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Comprehensive Evaluation of Ecological Sensitivity and the Characreristics of Spatial Variations in Luo River Basin

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ABSTRACT

This study focuses on the Luo River Basin in Henan Province, selecting six ecological evaluation factors—elevation, slope, land use, NDVI, aspect, and water buffer zone—to assess ecological sensitivity. The Analytic Hierarchy Process (AHP) and spatial autocorrelation analysis were employed to determine the weights and spatial distribution of each factor. Based on the GIS platform, comprehensive ecological sensitivity was classified into five levels, facilitating an integrated analysis of sensitivity distribution and spatial autocorrelation clustering patterns in the Luo River Basin from 1990 to 2020. The results indicate: ① According to single-factor evaluations, the weights of ecological sensitivity influence, in descending order, are NDVI, land use, elevation, slope, aspect, and water buffer zone. Among these, NDVI exerts the strongest impact on ecological sensitivity in the Luo River Basin, with a weight value of 0.345.② From 1990 to 2020 the eco-environmental sensitivity of the study area was predominantly extremely high, followed by low and high sensitivity. Extremely high and high sensitivity areas together accounted for 42.32% to 51.45% of the total regional area, exhibiting an increasing trend over time, with the proportion of extremely high sensitivity areas reaching up to 32.27%. moderate and low sensitivity areas displayed a declining trend, while very low sensitivity areas remained relatively stable at approximately 16%.③ The spatiotemporal variations in ecological sensitivity within the study area are pronounced. Overall, extremely high and high sensitivity areas are primarily concentrated in the mountainous and hilly regions of the western and central-southern parts, characterized by high elevations and steep slopes. Very low and low sensitivity areas are mainly distributed near urban clusters in the eastern and central valley regions of the Luo River Basin. The ecological sensitivity index in the basin exhibits a zonal clustering pattern at the spatial scale, with clustering intensity fluctuating slightly over time but showing an overall increasing trend.

KEYWORDS

GIS; Luo River Basin; Ecological Evaluation Indicator; Ecological Sensitivity.

1. INTRODUCTION

Ecological sensitivity is a measure of an ecosystem's ability to withstand risks when it is invaded by social activities, natural changes,etc. Under normal circumstances, the higher the ecological sensitivity, the more vulnerable the ecological environment is to external disturbances[1-3]. Unlike traditional environmental surveys, ecological sensitivity combines multiple environmental impact factors and, in the combination of landscape ecology and spatial pattern, pays more attention to the spatio-temporal specificity of risk mechanism division and the impact of spatial trade-off scale effects[4-5]. Ecological sensitivity is not only an important topic of discussion in earth environmental science, ecological science, and global geography, but also the foundation for environmental ecological restoration, sustainable development, and the establishment of ecological service systems[6-7].

At present, foreign scholars mainly focus on exploring ecological sensitivity in small-scale regions such as a single administrative region, the demarcation of nature reserves, and specific ecological processes[8-9]. Specific ecological processes refer to perspectives such as climate change, material cycling, and biodiversity to analyze ecological sensitivity. For example, Azene scholars analyzed the sensitivity of ecological farmland under the influence of weather change, and Walker et al. studied the influence of climate change and economic factors on the sensitivity of animal communities[10-11]. Italian scholar Vittorio used sensitivity as an important condition for social planning reference, and RajAlok et al. constructed a spatial E-PSR model to obtain grassland resilience sensitivity in arid regions, and obtained the susceptibility zoning of grassland areas to drought erosion[12-13]. With the deepening of domestic research, domestic scholars have focused on using multiple indicators to establish comprehensive ecological sensitivity in the study area and have explored the appropriate selection criteria for different indicator factors[14-15]; Yang Ping et al. studied the impact of the development of Manas County in Xinjiang on ecological assessment starting from a small area, and Hu Xiumei et al. discussed the management and planning of sensitive areas in underdeveloped villages and towns[16-17]; Dong Jiaqi and other scholars conducted a sensitivity analysis of the special desert climate in the Kubuqi area, providing an important reference for the assessment of the ecological function value of the research area. Overall, most studies on ecological sensitivity are still explanations and descriptions of natural features in specific regions, while there are fewer studies on the spatio-temporal correlations of sensitivity at the basin scale[18].

The Luo River Basin is one of the birthplaces of Central Plains culture, with a long history of development and abundant resources. Luoyang, the center of the basin, has a splendid ancient civilization and a unique humanistic environment[19]. The basin has a complex landform, located at the edge of loess, at the junction of valleys and plains, with a rich variety of species and lush vegetation, and is an important transitional zone for the ecological environment of the Yellow River Basin[20]. The water and soil erosion in the basin is mainly moderate and light, the distribution of water and soil resources is uneven, water use is concentrated in urban areas, the problem of disorderly development is serious, and the contradiction of deterioration of the water ecological environment is acute[21].

Taking the Luo River Basin as the research object and considering the natural conditions and spatial relations, six evaluation indicators were determined from the basic data, namely elevation, slope, land use, vegetation coverage, slope and water buffer zone, and the weights of the above indicators were determined based on the analytic hierarchy process To explore the current status of ecological sensitivity in 2020 and the trend of comprehensive ecological sensitivity changes from 1990 to 2000, further combined with spatial autocorrelation analysis to obtain the evaluation of ecological sensitivity, reveal the spatio-temporal characteristics of ecological risk, and provide decision-making basis for high-quality development, ecological protection and scientific management of the Luo River Basin.

2. DATA AND METHODS

2.1. Study area

The Luo River Basin (33°33'-35°05’N,109°45'-113°06’E) is located in the transitional zone between the subtropical and warm temperate zones. It is hot and rainy in summer and autumn, cold and dry in spring and winter, with an average annual rainfall of 600mm to 800mm and an average annual temperature of about 12°C to 14.5°C; The terrain is high in the northwest and low in the southeast, with the Qinling and Huashan Mountains to the north and the Mangling and Funiu Mountains to the south, with obvious vertical variations in the natural environment[22]. The Luo River originates in Lantian County, Shaanxi Province, converges in Luoyuan Township, Luonan County, then flows eastward into Hekou Street, Lushi County and enters Henan Province, and joins the Yellow River at

Shenti in Gongyi City. The main stream of the river is 446.90km long and the drainage area is 18,8281 km. It is one of the important tributaries of the Yellow River(Fig.1).The upper and middle reaches of the river basin are dominated by Rocky Mountains and low hills (accounting for 45.51% of the basin area), with large areas of forest covering and good water conservation; The middle and lower reaches are loess hilly areas and alluvial plains, accounting for 40.73% and 13.8% of the basin area respectively. Vegetation is relatively sparse and human activities are relatively abundant[23].

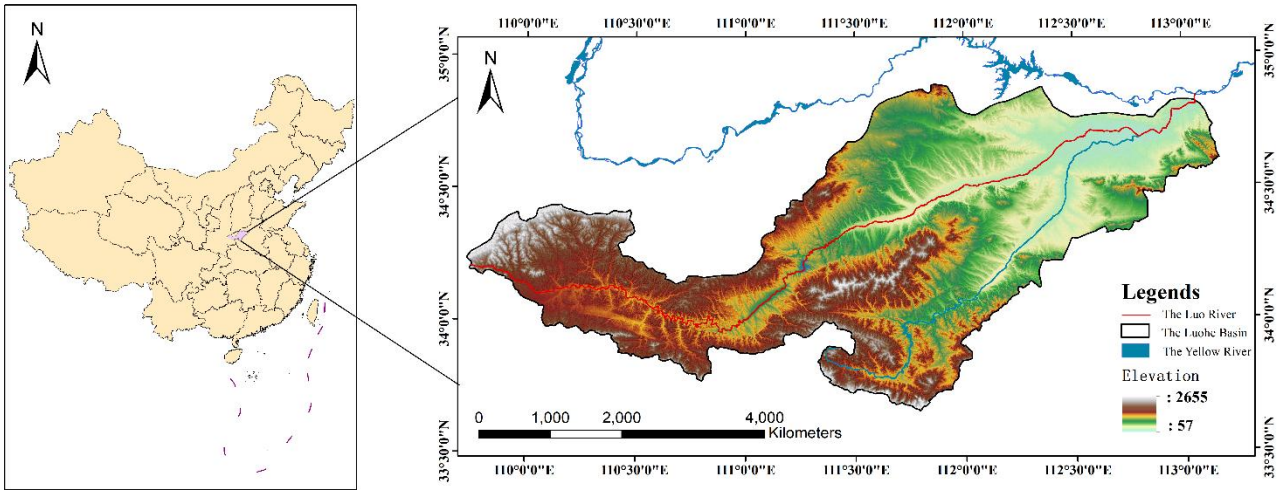

Fig. 1 Overview of the Study Area

2.2. Data Sources

The data studied in this paper mainly include DEM, topographic undulations, vegetation cover, land use and water bodies, etc. DEM by geospatial data cloud GDEMV2 digital image (https://www.gscloud.cn/search) provides, resolution of 30 m by 30 m; The terrain undulation data were extracted from the DEM by the Surface tool on the ArcGIS 10.7 platform for slope and aspect; Vegetation coverage is NDVI data calculated from Landsat TM/OIL images in the Google Earth Engine (GEE) platform, with a resolution of 1000m×1000m; Land use is by Yang jie, Huang Xin team interpretation of the data of wuhan university (http://doi.org/10.5281/zenodo.4417809), resolution of 30 m by 30 m. In addition, water buffer data was obtained from the land use data using the Neighborhood tool on the ArcGIS10.7 platform; Based on the ENVI software processing NDVI images, the ENVI band inversion tool was used to precisely calculate the quantified vegetation cover of the Luo River Basin in the 5% to 95% confidence interval, and the calculation results were FVC data.

2.3. Methodologies

2.3.1. Analytic Hierarchy Process

The Analytic hierarchy process (AHP), which is widely used, is employed in this paper to clarify the feasibility and importance of the various ecological influencing factors in the Luo River Basin and to provide evaluation criteria for further accurate assessment. By constructing a tree-like hierarchy, objects at each level are determined based on the primary and secondary relationship, the weights of the factors at each level are obtained through the judgment matrix, and the consistency test of the target weight results is conducted[24-25]. The ecological sensitivity influencing factors of the Luo River Basin (criterion layer) are classified as: elevation, slope, aspect, land use, NDVI, and water buffer zone.

1) Judgment matrix. Give quantified values based on importance: 1 (equivalent importance), 3 (more important), 5 (stronger importance), 7 (strongly important), 9 (very important), and construct the judgment matrix based on the comparison results with the formula:

$$a_{ij} = \frac{1}{a_{ji}} \tag{1}$$

In the formula, i and j represent the evaluation indicators.

2) Test matrix. Test the consistency of the judgment matrix based on the calculated single-factor weight values by the formula[26]:

$$\lambda_{\max} = \sum_{i=1}^{n} \frac{[A\omega]_i}{n\omega_i} \tag{2}$$

$$CI = \frac{\lambda_{\max} - n}{n-1} \tag{3}$$

$$CR = \frac{CI}{RI} \tag{4}$$

In the formula, λmax is the maximum eigenvalue; A is the judgment matrix; ω is the eigenvector; n is the order of the matrix; CI is the consistency metric; CR is the test coefficient; RI is the mean stochastic consistency measure. If the CR of the matrix is less than 0.1, it passes the consistency test.

It is calculated that the λmax of the judgment matrix is 6.0489, CI is 0.0078, RI is 1.26, and the final test coefficient CR is 0.0062, indicating that the weights of each ecological evaluation factor derived from the judgment matrix are appropriate.

2.3.2. GIS Spatial Analysis Method

(1) Buffer analysis. Using land use in ArcGIS 10.7 to extract water body data of the Luo River Basin, establish multi-loop buffer zones in water areas, and conduct ecological sensitivity analysis of the water environment of the Luo River.

(2) Overlay analysis. Spatial superposition of multiple layers of influencing factors to create new spatial subordination relationships further elucifies the comprehensive analysis process of ecological sensitivity in the Luo River Basin. Based on the weight values of each factor, this paper will use the overlay analysis function of ArcGIS 10.7 to reclassify, grade assign and overlay six ecological factors in accordance with the ecological evaluation index system to obtain the comprehensive ecological sensitivity distribution map of the Luo River Basin in 2020.

(3) Spatial autocorrelation analysis. Spatial differences and clustering characteristics analysis for 1990, 2000, 2010 and 2020 were conducted using the ArcGIS 10.7 platform, and the results were expressed as global Moran's I index and local Moran's I index with the formula[27]:

The global Moran's I index is:

$$I = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} \omega_{ij}(x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^{n}\sum_{j=1}^{n} \omega_{ij} \sum_{i=1}^{n}(x_i - \bar{x})^2} \tag{5}$$

Local Moran's I index:

$$I = \frac{(x_i - \bar{x})}{S^2} \sum_{j} \omega_{ij}(x_j - \bar{x}) \tag{6}$$

Where I is the Moran's I index; xi and xj represent the mean of the combined ecological sensitivity index in row i and column j; $\bar{x}$ represents the average value of all ecological sensitivity indices,ωij is the weight of adjacent ecological sensitivity indices, and S is the sum of spatial weight matrices. The

global Moran's I index results were tested using the Z test, and when Z >2.58, the P<0.01 significance test was passed.

2.3.3. Selection and classification of ecological sensitivity factors

Table. 1 Selection and Weighting of Ecological Sensitivity Evaluation Indicators in the Luo River Basin

Criteria Layer	Very low sensitive area	Low sensitivity area	Intermediate sensitive area	Highly sensitive area	Extremely sensitive area	Weights
Elevation	< 500m	500~1000m	1000~1500m	1500~2000m	> 2000m	0.174
Slope	< 5°	5 ° ~ 10 °	10 ° ~ 15 °	15 ° ~ 20 °	> 20°	0.137
Slope direction	Flat ground, directly south	Southeast, southwest	Just east, just west	Northeast, Northwest	True north	0.064
Water buffer zone	> 800m	600~800m	400~600m	200~400m	≤200m	0.044
Land use	Urban land	Unused land	Cultivated land	Woodland, grassland, shrub	Water body	0.236
NDVI	≤0.2	0.2 ~ 0.3	0.3 ~ 0.45	0.45 ~ 0.6	0.6 ~ 1	0.345

The causes of ecological environment changes in the basin are complex. Based on field investigations, combined with land use changes and ecological environment characteristics (Table 1), six evaluation factors, namely elevation, slope, aspect, land use, vegetation coverage, and water buffer zone, were selected to evaluate and analyze the ecological sensitivity of the Luo River Basin. Based on previous studies, through the analytic hierarchy process, it was determined that the ecological sensitivity of the Luo River Basin was divided into five grades, namely very low sensitivity, low sensitivity, medium sensitivity, high sensitivity and extremely high sensitivity[28-29].

3. RESULTS AND ANALYSIS

3.1. Single-factor ecological sensitivity analysis of the Luo River Basin in 2020

3.1.1. Elevation sensitivity

The elevation ecological sensitivity in the Luo River Basin shows a significant vertical distribution difference(Fig.2). Overall, the altitude gradually decreases from west to east with a large drop. Very low sensitive areas account for 34.98% of the basin area and are distributed in the lower eastern part of the Luo River Basin and the eastern part of the middle reaches, mainly including: The River-Luo region, which is densely populated and converges with the Yellow River in the lower reaches, is a strong river valley accumulation area formed by the proximity of the Yellow River, mainly loess low hills and loess terraces, and the strong river valley accumulation area formed by the alluvial plain of low mountains, hills, terraces and the Luo River, along the main stream of the Luo River to the Luoyang Basin area, the loess hills of Yichuan County and the area around the Luhun Reservoir of Song County are connected. It belongs to the tableland and gully areas[30]; The largest proportion of the low-sensitive area (37.07%) is mainly concentrated in the upper Lushi Basin and the middle Xichangshui flowing through the tributaries of the Luo River, with a small amount distributed along the lower edge of the Luo River and the eastern part of Yichuan, which are tectonic low mountains and erosion-eroded hills, with similar areas. The medium-sensitive areas are mainly along the direction of tectonic mountains and valleys, forming folded block belts, during which there are more developed river valleys and canyons distributed in the western upper reaches and southern middle

reaches of the Luo River Basin, accounting for 24.75% of the total area; The most sensitive and highly sensitive areas, at 3.04% and 0.16% respectively, are located in the upper edge and the middle edge of Xiong 'ershan and the southern edge, belonging to the Funiu Mountains, Xiong 'ershan, Waifang Mountain, the eastern peak of the Qinling Mountains, Huashan, and the main peak of Xiaoshan.

3.1.2. Analysis of slope sensitivity

Excessive slope can cause landslides, geological disasters, soil erosion and other hazards, and is one of the main reasons that affect land use in the Luo River Basin and make the environment complex and changeable. The overall distribution of slope sensitivity in the Luo River Basin is concentrated (Fig.2). The extremely sensitive areas are mostly located in the southern middle reaches and the upper reaches of the Luo River Basin, accounting for the largest area of 27.45%, and develop along the trend of several major mountain ranges in the Luo River Basin. The slope increases from north to south and from east to west, and the risk of soil erosion is higher. The very low slope sensitive areas are mainly concentrated in the middle reaches of the river Luo region and the upper reaches of the alluvial plain, and extend along the Luo River and the river valley, accounting for 19.99% of the total area; The medium-sensitive and high-sensitive areas are more scattered, accounting for 12.97% and 16.3% respectively, and are often accompanied by more low mountains and canyons in the folds and fault blocks. The mild sensitive area in the east accounts for 23.29% of the total area and often appears together with the very low sensitive area, with a large number of gentle slopes.

3.1.3. Land use sensitivity analysis

The types of land use mainly reflect the situation of land use under the influence of human survival activities(Fig.2). The types of land use in the Luo River Basin mainly include unused land, urban land, water bodies, grassland, forest land, shrubs and cultivated land. The area of water and unused land in the Luo River Basin is very small. The area of very low (unused land) and very high (rivers, lakes, wetlands) sensitive areas is 98.51km², accounting for 0.54% of the total area. They are mostly distributed near the Luo River, the Iluo River Valley and its tributaries and reservoirs. The distribution of water and soil resources in the Luo River Basin is uneven and the development is difficult. The low sensitive area accounts for 7.37%, and the construction land area is only 1,339.95 km². The Luo River Basin is a typical basin with abundant natural resources, mountains and landforms, with more than 40 percent of the area being high mountains or hills. The highest proportion is the highly sensitive area (forest, shrub, grassland), at 48.84%, which is distributed in the mountain gullies connecting the upper and middle reaches and in Songshan Mountain in the lower reaches. Meanwhile, the proportion of the sensitive area (cultivated land) in the river is similar, at 43.52%, distributed in the alluvial plain and the open area of the loess plateau. Both the medium and highly sensitive areas are widely distributed in the Luo River region. There is a distinct geographical distinction in the distribution. According to the land use analysis, the ecological sensitivity of the Luo River region is generally reflected as medium to high sensitivity.

3.1.4. NDVI ecological sensitivity analysis

NDVI can directly reflect the growth and distribution of vegetation(Fig.2). In some areas of the northern and eastern parts of the Luo River Basin, the terrain is relatively flat. The proportion of extremely low sensitive areas and mild sensitive areas is only 11.3% and 6.48% respectively. Human activities are intense, and a large amount of cultivated land, farmlands, towns and artificial greenery are concentrated. However, the vegetation is mainly distributed in high-altitude areas. The NDVI ecological sensitivity in the southern and western parts of the basin is generally high, with the area proportions of extremely sensitive and highly sensitive areas being 48.79% and 17.66% respectively. The abundant mountainous terrain provides a certain living environment for plants, while increasing the difficulty of environmental restoration. The medium-sensitive areas account for 15.77% of the total area and are more scattered, mainly distributed in the gentle slopes of the loess plateau structure, mostly sloping fields and sloping forests above the river valleys, with a single species.

3.1.5. Slope ecological analysis

Slope can affect the microclimate of a local area and the ecological cycle of plants and the surrounding environment. The Luo River Basin is dominated by high-sensitive, medium-sensitive and low-sensitive areas (Fig.2), with similar areas, accounting for 25.11%, 25.14% and 20.69% respectively, and areas ranging from 4,000 km² to 4,560 km². The medium-sensitive areas are usually located in the less undulating folds and often appear together with the low-sensitive areas. After being cut by the low-sensitive areas, they form band-shaped patches, which are more obvious in the alluvial plains of the Luo and Yi rivers. Extremely sensitive and very low sensitive areas are less common, accounting for 13.88% and 15.18% of the study area, respectively. Extremely sensitive and highly sensitive areas are concentrated, and it can be seen that they are clearly distributed along the ridge lines of major mountain ranges. Medium-sensitive and low-sensitive areas are widely distributed, while very low-sensitive areas are more scattered, generally in sunny areas and water river valleys.

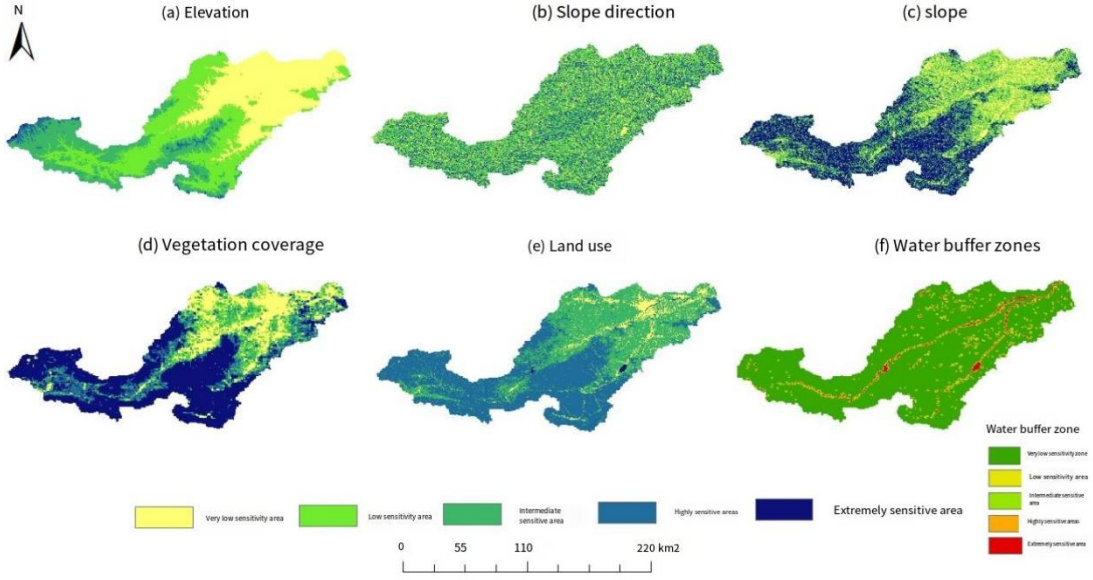

Fig. 2 Spatial distribution of ecological sensitivity to individual factors in the Luohe River Basin,2020

3.1.6. Sensitivity analysis of water buffer zones

Water is one of the important components of the ecosystem, as evidenced by its ability to resist human activities. In areas close to water bodies, there is often greater biodiversity and a larger number of species, and the ecological sensitivity is also higher. GIS was used to extract the raster data of water bodies in the study area, with 200m, 400m, 600m, and 800m as the dividing lines for water sensitivity. It can be seen that the overall water resources in the Luo River Basin are relatively scarce (Fig.2), and the surface water is concentrated near the main stream of the Luo River and the main stream of the Yi River in the middle and lower reaches, and is more scattered on the tributaries. The basin is mainly a very low sensitive area, accounting for 89.87%; The area of the low-sensitive zone is 535.2km², accounting for 2.94% of the total area; The proportion of medium-sensitive, highly sensitive and extremely sensitive areas is relatively small, at 2.64%, 2.25% and 2.3% respectively. It can be known that the water buffer zone sensitive area accounts for less than 10% of the total, has a relatively low impact on the ecological sensitivity of the entire Luo River Basin, and its factor weight is also the lowest. According to the water buffer zone of the Luo River Basin, efforts should be made to strengthen the management and protection of water resources.

3.2. Ecological sensitivity analysis of the Luohe River Basin in 2020

According to the spatial weighted overlay analysis of the ArcGIS10.7 platform(Fig.3), the comprehensive ecological evaluation index of the Luo River Basin ranges from 1.064 to 4.652. The lowest proportion (evaluation index 1.064-2.033) in the Luo River Basin is 13.13%, mainly distributed in the northern part of the middle reaches and the alluvial plain and loess hilly area of the lower reaches, with a small amount distributed in the relatively flat area of the Lushu Basin in the upper reaches and the southern part of the middle reaches, which is mainly a concentrated area of urban villages and towns and human activities; The sensitivity index ranges for the low-sensitive, medium-sensitive and high-sensitive areas are 2.033 ～ 2.654,2.654 ～ 3.24 and 3.24 ～ 3.785 respectively, and the area proportions are: 18.41%, 16.47%, 19.73%. The low-sensitive areas are mostly distributed in the north-central and southwestern parts. The medium-sensitive areas extend outward along the light-sensitive areas. The light-sensitive and medium-sensitive areas are mainly close to places and river basins where human activities occur, and are affected by certain human modifications and catchment areas. High-sensitivity areas are more scattered, with more scattered areas in the central and southern and western regions, where there are large areas of exposed rocks and mining areas. The highly sensitive areas (with a sensitivity index of 3.785 to 4.652) in the Luo River Basin account for 32.27 percent of the total area. They are mainly distributed in the western and central-southern parts of the Luo River region, with a small number also distributed along the eastern edge. The main land types in this area are forest land, grassland and cultivated land.

3.3. Temporal dynamics of ecological environment sensitivity in the Luo River Basin

Table 2 Structural Composition of Comprehensive Ecological Sensitivity in the Luo River Basin from 1990 to 2020

Sensitivity levels	1990		2000		2010		2020	
	Area /km²	Proportion/%	Area /km²	Proportion/%	Area /km²	Proportion/%	Area /km²	Proportion/%
Very low sensitivity	3167.68	17.43	1809.93	9.96	2703.68	14.88	2972.53	16.35
Low sensitivity	3833.30	21.09	3106.71	17.09	4064.75	22.36	3133.87	17.24
Moderate sensitivity	3484.72	19.17	4286.45	23.58	3107.13	17.10	2717.95	14.95
High sensitivity	2860.76	15.74	3634.97	19.99	3663.11	20.15	3400.74	18.71
Extremely sensitive	4832.21	26.58	5341.60	29.38	4636.93	25.51	5950.51	32.74

It can be seen from Table 2 and Figure 3 that from 1990 to 2020, the sensitive type in the study area was mainly extremely sensitive, with the area proportions being 26.58%, 29.38%, 25.51%, and 32.74% respectively, showing an increasing trend. In 2000, compared with 1990, there was a significant downward trend in the proportion of very low sensitivity and low sensitivity areas, especially the area of very low sensitivity, which decreased by 7.47% to only 1,809.93 km²; The low-sensitive area declined by 4%, accounting for 17.09% of the study area; In contrast, the moderately sensitive and highly sensitive areas increased by about 4 percent, followed by the highly sensitive areas. The distribution of sensitivity in 2010 was generally similar to that in 1990, but there were significant changes compared to 2000. The area of very low and low sensitive areas increased significantly, while that of medium and very high sensitive areas decreased significantly, with changes ranging from 5% of the basin area. In 2020, there was the greatest change in sensitivity, with different levels of sensitivity compared to other years. Except for the extremely sensitive areas, which showed a

significant upward trend, the proportion of extremely sensitive areas increased by 7.23%. On the contrary, the areas of the low sensitive areas and the medium sensitive areas decreased significantly, and the proportions of the very low sensitive areas, the lower sensitive areas, the medium sensitive areas and the high sensitive areas were generally similar.

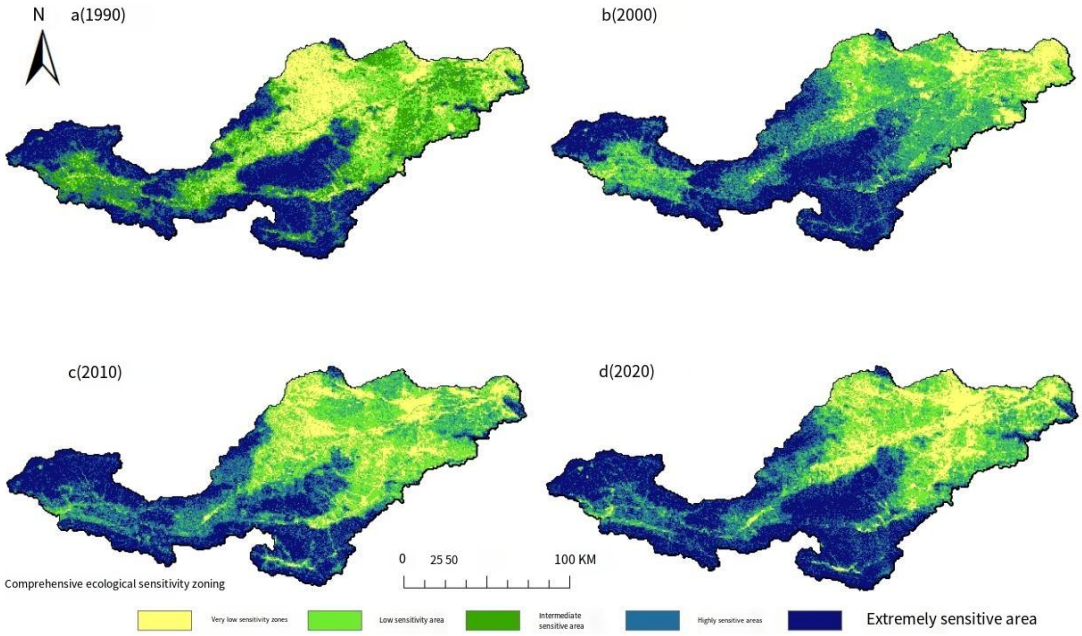

Fig. 3 Spatial Distribution of Integrated Ecological Sensitivity in the Luo River Basin, 1990-2020

3.4. Evaluation of ecological sensitivity in different administrative regions of the Luo River Basin

The regional statistics function of ArcGIS 10.7 platform was used to conduct statistics on the ecological sensitivity levels of the main regions in the Luo River Basin (Figure 4), and the median, average and standard deviation of the ecological sensitivity levels of the regions in the basin were obtained. According to the statistical results of ecological sensitivity levels in the 20 main administrative regions of the Luo River Basin, the counties in the western and southern middle reaches, due to the complex mountainous terrain and proximity to the four major mountain ranges, are mainly extremely sensitive and highly sensitive types. The middle reaches form a band of medium-sensitive areas with the Luo River alluvial plain as the axis, while the urban circle of the Luoyang Basin and north are mainly low-sensitive and very low-sensitive types. The spatial features are distinct. Among them, the sensitivity levels in the urban areas of the northern Luoyang Basin fluctuated over 20 years but decreased significantly within 30 years, showing an overall downward trend in sensitivity levels; In the central River-Luo region and the middle and southwestern parts of the basin, there were fluctuations in sensitivity levels that rose first and then fell, showing an overall upward trend and a relatively stable sensitivity situation; In the upper reaches of the river basin, there is a situation where the sensitivity level drops first and then rises, with a significant increase in the 30th year. This indicates that urban environmental fragility has improved significantly over the past three decades, the ecological environment in the central plain region has stabilized, while the ecological sensitivity in the four mountain ranges far from the city is not optimistic and there is a risk of environmental deterioration.

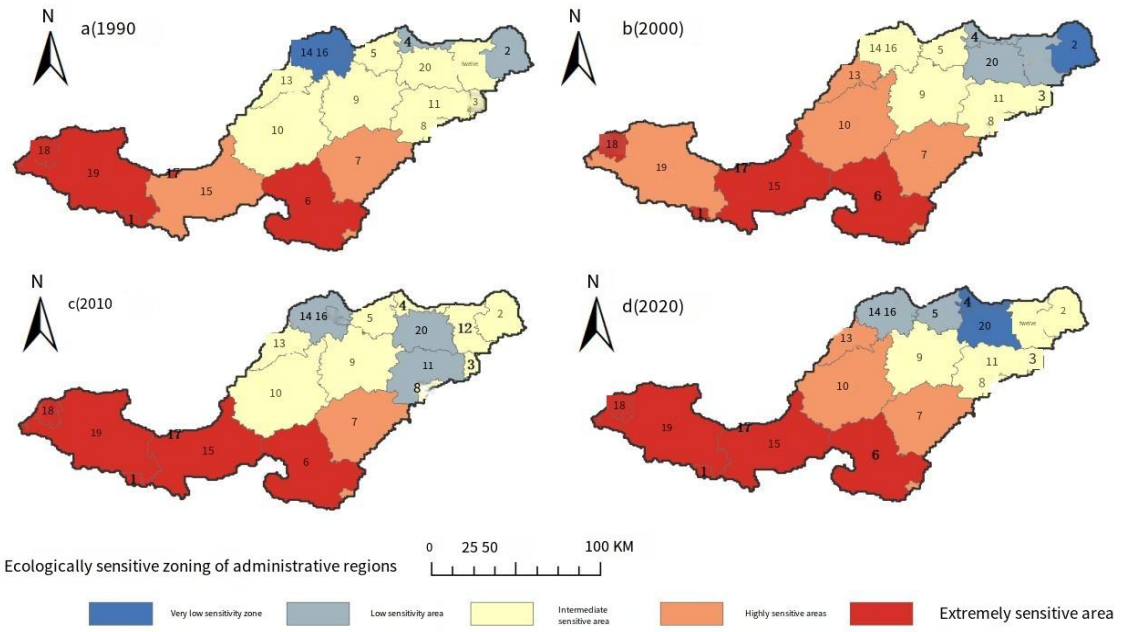

Fig. 4 Spatial Distribution of Ecological Sensitivity Across Administrative Units in the Luo River Basin, 1990-2020

Note：1- Danfeng County; 2- Gongyi City; 3- Dengfeng City; 4- Mengjin County; 5- Xin 'an County; 6- Luanchuan County; 7- Song County; 8- Ruyang County; 9- Yiyang County; 10- Luoning County; 11- Yichuan County; 12- Yanshi District; 13- Shanzhou District; 14- Mianchi County; 15- Lushi County; 16- Yima City; 17- Lingbao City; 18- Huazhou District; 19- Luonan County; 20- Luoyang City.

3.5. Spatial aggregation characteristics of ecological sensitivity in the Luo River Basin

3.5.1. Global Spatial autocorrelation analysis of ecological sensitivity in the Luo River Basin

Table 3 Global Moran's I for Spatial Autocorrelation in the Luo River Basin, 1990-2020

Index	1990	2000	2010	2020
Moran’s I	0.915	0.905	0.913	0.927
Z-statistic	176.2935	174.2532	175.8356	178.4630
P value	0.001	0.001	0.001	0.001

Spatial autocorrelation analysis of the comprehensive ecological sensitivity index of the Luo River Basin in 1990, 2000, 2010, and 2020 (Table 3) showed that the P-values of the Moran's I index in each year were all <0.01. Through a 99% confidence test, it indicates that ecological sensitivity is significantly positively correlated spatially. The Z-statistic was greater than 2.58, and the null hypothesis was not valid, which led to the spatially valid and positively aggregated autocorrelation. Over time, the Z-score first slightly decreased and then increased, indicating an overall upward trend in the spatial aggregation of ecological sensitivity and a relatively higher spatial convergence.

3.5.2. Analysis of local spatial autocorrelation in the Luo River Basin

Spatial clustering analysis of the Moran's I index for each year was conducted using the ArcGIS 10.7 platform (Figure 5), which was divided into high and low aggregation areas (H-L), high aggregation areas (H-H), low low aggregation areas (L-L), low high aggregation areas (L-H), and not significant areas. Overall, the ecological sensitivity index of the Luo River Basin was distributed in a band-like

pattern on the spatial scale, with the degree of aggregation fluctuating slightly over time but showing an overall upward trend. The low value of the comprehensive ecological sensitivity index of the Luo River Basin is mainly distributed in the surrounding areas centered on the Luoyang Basin, starting from the middle reaches of the Luo River with Changshui in Luoning County as the dividing line, extending eastward along the Xiong 'er Mountains to Gongyi City in the lower reaches of the Luo River Basin, southward to the western section of the Funiu Mountains in Song County, and northward to parts of Xin 'an County and Mianchi County, forming a low aggregation area. It is mainly associated with very low sensitive areas and low sensitive areas. The high concentration area is mainly distributed in the area of Jianyu Ridge, Xiaoshan and Mangling on the southeast side of the Qinling Mountains at the source of the upper reaches of the Luo River Basin. In the middle reaches of the basin, the three major mountain ranges of Xiong 'er Mountain, Funiu Mountain and Waifang Mountain are most densely concentrated. The high concentration area is mainly associated with the extremely sensitive area and the highly sensitive area. Since 2000, the number of low-low and high-high aggregation grids has increased year by year, indicating that the ecological sensitivity index of the basin tends to be concentrated in spatial structure. According to the LISA map, the low-concentration areas are mainly concentrated in the central Luoyang Basin and the northeastern lower plain area, while the high-concentration areas are mainly concentrated in the major mountain ranges in the west and south. The number of grids in the low region increased from 4,550 in 1990 to 4,930 in 2020, and the number of grids in the high region increased from 5,770 in 1990 to 5,873 in 2020. The significant increase in the biosensitivity index of the low aggregation indicates an increasing spatial distribution of areas with low ecological sensitivity and some improvement in the ecological environment of the basin. But the high concentration remains at a high level, and there is a certain risk to the ecological situation.

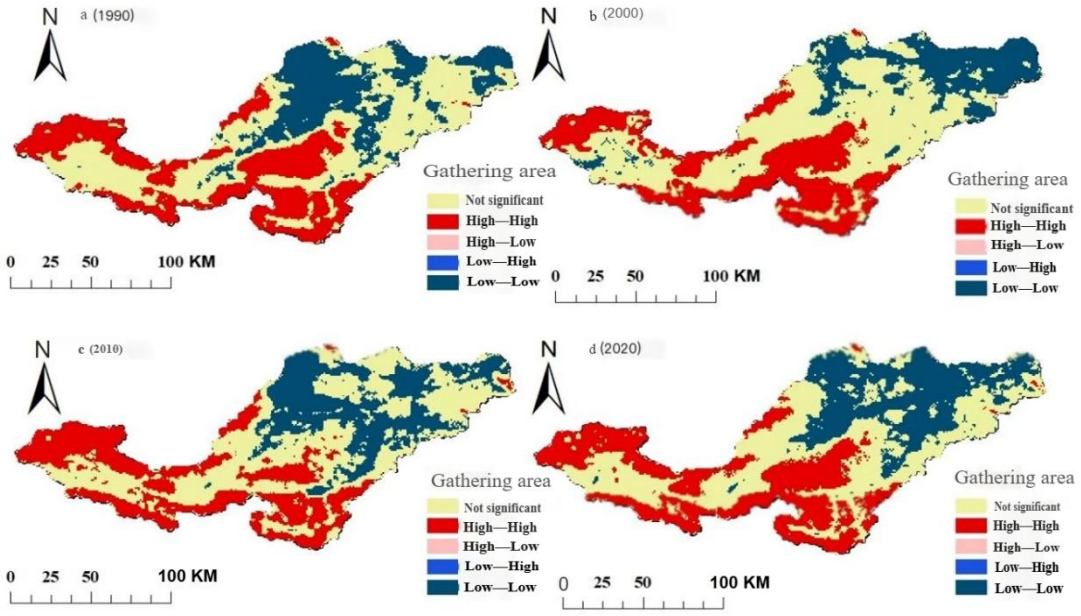

Fig. 5 LISA Clustering Map of Ecological Sensitivity in the Luo River Basin, 1990-2020

4. DISCUSSION

In the single-factor assessment, the factor with the greatest impact on the ecological sensitivity of the Luo River Basin was NDVI, and the factor with the least impact was the water buffer zone, with weights of 0.345 and 0.044 respectively. The land use factor (with a weight of 0.236) had an impact that was similar to the ecological sensitivity distribution of NDVI, which was largely consistent with the overall ecological sensitivity distribution trend of the Luo River Basin that was ultimately derived.

From 1990 to 2020, the overall ecological sensitivity of the Luo River Basin showed east-west differences. The sensitivity in the middle and lower reaches improved over the past 20 years, and the risk of ecological sensitivity was alleviated. The very low and low sensitive areas continued to concentrate in the Luoyang Basin, the Luo River alluvial plain, and the loess hills. There are significant fluctuations in the extremely sensitive and highly sensitive areas, with the sensitivity in the upper reaches remaining at a high level throughout the year and the degree of aggregation increasing significantly. From 2010 to 2020, the dispersion of low-risk areas in the upper reaches and the southern part of the middle reaches intensified, the area decreased, and they turned into high-risk areas. The ecological environment deteriorated. This area is a low mountain range formed by the outer folds and faults of Zhongshan and outside the Lushi Basin. The terrain is fragmented and complex, with an annual precipitation of up to 610mm, severe soil erosion, and is greatly restricted by natural factors and susceptible to human activities. The ecosystem is inherently fragile. The strength of human activities often affects the stability of ecosystems. From 2010 to 2020, there was a significant increase in cultivated land area in the upper reaches of the basin, and extensive slope farming exacerbated soil erosion. The area of cultivated land, forest land and grassland in the middle and lower reaches also shifted to construction land. Coupled with unreasonable exploitation of resources, the ecological environment is under great pressure and should continue to strengthen the management of cultivated land and forest land. The upper reaches of the Yiluo River have maintained more terrestrial and forest ecosystems, with a high degree of sensitivity change and high concentration. The risk has significantly increased in the past decade. It is necessary to strengthen supervision and ecological restoration, reduce human interference, and intensify efforts to conserve water and soil.

From 1990 to 2020, the sensitivity of the middle reaches of the Luo River Basin was more complex, showing differences between the north and the south. The terrain and landforms of the middle reaches of the basin were complex, and it was also an important economic activity area for humans. From 1990 to 2000, the sensitivity was poor. With the development of the social economy, it changed from very low sensitivity to low-sensitive and medium-sensitive areas, and the area of low-risk areas decreased. 2000-2020 With the implementation of policies such as the "Regulations on Returning Farmland to Forest", the "Comprehensive Planning for the Yiluo River Basin" and the "Construction of the Yiluo River Ecological Civilization Demonstration Zone", the area of the extremely low and low sensitive areas in the northern middle reaches of the basin has increased and the concentration has risen. The ecological risks in the loess hilly area and the river-Luo plain are improving, but it is worth noting, Some areas along both sides of the river in the central and western part of the basin have been disturbed by human factors, resulting in a slight degradation trend in vegetation coverage, with obvious degradation[37] in some areas. Construction and protection of ecological wetlands, Luo River waters and landscape parks should be strengthened, and the water conservation capacity of water resources should be reasonably regulated. From 1990 to 2010, the transition from the extremely sensitive area in the southern middle reaches to the highly sensitive area was significant, the degree of aggregation weakened, and the environmental risk pressure decreased; However, from 2010 to 2020, there was a significant change in ecological sensitivity in the Xiong 'ershan and Funiu Mountain areas in the southern part of the basin, and high-risk aggregation intensified. This is because there are abundant mineral resources within the Luo River Basin, with Luoning, Song County and Luanchuan forming a key development area for heavy industry of polymetallic mines, and the distribution of water and soil resources in the basin has been uneven in recent years, water resources are tight. The relatively lagging ecological protection efforts have caused a contradiction between economic development and ecological protection, resulting in insignificant improvement of the ecological environment in the middle reaches.

The sensitivity of the lower reaches of the Luo River was relatively stable from 1990 to 2020. The concentration of low-risk areas increased from 1990 to 2000 and from 2010 to 2020, while the area of high-risk areas is gradually decreasing. The lower reaches are located at the confluence of the Luo River and the Yellow River. The terrain is flat and open. In recent years, after certain governance through the "Vigorous Promotion of Comprehensive Governance of the Yi and Luo Rivers under the

High-Quality Development of the Yellow River Basin" by the state, the ecological landscape has been improved, providing a good foundation for the development of the economic base, and the relative ecological sensitivity risk is relatively small.

In general, the strength of human activities is shown as: middle reaches > lower reaches > upper reaches, and the sensitivity risk is shown as: upper reaches > middle reaches > lower reaches. The upper reaches are the area with the best basic ecology in the basin, but it is the most sensitive area, vulnerable to human influence, and requires restrictions on human activities, cautious development, so that society and the environment can coexist in harmony. In the middle reaches, human activities are intense. Relying on a better economic foundation, there is a certain ability to withstand risks, making sensitivity and social economy compatible. However, vigilance should be exercised against the risk of environmental deterioration and increased ecological sensitivity. In the lower reaches, human activities are more vigorous. In the two-way development of economic activities and improved ecological foundation, the sensitivity risk is the least, demonstrating the promoting effect of human activities on ecological protection.

5. CONCLUSIONS

(1)From the results of the single-factor evaluation, it can be concluded that the ecological sensitivity zones of NDVI and land use have a strong correlation in spatial distribution. Combined with the elevation factor, it shows a trend that the sensitivity on both sides of the Luo River gradually increases from east to west as the altitude rises. This is mainly related to the fact that the intensity of human activity interference has a significant impact on vegetation coverage.

(2) The mining areas in the Luo River Basin are distributed in the central and northern regions, represented by the Xin 'an-Yanshi-Yiyang-Yichuan coal mine. Therefore, the frequency of soil erosion and debris flow, environmental pollution and other disasters in the northeastern and central regions is higher than in other regions. From the perspective of land use evaluation factors, the degree of land use in the Luo River Basin is relatively low, and the spatial use of land resources should be rationally planned to improve the spatial layout of land resources.

(3) The results of the comprehensive ecological sensitivity analysis of the Luo River region show that the overall ecological environment sensitivity of the basin is relatively high. The proportion of medium-sensitive areas is actually lower than that of light-sensitive areas. The distribution of low-sensitive areas is basically centered on the river valley and extends to the north and south sides. The closer to the edge of the Luo River, the higher the ecological sensitivity; the closer to the central urban area, the lower the ecological sensitivity. This indicates that there is a significant difference in ecological sensitivity, due to the influence of the difference between human activities and natural activities.

(4) The results of the comprehensive ecological sensitivity of the Luo River Basin from 1990 to 2020 show that the most prominent are the extremely sensitive areas, which are distributed in the central, southern, western and marginal regions. The proportion of the area has remained high and has shown an overall upward trend, with a significant increase in the past decade, high altitude, rich vegetation coverage, complex terrain, and mostly in natural conditions. There is still a need to strengthen the management of human risks.

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