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Original Article

# Dual-objective pattern optimization method for land suitability zoning in mountain counties

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**Abstract:** As the basic administrative unit of China, counties have grown rapidly in recent years in the context of rapid urbanization, especially for counties located in mountainous areas. The drastic changes in land in mountainous areas can easily cause irreversible damage to the sensitive ecological environment. Through the dual-objective suitability zoning of ecological and construction balance, regional sustainable land use patterns can be realized. In this study, Hantai District in Southern Shaanxi province, China, was chosen as the research area aiming at creating a balance between ecological supply and the development of construction in spatial planning. A dual-objective process evaluation system for ecological protection and construction development was proposed with 15 resistance factors selected from three attributes: natural ecology, economic society, and policy. The minimum resistance surface discrimination methods for ecological land and construction development land were proposed based on vertical space superposition and horizontal minimum cumulative resistance models. Finally, the land in Hantai District was divided into four development grades from the optimal angle of dual goals, i.e., the construction core zone being 134.56 km², the suitable construction zone 115.77 km², the ecological buffer zone 153.74 km², and the ecological control zone 151.93 km²,using the method combining resistance difference and threshold division. In addition, the development direction of each town under jurisdiction was identified. This study compensates for the deficiency of traditional methods that evaluate land only from a single vertical or horizontal process.

**Keywords:** Dual-objective pattern; Land suitability zoning; Minimum cumulative resistance model; Mountain county; Hantai District

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## 1 Introduction

With rapid urbanization, there is a continuous increase in the development of the surface of the earth (Brown 2017). The transition of land patch from ecological land and production land to energy consumption land is apparent (Lambin and Meyfroidt 2011). Issues between land use and the ecological environment have gradually emerged (Brown et al. 2014), including climate warming (Zhao et al. 2006; Kalnay and Cai 2003), ecological degradation (Metzger et al. 2005; Meyer et al. 2013), and resource waste (Wright and Wimberly 2013). In the United Nations *2030 Agenda for Sustainable Development,* a series of goals is proposed to achieve food security, build sustainable human settlements, and restore terrestrial ecosystems (Nilsson et al. 2016; United Nations 2019). It could be seen that guiding the rational distribution of human activities is a key issue (Fan et al. 2019). China is a representative of the rapidly rising developing countries. It is the second-largest land area in the world. Mountains, plateaus, and hills account for approximately 67% of China's land area. The famous mountain ranges, such as the Kunlun, Tianshan, and Qinling Mountains, have important ecological significance (Xu et al. 2008; Deng et al. 2015; Liu et al. 2006). In the hilly coastal areas of western, central and southeastern China, mountain cities are widely distributed. Mountain ecosystems are characterized by complexity, diversity, fragility and sensitivity which limits the spatial organization, structure, and expansion direction of the cities (Huang 2021). Meanwhile, the mountainous area has most of the minerals, water energy, forests resources. However, under the background of worldwide urbanization, the rapid capital intervention in mountainous areas has promoted the development of tourism and mining industry (Richins and Hull 2016; Hansen and Johnstone 2019). In addition, with the population continues to gather in cities and towns, the real estate industry develops rapidly in recent years, the land for construction has continued to increase. The development at the expense of the ecological environment due to limited land is more evident, these types of problems were occurred in mountain cities around the world (Falcucci et al. 2006, Yu et al. 2020). The problem of profit orientation and uncontrolled development in mountainous urban development is obvious (Zhang et al. 2004, Yu et al. 2020). Mountain cities have many overlaps physical geographic and cultural geographic processes, resulting in more complex natural and social structures than plain areas. At the same time, it faces various challenges such as adapting to geological structure, topography, atmosphere, social culture (Borsdorf and Haller 2020). Therefore, how to coordinate the balance between social development and ecological protection in mountain cities through land suitability zoning is an urgent problem to be solved. (Gao and Bryan 2017).

Land zoning is the process of dividing regional land resources into a systematic number of zones based on the differentiation of land use and the characteristics of development, in accordance with the needs of use control, objective requirements of economic and social development and management objectives. The study of land zoning mainly involves suitability evaluation, zoning model, and management methods. Suitability evaluation is commonly used as the basis for land-use zoning. The suitability of a unit of land for a certain purpose is determined by the comprehensive elements of biological, geological, and cultural characteristics (Shi et al. 2007; Yu et al. 2015). The earliest suitability evaluation originated from the landscape design model of the vertical stacking of ecological factors using the principles of ecology (McHarg 2006). Subsequent suitability evaluations revealed a diverse development trend. Most studies, which used a combination of various analysis methods and GIS, focused on the evaluation of the suitability of the land function. Among these, the studies on production land are widely reported. For instance, Wang (1994) evaluated the suitability of agricultural land using artificial neural networks. Halder (2013) combined remote sensing and GIS to evaluate the suitability of planting rice and wheat in Paschim Medinipur District. Geng et al. (2019) used a fuzzy matter-element model to evaluate suitability of farmland in Taihang Mountains. Suitability evaluation also includes studies related to traffic location (Li et al. 2021), industry land (Xu et al. 2011; Fan et al. 2018), and scientific research land reserves (Stoms et al. 2002). Most studies have focused on the evaluation of single land use rather than the overall land use.

Currently, the land zoning model based on the principle of sustainable development is the focus of spatial pattern optimization (Brown et al. 2018). The existing zoning methods can be summarized as vertical and horizontal models. The vertical model focuses on the quantitative superposition analysis of socioeconomic indicators, such as total economic volume, forest coverage, and population density on landscape units. For example, Jankowski and Richard (1994) proposed a fuzzy sets and multi-criteria evaluation zoning model to identify optimal traffic corridors in King County, Washington, by using buffer zones and various overlay operations in geospatial information system. Cong et al. (2010) used spatial clustering method and selected indicators from the structure, input, output, ecology, dynamics, and potential of land use to divide Jiangsu Province into four large land-use areas and seven sub-areas. The analytic hierarchy process (AHP), which selects economic, social, and environmental factors, was used for sustainable zoning in Ismailia Governorate, Egypt (Ramadan et al. 2021). Qu et al. (2010) studied the regulation method of rural settlement zoning in Pinggu District, Beijing, based on the ecological niche model. With the deepening of research, the horizontal models based on predictive simulations have gradually developed, and focused more on the ecological processes and spatial connectivity between land-use units under landscapes. The horizontal models established future-oriented land use trends and constructed different land development goals according to scenarios, such as prioritizing economic benefits (Wu et al. 2012), maximizing ecological security (Su et al. 2016), and minimizing pollution (Anaya-Romero et al. 2015). The related methods like: habitat patches delineation based on network and corridor model. (Nikloakaki 2004); the two-dimensional graph theory was used to partition the utilization of cultivated land reserve resources at the county scale (Zhou et al. 2017); the CA-Markov (Cheng et al. 2020) model and cost distance model (Jin et al. 2013) was used to simulate land evolution trend and proposed an ecological division. Overall, the vertical model combines map and algorithm overlay of land elements were comprehensively considered variety of elements. However, the dynamic development process of land change was ignored, the vertical model cannot reveal the relationship between evaluation units and ecological processes. The horizontal models mainly focus on the limiting and supporting role of natural factors in the land development process. It can reflect the change trend of land use under ecological process, but weakly integrated with socioeconomic factors. At present, there is lack of research that combines the two models to simultaneously consider natural economic factors and ecological processes, and balance economic development and ecological conservation.

The ultimate goal of land zoning is to develop reasonable spatial management methods to achieve sustainable development (Komarov et al. 2019). The current research realizes spatial management based on different perspectives. Such as giving priority to ecology, use the spatial distribution of ecosystems to determine priority areas for protection (Nguyen et al 2016). With the goal of eliminating exclusivity and racial segregation, regional zoning management is realized from the perspective of spatial justice (Nel 2015). Formulation of zoning management measures aimed at coordination of land ecology, production and living functions (Zhang et al. 2022). The development of land is a constant process (Liang et al. 2021). Although the formulation of these space management methods is based on their specific research perspectives, the dynamic development of the land was not factored into the assessment.

To summarize, progress has been made in the suitability evaluation, zoning models, and management methods of land zoning; however, limitations still exist in the research perspectives. Current studies mostly focus on the suitability zoning of certain types of land, mainly concentrating on ecological and production space, with relatively more studies on zoning of agricultural (Xu et al. 2006), tourism (Blasco et al. 2013), and ecological functional areas (Liu et al. 2021). Additionally, these studies are mostly from a single vertical or horizontal perspective. Few studies treated the land as a dynamic expansion process influenced by multiple elements, and comprehensively use vertical assessment methods combined with horizontal prediction models for zoning studies. Land and space planning of China emphasizes the linkage among the five levels of the state, province, city, county, and township. County-level spatial planning plays a key role in linking superior and subordinate planning (Fan et al. 2019). Especially for mountainous counties with special geographical units, their ecological environment is fragile and sensitive, and is highly susceptible to change due to the influence of many elements. Due to the fragile and sensitive environment, the static natural and social impacts elements and the dynamic processes of regional environmental development need to be considered simultaneously. Combining vertical and horizontal models allows to consider both static elements and their dynamic expansion. It is more able to comprehensively consider factors affecting land change than a single-angle approach, and could lay the foundation for land use planning in micro perspective.

This study proposes a dual-objective pattern optimization method for land suitability zoning in a mountainous county. Hantai District, a county-level administrative region in Qinba Mountains, China, was used as the research area. A dual-objective vertical evaluation of suitability zoning for ecological protection and development was conducted. This was combined with horizontal evaluation to simulate resistance to the expansion of ecological and construction land. The suitable land-use tendency of the land unit was analyzed by comparing the degree of mutual hindrance and stimulus between the ecological process and the development process in the same unit. Finally, zoning was demarcated by the resistance threshold and identified areas pf existing land conflict. The main problems solved in this study are the establishment of a land suitability evaluation system under the dual objectives of ecological protection and development, simulation of resistance to the expansion of ecological and construction land, and determination of the division threshold of the suitability zone.

## 2 Study Area and Data Sources

### 2.1 Study area

Hantai District is located in the central area of Hanzhong, southwest of Shaanxi Province, China (106°51'–107°10'E, 33°02'–33°22'N), as shown in Fig. 1. The three-level landforms - the plains, hills, and mountains - in the area have apparent differences, the total area of jurisdiction is 556 km$^{2}$, including 15 township administrative districts such as Hedongdian town, Xuwang town, and Longjiang street. The streets and towns in China belong to the same level of administrative region, but the subject of management is different. In addition, the five town-level administrative region of Beiguan, Dongguan, Zhongshan, Hanzhong Road and Dongda Street in the south together constitute the downtown area of Hantai District. Therefore, we considered the downtown area as a whole.

Hantai District belongs to the Qinba Mountain Area of China. It has rich ecological resources, making it an important strategic position in China. In addition, it is an important water conservation area in the middle route of the South-to-North Water Diversion Project, which is a water source protection area in the Diversion of Shaanxi Province from the Han Water to Wei Water Project, and a national Qinba biodiversity functional area. Moreover, it is

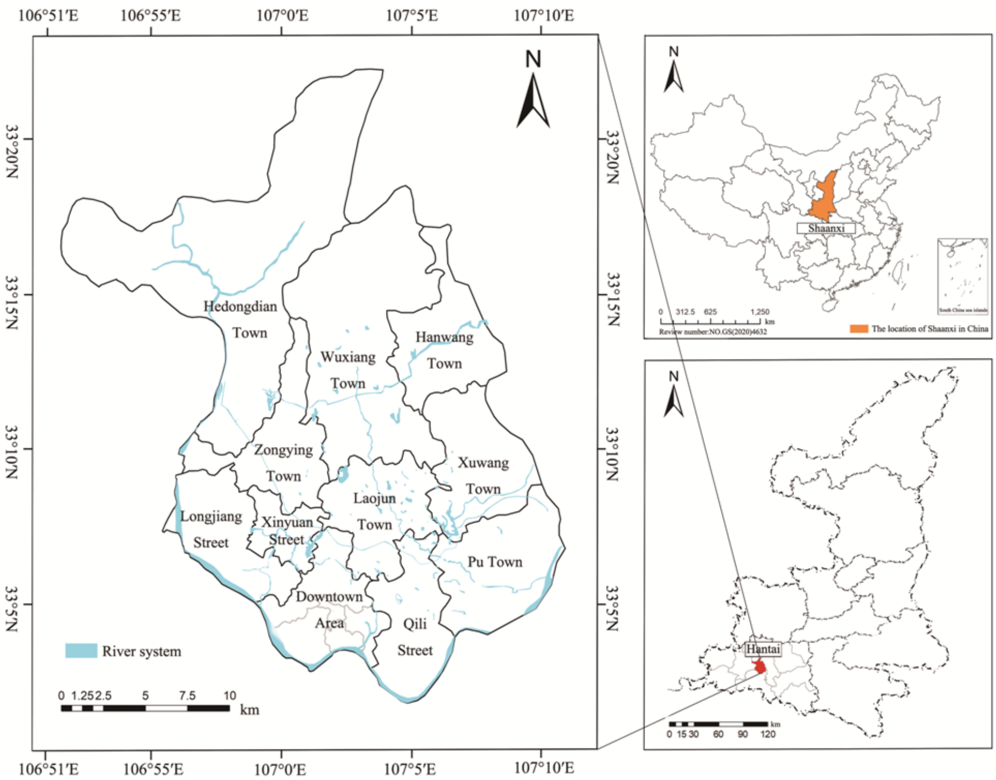


**Fig. 1** Map of Shaanxi Province in China (top right); Map of Hantai District in Shaanxi Province (bottom right); Enlarged map of Hantai District (left). The streets and towns in China belong to the same level of administrative region under the county. The Chinese map is based on the standard map with the approval number GS (2020)4632 downloaded from the standard map service website of the National Bureau of Surveying, Mapping and Geographic Information, and the base map has not been modified.

also a national ecological demonstration zone and an important agricultural sector. In recent years, the Chinese government has provided significant support for the development of the western region, including the study area. Hantai is currently experiencing a period of important strategic opportunities for high-quality development. However, the rapid expansion of construction spaces driven by the economy led to the decreasing of ecological and agricultural spaces. Various problems, such as unbalanced land structures and fragmentation of landscape patches, are apparent (Wang et al. 2021). Therefore, it is necessary to plan suitable land zoning to ensure sustainable development.

### 2.2 Data sources

Landsat 8 OLI from September 7, 2020 (path/row 128/37) and ASTER GDEM 30M digital elevation data (ASTGTM_N33E106 and ASTGTM_N33E107) were used as the original data to obtain natural factor data, such as type of landscape, elevation, and slope (http://www.gscloud.cn). Geological disaster data were obtained from the Shaanxi Provincial Geological Environment Monitoring Station, China. Economic and social data were obtained from the 2020 statistical yearbook of the Hantai District. Meanwhile, traffic vector data were obtained from the Hantai District Transportation Bureau. Moreover, the data of ecological function area initial location determined from field surveys in 2020, and then combined with the land-use master plans to determine the final scope. All data were imported into ArcGIS 10.5 for vectorization processing, and the projections were unified as a UTM (Universal Transverse Mercator), the study area is located at Zone 48N in UMT.

## 3 Methodology

### 3.1 Evaluation of dual-objective land expansion cost

In this study, the land uses in mountainous counties are divided into two categories from the macroscopic scale: suitable construction land and suitable ecological land. Suitable construction land refers to the land units in the region with strong developability in the area and more suitable for construction activities in the future. Urban and rural construction land is the most suitable construction land. Suitable ecological land refers to the land units with a high ecologically oriented in the region and units that are more conducive to the expansion of ecological activities in the future. The nature reserves areas and woodlands are the most suitable ecological land. The arable land has the ecological benefit of recycling microorganisms, so the arable land is also included in it. This investigation was based on the following assumption: suitable construction land tends to expand the most to maximize social economic benefits; suitable ecological land retains and mounts as much as possible to maximize social ecological benefits. In other words, the expansion of suitable ecological land is stimulated and promoted by ecological attribute elements, while the expansion of suitable construction land is constrained by ecological attribute elements. Therefore, the resistance value of suitable ecological land and suitable construction land is in a relationship that one dissipates and the other grows.

Both inherent and extrinsic properties of region space will have a significant impact on its ecological or construction expansion process (Arowolo and Deng 2017). The inherent properties refer to the natural ecological properties of the space itself. The extrinsic properties are based on elements that arise from later human activities, it refers to the elements under social economic, traffic, policy, such as construction and population density, transportation accessibility, and function areas defined by policies. Compared with plain areas, the natural environment of mountainous areas is closed. Their economic development generally lags behind that of the plain areas, while the ecological sensitivity is higher and the contradiction between ecological protection and economic development is more prominent (Zhu et al. 2019). Because of the sensitive environment in the mountains, in the model construction of assessing the cost of land expansion in mountainous areas, more attention should be paid to the consideration of specific intrinsic properties to mountainous areas. The disturbance of these elements is more likely to cause irreversible effects on the ecological environment of mountainous areas, such as topography, geological hazard susceptibility, forest vegetation, etc.. At the same time, the lagging development also makes the mountainous areas have a strong demand for economic development.

Transportation accessibility is critical to the development of mountainous counties. Consideration of road elements at different scales will help enhance regional development opportunities. In addition, the factors related to social development such as economy and policy should also be considered. Therefore, the selection of resistance elements will be based on the special geographical characteristics and relatively closed development situation of the mountainous area, and selected from the aspects of nature, society, traffic and policy factors respectively. In natural factors, mountainous areas should pay more attention to the slope, vegetation cover and the vulnerability of geological hazards. In traffic factors, more attention should be paid to the accessibility of roads from settlements to all levels of roads. In social factors, more attention is paid to the possible ecological impact of construction density. In policy factors, more attention should be paid to the consideration of ecological functional areas.

Combining the existing investigation results (Liu et al. 2010; Li et al. 2014), and the special geographical conditions of mountainous counties. To propose a dual-objective landscape process evaluation system, 15 basic elements were selected from the four composite attributes of natural, social, traffic, and policy that affect environment change in mountainous counties, as shown in Table 1. Among them, the natural elements such as terrain, ecological resources, and natural disasters in mountainous areas are often the key links that restrict regional development. Therefore, elements such as land cover type, terrain, normalized difference vegetation index (NDVI), and natural disasters were mainly considered in natural factors. Some social factors such as construction status, population and income could represent the current regional economic development level, so the construction density value, permanent residents and disposable income per capita were selected as the evaluation index elements at social level. The convenience of transportation is closely related to social development, so the distance to each level of road within the county is mainly considered in the transportation factor. The scenic spots, forest parks, and drinking water sources defined by the policy are rigid constraints, so these elements were selected as policy evaluation factors. Meanwhile, the expansion demand of ecological and construction land was considered, and classify the resistance to expansion of these two types of land respectively. The opposite resistance value evaluation was used because the expansion of ecological and construction lands in the same unit restricts each other. The expansion resistance was divided into five grades: 5, 4, 3, 2, and 1. Five represents the greatest resistance to expansion, and one represents the least resistance to expansion. Each element has different effects on the expansion of ecological and construction land. Resistance values were assigned through combination of expert scoring and segmentation point method. For quantifiable factors, such as elevation, slope, NDVI, etc., we use the natural segment point method to classify them into five categories and then combine them with expert scoring evaluation to correspond to the five levels of classification. For non-quantifiable factors, such as land cover type, geological disaster, ecological functional areas, etc., we combined the actual classification with expert scoring to correspond to the five categories. In addition, considering the difference in the degree of influence of each resistance element on the overall expansion process, AHP was used to determine the weight of each resistance element. On the basis of transforming the above static factor into raster data, ArcGIS was adopted to obtain the expansion suitability cost datasets through overlay analysis of expansion resistance and factor weight of the suitable ecological and suitable construction lands.

## 3.2 Construction of resistance surface in landscape process

The minimum cumulative resistance model was proposed by Knaapen et al. (1992) and then optimized and modified by Yu et al. (1999). It is mainly used in ecological studies to investigate the cost of species moving from the source to the destination. However, in recent years, this model is not only used in studying specific ecological processes but also in the simulation of land evolution processes (Xiang et al. 2016). The revised minimum cumulative resistance model is expressed as

$$\mathrm{MCR} = f_{min}\left(\sum_{j=n}^{i=l} D_{ij} \times R_i\right) \quad (1)$$

In the formula, MCR is the minimum cumulative resistance value, $D_{ij}$ is the spatial distance of the species from source $j$ to landscape unit $i$, $R_i$ is the resistance coefficient of landscape $i$ to the movement of a certain species, Σ is the cumulative sum of the distance and resistance between unit $i$ and source $j$

**Table 1** Evaluation system of landscape process resistance

| Factors | Elements | Type of expansion | Resistance level score and classification | | | | | Weight |
|---|---|---|---|---|---|---|---|---|
| | | Ecological land | 1 | 2 | 3 | 4 | 5 | |
| | | Construction land | 5 | 4 | 3 | 2 | 1 | |
| Natural factors | Land cover | | Woodland, water | Grassland, shrubland | Arable land | Unused land | Construction land | 0.16 |
| | Elevation (m) | | >1300 | 1000~ 1300 | 800~ 1000 | 600~ 800 | 461~ 600 | 0.03 |
| | Slope (degree) | | >35 | 25~35 | 15~25 | 8~15 | 0~8 | 0.08 |
| | Geological disaster | | Highly prone area | - | Central prone area | Low prone area | Non prone area | 0.10 |
| | NDVI | | 0.69~ 0.86 | 0.52~ 0.69 | 0.37~ 0.52 | 0.22~ 0.37 | 0.32~ 0.22 | 0.04 |
| | Distance to water (m) | | 0~50 | 50~100 | 100~150 | 150~200 | >200 | 0.02 |
| Social factors | Construction density value | | 0~0.11 | 0.11~0.34 | 0.34~ 0.58 | 0.58~ 0.83 | >0.83 | 0.04 |
| | Permanent residents (people) | | 11180~ 13154 | 13154~ 27506 | 27506~ 55512 | 55512~ 82774 | >82774 | 0.02 |
| | Disposable income per capita (USD/year) | | 1634~ 1647 | 1647~ 1860 | 1860~ 2491 | 2491~ 5691 | >5691 | 0.01 |
| Traffic factors | Distance to state road (m) | | >1200 | 800~ 1200 | 500~ 800 | 200~ 500 | 0~200 | 0.04 |
| | Distance to highway (m) | | >1500 | 900~ 1500 | 600~ 900 | 300~ 600 | 0~300 | 0.05 |
| | Distance to provincial way (m) | | >1200 | 900~ 1200 | 600~ 900 | 300~ 600 | 0~ 300 | 0.02 |
| | Distance to railway (m) | | 0~ 500 | 500~ 1000 | 1000~ 2000 | >5000 | 2000~ 5000 | 0.02 |
| | Distance to main road (m) | | >800 | 600~ 800 | 400~ 600 | 200~ 400 | 0~ 200 | 0.09 |
| Policy factors | Ecological function zone | | Scenic spots, forest parks, | Drinking water source, High-quality arable land | - | - | Other areas | 0.28 |

**Notes:** NDVI is the normalized difference vegetation index; the construction density value refers to the ratio of the number of pixels of construction land to the total number of pixels in a regional network centered on a certain pixel. For the resistance level score, 1 represents the minimum expansion resistance, 5 represents the maximum expansion resistance.

across all units, *min* indicates that the evaluated plaque takes the minimum cumulative resistance for different sources, and *f* is the positive correlation between the minimum cumulative resistance and the ecological process.

This study introduces the minimum cumulative resistance model into the expansion analysis of ecological and construction lands. Calculated the minimum cumulative resistance to the expansion of ecological and construction land respectively. This was combined with the vertical factor superposition evaluation in the previous study to realize a combination of vertical evaluation and horizontal simulation.

### 3.2.1 Source determination

The land cover types of mountains areas can be mainly classified as construction land, unused land, arable land, grassland, shrubland, woodland, and water areas. Different land cover types can stimulate or hinder the development of ecological processes. The source refers to the type of land cover that promotes the development of ecological processes. This is the starting point for the outward diffusion of things and plays a positive role in the evolution of landscape processes (Yu 1996). For the expansion of suitable ecological and suitable construction lands in the study area, this study identified the corresponding sources. The source of suitable construction land expansion is the existing construction land, and the source of suitable ecological land expansion is the area with rich biodiversity and strong ecological functions (i.e., scenic spots, forest parks, and other areas with high vegetation coverage in Hantai District).

### 3.2.2 Creating the resistance surface

"Cost Distance" module in ArcGIS was used, through input tow process source data into the cost data set and calculated the minimum cumulative resistance surface of two expansion processes.

## 3.3 Ecological suitability zoning of land

### 3.3.1 Preliminary evaluation based on the minimum cumulative resistance difference

The ecological suitability of the land in the study area is evaluated by the minimum cumulative resistance surface difference between the expansion of construction land and ecological land. The resistance difference surface was calculated using ArcGIS. The formula used is

$$MCR_{difference} = MCR_{ecology} - MCR_{construction} \quad (2)$$

where $MCR_{ecology}$ and $MCR_{construction}$ are the resistance surfaces of ecological and construction land expansions, respectively, and $MCR_{difference}$ is the difference in the resistance surface of the two. When the $MCR_{difference}$ is < 0, the expansion resistance of the ecological land is less than that of the construction land, and the grid is suitable as an ecological land unit. On the other hand, when the $MCR_{difference}$ is greater than 0, the expansion resistance of the construction land is less than that of ecological land, and this grid is more suitable as a construction land unit. Finally, when $MCR_{difference}=0$, it is the boundary between suitable the ecological and suitable construction lands.

### 3.3.2 Determination of the final partition threshold

In this study, the resistance threshold method was used to further refine the suitability zoning results (Li et al. 2006). The resistance threshold refers to some key points in the expansion process of ecological and construction lands, and the ecological process needs to try more in overcoming its resistance and continue to expand. The resistance threshold can be divided by the relationship between the resistance difference and the number of grids. The land before and after the resistance threshold can be divided into different subregions. This process can be realized in ArcGIS by identifying the mutation points of the pixel values and the number of grids. Finally, based on the preliminary evaluation, the land was divided into four zones: ecological control zone, ecological buffer zone, suitable construction zone and construction core zone. Fig. 2 shows the flow chart of this investigation.

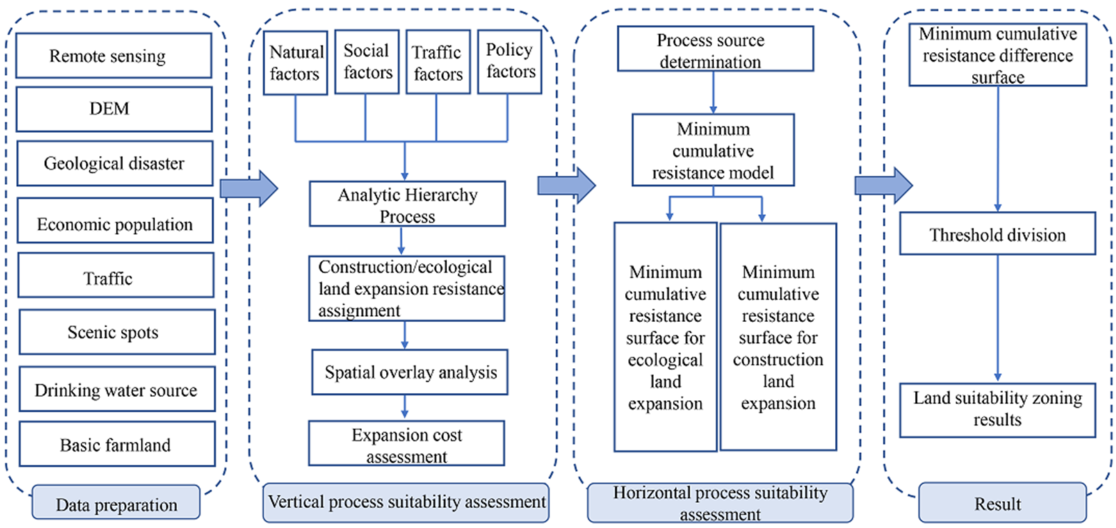


**Fig. 2** Flow chart of land suitability zoning.

### 3.4 Land use conflict identification

This investigation identified land use conflict area based on the results of land suitability zoning and the comparison of current land use. Land use conflict was defined as the unreasonable occupation of ecological space by multi-stakeholders due to economic construction activities such as urban expansion and agricultural farming, resulting in the result of competition for land resources. According to the types of human economic activities that trigger land use conflicts, this paper divided land use conflicts into two categories: cultivated land and construction land conflicts. Arable land conflicts and construction land conflicts are reflected in the occupation of suitable ecological land by agricultural farming and construction development activities, respectively. Based on the occupation of the ecological control zone, ecological buffer zone, suitable construction zone and construction core zone by arable and construction land respectively, the land use conflicts were divided into four types: intense conflict, general conflict, low conflict and no conflict areas. The classification criteria were shown in Table 2.

## 4 Results and Analysis

### 4.1 Land expansion cost analysis under the superposition of static factors

The static ecological process reflects the ecological attributes of the landscape unit. Fig. 3 shows the raster conversion results for each static factor. The expansion resistance value and weight of each factor of the land unit were superimposed using ArcGIS software. The expansion cost dataset for ecological and construction land expansions were obtained. The results are shown in Figs. 4 and 5.

Based on the figure, the cost surface patterns of ecological expansion and construction processes were the opposite. The more the grid color is biased toward red, the greater the expansion cost of the area and the less suitable it is for expansion. The more the grid color is biased to blue, the smaller the expansion cost of the area, and the more suitable it is for expansion. The cost of ecological land expansion was small in the Shimen Scenic Area, Tiantai Mountain Scenic Area, woodland, large-scale arable land, and water area in the northern and central parts of the Hantai District, as shown in Fig. 4. On the other hand, the expansion cost of construction land was lower in the existing construction land and grid units on both sides of the traffic road (see Fig. 5), which is similar with the setting rules of the resistance value system. Based on the preliminary static factor evaluation, the cost of ecological land expansion in the northern and eastern regions was lower, whereas the cost of expansion of construction land in the western and southern regions was lower.

### 4.2 Construction of resistance surface of land expansion under dynamic factor simulation

Dynamic ecological processes reflect the extensional attributes of the landscape unit under the action of comprehensive resistance. Based on the cost data generated in the previous study and further considering the influence of distance factors, the minimum cumulative resistance surface of the ecological and construction expansion processes was established to characterize the dynamic ecological process of the landscape. Figs. 6 and 7 show the results, respectively. The more yellow the grid, the smaller the cumulative resistance during the expansion of the landscape process. Meanwhile, the bluer the grid, the greater the cumulative resistance during the expansion of the landscape process.

Based on Fig. 6, the northern part of the study area has two contiguous and large ecological expansion low-resistance areas: the existing Shimen Scenic Area and Tiantai Mountain Scenic Area in Hantai District. Other patches with low resistance to ecological expansion were relatively scattered. These areas were mainly composed of patches with water,

**Table 2** Land use conflict classification system

| Land use type | Land suitability zoning | Types of land use conflicts |
|---|---|---|
| Arable land/Construction land | Ecological control zone | Intense conflict areas |
| Construction land | Ecological buffer zone | General conflict areas |
| Arable land | Ecological buffer zone | Low conflict areas |
| Arable land/Construction land | Suitable construction zone | No conflict areas |
| Arable land/Construction land | Construction core zone | No conflict areas |

wetlands, and woodlands as the core, which were scattered around them. Fig. 7 shows the expansion resistance surface of construction land. The expansion resistance showed an increasing trend from south to north. The area with the lowest resistance to expansion was the south of the study area. It is the core development area of Hantai District and the most densely constructed area. The woodlands in the

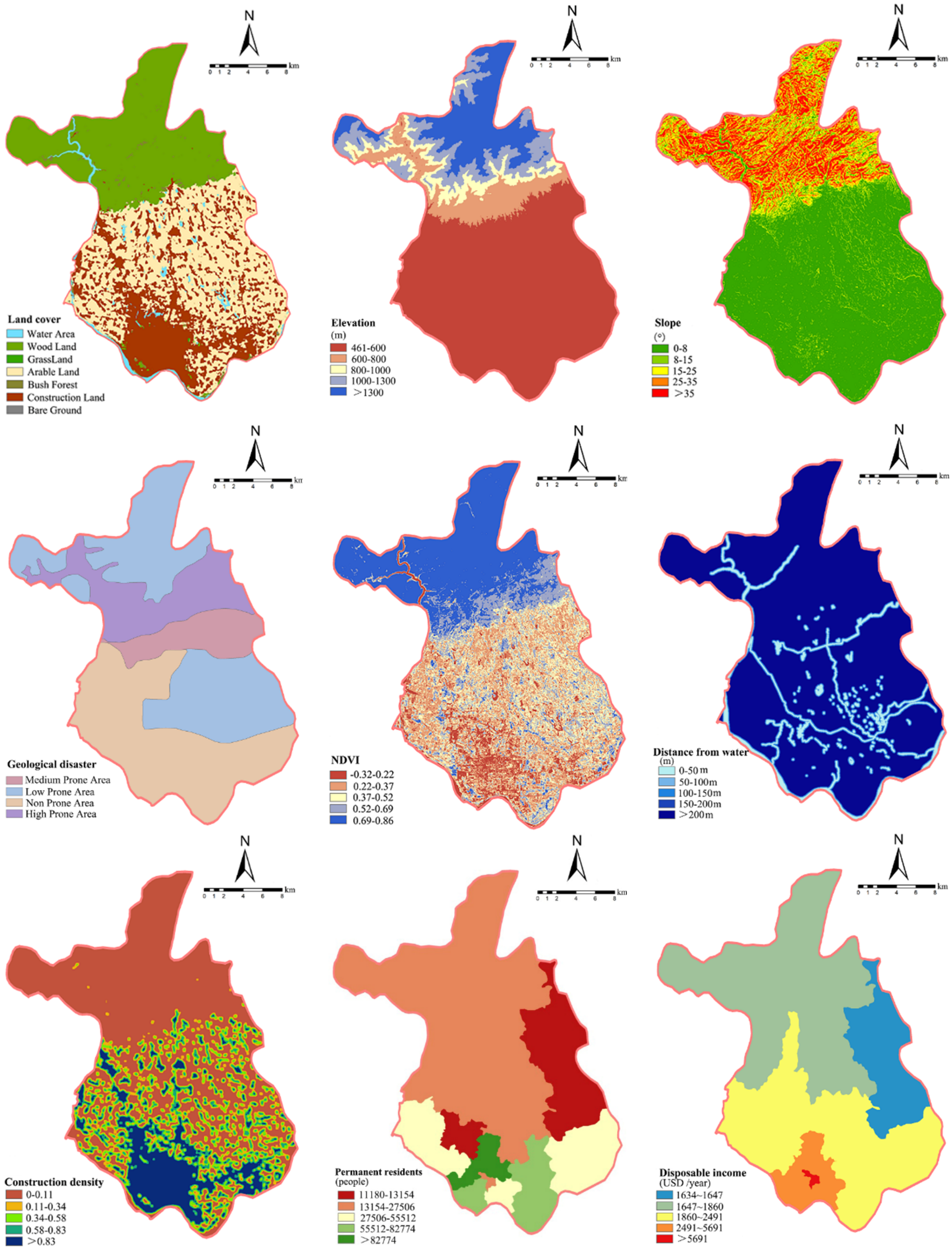


**Fig. 3** Situation of resistance factors in the landscape process in Hantai District.
(-To be continued-)

north had the highest resistance to expansion. The low expansion resistance areas were distributed in dots in the middle of the study area because these villages and towns were in the initial stage of development and the existing construction land tended to be scattered.

### 4.3 Land suitability zoning under dual objective optimization

Fig. 8 shows the results of resistance surface difference between the expansion of construction land and ecological land. Reclassification of the resistance difference surface based on the division method previously mentioned and the preliminary result of land suitability zoning are shown in Fig. 9. The land in Hantai District was preliminarily divided into suitable ecological and construction lands. The suitable ecological zone was distributed in most areas of the current ecological land and its adjacent grids, which account for 55% of the total area of Hantai District. On the other hand, suitable construction zones account for 45% of the total area. It was distributed particularly in the downtown area and organizational town construction land and in the surrounding areas far away from water and woodland.

The corresponding relationship between the resistance difference and the number of grids in Hantai District was counted in ArcGIS (Fig. 10). The mutation point is taken as the threshold interval of partition. In the suitable ecological region where the resistance difference is less than 0, there is a sudden rise in point A. Moreover, in the suitable construction area with the resistance difference value greater than 0, there is a sudden drop at point B. Therefore, the values of points A and B were determined as the resistance thresholds for the expansion of ecological land and construction land. The suitable ecological

(-Continued-)

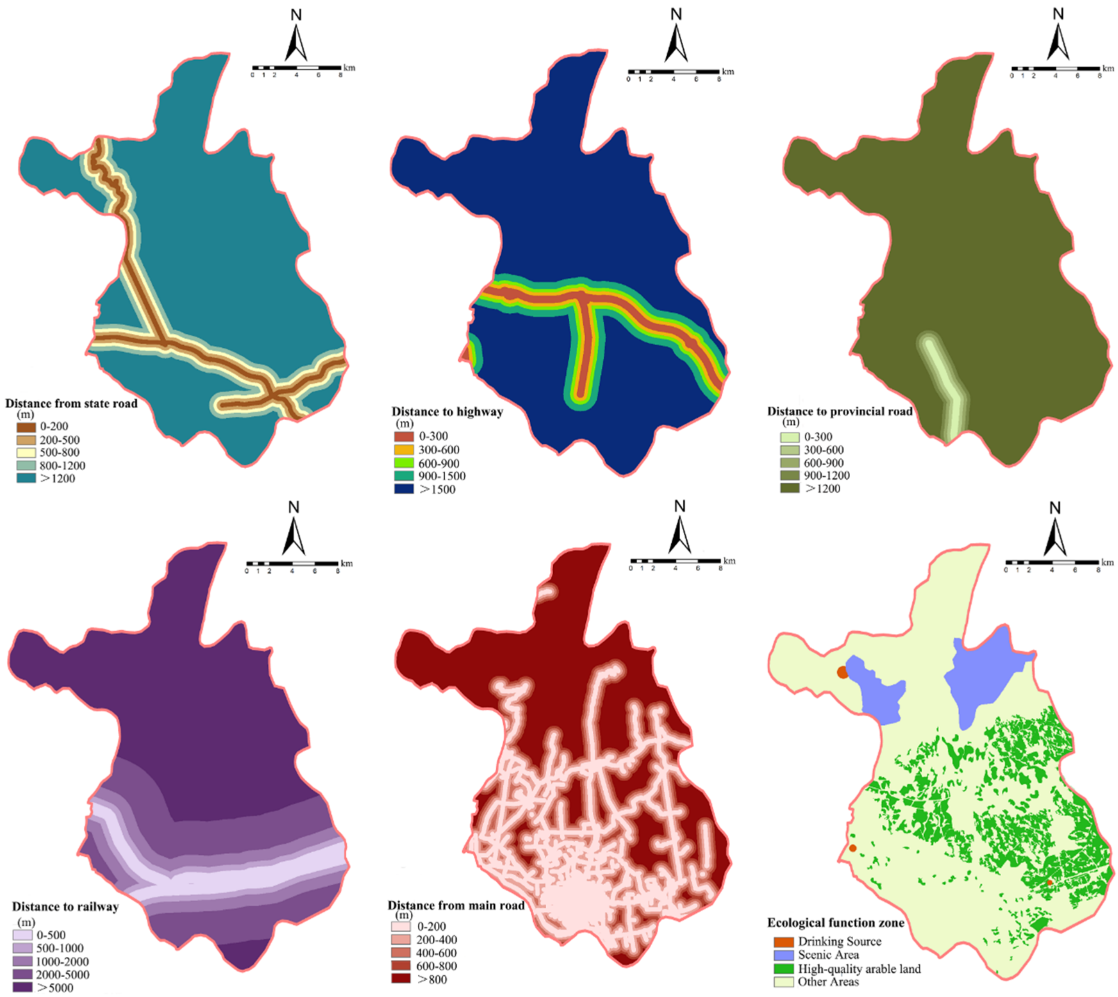


**Fig. 3** Situation of resistance factors in the landscape process in Hantai District.

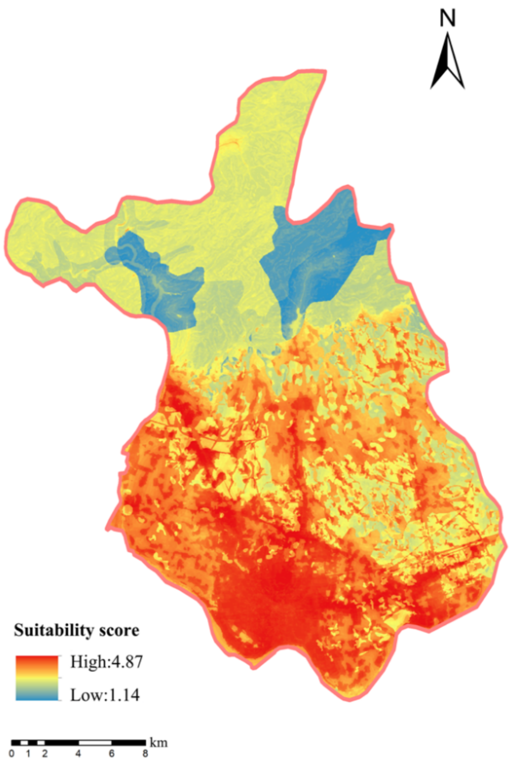


**Fig. 4** Suitability score of ecological land expansion in Hantai District in 2020 under the superposition of resistance elements.

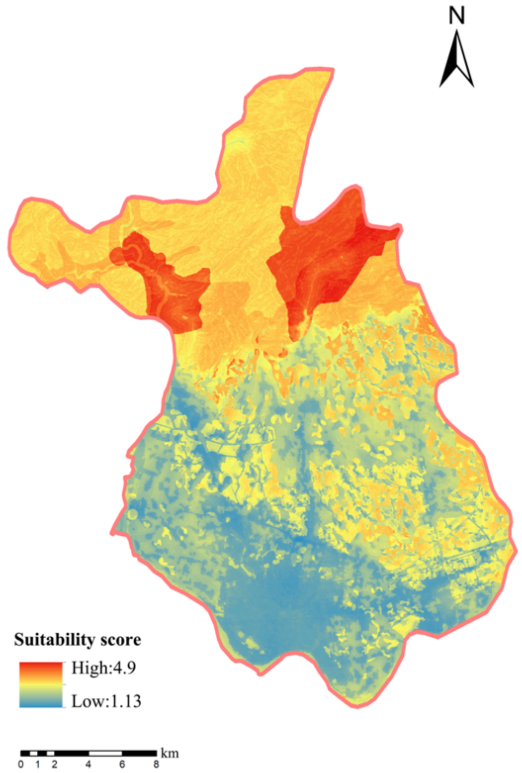


**Fig. 5** Suitability score of construction land expansion in Hantai District in 2020 under the superposition of resistance elements.

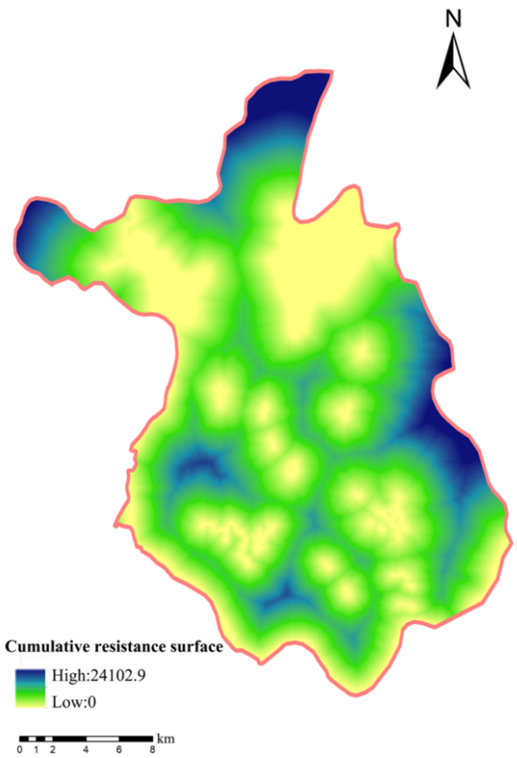


**Fig. 6** Minimum cumulative resistance surface of ecological land expansion in Hantai District in 2020 based on cost distance model.

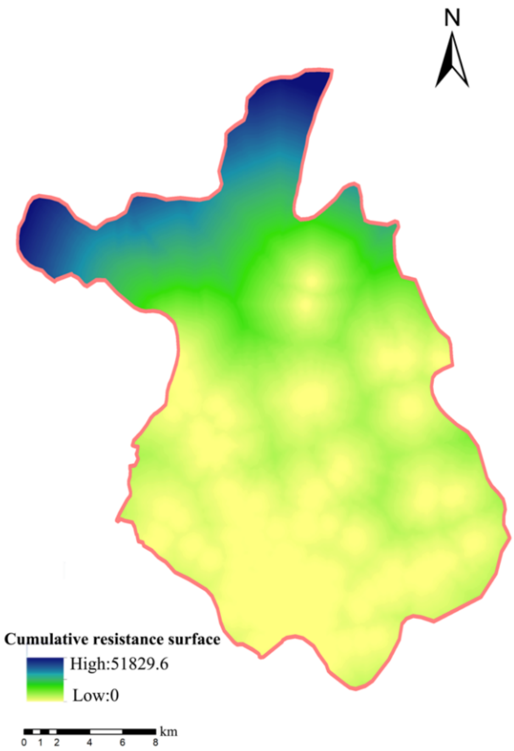


**Fig. 7** Minimum cumulative resistance surface of construction land expansion in Hantai District in 2020 based on cost distance model.

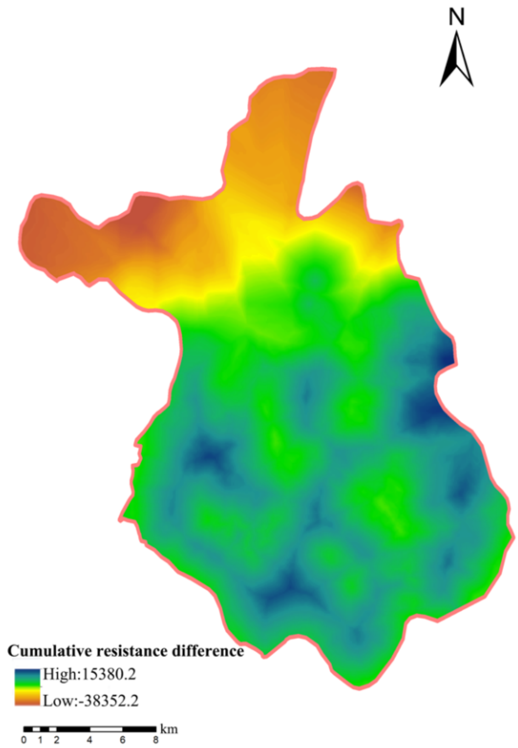


**Fig. 8** Minimum cumulative resistance difference surface between ecological land and construction land in Hantai District in 2020.


**Fig. 9** Preliminary results of land suitability zoning in Hantai District in 2020 based on minimum cumulative resistance difference classification.

**Table 3** Threshold range for land suitability zoning

| Preliminary partition | Land suitability zoning | Pixel value range |
|---|---|---|
| Suitable ecological zone | Ecological Control Zone | -38352~-8641 |
| | Ecological Buffer Zone | -8641~0 |
| Suitable construction zone | Suitable Constrution Zone | 0~3747 |
| | Construction Core Zone | 3747~15380 |

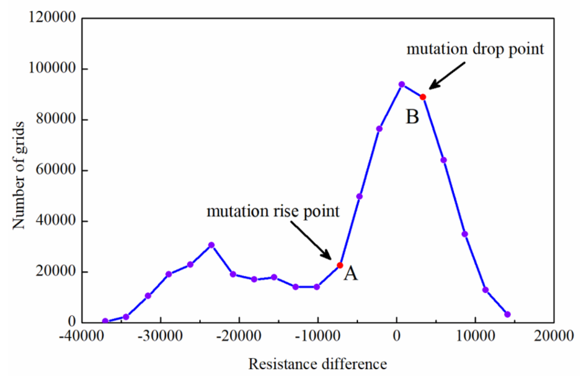


**Fig. 10** Statistics of the corresponding relationship between the minimum cumulative resistance difference and the number of grids in Hantai District.

zone and the suitable construction zone can be further divided into two sub-regions by each sub-zone. Suitable ecological zones were further subdivided into ecological control and ecological buffer zones, and suitable construction zones were subdivided into suitable construction and construction core zones. The pixel value interval of the final land suitability partition is shown in Table 3, and the final visualization results of land suitability zoning in Hantai District are shown in Fig. 11.

The final suitability zoning results listed in Table 4 were calculated and analyzed in combination with those shown in Fig. 11. It is apparent that the area of the ecological control zone was 151.93 km², accounting for 27% of the total area. It is mainly distributed in the northern part, with mountains and hills, and constitutes the ecological barrier of the Hantai District. The area of the ecological buffer zone is 153.74 km², accounting for 28% of the total area. It occupies the largest proportion of land and is distributed in the central and southern areas. This has great significance in maintaining the ecological patterns of Hantai District. The area of suitable construction zone was 115.77 km², accounting for 21%

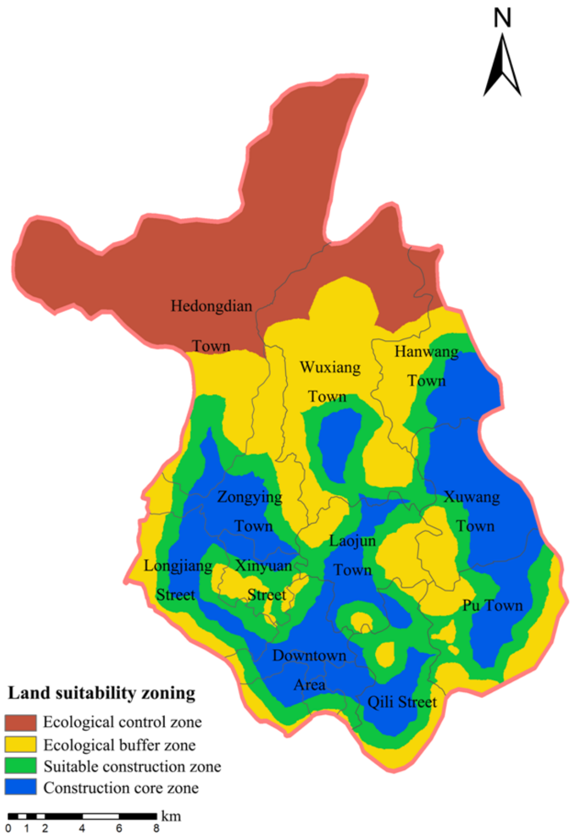


**Fig. 11** Map of land suitability zoning in Hantai District. The streets and towns in China belong to the same level of administrative region under the county.

of the total area. It was mainly distributed on the outskirts of the centralized construction area of the town center. Its superior location makes it a supplement to the core construction area. The area of the construction core zone is 134.56 km², accounting for 24% of the total area. It is concentrated in the plains of the southern part of the study area. These areas have a high population density and great economic development, and construction has less interference with ecology. It is a suitable core area for construction development.

### 4.4 Regional development direction under the synergy of dual goals

From the current situation of land use in Hantai District, the southern construction and development were relatively intensive, owing to 316 national highways in the middle as the boundary. The development space of the southern=downtown area has become saturated, and there is relatively weak development in the central and northern regions. According to the results of land conflict classification (Fig. 12), the conflict of construction land is mainly about intense conflict and general conflict, the area of intense conflict is mainly located in the town of Hedongdian in the northern part of Hantai District; the distribution of general conflict is relatively scattered, mainly distributed along the Han River, and Wuxiang, Hanwang and Hedongdian towns close to the hilly area. It also indicated that the degree of human influence on the ecological space in these areas is increasing. The conflict on arable land was expressed as low conflict and is mainly distributed in Hanwang, Wuxiang, Zongying, Laojun and Xuwang town. The no conflict areas of construction and arable land were mainly located in the southern towns. Although these areas are relatively intensive in construction and farming, their ecological sensitivity is weak, so the contradiction between human activity and ecological land is not obvious. Therefore, according to the results of land suitability zoning, differentiated management and control strategies should be formulated for each township in the Hantai District. The direction of development of each town can be determined by comparing the proportion of

**Table 4** Statistics of suitability grade area of subordinate towns (km²)

| Towns (Streets) | Ecological control zone | % | Ecological buffer zone | % | Suitable construction zone | % | Construction core zone | % |
|---|---|---|---|---|---|---|---|---|
| Hedongdian | 111.62 | 73 | 15.71 | 10 | 8.45 | 7 | 2.96 | 2 |
| Wuxiang | 36.20 | 24 | 44.25 | 29 | 13.44 | 12 | 6.99 | 5 |
| Hanwang | 2.90 | 2 | 18.61 | 12 | 6.48 | 6 | 10.70 | 7 |
| Zongying | 1.21 | 1 | 12.47 | 8 | 5.87 | 5 | 12.65 | 9 |
| Longjiang | 0 | 0 | 11.67 | 7 | 13.77 | 12 | 11.48 | 9 |
| Xinyuan | 0 | 0 | 3.91 | 3 | 6.06 | 5 | 4.13 | 3 |
| Laojun | 0 | 0 | 10.48 | 7 | 12.37 | 11 | 10.99 | 8 |
| Xuwang | 0 | 0 | 8.21 | 5 | 5.92 | 5 | 25.75 | 19 |
| Puzhen | 0 | 0 | 15.88 | 10 | 17.49 | 15 | 14.95 | 11 |
| Qili | 0 | 0 | 7.23 | 5 | 15.41 | 13 | 12.76 | 10 |
| Downtown area | 0 | 0 | 5.32 | 4 | 10.51 | 9 | 21.20 | 17 |
| Total | 151.93 | 100 | 153.74 | 100 | 115.77 | 100 | 134.56 | 100 |

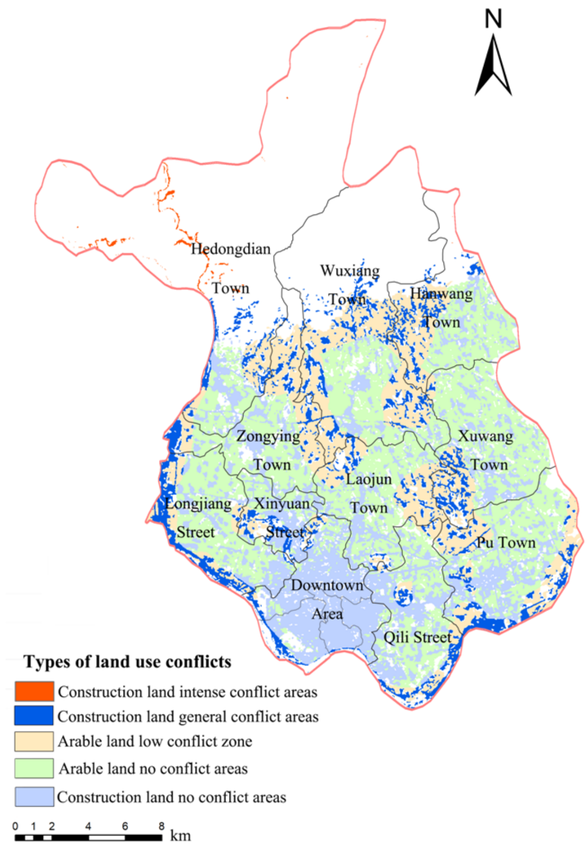


**Fig. 12** Types of land use conflicts in Hantai District. The streets and towns in China belong to the same level of administrative region under the county.

each town in land division and current land use conflicts. The main areas of Hedongdian Town are located in the northern mountainous area, which is ecologically sensitive and fragile. Based on the results of land-use zoning, most patches were located in the ecological control area. In addition, the area is mainly dominated by intense and general conflicts over construction land. Therefore, for patches located in ecological control areas, management strategies should focus on strictly adhering to the ecological bottom line. All kinds of production and construction activities should be carried out with ecological orientation, reserve permanent ecological space, form key areas for regional ecological network construction, and moderately develop activities such as eco-tourism. It is necessary to implement ecological migration to residential areas in ecological controlled areas. Simultaneously, at the vertical level, protecting the natural form of the mountain in this area and avoiding the phenomenon of mountain excavation is necessary. Wuxiang and Han Wang towns are mainly ecologically sub-sensitive areas, it is the main area of general conflict of construction land and low conflict of arable land. This area should form a green buffer zone around the urban development area to ensure that the total amount of basic farmland does not decrease. Wedge-shaped green spaces can be formed by relying on basic farmland, rivers, and lake wetlands. The connection between the natural ecological environment and green space in the construction area must be strengthened. Moreover, Laojun, Puzhen Town, Longjiang, Xinyuan, and Qili streets have more suitable construction areas. There is less land conflict. These areas are suitable for the development of low-density buildings and expansion of urban construction land during emergencies. Downtown area, Zongying Town, and Xuwang Town have mainly core construction areas. Although there are small scale land use conflicts, the construction core zone occupies the largest in these towns. At present, downtown areas are mostly built-up areas. Therefore, urban renewal should be the primary planning content for the downtown area in the future. The focus of construction should be shifted to Zongying and Xuwang Towns. During the development process, it is necessary to coordinate with the surrounding environment and optimize the restoration of the ecological environment.

## 5 Discussion

The innovation of this study is reflected in the research methodology. A regional land suitability zoning map was generated by evaluating multiple elements of land expansion costs and landscape ecological processes. In comparison, the existing research has not fully considered the specificity of ecological processes in mountainous geographical environments and failed to combine the vertical superposition algorithm model with the horizontal process model. Therefore, they did not adequately address the comprehensive and complex requirements of mountain region land zoning. In the case study of Hantai District, through the preliminary division results of resistance difference, with 0 value as the dividing line, the area of suitable ecological zone is 305.8 $km^2$, and the area of suitable construction zone is 250.2 $km^2$. Thus, the value of 305.8 and 250.2 $km^2$ are suggested as the lower limit of land ecological preservation and upper limit of construction. In emergency situations, such as natural disasters or regional transformation, the area of the four sub-zones can be appropriately adjusted based on different scenarios in combination with scenario analysis. (Roetter et al. 2005). However, the total number of construction and ecological zones should not exceed the upper limit or be lower than the lower limit. The area of ecological buffer zone and ecological control area in Hantai District accounts for 55% of the total area. Compared with the results in some livable and similar geographic region such as Washington King County, with Cascade Mountains in the east. In their comprehensive planning, the green space occupies more than half of the total area (*King County Comprehensive Plan 2020*). The growth management of King County is largely implemented by directing development toward the urban growth area, while protecting existing rural area, open spaces, and natural resource land. Under similar geographic units, the zoning results using the dual-objective optimal zoning method are the similar as those of King County, indicating the feasibility of the method.

In general, this method is reasonable for zoning under the dual goals of construction development and ecological protection. Compared with other common methods, our methodology can consider additional evaluation aspects. This evaluation method was combined with an analytic hierarchy process using the minimum cumulative resistance model. Other steps are completed by computer simulation, reducing the subjectivity of human judgment, except for the assignment of resistance factors and requires expert scores. This land zoning method is suitable for the preliminary division of the overall land-use tendency of the entire region. The subsequent division of specific land use can be deepened on this basis and combined with zoning for agriculture (Feizizadeh and Blaschke 2013), industry (Arabsheibani et al. 2020), and cities (Anderluh et al. 2020). Last but not least, this method can be used to guide the preliminary land use evaluation and space planning at mountain geographical conditions counties. In addition, since the evaluation index is easy to adjust and has universality. For areas with different geographic characteristics, the evaluation indicators can be adjusted to match regional characteristics.

Nevertheless, there are also some limitations in this study. Firstly, the premise assumptions of this paper are macroscopic. The zoning results can only indicate the land unit is more suitable for construction and development or ecological protection, rather than indicating specific suitability for residential, commercial or industrial land use, etc. Second, the process of selecting resistance factors and expert scoring assignments in the vertical overlay evaluation is subjective.

## 6 Conclusions

This paper presents an a dual-objective optimized land use zoning method based on geospatial information system for optimize the land use pattern in mountainous counties and promote the balanced development of economic construction and ecological protection. Selecting 15 indicators from indicators from the nature-society-transportation-policy composite system and constructed a dual-objective land vertical assessment model through AHP. This vertical assessment was combined with the horizontal landscape expansion process based on the minimum cumulative resistance model simulation to identify regional land-use tendencies.

Based on the dual-objective pattern optimization method, the land in Hantai District can be divided into four levels of development: the construction core zone is 134.56 km²; the suitable construction zone is 115.77 km²; the ecological buffer zone is 153.74 km²; and the ecological control zone is 151.93 km². From the zoning results, the spatial pattern of Hantai District has obvious characteristics of north-south differences. The south is dominated by construction core zone and suitable construction zone, while the north is dominated by ecological control zone and ecological buffer zone. The land cover type and the distribution of ecological function areas were the main factors affecting the results of zoning.

In addition, on the basis of the overall the partition, a horizontal comparison of the zoning proportion of townships and towns in the county in various subdistricts was conducted to determine their respective development directions. Hedongdian Town is an ecological conservation type that focuses on control and protection to maintain the ecological bottom line. Towns of Wuxiang and Hanwang are ecological industry development types suitable for the development of agriculture and ecological industries. Laojun, Puzhen, Xinyuan, Longjiang, and Qili streets are suitable for low-density development. The central cities of Zongying, Laojun, and Xuwang are the core development types. In view of the saturation of the development of the downtown area, the future development direction of Hantai District should shift from the south to the center since Zongying, Laojun, and Xuwang towns have great development potential. This study compensates for the defects of traditional methods that evaluate land only from a single vertical or horizontal process. Our future work will be centered around exploring the coupling relationship between macroscopic suitability and microscopic suitability, introducing nonlinear mathematical methods to improve the resistance assignment, so as to achieve a zoning of land suitability at a finer scale.

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