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Development of Highway Construction Route Selection Based on Ecological Sensitivity Evaluation and Intervention Optimization Strategy Research

Fan Yang [1,†], Yunlan Tang [1,†], Suwen Xiong [1], Chuntian Gu [2,3,*] and Yadan Xiao [4,*]

[1] School of Architecture and Art, Central South University, Changsha 410083, China; 207103@csu.edu.cn (F.Y.); 231312035@csu.edu.cn (Y.T.); xiongsuwen@csu.edu.cn (S.X.)
[2] School of Science and Technology, Hong Kong Metropolitan University, Hong Kong 999077, China
[3] Hunan Machinery Industry Design & Research Institute, Changsha 410011, China
[4] Hunan Provincial Communications Planning, Survey & Design Institute, Changsha 410200, China
* Correspondence: s1364622@live.hkmu.edu.hk (C.G.); xiaoyadan@hnjtsjy.com (Y.X.)
† These authors contributed equally to this work.

Abstract: Ecological sensitivity is an essential indicator for measuring the degree of ecological fragility of a region, and traditional highway routing ignores the ecological benefits of regional nature, which causes irreversible impacts on the natural environment. Based on the AHP method, this paper carries out a comprehensive assessment of the ecological sensitivity of the K0+000~K56+438 section of the Guanzhuang Tourist Highway in the Zhangjiajie Wuling Mountain Area from 2000 to 2020, and it utilizes the spatial autocorrelation analysis method to reveal the pattern of its spatial and temporal changes in ecological sensitivity. The following results were obtained. (1) The ecological condition of the study area is gradually improving, and the areas with higher sensitivity are mainly distributed in the northeast and southwest of the study area. (2) The ecological sensitivity of the study area has strong spatial autocorrelation, but the autocorrelation has been reduced in recent years, and the distribution of the ecological sensitivity has been gradually discretized. (3) There are problems of high ecological risk and construction difficulty in the traditional highway route selection scheme of the A line. The optimized route selection scheme, the K line, can effectively avoid highly sensitive areas by adjusting the route and bridge settings. Finally, the article proposes engineering construction suitability and ecological restoration strategies for different road sections regarding vegetation cover, landscape risk, and geological hazards. This study establishes a set of comprehensive technical chains for tourism highway routing in ecologically fragile areas based on the spatial and temporal evolution of sensitivity, which provides new ideas for traditional highway routing and is of great significance for maintaining the balance and stability of ecosystems within the road area.

Keywords: ecological sensitivity; spatial and temporal evolution; road alignment; spatial autocorrelation; intervention optimization strategy; AHP

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1. Introduction

Nature reserves are land or sea areas intended for the long-term protection of important natural ecosystems, natural relics, natural landscapes, and the natural resources, ecological functions, and cultural values they carry [1], which are characterized by natural resources such as beautiful natural scenery, concentration of rare and endangered species, special natural relics, etc. [2]. At the same time, they are accompanied by geographic ecological sensitivity characteristics such as high altitude [3], fragile ecosystems [4], and poverty [5]. Therefore, in the development and construction of nature reserves, maintaining ecological stability has become an important task as well as one of the goals to help global biodiversity conservation [6].

At present, China's nature reserves account for 18% of the terrestrial territory [7], achieving the Aichi Targets of the United Nations Convention on Biological Diversity (CBD) ahead of schedule. But at the same time, the ecosystems of China's nature reserves are facing greater degradation pressures: about 10% of the ecosystems of the nature reserves are in a highly fragile state [8]. As these areas also generally have development problems such as remote geographical location and regional economic poverty contiguity [9], it is imperative for transportation accessibility to drive the development of the regional tourism economy [10]. Therefore, it is urgent to optimize the routing of tourism highways in order to reduce the impact on nature reserves.

Tourism highway routing is the first step of regional tourism development [11], and reasonable highway route planning can link tourism resources, enhance the tourism experience, promote economic development, and ensure regional ecological stability [12]. However, wrong tourism highway routing, especially highway construction in ecologically fragile areas, is prone to pose a significant threat to biodiversity and ecosystems along the routes, bringing about derivative problems such as sharp reductions in biodiversity, soil erosion, high risk of geologic hazards, etc. Therefore, exploring low-sensitivity highway routing is crucial for reducing the impacts of ecologically fragile areas in the future. Tourism highway routing based on ecological sensitivity assessment is a complex technical task that needs to balance economic, social, and ecological aspects to ensure the development of tourism while minimizing ecological damage [13]. It involves multidisciplinary knowledge, refined environmental analysis, and coordination of the interests of multiple parties.

Existing research dimensions are broadly summarized into the following two categories. The first category focuses on the ability of highway road ecosystems to maintain ecological sustainability in the face of certain types of ecological problems, such as special adverse geology, soil degradation, vegetation change, slope instability, desertification, acid rain, and other challenges [14–16]. Li et al. [17] measured large-scale undesirable geologic bodies affecting the ecological safety of highway roads based on optical remote sensing, InSAR (synthetic aperture radar interferometry), and LiDAR technologies for geologic hazards in complex mountainous areas; Jia et al. [18] revealed the impacts of highway construction on the regional vegetation by using the Net Primary Productivity (NPP) as a quantitative indicator; Malemnganbi [19] measured the landslide susceptibility assessment of highway landslides in Manipur, India, based on the AHP model and multi-resolution DEM. Although some indicator systems have regional characteristics, they lack generality and are less concerned with the guiding significance of the comprehensive evaluation of ecological sensitivity for highway network planning from the perspective of roadway multivariate coordination, so it is necessary to analyze the relationship between highways and ecosystems in a more comprehensive way. The second category mainly focuses on the external disturbances faced by highway road ecosystems and assesses the probability size of ecological problems and ecosystem imbalance. For example, Guan Lei et al. [20] used the pressure–state–response framework model to construct a highway ecological evaluation index system; Zhang Dan et al. [21] constructed an ecological environmental impact evaluation of highway construction.

The evaluation indexes proposed in the related literature are generally divided into two categories: qualitative and quantitative indexes [22,23] with the drawbacks that some of the qualitative indexes (e.g., the degree of environmental coordination and the degree of promotion of economic development) are difficult to guide the design of highway routing, and they cannot be intuitively spatially visualized. Further, traditional road routing research focuses on safe routing and economic considerations of routes, but it lacks research on the ecological impacts, or it adopts static ecological research at a single point, ignoring the "dynamic" evolution of tourism highway routing and making insufficient predictions of ecological risks during the life cycle of the highway. In contrast, highway routing based on the spatial and temporal evaluation of ecological sensitivity is a more comprehensive and environmentally friendly routing method. It utilizes ArcGIS spatial analysis technology and other advanced means to carefully assess the spatial and temporal changes of ecological

sensitivity in the areas along the highway, identify the evolution characteristics of regional ecological sensitivity, and try to avoid the current and future potentially highly sensitive areas of ecological sensitivity in order to formulate a more scientific routing strategy. It not only pays attention to the safety and economy of the highway but also strives to find the best balance between highway construction and ecological protection to realize the goal of sustainable development.

Therefore, this research takes a typical tourist highway (Zhangjiajie–Guanzhuang Highway) in the Wuling Mountain Region as the research object, aiming to establish a set of comprehensive technical chains for the selection of tourist highway routes in ecologically fragile areas based on the spatio-temporal evolution of sensitivity as a suitable framework for diagnosing the ecological security pattern of tourist highways in their whole life cycle. Firstly, the ecological situation of the highway in the study area for 20 years (2000, 2010, 2020) was systematically organized, and the index system was established by selecting the ecological sensitivity assessment index factors considering the principles of scientificity, typicality and accessibility of data. Then, the weights of the indexes were delineated by using the hierarchical analysis method (AHP) [24] to establish the quantitative and comprehensive evaluation model of ecological sensitivity. After that, the spatial weighting superposition of various indexes was carried out by using ArcGIS (Geographic Information System) 10.8 software, analyzing the spatially weighted superposition, the tourism highway in the 2000–2020 period, and the spatial and temporal evolution of ecological sensitivity characteristics. In addition, I used the spatial autocorrelation analysis method [25] and GeoDa V1.20 software to further study the tourism highway in the past 20 years, analyzing the ecological sensitivity trends as well as the selection of the highway in the past 20 years. I analyzed key ecological sensitivity hotspot areas that should be prioritized for protection during the route selection process and developed an optimized routing scheme based on these findings. By presenting the ecological sensitivity, engineering construction suitability, and ecological restoration strategies of different sections in kilometers, the results can effectively reduce the impact and influence of tourism road alignment on ecologically fragile areas.

2. Materials and Methods

2.1. Study Area

The Zhangjiajie–Guanzhuang Tourist Highway in Hunan Province is located in an essential area for biodiversity conservation and water conservation (I-02-14) of the Wuling Mountain Region [26,27], and the study area covers highway A0+000~A56+438 and its surrounding townships (Figure 1), which spans 108°16′ to 109°05′ E longitude and 27°01′ to 27°25′ N latitude. The highway passes through the lofty mountains of the Wuling Mountains with an altitude of 183–1520 m. The terrain has great undulations, steep slopes and deep valleys, and cliffs, including dissolution karst hills, tectonic denudation hills, hillocks, erosive tectonic low mountains, erosion, accumulation of river erosion, etc. [28]. The distribution of undesirable geologic features is characterized by karst, landslide, air-mining areas, rock piles, avalanches, hazardous rock bodies, soft rocks, etc., and the special geotechnical features are mainly soft soil, red clay soil, and land fills. Soil erosion mainly involves the Wuling Mountain National Key Erosion Prevention Area (GY2) and Fenghuang Mountain~Wuyunjie Provincial Key Erosion Prevention Area (SY4) in northwest Hunan Province; the water system is developed along the highway with the distribution of the Li River and its tributary JiuDu Creek, the Yuan River and its tributary DongTing Creek, etc. [29]. Ecosystems are relatively intact, with dense vegetation, and the road is located in the Hunan Zhangjiajie Giant Salamander National Nature Reserve [30] and Hunan Wuqiang Creek National Wetland Park Protection and Conservation Area, which will form the golden tourism channel of Xiang-E-Gui (Sanmenxia–Zhangjiajie–Guilin–Beihai) and build a green infrastructure that is ecologically friendly, resource saving and environmentally friendly.

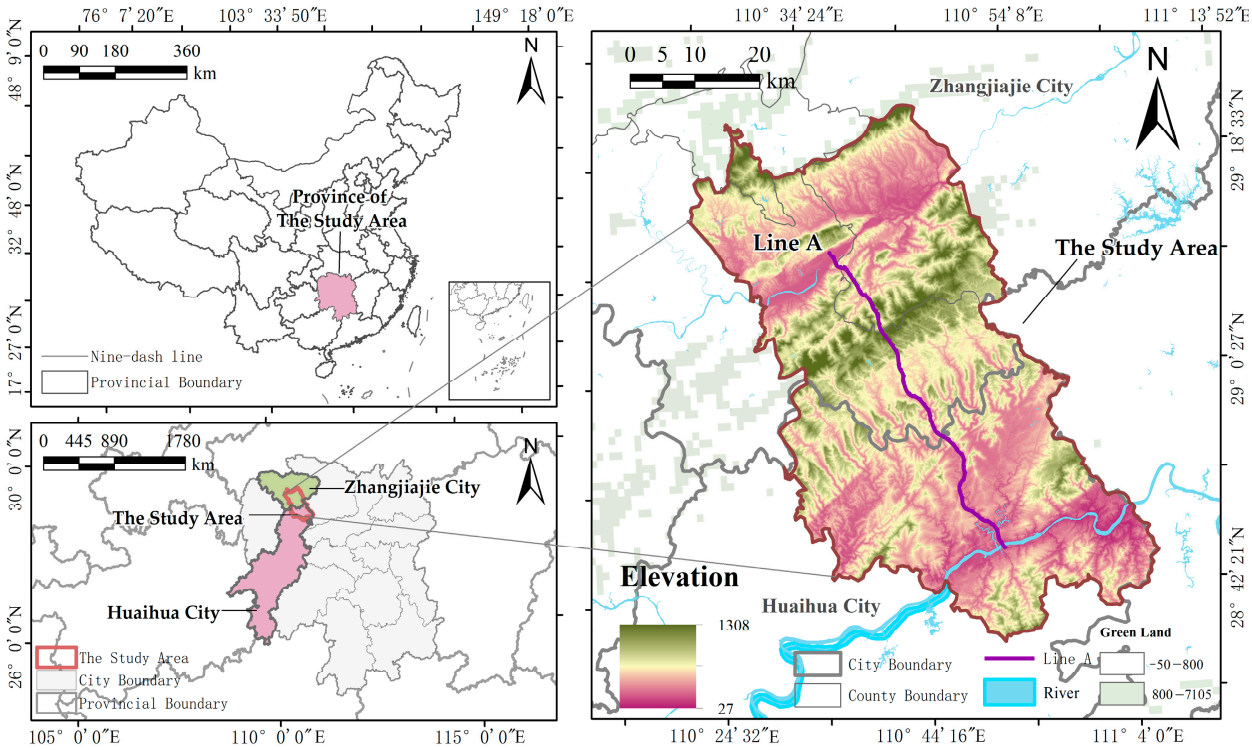


Figure 1. Geographical location of the study area.

2.2. Data Sources and Processing

The Zhangjiajie Wuling Mountain Region experienced a significant transition from rapid development to ecological protection and sustainable development between 2000 and 2020. The years 2000, 2010, and 2020 represent the key nodes of this transition, and the ecological quality of the regional environment changes are more obvious. At the same time, the data in the study area during the 20-year period are more complete. Therefore, the data analysis of this study used the spatial data of the study area for the three periods of 2000, 2010, and 2020, which were obtained from the China Multi-Period Remote Sensing Monitoring Data of the Institute of Geographic Sciences and Resources of the Chinese Academy of Sciences (http://www.resdc.cn/), local governmental departments, the Resource Environment and Data Platform of the Chinese Academy of Sciences (https://www.resdc.cn/), Geospatial Data Cloud (http://www.gscloud.cn/) and field research acquisition. The Landsat remote sensing images were radiometrically calibrated, atmospherically corrected, image cropped using ENVI5.1 software, and manually and interactively interpreted, and the 1:2000 mapped topographic maps, annual change data of land survey and remote sensing visualization data were retrieved from the study area. After manual interactive interpretation, the "1:2000 mapping topographic maps" and "annual change data of land survey" of the study area were retrieved and compared with the results of remote sensing visual interpretation to calculate the accuracy of land use type interpretation and the accuracy of land use type area statistics in order to form the vector data of land use status quo. Based on the land use data, Fragstats 4.3 software was used to calculate the fragmentation of the landscape of the study area [31]; NDVI (Normalized Difference Vegetation Index) was used to estimate the vegetation cover [32]; based on the DEM (Digital Elevation Model) data, the slope and direction data were obtained by using the slope and direction tool of ArcGIS 10.5 software [33]. Finally, the above raster data were entered into the ArcGIS platform and resampled to 30 m resolution raster data, and all the raster data were unified using the WGS_1984 (World Geodetic System-1984 Coordinate System) geographic coordinate system. The specific data sources (Table 1) are listed below.

Table 1. Statistical table of research data sources.

Data Name	Data Sources	Data Format	Original Resolution	Data Years
Landsat 8 OLI_TIRS	Geospatial Data Cloud (www.gscloud.cn, accessed on 3 May 2024)	TM	30 m	2023
DEM data	Geospatial Data Cloud (www.gscloud.cn, accessed on 3 May 2024)	TIF	30 m	2023
Geohazard data	CAS Resource Environment and Data Platform (https://www.resdc.cn/, accessed on 15 May 2024)	SHP	--	2000–2020
Water Source Area data	OpenStreetMap (OSM platform) (https://openmaptiles.org/, accessed on 15 May 2024)	SHP	--	2000–2020
Nature Reserve Data	China Nature Reserve Specimen Resource Sharing Platform (http://bhq.papc.cn/specimen.html, accessed on 2 June 2024)	SHP	--	2000–2020
NDVI Data	GEE platform (https://developers.google.cn/earth-engine/, accessed on 2 June 2024)	TIF	30 m	2000–2020
Land Use Data	CAS Resource Environment and Data Platform (https://www.resdc.cn/, accessed on 10 June 2024)	TIF	30 m	2000–2020

2.3. Research Design

My research design is based on the spatial and temporal evolution of the ecologically fragile area tourism highway routing of the integrated technology chain. It mainly consists of (1) a quantitative and comprehensive evaluation of highway ecological sensitivity based on spatial and temporal evolution characteristics, (2) a spatial autocorrelation analysis of the ecological sensitivity of highways and identification of cold hot spots, and (3) an optimization study of tourist highway routing based on ecological sensitivity assessment.

The first part establishes a scientific ecological sensitivity evaluation index system, clarifying the spatial distribution and evolution trends of ecological sensitivity in the study area, providing a data foundation for further research (Figure 2). The second part employs spatial autocorrelation methods to analyze ecological sensitivity over time and space, identifying highly sensitive areas and delineating "red line areas" to avoid during route selection. The third part formulates engineering construction and ecological restoration strategies based on the analysis results, ensuring highway construction meets tourism demands while minimizing ecological impacts.

2.3.1. Analysis of the Spatial and Temporal Evolution of Ecological Sensitivity

1. Selection and grading of evaluation indicators

The selection of highway ecological sensitivity evaluation indexes is based on the comprehensive consideration of the actual situation of the study area and the research results of previous researchers [34–36] with reference to the "National Ecological Functional Zoning (Revised Edition)", "Technical Specification for Ecological Functional Partitioning", the classification of national important ecological functional zones, combined with the field research of the highway, and the opinions of the experts in urban and rural planning, geography, roads and bridges, landscape architecture, ecology, etc. Nine evaluation indicators were selected from three levels: the natural environment, social development, and ecological security: elevation, slope, slope direction, water protection, land use status, scenic resources protection, vegetation coverage, landscape fragmentation, and geologic hazards (Table 2). These indicators were selected on the basis of field analysis and can be effectively applied to the study area, reflecting the geographic and ecological characteristics of the study area in a practical and accurate manner and ensuring the scientific, ecologically friendly and sustainable development of the highway routing scheme.

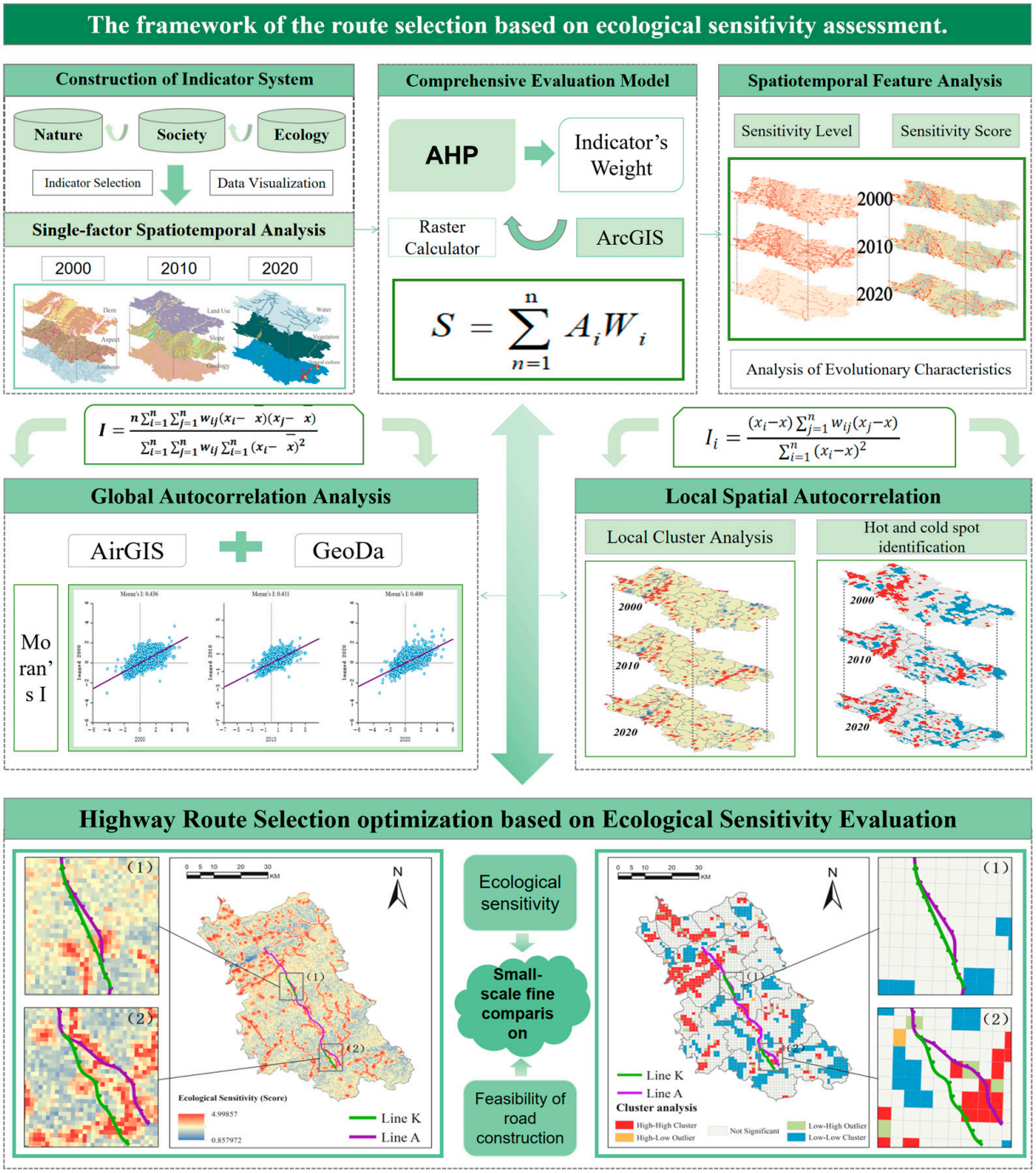


Figure 2. The framework of the route selection based on ecological sensitivity assessment.

The grading of the evaluation indicators is based on the national ecological environment quality scoring standards identified in the ecological function zoning as well as the Technical Specification for the Evaluation of Ecological Environment Condition, Environmental Quality Standards for Surface Water, Environmental Impact Assessment Specification for Highway Construction Projects, Design Specification for Highway Environmental Protection and other standard specifications and literature research, which are used for grading the evaluation indicators of highway ecological sensitivity. I assigned the five values of the evaluation indicators as 9, 7, 5, 3, and 1, respectively for the indicators of extreme, high, medium, light and no ecological sensitivity (Table 3).

Table 2. Indicator Explanation Table.

Indicator	Indicator Description
Elevation	The Wuling Mountain area's elevation changes are significant, leading to considerable differences in climate, vegetation, and ecological functions across various elevation zones.
Slope	The slope is related to the suitability of engineering construction and the potential geological disaster impacts during the highway construction process.
Aspect	The aspect affects environmental factors such as light, temperature, and precipitation, which in turn influence vegetation growth and ecological functions.
Water source protection	The Wuling Mountain area has a wide distribution of water resources. The natural water resources around the highways include the Li River, Yuan River, and Wuqiangxi Wetland. Highway construction should strive to minimize threats to water sources, ensuring the sustainable use of regional water resources.
Land use status	The land use types in the Wuling Mountain area are diverse, and there is a clear trend of transition among different categories. It is essential to identify potential routes under the evolving land use patterns to ensure that the selected alignment plans comply with the regional land use planning.
Conservation of natural culture resources	The Wuling Mountain area is home to numerous officially designated scenic resources, such as the Wuqiangxi National Wetland Park and the Chinese Giant Salamander National Nature Reserve. It is essential to ensure that road construction does not harm these precious natural landscapes.
Vegetation coverage	Vegetation coverage is an important indicator for assessing the ecological status of a region. In the Wuling Mountain area, the high vegetation coverage contributes to a complex ecosystem.
Landscape fragmentation	The Wuling Mountain area is home to numerous regions with fragile natural landscapes. The construction of roads may lead to the fragmentation of these vulnerable areas. By assessing the impact of road construction on the integrity of natural landscapes, we can optimize route selection plans and mitigate the severity of landscape fragmentation.
Geological hazards	The geological conditions in the Wuling Mountain area are complex with numerous adverse geological features such as karst formations, landslides, and softened rocks. The highway alignment plan must avoid these high-risk areas to ensure the safety of highway construction and operation.

2. Determination of evaluation indicator weights

The determination of the weights of the ecological sensitivity evaluation indexes is calculated using the AHP analysis method [37], which divides the complex problem into assigning weights according to the importance of different levels, and its calculation steps are as follows:

(1) Establishment of a hierarchical model for evaluating the ecological sensitivity of roads in ecologically fragile areas

Taking the ecological sensitivity evaluation of highways in ecologically fragile areas as the target layer, the natural environment, social development and ecological security as the criterion layer, and the evaluation factors as the indicator layer, we constructed the hierarchical structure model of highway ecological sensitivity evaluation.

(2) Constructing a two-by-two comparison judgment matrix

In this study, the importance of each evaluation index is quantified by the scale method of 1–9 and its reciprocal, and the judgment matrix is constructed. In this study, the Delphi method [38] and the hierarchical analysis method (AHP) were used to set the weights of 3 criteria and 9 indicators by distributing the expert consultation from the hierarchical analysis method of the "Highway Ecological Sensitivity Evaluation Indicator System". Fifteen experts in the fields of geography, landscape gardening, forestry, urban and rural planning, civil engineering, transportation engineering, and architecture compared the relative importance of the indicators two by two and set the weights of the indicators on a scale of 1–9 [39].

(3) Consistency testing

I calculated the maximum eigenvalue of the judgment matrix and its corresponding consistency index (CI) and compared it with the average random consistency index (RI); then, I calculated the consistency ratio (CR). If CR is less than 0.1, the consistency of the

judgment matrix is considered acceptable; otherwise, the judgment matrix needs to be corrected in order to ensure that the decision-making process is reasonable and accurate.

(4) Determination of indicator weights

After passing the consistency test, the eigenvectors corresponding to the judgment matrix are the sibling weights of the criterion layer and indicator layer in the ecological sensitivity evaluation index system. By calculating the product of the criterion layer and indicator layer, the factor weights are finally derived.

$$W_i = \sum_{n=1}^{n} C_i A_i \quad (1)$$

where W_i is the combination weight of each ecological sensitivity evaluation index; C_i is the sibling weight of the guideline layer in the ecological sensitivity evaluation index system; A_i is the sibling weight of the indicator layer in the ecological sensitivity evaluation index system; i = 1, 2, 3 . . . n.

The results show the eigenvectors of the criterion layer: [0.3601, 0.1755, 0.4644]. The maximum characteristic root is 3.0002; CI = 0.0001; RI = 0.5, CR = CI/RI = 0.0002 < 0.1; the consistency test was passed. The results show that the allocation of weights in the criterion layer is reasonable.

The eigenvector of the environment of the indicator layer is [0.1771, 0.2291, 0.1066, 0.4872], the largest eigenroot is 4.0325; CI = 0.0108; RI = 0.8852, CR = CI/RI = 0.0122 < 0.1; the consistency test is passed. The eigenvector of socio-economy in the indicator layer is [0.2753, 0.7247], the largest eigenroot is 2; CI = 0; RI = 0, CR = CI/RI = 0 < 0.1, the consistency test passes. The eigenvector of ecological security in the indicator layer is [0.2322, 0.3026, 0.4653], the largest eigenroot is 3.0011; CI = 0.0006; RI = 0.5455. CR = CI/RI = 0.0011 < 0.1; the consistency test is passed. The results show (Table 4) that the weights of the indicator layer are allocated reasonably.

According to the results of indicator weights, the size of the weight value of 9 indicators is B9 > B4 > B8 > B6 > B7 > B2 > B1 > B5 > B3, of which B9 has the largest weight, i.e., geological hazards has the largest impact on the ecological sensitivity of the highway, and B3 has the smallest weight; i.e., aspect has the smallest impact on the ecological sensitivity of the highway.

3. Evaluation of spatial and temporal evolution characteristics of ecological sensitivity

Based on the spatial and temporal trends and future risk prediction of the study area, this study uses the AHP method and ArcGIS spatial weighted superposition [40] to obtain the ecological sensitivity evaluation level and spatial distribution law of the tourism highway, dynamically study the sensitive targets and road sections that should be focused on for the protection of tourism highway routing under the future trend, and form the optimized routing scheme. In this study, the relevant vector data were recorded into the ArcGIS platform, and the single-factor elements were visualized and analyzed through the functions of Spatial Analysis Tools, 3D Analysis Tools, etc. The ecological sensitivity of the highway is the result of the comprehensive influence of multiple factors [41]. Therefore, in this study, the comprehensive evaluation of highway ecological sensitivity adopts the multi-factor weighted summation model [42], which utilizes the raster calculator of ArcGIS software to weigh and sum the single-factor raster data with its corresponding weights so as to obtain the distribution map of the comprehensive ecological sensitivity evaluation of the highway. The multi-factor integrated weighted summation formula is as follows:

$$S = \sum_{n=1}^{n} A_i W_i \quad (2)$$

where S denotes the comprehensive evaluation score of the ecological sensitivity of the highway; A_i shows the ith evaluation index raster layer, i = 1, 2, 3, . . . n; W_i denotes the weight of the ith evaluation factor.

Table 3. Grading and assignment table of ecological sensitivity evaluation indicators of highways.

Criterion Layer	Index Layer	Ecological Sensitivity Classification					Grading Instructions
		Extremely Sensitive	Highly Sensitive	Moderately Sensitive	Hyposensitive	Insensitive	
A1 Environment	B1 elevation	≥1500 m	1000–1500 m	500–1000 m	200–500 m	<200 m	According to China's basic geomorphology and standard classification level
	B2 Slope	≥35°	25–35°	15–25°	5–15°	0–5°	Based on the International Geographical Union classification of slopes for the application of geomorphological detail maps.
	B3 Aspect	dark slope (due north)	dark slope (North-East, Northwest)	semishaded slope (due east, due west)	semipermanent slope (southeast, southwest)	sunny slope (directly south)	Grading based on engineering and construction experience
A2 Social development	B4 Water source protection	0–500 m buffer	500–1000 m buffer	1000–1500 m buffer	1500–2000 m buffer	2000 m away buffer	According to the "Environmental Quality Standards for Surface Water" classification level
	B5 Land use status	body of water	forest land, cropland	rural settlements	grassland, garden	building site unutilized land	According to the Classification of Land Use Status
	B6 Conservation of natural culture resources	national, world-class	provincial level (e.g., government)	municipal	county level	not have	According to the Technical Specification for Ecological Functional Zoning
A3 Ecological security	B7 Vegetation coverage	≥0.7	0.6–0.7	0.5–0.6	0.35–0.5	<0.35	According to the "Technical Specification for Evaluation of Ecological Environment Condition"
	B8 Landscape fragmentation	≥0.45	0.35–0.45	0.25–0.35	0.15–0.25	<0.15	Based on landscape ecology and Fragstats Landscape Pattern Index classification
	B9 Geological hazards	0–100 m buffer	100–200 m buffer	200–500 m buffer	500–1000 m buffer	1000 m away buffer	It is classified according to the Technical Code for Ecological Functional Partitioning.
Grading assignment		9	7	5	3	1	

Table 4. Ecological sensitivity evaluation index weighting table.

Target Level	Criterion Layer	Indicator Layer	Peer Weighting	Portfolio Weighting
Ecological sensitivity evaluation of tourist highways	A1 Environment (0.3601)	B1 Elevation	0.1771	0.0638 (7)
		B2 Slope	0.2291	0.0825 (6)
		B3 Aspect	0.1066	0.0384 (9)
		B4 Water source protection	0.4872	0.1754 (2)
	A2 Social development (0.1755)	B5 Land use status	0.2753	0.0483 (8)
		B6 Conservation of scenic resources	0.7247	0.1272 (4)
	A3 Ecological security (0.4644)	B7 Vegetation coverage	0.2322	0.1078 (5)
		B8 Landscape fragmentation	0.3026	0.1405 (3)
		B9 Geological hazards	0.4653	0.2161 (1)

2.3.2. Spatial Autocorrelation Analysis

Spatial autocorrelation analysis is a commonly used analytical method in spatial statistics, which is used to synthesize the quantitative and spatial location relationships between variables, including global autocorrelation and local autocorrelation [43]. Global spatial autocorrelation is used for the overall distribution pattern and aggregation characteristics of spatial data in the whole study area and to quantify the strength and significance of the aggregation trend [44,45], while local autocorrelation analysis is used to refine the results of the global analysis to identify the spatial differences and correlations between a specific area or unit and the surrounding areas [46]. In this paper, the autocorrelation coefficients of the distribution of ecological sensitivity in the study area were obtained by using Global Moran's *I* to describe the global autocorrelation of ecological sensitivity, and the local indicators of spatial association were used to further analyze the local clustering of sensitivity. The local indicators of spatial association were used to further analyze the local clustering of sensitivity. The formula is as follows [47]:

$$I = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(x_i - \overline{x})(x_j - \overline{x})}{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}\sum_{i=1}^{n}(x_i - \overline{x})^2} \quad (3)$$

$$I_i = \frac{(x_i - x)\sum_{j=1}^{n} w_{ij}(x_j - x)}{\sum_{i=1}^{n}(x_i - x)^2} \quad (4)$$

where I is the global Moran's index, I_i is the local Moran's index, n is the number of data, x_i and x_j are the observed values of regions i and j, $\overline{x}$ is the mean value of the whole domain, and w_{ij} is the spatial weight of i and j.

2.3.3. Optimization of Road Alignment Based on Ecological Sensitivity Assessment

Traditional highway routing techniques usually lack quantitative indicators to assess the ecological impacts of the routes, while highway routing methods based on ecological sensitivity evaluation can realize a new decision-making model for sustainable development and effectively reduce the impacts of tourism highway routing on ecologically fragile areas. In this section, firstly, the traditional routing scheme is incorporated into the comprehensive evaluation of ecological sensitivity by obtaining the ecological sensitivity score of the whole route, targeting the highly sensitive road sections, and analyzing the related problems so as to clarify the impact factors, including elevation, land use and water source protection. Secondly, the road alignment is optimized to avoid highly ecologically sensitive corridors, combining the protection of scenic resources and infrastructure construction requirements to find the most optimal alignment plan to minimize the impact on the ecological environment. Finally, based on the ecological sensitivity of different road sections and the interpretation of the nine assessment indicators, appropriate engineering

construction and ecological restoration strategies are proposed to ensure the coordinated development of ecological protection and highway construction.

3. Results

3.1. Analysis of the Spatial and Temporal Evolution of Ecological Sensitivity

3.1.1. Single-Factor Ecological Sensitivity Evaluation

The data of each indicator factor in the study area in 2000, 2010, and 2020 were collected at the road scale to reveal the spatial distribution of various factors affecting the ecological sensitivity and the trend of change. As a result, the spatial distribution of elevation in the study area shows a trend of high in the center and low in the north and south with the central area mainly consisting of mountains and hills with higher elevation. The central area is mainly mountainous and hilly with high elevation, while the northern and southern parts have main streams with low elevation; the slope is higher in the central area and smaller in the southern and northern parts. The high slope area is distributed in a band from southwest to northeast, and the rest of the area is relatively gentle; the overall aspect sensitivity is high, and it is mainly concentrated in the northern area and the southern side of the river in the south. The high value of watershed sensitivity in the study area is mainly distributed around the two main streams and their derived tributaries on the north and south sides of the study area. With the passage of time, the overall watershed sensitivity increases significantly (Figure 3).

In terms of land use, highly sensitive areas in the study area are mainly distributed in the central and southeastern regions, which have high forest and grass cover and a large amount of ecological woodland. The southwestern region is significantly more sensitive to subsequent changes over time, and the rest of the region has less change. There are three nature reserves in the study area with a higher sensitivity of natural culture resources on the north and south sides and significant changes in the south of the area, which are mainly due to the establishment of the Wuqiangxi Nature Reserve in the south of the area as well as Wuxi Lake Nature Reserve a little later, which leads to significant time differences in sensitivity (Figure 4).

The overall landscape fragmentation is low, and the higher sensitivity area is mainly concentrated in the northern part of the study area. In terms of temporal changes, minor changes were not significant in various places. The vegetation cover sensitivity of the study area as a whole is high, with a large number of woodlands and grasslands, and low-sensitivity areas are mainly distributed in the built-up areas near the city as well as the internal rivers, which account for a small percentage. Meanwhile, the sensitivity of the northwestern area decreases significantly with time. In terms of geological hazards, the northwestern part of the study area has a high geological hazards sensitivity. In the rest of the area, the distribution of disaster sites is more decentralized, and the sensitivity is relatively low (Figure 5).

3.1.2. Results of the Comprehensive Evaluation of Ecological Sensitivity

On the basis of the above results of the analysis of each factor under the road scale, the factor indicators were weighted correspondingly according to Table 4. As shown in the figure, in 2000, 2010, and 2020, the ecological sensitivity scores in the study area were 1.5858~5.7956, 1.2924~6.1138, and 0.8579~4.9985, respectively. The average sensitivity level in the region over the years was relatively low, and the areas of higher sensitivity were located in the north and south poles, while the central part of the region had good ecological resilience. The ecological sensitivity of the study area has relatively increased from 2000 to 2010 with the area of moderately ecologically sensitive areas increasing by 0.2% and less ecologically sensitive areas increasing by 7.96%. Within this interval, the main changes within the region were concentrated in the north and south sides, and the changes in the rest of the area were less obvious; while in 2010–2020, the ecological sensitivity within the study area generally decreased significantly, and the highly sensitive areas in the north and south sides gradually diminished. The moderately ecologically sensitive areas in the

region were zero; the less sensitive areas were scattered and accounted for only 6.05%, while the less sensitive areas reached 93.95%, occupying most of the area within the study area (Figure 6).

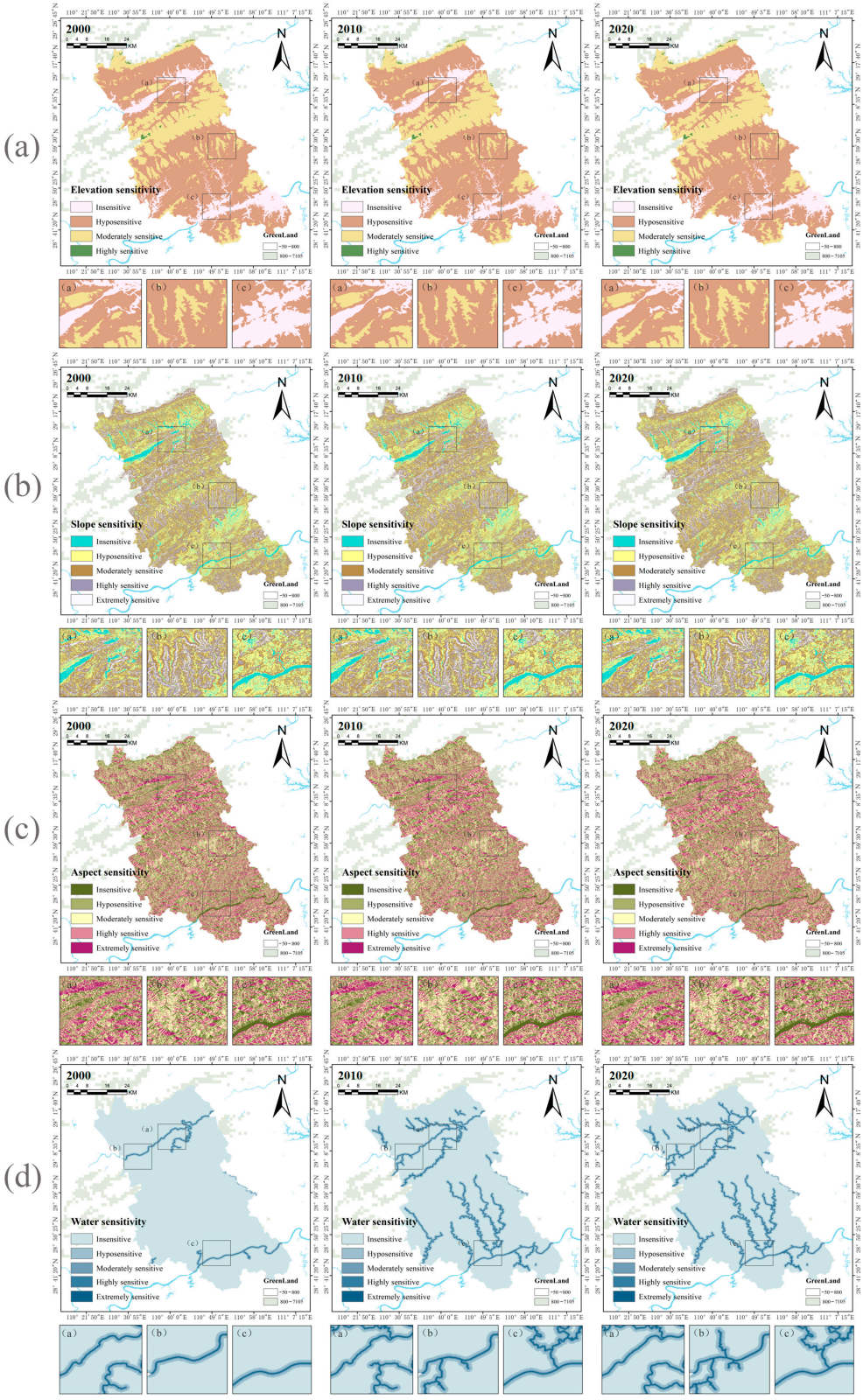


Figure 3. Indicators for the environmental layer: (**a**) elevation; (**b**) slope; (**c**) aspect; (**d**) water protection.

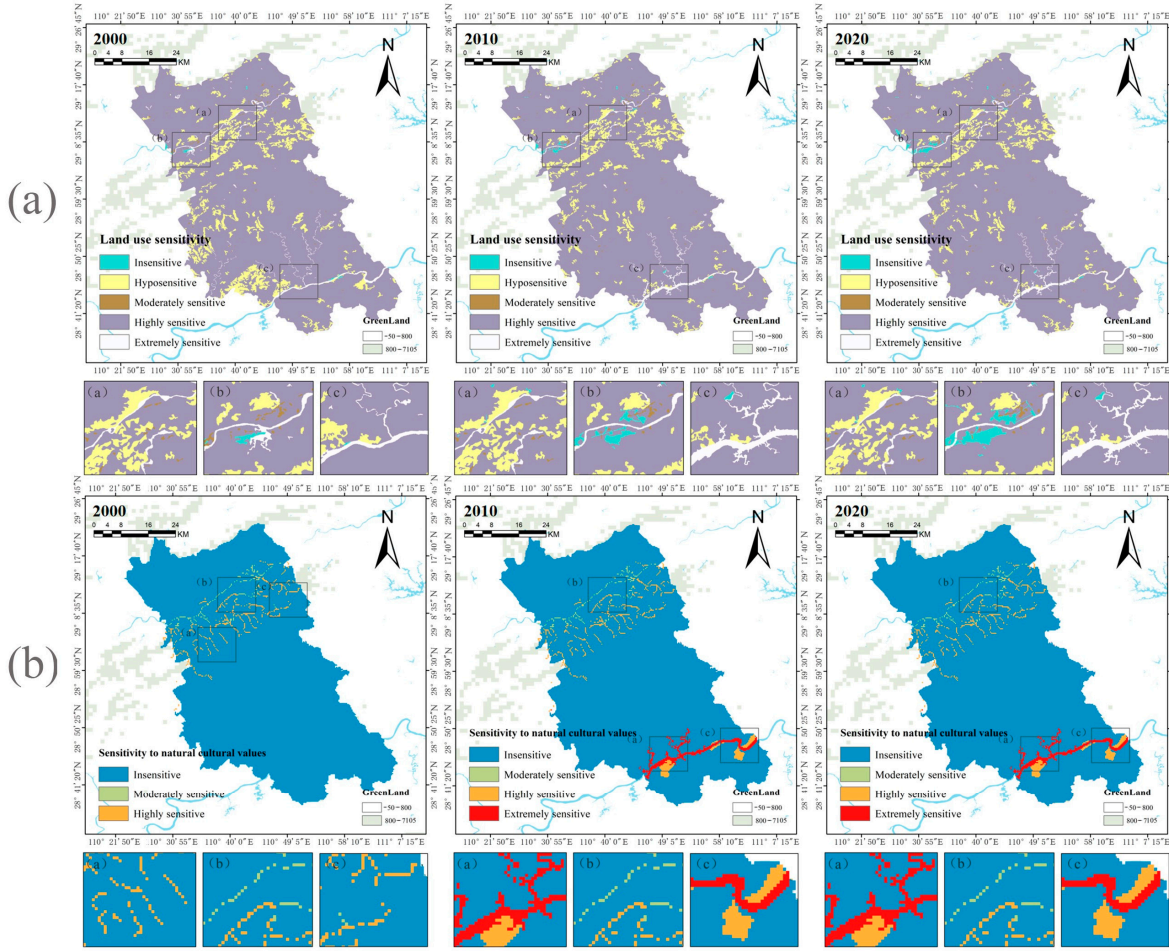


Figure 4. Indicators for the social development layer: (**a**) land use; (**b**) conservation of scenic resources.

Overall, the ecological sensitivity of the study area has experienced a growth-decay trend from 2000 to 2020 with most of the area at a low sensitivity level. From the perspective of highway construction, the current overall ecological sensitivity of the region is at a low level, and the impact of highway construction on nature is less threatening with good conditions for highway construction. It provides a database for subsequent road alignment optimization.

3.2. Spatial Autocorrelation Analysis of Ecological Sensitivity in the Study Area

3.2.1. Global Autocorrelation Analysis

Using ArcGIS 10.8 software to create a fishing net, the ecological sensitivity values of the study area in 2000, 2010, and 2020 were extracted to the fishing net, and GeoDa software was used to calculate the global Moran's index of the distribution of ecological sensitivity, and the results are shown in Table 5. The global Moran's indices of the study area for the years 2000, 2010, and 2020 were 0.4360, 0.4111, and 0.4000 (Figure 7), respectively. These values are all greater than 0, indicating that there is a strong positive correlation between the spatial distribution of ecological sensitivity within the study area [48]; i.e., the areas with higher ecological sensitivity tend to be clustered together, resulting in the phenomenon of agglomeration. The Z values are all greater than 2.58, and p is less than 0.01, which passed the 99% confidence test, proving that the spatial autocorrelation of ecological sensitivity in the study area is extremely significant [49]. From 2000 to 2020, the degree of autocorrelation of ecological sensitivity in the study area gradually decreased, and the overall trend was toward discrete. The spatial autocorrelation was strongest in 2000, and it decreased slightly in 2010 and 2020 but still had a strong degree of correlation.

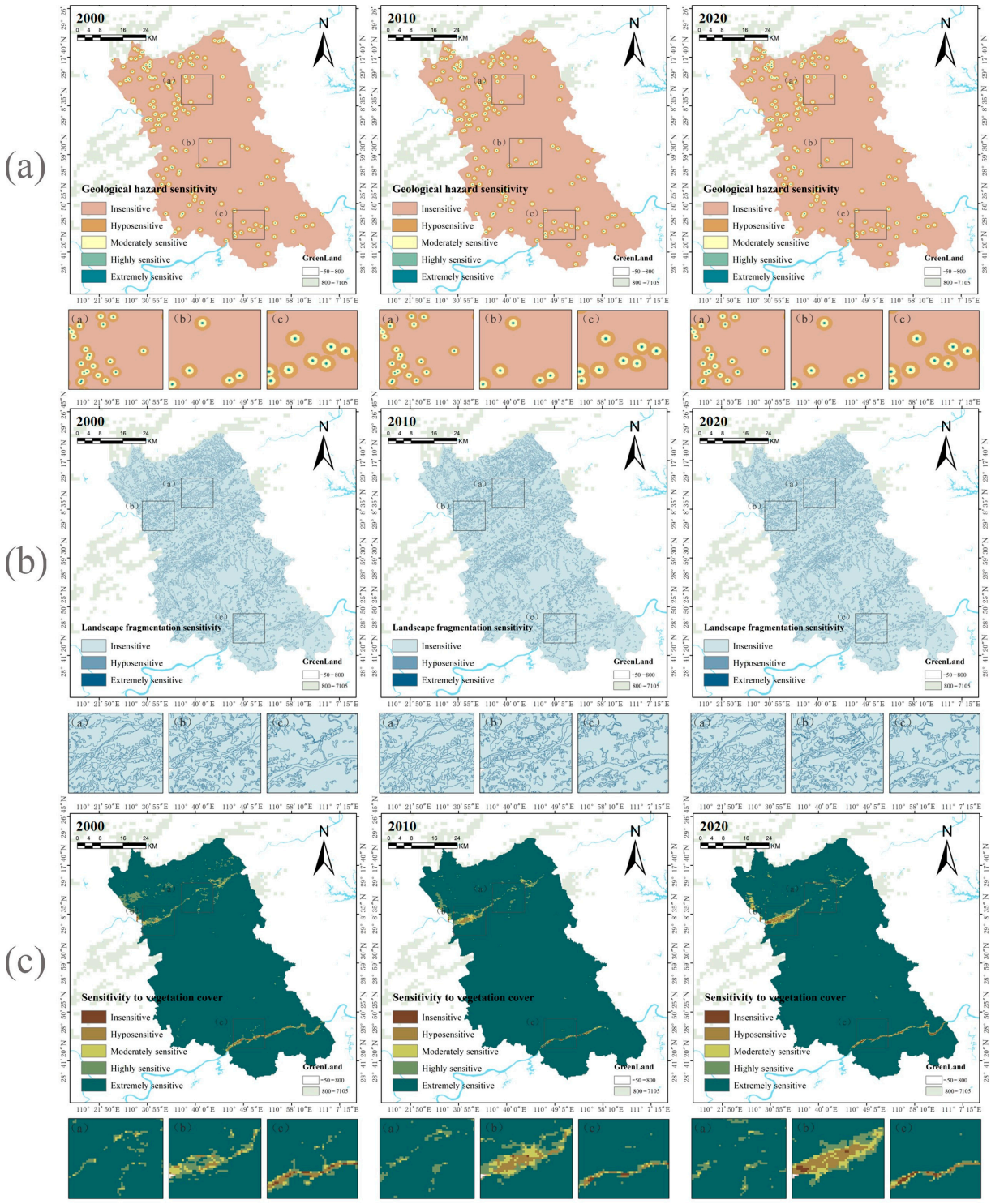


Figure 5. Indicators for the ecological security layer: (**a**) geological hazards; (**b**) landscape fragmentation; (**c**) vegetation coverage.

Table 5. Results of global spatial autocorrelation analysis.

Time (Years)	Global Moran's I	Z	*p*
2000	0.4360	45.7511	$p < 0.01$
2010	0.4111	42.0636	$p < 0.01$
2020	0.4000	40.7438	$p < 0.01$

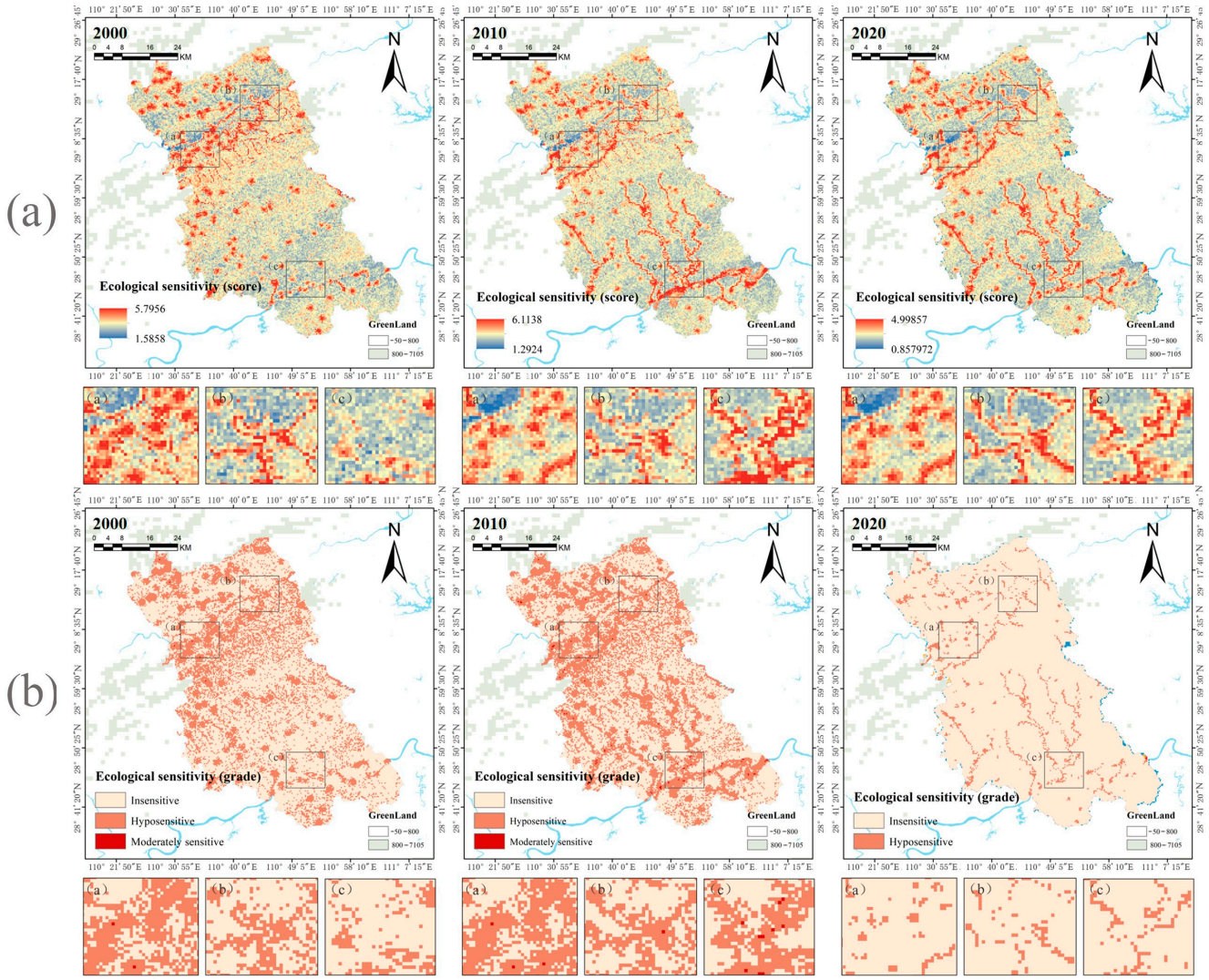


Figure 6. Comprehensive assessment map of ecological sensitivity: (**a**) ecological sensitivity values; (**b**) ecological sensitivity level.

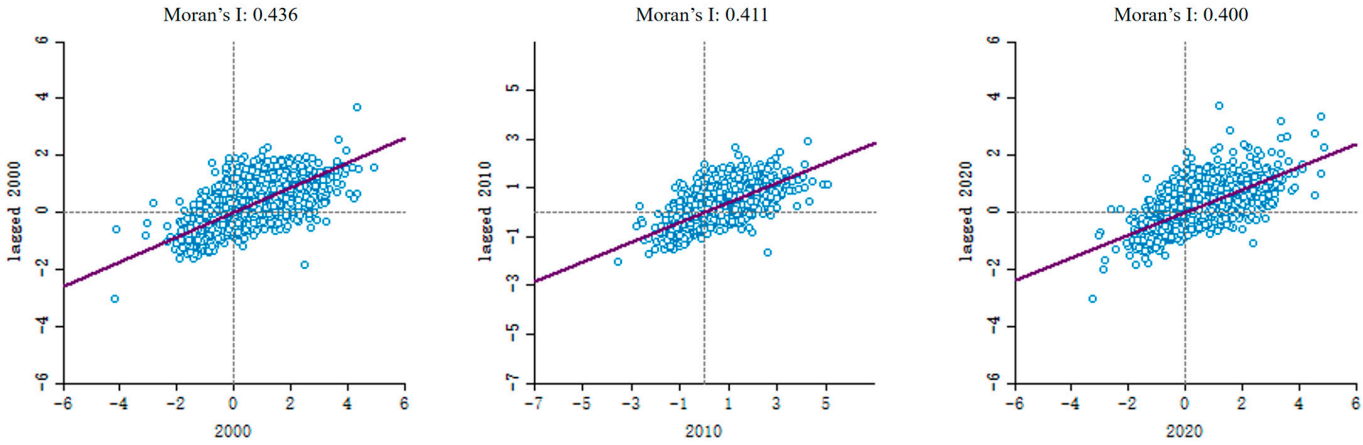


Figure 7. Scatter plot of Moran's index.

3.2.2. Local Autocorrelation Analysis

For further analysis, the local specific analysis of spatial autocorrelation of ecological sensitivity in the study area was carried out by calculating the local Moran index to analyze

the specific spatial clustering characteristics, identifying "red line areas" to be avoided as much as possible for subsequent highway alignments (Figure 8). The local spatial autocorrelation divides the study area into five scenarios: High–High clustering (HH), High–Low clustering (HL), Low–High clustering (LH), Low–Low clustering (LL), and insignificant to explain the local clustering situation in the study area. For example, HH that means that the area itself belongs to the high-value region, and the periphery is still surrounded by high-value regions, so it is called High–High clustering.

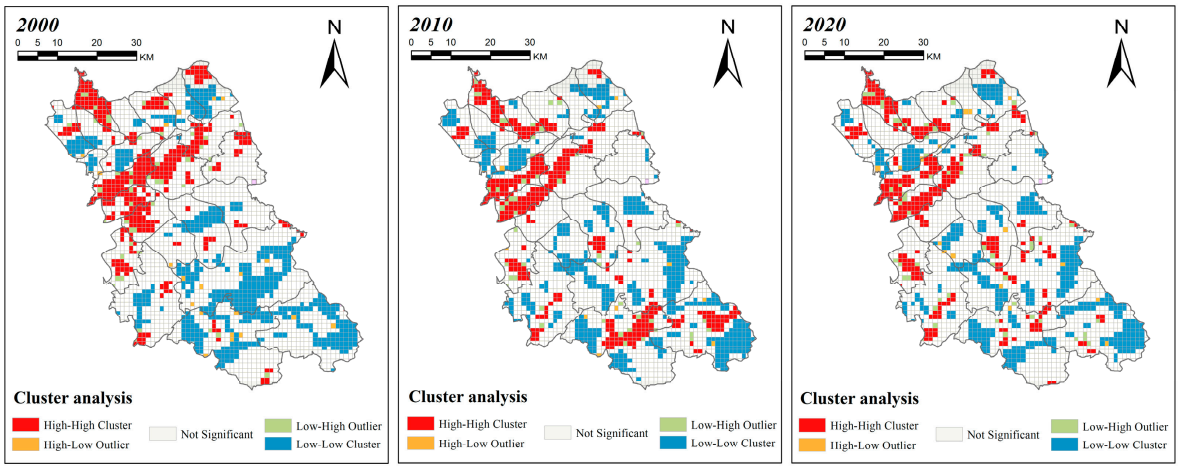


Figure 8. Local autocorrelation clustering diagram.

The results of the analysis show that the aggregation of ecological sensitivity in the study area mainly shows a trend of high in the northwest and low in the southeast. Areas of the HH clustering are mainly located in the northwestern Xixiping Township, Jinyan Township, Shuangxiqiao Township, and Xiehe Township. The LL clustering area is mainly located in the southeastern Qijiaping Township, Qinglang Township and Wuqiangxi Township. Between 2000 and 2010, Qinglang Township and Wuqiangxi Township in the southeast of the study area generated a large amount of HH, while at the same time, the LL clustering area in the neighboring Qijaping Township decreased significantly. However, between 2010 and 2020, both the high-value aggregation area and the low-value aggregation area in Qinglang Township and Wuqiangxi Township decreased and dispersed, and the whole area tended to be discrete. The overall tendency is toward discrete development. In conclusion, during 2000–2020, the spatial distribution of ecological sensitivity in the study area fluctuated but overall tended to be discrete.

3.2.3. Cold and Hot Spot Identification

Cold and hot spot analysis was carried out by the Getis-Ord G*I index [50] in ArcGIS to identify the key areas of ecological sensitivity cold hotspot distribution in the study area. The results showed that the highly significant hotspot areas (99% confidence level) for ecological sensitivity in the study area were mainly concentrated in the northwestern Xixiping Township, Sanqiao Township, and Jinyan Township areas, and the rest of the hotspot significant areas were mostly distributed in their periphery. There are fewer ecologically sensitive cold spots than hot spots, and the highly significant cold spots (99% confidence level) are mainly located within Yanghuping Township and Wuqiangxi Township (Figure 9).

Between 2000 and 2010, a large number of highly sensitive hotspots appeared in the Yuan River watershed within Wuqiangxi Township and Qinglang Township; however, the hotspots in the watershed were gradually dispersed from 2010 to 2020, and the hotspots in the northeastern part of the study area also showed the same trend of dispersion. The overall ecological sensitivity of cold spots and hot spots in the study area in 2020 showed

the phenomenon of "small patches, fragmentation". As the clustering of the study area is decentralized, the distribution of regional hot and cold spots is also gradually dispersed.

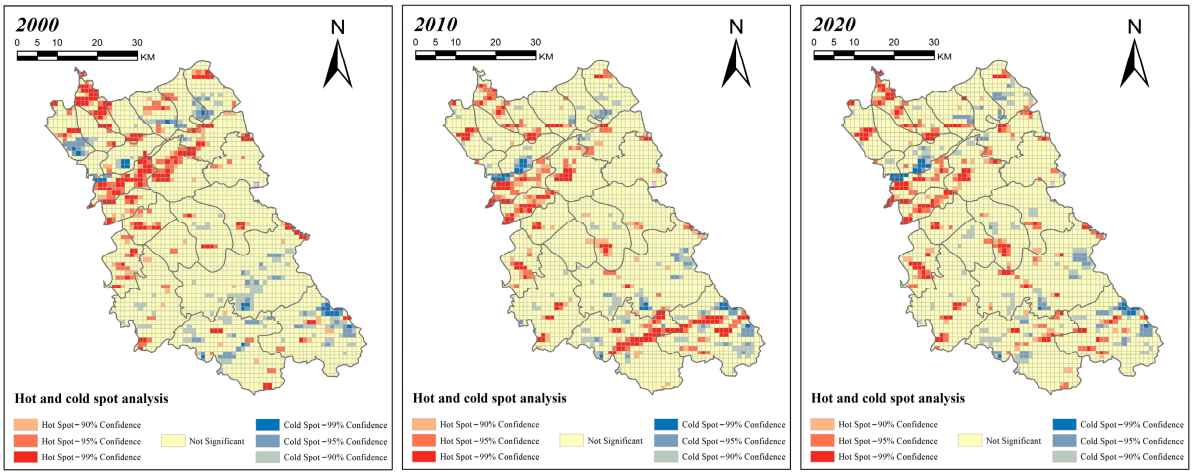


Figure 9. Cold and hot spot analysis map.

3.3. Optimization of Road Alignment Based on Ecological Sensitivity Evaluation

3.3.1. Interpretation of Ecological Sensitivity of Traditional Highway Alignments

Traditional highway alignment mainly focuses on all kinds of technical and economic indicators [51], such as road length, project cost, etc., with less direct consideration of ecological environment factors. Preliminary interpretation shows that the A-line scheme, which is more advantageous in the traditional alignment selection, involves the ecological sensitivity of high-value aggregation areas mainly for A5+100~A12+000, A47+300~A56+200, and other road sections (Figure 10). These are in the area of the nature reserve and other highly sensitive areas, with high impacts on biodiversity and water conservation, and overloaded environmental carrying capacity. Among them, the section A7+600~A12+000 involves the northwestern HH gathering area and crosses the giant salamander national nature reserve six times, which has a significant impact on the ecological environment, and the topography of the ravine is steep and narrow, which makes it difficult to construct the bridges and roadbeds of the A-line scheme. The section A48+300~A56+340 involves the southern HH gathering area and crosses a large area of ecological red line area. The A47+600~A48+500 Dongting Creek Yuanshui Bridge section terrain is cut by Dongting Creek three times, resulting in a large bridge size and complex construction environment when the route plan crosses the reservoir, in which the geological conditions at Duquanping Bridge Platform are poor, the bank slope stability presents a potential danger, and there are problems such as the long-distance occupation of an ecological red line. The A32+120~A34+080 section routed against the mountain to shorten the bridge size to 395 m, but because of the steep terrain, there are two high slopes (H1: 95 m, H2: 75 m) that present problems. For A49+500 in Duquanping, 65 m above the tunnel, there is a reservoir in the Wuqiangxi Formation slate and Aurora Nantuo Formation moraine containing conglomeratic siltstone with an uneven and broken contact surface of the rock, making it prone to water surge phenomena. Comparative studies of ecological sensitivity data and related clustering in the research area from 2000 to 2020 reveal significant spatial patterns in the evolution of ecological risk. To prevent the further fragmentation of ecologically vulnerable zones, there is an urgent need for more refined route optimization strategies to address this challenge.

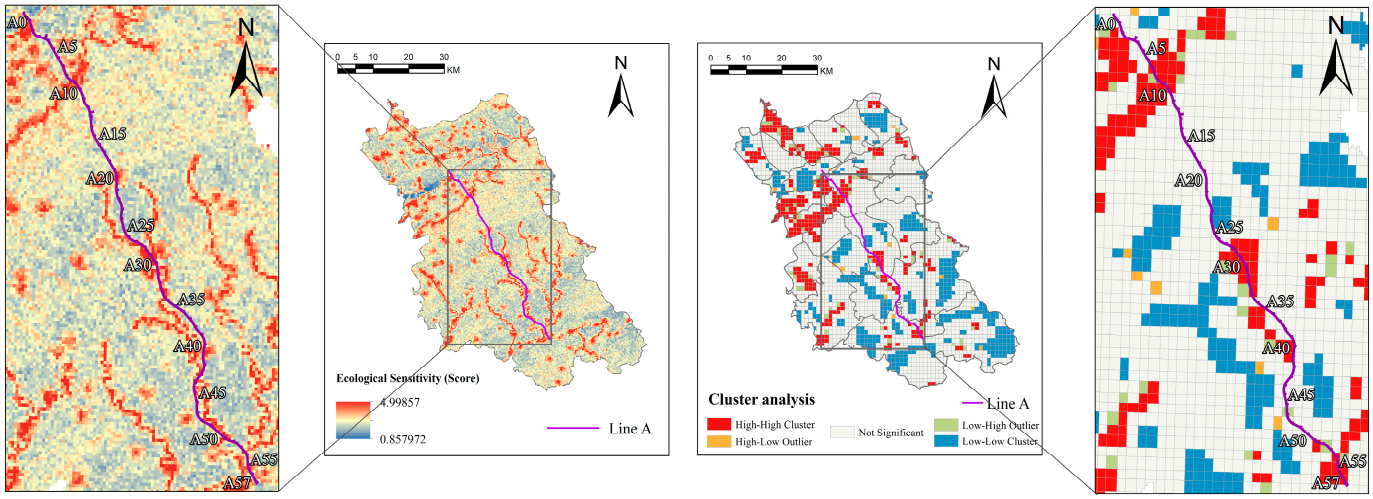


Figure 10. The ecological sensitivity of the area through which the A line passes.

3.3.2. Optimization of Road Alignment Based on Ecological Sensitivity Assessment

Based on the results of the ecological sensitivity assessment and the spatial autocorrelation of ecological sensitivity mentioned above, the K-line of the optimization plan is drawn, taking into account the appropriateness of the project construction as well as the economy (Figure 11). The K line basically avoids the northwest and the south of the ecological sensitivity of the higher corridor zone, which is the route for the Tou Shu Chong–Lao Yangping–Xinqiao–Hejia Au medium and low ecological sensitivity corridor zone.

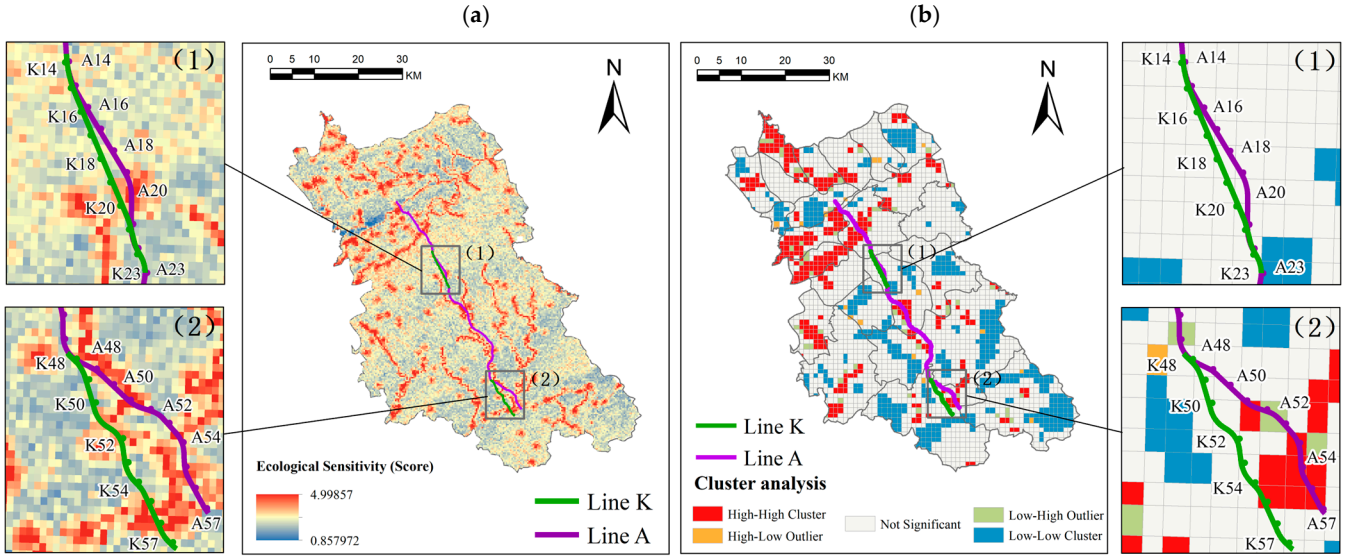


Figure 11. K-line optimization scheme: (**a**) K-line involves ecologically sensitive values; (**b**) K-line involves ecologically sensitive clustering areas.

(1) HH clustering in the southern nature reserve: The ecological patches in this area are fragile and highly disturbed by human activities. Therefore, for environmental protection, the avoidance and protection of highway alignment is very important. Firstly, the line position of the A48+300~A56+540 section is moved to the K48~K56 section to avoid occupying Wuqiangxi National Wetland Park and the ecological red line, reflecting the idea of "strengthening ecological alignment, avoiding ecological environment-sensitive areas such as nature reserves and water source protection zones according to law". The K45+000~K63+100 section in the Dongting Creek Yuan River Bridge is moved to the west side of the A-line position 2 km near Qinglang Township, solving the A-line program of

complex geological conditions, difficult construction conditions, poor ecological benefits, etc. For the main span of the 800 m span across the Yuan River, no piers fall into the river channel nor do they encroach on the water area, and the width of the river reduces water pollution. The bridge length is reduced by 3319.5 m, the tunnel is increased by 1835 m, and the bridge–tunnel ratio is more reasonable, reflecting the principle of "integrated planning, rational layout, intensive and efficient" for green highways.

(2) HH clustering in the northwest source protection area: This area is mainly the Zhangjiajie Giant Salamander National Nature Reserve, which is the birthplace of the river and Yuan River in China, a regional ecological protection barrier and a key ecological source protection area. Thus, the protection and restoration of the habitats of rare and endangered species should be strengthened. The route scheme of the K7+600~K12+000 section is 1.8 km eastward compared with the plane of the A line, and it adopts bypassing and setting up tunnels, which reduces two instances of crossing the buffer zone of the giant salamander protection area. The A7+600~A12+000 section is shifted 1.8 km to the east, bypassing and tunneling, reducing the number of crossings of the buffer zone of the giant salamander protection zone, avoiding the steep terrain on both sides of the valley, reducing the ecological damage, and increasing the feasibility of implementation.

(3) Soil and water conservation area: The region is mainly located in the central part of the study area, and the distribution area is wide. The ecological function area of the Wuling Mountains features irrational land use, especially high and steep slopes, and forest destruction, leading to vegetation degradation in the region, soil erosion, and aggravated geologic hazards. In the A32+120~A34+080 section, the lithology of the strong weathering of sandy slate is dominated by the use of continuous high steep slopes, and it is not conducive to the project safety. There are two high slopes with a large amount of earth and rock, as well as mountain crushing on the environment, making it not conducive to soil and water conservation. There is a need for careful consideration of the section to bridge instead of the high slopes roadbed. The A49+500 Duquanping Tunnel has contact face rock fragmentation, necessitating rerouting the K line 2.2 km to avoid reservoirs and tunnels susceptible to water surge hazards. A32+120~A48+500 along the line of the sloping mountain and backward-sloping valleys are arranged in between, featuring the formation of a large number of smooth slopes. Smooth slopes are stable in the natural state [52], which is good for the stability of the bridge pier slope and the stability of the tunnel entrance and exit side slope.

3.3.3. Highway Construction Suitability and Ecological Restoration Strategies

Highway optimization based on the analysis of the spatial and temporal evolution of sensitivity in ecologically fragile areas allows for site-specific ecological restoration measures to effectively prevent further fragmentation and the loss of ecosystems.

In terms of vegetation cover and landscape fragmentation, the A36–A42 section mainly passes through the Taiping Mountain, Jingzhushan and other hilly areas in the central mountains with the distribution of meso-subtropical evergreen broad-leaved forests (A36–A38, A40–A42), economic forests (A48–A52), and thickets (A34–A35). It is important to pay attention to the ecological stability of meso-subtropical evergreen deciduous forests and mixed forests. The ecological stability of subtropical evergreen deciduous forests and mixed forests reduces anthropogenic activities' interference on the region. The homogeneous landscape tends to discontinuous, heterogeneous, and complex patches; the design does not cross the ecological function protection zone, and it also avoids high filling and deep excavation of the roadbed. It mainly passes through the bridge and tunnel, reducing the ecological interference to a minimum. The extremely sensitive and highly sensitive areas in the road range are ecologically restored by Soil-Moisture Spray Irrigation Technology [53], and the red and yellow loam section (including maroon soil) adopts grass seed (40% bermudagrass + 30% tall fescue + 30% white clover) with shrub seed (25% big-leaf huzhizi + 25% firebuckthorn + 10% yellow bauhinia + 10% silver cohosh + 15% multiflora magnolia + 15% yellow acacia). The crushed stone and all strongly weathered slate slopes

adopt grass seed (40% bermudagrass + 60% tall fescue) and shrub seeds (20% magnolia + 20% sea buckthorn + 20% saltbush + 20% acacia + 20% acacia japonica) to restore the regional native characteristic vegetation.

In terms of the protection of waters and scenic resources, there are many water systems and protected areas along the project, mainly involving the river and part of the Dongting Lake watershed, and the upper reaches of the river are dominated by medium to highly sensitive zones, which can be protected against soil erosion through ecological measures such as slope protection and soil consolidation. In the buffer zone of the watershed of the mountain broken area, one can choose moisture-resistant vegetation for greening and restoration to achieve ecological flood control and water retention and transportation. Meanwhile, at present, Wuqiangxi National Wetland Park has been developed to a certain extent and is oriented as a narrow corridor from the southwest to the northeast. Dongting Creek Yuan Shui in the park area is at A9+540, so a special bridge is used to span across, which does not involve the scope of the red line of ecological protection, and none of the bridge schemes involve the construction of underwater piers. The bridge runoff collection system, oil-water separation tank, and other facilities are set up to prevent the oil pollution from flowing directly into Dongting Creek, Yuan Shui, and other protected waters. It is important to establish an emergency plan to prevent possible risky accidents.

In terms of land use and geologic hazards, the project along the route is mostly a mountainous area with complex topography with a height difference of 120–600 m, and there are more lateral steep sections; conventional filling will form high fill and occupy more land, and it is necessary to set up higher embankment walls. It is also recommended to set up a lightweight roadbed for A31+930–A32+990 and A43+732–A44+298; for the land use of the areas of medium and low sensitivity, the land use of the areas should expand the biodiversity growth potential, improve the stability of plant communities and optimize the ecosystem structure. Geological hazards along the route are mainly landslides and caves (A46–A47), which should be avoided as much as possible in the selection of routes, and anti-slip support, anchoring, and slope slowing and other measures should be adopted in the engineering.

4. Discussion

Traditional routing research primarily emphasizes the economic and safety aspects of highway construction, often overlooking ecological protection. This study, however, prioritizes ecological sensitivity by conducting field assessments of regional ecological characteristics and selecting various suitability indicators. It comprehensively evaluates the spatial and temporal distribution of ecological sensitivity, aiming to avoid highly sensitive areas to develop an optimal highway routing strategy that minimizes ecological damage during construction. Additionally, it offers a novel perspective and methodology for considering ecological impacts in highway planning and design. This research approach can also serve as a comprehensive technical framework for routing tourism highways in ecologically fragile areas, guiding practical applications in highway routing. The following discussion is based on these research findings:

(1) This study uses ecological sensitivity analysis, spatial autocorrelation and other methods, while taking into account the suitability and economy of the project, to optimize the selection of the road in the ecologically sensitive area of Zhangjiajie Wuling Mountain Area, section A0+000~A56+438. After examination, the original A line has crossed the ecological protection zone many times and involves more highly sensitive areas. Therefore, this sensitivity study is focused on optimizing the selection of the K line. The K line in its road section greatly reduces the crossing of the ecological protection zone and reduces the impact on the ecological environment, but there are still parts of the road section that inevitably cross the ecological protection zone. Therefore, in the subsequent control, it is still necessary to strengthen the supervision and monitoring of these road sections to ensure that they do not affect the migration of organisms in the protected areas and to protect the natural ecosystem while ensuring the safety of driving.

(2) This study's highway routing method, focused on ecological sensitivity, theoretically avoids highly sensitive areas, reducing ecological damage. However, practical implementation must consider additional factors. The optimal ecological route may not be the best highway route due to constraints like geological stability and land use planning. The selected optimization scheme K incorporates ecological sensitivity alongside engineering suitability and economic conditions. Therefore, future research should comprehensively address various factors and refine the alignment optimization strategy based on local site characteristics.

(3) Government policy cooperation is particularly important in the practical application of this study [54]. Although theoretical and methodological aspects were explored, the route selection process involved multiple local government departments. Future research should focus on the operationalization of policy development to gain deeper insights. Policy development should consider the feasibility of embedding ecologically sensitive service routes. After proposing an optimization strategy for highway routing, a basic implementation framework is crucial to guide constructors in applying ecologically sensitive routing techniques. In addition, dynamic ecosystems require continuous assessment and policy adjustments by the government are required during the implementation process. Establishing an ecological monitoring system to assess the environmental impacts of highway construction in real time [55,56] will provide a scientific basis for policy adjustments and ensure flexibility and long-term ecological protection.

In addition, there are still some areas for improvement, particularly in the selection of the nine key indicators for assessing ecological sensitivity, which, while generally adequate, have limitations. Future research should consider expanding the assessment indicators to better reflect local ecological resource characteristics and enhance ecological analysis. Additionally, the use of the Analytic Hierarchy Process (AHP) for weighting ecological sensitivity indicators presents challenges, including subjectivity and limited scientific rigor. It is advisable to explore the integration of AHP with quantitative models (e.g., cost–benefit analysis [57], system dynamics [58]) in future studies to mitigate subjectivity through expert assessment and data validation, yielding more reliable outcomes.

5. Conclusions

This paper carries out a comprehensive assessment of the ecological sensitivity of the A0+000~A56+438 section of the Guanzhuang Tourist Highway in the Zhangjiajie Wuling Mountain Area from 2000 to 2020 based on the AHP method and uses spatial autocorrelation analysis to reveal the spatio-temporal pattern of regional ecological sensitivity, and it finally optimizes the highway routing strategy based on the assessment results. The specific results contain the following three points:

(1) In 2000, 2010, and 2020, the ecological sensitivity scores in the study area were 1.5858–5.7956, 1.2924–6.1138, and 0.8579–4.9985, respectively; the overall ecological sensitivity scores were low, and the areas of relatively high sensitivity were mainly located on both sides of the north and south rivers. In 2000–2010, the sensitivity slightly increased, but in 2010–2020, the ecological sensitivity within the region significantly decreased, and the area of moderate ecological sensitivity went to zero. Generally speaking, the overall ecological sensitivity of the study area is at a low level, and the natural environment is highly resilient to highway construction and presents good conditions for highway construction.

(2) The global Moran index of the study area in 2000, 2010, and 2020 is 0.4360, 0.4111, and 0.4000, respectively, which are all greater than 0. That is to say, the spatial distribution of ecological sensitivity in the study area has strong autocorrelation, and the areas of higher ecological sensitivity have produced the phenomenon of aggregation. The hotspot areas are mainly distributed in the northwest as well as the southeast, and the significant hotspot areas are mainly concentrated in the northwestern Xixiping Township, Sanqiao Township, and Jinyan Township areas. Finally, although the distribution of ecological sensitivity in the study area fluctuated during the period of 2000–2020, the overall trend toward discrete development has been formed.

(3) The A-line scheme of traditional highway routing crosses several ecologically fragile areas, which are characterized by high ecological risks and difficult construction. In order to improve the ecological protection effect, based on the ecological sensitivity optimization, the K-line scheme of route selection can effectively avoid highly sensitive areas and minimize ecological damage by adjusting the route and bridge settings. In addition, based on the differences in the ecological conditions of each road section, the suitability of engineering construction and ecological restoration strategies for different road sections are proposed in terms of vegetation cover, landscape risk, and geological hazards with the road stumps of each section as the boundaries to realize the harmonious development of highway construction and ecological environment.

The optimization strategy of highway routing proposed in this paper based on the ecological sensitivity study can effectively maintain the health of the regional ecological environment and guarantee the sustainable development of the road, providing a new perspective and methodology for the field of highway planning and design to comprehensively consider the impact of the ecological environment, enriching the theoretical system for the coordinated development of infrastructure construction and ecological protection in ecologically fragile areas. The results of the study can be used as a comprehensive technical chain for tourism highway routing in ecologically fragile areas, guiding the practice of highway routing, effectively avoiding high ecological risk areas, reducing construction difficulties and ecological damage, and promoting the harmonious development of highway construction and ecological environment.

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