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Original Research

Ecological Sensitivity Assessment of Central Plains Cities Using RS/GIS Technology: A Case Study of the Zheng-Bian-Luo Urban Agglomeration

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Abstract

Focusing on the Zheng-Bian-Luo urban agglomeration in the Central Plains, this study selected six key indicators: elevation, aspect, slope, land-use type, vegetation coverage, and water buffer zone. The Delphi method, analytic hierarchy process, and weighted overlay were used to conduct a comprehensive ecological sensitivity analysis. The findings indicate that the water buffer zone exerts the most significant influence on the ecological sensitivity of the Zheng-Bian-Luo urban agglomeration, while elevation has the least impact, with respective weights of 0.308 and 0.049. The areas of extremely low and mildly sensitive ecological sensitivity in the Zheng-Bian-Luo urban agglomeration cover approximately 5872.48km², representing 31.59% of the total. These areas, primarily human-occupied and urbanized, are dispersed and concentrated in the eastern and southeastern coastal regions. The moderately sensitive areas encompass approximately 10,763.64km², constituting 37.07% of the total area. The area is mainly affected by factors such as terrain, vegetation coverage, aspect, and slope. The overall layout is relatively scattered. Therefore, while moderately developing the area, we must also pay attention to ecological protection and increase vegetation planting on the basis of shrubs. The areas classified as extremely high and highly sensitive encompass approximately 9096.96km², constituting 31.33% of the total. Primarily situated in water bodies and buffer zones, these areas require a focus on water and soil erosion issues. Overall, there is a consistent spatial distribution pattern showing a gradual decrease from northwest to southeast. Evaluating and analyzing the spatial distribution and extent of the ecological environment in the Zheng-Bian-Luo urban agglomeration provides valuable insights for future environmental protection and urban planning efforts in the region.

Keywords: RS/GIS technology, Zheng-Bian-Luo urban agglomeration, ecological sensitivity, spatial distribution

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Introduction

As the economy and society rapidly develop, the scope and intensity of human activities' impact on the natural environment are escalating, posing a serious threat to ecosystem functions and services across various scales [1, 2]. In a natural state, various elements of the ecological environment maintain a delicate balance and coupling. When an element is perturbed by external factors and surpasses a specific threshold, the original balance is disrupted, resulting in ecological environment degradation [3, 4]. Specific change results: Ecological environment sensitivity is a concept that describes an ecosystem's reaction to disturbances, which can come from human activities or shifts in the natural environment. It measures how much an ecosystem is affected by these external factors and signifies the potential risk for regional ecological and environmental issues. When human activities or external forces are of the same intensity, this sensitivity level can predict the severity of problems. Performing an ecological sensitivity assessment is crucial because it can serve as an early warning for potential ecological and environmental problems in a region. Furthermore, it provides critical guidance, helping to balance regional development with the need for ecological protection [5].

Ecological sensitivity delineates the degree to which an ecosystem is influenced by both natural environmental factors and anthropogenic activities, indicating the magnitude and probability of ecological and environmental challenges within the study area [6, 7]. Both domestic and international researchers have undertaken extensive investigations into ecological sensitivity, with their inquiries concentrating on the impact of ecological sensitivity assessments on the broader ecological environment.

Scholars both domestically and internationally have shown significant interest in ecological sensitivity. Foreign studies in this field predominantly concentrate on the responsiveness of wetlands and their flora to climate fluctuations, the ecological sensitivity of rainforests to selective logging practices, the hydrological system's susceptibility to climate change, and the ecological dynamics of coastal zones and continental shelves, including the demarcation of nature reserves and related sensitivities [8, 9]. Investigating the ecological sensitivity of lakes to climate warming, it was determined that such warming has precipitated increased ecological vulnerability in mountain lakes [10]. Establish nature reserves based on assessments of the habitat ecological sensitivity index, ecosystem pressure value index, and population pressure index [11].

Domestic research into ecosystem sensitivity has garnered growing interest. Evaluation criteria have transitioned from addressing singular ecological sensitivity issues to a more holistic evaluation of ecological sensitivity. Nonetheless, studies have predominantly centered on specific ecological concerns, cities, or broader-scale investigations. The methodology has evolved from qualitative approaches to quantitative evaluation techniques, notably by leveraging GIS and other advanced technologies, thus facilitating a more precise and geographically targeted analysis of evaluation outcomes [12-14]. By targeting prevalent ecological issues such as land desertification, soil erosion, and rocky desertification within terrestrial ecosystems, we aim to develop evaluation criteria and models for conducting a thorough assessment of ecological sensitivity [15]. An ecological sensitivity assessment of the land was conducted based on five dimensions: soil erosion, rocky desertification, biodiversity, geological hazards, and aquatic environments [16]. Employing the ArcGIS area-based statistical approach, four indicators – soil erosion, soil salinization, soil desertification, and biodiversity – were chosen for a quantitative assessment of land ecological sensitivity [17]. Leveraging mountainous ecological features and human activities, remote sensing and GIS technologies were employed, utilizing a factor-weighted superposition method to identify five key factors: elevation, slope, vegetation coverage, water area, and susceptibility to geological disasters, for a comprehensive ecological sensitivity assessment of the urban area [18]. A multi-factor comprehensive analysis approach was employed to identify indicators for ecological sensitivity evaluation, including hydraulic erosion sensitivity, freeze-thaw erosion sensitivity, desertification sensitivity, and rocky desertification sensitivity [19].

However, the depth of research into the ecological sensitivity evaluation of the Central Plains urban agglomeration in inland areas is still inadequate. In recent years, the Zheng-Bian-Luo urban agglomeration has faced increasingly prominent ecological and environmental challenges, with economic interests fueling unsustainable industrial expansion. Urban domestic sewage management lacks standardization, leading to a significant decline in the proportion of high-quality water. Additionally, non-point source pollution from agriculture and animal husbandry has emerged as a serious issue.

The development of the Zheng-Bian-Luo urban agglomeration, coupled with ecological environmental imbalances, has heightened scholarly focus on urban ecological issues. Nonetheless, the exploration of ecological sensitivity within the Zheng-Bian-Luo urban agglomeration remains superficial. In light of this background, this study targets the Zheng-Bian-Luo urban agglomeration, amalgamates existing ecological challenges, identifies factors for ecological sensitivity evaluation, and formulates a scientifically robust evaluation index system. Utilizing GIS support, the study evaluates and analyzes the spatial distribution and magnitude of ecological challenges in the Zheng-Bian-Luo urban agglomeration, providing insights for subsequent efforts in environmental conservation and urban planning.

Study Area Overview

The Zheng-Bian-Luo urban agglomeration, located in Henan Province, China, comprises three primary cities: Zhengzhou, Kaifeng, and Luoyang, along with several surrounding secondary cities and counties (Fig. 1). Zhengzhou covers an area of 7567 square kilometers, Luoyang spans 15230 square kilometers, and Kaifeng encompasses 6239 square kilometers. Collectively, the Zheng-Bian-Luo urban agglomeration occupies 29036 square kilometers. This region boasts a rich history and deep cultural heritage, serving as the political, economic, and cultural hub of Henan Province [20].

Economically, the Zheng-Bian-Luo urban agglomeration boasts substantial regional advantages and collaboration potential. As the capital and a vital transportation hub of Henan Province, Zhengzhou has thrived in the manufacturing, logistics, and modern service sectors. Meanwhile, Kaifeng and Luoyang are renowned for their abundant historical and cultural assets, making them significant cultural and tourist hubs in China. However, urban agglomeration faces significant ecological and environmental challenges, such as water scarcity, soil degradation, and biodiversity loss [21]. Owing to rampant urbanization and industrial expansion, the region's ecosystem has undergone significant degradation and strain, leading to an escalation in ecological sensitivity [22].

Ecological sensitivity is a crucial metric for assessing a regional ecosystem's vulnerability to external disruptions and pressures, including factors like biodiversity, ecological stability, and land cover changes. In the Zheng-Bian-Luo urban agglomeration, heightened ecological sensitivity not only jeopardizes regional ecological security and sustainable development but may also exert adverse impacts on human health and socioeconomic stability.

Therefore, conducting comprehensive research on the ecological sensitivity of the Zheng-Bian-Luo urban agglomeration will not only clarify the ecological and environmental challenges in the region but also provide a vital scientific basis for regional sustainable development and ecological conservation.

Data Sources and Research Methods

Data Sources

This study primarily employs GIS spatial analysis and raster computing techniques, utilizing ArcGIS 10.2 and ENVI 5.3 as the data processing platforms. The dataset comprises GDEMV2 digital elevation data at a 30m resolution, administrative boundary data for the Zheng-Bian-Luo urban agglomeration, and Landsat 8 OLI remote sensing imagery. After preprocessing the Landsat 8 images from September 2020, the Normalized Difference Vegetation Index (NDVI) data was derived by computing the near-infrared and red bands. Land use data for the year 2020 was obtained from GLOBELAND30 (http://www.globallandcover.com/).

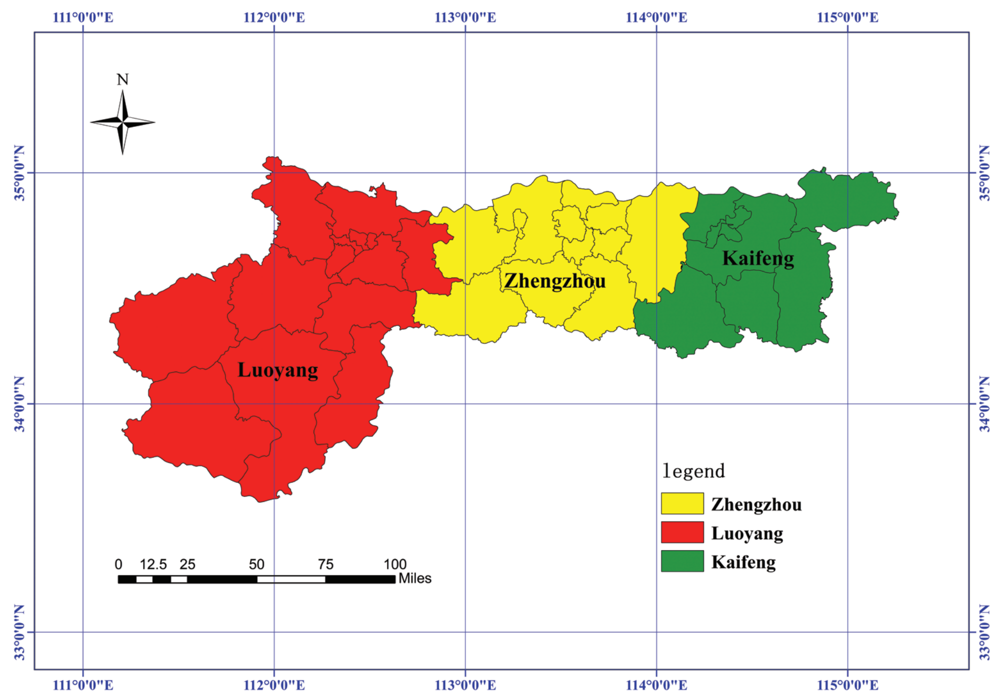

Fig. 1. Location Overview of the Zheng-Bian-Luo Urban Agglomeration.
(The illustration was crafted utilizing ArcGIS software, version 10.2. For further reference, the URL link is provided: https://www.arcgis.com/index.html)

Research Methods

Comprehensive Index Model

Utilize ArcGIS to generate a grid tool with a grid size set to 150m×150m, assigning each factor score to the respective evaluation unit. Subsequently, factors are weighted and overlaid, and the comprehensive ecological sensitivity index is computed using the weighted index method as per the following formula:

$$S_j = \sum_{i=1}^{n} C_{(i,j)} \cdot W_i \tag{1}$$

In the formula: i represents the evaluation index; j denotes the evaluation unit; W_i signifies the weight of the evaluation index i; S_j indicates the ecological sensitivity index of the evaluation unit j; C(i,j) signifies the score of the evaluation index i for the evaluation unit j.

Spatial Statistical Analysis

Utilize the ArcGIS statistical analysis function to conduct mathematical calculations on the spatial data of the Zheng-Bian-Luo urban agglomeration using various modeling methods. Calculate the proportion and regional area of each sensitivity level to analyze and assess the ecological sensitivity of the Zheng-Bian-Luo urban agglomeration.

Selection and Weight Determination of Evaluation Factors

The assessment of ecological sensitivity encompasses a diverse range of ecological factors, incorporating both natural and anthropogenic elements. Informed by the systematic and distinct attributes of the ecosystem, we draw upon the "Interim Regulations for Ecological Function Zoning" and "Guidelines for Delimiting Ecological Protection Red Lines" [23, 24]. Considering the ecological status of the Zheng-Bian-Luo urban agglomeration and other relevant factors, and grounded in the principles of scientific precision, the integration of quantitative and qualitative approaches, and practical applicability, we employed the Analytic Hierarchy Process (AHP) to establish an evaluation index framework [25]. Targeting comprehensive ecological sensitivity as the primary layer, we selected six ecological sensitivity factors – slope, elevation, aspect, distance to water, land use type, and NDVI – as the criteria layer for the Analytic Hierarchy Process (AHP). Each factor's ecological sensitivity was categorized into five levels, corresponding to the assigned values of 1, 3, 5, 7, and 9, respectively, and subsequently submitted to experts for sensitivity assessment. Following a consistency test of the data for each evaluation factor, weights were computed using Matlab software through the AHP methodology, as illustrated in Table 1.

These indicators were selected based on their measurability, impact on ecosystem processes, and their widespread recognition and application in ecological assessments. Elevation is a key topographic factor affecting climate, the hydrological cycle, and biodiversity distribution. Areas at different elevations may support different ecosystem types and thus have varying susceptibility to environmental changes. Slope affects the speed and direction of surface water flow, which in turn affects soil erosion, material transfer, and the quality of biological habitats. Steeper slopes are generally more susceptible to soil erosion. The slope aspect determines the degree to which the terrain receives solar radiation, affecting local climate and vegetation growth. Areas with different slope aspects can have significant differences in temperature, humidity, and biodiversity. In addition to the above indicators, CESI may also include soil type, vegetation coverage, surface moisture, etc. These indicators jointly determine the ecological sensitivity of the region.

The study of the Comprehensive Ecological Sensitivity Index provides a scientific basis for the government and relevant departments to formulate environmental policies and regulations, ensuring their scientific basis and effectiveness. At the same time, it also helps policymakers and environmental planners identify ecologically fragile and sensitive areas to take appropriate measures in land use planning, resource development, and ecological protection.

Table 1. Grading Criteria for Ecological Sensitivity Evaluation Factors in the Zheng-Bian-Luo Urban Agglomeration.

Rate	Elevation	Slope	Aspect	NDVI	Land Use Type	Distance to water	Rate
Very Low Sensitivity	0-320 m	0-5°	South	<0.1	Construction land unused land	>800 m	1
Mild Sensitivity	320-640 m	5-15°	Southeast, southwest	0.1-0.3	Arable land	600-800 m	3
Moderate Sensitivity	640-960 m	15-30°	East, west	0.3-0.5	Grassland	400-600 m	5
High Sensitivity	960-1300 m	30-45°	Northeast, Northwest	0.5-0.7	Woodland	200-400 m	7
Extreme Sensitivity	>1300 m	>5°	North	0.7-1	Water body	<200 m	9
Weights (%)	4.73%	7.51%	10.15%	28.30%	18.72%	30.59%	-

Table 2. Single-Factor Ecological Sensitivity Evaluation of the Zheng-Bian-Luo Urban Agglomeration.

Rate		Elevation	Aspect	Slope	NDVI	Land Use Type	Distance To Water
Very Low Sensitivity	Acreage	7981.99	4308.94	2450.63	34.84	574.91	22595.81
	Weights (%)	27.27	14.84	8.44	0.12	1.98	77.82
Mild Sensitivity	Acreage	7982.00	7479.67	9099.88	188.73	7627.75	1983.15
	Weights (%)	27.49	25.76	31.34	0.65	26.27	6.83
Moderate Sensitivity	Acreage	9126.01	6596.97	13675.95	963.99	813.01	1570.84
	Weights (%)	31.43	22.72	47.10	3.32	2.80	5.41
High Sensitivity	Acreage	3815.33	6936.70	3620.78	3713.70	19372.81	1681.18
	Weights (%)	13.14	23.89	12.47	12.79	66.72	5.79
Extreme Sensitivity	Acreage	130.67	3687.57	185.83	24137.62	638.79	1204.99
	Weights (%)	0.68	12.79	0.64	83.13	2.22	4.15

Results and Analysis

Single-Factor Ecological Sensitivity Analysis

Single-factor analysis of ecological sensitivity is a method employed to assess the influence of individual factors on ecosystem sensitivity [26, 27]. Within the context of the Zheng-Bian-Luo urban agglomeration, single-factor analysis of ecological sensitivity allows for the assessment of the influence of various factors – including slope, elevation, aspect, distance to water, land use type, and NDVI – on the area's ecosystem sensitivity.

Elevation

Elevation stands as a pivotal factor in ecological sensitivity assessment. Regional vertical differentiation primarily arises from fluctuations in elevation. Alterations in elevation induce climatic shifts, subsequently influencing the distribution of organisms and the vertical distribution patterns of ecosystems based on elevation [28, 29].

The altitude-based ecological sensitivity within the Zheng-Bian-Luo urban agglomeration is relatively modest. The areas of extremely high sensitivity and high sensitivity are predominantly located in the west and northwest, covering a combined area of 3946 km², which constitutes 13.82% of the total area. The moderate sensitivity zone spans 9126.01 km², making up 31.43% of the total area, and is situated

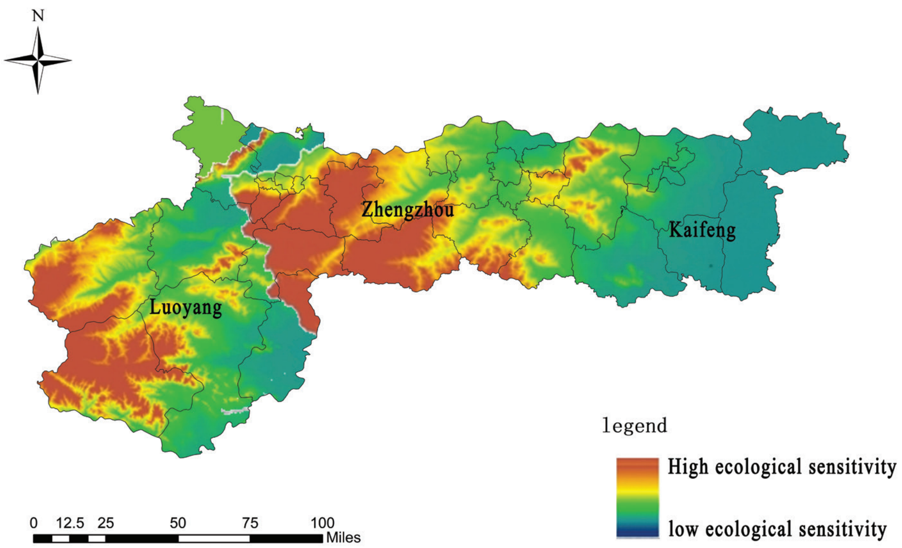

Fig. 2. Ecological Sensitivity Analysis Map Based on Elevation.
(The illustration was crafted utilizing ArcGIS software, version 10.2. For further reference, the URL link is provided: https://www.arcgis.com/index.html)

in the southwestern, central, and northern regions of the urban agglomeration. The low and extremely low sensitivity zones encompass 15963.94 km², accounting for 54.76% of the total area. These zones in the Zheng-Bian-Luo urban agglomeration mainly extend along the eastern and southeastern edges towards the southeast and south, following the direction of the valley. The topography generally rises from north to south and from west to east, as depicted in Fig. 2 and Table 2.

Slope

The slope indicates the steepness of the terrain. Such steepness frequently influences surface material movement and energy distribution, leading to environmental and ecological issues like water and soil erosion [30].

Within the Zheng-Bian-Luo urban agglomeration, slope-sensitive zones are mainly dispersed. However, areas of extreme and high sensitivity are mainly situated in the northern and northwestern regions, covering 3818.61 km², or 13.11% of the total area. The moderately sensitive area spans 13675.95 km², making up 47.10% of the total area. Regions with extremely low and mild slope sensitivity are relatively clustered, primarily located in the southern, southeastern, and southwestern water areas, covering 11550.51 km², or 39.78% of the total area. Consequently, the ecological sensitivity to slope across the entire Zheng-Bian-Luo urban agglomeration is predominantly moderate, with significant slope variations mainly concentrated in river valleys around water bodies, as illustrated in Fig. 3 and Table 2.

Aspect

The slope aspect affects solar radiation, light, and rainfall and therefore also affects ecological sensitivity. It is an important factor in the formation of microclimate conditions [31].

As illustrated in Fig. 4 and Table 2, the slope-sensitive zones also exhibit a dispersed distribution. The combined area of extremely low, low, and moderate sensitivity covers 18385.58km², making up 63.32% of the total area, while the high and extremely high sensitivity areas span 10624.27km², accounting for 36.68% of the total area. This indicates a relatively even distribution of sensitivity zones within the Zheng-Bian-Luo urban agglomeration, where mountains trend in diverse directions and the terrain is intricate.

Land Use Type

The land use categories within the Zheng-Bian-Luo urban agglomeration mainly consist of construction land, unused land, cultivated land, bare land, grassland, shrubland, and woodland [32, 33]. As illustrated in Fig. 5 and Table 2, the area of extremely low and lightly sensitive land use types spans 8202.66km², making up 28.25% of the total area, primarily concentrated in river valleys and flatlands. The area of moderately sensitive areas cover 813.01km², accounting for 2.8% of the total area, showcasing a dispersed distribution pattern within the Zheng-Bian-Luo urban agglomeration. The highly and extremely highly sensitive areas encompass 20,011.60km², constituting 68.94% of the total area, and are extensively distributed. The land types in the Zheng-Bian-Luo urban agglomeration generally exhibit high sensitivity, with woodlands, water bodies, and wetlands representing

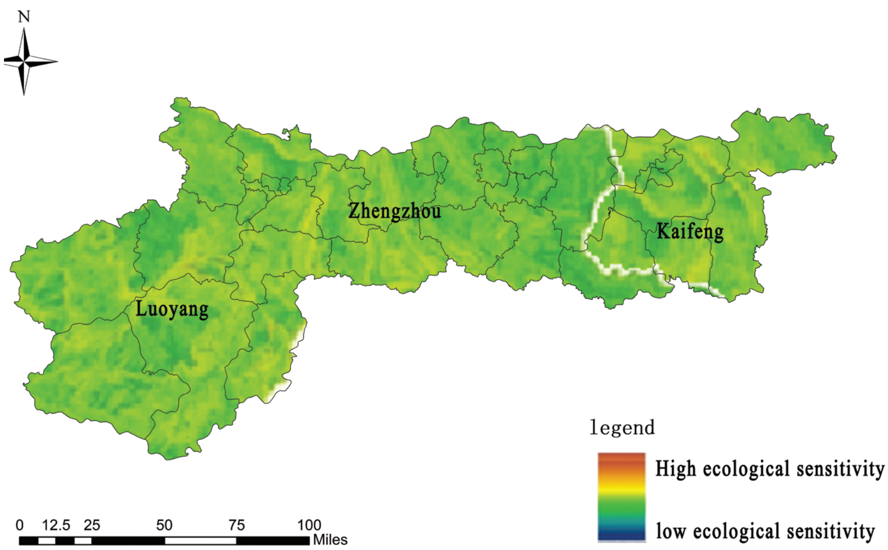

Fig. 3. Ecological Sensitivity Analysis Chart Based on Slope.
(The illustration was crafted utilizing ArcGIS software, version 10.2. For further reference, the URL link is provided: https://www.arcgis.com/index.html)

a significant proportion. Therefore, cautious approaches to development and construction are necessary, and comprehensive ecological planning should be implemented.

NDVI

Vegetation coverage serves as a crucial metric for evaluating surface vegetation conditions, providing valuable insights into vegetation growth and distribution patterns. As illustrated in Fig. 6 and Table 2, the area characterized by extremely low and mild ecological sensitivity spans 223.57 km², representing 0.77% of the total area, predominantly situated in the primary urban area and its adjacent suburban regions. The moderate ecological sensitivity area covers 963.99 km², accounting for 3.32%, mainly found in the northwest and east sectors of the city. The highly and extremely highly ecologically sensitive areas encompass 27851.32 km², constituting 95.92% of the total area.

The Zheng-Bian-Luo urban agglomeration exhibits a relatively high ecological sensitivity in terms of vegetation coverage, indicating abundant vegetation presence. In the developmental trajectory

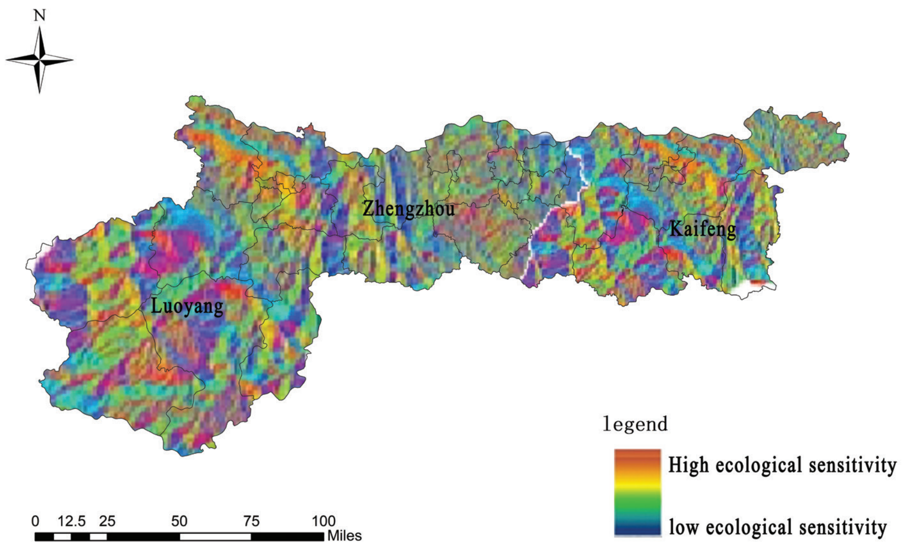

Fig. 4. Ecological Sensitivity Analysis Chart Based on Slope Aspect.
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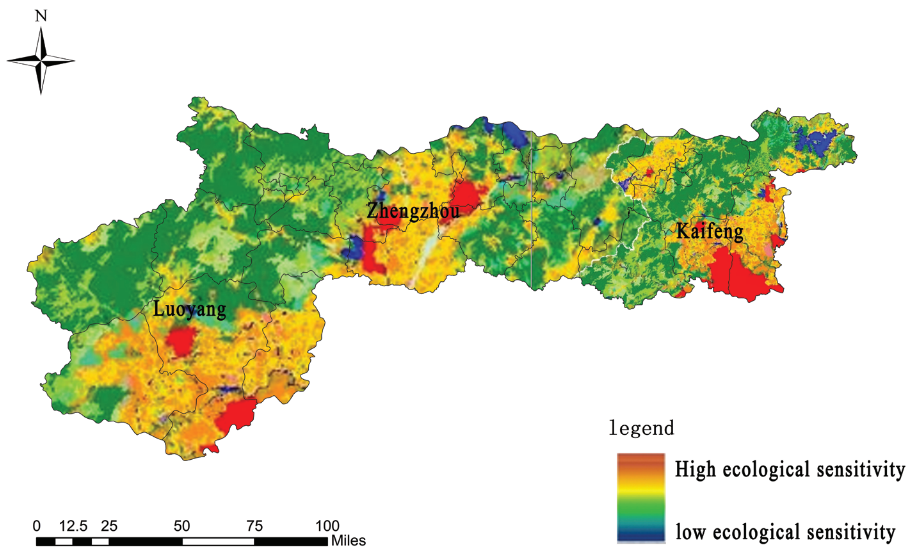

Fig. 5. Ecological Sensitivity Analysis Chart Based on Land Use Types.
(The illustration was crafted utilizing ArcGIS software, version 10.2. For further reference, the URL link is provided: https://www.arcgis.com/index.html)

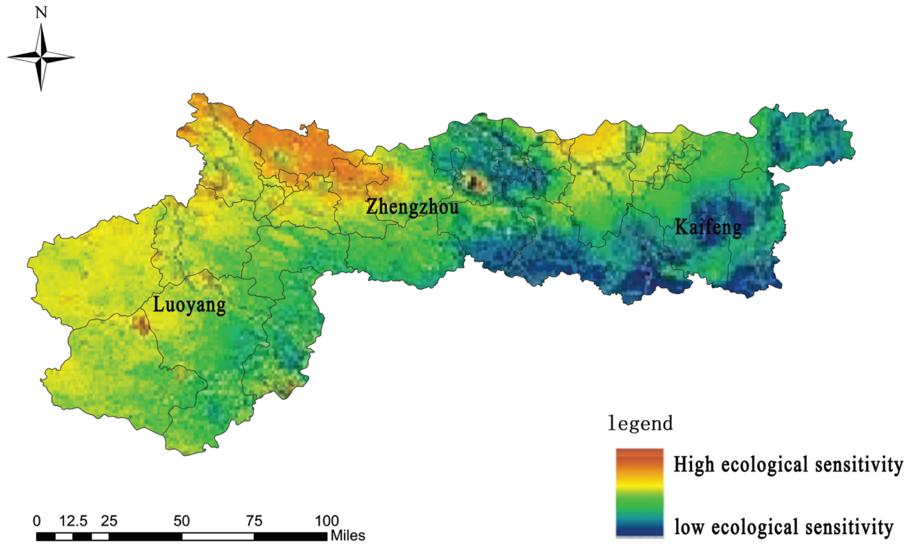

Fig. 6. Ecological Sensitivity Analysis Chart Based on NDVI.
(The illustration was crafted utilizing ArcGIS software, version 10.2. For further reference, the URL link is provided: https://www.arcgis.com/index.html)

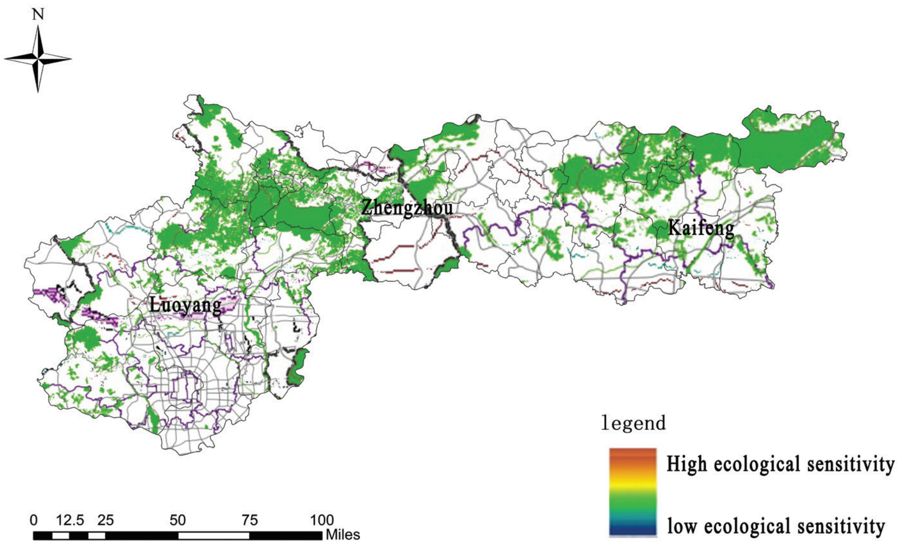

Fig. 7. Ecological Sensitivity Analysis Chart Based on Water System.
(The illustration was crafted utilizing ArcGIS software, version 10.2. For further reference, the URL link is provided: https://www.arcgis.com/index.html)

of the Zheng-Bian-Luo urban agglomeration, special attention should be paid to the conservation of greenery in areas of high ecological sensitivity. Concurrently, afforestation initiatives should be prioritized in low-sensitivity zones to mitigate potential ecological degradation.

Distance to Water

Positioned as a significant urban agglomeration along the Yellow River basin, the Zheng-Bian-Luo urban agglomeration boasts abundant and widely dispersed water resources [34-36].

As depicted in Fig. 7 and Table 2, the area characterized by extremely low ecological sensitivity predominates within the region, spanning 22595.81 km² and constituting 77.82% of the total area. Conversely, the high and extremely high sensitivity areas cover 2886.17 km², accounting for 9.94%, predominantly located in the Hutuo River, Luo River, Ru River, and Quan River basins. The Zheng-Bian-Luo urban agglomeration is intersected by numerous rivers, highlighting the necessity of establishing buffer zones to enhance water ecology protection. Effective management and conservation of the water system within the Zheng-Bian-Luo urban agglomeration

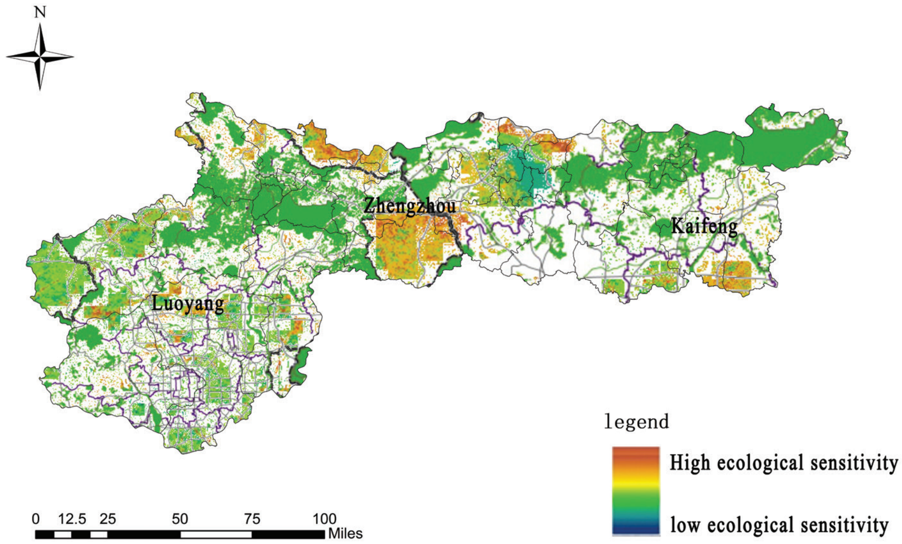

Fig. 8. Comprehensive Ecological Sensitivity Assessment Map of the Zheng-Bian-Luo Urban Agglomeration.
(The illustration was crafted utilizing ArcGIS software, version 10.2. For further reference, the URL link is provided: https://www.arcgis.com/index.html)

are pivotal for attaining regional ecological security and sustainable development. Therefore, enhancing the comprehensive management of water resources, optimizing water utilization efficiency, mitigating water pollution, and safeguarding the water ecological environment is essential to ensure the sustainable development and ecological security of the Zheng-Bian-Luo urban agglomeration.

Comprehensive Assessment of Ecological Sensitivity

The Comprehensive Ecological Sensitivity Index (CESI) serves as a quantitative tool for assessing ecological sensitivity and ecosystem vulnerability within a specific area. It determines how sensitive different areas are to natural or man-made disturbances by considering a variety of ecological and environmental factors. CESI is usually calculated through multi-criteria evaluation (MCE) or similar methods, involving the weighting and aggregation of individual ecological factors to form a single indicator value. The index can be used in environmental planning and management, especially in formulating land use strategies and ecological protection and restoration plans, to identify areas that require special attention.

Utilizing the spatial distribution data of single-factor ecological sensitivity and incorporating weights, we conducted overlay analysis in ArcGIS to derive a comprehensive ecological sensitivity distribution map for the Zheng-Bian-Luo urban agglomeration (Fig. 8).

As illustrated in Fig. 8 and detailed in Table 3, the areas of extremely low and mildly sensitive ecological zones in the Zheng-Bian-Luo urban agglomeration encompass approximately 5872.48 km², constituting 31.59% of the total area. These are mainly dispersed throughout the eastern and southeastern coastal regions, predominantly composed of human settlements and urbanized land. The moderately sensitive area spans approximately 10,763.64 km², accounting for 37.07% of the area, and is influenced by factors such as terrain, vegetation coverage, slope aspect, and gradient, exhibiting a relatively scattered distribution. Sustainable development in this region necessitates heightened ecological protection and the enhancement of vegetation, particularly focusing on shrub planting. The extremely high and highly sensitive areas cover about 9096.96 km²,

Table 3. Comprehensive Classification and Evaluation of Ecological Sensitivity in the Zheng-Bian-Luo Urban Agglomeration.

Rate	Rate	Ecological Sensitivity Index Classification	Acreage	Weights (%)
Very Low Sensitivity	1	1-2.52	2665.51	9.18
Mild Sensitivity	3	2.52-2.89	5605.97	22.41
Moderate Sensitivity	5	2.89-3.20	10763.64	37.07
High Sensitivity	7	3.20-3.67	6565.03	22.61
Extreme Sensitivity	9	3.67-4.86	2531.93	8.72

making up 31.33% of the region, and are primarily situated within water bodies and their buffer zones, warranting attention to water and soil conservation.

Conclusions and Discussion

The water buffer zone exerts the most significant influence on the ecological sensitivity of the Zheng-Bian-Luo urban agglomeration, while elevation has the least impact, with weights of 0.308 and 0.049, respectively. The findings of this study indicate a correlation between the distribution patterns of the factor with the highest weight and the overall ecological sensitivity distribution.

The single-factor evaluation of the Zheng-Bian-Luo urban agglomeration reveals that the areas of high and extremely high sensitivity within the water buffer zone are not widespread. Nevertheless, due to the abundant watersheds and intricate stream networks within the Zheng-Bian-Luo urban agglomeration, their spatial distribution remains notably expansive. Vegetation coverage, which carries the second highest weight, aligns with the distribution patterns of slope and elevation sensitivities. Specifically, land use in the northwest, characterized by higher elevations, consists predominantly of woodland and grasslands, while the southeastern region, with lower elevations, encompasses a broader spectrum of human activities and exhibits lower sensitivity. The sensitivity distribution in terms of slope aspect diverges from other factors, exhibiting a diverse and intricate pattern. This suggests that the terrain of the Zheng-Bian-Luo urban agglomeration is predominantly mountainous and hilly, with a multitude of valleys resulting in a dense distribution of slope aspects. Based on the various evaluation factors, the Zheng-Bian-Luo urban agglomeration should address issues of water and soil erosion stemming from elevation and slope, emphasize forestry protection, and concentrate on mitigating slope runoff while conserving and judiciously utilizing water and soil resources in the north and northwest.

The comprehensive ecological sensitivity in the Zheng-Bian-Luo urban agglomeration is predominantly moderate, exhibiting a spatial distribution that decreases gradually from northwest to southeast. Highly sensitive areas are predominantly influenced by water buffer factors, concentrating mainly in the Hutuo River and Ruhe River basins and their associated buffer zones. These sensitive zones extend from the river basins into the valleys, with ecological sensitivity diminishing progressively. Areas of extremely high sensitivity harbor rich ecological diversity and are susceptible to environmental disturbances. Hence, urban expansion must be tightly restricted, and the utilization of water and land resources necessitates stringent oversight. Measures ought to be taken to safeguard and cultivate ecological attractions in order to alleviate the repercussions of human endeavors. The vast, moderately sensitive zones, covering considerable expanses, are fragmented and dispersed. Management and control in this region should be prioritized, with an emphasis on enhancing vegetation coverage, optimizing groundwater utilization in coastal areas, employing deep tillage techniques, planting green manure crops, and mitigating soil salinization in coastal regions. Extremely low and mildly sensitive areas are also prevalent but are primarily situated along the southeastern coast. Urban development and construction in these regions should be carefully executed, aligning with the principles of sustainable growth. This involves capitalizing on the benefits of local topography, climate, land utilization, and diverse natural assets to avert resource depletion and ecological deterioration.

The Zheng-Bian-Luo urban agglomeration boasts intricate topography, a temperate climate, and abundant ecological resources. Within the context of regional coordinated development, it is essential to strike a harmonious balance between economic advancement and environmental conservation. Based on the findings of this study, the Zheng-Bian-Luo urban agglomeration should prioritize ecological conservation, manage water and land resources judiciously within a sustainable development framework, bolster environmental law enforcement and oversight, strongly advocate for the ecological rejuvenation of the region, and safeguard the integrity of the ecological environment.

This study aims to advance the utilization and evolution of RS/GIS technology in urban ecological research and augment the repertoire and methodologies of remote sensing and GIS technology in ecological assessment, monitoring, and management, thereby amplifying its impact and utility in ecological research. As an exemplar of the urban agglomeration in the Central Plains, the ecological conditions and assessment methodologies of the Zheng-Bian-Luo agglomeration are both typical and representative. The insights and findings from this research offer valuable references for ecological sensitivity evaluations in other Central Plains urban agglomerations.

Countermeasures for Sustainable Development of the Ecological Environment in the Zheng-Bian-Luo Urban Agglomeration

(1) Clarify the "District Line" Planning and Rationally Utilize Natural Resources

Elucidate the zoning plan for the Zheng-Bian-Luo urban agglomeration to ensure the coherence of planning and resource distribution. Environmental quality, capacity, and carrying capacity fluctuate among disparate regions. Strengthen monitoring of highly sensitive forest areas within the ecological red line, utilize native tree species and natural scenery to establish isolation zones, and implement ecological restoration measures. Based on the current status of red line planning in the study area and considering the sensitive distribution of land types discussed in this article, this analysis provides valuable insights for future resource allocation, adjustments to red line controls, and differentiated management of development across different regions of the Zheng-Bian-Luo urban agglomeration.

(2) Use “3S” Technology to Conduct Real-Time Ecological Environment Tracking and Monitoring

The topography, climate, and soil sensitivity that cause ecological and environmental problems in the Zheng-Bian-Luo urban agglomeration are most likely irreversible, but the impact of urban infrastructure construction and human activities on the ecosystem can be mitigated to a certain extent. The Zheng-Bian-Luo urban agglomeration is an important industrial base in the Central Plains region, with frequent light and heavy industrial activities. The discharge of industrial wastewater and domestic sewage often affects the surrounding soil and water systems, making the promotion of ecological construction passive. Based on this, remote sensing data can be used to conduct large-scale ecological monitoring of the city's water systems, forests, and soils. In addition, the acquisition time is short, the data is relatively objective and accurate, and timely and effective measures can be taken to control and improve those budding ecological problems.

(3) Relying on the Improvement of the "Along the Yellow River” Water System to Optimize the Landscape Corridors in the Waterfront Area

The water sensitivity index of the Zheng-Bian-Luo urban agglomeration is high, and the development and utilization activities of the water system are relatively frequent. In addition, the Central Plains urban agglomeration is an important "along the Yellow River" basin city, and the waterfront ecology is relatively fragile. Both natural and human interference can easily damage the ecological environment. Make an impact. Taking into account the ecological problems of soil erosion and flooding in the Bianluo urban agglomeration, when planning the future waterfront area, the infrastructure should try to conform to the terrain and river direction, reduce land ecological problems caused by construction, integrate the "sponge city" concept, and use green and environmentally friendly The materials collect and utilize rainwater, maximize the benefits of green space in the waterfront area, and promote sustainable urban development.

Limitations and Future Directions

This study reveals significant ecological differences among different regions within the Zheng-Bian-Luo urban agglomeration, emphasizing the need to develop region-specific conservation strategies. However, ecologically sensitive areas may encounter unique environmental challenges, such as increased vulnerability to climate change or habitat degradation. It is critical to recognize that these areas may necessitate tailored approaches to effectively address their specific ecological problems. However, our study has certain limitations that necessitate further exploration. For example, the generalizability of our findings may be limited due to geographical and climatic conditions specific to the study area. Future studies should broaden their scope to encompass a wider range of ecological conditions and integrate long-term monitoring data. Additionally, policy implications should be considered, emphasizing the importance of adaptive management practices that respond to the dynamic nature of ecosystems.

As urbanization accelerates and climate change intensifies, the urban ecological environment confronts escalating challenges. While the ecological sensitivity assessment approach grounded in RS/GIS technology furnishes robust methodologies and fresh perspectives for urban ecological research, there remain areas warranting deeper exploration and refinement. Future research endeavors could explore multi-scale and multi-dimensional techniques for ecological sensitivity assessment to comprehensively grasp the complex and diverse urban ecological landscape. Moreover, these efforts could provide deeper insights into the mechanisms by which human activities, such as urbanization, land-use changes, and climate fluctuations, impact ecological sensitivity.

As science and technology continue to progress, the integration of emerging technologies, including artificial intelligence and big data, into ecological environment research is poised to be a pivotal focus in forthcoming studies. Enhancing interdisciplinary collaboration and communication, as well as continuously refining evaluation methodologies and technical tools, is crucial for advancing urban ecological research. This will not only provide a scientific foundation but also serve as a decision-making reference for promoting harmonious coexistence between humans and nature and facilitating sustainable urban development.

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Conflict of Interest

The authors declare no conflict of interest.

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