A method of delineating ecological red lines based on gray relational analysis and the minimum cumulative resistance model: a case study of Shawan District, China

Jiaqi Sun®, Jiejun Huang®, Qi Wang and Han Zhou®
School of Resources & Environmental Engineering, Wuhan University of Technology, 430070 Wuhan, People’s Republic of China
* Author to whom any correspondence should be addressed.
E-mail: hjj@whut.edu.cn

Keywords: ecological red lines, ecological security patterns, gray relational analysis, minimum cumulative resistance model, GIS

Abstract

The delineation of ecological red lines (ERLs) is of great significance to ensure ecological security and improve the quality of the ecological environment. However, most of the current ERL delineation only focuses on the natural environment, lacks consideration of the spatial pattern of ecological landscape, and there is no scientific standard for ERL delineation. From the perspective of ecological security patterns (ESPs), this study proposed an ERL delineation method based on gray relational analysis (GRA) and the minimum cumulative resistance (MCR) model. Then taking Shawan District as an example, the effectiveness of the method was verified by comparing the delineated ERL in this study with that of traditional evaluation methods. A total of 321.43 km² of ERL was delineated, accounting for 67.75% of the total area of Shawan District, including 69.70 km² of Grade I ERL zones, 251.73 km² of Grade II ERL zones. The results show that ERLs based on GRA and MCR exhibit better connectivity and contain more ecological land. The method has guiding significance and reference value for regional ERL delineation, which is conducive to the decision-making of environmental protection departments. Conservation measures for different landscapes are more targeted to constrain people’s productive activities precisely.

1. Introduction

In recent years, due to the rapid development of cities and the continuous consumption of resources, the ecological environment has also been destroyed [1, 2]. Coordinating the relationship between environmental protection and human production activities is a prerequisite for promoting regional sustainable development [3, 4]. The ERL is defined by the state to ensure and maintain ecological security, it has special ecological functions and must be strictly protected [5]. Delineating ERL is important to the coordination of urban construction and ecological environmental protection. Its strict ecological protection system and regulatory requirements can better constrain human activities, thereby curbing environmental degradation and promoting environmental restoration [6, 7]. The State Council of China launched the ‘Delineation of ERL’ plan in 2011 as a national ecological security strategy [8]. Subsequently, in the context of ecological civilization construction, national departments continued to improve the relevant requirements for the delineation of ERL and proposed methods for the national level. At the same time, the delineation of ERL in various regions was conducted successively [9].

The delineation of ERL is uniquely developed and practiced in the context of China [10, 11]. However, its ultimate goal is similar to the National Ecosystem Assessment implemented by the United Kingdom [12], the Green Infrastructure Strategy supported by the European Union [13], and the nature reserves established by the United States [14], all for ecological protection. Currently, the research on the delineation of ERL can be divided into three categories. The first is to evaluate the importance of ecosystem services, ecological sensitivity, and ecological carrying capacity by selecting indicators, and then delineate ERL based on the comprehensive
evaluation results [15, 16]. The second is to delineate ERL based on intelligent computing, such as neural networks, multi-agents, discrete particle swarms, etc [17, 18]. The third is to combine ERL delineation with landscapes or other ecological hotspots to explore ecological environmental protection strategies [19, 20]. However, most of these studies focus on the ecological environment of landscapes and pay less attention to the horizontal relationship between landscapes. In addition, in the process of delineating ERL, the selection of indicators varies greatly and only stays at the theoretical level, which does not effectively represent the actual value of ERL.

The current research on ecological security patterns (ESPs) in China and abroad involves biodiversity protection [21], forest ecological corridor construction [22], infrastructure improvement [23], and other aspects. The spatial scope involves different scales such as landscape, region, and country [24]. The construction method of ESP provides a new idea for the delineation of the ERL. In these studies, the minimum cumulative resistance model (MCR) based on the ‘source-sink’ theory is the mainstream method for constructing the ESP [25]. It can not only characterize the horizontal connections between landscapes but also integrate multiple models to reflect the impact of landscapes on ecological processes [26]. Currently, the construction of ESPs based on the MCR model mostly adopts a combination with other models, such as the analytic hierarchy process and principal component analysis [27, 28]. Although the above method has some improvement, it is still subjective in determining the index weight of the resistance surface. Therefore, the gray relational analysis (GRA) is introduced into the construction of ESPs. According to the closeness between the reference sequence and the contrast sequence, the weighting coefficient of important indicators is strengthened, to avoid the deviation caused by the weight determination through experience, which can make the results more scientific and reasonable [29].

Based on GRA and the MCR model, combined with the concept of ESPs, this study proposed an ERL delineation method. Then, this method was applied to delineate ERLs with Shawan District as an example. Finally, the delineated ERLs in this study were compared with those by traditional evaluation methods to verify the method’s rationality and provide a reference for ecological protection in other regions.

2. Study area and data

2.1. Study area

Shawan District is in the southwest of Jingning She Autonomous County, Lishui City, Zhejiang Province (119° 482′E—119° 569′E, 27° 776′N—27° 964′N), including one town and four townships, namely Shawan Town, Dajun Township, Wutong Township, Biaoxi Township and Jiadi Township (figure 1). The land area is 474.46 km², and the population is approximately 33,600. Shawan District has various topographies and landforms, with large altitude differences. The terrain gradually dips from southwest to northeast. This place has a subtropical monsoon climate with four distinct seasons. The climate is warm and humid with a mean annual temperature of 18.3 °C and annual precipitation of 1824.8 mm. This area has a dense distribution of rare animals and plants, with Qianjiangyuan-Baishanzu National Reserve, Jiulong Provincial Geopark, etc, which has important ecological functions.

2.2. Data

Administrative division data, landform data, meteorological data, vegetation data, soil data, and land-use type data were used to delineate ERLs (table 1). The formats of the data were Shapefile (vector data) and GRID (raster data), and the projection was Universal Transverse Mercator (UTM) with coordinates of the World Geodetic System 1984 Coordinate System (WGS84). Raster data were uniformly resampled to 30 m for research purposes.

3. Methods

3.1. Research framework of ERL

The essence of ERLs is to restrict human activities. The ERL is a ‘rigid’ constraint for ecological protection [5]. Therefore, the impact of production activities should be fully considered in the delineation. The ESP reflects the ‘flexible’ requirement of ecological protection, and in its construction process, the interaction between humans and nature can be included [19, 30]. This study proposes a new research framework of ERL delineation for reasonability that reflects the characteristics of rigidity and flexibility in the process of ecological protection (figure 2). Step 1: According to the ecological environment in the study area, ecosystem service functions and ecological sensitivity are evaluated. Combined with the concept and method in the ‘Guidelines for the Delimitation of the Red Line of Ecological Protection’ [31], the ecological sources were determined. Ecological
sources generally refer to the areas with important ecological functions and high ecological value \cite{32} and are also the ‘rigid’ boundary of ecological protection. Step 2: The indicators that affect the expansion of ecological sources are selected from two aspects of natural environmental factors and social factors, and then a comprehensive resistance surface was established based on GRA. Step 3: Based on the established ecological source and comprehensive resistance surface, the MCR model was used to construct the ESP of the study area, and the ‘flexible’ range of environmental protection was determined. Step 4: Combined with the constructed ecological security pattern and the environmental protection policy in the study area, the initial ERLs were delimitated, and then patch verification and boundary verification were conducted to determine the final two-grade ERL range.
3.2. Construction of ESPs
The ecological security pattern of the study area was quantitatively analyzed to provide a basis for the delineation of ERLs. Firstly, the ecological source area was determined by ecological function evaluation. Then, the factors affecting ecological security were selected and the weight of each factor was calculated by using GRA to construct the ecological resistance surface. Finally, based on the ecological sources and the constructed ecological resistance surface, the MCR model was used to construct ESPs.

### 3.2.1. Selection of ecological sources
We quantitatively evaluated water conservation, soil retention, and biodiversity maintenance (table 2). We overlaid them to obtain ecological functions (EFs) [16]. EFs were normalized and classified into five levels from low, comparatively lower, median, comparatively higher to high by natural breaks. High levels of areas were

| Indicators                  | Calculation process                                                                 | Indicator interpretation                                                                 |
|-----------------------------|-------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------|
| Water conservation          | \( S_{\text{wr}} = NPP_{\text{mean}} \times F_{\text{pre}} \times F_{\text{tem}} \times (1 - F_{\text{alt}}) \) | \( S_{\text{wr}}, S_{\text{pre}}, \text{and} S_{\text{alt}} \) are the importance indexes of water conservation, soil retention, and biodiversity maintenance respectively. \( NPP_{\text{mean}} \) is the mean annual vegetation net primary productivity from 2010 to 2015, \( F_{\text{pre}} \) and \( F_{\text{tem}} \) are mean annual precipitation and mean annual temperature from 2010 to 2015, \( F_{\text{alt}} \) is the slope factor, \( E_{\text{alt}} \) is the altitude factor, \( F_{\text{sic}} \) is the capacity factor of the soil seepage, \( K \) is the soil erodibility factor. |
| Soil retention              | \( S_{\text{pro}} = NPP_{\text{mean}} \times (1 - K) \times (1 - F_{\text{alt}}) \)       |                                                                                         |
| Biodiversity maintenance    | \( S_{\text{bio}} = NPP_{\text{mean}} \times F_{\text{pre}} \times F_{\text{tem}} \times (1 - F_{\text{alt}}) \) |                                                                                         |
| Soil erosion                | \( SS = \sqrt{R \times K \times LS \times C} \)                                       | \( SS \) is the sensitivity index of soil erosion, \( R \) is rainfall erosivity, \( LS \) is the topographic relief, \( C \) is the vegetation coverage. |

Figure 2. The research framework of ERL.

Table 2. The evaluation system of ecological functions [16, 31].
applied to the initial ecological source because these areas are of high importance and sensitivity. Then some prohibited development zones (national reserves, provincial geological reserves) were overlaid into the initial ecological source and others (permanent basic farmland zones) were excluded. Finally, to maintain the continuity and integrity of the patches, patches with fewer than 250 m were aggregated, and patches with an area of less than 1 km² were eliminated [31, 33]. In this way, ecological sources with a low degree of fragmentation and key ecological functions were obtained. The areas selected as the ecological source were set with ‘Y’, and other areas to be excluded were set with ‘N’ (table 3).

3.2.2. Establishment of resistance surface

Information on natural, social, and economic factors in ecosystems is often complex, incomplete, and interrelated, the ecosystem is a complex gray system [34]. Gray relational analysis (GRA) is a quantitative method of describing and comparing the relationship between indicators according to investigating trends [35]. GRA was used to determine the weight by measuring the correlation between EFs and influence indicators, to construct the comprehensive resistance surface, and to identify ESPs.

Because of the different measurement units of indicators, the method of range standardization was used for dimensionless processing. The formula used to standardize the positive indicator is:

$$X'_i = \frac{X_i - \min(X_i)}{\max(X_i) - \min(X_i)} \quad (i = 1, 2, \ldots, m; j = 1, 2, \ldots, n)$$

(1)

The formula used to standardize the negative indicators is:

$$X'_{ij} = \frac{\max(X_{ij}) - X_{ij}}{\max(X_i) - \min(X_i)} \quad (i = 1, 2, \ldots, m; j = 1, 2, \ldots, n)$$

(2)

The dimensionless matrix can be obtained by normalized processing:

$$X'_{0j} = (X'_{01}, X'_{02}, \ldots, X'_{0n}), \quad X'_i = (X'_1, X'_2, \ldots, X'_m)$$

(3)

where $X'_{0j}$ represents the reference sequence, which is the standardized comprehensive evaluation result of EF in this study; $X'_i$ represents the comparison sequence, which is the indicator that affects the ecological environment; $X'_{ij}$ is the standardized result; $i$ is the selected indicator, $m$ is the total number of indicators; $j$ is the selected patch in the indicator, and $n$ is the total number of patches in the current indicator.

The formula used to calculate association coefficients on each patch of $X'_{0j}$ and $X'_i$ is as follows:

$$\delta_{ij} = \frac{\min_i \min_j |X'_{ij} - X'_{0j}| + \rho \times \max_i \max_j |X'_{ij} - X'_{ij}|}{|X'_{ij} - X'_{0j}| + \rho \times \max_i \max_j |X'_{ij} - X'_{ij}|}$$

(4)

where $\delta_{ij}$ is the association coefficient between $X'_{0j}$ and $X'_i$, $|X'_{ij} - X'_{0j}|$ is the absolute value of the difference between $X'_{ij}$ and $X'_{0j}$; $\rho$ is the identification coefficient and $\rho = 0.5$.

$\delta_i$ is the association coefficient between $X'_{0j}$ and $X'_i$, $\omega_i$ is the weight of the influencing indicator:

$$\delta_i = \sum_{j=1}^{n} \frac{\delta_{ij}}{n}, \quad \omega_i = \frac{\delta_i}{\sum_{i=1}^{m} \delta_i}$$

(5)

$R_j$ represents the comprehensive resistance coefficient that affects the expansion of ecological sources, and the expression is shown as follows:

| Factors                      | Criteria                  |
|------------------------------|---------------------------|
| EFs                          | High levels of EFs        |
|                              | Others                    |
| Prohibited development zones | National and provincial geological reserves |
| Permanent basic farmland zones |                                      |
| Patches                      | Patch sizes >1 km²        |
|                              | Patch distances <250 m    |

Table 3. Criteria for the selection of ecological sources.
The positive correlation function $D$ evaluated. The larger the value of the ecosystem service functions and ecological sensitivity based on the natural conditions in Shawan District were

4.1.1. Ecological sources

4. Results

3.2.3. Identification of ESPs

The minimum cumulative resistance (MCR) model proposed by Knaapen et al. [36] can connect various sources by constructing ecological corridors to promote species diffusion and energy circulation [37, 38], which is the main way to identify an ESP [39]. The formula for MCR calculation is:

$$MCR = \min \sum_{j=1}^{m} D_{ij} \times R_j$$

(7)

where $MCR$ represents the value of the minimum cumulative resistance, $f$ is the positive correlation function between $D_{ij}$ and $R_j$, $D_{ij}$ is the spatial distance from source unit $l$ to patch unit $j$, and $R_j$ is the resistance coefficient that exists in transition from patch unit $j$ to source unit $l$.

Based on the ArcGIS 10.4 platform, the minimum cost path between ecological sources is calculated by using the ecological resistance surface and the MCR model. Then the repeated paths are removed and spatial superposition is carried out to obtain the ecological corridors. The cumulative cost-distance surface is constructed depending on the ecological resistance surface and sources, which indicates the minimum cumulative resistance consumed by the expansion of the sources. Different levels of ecological security patterns are identified according to the cumulative cost-distance surface, which guides the delineation of ERLs.

3.3. Criteria for delineating ERLs

The criteria for delineating ERLs are mainly derived from the national guidelines of the Ministry of Environmental Protection. In addition, the concept of ESPs is also considered. Grade I ERLs are the bottom lines and the rigid boundaries of ecological protection. Any human activities should be prohibited for long-term ecological security. Grade II ERLs are the transition of the expansion of the ecological sources to the outside and are flexible boundaries for ecological protection. As a matter of principle, human activities and construction are prohibited in such zones, but under the premise of meeting the provisions of the law, it can be appropriately engaged in activities that do not cause damage to the ecological environment according to the needs. Such zones are generic protected areas to meet the basic needs of residents for a livable environment and human well-being.

The ESPs and EFs were classified into five levels from low, comparatively lower, median, comparatively higher to high by natural breaks to delineate different grades of ERLs. Ecological sources had high levels (0.49-1) of EFs and included core zones for national and provincial geological reserves with patch areas greater than 1km² and patch distance fewer than 250m (table 3), which were applied to Grade I ERL zones. EFs with comparatively higher levels (0.36-0.49), corridors, ESPs with low (0-0.0004), and comparatively lower (0.0004-0.0051) levels were set as Grade II ERL zones. In addition, to ensure that the ERL ranges did not cross and overlap, we gradually eliminated overlapping patches according to the priority standard of ‘Grade I > Grade II’.

4. Results

4.1. Analysis of ESPs

4.1.1. Ecological sources

Ecosystem service functions and ecological sensitivity based on the natural conditions in Shawan District were evaluated. The larger the value of the figures is, the higher the importance or sensitivity level is (figure 3). The areas with a high value of water conservation function were mainly distributed in southwestern Shawan Town, northwestern and southeastern Biaoxi Township, and Jiadi Township. The distribution of such areas was associated with the location of rivers (figure 3(a)). The areas with a high value of soil retention function were distributed almost all over the entire area of Shawan District due to high vegetation coverage (figure 3(b)). The distribution of a high value of biodiversity maintenance function was relatively dispersed but was generally concentrated in higher elevations where there were fewer human activities (figure 3(c)). The sensitivity values of soil erosion in southern Shawan Town and Jiadi Township were high, indicating that soil erosion was prone to occur in these areas (figure 3(d)). The comprehensive evaluation of EFs can be obtained by superposition of single factor evaluation results, and then it was normalized and separated into five grades based on natural breaks (table 4, figure 3(e)). EF with a cumulative service value greater than 0.49 was 66.34 km², accounting for 13.98% of Shawan District, mainly distributed in the south of Shawan Town and Jiadi Township. Such areas had prominent ecological functions and played a very important role in the sustainable development of the ecological environment, so they were regarded as the initial ecological sources. EF with comparatively higher levels was 191.38 km², accounting for 40.34% of Shawan District, which performed relatively important ecological functions. EF with high and comparatively higher levels played an important role in ecological
protection, which provided the database for setting ERLs. There were fewer areas of EF with low and comparatively lower levels (3.30% and 6.91% of Shawan District), indicating that the overall ecological function level was relatively high.

The ecological sources were identified as 69.70 km² (figure 3(f)), which were centrally distributed in the south of Shawan District, including the east and southwest of Biaoxi Township, the south of Shawan Town, and Jiadi Township. In addition, Wutong Township and Dajun Township also have a similar distribution, although there appear to be few and scattered. Second, the land-use types of ecological source areas were mainly ecological land, including 65.54 km² woodland, 0.72 km² river surface, 0.12 km² grassland, and 0.30 km² garden lands. To maintain the integrity and continuity of patches, 2.43 km² ordinary farmland, and 0.59 km² construction land were also included.

Table 4. The spatial distribution of EFs with different levels in shawan district.

| Distribution       | High (0.49-1.00) | Comparatively higher (0.36-0.49) | Median (0.18-0.36) | Comparatively lower (0.08-0.18) | Low (0.00-0.08) | Subtotal |
|--------------------|------------------|----------------------------------|--------------------|-------------------------------|----------------|----------|
| Shawan Town        | 31.96            | 76.70                            | 35.50              | 12.36                         | 5.96           | 162.48   |
| Dajun Township     | 0.38             | 9.52                             | 70.96              | 16.34                         | 8.50           | 105.69   |
| Wutong Township    | 1.17             | 35.02                            | 40.89              | 4.04                          | 1.18           | 82.31    |
| Biaoxi Township    | 5.50             | 37.40                            | 20.23              | 0.03                          | 0.01           | 63.17    |
| Jiadi Township     | 27.33            | 32.75                            | 168.31             | 32.78                         | 15.64          | 474.46   |
| Total              | 66.34            | 191.38                           | 168.31             | 32.78                         | 15.64          | 474.46   |
| Percentage(%)      | 13.98            | 40.34                            | 35.47              | 6.91                          | 3.30           | 100      |
4.1.2. Ecological resistance surface

Natural environmental indicators such as topography, vegetation coverage, and river distribution control the differentiation and change of landscape and affect the ecological functions such as soil retention and water conservation, as well as the occurrence of disasters such as soil erosion. Residential areas, highways, industrial land, and other areas with intensive human activities threaten ecological security and hinder the expansion of ecological sources [21, 28, 33]. Ten influencing factors were selected as evaluation indicators from both the natural environment and the social economy, and then the weight of each indicator was calculated based on GRA (table 5). Overall, the natural environmental indicators had a profound impact on the evaluation results of EFs, and their relational coefficients were greater than 0.6. Among all the factors, the relational coefficient between vegetation coverage and EF was the highest. The ecological environment was generally better and the EF was more important in areas with high vegetation coverage. The distance from industrial land was highly correlated with the comprehensive evaluation results of the EF and the relational coefficient was 0.741. Due to frequent human production activities, the closer the distance from industrial land was and the lower the ecological security level was.

The ecological resistance surface of Shawan District was calculated by weighted summation (figure 4). The areas with low resistance values were mainly distributed in the northernmost and southernmost parts of Shawan District, including south of Shawan Town and Biaoxi Township, north of Dajun Township, Jiadi Township. Areas with low resistance values were more amenable to large-scale expansion for ecological sources, and the situation of ecological security may be better. However, the central areas of Shawan District such as the northern areas of Shawan Town, Wutong Township, and the southern areas of Dajun Town, had higher resistance values, indicating that these areas were greatly affected by human beings and are not conducive to the expansion of ecological sources. The ecological resistance surface was characterized by 'low around and high in the middle', which may be related to the dense towns in the middle of Shawan District. The ecological sources are mainly distributed in the south, but the ecological resistance surface with high values in the middle will affect their expansion. This feature may make the circulation of ecological material and energy to the north poor, which may lead to the 'north-south differentiation' characteristics of the ecological environment in Shawan District.

4.1.3. Evaluation of Comprehensive ESPs

According to the ecological sources and ecological resistance surface, the cumulative cost-distance surface and corridors were calculated based on the MCR model (figures 5(a), (b)). The value of the cumulative cost-distance surface from 0 to 0.0364 indicated the difficulty of source expansion from low to high. Low values demonstrated a low ecological security level and needed more protection. The low-value area was mainly distributed in the south and central part of Shawan District, while the high-value area was mainly distributed in the north of Shawan District near the administrative boundary. Sixty-eight ecological corridors with a total length of 147.41 km were identified. They were probably distributed in the low-value areas of ecological security resistance, and they were the least cost paths to connect the sources and facilitate the spread of species.

The cumulative cost-distance surface was classified into five levels from low (0-0.0004), comparatively lower (0.0004-0.0051), median (0.0051-0.0126), comparatively higher (0.0126-0.0225) to high (0.0255-0.0364) by nature breaks to establish different level security patterns(figure 5(c)). In addition, the proportion of different levels of ESPs was calculated (figure 6).

From the proportion and spatial distribution of different security level patterns, areas of a low-security level and a comparatively lower security level were 23.57 km² and 144.57 km², accounting for 4.97% and 30.47% of the total area of Shawan District. These areas were mainly distributed in southern Shawan District, including southern Shawan Town and Biaoxi Township, and Jiadi Township. The activities of human production and construction in such areas should be appropriately restricted to strengthen ecological protection. Areas of

| Resistance types                      | Resistance factors                          | GRCs    | Weights |
|--------------------------------------|--------------------------------------------|---------|---------|
| Natural environmental indicators     | Elevation                                  | 0.641   | 0.096633|
|                                      | Slope                                      | 0.717   | 0.107755|
|                                      | Vegetation coverage                        | 0.790   | 0.118726|
|                                      | Distance from rivers                       | 0.726   | 0.109107|
| Socio-economic indicators            | Distance from highways                     | 0.626   | 0.094079|
|                                      | Distance from residential areas            | 0.511   | 0.076796|
|                                      | Distance from permanent basic farmland zones| 0.473   | 0.071085|
|                                      | Distance from reservoirs                   | 0.610   | 0.091674|
|                                      | Distance from industrial land              | 0.741   | 0.111362|
|                                      | Distance from cultural reserves             | 0.473   | 0.071085|

Table 5. Gray relational coefficients (GRCs) and weights.
high-security level and a comparatively higher security level are 19.13 km$^2$ and 91.42 km$^2$, accounting for 4.03% and 19.27%, which were mainly distributed in Wutong Township, Dajun Township, and northern Shawan Town. The pattern of ecological security levels in Shawan District generally presents the characteristics of 'north-south differentiation'. The ecological security level in the south was low, so it was necessary to strengthen ecological protection to prevent interference and destruction of human activities. The ecological security level in the north was relatively high, urban construction and development can be conducted appropriately without damaging ecological environments.

**Figure 4.** Spatial distribution of ecological resistance surfaces in Shawan District.

**Figure 5.** Spatial distribution of ESPs. (a) Cumulative cost-distance surface; (b) Corridors; (c) Comprehensive ESPs.
4.2. Delineation of ERLs
According to the EFs (figure 3) and the ESPs constructed (figure 5), two grades of ERL areas were delineated (figure 7), and different grades of ERL areas adopted different control methods. Grade I ERL zones were 69.70 km², accounting for 14.69% of the total area of Shawan District. It was composed of ecological sources, mainly distributed in southern Shawan District, including Shawan Town, the south of Jiadi Township, and Biaoxi Township. A total of 251.73 km² areas were delineated as Grade II ERL zones, which accounted for 53.06% of the total area of Shawan District. They were the easiest areas for ecological sources to expand outward, and they were distributed around the source areas, mainly in the south and central part of Shawan District. In addition, there were 68 linear ecological corridors with a total of 147.41 km that connected the various protected areas to make them closer together.

Figure 6. The proportion of different levels of ESPs.

Figure 7. ERLs in Shawan District.
5. Discussion

Compared with the national guidelines, the revised framework of this study integrated EFs and ESPs, providing a comprehensive approach to understanding the ecological function of patches and the interactions between patches. To verify the rationality of the results, this study used the same data and delineated the ERLs of Shawan District based on the traditional ecological evaluation methods mentioned in the guide. Overall, the ERL by the traditional method was roughly the same as the ERL in this study, but there were also some differences. To facilitate analysis, five areas with large differences were selected for identification (figure 8). Three advantages of the method in this study compared with the traditional evaluation method deserve mention.

First, the addition of ESPs is better to reflect the connectivity and horizontal movement process between patches. The ecological corridors could connect each ERL area. In the northernmost part of Dajun Township (Area A), the ERL was delineated by both methods. However, in the method of this study, a corridor was set to promote the circulation of species, which could facilitate the exchange of species among various protected ERLs. The traditional evaluation method made the northern red line area an independent individual. The use of traditional assessment methods made the northern ERL an independent area. A similar situation exists in northern Shawan Town and eastern Wutong Township (Area C). Next, buffer zones with different ESPs can better protect Grade I ERL zones from human activities. Grade I ERL zones delineated by the traditional method, such as in the south of Dajun Township and the north of Shawan Town (Area B), were almost directly connected with other human activity-intensive areas, increasing the possibility of human activity interference, which was unfavorable to the protection of Grade I ERL zones.

Second, in the method of this study, in addition to water conservation, soil retention, biodiversity maintenance, and soil erosion, the delineation of Grade I ERL zones also add the determination of prohibited development zones, which is in line with the national policy. In the south of Shawan Town (Area D), the Qianjiangyuan-Baishanzu National Park was not identified by the traditional method but was delineated as Grade II ERL zones for flexible protection, which was not enough to protect the National Park and did not conform to the national policy. Similarly, the Jiulong Provincial Geopark (Area E) in the east of Biaoxi Township has not been identified.

Third, compared with the traditional method, the ERL zones delineated in this study have a higher proportion of ecological lands such as woodland, grassland, and river surface. The ERL zones should mainly include forests, rivers, and other ecological lands with important ecological functions [5].
land-use types in Shawan District within different ERL grades was calculated and the results of the two methods were compared (table 6). In the Grade I ERL zones, the proportion of all the ecological land (Woodland, grassland, garden land, river surface, and wetland) in this study was 14.05%, which was higher than that in the traditional method (12.46%). The proportion of ecological land in the Grade II ERL zones was 45.29%, which was also higher than that (40.5%) in traditional methods. In addition, both methods included a small amount of farmland and construction land. Among them, there was little difference in the proportion of construction land and it was 0.80% (in this study) and 0.79% (in traditional methods) respectively. The proportion of farmland within Grade I ERL zones in this paper was 0.51%, which was lower than 1.17% in the traditional method. The permanent basic farmland zones were excluded in this paper, and to maintain the continuity of patches, it was delineated as Grade II ERL zones with the lower control level.

### 6. Conclusions

The delineation of ERLs is of great significance to the protection of the ecological environment and the development of urban construction. This study proposed a new method of delineating ERLs, which combines the concept of ESPs and is based on GRA and the MCR model. Finally, the ERLs delineated in this study were compared with the ERLs delineated by traditional methods to verify the rationality of the research framework. The conclusions are as follows:

1. According to the comprehensive evaluation results of EFs, the southern area of Shawan District, especially Shawan Town and Jiadi Township, undertakes very important ecological functions. Therefore, ecological sources were mainly distributed in the south of Shawan District, and finally, 69.70 km² of ecological sources were identified, accounting for 14.69 % of the total area of Shawan District. The ecological resistance surface presents a distribution characteristic of ‘low around and high in the middle’, which affects the expansion trend of ecological sources and the location of ecological corridors. The ESPs generally present the characteristics of ‘north-south differentiation’. The area of low-security level and a comparatively lower security level was 168.14 km², accounting for 35.44% of the total area of Shawan District, which was widely distributed in Shawan Town and Jiadi Township. Protective measures should be taken in these areas. The area of a high-security level and a comparatively higher security level was 110.55 km², accounting for 23.30% of the total area of Shawan District, which was mainly distributed in the north of Dajun Township, Wutong Township, and Shawan Town. Sixty-eight ecological corridors of 147.41 km were identified, which were used to connect source areas and facilitate species movement.

2. Combined with the constructed ESPs, two grades of ERLs were delineated. Grade I ERL zones were composed of ecological sources, which were the bottom line of ecological environment protection. The area was 69.70 km², accounting for 14.69% of the total area of Shawan District. Grade II ERL zones were composed of low and comparatively lower levels of ESPs, corridors, and comparatively higher levels of EFs, which were the elastic boundaries outside the primary reserve, with a total of 251.73 km², accounting for 53.06% of the total area of Shawan District. Furthermore, 147.41 km linear corridors were also included. By comparing the ERLs delineated in this study with the ERLs in traditional evaluation methods, the ERLs delineated in this study exhibited better connectivity and contained more ecological land. The result indicates the feasibility of the delineation method of ERLs based on GRA and the MCR model.
There was no complete system or unified standard for the delineation of ERLs. The research in this article can provide a new idea for delineating ERLs. However, the delineation of ERLs is often a complicated process, that requires ecological safety analysis, combined with on-site investigations such as industrial structure, tourism resources, and local characteristics. Local development planning and management policies also need to be considered.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (No. 42001018, 41071104).

Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

ORCID iDs

Jiaqi Sun https://orcid.org/0000-0002-7372-4240
Jiejun Huang https://orcid.org/0000-0003-2595-4946
Han Zhou https://orcid.org/0000-0001-5464-9209

References

[1] Tang P et al 2021 Local and telecoupling coordination degree model of urbanization and the eco-environment based on RS and GIS: A case study in the Wuhan urban agglomeration Sustainable Cities and Society 75 103405
[2] Huang Q et al 2019 Quantifying the seasonal contribution degree of coupling urban land use types on Urban Heat Island using Land Contribution Index: A case study in Wuhan, China Sustainable Cities and Society 44 666–75
[3] Fang C and Lin X 2009 The eco-environmental guarantee for China’s urbanization process J. Geog. Sci. 19 95–106
[4] Ouyang Z et al 2016 Improvements in ecosystem services from investments in natural capital Science 352 1455–9
[5] Bai Y et al 2016 New ecological redline policy (ERP) to secure ecosystem services in China Land Use Policy 55 348–51
[6] Gao J 2015 Exploring the delineation and supervision of ecological protection red-lines in China Biodiversity Science 23 705–707
[7] Gao J et al 2020 The establishment of Chinese ecological conservation redline and insights into improving international protected areas J. Environ. Manage 264 110505
[8] Jiang B et al 2019 China’s ecological civilization program—Implementing ecological redline policy Land Use Policy 81 111–4
[9] Lu Y et al 2013 Redlines for the greening of China Environ. Sci. Policy 33 346–53
[10] Xu X, Yang G and Tan Y 2019 Identifying ecological red lines in china’s yangtze river economic belt: a regional approach Ecol. Indic. 96 635–46
[11] Gao J et al 2020 China’s ecological conservation redline: A solution for future nature conservation Ambio. 49 1519–29
[12] Bai Y et al 2018 Developing China’s Ecological Redline Policy using ecosystem services assessments for land use planning Nat. Commun. 9 3013–34
[13] Saura S et al 2017 Protected areas in the world’s ecoregions: How well connected are they? Ecol. Indic. 76 144–58
[14] Pressey R.L, Visconti P and Ferraro P J 2015 Making parks make a difference: poor alignment of policy, planning and management with protected-area impact, and ways forward Philos Trans B. Soc Land B Biol Sci. 379 20140280
[15] Chen D et al 2021 The delineation of ecological redline area for catchment sustainable management from the perspective of ecosystem services and social needs: A case study of the Xiangjiang watershed, China Ecol. Induc. 121 107130
[16] Yang Y, Song G and Lu S 2020 Study on the ecological protection red line (EPR) demarcation process and the ecosystem service value (ESV) of the EPR zone: A case study on the city of Qiqihar in China Ecol. Induc. 109 105754
[17] Li B et al 2018 A method of delimiting urban ecological red line protection area based on Bayesian network Acta Ecologica Sinica. 38 800–11
[18] Hou J, Mi W and Sun J 2014 Optimal spatial allocation of water resources based on Pareto ant colony algorithm International Journal of Geographical Information Science 28 213–233
[19] Lu D, Yaobin L and Xiaoyi L 2021 Integrating the MCR and DOI models to construct an ecological security network for the urban agglomeration around poyang lake, china. Sci. Total Environ. 754 141868
[20] Yu P et al 2020 Demarcation and administration of watershed ecological protection red line considering the ecological security pattern —A case of the Qilu Lake watershed, Yunnan Province Journal of Lake Sciences 32 89–99
[21] Zhao X Q and Xu X H 2013 Research on landscape ecological security pattern in a Eucalyptus introduced region based on biodiversity conservation Russian Journal of Ecology 46 59–70
[22] Santos J S et al 2018 Delimitation of ecological corridors in the Brazilian Atlantic Forest Ecol. Induc. 88 414–24
[23] Sutton-Grier A E, Wosek K and Bamford H 2015 Future of our coasts: The potential for natural and hybrid infrastructure to enhance the resilience of our coastal communities, economies and ecosystems Environ. Sci. Polity 51 137–48
[24] Peng J et al 2017 Research progress and prospect on regional ecological security pattern construction Geographical Research 36 607–19
[25] Liu D and Chang Q 2015 Ecological security research progress in china Acta Ecologica Sinica 35 111–21
[26] Li Y et al 2021 Integrating morphological spatial pattern analysis and the minimal cumulative resistance model to optimize urban ecological networks: a case study in shenzhen city, china Ecological Processes 10 63
[27] Wei S, Pan J and Liu X 2020 Landscape ecological safety assessment and landscape pattern optimization in arid inland river basin: Take Ganzhou District as an example Human and Ecological Risk Assessment 26 782–806
[28] Li H et al 2010 Application of least-cost path model to identify a giant panda dispersal corridor network after the wenchuan earthquake — case study of wolong nature reserve in china Ecol. Modell 221 944–52
[29] Wei G 2011 Grey relational analysis model for dynamic hybrid multiple attribute decision making Knowl.-Based Syst. 24 672–9
[30] Zhao Y, Zou X, Cheng H et al 2006 Assessing the ecological security of the Tibetan plateau: Methodology and a case study for Lhaze County J. Environ. Manage 80 120–31
[31] Zhou C, Wang L and Liu J 2015 Classification and management of ecological protection redlines in China Biodiversity Science 23 716–724
[32] Peng J et al 2018 Linking ecological degradation risk to identify ecological security patterns in a rapidly urbanizing landscape Habitat International 71 110–24
[33] Yu C et al 2021 Construction of ecological security pattern in northeast china based on MCR model Acta Ecologica Sinica 41 290–301
[34] Zhang F, Su W and Zhou J 2008 Assessment of urban ecological security based on entropy-weighted gray correlation analysis Chinese Journal of Ecology 27 1249–54
[35] Wei G 2011 Gray relational analysis method for intuitionistic fuzzy multiple attribute decision making Expert Syst. Appl. 38 11671–7
[36] Knaapen JP, Scheffer M and Harms B 1992 Estimating habitat isolation in landscape planning Landscape and Urban Planning 23 1–16
[37] Li F et al 2015 Evaluation of urban suitable ecological land based on the minimum cumulative resistance model: A case study from Changzhou, China Ecol. Modell. 318 194–203
[38] Tang Y, Gao C and Wu X 2020 Urban ecological corridor network construction: an integration of the least cost path model and the invest model ISPRS International Journal of Geo-Information 9 33
[39] Li S et al 2019 Quantitative analysis of the ecological security pattern for regional sustainable development: case study of chaohu basin in eastern china J. Urban Plann. Dev. 145 04019009