Early Warning Assessment and Spatio-temporal Evolution of Land Ecological Security in Ecologically Sensitive Areas of the Three Gorges Reservoir Area: A Case Study of Wanzhou District, Chongqing (Postprint)

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Abstract

Taking Wanzhou District, a typical ecologically sensitive area in the Three Gorges Reservoir Region, as the study area, a land ecological security early warning index system was constructed based on the Pressure-State-Response (P-S-R) framework, the entropy method was employed to conduct land ecological security early warning analysis, and spatial statistical methods were used to investigate the spatial distribution characteristics, variation patterns, and spatial association patterns of land ecological security warning degrees in the study area, aiming to provide decision-making references for regional land resource utilization planning, management, and ecological protection. The results indicate that: From 2000 to 2014, the land ecological security warning degree in the study area showed a continuous upward trend, with areas of higher warning degrees continuously diffusing from the central urban area of Wanzhou District to the surrounding areas; however, the increase in land ecological security warning degree during 2000-2009 was more pronounced than that during 2009-2014, making the period of 2000-2009 a critical time interval for changes in regional land ecological security warning degree. From 2000 to 2014, C0/(C0+C) in the study area showed a continuous upward trend, indicating that the influence of non-structural factors on regional land ecological security warning degree was continuously increasing, which is consistent with the actual situation of rapid economic development, intensified human utilization of land resources, and frequent regional natural disasters in the study area over the past 14 years. The global Moran' s I values for the study area in 2000, 2009, and 2014 were 0.7823, 0.7772, and 0.775, respectively, indicating that there exists a strong positive spatial correlation in the land ecological security early warning index and that

regional land ecological security warning degree exhibits strong spatial clustering. Both the "high-high"and "low-low"value zones in the study area exhibited a trend of gradually increasing scope during 2000-2009, while gradually decreasing during 2009-2014; moreover, "high-high" value zones were mainly concentrated in the central urban area and its adjacent regions, while "low-low" value zones were primarily distributed in the northwestern and southeastern parts of the study area, where land use intensity is relatively weak and vegetation coverage is relatively good; "low-high" value zones surrounding the central urban area will be priority areas for occupation during urban development, and in future land use, special attention should be paid to strengthening the protection of regional "low-high" value zones.

Full Text

Preamble

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Measures of Land Ecological Security Early Warning and Its Spatio-Temporal Evolution in the Ecologically Sensitive Area of the Three Gorges Reservoir Area: A Case Study of Wanzhou District, Chongqing City

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Abstract

This study examines Wanzhou District, a typical ecologically sensitive area in the Three Gorges Reservoir region, to construct a land ecological security early warning indicator system based on the Pressure-State-Response (P-S-R) framework. Using spatial statistical methods, we analyze the spatial distribution characteristics, variation patterns, and spatial correlation patterns of land ecological security alarm degrees in the study area, aiming to provide decision-making references for regional land resource utilization planning, management, and ecological protection.

The results show: (1) From 2000 to 2014, land ecological security alarm degrees in the study area showed a continuous upward trend, with high-alarm areas spreading outward from the central urban area of Wanzhou District. This trend was more pronounced during 2000–2009, indicating this period as critical for changes in regional land ecological security. (2) The ratio of random factors affecting regional land ecological security increased from 2000 to 2014, consistent with the region' s rapid economic development, intensified land resource utilization, and frequent natural disasters over the past 14 years. (3) Global Moran' s I values for the study area were 0.7823, 0.7772, and 0.7750 in 2000, 2009, and 2014, respectively, indicating strong positive spatial correlation of land ecological security warning indices and significant spatial clustering of alarm degrees. (4) "High-high" and "low-low" clusters showed gradually increasing ranges from 2000 to 2009 and decreasing ranges from 2009 to 2014. "High-high" areas are mainly distributed in the central city and adjacent regions, while "low-low" areas are concentrated in the northwest and southeast where land use intensity is relatively low and vegetation coverage is relatively good. The "low-high" areas around the central city will be priority zones for urban development, necessitating strengthened protection of these areas in future land use planning.

Keywords: Three Gorges Reservoir Region; ecologically sensitive area; land ecological security; early warning; spatio-temporal evolution

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1. Introduction

Ecological security represents a crucial component of 21st-century sustainable development and has become a frontier topic in research on sustainable land resource utilization. As an extension of ecological security studies, land ecological security issues have emerged as primary constraints on regional sustainable land use in China due to rapid population growth, accelerated urbanization, and increasingly prominent human-land conflicts. Unreasonable land use patterns and intensifying land use pressure have caused severe threats and damage to land ecosystems, making the protection of regional land ecosystem security a critical challenge for stable and sustainable human development.

Land ecological security early warning research originated from ecological security monitoring in the 1970s, marked by the establishment of the Global Environmental Monitoring System (GEMS). Since then, scholars have conducted pioneering studies on ecological environment early warning from various perspectives, continuously improving theoretical frameworks and technical methods. The field has evolved from single-item to comprehensive early warning, and from thematic to regional early warning. With deepening theoretical research, ecological environment early warning theories were gradually introduced into land science, giving rise to land ecological security early warning alongside the development of information technology.

International research on land ecological security early warning has focused primarily on monitoring and warning systems, including soil monitoring system construction, comprehensive dynamic monitoring of land use changes, and agricultural resource environments. Domestic research has covered theoretical frameworks, indicator systems, methods such as extension analysis and the TOPSIS method, and early warning information system construction. However, existing studies exhibit several limitations: (1) Most evaluations use counties or administrative units as assessment units, making it difficult to reflect intra-county differences in ecological security conditions; (2) Indicator systems rely excessively on social statistics from yearbooks, inadequately emphasizing the natural attributes of ecological conditions; and (3) Spatial clustering patterns and spatial correlation modes of land ecological security alarm degrees have been overlooked. Spatio-temporal evolution patterns of land ecological security alarm degrees are more practical for revealing regional land ecological condition changes and provide better references for ecological protection and coordinated human-land relationships.

The ecologically sensitive area of the Three Gorges Reservoir is located in the critical throat zone of the ecological barrier in the Yangtze River Basin and represents a key biodiversity conservation area of global significance in China. It also serves as the western hub of the upper Yangtze River economic belt, where conflicts between resource protection and economic development have become increasingly prominent. This study selects Wanzhou District, a typical area in the Three Gorges ecologically sensitive zone, and uses administrative villages as evaluation units for three periods (2000, 2009, 2014) to conduct research on land ecological security early warning measurement and spatio-temporal evolution. Applying geostatistical methods and spatial autocorrelation models, we analyze the spatial differentiation characteristics, variation patterns, and driving mechanisms of regional land ecological security alarm degrees to provide decision-making references for addressing ecological bottlenecks and achieving sustainable land resource utilization and socio-economic development in the Three Gorges ecologically sensitive area.

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2. Study Area

Wanzhou District of Chongqing City is located in the heart of the Three Gorges Reservoir area, on the eastern edge of the Sichuan Basin, at the transition zone between the Sichuan Basin and the Qinba Mountains and Yunnan-Guizhou Plateau. Geographically situated at 107°52 22 -108°53 25 E, 30°24 25 -31°14 58 N, it covers an area of 3,456.55 km^2. The district borders Kaixian County and Dazhou City of Sichuan Province to the north, Zhong County and Liangping County to the west, Shizhu County and Lichuan City of Hubei Province to the south, and Yunyang County to the east. Topographically, Wanzhou lies on the eastern edge of China' s second topographic step, with the Yangtze River serving as the boundary: north of the river shows high-north-low-south topography, while south of the river shows high-south-low-north. Mountains run parallel with alternating valleys and ridges, forming a landscape dominated by mid-low mountains and hills. The region has a subtropical monsoon humid climate with an average annual rainfall of 1,416 mm. As a water-land transportation hub and material distribution center radiating to eastern Sichuan and western Hunan, Wanzhou' s location advantage is prominent. With the deepening implementation of the national Yangtze River Economic Belt strategy, Wanzhou' s role as a regional central city in the heart of the Three Gorges Reservoir area has become increasingly important. Known as the "Gateway to the Three Gorges," its land ecological security construction is not only a goal of regional economic sustainable development but also an important guarantee for national land resource security and ecological civilization construction in the Three Gorges Reservoir area.

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3. Data Sources

Land use data for this study were derived from Wanzhou District' s land use vector maps for 2000, 2009, and 2014, combined with natural geographic data on regional soil and vegetation. The land use data were processed and analyzed using ArcGIS 10.2 and GeoDa software. Other socio-economic data were obtained from Wanzhou District Statistical Yearbooks (2001, 2010, 2015) and statistical materials from forestry, agriculture, and other departments, supplemented by field survey data.

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4. Methodology

4.1 Early Warning Indicator System Construction

Following principles of scientific validity, comprehensive dynamism, data availability, operability, and sensitivity, and considering the actual ecological conditions of the Three Gorges ecologically sensitive area, this study constructed

an early warning indicator system based on the Pressure-State-Response (P-S-R) framework. The P-S-R model, proposed by UNEP and OECD in the late 1970s, has been widely applied in ecology, land, and agriculture. In our land ecological security early warning indicator system, **Pressure** refers to human activity impacts on land ecosystem security, specifically from population, urbanization, and transportation development. **State** reflects land ecological security conditions and dynamic characteristics at specific times, including natural environmental conditions and land use status. **Response** indicates capacities to address land ecological security issues and maintain/improve security status.

Using the Delphi method and expert consultation with professionals from land, environmental protection, and agriculture sectors who have solid theoretical knowledge and rich practical experience, we selected 24 indicators to build the early warning indicator system (Table 1).

4.2 Indicator Threshold Determination and Standardization

Referring to relevant studies and environmental quality standards at national and local levels, we divided Three Gorges ecologically sensitive area land ecological security into five levels: No Warning, Light Warning, Moderate Warning, Severe Warning, and Huge Warning. Using absolute determination, relative determination, optimization methods, expert consultation, and natural classification methods that minimize internal variance at each level, we determined threshold boundaries for each indicator and applied interpolation for standardization.

4.3 Weight Determination

This study employed the entropy method to calculate indicator weights, combined with Delphi method consultation from 20 experts in land, agriculture, and related fields. The entropy weight calculation process is as follows:

First, calculate the information entropy e_j of indicator j:

$$e_j = -k \sum_{i=1}^{m} p_{ij} \ln p_{ij}$$

where p_{ij} is the standardized value of evaluation indicator j for object i, and $k = 1/\ln m$.

Then calculate the effect value g_j:

$$g_j = 1 - e_j$$

Finally, calculate the weight w_j:

$$w_j = \frac{g_j}{\sum_{j=1}^{n} g_j}$$

The greater the entropy value of an indicator, the smaller its weight.

4.4 Land Ecological Security Early Warning Index Calculation

Referring to relevant studies, we used a multiplicative model to calculate the early warning index for each evaluation unit:

$$ESWI = \sum_{i=1}^{n} A_i \times W_i$$

where $ESWI$ is the land ecological security warning index, A_i is the standardized value of indicator i, W_i is the weight of indicator i, and n is the total number of indicators.

4.5 Alarm Degree Classification Standards

Using systematic clustering and the ISODATA method for iterative classification, we established warning limits including no-warning, light-warning, moderate-warning, severe-warning, and huge-warning points, dividing them into five land ecological security early warning grades (Table 2).

4.6 Geostatistical Methods

Geostatistics has become an effective method for studying spatial variability in ecological security. As a spatial variable, regional land ecological security warning indices exhibit both structural and random characteristics, which can be analyzed using variogram methods:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2$$

where $\gamma(h)$ is the semivariogram, $Z(x_i)$ and $Z(x_i + h)$ are values at spatial positions x_i and $x_i + h$, and $N(h)$ is the number of sample pairs at distance h.

4.7 Spatial Autocorrelation

Geography' s First Law states that everything is related, but near things are more related than distant things. Spatial autocorrelation analysis, a fundamental method in theoretical geography, examines statistical distribution patterns of spatial data. It includes global spatial autocorrelation for verifying overall regional patterns and local spatial autocorrelation for reflecting relationships between a local unit and its neighbors.

Global Moran' s I is calculated as:

$$I = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}(x_i - \bar{x})(x_j - \bar{x})}{S^2 \sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}}$$

where x_i is the observed value in region i, $\bar{x}$ is the mean, S^2 is the variance, and W_{ij} is a binary spatial weight matrix (1 when regions i and j are adjacent, 0 otherwise). Moran' s I generally ranges between -1 and 1, with larger absolute values indicating stronger spatial association.

Local spatial autocorrelation (LISA) decomposes Moran's I to individual spatial units:

$$I_i = \frac{x_i - \bar{x}}{S^2} \sum_{j=1}^{n} W_{ij}(x_j - \bar{x})$$

Positive I_i indicates spatial clustering of similar values (high-high or low-low), while negative I_i indicates spatial clustering of dissimilar values (high-low or low-high).

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5. Results

5.1 Temporal Evolution Characteristics of Regional Land Ecological Security Alarm Degrees

In 2000, land ecological security alarm degrees in Wanzhou District were dominated by No Warning and Light Warning, which together accounted for 78.1% of the total area, indicating generally good ecological conditions. High-alarm areas (Severe and Huge Warning) were concentrated in the central urban area (Gaosuntang, Zhoujiaba, Bai' anba, Shuanghekou, Zhonggulou, and Chenjiaba streets) and adjacent townships, covering only 7.08% of the total area.

By 2009, significant changes occurred. The proportion of low-alarm areas decreased to 48.34%, while high-alarm areas increased to 18.47%. Areas such as Xiongji Town and other central city-adjacent regions transitioned from low-alarm to high-alarm zones. The period 2000–2009 represents a critical transition, with alarm degrees showing a continuous upward trend, more pronounced than during 2009–2014.

In 2014, alarm degree changes were less dramatic. The proportion of low-alarm areas further decreased to 45.61%, while high-alarm areas slightly decreased to 15.63%, as some severe-warning areas from 2009 improved to moderate-warning status. Overall, land ecological security alarm degrees showed a continuous upward trend from 2000 to 2014, with the increase during 2000–2009 being more

significant than during 2009–2014. This aligns with the region' s rapid economic development, intensified land resource utilization, and frequent natural disasters. However, with recent implementation of national ecological civilization strategies and green development concepts, the region' s land ecological conditions have received enhanced protection, somewhat alleviating the rapid deterioration trend observed during 2000–2009.

[Figure 1: see original paper]

5.2 Spatial Structure Variability Analysis

Based on land ecological security warning indices and geostatistical software, we fitted variogram models for the study area (Table 4). The spherical model provided the best fit for all three years, with R^2 values of 0.838, 0.949, and 0.961 for 2000, 2009, and 2014, respectively.

Land ecological conditions exhibit spatial heterogeneity influenced by both structural and random (non-structural) factors. The nugget effect (C_0) represents random spatial variation at zero distance, reflecting random characteristics of regionalized land ecological conditions. The sill ($C_0 + C$) represents maximum spatial variation, with higher values indicating greater spatial heterogeneity. The nugget-to-sill ratio ($C_0/(C_0 + C)$) indicates the proportion of random variation: higher ratios mean greater influence of random factors (including natural disasters and human activities), while lower ratios indicate dominance of structural factors (such as terrain and vegetation type).

From 2000 to 2014, the nugget effect of land ecological security alarm degrees gradually increased (13.8%, 18.07%, 19.34%), indicating strengthening random factors and their increasing influence on spatial differentiation. This corresponds to the region' s rapid economic development, intensified land use, and frequent natural disasters. The ranges of spatial autocorrelation also expanded (22.6 km, 34.3 km, 35.9 km), indicating expanding spatial correlation scales.

5.3 Spatial Structure Correlation Analysis

5.3.1 Global Autocorrelation Analysis Global Moran' s I values of 0.7823, 0.7772, and 0.7750 for 2000, 2009, and 2014 indicate strong positive spatial correlation and significant clustering of land ecological security alarm degrees. Although showing a slight overall decline, the values remain high, demonstrating persistent spatial clustering.

Moran scatter plots qualitatively distinguish relationships between a region and its neighbors (Figure 2). The plots show land ecological security alarm degrees concentrated in the first (high-high) and third (low-low) quadrants, with smaller distributions in the second (low-high) and fourth (high-low) quadrants, confirming significant spatial clustering tendencies.

[Figure 2: see original paper]

5.3.2 Local Autocorrelation Analysis While global Moran' s I reveals overall spatial patterns, local spatial autocorrelation identifies local clustering patterns and significance levels. LISA analysis shows:

- **High-high clusters**: Concentrated in central urban townships and adjacent areas (Gaosuntang, Zhoujiaba, Bai' anba, Shuanghekou, Zhonggulou, Chenjiaba streets) with scattered distribution in Houbao Township. These areas experience intense human land use activities and have high land ecological security alarm degrees.
- **Low-low clusters**: Mainly distributed in northwestern (Tanzi Town, Wuling Town) and southeastern (Xintian Town) regions with relatively low land use intensity and good vegetation coverage.

From 2000 to 2009, high-high cluster areas expanded significantly, while from 2009 to 2014, they slightly contracted, with some areas (Gaoliang Town, Xiongji Town) becoming non-significant. Low-low clusters remained stable in the northwest and southeast. The proportion of significantly clustered areas ($p < 0.01$) increased overall, consistent with the general deterioration trend during 2000–2009 and slight relief during 2009–2014.

[Figure 3: see original paper]
[Figure 4: see original paper]

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6. Conclusions and Discussion

This study analyzed spatio-temporal evolution of land ecological security alarm degrees in Wanzhou District, a typical ecologically sensitive area in the Three Gorges Reservoir region, using the P-S-R framework, entropy method, and spatial autocorrelation analysis for three years (2000, 2009, 2014). Key findings include:

1. **Temporal Trends**: Land ecological security conditions showed a continuous declining trend from 2000 to 2014, with high-alarm areas spreading outward from the central urban area. The period 2000–2009 was more critical than 2009–2014, primarily due to accelerated urbanization and industrialization that intensified human-land conflicts. However, recent national ecological civilization strategies and green development concepts have enhanced protection efforts, alleviating the rapid deterioration trend.
2. **Spatial Patterns**: Strong spatial clustering exists, with Moran' s I values around 0.78 for all three years. High-high clusters are concentrated in central urban and adjacent areas, while low-low clusters are in the northwest and southeast with lower land use intensity and better vegetation. The range of clusters increased from 2000 to 2009 then decreased from 2009 to 2014.

3. **Policy Implications**: As Chongqing' s "Five Functional Districts" strategy and new industrialization/urbanization advance, land use structure has changed significantly. Low-high areas around the central city will be priority zones for urban development, requiring strengthened protection. Future land use must prioritize protecting low-high areas, controlling construction land expansion, preventing geological disasters, reducing pollutant emissions, and increasing green infrastructure.

This study' s personalized indicator system, based on the Three Gorges ecologically sensitive area' s natural ecological baseline and human development demands, better reflects actual land ecological conditions than previous studies that over-relied on socio-economic statistics. Using administrative villages as evaluation units significantly improves assessment precision and provides valuable references for land ecological security patterns in the entire Three Gorges ecologically sensitive area.

However, land ecological security early warning is a complex systematic and academic problem without established consensus. Issues such as indicator threshold setting require long-term, in-depth research. This study provides important insights for national ecological security strategy and offers decision-making references for regional land resource planning, management, and sustainable socio-economic development.

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Note: Figure translations are in progress. See original paper for figures.