3.0	2.4

Table 2. *Sensitivity of different land use types to different ecological threat factors*

Land cover type	Habitat suitability	Threat factor					
		Cultivated land	Mining land	Urban land	Rural residential land	Highways and rural	Other road
Paddy field	0.4	0.3	0.5	0.5	0.4	0.4	0.3
Dry land	0.3	0.2	0.4	0.5	0.3	0.3	0.2
Orchard land	0.6	0.4	0.6	0.5	0.4	0.4	0.3
Forest land	1	0.8	0.8	0.9	0.7	0.8	0.6
Bamboo forest land	0.9	0.7	0.7	0.8	0.7	0.7	0.5
Shrubland	0.6	0.6	0.7	0.7	0.6	0.5	0.4
Other forest	0.7	0.8	0.7	0.8	0.6	0.6	0.5
Grassland	0.5	0.6	0.5	0.6	0.5	0.4	0.2
River	1	0.7	0.9	0.9	0.8	0.6	0.4
Reservoir	0.8	0.7	0.8	0.8	0.7	0.5	0.3
Swag	0.7	0.7	0.6	0.7	0.7	0.4	0.3
Raceline	0.6	0.2	0.3	0.4	0.5	0.3	0.2
Urban land	0	0	0	0	0	0	0
Rural residential land	0	0	0	0	0	0	0
Highway land	0	0	0	0	0	0	0
Rural road	0	0	0	0	0	0	0
Mining land	0	0	0	0	0	0	0
Unused land	0	0	0	0	0	0	0
Bare land	0	0	0	0	0	0	0
Facilities land	0	0	0	0	0	0	0
Railways land	0	0	0	0	0	0	0

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Table 3. *Threat factors and their maximum influence distance, weight, and type of decay*

Threat factor	Maximum impact distance (km)	Weight	Type of decay
Cultivated land	0.5	0.4	linear
Mining land	3	0.75	exponential
Urban land	3	1	exponential
Rural residential land	2.5	0.6	exponential
Highways and rural	2	1	linear
Other road	1	0.55	linear

Landscape connectivity

We used the integral index of connectivity (IIC) and the probability of connectivity (PC) to identify potential ecological source areas, and calculated importance indices (dl) as a criterion for prioritizing habitat source areas. The source areas with higher dI values were selected as important source areas.

Ecological source areas

We extracted potential ecological source areas based on the overlap of the core patches from the MSPA results and the high-quality areas from the InVEST. Then we selected core patches with an area larger than 1 km^2 for landscape connectivity analysis. Afterward, we overlapped them with natural protected areas and ecological protection red lines, considering the actual situation of Wanyuan, and determined the important ecological source areas.

Resistance surface

We constructed the resistance surface based on the MCR model, which quantified the cost of species dispersal and the difficulty of preventing species migration and expansion (Du et al., 2022). Following other studies (Han et al., 2021; Peng et al., 2018; Wei et al., 2022) and the actual situation of Wanyuan, we chose land cover type, elevation, slope, habitat quality, NDVI, distance to water bodies, distance to railways and roads, distance to rural and urban settlements as indicators for the MCR model. We assigned resistance value of 1, 3, 5, 7, 9 to these indicators. The higher the resistance value, the greater the resistance value that impedes species dispersal (*Table 4*). It should be noted that the resistance assignment of elevation is based on relevant studies (Liu, 2007; Wang, 2012), which suggest that the altitude range with the richest biological resources in this area is 1000−1400 m. We assigned a resistance value of 1 to this altitude range, and then increased the resistance value as the altitude deviates from this range (*Fig. 3*).

We used three different methods to weight the resistance factors, namely the AHP, the SPCA, and the EM. The AHP relies on experts' subjective judgments to score the relative importance weights of indicators at each level, usually using pairwise comparisons of indicators. The EM determines the indicator weights based on the variation and information content of each value. The SPCA reduces the dimensionality of the data and eliminates the possible correlation between factors, reducing redundant information (Nie et al., 2021). By applying these three methods of weighting, we generated three comprehensive resistance surfaces (*Fig. 6*).

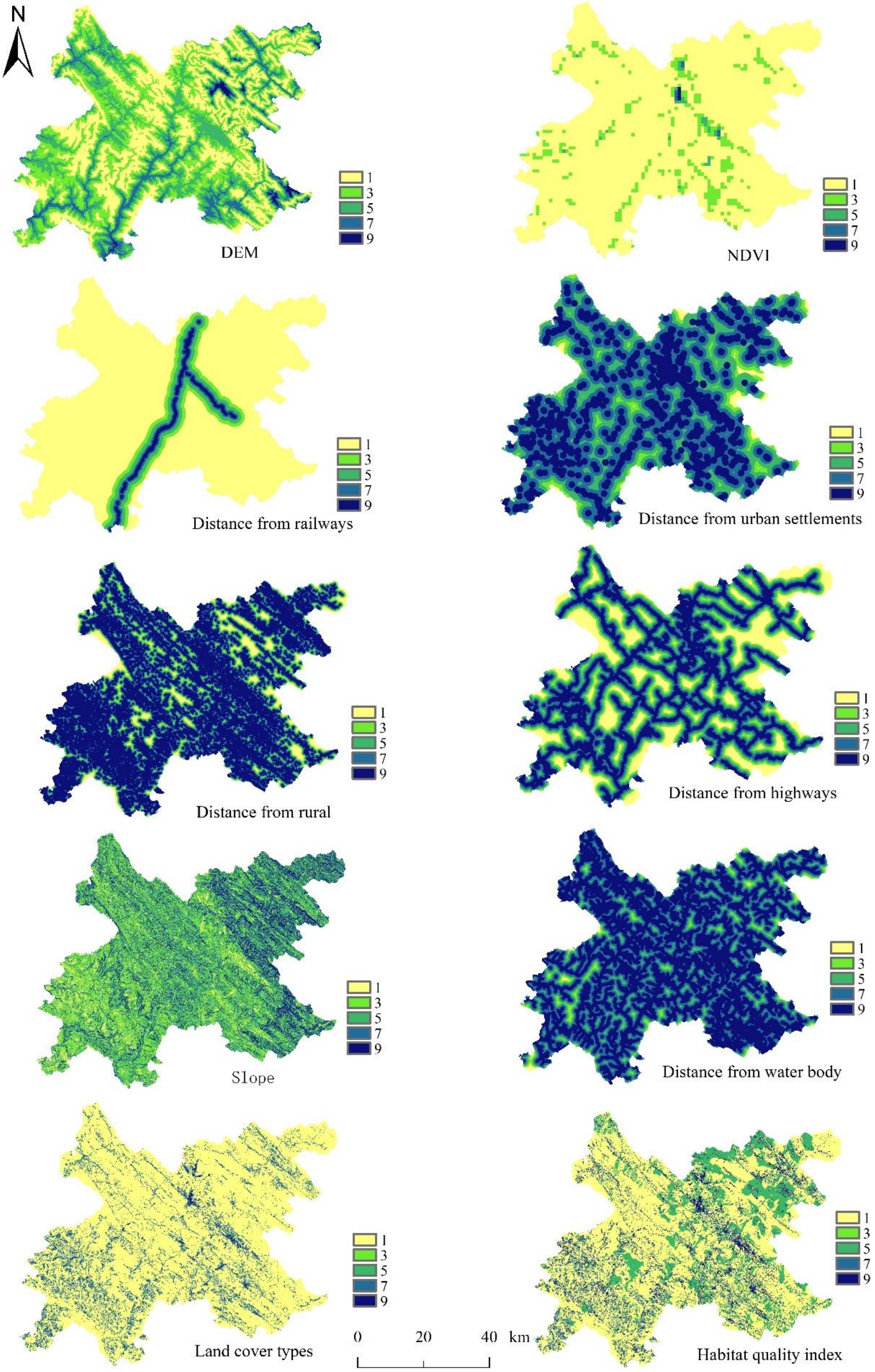

Figure 3. *The resistance surface of each resistance factor*

Table 4. *Resistance factor values and weight*

Resistance factors	**Resistance value**					**Weight (%)**		
	1	**3**	**5**	**7**	**9**	**AHP**	**SPCA**	**EM**
Land cover types	Forest	Grassland	Water body and unutilized land	Cultivated land	Construction land and others	0.2469	0.1048	0.0247
DEM (m)	1000-1400	800-1000, 1400-1600	600-800, 1600-1800	400-600, 1800-200	> 2000, < 400	0.0845	0.0265	0.0192
Slope (°)	< 10	10~20	20~30	30-40	> 40	0.0821	0.0891	0.0582
NDVI vegetation index	> 0.85	0.75-0.85	0.65-0.75	0.55-0.65	< 0.55	0.0721	0.0101	0.0016
Distance from water body (m)	> 2000	2000-1500	1000-1500	500-1000	< 500	0.0514	0.1813	0.2423
Distance from rural (m)	> 1000	1000-700	500-700	300-500	< 300	0.0947	0.2325	0.2921
Distance from highways (m)	> 2000	1500-2000	1000-1500	500-1000	< 500	0.0832	0.2224	0.1465
Distance from railways (m)	> 3000	2000-3000	1500~2000	1000~1500	< 1000	0.0638	0.0018	0.0127
Distance from urban settlements (m)	> 4000	3000-4000	2000-3000	1000-2000	< 1000	0.1190	0.1021	0.1558
Habitat quality index	> 0.898	0.698-0.898	0.6-0.698	0.396-0.6	< 0.396	0.1023	0.0294	0.0469

Construction of ecological network

We used Linkage Mapper, a common tool for constructing ecological corridors between patches, to draw the minimum cost paths between ecological source areas based on the vector data of ecological source areas and the raster data of resistance surface (McRae et al., 2017). We used three different resistance surface data to obtain three different ecological corridor schemes. We also used the Pinch Point Mapper and Barrier Mapper in Linkage Mapper to extract ecological stepping stones and ecological barriers, and to finally construct three different ecological networks (*Fig. 7*).

Evaluation of ecological network

(1) Evaluation of ecological network

We used four indicators to evaluate the structure of the ecological network, namely the network closure index α, the line-point ratio β, the network connectivity index γ, and the Cost ratio, C. The α index indicates the circulation of the network, and the larger the value, the better. The β index indicates the number of lines corresponding to each node in the network. When $\beta < 1$, the network is a tree structure. When $\beta = 1$, the network is a single loop structure. When $\beta > 1$, the connection level of the network is more complex. The γ index indicates the degree of connection between nodes in the network. When $\gamma = 0$, there is no corridor connection between nodes. When $\gamma = 1$, the connectivity of nodes in the network is high (Nie et al., 2021). The Cost ratio c represents the input-output relationship. The lower the value, the more conducive to the construction of the ecological corridor network. The calculation formulas are as follows:

$$\alpha = \frac{l - v + 1}{2v - 5} \qquad \text{(Eq.1)}$$

$$\beta = \frac{l}{v} \quad \text{(Eq.2)}$$

$$\gamma = \frac{l}{l_{\max}} = \frac{l}{3(v-5)} \quad \text{(Eq.3)}$$

$$C = 1 - \frac{l}{d} \quad \text{(Eq.4)}$$

where l is the number of corridors; v is the number of nodes (the number of ecological sources); d is the total length of ecological corridor.

(2) Ecological network connectivity evaluation

We selected the IIC and the PC as the indicators of landscape connectivity. The higher the values of these indicators, the better the connectivity. We used Conefor 2.6 software to quantify these indicators, setting the probability of connection at 0.5, and varying the distance thresholds. We then evaluated the connectivity of the three ecological network methods.

Results and analysis

Construction of ecological source areas in Wanyuan

Analysis for the results of the MSPA

Figure 4a and *Table 1* show that the core area of the landscape in Wanyuan covered about 2526.32 km^2, which was 75.9% of the total forest area and 62.3% of the city's total area. The core areas were mainly distributed in the eastern and northwestern regions, forming a strip-like pattern with good spatial connectivity. The southwestern and southern regions had more fragmented core areas, leading to poor landscape connectivity. The bridge area, which connected two different core patches, covered about 149.82 km^2, which is 2.7% of the total forest area. The bridge area had important ecological significance for the migration and expansion of species in the study area. The edge area, which was affected by edge effects, covered about 11.2% of the total forest area. The island patches, which were isolated from other patches, covered about 0.6% of the total forest area, but the distribution is clearly more concentrated in the southern region, excluding the Batai Mountain Provincial Scenic Spot.

Analysis for the results of habitat quality

We used the Habitat Quality in the InVEST to obtain the habitat quality index distribution map of Wanyua, with the index range from 0 to 1. The habitat quality index was classified into five categories according to the natural breakpoint method, as shown in *Figure 4b*. We calculated the area and proportion of habitats with different qualities, and found that the high-quality habitats (1-0.8980) covered 2580.33 km^2, accounting for 63.7% of the total area, while the low-quality habitats (0-0.3960) covered 405.94 km^2, accounting for 10.0%. The remaining area accounted for 26.3%, indicating a polarization trend in the habitat quality index distribution. Spatially, the habitat quality was better in the northwest and west, mainly because of less human disturbance. In the eastern region, due to urbanization and transportation development, the high-quality habitats were concentrated in protected areas and scenic spots, such as Hua’e Mountain Nature Reserve and Batai Mountain Provincial Scenic Spot.

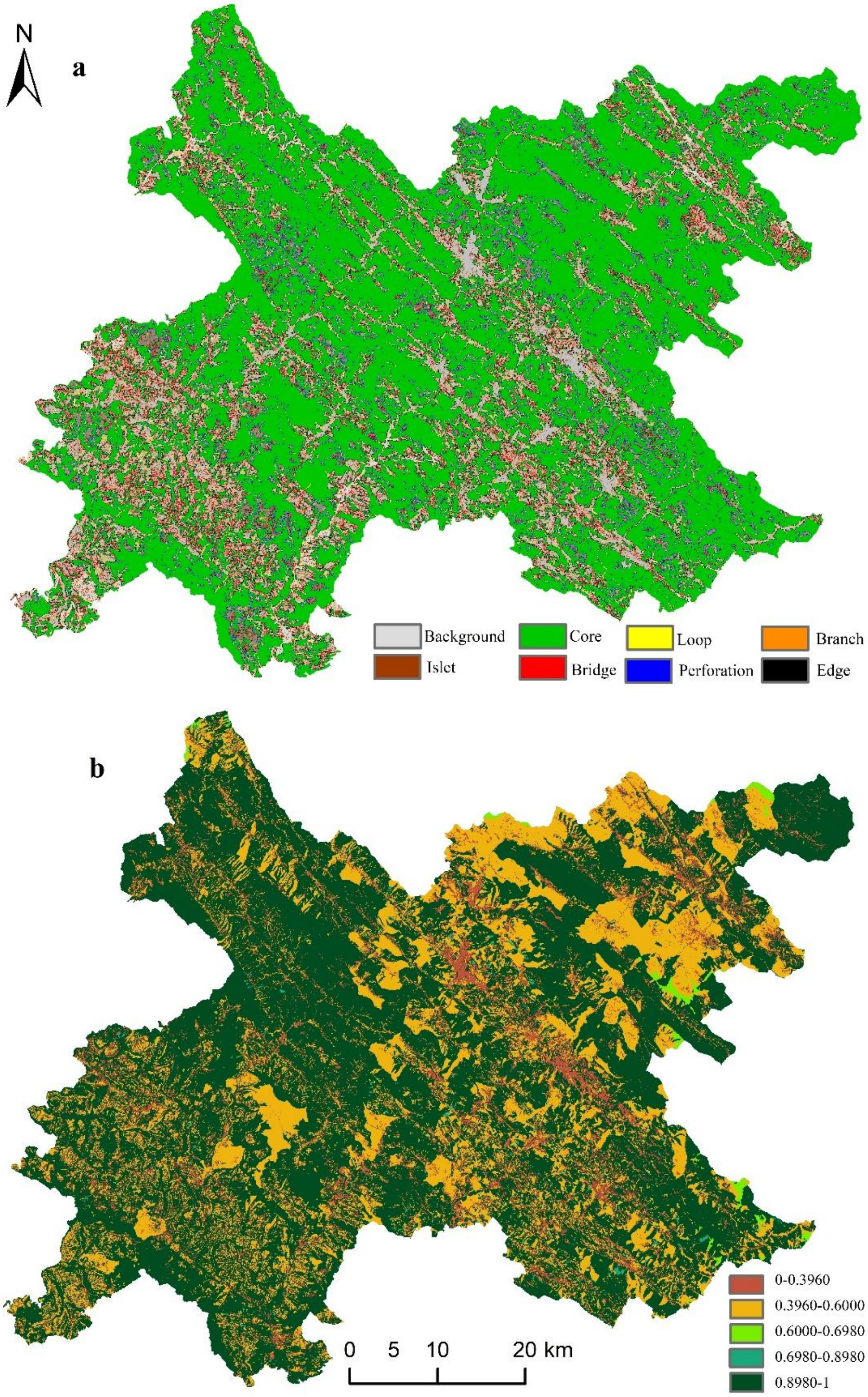

Figure 4. *Spatial distribution of MSPA landscape types (a) and habitat quality assessment (b) in the study area*

Identification of important ecological source areas

We used ArcGIS 10.7 to extract the areas that overlapped between the core areas from the landscape pattern analysis and the high-quality habitat areas from the habitat quality analysis. We obtained the ecological source areas of Wanyuan, covering a total area of 1912.12 km^2. This was 75.7% of the core areas and 74.1% of the high-quality habitat areas. This shows that 24.3% of the core areas from the landscape pattern analysis were not high-quality habitat areas, which proves the necessity of coupling the MSPA and the InVEST. We further selected 159 source patches with an area larger than 1 km^2, and determined the priority level of the source areas.

We used Conefor 2.6 software to calculate the integral connectivity index (dIIC), the probability of connectivity (dPC), and the relative importance (dI) of the 159 patches. We selected 44 patches with dI > 1 as potential ecological source areas. Among these potential source areas are concentrated in the northwestern part of the study area, as well as in the nature reserve. Finally, we added the protected areas such as natural reserves, forest parks, scenic spots, wetland parks, etc., and the ecological red lines in Wanyuan to the potential patches (*Fig. 5a*). We overlapped them to extract the important ecological source areas in Wanyuan (*Fig. 5b*).

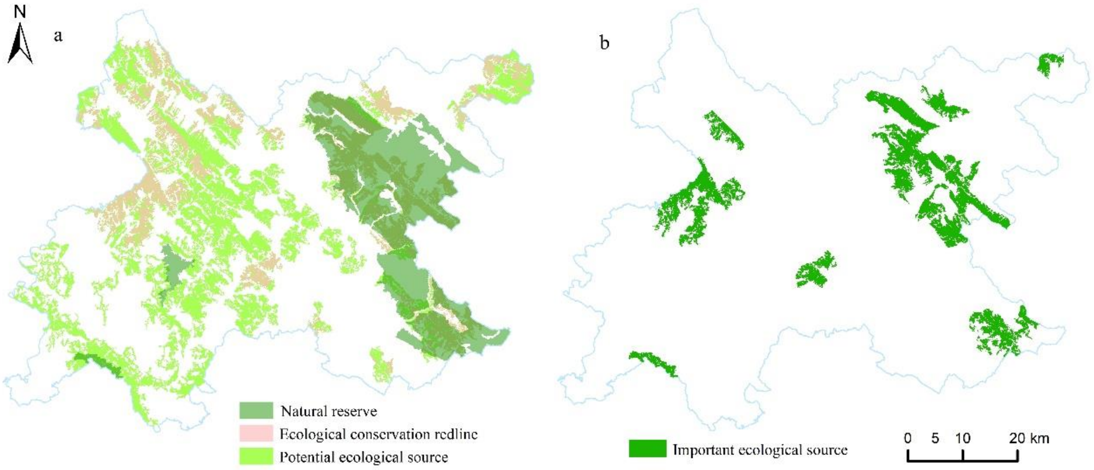

Figure 5. *Process diagram of ecological source identification (a) and spatial distribution of important ecological sources (b)*

Analysis for the comprehensive resistance surfaces

The resistance factor weighting results based on AHP show that land cover type had the highest weight value of 0.2469, indicating that the experts agreed that it was the most important factor affecting species migration and expansion. The second most important factor was the distance to urban settlements, with a weight value of 0.1190. The least important factor is the distance to water bodies, with a weight value of 0.0514, because Wanyuan has many rivers with a wide distribution. Therefore, the experts agreed that they had a relatively small impact on species migration. The resistance factor weights ranked first by SPCA and EM were both rural settlements, with weight values of 0.2325 and 0.2921 respectively, mainly because the study area has many scattered rural settlements. The second most important resistance factor weight by SPCA was the distance to roads, with a weight value of 0.2224, and by EM was the distance to water bodies, which were both low in proportion by AHP. Among them, NDVI had a low proportion in all three methods, indicating that it had a low impact on species migration and expansion in Wanyuan.

The three methods (*Fig. 6*) generated comprehensive resistance surfaces that had similar distributions of high and low resistance values. The high resistance values were located in the mountainous and canyon areas, where the terrain was low, the rivers were dense, and the transportation followed the rivers. The urban and rural settlements also followed the river transportation, so the high resistance value areas of factors such as canyons, rivers, and transportation overlapped. The low resistance values were mainly located in the eastern Hua’e Mountain National Nature Reserve and the alpine area in the northwest. This part of the area had a high altitude, a steep slope, and inconvenient transportation, so there were few settlements and less human disturbance. However, the comprehensive resistance surface generated by the AHP had a smaller proportion of high-value areas, among which the Xiangyu Railway, Baomao Expressway, and the urban areas of Wanyuan were high-resistance value concentration areas, forming a reserved “V” shaped high-resistance value on the resistance surface. The distribution of resistance values in other areas was roughly consistent with the that of land cover types. The comprehensive resistance surfaces generated by the SPCA and the EM were very similar, and the high resistance values were distributed in strips. The only difference was that the strip area generated by the EM’s high-value area was wider than that of the SPCA’s high-resistance value strip area.

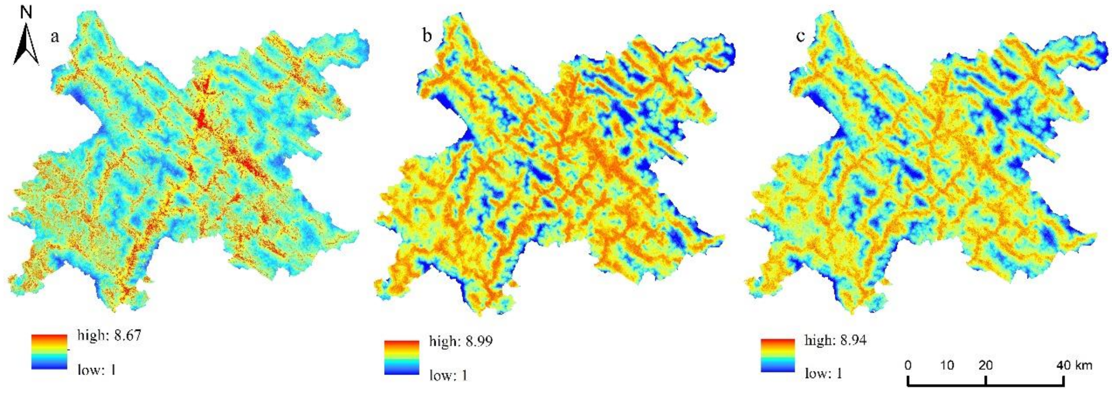

Figure 6. *The three resistance surfaces. (a) AHP - Composite resistance surface; (b) EM - Composite resistance surface; (c) SPCA - Composite resistance surface*

Analysis and evaluation of ecological network

We constructed ecological corridors between ecological source areas using the Linkage Mapper in ArcGIS (*Fig. 7*). The AHP and the EM identified 17 effective ecological corridors each, with corridor lengths of 277.20 km and 286.55 km respectively. The SPCA identified 18 effective ecological corridors, with a corridor length of 311.70 km. The SPCA added a direct connection corridor from patch 10 to patch 8, which made the network structure generated by the SPCA more complex. Spatially, the three methods had a high overlap of the corridors from patch 2 to 3, 3 to 4, and 1 to 7. It is worth noting that the EM and the SPCA had a relatively high overlap rate of the corridors, and only differed in the distribution of the corridors from patch 1 to 2, 3 to 6, 4 to 5, and 10 to 8. The distribution of other corridors was basically coincident, mainly because the distribution of resistance surfaces in the two methods was relatively similar.

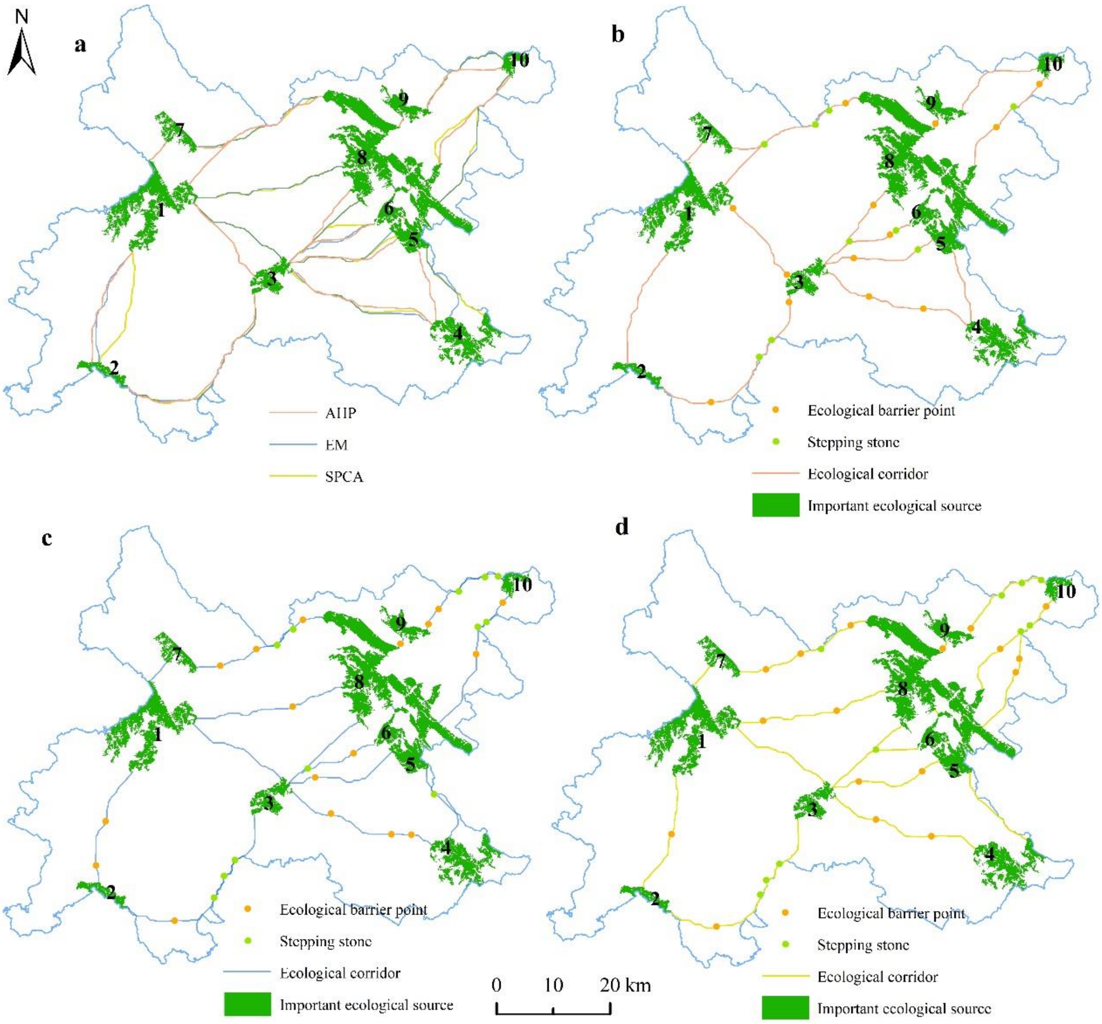

Figure 7. *Spatial distribution of ecological network. (a) Three ecological corridors are superimposed; (b) AHP- ecological network; (c) EM- ecological network; (d) SPCA-ecological network*

Referring to relevant literature (Bueno et al., 1995; Zhu et al., 2005), and considering the protected species in Wanyuan, we set the corridor width of the three schemes to 600 m, and analyzed the area proportion of landscape types in the three ecological networks (*Table 5*). The forest proportion of the three methods was very high, although there was not much difference between them, but the SPCA's forest proportion was slightly higher than the other two methods. Even if the grassland proportion was added, the SPCA's landscape type proportion was still the highest.

The network structure index results (*Table 6*) show that the three ecological networks had formed closed loops. The AHP and the EM identified the same number of ecological corridors, so they had the same network closure index (α index), line-point ratio (β index), and connectivity index (γ index). The SPCA had higher values for these indices than the other two methods, indicating that SPCA’s network had better circulation and integration, and the network connection level was more complex. However, the resistance ratios of the AHP, the EM, and the SPCA increased in turn, indicating that the SPCA’s average resistance was slightly higher. Overall, the SPCA had higher network structure index.

Table 5. *The proportion of landscape types with a corridor width of 600 m*

Landscape type	**Area ratio (%)**		
	AHP	**EM**	**SPCA**
Forest	87.0%	87.4%	87.8%
Grassland	0.7%	0.6%	0.6%
Construction land	2.0%	2.1%	2.1%
Field	9.5%	9.0%	8.6%
Water body	0.8%	0.8%	0.8%
Unutilized land	0.1%	0.1%	0.2%

Table 6. *Three ecological network structure index indices*

Index	**AHP**	**EM**	**SPCA**
α	0.5333	0.5333	0.6
β	1.7	1.7	1.8
γ	1.1333	1.1333	1.2
C	0.9386	0.9406	0.9422
V	10	10	10
L	17	17	18
D (km)	277.20	286.55	311.70

The landscape connectivity index results (*Table 7*) show that the ICC and the PC of the network structure of the three methods increased as the threshold increased. When the distance threshold was less than 10 km, the ICC and the PC values of the two ecological networks constructed by the AHP and the EM were similar, and there was no obvious difference in their trends. When the distance threshold was greater than or equal to 10 km, the EM’s ICC and PC values were significantly higher than those of the AHP. The ICC and the PC values of the ecological network constructed by the SPCA were always higher than those of the other two methods, regardless of the distance threshold, indicating that the SPCA had the best landscape connectivity of the ecological network, followed by the EM, and then the AHP. Therefore, it was more reasonable to use the SPCA to construct an ecological network in Wanyuan.

Discussion

The subjective method AHP and the objective methods EM and SPCA generated quite different weight values. Among them, in the AHP, land cover type had the highest proportion, which was consistent with previous studies (Chen et al., 2021; Han et al., 2021; Zheng et al., 2021; Wang et al., 2022a, b), indicating that experts usually considered land cover type as the most important factor for constructing the resistance surface. In the EM, the distance to rural settlements and the distance to water bodies had higher proportions, mainly because these two factors were evenly distributed in Wanyuan, resulting in a low information entropy value, so they had a large proportion. In the SPCA, the distance to rural settlements, the distance to roads, and the distance to water bodies had higher proportions, indicating that these three factors were the main factors affecting the resistance surface. The weights generated by the EM and the SPCA differed from previous studies, mainly because the objective weighting method could better reflect the actual situation of Wanyuan.

Table 7. *Landscape connectivity index of three ecological networks at different distance thresholds*

Index	**Program**	**Distance threshold（km）**						
		1	**3**	**5**	**8**	**10**	**13**	**15**
ICC	AHP	0.0084	0.0113	0.0142	0.0287	0.0314	0.0317	0.0333
	EM	0.0080	0.0129	0.0153	0.0267	0.0349	0.0361	0.0373
	SPCA	0.0092	0.0142	0.0157	0.0309	0.0404	0.0414	0.0400
PC	AHP	0.0101	0.0143	0.0187	0.0365	0.0413	0.0466	0.0499
	EM	0.0089	0.0159	0.0203	0.0351	0.0454	0.0513	0.0544
	SPCA	0.0108	0.0177	0.0210	0.0407	0.0527	0.0598	0.0575

The three methods had different weight proportions for the resistance factors, but the three comprehensive resistance surfaces they generated had roughly the same distribution areas of high and low resistance values. The main reason was that the canyon area had a high concentration of resistance factors such as river system, roads, and settlements, so the high resistance values were located in the canyon area. The comprehensive resistance surfaces generated by the SPCA and the EM were very similar, and the only difference was that the strip area generated by the EM’s high-value area was slightly wider than that of SPCA’s high-resistance value strip area. This was because the SPCA reduced the dimensionality and simplified the original data, thus decreasing redundant information.

In the ecological network evaluation, we used the network structure index and the landscape connectivity index to jointly evaluate the three methods: the SPCA, the EM, and the AHP. We found that the SPCA > the EM > the AHP. The main reasons for this result might be as follows: First, Wanyuan has a large land area, and experts may have problems such as subjectivity, lack of experience, and insufficient research data when scoring the analytic hierarchy process based on their own experience and research materials. This might lead to unsatisfactory results of the AHP. Second, due to the influence of terrain, the river system, roads, and settlements in the resistance factors were distributed in the canyon area. This indicates that the resistance factors were highly correlated. For the SPCA, the higher the correlation among the resistance factors, the better the SPCA performance (Abdi et al., 2010).

Third, there were 10 resistance factors in Wanyuan, and they were also correlated with each other. The EM could not reduce the dimensionality of the resistance factors, which might cause redundant information. Therefore, in this study area, the results of the EM were not as good as the results of the SPCA. This was consistent with the result of previous research. When the resistance factors reach 7 or more, many scholars choose the SPCA (Dai et al., 2020; Nie et al., 2021; Wang et al., 2021), and when the resistance factors are less than 7, the EM is mostly used (Wei et al., 2022; Yang et al., 2018).

It is more scientific to use the SPCA to construct the ecological network in Wanyuan, and the two factors with higher resistance weights in the SPCA are the distance to rural settlements and the distance to roads, thus indicating that the most important anthropogenic factors affecting habitat fragmentation in Wanyuan are rural settlements and transportation roads. Therefore, it is recommended that when the government formulates ecological restoration programs, rural settlements near ecological corridors should be planned and centrally resettled in order to reduce barriers to the circulation of species; road traffic near ecological corridors should consider erecting viaducts so that species can cross these barriers smoothly.

The AHP, the EM, and the SPCA have their own strengths and weaknesses. In future research, different resistance weighting methods should be chosen according to the specific situation of different study areas. In this study, in the ecological resistance factors, the distance assignment was determined by referring to previous studies, due to the lack of detailed ecological data of the study area. This has some limitations. In future research, there is a need to assign resistance distance according to the authentic research data of the study area and previous literature.

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