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The Optimization of Urban Ecological Network Planning Based on the Minimum Cumulative Resistance Model and Granularity Reverse Method: A Case Study of Haikou, China

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ABSTRACT In recent years, the high-speed urbanization process and human activities have led to the fragmentation and the connectivity reduction of natural landscape patches, resulting in the degradation of urban ecological services and biodiversity. The construction of ecological network and the optimization of landscape pattern are significantly important to improve the urban ecological environment and urban ecological security. In this paper, a case study of Haikou, an island city of China is performed, the selection of ecological source areas is optimized by granularity reverse method and principal component analysis. The minimum cumulative resistance model (MCRM) is used to construct the ecological resistance surface, and ecological corridors and ecological nodes are obtained, so as to optimize the urban ecological network and the connectivity of landscape patches. The results show that the 1400m granularity landscape component is the optimal landscape component structure for Haikou. There are 38 ecological source areas in Haikou, and 14 ecological landscape patches need to be added. The distribution of ecological source areas is mainly affected by topography and geomorphology. The northwest has huge and scattered ecological source areas, while the southeast has small and concentrated ecological source areas. In the areas around Meilan airport and Hongcheng lake, there is an ecological trap with significant difference between dominant and recessive ecological resistance separately. Haikou ecological network consists of 81 ecological corridors and 76 ecological nodes. Affected by the main urban area in the north, Haikou ecological network has the high density in the middle and southern areas. The construction of ecological network has significantly improved the overall connectivity of the ecosystem in the study region. This research provides a scientific basis for the future urban ecological environment planning of Haikou.

INDEX TERMS Ecological network, landscape index, minimum cumulative resistance model, ecological source area, ecological corridor, ecological node, ecological resistance.

I. INTRODUCTION

With the large-scale expansion of cities and the sharp increase in urban population, the demand for natural resources in human society has increased dramatically. Human beings not only overdevelop natural resources, but also litter pollutants and wastes into the natural environment, resulting in serious ecological and environmental problems such as surface

hardening, vegetation degradation, river diversion, air pollution, heat island effect, biodiversity decline [1], [2]. The contradiction between human and nature is becoming increasingly acute, which seriously threatens the survival and development of human beings. Therefore, it is particularly important to improve the value of urban ecosystem services by building ecological networks [3], [4].

The urban ecological network is mainly composed of vegetation belt, river, farmland and other natural landscapes. Through the linear corridor, various types of scattered and

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isolated landscape patches in the city are connected, a complete natural ecosystem of a “point-line-surface” combination is formed with certain self-regulation ability [5], [6]. The construction of ecological network can improve the function and structure of the ecosystem, protect the biodiversity and improve the regional ecological security. In recent years, the research on the construction of the ecological network has been widely carried out all over the world [7]. Research methods can be divided into two categories: 1) By observing the migration process of animals and combining the compound dynamic model, the probability of a species is calculated to establish the corresponding ecological network. However, this method is time-consuming and mainly applicable to the wild natural environment. It also requires high quality of original data which are difficult to be obtained [8]–[10]. 2) Based on GIS technology, minimum cumulative resistance model (MCRM) is used to calculate the path (corridor) of the minimum resistance of biological migration to construct the ecological network [11]. This method can clearly simulate the resistance of landscape to ecological process and evaluate the connectivity of landscape. Moreover, it has the advantages of less data and clear picture expression. Therefore, the latter is widely used in urban ecological security mode and ecological planning [12], [13], usually combined with gravity model [14], [15], map theory [16], connectivity index [17], so as to evaluate and optimize the ecological network. In this study, MCRM is used to simulate the construction of an ecological network.

Although the ecological network has been developed rapidly in theory, it still has some shortcomings in practice, such as the high subjectivity and randomness of the selection of ecological source area; the current situation of land use is only considered in the construction of ecological resistance surface, while the interaction between different landscapes is rarely considered. Due to the heterogeneity of the landscape in different ecosystems, it is difficult to get a unified standard or method for different ecosystems. Since granularity change leads to the change of landscape structure [18], [19], the granularity change is used in this study to determine the optimal landscape component structure in a specific region and the ecological source area in the study region. In addition, geostatistics is employed to simulate the interaction between objects [13]. Kriging method is introduced to simulate the interaction between ecological resistances in constructing ecological resistance surface from landscape types, and a novel way is explored to accurately simulate the actual ecological resistance in the study region.

Haikou is the political, economic and cultural center of Hainan Province and the window for foreign exchange. With the development strategy of “Hainan International Tourism Island”, the strategic position of Haikou has been risen to the international level. However, the influx of tourists and rapid urban expansion result in the destruction of the regional ecological environment. Fragile island ecosystems and frequent natural disasters post series challenges to the sustainable development of the local economy and society. From the

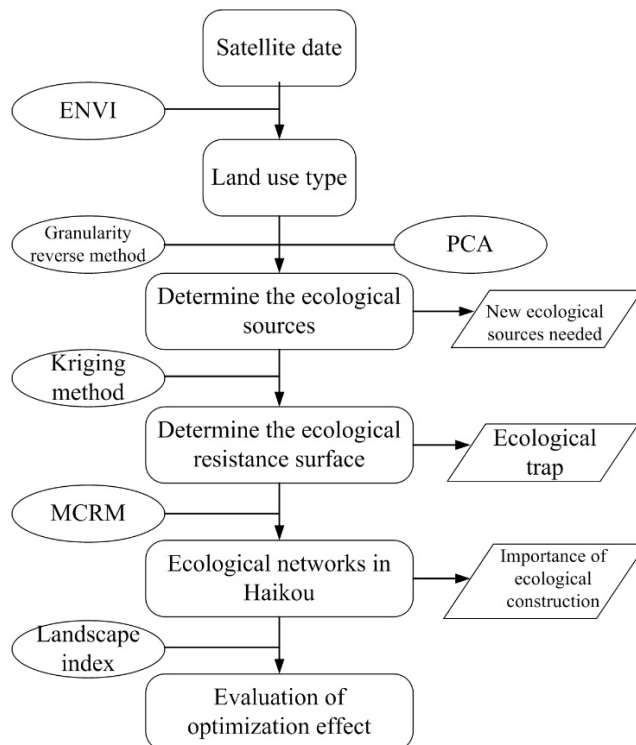


FIGURE 1. The flowchart of present research.

perspective of enhancing the overall connectivity of ecosystem, the concept of ecological functional resistance is employed to MCRM, and the planning and optimization method of urban ecological network are proposed in this paper. In this study, a case study of Haikou is performed, the urban ecological network is studied and optimized based on the type of urban landscape. Firstly, combined with the purposes of the present study, the landscape pattern indexes are selected, and the ecological source area is determined by granularity reverse method and principal component analysis. Secondly, the Kriging method is used to construct the comprehensive ecological resistance surface and determine the ecological trap. Finally, the improved MCRM is used to optimize the ecological landscape pattern of Haikou city. The results show that the optimized ecological network significantly improves the connectivity and network closure of the urban ecological pattern. Thus, the stability of the ecological system of Haikou is enhanced. Figure 1 shows the flow chart of this study.

II. OUTLINE OF THE STUDY AREA

Haikou is located in the northeastern part of Hainan Province at $19^{\circ}31'44'' \sim 20^{\circ}04'52''\text{N}$, $110^{\circ}7'40'' \sim 110^{\circ}42'39''\text{E}$. As a heart-shaped special scale with the total area of 2289.09 km², it is 18 nautical miles from Qiongzhou Strait in Hai'an Town of Guangdong Province; adjacent to Wenchang City in the east and south, Chengmai County in the west, Ding'an County in the west and south, Qiongzhou Strait in the north. The overall terrain is lower in the south and higher

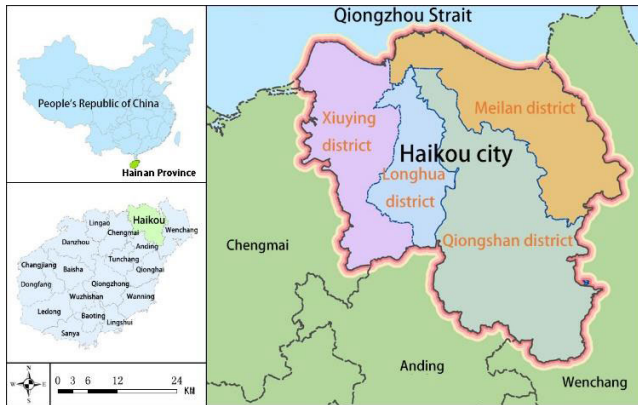


FIGURE 2. Location of the study area.

in the north, and slightly inclined from south to north and west to east. As July to August. With the strong solar radiation, the average annual sunshine duration is 2000 h, the annual average temperature is 23.8 °C, and the annual average rainfall and evaporation are 1684 mm and 1834 mm, respectively. Haikou has abundant surface and underground water resources. The total amount of water resources is 19.07×10^9 m³. Nandu River, the largest river in Hainan Province, flows eastward from Dongshan Town in the west of Haikou to Jiuzhou Town, and then flows northward across Haikou to the Qiongzhou Strait. It is 75 km long in Haikou with a basin area of 1,300 km². Laterite and paddy soil are the main patterns of soil. The vegetation is mostly the wild shrub and grassland plant population which is common in the southern tropical region, and the secondary forest community formed after the destruction of primary forest. As shown in Figure 2, Haikou has 4 districts, (namely Xiuying District, Longhua District, Qiongsan District and Meilan District), 43 villages and towns with a permanent population of 2.246 million. The proportion of the first, second and third industrial structures is 4.9:19.3:75.8. In the current situation of landscape patterns, cultivated land, garden land and construction land account for a large proportion, while forest land and water area have a small proportion, accounting for about 17% of the total. Landscape patterns with higher ecological service functions such as forest land and water area are blocked by cultivated land and construction land, showing an obvious fragmentation. Therefore, the quality of ecological environment needs to be improved.

Based on Haikou 2010 second-class survey data, 1:10000 topographic map, DEM digital elevation model, Google Earth remote sensing image data of February 19, 2016 (resolution 0.54m, scale 1:1500) and DEM data, remote sensing image data are registered in Beijing 54 Coordinate with reference to the topographic map. Remote sensing interpretation signs are constructed by field survey, and the second-harmonic data are adjusted and checked. As shown in Figure 3, Landscape patterns of Haikou are classified into seven patterns: forest land, garden land, cultivated land, grassland, water area, unused land and construction land.

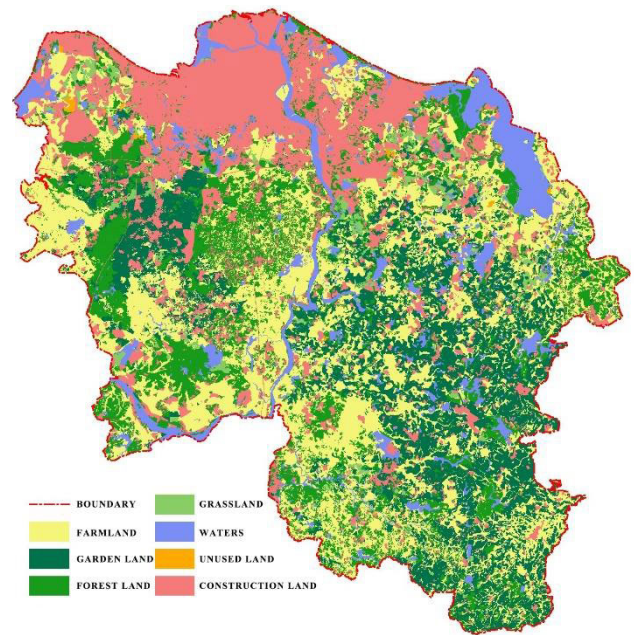


FIGURE 3. Landscape type spatial distribution map of Haikou City.

III. RESEARCH METHOD

A. SELECTION OF ECOLOGICAL SOURCE AREAS

The ecological network is mainly composed of ecological source areas, ecological corridors and ecological nodes. Urban ecological source area aims to improve the life quality of urban residents, protect important ecosystems and habitats, maintain and improve natural and urban artificial ecological units, and stabilize the urban ecosystem services to a certain extent [20]. The relevant landscape pattern index is selected as the index to evaluate the landscape components, and the grid landscape space of different scales is simulated by granularity reverse method. Then the overall score of each landscape component structure is calculated by principal component analysis, so as to select the ecological source areas.

1) SELECTION OF LANDSCAPE PATTERN INDEX

As the important contents of landscape ecological security research, the connectivity and integrity of ecological patches are the basis of regional ecological process and development, important factors to maintain the stability, sustainability and integrity of natural ecosystem, Both of them have an important impact on the flow of material and energy, the interaction and penetration of ecological process [21]–[23].

In this study, the following landscape indexes are selected as the evaluation index of the optimal landscape component structure: NP (the total number of patches); LNC (the largest number of patches, reflecting the scale of ecological source area); PD (patch density); PROX-MN (average proximity distance, reflecting the average distance between patches and central patches; and the smaller the distance, the higher the overall aggregation degree of patches); PLADJ

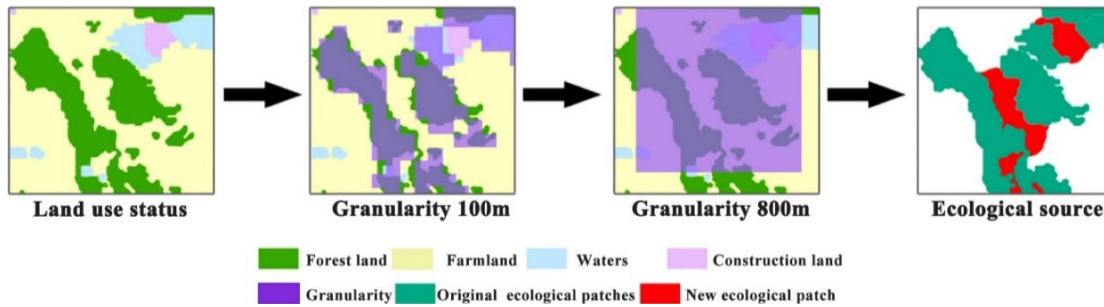


FIGURE 4. Diagram of granularity reverse method.

(adjacency ratio, suggesting the aggregation degree of patches in space); AI (aggregation degree, suggesting the aggregation degree of patches in space), DIVISION (the proportion of patch area to the total area of landscape, reflecting the degree of landscape being divided in space); CONNECT (reflecting the functional connectivity between landscape components); COHESION (reflecting the natural connectivity of patches), the percentage of connectivity increase (compared with the connection degree of the above granularity, it reflects the connection effect of landscape component structure with the change of threshold value) [24], [25].

2) GRANULARITY REVERSE METHOD

Granularity reverse method is performed as follow: 1) the ecological landscape component structure of the study region is assumed based on the counterevidence idea; 2) with the help of the overall connectivity, the ecological source area is selected by analyzing the optimal landscape component structure [26]. The grid of different scales is used to simulate the spatial structure of ecological landscape. From the perspective of integrity and connectivity, the measurement indexes are selected to measure the spatial structure of each scale grid. According to the overall change of the measurement indexes, the optimal landscape component structure is determined, and then the appropriate ecological source area is selected.

Due to the service scope of the ecological patches, the granularity reverse method considers that, the unconnected but closely separated ecological patches can form the ecological source area together. Therefore, in the process of granularity change, the small-scale and scattered ecological patches are removed, and the connected or adjacent ecological patches are merged to form the expanded ecological landscape components. Then the corresponding experimental data of different grain sizes are calculated to guide the construction of ecological source areas. As shown in Figure 4, it is assumed that the components of the ecological landscape in the region are composed of landscape components with different granularity of 100m and 800m. When the granularity is 100m, the components are separated from each other, and each landscape component area fails to meet the requirements of the scale of the ecological source area, then the ecological

TABLE 1. Ecological resistance value of landscape patterns.

Pattern	Value of ecological function per unit	Ecological
Forest	19334.0	20
Garden	12870.3	45
Cultivated	6114.3	55
Grassland	6406.5	70
Waters	40676.4	1
Unused	371.4	80
Construction	-8852.1	100

source area cannot be formed. However, when the granularity is 800m, ecological landscape components form a large-scale landscape component. The scale of the formed landscape component reaches the standard of ecological source area. In other words, these landscape components together constitute an ecological source area to exert ecological benefits.

3) PRINCIPAL COMPONENT ANALYSIS

Principal component analysis (PCA) is a study of transforming multiple indexes into a small number of comprehensive indexes based on the idea of dimensionality reduction and the premise of maintaining the original data characteristics [32]. According to the cumulative contribution rate and eigenvalue, PCA can build the evaluation function, comprehensively score the research object, and realize the comprehensive and quantitative evaluation of the research object [27]. Principal component analysis is used to comprehensively score the landscape pattern index obtained by granularity reverse method. The landscape component structure with the highest score has the best overall connectivity. In other words, the comprehensive score of landscape pattern index is used as an important reference for selecting ecological source area.

B. CONSTRUCTION OF ECOLOGICAL RESISTANCE SURFACE

Different types of landscape are inlaid and arranged in space to form a landscape pattern. The movement of ecological flow in the landscape needs to overcome the ecological resistance brought by landscape heterogeneity. The higher the ecological service function of landscape type, the less the obstruction

TABLE 2. Statistical table of landscape pattern index.

Granularity (m)	NP	PD	PROX-MN	PLADJ (%)	CONNECT (%)	AI (%)	DIVISION	COHESION (%)	Increased Percentage of Connectivity (%)	LNC
100	2684	5.9308	23.0532	72.1489	0.0206	94.6576	0.9609	72.4901	0.00	266
200	1179	2.5887	7.9824	61.4395	0.0507	90.2089	0.9633	62.0223	82.58	249
300	696	1.5473	5.2062	54.7019	0.0918	86.3896	0.9631	55.4902	46.29	228
400	473	1.0275	3.4001	50.0521	0.1541	83.9079	0.9625	51.0096	34.78	227
500	328	0.7472	2.8323	46.8679	0.2312	79.2188	0.9607	48.0163	27.78	228
600	237	0.5237	1.7521	44.471	0.3111	78.6373	0.9603	45.7634	23.70	213
700	202	0.4481	1.7153	40.7065	0.3251	78.3636	0.952	42.1023	20.92	224
800	157	0.3431	1.7659	40.2098	0.5145	75.9435	0.9547	41.7878	18.71	239
900	123	0.2707	1.1077	39.7504	0.5065	74.3673	0.952	41.527	16.90	227
1000	113	0.2325	1.3341	38.9918	0.6795	73.067	0.9529	40.8846	15.64	232
1100	104	0.2154	0.9928	36.2155	0.6721	68.3934	0.9564	38.1266	13.88	209
1200	82	0.1752	1.1555	32.4615	0.9937	69.6596	0.9524	34.4209	12.98	200
1300	78	0.1748	0.8782	32.0076	0.9324	64.4264	0.9487	34.1414	11.78	255
1400	57	0.1202	1.8947	33.8843	1.5664	73.7644	0.9149	36.2832	10.66	311
1500	68	0.1634	0.511	30.8108	1.0975	57.9736	0.9509	33.3333	10.44	261
1600	51	0.1089	0.5882	30.3279	1.1765	66.3817	0.9423	32.8402	9.64	172
1700	43	0.0942	0.8198	29.1139	1.1396	67.0591	0.9365	31.7241	9.08	215
1800	41	0.0924	0.4634	28.4672	1.0415	59.6637	0.9438	31.2	8.77	229
1900	43	0.0976	0.8198	28.2787	1.0826	58.4523	0.941	31.2217	8.60	208
2000	38	0.0922	0.4145	25.2427	1.1647	57.6847	0.9335	28.1081	8.21	273

of ecological flow, and vice versa. These resistance forms the ecological resistance surface [28]. From the perspective of the interaction of ecological resistance, ecological resistance is divided into dominant and recessive ecological resistance [26]. The dominant ecological resistance can be judged by experience and intuition, for example, the type of land use can cause the most direct impact on the flow of material and energy. The recessive ecological resistance is difficult to be detected directly, such as the flow of air and water between landscape patches, the diffusion of pollutants in the environment. Nevertheless, this non-intuitive form of communication is also accompanied by frequent exchange of material and energy.

1) DOMINANT ECOLOGICAL RESISTANCE SURFACE

The dominant ecological resistance surface is considered from the type of land use. Table 1 shows the corresponding resistance values of different types of landscape [29]–[31].

2) RECESSIVE ECOLOGICAL RESISTANCE SURFACE

Kriging method absorbs the idea of spatial statistics, and makes the best use of the information provided by spatial sampling based on the theory of variation function and structural analysis. When estimating the value of an unknown sample point, it also considers the relationship of the data

and position of adjacent sample points. Therefore, Kriging is a method of linear optimal estimation of regional variables of unsampled points [32], [33]. When there are many data points, Kriging method can still maintain the high reliability of its interpolation results. Thus, it has been widely used in groundwater simulation [34], [35], soil mapping [36], atmospheric science [37] and other fields. As a geostatistical grid method that can accurately express the interrelation and impact between things, Kriging method can be used to accurately simulate the interaction of ecological resistance of different landscape types in the spatial distribution of the study region. Therefore, Kriging is suitable for the construction of recessive ecological resistance surface. The calculation formula of fitting prediction model obtained by Kriging method is expressed as:

$$Z(x_0) = \sum_{i=1}^n \lambda_i Z(x_i) \quad (1)$$

where $Z(x_0)$ is the unknown sample point value; $Z(x_i)$ is the known sample point value around the unknown sample point, λ_i is the weight of the i^{th} known sample point, and n is the number of known sample points.

3) COMPREHENSIVE RESISTANCE SURFACE

The spatial principal component analysis is used to construct the comprehensive ecological resistance surface based on the



FIGURE 5. Landscape component structure with different granularity. The landscape component structure includes 6 landscape types: water area, secondary broad-leaved forest, mangrove, casuarina, rubber forest and eucalyptus.

dominant and recessive ecological resistance surface. Slope is calculated and reclassified according to DEM. With reference to the triangle side length calculation method, the correction coefficient of ecological resistance value in different slope is obtained. Then comprehensive ecological resistance surface is obtained by modifying the original ecological resistance value.

C. CONSTRUCTION OF ECOLOGICAL CORRIDOR

The ecological environment is the result of the operation and interaction of the ecological flow. The operation of the ecological flow in the ecological environment needs to overcome certain obstacles. The higher the ecological service function of landscape type, the smaller the obstruction of ecological flow, and vice versa. In the cumulative resistance model,

TABLE 3. Statistics of variance contribution rate.

Component	Initial eigenvalue			Loading and Extraction of Square		
	Eigenvalue	Variance contribution rate (%)	Accumulative contribution rate (%)	Eigenvalue	Variance contribution rate (%)	Accumulative contribution rate (%)
1	5.933	65.927	65.927	5.933	65.927	65.927
2	1.638	18.204	84.131	1.638	18.204	84.131
3	0.870	9.670	93.800			
4	0.306	3.404	97.204			
5	0.202	2.247	99.451			
6	0.039	0.430	99.881			
7	0.010	0.113	99.994			
8	0.001	0.006	100.000			

the operation mechanism of the ecological flow is considered from the aspects of source, distance and resistance. Grid data are used to build the cost surface of the ecological flow operation; the cumulative distance is employed to show the obstruction degree, and then the development trend of the ecosystem can be simulated [13], [38]. Subsequently, the path with the minimum obstruction degree is determined, that is, the potential channel of the ecological flow operation. The formula is as follows:

$$MCR = f_{\min}(D_{ij} \times R_{ij}) (i=1,2,3,\dots,m; j=1,2,3,\dots,n) \quad (2)$$

D_{ij} is the distance of ecological flow from landscape base i to source j ; R_i is the resistance value of landscape i ; m is the number of landscape types; and n is the basic unit total.

D. DETERMINATION OF ECOLOGICAL NODES

The ecological node is the fragile point on the ecological corridor and the key position in the construction of ecological environment. It is of great significance to strengthen the ecological corridor. The hydrological analysis module in ArcGIS software is used to extract the potential “ridge line” in the ecological resistance surface (i.e. the maximum path of accumulated resistance). The intersection point of the ridge line and the ecological corridor is the ecological node [39]. In addition, the intersection of corridors is also a common phenomenon in the construction process of ecological corridors. Such intersections have the characteristics of rapid exchange of ecological materials, so they can also be regarded as ecological nodes. To distinguish the two, when the corridor intersects the path of maximum resistance, the intersection is defined as ‘corridor-resistance’ ecological node; and when the corridor intersects another corridor, the intersection is defined as “corridor-corridor” ecological node.

IV. RESULT AND DISCUSSION

A. ECOLOGICAL SOURCE AREA

According to the present situation of land use in Haikou, forest land and water areas are extracted, and 20 landscape

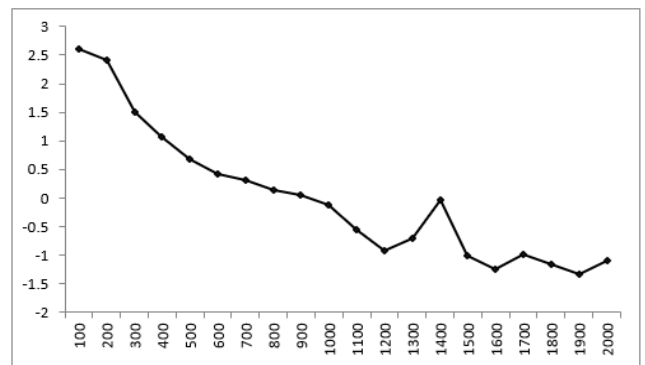


FIGURE 6. Synthesis score of landscape components structure. With the increase of granularity, the overall trend of comprehensive score decreases. The optimal granularity of landscape component structure is 1400m.

component structures of 100m-2000m are generated at intervals of 100 m (see Figure 5). The landscape pattern index of landscape component structure is calculated in Fragstats. Table 2 shows the calculation results.

Considering the comparability of the data, indicators are standardized first. Principal component analysis is used to analyze the determination indexes. As listed in Table 3 and Table 4, the accumulative contribution rate >80% and the eigenvalue >1 is taken as the main principle of component extraction, then two principal components are extracted. Principal component 1 and the index of AI, CONNECT, COHESION, PLADJ and PD are closely related, therefore Principal component 1 can represent the overall connectivity index. Principal component 2 has a higher correlation with LNC and DIVISION, reflecting the separation degree of the component structure, and it can be regarded as the index of fragmentation degree. Combining with the contribution accumulative rate, it is concluded that the overall connectivity is the main factor affecting the structural stability of ecological source areas in Haikou. Particularly, the integrity is of great importance to the critical section of the ecosystem.

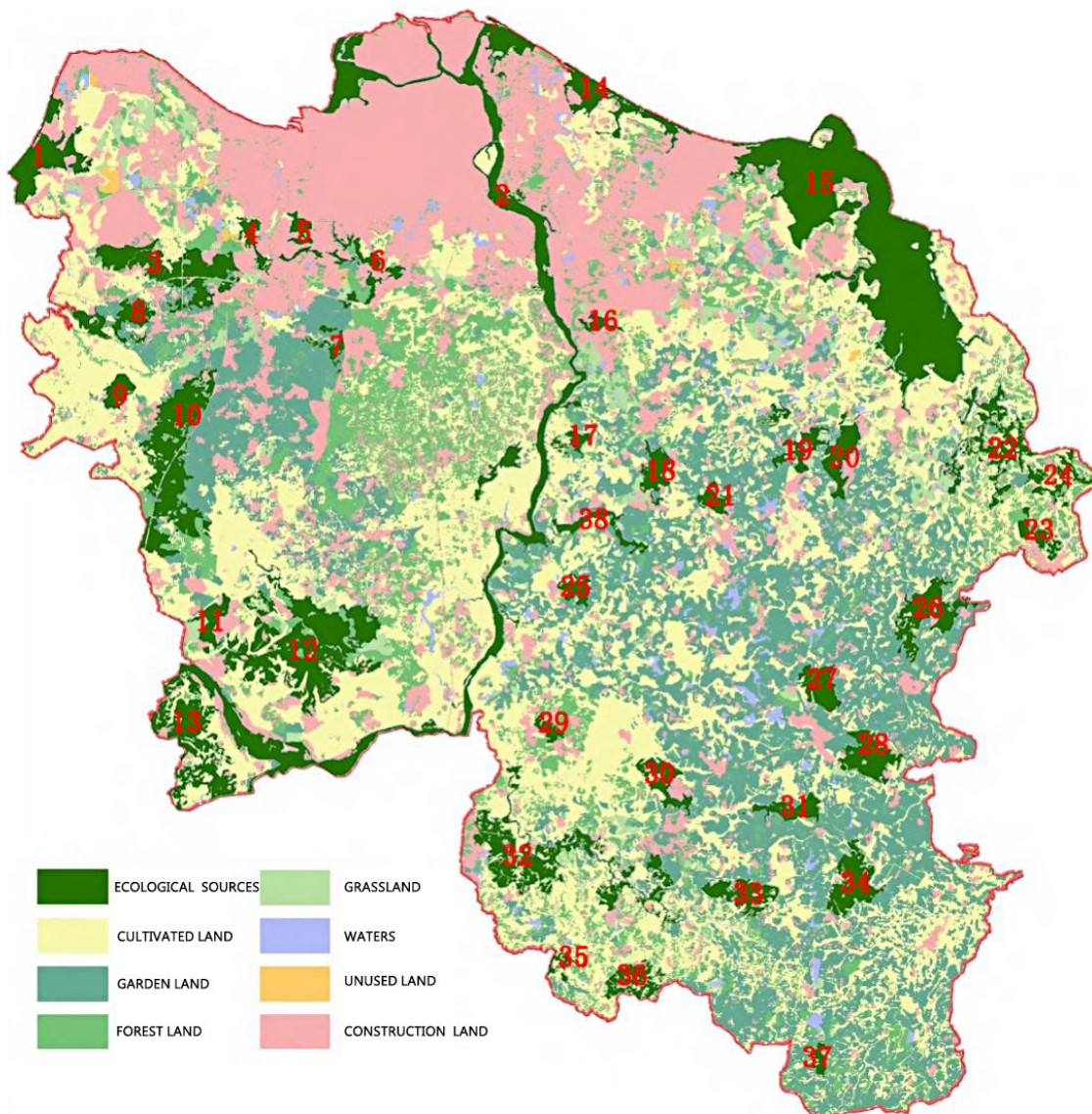


FIGURE 7. Land use status and ecological source extraction. The ecological source area was selected according to the optimum landscape component structure of 1400m granularity.

The function expression of principal component analysis is expressed as follows:

$$Z1 = 0.3555X1 + 0.3375X2 + 0.4081X3 + 0.3695X4 + 0.3830X5 + 0.2997X6 + 0.4077X7 + 0.2291X8 + 0.0415X9 \tag{3}$$

$$Z2 = 0.3094X1 + 0.3680X2 + 0.0547X3 + 0.2672X4 + 0.0039X5 + 0.4368X6 + 0.0656X7 + 0.3399X8 + 0.6196X9 \tag{4}$$

By substituting the data into the Equations (3) and (4), the principal component scores of measured indexes are obtained. By multiplying scores with the variance contribution rates of corresponding principal components,

comprehensive scores of the landscape component structures of each granularity can be obtained (see Figure.6). With the increase of granularity, the overall trend of comprehensive score decreases. This is mainly caused by the increase of granularity. Smaller ecological patches are constantly removed and merged, increasing the distance between components and the fragmentation of landscape component structure. Therefore, the score decreases gradually. The change of landscape component structure causes the change of the overall characteristics. There is a local trend change in the overall downward trend. The comprehensive score of landscape component structure with 1400 m granularity is obviously higher than that of surrounding granularity. It indicates that this granularity is a critical point and conducive to the development of ecosystem.

TABLE 4. Component matrix.

Determination index	Component	
	F1	F2
Patch density	0.866	0.396
Average proximity distance	-0.822	-0.471
Adjacency ratio(%)	0.994	0.070
Connectivity (%)	-0.900	0.342
Polymerization (%)	0.933	-0.005
Sub dimension	-0.730	0.559
Cohesive force (%)	0.993	0.084
Increased Percentage of Connectivity (%)	0.558	-0.435
Patch Number of Maximum Component	0.101	0.793

Based on the landscape component structure of 1400m granularity, 32 large-scale ecological source areas are finally obtained by combining the adjacent and connected patches from the landscape patches that make up the ecological source areas. The minimum ecological source area of 91.40 hm² is taken as the basic standard, the landscape components that are not selected and larger than 91.40 hm² are also classified as ecological source areas. A total of 38 ecological source area with a total area of 31021.06 hm² are obtained. As shown in Figure 7, the overall distribution of ecological source areas in Haikou is relatively uniform, with the general trend of scattered and large-scale distribution in the northwest, concentrated and small-scale distribution in the southeast. The northwest is the main urban area of Haikou, with flat terrain, wide distribution of construction land and cultivated land. Ecological source areas are separated from each other in the northwest. The southeast is the agricultural development area, with relatively large and complex terrain fluctuations, forming a small-scale and numerous ecological source areas.

By overlaying 1400m granularity grid map and present land use map, the patches with similar distance in the same ecological source area are connected through landscape type conversion of patches, so as to improve the overall connectivity of ecological source area. As shown in Figure 8, 14 landscape patches need to be converted, with a total area of 11.07hm², including 6 cultivated lands of 4.73hm², 5 garden lands of 2.59hm², 1 grassland of 0.24hm² and 2 construction lands of 3.51hm². By adding new patches, the original separated ecological source areas can be connected, which is the key to enhance the overall connectivity of ecological source areas.

B. COMPREHENSIVE ECOLOGICAL RESISTANCE

Dominant (Figure.9-a) and the recessive ecological resistance (Figure.9-b) are constructed by the spatial range of landscape patches and the interaction of ecological resistance among patches. The transition of recessive ecological resistance is smoother than that of dominant one. The distribution of

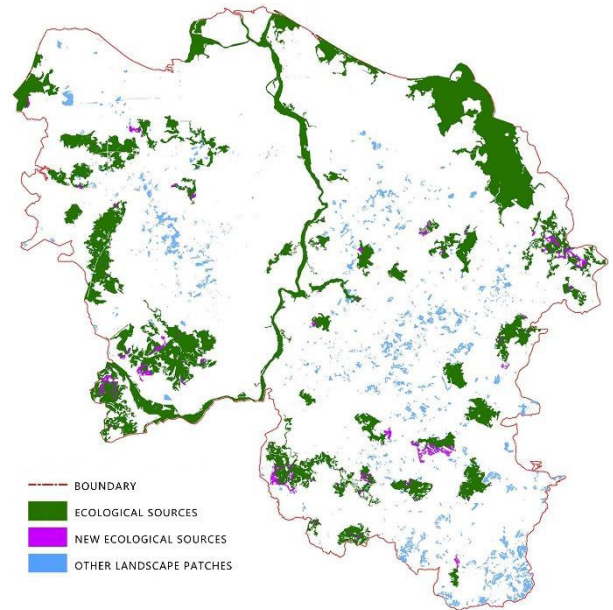


FIGURE 8. Distribution map of landscape patches that integrated into ecological sources.

resistance value and landscape patterns is obviously different in certain regions. For the same region, it may have lower accumulative ecological resistance in terms of dominant one, but higher in terms of recessive one. This is because the interaction of surrounding environment is considered in recessive ecological resistance, leading to higher ecological resistance of patches with higher ecological functions such as fragmented water areas and forest land. The difference of the ecological resistance is obtained by subtracting the dominant resistance from the recessive resistance. If the difference is less than 0, it indicates that the recessive resistance is lower than the dominant one, namely the ecological benefit of the surrounding landscape is higher and the resistance is reduced; If the difference is greater than 0, it indicates that the recessive resistance is higher than the dominant one, namely the ecological benefit of the surrounding landscape is lower and the resistance is increased. These differences tend to be ignored, forming an ecological trap, and measures should be taken in construction. As shown in Figure.9-c, the great difference mainly occurs in the north-central region, among which the largest difference is located in the area of Hongcheng Lake and the area between the urban and Meilan Airport. Water areas or wood lands in this region have small scales. The surrounding areas are construction land and cultivated land with high ecological resistance. It is difficult for the ecosystem to maintain the stability. However, from the perspective of landscape patterns, the ecological resistance of the region is low, so it is a typical ecological trap.

Spatial principal components are used to combine dominant and recessive ecological resistance. The fitting error of Exponential model is the smallest through the comparison of fitting models, so it is used to predict the recessive

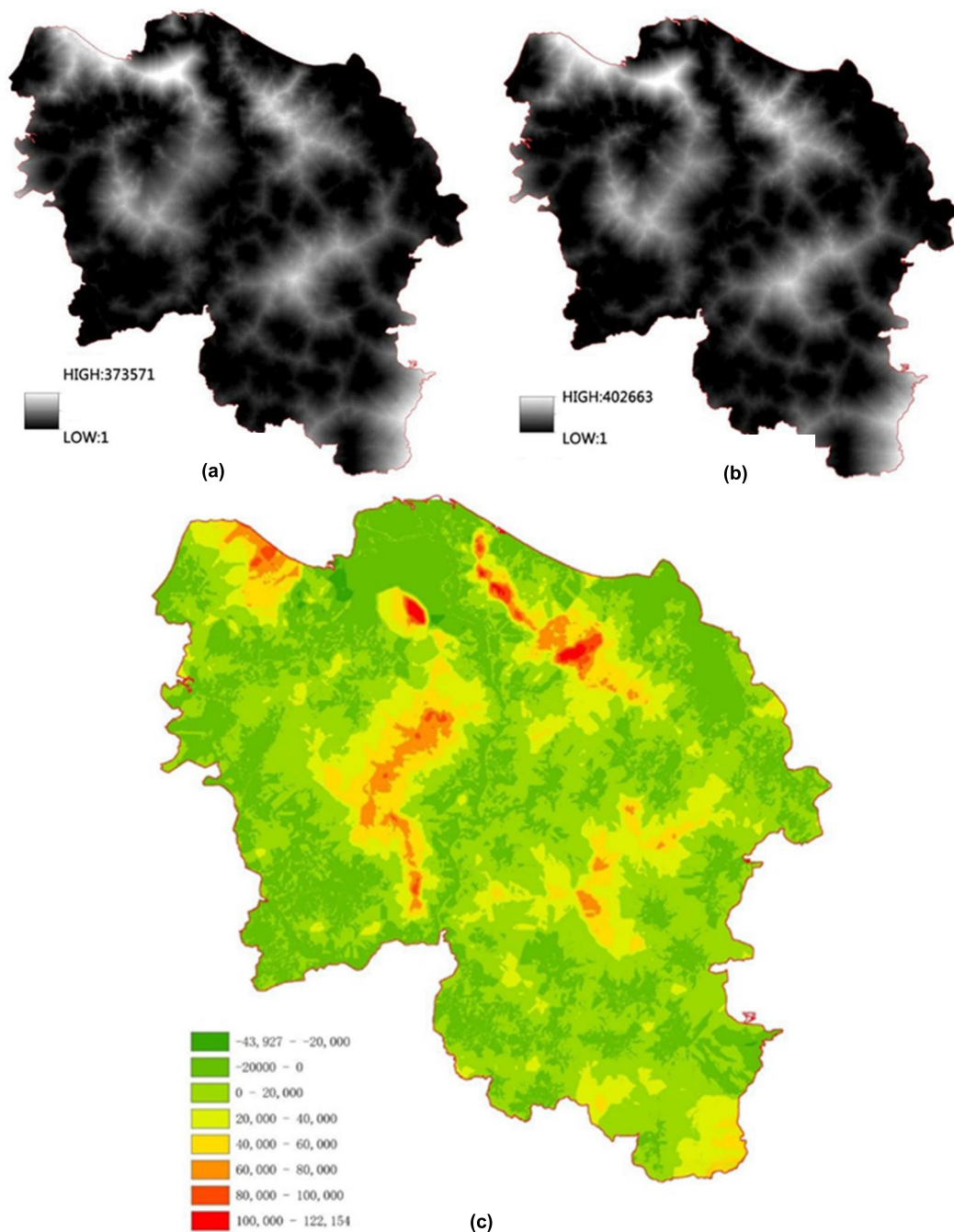


FIGURE 9. Difference between dominant and recessive ecological resistance. The graphs a, b and c indicate the dominant ecological resistance, recessive ecological resistance, and the difference of ecological resistance.

resistance. According to the spatial principal component analysis, the dominant and recessive resistance overlap to form a comprehensive resistance. The accumulative variance is 97.35%, which can better reflect the spatial characteristics of the dominant and recessive resistance. To reflect the influence of topography and landform on ecological resistance, the correction coefficient of resistance is calculated based on slope (see Table 5), and the ecological resistance is revised

to obtain comprehensive ecological resistance of Haikou (see Figure.10).

C. ECOLOGICAL CORRIDOR

Based on the comprehensive ecological resistance surface, a total of 81 ecological corridors with a total length of 402.46km are calculated by the cumulative resistance

TABLE 5. Slope correction coefficient of ecological resistance.

Slope (°)	Correction coefficient	Slope (°)	Correction coefficient
0~10	1.0038	30~40	1.2208
10~20	1.0353	40~50	1.4142
20~30	1.1034		

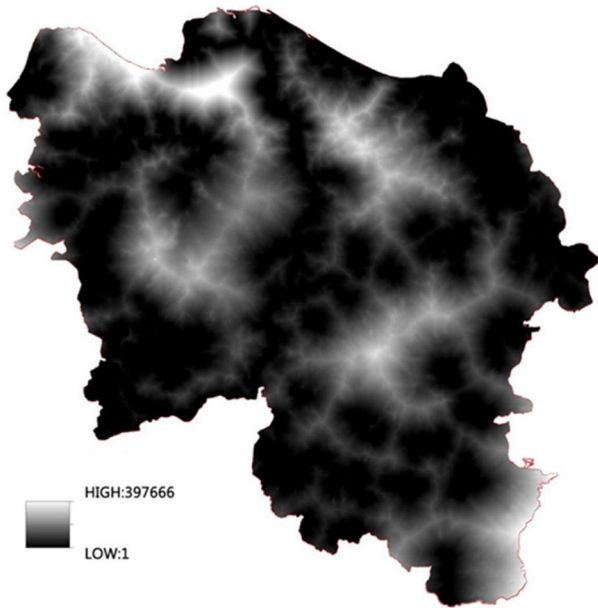


FIGURE 10. Comprehensive ecological resistance.

model, and the spatial distribution is shown in Figure 11. The longest ecological corridor is 18.68km long, located in the Middle East of Haikou, connecting No. 25 and No. 26 ecological source areas; the shortest ecological corridor is 0.15km long, connecting No. 11 and No. 12 ecological source areas. In terms of length, the ecological corridor in the middle of Haikou is longer, while the ecological corridor in the southeast is shorter. The main landscape in the middle of Haikou is cultivated land and garden land, which are strongly affected by human disturbance, and the ecological landscape components are difficult to form scale. Therefore, the ecological source area is separated by other landscape types, and the ecological corridor is longer. In the southeast, the topography fluctuates greatly, which is not conducive to the development and construction. Thus, a large number of water areas and forest topography are reserved as the ecological source areas. Ecological source areas are relatively small from each other, and the ecological corridor is relatively short.

Functions of ecological corridors are determined by different substrates. According to the distribution of ecological corridors in the landscape pattern and functional characteristics of ecological source areas, there are 33 ecological corridors for cultivated land, 30 for garden land, 11 for forest land

and 7 for construction land. Forest land ecological corridor is defined for protection and enclosure based on existing forest land; the garden land ecological corridor is similar to the forest land ecological corridor. It can be constructed by delineating the protection scope for forest structural transformation and the reduction of human disturbance; ecological corridors of farmland and the construction land aim at reducing man-made interference in construction. The difference is that the cultivated land ecological corridor needs to consider the resistance to pollutants; while the environment and quality of life should be considered comprehensively in the construction of ecological corridor of construction land.

D. ECOLOGICAL NODE

As shown in Figure 11, there are 76 ecological nodes in Haikou, which have the same distribution characteristics as the ecological corridor. In the southeast, the terrain is diverse, and there are many and scattered ecological corridors, so there are many ecological nodes. In the north, ecological corridors are not affected by topography, so there are few ecological nodes. There are two types of ecological nodes, one is “corridor-resistance” with a total of 57, the other is “corridor-corridor” with a total of 19. Among them, the ecological resistance value of “corridor-resistance” ecological node is higher, so external interference should be reduced. For example, a buffer zone prohibiting human activities should be established to protect the ecological node and improve the ecological stability. The ecological resistance value of “corridor resistance” ecological node is relatively low, whose function is to strengthen the ecological corridor and promote the communication and operation of ecological flow. Therefore, on the basis of protection, the layer of landscape should be enriched, and the compatibility of landscape should be strengthened to improve the function of ecological services.

E. EVALUATION ON THE OPTIMIZATION EFFECT

The landscape pattern index of Haikou before and after the optimization is calculated, as shown in Table 6. The results show that index CONNECT of the optimized landscape pattern increases by 10.86%, index DIVISION decreases by 24.65%, and index PROX-MN decreases by 23.08%. This is mainly because the increased ecological corridors and ecological nodes connecting the scattered ecological source areas as an entirety, so that the connectivity of the ecosystem is significantly improved. However, there is little change in index PLADJ and index AI. The reason is inferred as follows: the adjacency ratio and aggregation degree are mainly affected by the landscape components, but the optimization of ecological network is difficult to produce significant effect on the landscape components. Thus, the adjacency ratio and aggregation degree rarely change. In conclusion, the overall connectivity of Haikou landscape pattern before and after the optimization has been significantly improved, and the optimization effect is good.

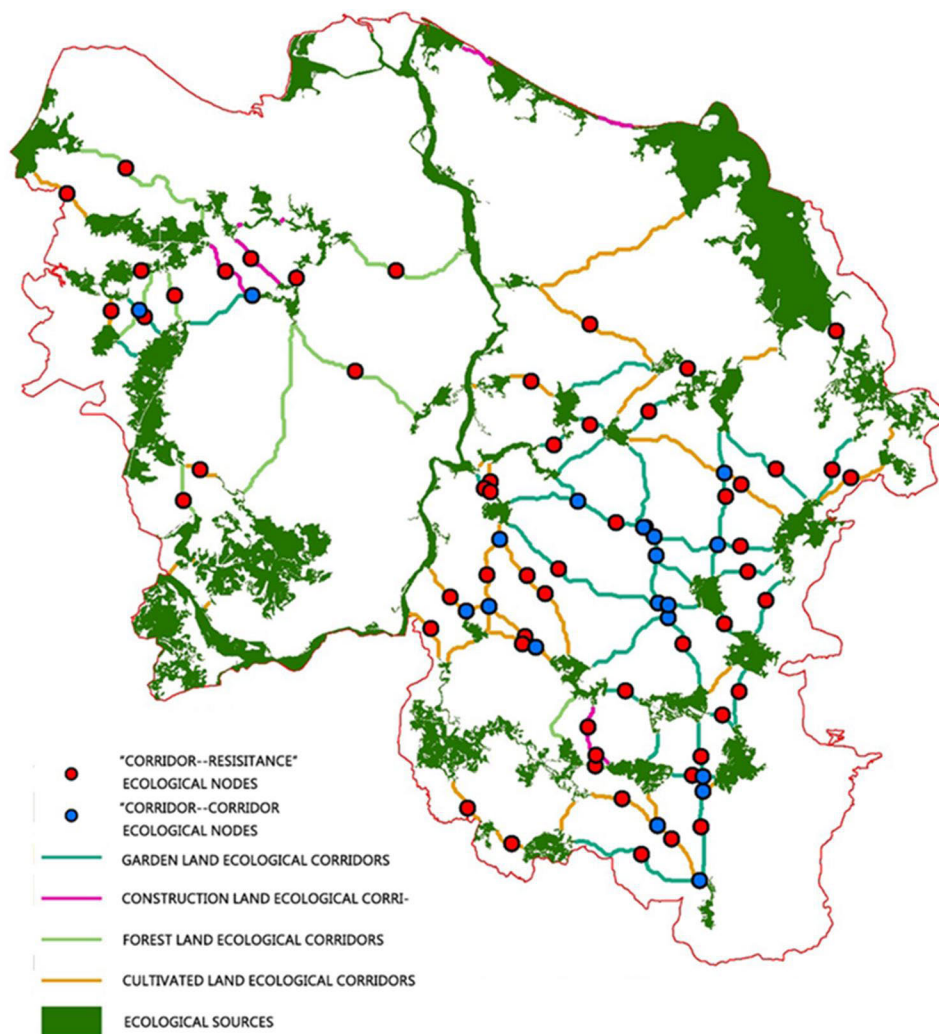


FIGURE 11. Construction of ecological network in Haikou.

TABLE 6. Slope correction coefficient of ecological resistance.

	CONNECT	DIVISION	PLADJ	PROX-MN	AI
Before	1.566	0.915	33.884	1.895	73.764
After	1.736	0.689	33.891	1.458	73.906

V. CONCLUSION

The construction of ecological network is significantly important for the sustainable development of cities. In this paper, granularity reverse method and MCRM are used to build the ecological network in Haikou, optimization results are evaluated, and the corresponding suggestions are put forward. The main conclusions are as follows:

The granularity of 1400m is the optimal granularity of landscape component structure in Haikou. As a reference, 38 ecological source areas are selected. The scattered and large-scale ecological source areas are distributed in the northwest, while concentrated and small-scale ecological

source areas are distributed in the southeast. The distribution and scale of ecological source areas are highly related to the topography and geomorphology, and obviously affected by human interference. To improve the stability of the ecological source area, 14 new ecological landscape patches with a total area of 11.07hm² are needed to form a larger ecological source area.

Considering the influence of slope, the comprehensive ecological resistance surface is constructed by using the dominant and recessive ecological resistance surfaces. There are obvious differences between the dominant and recessive ecological resistance areas, which are manifested as the fragile zone of ecological environment located in Hongcheng lake and Meilan airport. In the future, it is necessary to strengthen the maintenance and construction of the ecological landscape in the region to improve the ecological stability. The existence of ecological fragile zone also proves that the comprehensive ecological resistance surface can more accurately simulate the ecological process.

There are 81 ecological corridors and 76 ecological nodes in Haikou. According to the types, characteristics and functions of landscape, ecological corridors and ecological nodes are classified. The corresponding suggestions and optimization measures are put forward. After the optimization, the connectivity and closure of the ecological network in Haikou have been significantly improved, which is conducive to the survival of animals, plants and the exchange of material and energy.

The results show that it is feasible to combine the granularity reverse method, landscape spatial structure and connectivity to determine the optimal source structure, and the calculation process and results are objective. From the perspective of operation, this method is applicable to the situation of more landscape types, higher degree of landscape fragmentation and larger research area. It can provide help for urban ecological environment construction in the future.

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