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Evaluation of Ecological Vulnerability and Analysis of Its Spatiotemporal Evolution Based on the Fuzzy Comprehensive Evaluation/Catastrophe Progression Method: A Case Study of the Danjiang River Basin (Henan Section)

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Abstract: In recent years, with the implementation of the South-to-North Water Diversion Project, the land use problem and its ecological effects on the Danjiang River Basin (DRB), which is a water source in the project, have become some of the focal points of current research in ecology and environmental science. Selecting the DRB (Henan section) as the study area, an ecological vulnerability evaluation model based on the fuzzy comprehensive evaluation/catastrophe progression method was constructed to evaluate the ecological vulnerability of the study area. The spatiotemporal evolution patterns of ecological vulnerability in the study area were quantitatively analyzed, and the main evolutionary drivers were identified by using GeoDetector. The results showed that: (1) the ecological vulnerability of the DRB (Henan section) was mainly moderate and mild, with areas of 2535.26 km^2 and 2717.33 km^2, respectively, by 2020, accounting for 30.14% and 32.30%, respectively, of the total area of the basin, with an overall vulnerability distribution characteristic of "low in the north and high in the south"; (2) the ecological vulnerability indices of the DRB (Henan section) in 2000, 2010, and 2020 were 0.56, 0.61, and 0.58, indicating that the ecological quality first decreased and then increased; and (3) the influence of vegetation factors on ecological vulnerability was large, with explanatory power above 4%. The influence of economic pressures and surface factors on ecological vulnerability gradually increased. This study can provide a reference for ecological environmental protection in the water source of the middle route of the South-to-North Water Diversion Project.

Keywords: ecological vulnerability; fuzzy comprehensive evaluation/catastrophe progression method; GeoDetector; spatiotemporal evolution; Danjiang River Basin

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1. Introduction

In recent decades, the conflict between ecosystem vulnerability and economic development has become increasingly prominent, and many environmental problems affecting ecosystems have emerged. Studies of ecological vulnerability aim to provide a scientific basis for the governance and restoration of the ecological environment [1]. At present, the study of ecological vulnerability has become an important topic in the research on global sustainable development and ecological environmental change [2] and is of great significance for the sustainable development of ecosystems.

Ecological vulnerability refers to the sensitivity of the natural environment to external disturbances (including natural and human disturbances) and its capacity for spontaneous recovery within a specific time and space. The disturbances are caused by the joint impact of human socioeconomic behavior and natural conditions [3,4]. Research into the ecological vulnerability in China began in the 1980s. In 1989, Niu [5,6] defined the notion of a fragile zone in an ecological environment, and comprehensively and logically described its essence and spatial attributes. With the advances in studies of ecological fragility, the scope of the research gradually transitioned from the ecologically fragile zone to the ecologically fragile area [7]. Different scholars and different disciplines have diverse understandings of the meaning of ecological vulnerability. For example, Wang et al. [8,9] discussed the scientific significance of vulnerability among various research fields and different perspectives on ecological environment vulnerability, as well as the relationships between ecological environment vulnerability and sensitivity, stability, and the ecologically fragile zone. Scholars around the world have conducted in-depth research on vulnerability and gradually formed evaluation models such as the "Vulnerability Scoping Diagram" (VSD) [10], "Pressure State Response" (PSR) [11,12], "Sensitivity–Resilience–Pressure" (SRP) [13,14], "Natural Cause Index–Performance Index", and "Natural–Ecological–Socioeconomic Index System" [15]. Based on the grey trigonometrically whitening weight set pair analysis (SPA) model, Shu et al. [16] provided a new method and idea for assessing eco-environmental vulnerability; Xiao [17] applied two types of artificial neural networks combined with 3 s technology, thus making a valuable contribution to provincial vulnerability assessment research [18]. Tang et al. [19] discussed the uncertainties surrounding the concept of ecological vulnerability, the complexity of evaluation indicators, and the applicability of research methods. In addition, Lin et al. [20] applied an ecological vulnerability assessment to tourism poverty and precision poverty alleviation and carried out research on ecological vulnerability and its driving factors in key villages of rural tourism poverty alleviation in China. Research and development in ecological vulnerability assessment has entered a comprehensive and mature stage, from simple quantitative growth to theoretical connotation constructs [21].

The Henan section of the Danjiang River Basin (DRB) is the water source of the middle route of China's South-to-North Water Diversion Project. This water diversion project is of great significance in seeking to alleviate the problem of water shortages in Northern China, and its ecological benefits are also reflected in the increase in water volume. For example, in addition to the surface runoff in the receiving area having been ecologically complemented by water from the south, the groundwater level in the receiving area has also, to some extent, been restored, the ecological environment along the river course improved, and the regional climate adjusted. However, the region continues to face major ecological problems. The problem of soil and water loss in the water source area remains critical, while rapid industrial and agricultural developments have led to a deterioration in water quality [22]. Therefore, the present ecological vulnerability assessment study of the water sources is aimed to provide effective technical support and a reference basis for improving regional ecological environments, enhancing ecological performance, and achieving water diversion security over the middle route of the South-to-North Water Diversion Project. Nonetheless, few studies have been conducted to date on the spatiotemporal evolution of ecological vulnerability in the water source areas of large-scale water diversion projects. The purpose of this study was to design a fuzzy comprehensive evaluation/catastrophe progression method, which was devised to dynamically and quantitatively evaluate the ecological vulnerability of the DRB (Henan section) from 2000 to 2020, and to reveal the spatiotemporal evolution characteristics of regional ecological vulnerability and its driving factors, in order to provide new ideas and methods for the study of ecological vulnerability in the DRB (Henan section) and similar areas.

2. Materials and Methods

2.1. Study Area

The DRB (Henan section), which, as previously indicated, is the main water source of the middle course of the South-to-North Water Diversion Project, is located in the southwest of Henan Province. It mainly encompasses Xichuan County and Xixia County of Nanyang City, Luanchuan County of Luoyang City, and Lushi County of Sanmenxia City. Its geographical coordinates are 110°35′–111°58′ E and 32°30′–34°01′ N, with a total study area of 8412.42 km^2. The main water course of the Danjiang River comes from Jingziguan

Town, Xichuan County, whose catchment area accounts for 3.11% of the study area. The western and northern parts of the study area are surrounded by the foothills of the Niushan Mountain. The topography of the eastern parts, which comprises mountains, hills, ridges, and plains, reflects a decrease in altitude from north to south, with significant drops in elevation in places (2096 m to 114 m). The geographical location is shown in Figure 1 below.

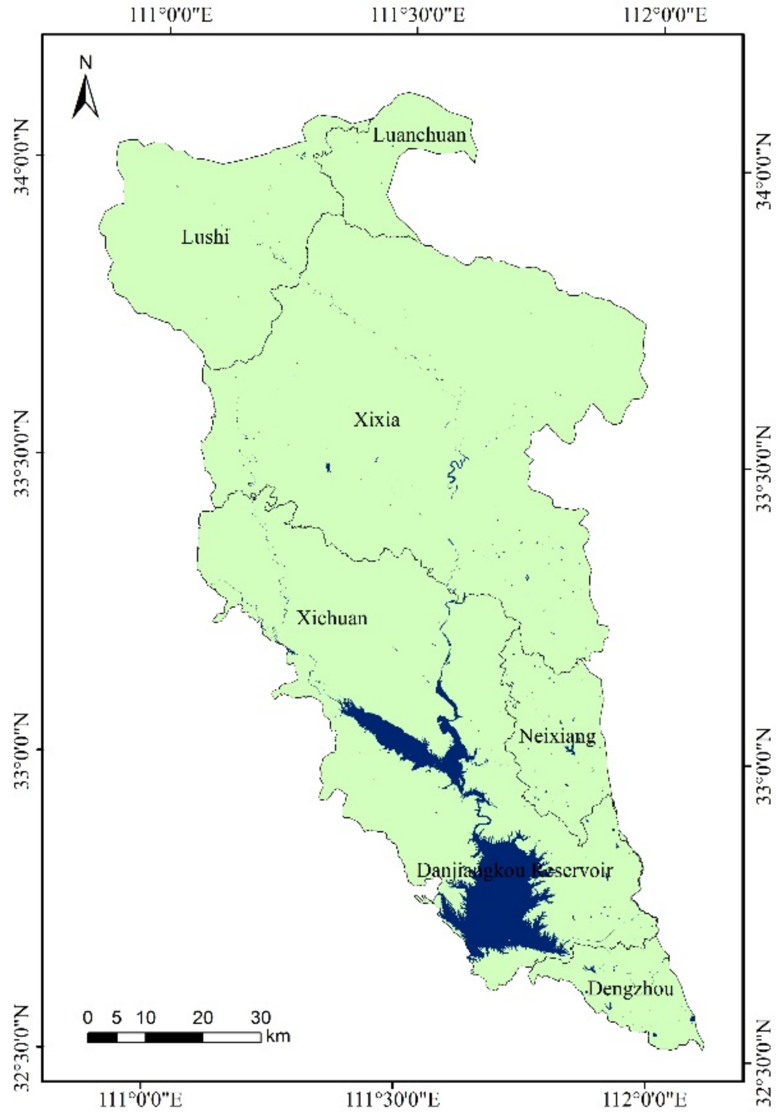


Figure 1. Overview of the study area.

2.2. Datasets

The original data used in this study primarily included Landsat series remote sensing images, digital elevation data, and basic data such as the third national land survey data, hydrological data, and socioeconomic and population data, as shown in Table 1 below. Using the classified land use data, the landscape fragmentation degree and diversity index data were calculated using the Fragstats4.1 software (Amherst, MA, USA).

Table 1. Data sources and uses.

Data Type	Data Name	Time	Source	Uses
Raster	Landsat TM Landsat OLI Landsat OLI	15 August 2000 14 August 2010 15 August 2020	USGS (Resolution: 30 m)	Extraction of land use data
	Digital elevation	2019	NASA (Resolution: 30 m)	Access to elevation, slope, and degree of topographic fluctuation
	Vegetation factor data	2000, 2010, and 2020	Geospatial Data Cloud (Resolution: 30 m)	Access to vegetation coverage, net primary productivity, gross primary productivity, and leaf area index
Database	The Third National Land Survey data	2019		Verification of accuracy of classification
Vector	River system data	2018		Extraction of hydrological factors
Statistical data	Meteorological data	2000, 2010, and 2020	National Earth System Science Data Center, National Meteorological Science Data Center	Extraction of meteorological factors
	Economic data		Statistical Yearbook, Resource and Environmental Science and Data Center	Access to per capita GDP
	Population data			Access to per capita cultivated land and population density

2.3. Methods

2.3.1. Construction of the Ecological Vulnerability Index System

1. Establishment of the evaluation index system

In accordance with the principles of comprehensiveness, representativeness, accessibility, and hierarchy of index selection, lessons were drawn from relevant research results [23–25], the relevant indicators of ecological vulnerability assessment were summed up and triaged, and the environmental characteristics of the DRB were carefully considered. Following these preparatory measures, the SRP model was chosen as the basis for selecting indicators. From seven aspects of topography, surface, meteorology, hydrology, vegetation, human activities, and economic pressures, 18 representative indicators (Table 2) were selected to form the definitive ecological vulnerability evaluation index system for the DRB (Henan section).

Table 2. Evaluation index system of ecological vulnerability.

Target Layer	Criterion Layer	Index Layer	Factor Layer	Indicator Description	Weight
SRP	S (Sensitivity)	Topographic factors	Elevation (C1)	Positive indicators	0.0347
			Slope (C2)	Positive indicators	0.1015
			Degree of topographic fluctuation (C3)	Positive indicators	0.0347
		Surface factors	Land use type (C4)	Assigning values by type	0.0217
			Landscape fragmentation (C5)	Positive indicators	0.1254
			Diversity index (C6)	Negative indicators	0.0603
		Meteorological factors	Average annual precipitation (C7)	Negative indicators	0.0200
			Average annual temperature (C8)	Negative indicators	0.0230
		Hydrological factors	Annual runoff (C9)	Positive indicators	0.0967
			Per capita water resources (C10)	Positive indicators	0.1171
			Average annual sediment concentration (C11)	Negative indicators	0.1034
	R (Resilience)	Vegetation factors	Vegetation coverage (C12)	Negative indicators	0.0299
			Net primary productivity (C13)	Negative indicators	0.0171
			Gross primary productivity (C14)	Negative indicators	0.0195
			Leaf area index (C15)	Negative indicators	0.0286
	P (Pressure)	Pressure of human activities	Population density (C16)	Positive indicators	0.0183
			Per capita cultivated land (C17)	Positive indicators	0.0328
		Economic pressures	Per capita GDP (C18)	Positive indicators	0.1153

2. Index normalization

The indicators were divided into positive and negative indicators according to their impact on ecological vulnerability and were standardized. Positive indicators showed that the higher the index value, the worse the ecological status, and the greater the degree of vulnerability; negative indicators indicated that the larger the index value, the better the ecological status, and the lower the degree of vulnerability. The indicators with positive vulnerability correlations were standardized by Formula (1), and the indicators with negative vulnerability correlations were standardized by Formula (2).

$$x_i = \frac{x - x_{\min}}{x_{\max} - x_{\min}} \quad (1)$$

$$x_j = \frac{x_{\max} - x}{x_{\max} - x_{\min}} \quad (2)$$

where x_i is the standardized value of the positive index, and x_j is the standardized value of the negative index.

3. Determination of index weighting by the entropy grey relational method

In this study, based on the notion of the grey correlation degree and its mathematical model, the more objective results obtained by the entropy method [26] were used to replace the traditional resolution coefficient ρ in the grey correlation degree analysis, and the distribution value of index weighting was calculated more objectively. The entropy results were obtained according to Formulas (3)–(5), and the weight calculation results were attained by combining Formulas (6) and (7).

$$e_j = -k\sum_{i=1}^{n} P_{ij} \ln P_{ij} \quad (3)$$

$$P_{ij} = x_{ij} / \sum_{j=1}^{m} x_{ij} \quad (4)$$

$$w_j = \frac{1 - e_j}{\sum_{i=1}^{n}(1 - e_j)} \quad (5)$$

$$e_{ij} = \frac{\min_i \min_j |k_j - x_{ij}| + \rho \max_i \max_j |k_j - x_{ij}|}{|k_j - x_{ij}| + \rho \max_i \max_j |k_j - x_{ij}|} \quad (6)$$

$$w_j = \frac{1}{n}\sum_{i=1}^{n} e_{ij} / \sum_{j=1}^{m} \frac{1}{n}\sum_{i=1}^{n} e_{ij} (j = 1, 2, \ldots, m) \quad (7)$$

where $k = 1/ln(n)$, when $P_{ij} = 0$, $P_{ij} lnP_{ij} = 0$; ρ is the resolution coefficient, and its value range is within [0, 1]; $min_i min_j |k_j - x_{ij}|$ is the minimum difference between the two levels; $max_i max_j |k_j - x_{ij}|$ is the maximum difference between the two levels; and $W = (w_1, w_2, \ldots w_m)$ is the weight of the index.

2.3.2. Ecological Vulnerability Assessment Method

(1) Ecological vulnerability assessment model

The model was constructed using MATLAB software. A fuzzy comprehensive evaluation/catastrophe progression method was established on the basis of the catastrophe series and fuzzy comprehensive evaluation methods. The technical process of the model consisted of the following: firstly, determining the set of index factors and a total of 18 indicators according to the established ecological vulnerability evaluation index system; secondly, ranking all indicators in order of importance by using the results of the weighting calculations; thirdly, using the fuzzy comprehensive evaluation method to determine the membership function and evaluation set; fourthly, selecting the appropriate membership function to determine the membership degree; and, lastly, carrying out a normalization operation and comprehensive evaluation of the results. When all the results of the ecological vulnerability assessment were obtained, the cycle was terminated.

The main process was as follows:

1. Determining the index factor set according to the established ecological vulnerability evaluation index system. There were a total of three periods of data, each period comprising 18 indicators.
2. Obtaining a more objective and accurate ranking result of the importance index using the weighting calculation results.
3. Subdividing the evaluation indicators into five grades on the basis of previous research results and relevant industry standards. The five grades [27,28] V were: (i) extremely fragile, (ii) significantly vulnerable, (iii) moderately vulnerable, (iv) mildly vulnerable, and (v) potentially vulnerable.
4. Determining the membership function of positive and negative indices using the fuzzy comprehensive evaluation method.
   Membership function of positive index:

$$\mu_1(x) = \begin{cases} 1 & x \leq A_1 \\ \frac{A_2 - x}{A_2 - A_1} & A_1 < x < A_2 \\ 0 & x \geq A_2 \end{cases}, \ \mu_i(x) = \begin{cases} 0 & x \leq A_{i-1} \\ \frac{A_{i-1} - x}{A_{i-1} - A_i} & A_{i-1} < x < A_i \\ \frac{A_{i+1} - x}{A_{i+1} - A_i} & A_i < x < A_{i+1} \\ 0 & x \geq A_{i+1} \end{cases}, \ \mu_5(x) = \begin{cases} 0 & x \leq A_4 \\ \frac{A_4 - x}{A_4 - A_5} & A_4 < x < A_5 \\ 1 & x \geq A_5 \end{cases} \quad (8)$$

   Membership function of negative index:

$$\mu_1(x) = \begin{cases} 0 & x \leq A_2 \\ \frac{A_2 - x}{A_2 - A_1} & A_2 < x < A_1 \\ 1 & x \geq A_1 \end{cases}, \ \mu_i(x) = \begin{cases} 0 & x \leq A_{i+1} \\ \frac{A_{i+1} - x}{A_{i+1} - A_i} & A_{i+1} < x < A_i \\ \frac{A_{i-1} - x}{A_{i-1} - A_i} & A_i < x < A_{i-1} \\ 0 & x \geq A_{i-1} \end{cases}, \ \mu_5(x) = \begin{cases} 1 & x \leq A_5 \\ \frac{A_4 - x}{A_4 - A_5} & A_5 < x < A_4 \\ 0 & x \geq A_4 \end{cases} \quad (9)$$

   where $u_i(x)$ is the degree of membership of the ecological vulnerability evaluation index in the i evaluation grade; and A_i is the threshold of the i evaluation grade (i = 1, 2, . . . , 5).
5. Selecting and normalizing the catastrophe model, as illustrated in Table 3 below, from lowest to highest according to the order of importance of the indicators and the number of indicators in each layer of the evaluation indicators.

Table 3. Normalized formulae for various common mutation types.

Mutation Type	Control Variable	State Variable	Normalized Equation
Folding catastrophe	1	1	$x_\mu = \sqrt{\mu}$
Cusp catastrophe	1	2	$x_\mu = \sqrt{\mu}, x_v = \sqrt[3]{v}$
Dovetail catastrophe	1	3	$x_\mu = \sqrt{\mu}, x_v = \sqrt[3]{v}, x_\omega = \sqrt[4]{\omega}$
Butterfly catastrophe	1	4	$x_\mu = \sqrt{\mu}, x_v = \sqrt[3]{v}, x_\omega = \sqrt[4]{\omega}, x_t = \sqrt[5]{t}$
Indian cottage catastrophe	1	5	$x_\mu = \sqrt{\mu}, x_v = \sqrt[3]{v}, x_\omega = \sqrt[4]{\omega}, x_t = \sqrt[5]{t}, x_s = \sqrt[6]{s}$

6. Performing a comprehensive evaluation of the normalized results. Once all the data were processed and the calculations completed, the seventh step could be initiated; otherwise, we returned to the fourth step.
7. Obtaining the global ecological vulnerability assessment results and classifying the results with a resolution of 30 m × 30 m.

(2) Classification of ecological vulnerability

According to the clustering principle [29,30], and with reference to previous studies [31,32], combined with the natural and socioeconomic conditions of the DRB (Henan section), ecological vulnerability was subdivided into five grades. The standards and characteristics of each grade are shown in Table 4 below.

Table 4. Ecological vulnerability grading standard.

Grade	Evaluation Result	Degree of Fragility
I	<0.50	Potentially vulnerable
II	0.50–0.60	Mildly vulnerable
III	0.60–0.62	Moderately vulnerable
IV	0.62–0.70	Significantly vulnerable
V	>0.70	Extremely vulnerable

2.3.3. GeoDetector

GeoDetector technology is a set of statistical methods to detect spatial differentiation and identify the driving factors involved. This method does not rest on any linear hypothesis, is of elegant form, and provides a clear physical meaning. The geographic detection device comprises four detectors, which were utilized to quantitatively analyze the driving factors responsible for the spatial differences in ecological vulnerability within the DRB (Henan section). The specific formula was as follows [33,34].

Factor detection: the extent to which the spatial differentiation of attribute Y is explained by detecting the spatial differentiation of Y and the detection of a certain factor X. The factor detection was measured by the value of q [35]; the calculations can be expressed as follows:

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma^2} = 1 - \frac{SSW}{SST} \tag{10}$$

$$SSW = \sum_{h=1}^{L} N_h \sigma_h^2,\ SST = N\sigma^2 \tag{11}$$

where $h = 1, \ldots, L$; L is the stratum of variable Y or factor X—that is, classification or partition; N_h and N are the numbers of units of layer h and the entire region, respectively; and σ_h^2 and σ^2 are the variance of the value of Y of layer h and the entire region, respectively. SSW and SST are the sum of intra-layer variance and the total variance of the whole region, respectively. The range of q is [0, 1]. The higher the q value, the stronger the explanatory impact of the independent variable X on attribute Y, and vice versa.

3. Results

3.1. Analysis of the General Characteristics of Ecological Vulnerability

The distribution of the ecological vulnerability assessment results produced over the past 20 years was obtained using the fuzzy comprehensive evaluation/catastrophe progression method, as shown in Figure 2 below, and the statistical results of the ecological vulnerability assessment are shown in Table 5 below.

From Figure 2 and Table 5, it can be observed that the evaluation results of ecological vulnerability over the past 20 years revealed a normal asymmetric distribution, and that the peak values of ecological vulnerability for 2000, 2010, and 2020 were mildly vulnerable, moderately vulnerable, and mildly vulnerable, respectively. The ecological vulnerability grade distribution was found to vary significantly in the DRB (Henan section). The grade distribution was "middle: low, north and south: high", and "south: high, north: low".

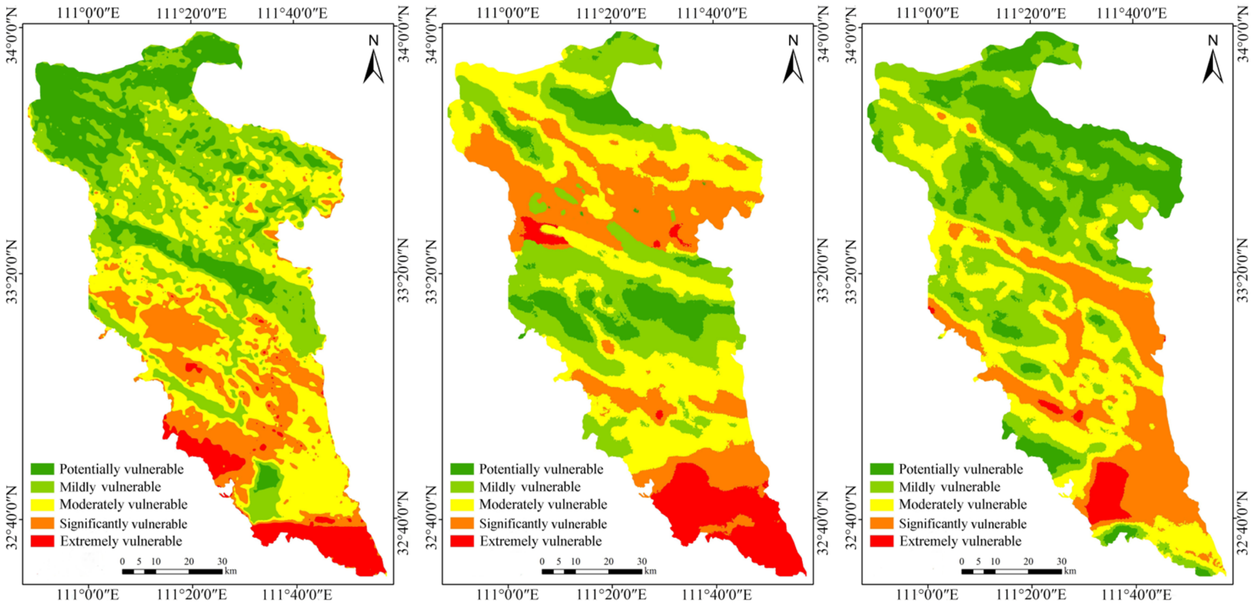


Figure 2. Distribution map of ecological vulnerability assessment results obtained by the fuzzy synthesis/catastrophic progression method. (**a**) 2000; (**b**) 2010; (**c**) 2020.

Table 5. Results of the ecological vulnerability assessment in the study area from 2000 to 2020.

Year		Potentially Vulnerable	Mildly Vulnerable	Moderately Vulnerable	Significantly Vulnerable	Extremely Vulnerable	Evaluation Value
2000	Area/km^2	1532.96	2762.86	2290.80	1181.64	644.16	0.56
	%	18.22	32.84	27.23	14.05	7.66	
2010	Area/km^2	720.95	2086.33	2968.03	1701.86	935.26	0.61
	%	8.57	24.80	35.28	20.23	11.12	
2020	Area/km^2	1148.70	2717.33	2535.26	1570.55	440.58	0.58
	%	13.65	32.30	30.14	18.67	5.24	

From the perspective of the distribution of ecological vulnerability between 2000 and 2020, the areas with high degrees of ecological vulnerability were found to have shifted from the north to the south of the study area. The changes in the proportions of extremely vulnerable and significantly vulnerable areas in the DRB (Henan section) revealed that the area of its unstable ecosystem initially increased and then decreased. The extremely vulnerable area was observed to have gradually moved from the northern mountain area to the southern plain. This was mainly ascribed to the rapid development of urbanization and industrialization in the southern plain area before 2014 and the corresponding gradual rise in the land use area. The increased rate of interference from human activities resulted in a deterioration in the capacity for interference resilience and self-recovery of the ecosystem in the southern plain. However, after the formal opening of the middle route of the South-to-North Water Diversion Project in 2014, the DRB began gradually to strengthen its control of the water environment and soil erosion, which, to some extent, restrained the further deterioration of the ecological environment.

The changes in the proportions of moderately, mildly, and potentially vulnerable areas indicated that the proportion of stable ecosystem areas in the DRB (Henan section) has initially decreased and then increased over recent years, revealing a downward trend overall. The stable areas were seen to have transferred from the central and northern parts to the central and southern parts of the study area. This was hypothesized to be mainly because the northern part of the study area has relatively high topography, abundant vegetation, good ecological resilience, and fewer stressors on the environment. With the completion of the middle route of the South-to-North Water Diversion Project, the intensity of environmental protection has gradually increased over recent years, with a corresponding reduction in pressure on the ecological environment. The outlook for the ecological environment in the northern part of the study area thus appears relatively optimistic.

Overall, from 2000 to 2020, the areas of extreme and potential vulnerability were found to be relatively small, while those of mild and moderate vulnerability were seen to be relatively large. The stable areas of ecological vulnerability showed a trend of initial decrease and then an increase, suggesting that the ecological environment was gradually improving.

3.2. Distribution Characteristics of Ecological Vulnerability Based on Different Land Use Types

Different land use patterns have different effects on ecological vulnerability. The present study therefore further analyzed the characteristics of ecological vulnerability on the basis of the diverse land use types in the DRB (Henan section) from 2000 to 2020. This was intended to provide supporting data to inform future land use adjustments [36] as well as ecological engineering planning and implementation [37].

Figure 3 below shows the ecological vulnerability grade distribution of different land use types in the DRB (Henan section). Between 2000 and 2020, the area of cultivated land was observed to have gradually decreased, with an upward trend in the proportion of moderately and significantly vulnerable areas. This was interpreted to indicate that cultivated land principally lay in the areas with moderate and significant vulnerability, poor eco-environmental quality, and fragile ecology. In contrast, the area of woodland was found to have increased gradually, and the ratio of potentially and mildly vulnerable areas showed an upward trend over the same period, suggesting that the woodland areas mostly found themselves in a potentially and mildly vulnerable state, with a gradual improvement in the quality of their ecological environment. Meanwhile, the grassland area was seen to have gradually decreased, with mainly moderate and significant ecological vulnerability levels and deteriorating ecological quality, thus imperatively calling for more stringent management measures of the grassland ecological environment. The water area was observed to have gradually increased over the same period, with the proportion of mild and moderately vulnerable areas showing an upward trend. This suggested that the water area was primarily moderately fragile, with average environmental and ecological quality, thus requiring further investment in water treatment procedures. The area of built land was likewise seen to have increased gradually, with ratios of moderately and significantly vulnerable areas of 94.28%, 68.58%, and 66.51%, respectively. While the proportions of moderately and significantly vulnerable areas were observed to have decreased, the proportion of extremely vulnerable areas showed an alarming increase from 1.28% to 30.34%, illustrating the poor eco-environmental quality of the built land. In summary, cultivated land, grassland, and built land were the primary land use types affected by the high ecological fragility in the DRB (Henan section), indicating that these land use types should be the priority and focus of ecological environment management efforts in the future.

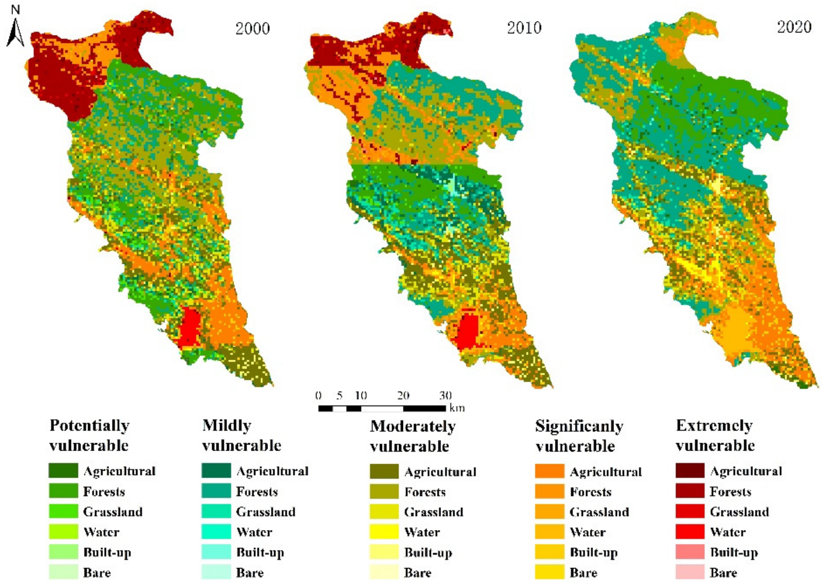


Figure 3. Spatial distribution of ecological vulnerability under different land use types.

3.3. Spatiotemporal Evolution of Ecological Vulnerability

In order to more accurately describe the spatiotemporal dynamic characteristics of ecological vulnerability in the DRB (Henan section), ArcGIS software was used in this study to analyze the vulnerability results and acquire the distribution maps of grade changes in ecological vulnerability for the periods 2000–2010, 2010–2020, and 2000–2020 within the study area. The results of ecological vulnerability changes were then standardized and redivided into five grades. The overall changes in ecological vulnerability in the DRB (Henan section) over the past 20 years were subsequently reflected more intuitively, as shown in Figures 4–6 below. At the same time, the ecological vulnerability grade transfer matrices for the periods 2000–2010, 2010–2020, and 2000–2020 within the study area were obtained, as shown in Tables 6–8 below.

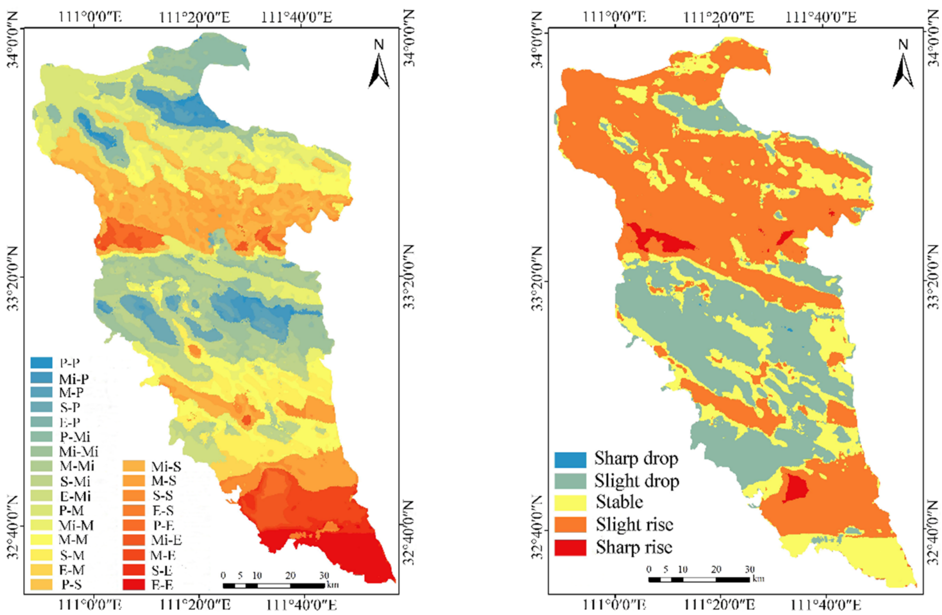


Figure 4. Distribution map of changes in ecological vulnerability levels in the study area from 2000 to 2010 (P = potentially vulnerable; Mi = mildly vulnerable; M: moderately vulnerable; S: significantly vulnerable; E: extremely vulnerable).

Table 6. Transition matrix of different ecological fragility levels from 2000 to 2010 (km^2).

Year	2010						
	Vulnerability Level	**Potentially Vulnerable**	**Mildly Vulnerable**	**Moderately Vulnerable**	**Significantly Vulnerable**	**Extremely Vulnerable**	**Total**
2000	Potentially vulnerable	231.96	877.00	368.35	55.51	0.14	1532.96
	Mildly vulnerable	421.24	729.19	1333.98	269.45	9.00	2762.86
	Moderately vulnerable	58.75	429.60	1110.99	616.65	74.81	2290.80
	Significantly vulnerable	8.00	49.54	154.55	551.93	417.61	1181.64
	Extremely vulnerable	1.00	1.00	0.15	208.31	433.70	644.16
	Total	720.95	2086.33	2968.03	1701.86	935.26	8412.42

Table 6 and Figure 4 show that the combined area with a sharp increase in ecological fragility in the DRB (Henan section) from 2000 to 2010 was 64.65 km^2, accounting for 0.77% of the total surface; the area with increased vulnerability amounted to 3957.85 km^2, accounting for 47.05% of the total area; the area with a stable vulnerability amounted to 3057.77 km^2, accounting for 36.35% of the total area; the area with reduced vulnerability amounted to 1322.15 km^2, accounting for 15.72% of the total area; and the area with a sharp decrease in vulnerability amounted to 10.00 km^2, accounting for 0.12% of the total area. Among the overall changes identified, the areas of rising ecological fragility markedly outweighed those characterized by decline. Most of the area of ecological vulnerability in the DRB (Henan section) from 2000 to 2010 was generally found to be either rising or stable, with no obvious severe change overall.

From the perspective of regional changes, the area with a sharp increase in ecological fragility was relatively small, dispersed among the southern part of Xichuan County and some areas of Xixia County, and the regional distribution was not continuous. While the areas revealing increasing degrees of ecological fragility were distributed among most parts of the study area, they were predominantly found in the north and southwest—that is, the north of Xixia County and the southern parts of Lushi County and Xichuan County. This was mainly attributed to the fact that, during the period from 2000 to 2010, with the implementation of the middle route of the South-to-North Water Diversion Project, the area of built land had shown an expanding trend, with a significant rise in per capita GDP. The terrain in the southern region of Xixia County is gently undulating and its ecological environment is exposed to further exacerbation due to severe disturbances caused by human activities, which are in turn gradually increasing its ecological fragility. The area showing a sharp decline in ecological fragility was small and distributed in the middle of the study area, whereas the areas with increasing ecological quality were spread among most parts of the study area, but mainly in the central, southern, and northwestern locations—that is, the south of Xixia County, the north of Xichuan County, and the southwest of Lushi County. This was mainly ascribed to the relatively high topography, high vegetation coverage, and low population density in those regions. In addition, the implementation of the "Danjiangkou Reservoir Area and Upper Reaches Water Pollution Prevention and Soil and Water Conservation Plan" in 2005 had gradually strengthened the controlled management of the water environment and soil erosion, and to some extent slowed the increase in ecological fragility. The areas with stable ecological fragility were mainly distributed in the south of Xixia County and the north of Xichuan County—that is, in the southwest of Lushi County. These are mostly hilly and mountainous areas, with fewer human activities, abundant vegetation, and good capacity of the ecosystem for self-recovery, and the ecological vulnerability in this area is in a stable state, thus, to some extent, restraining any ecological deterioration.

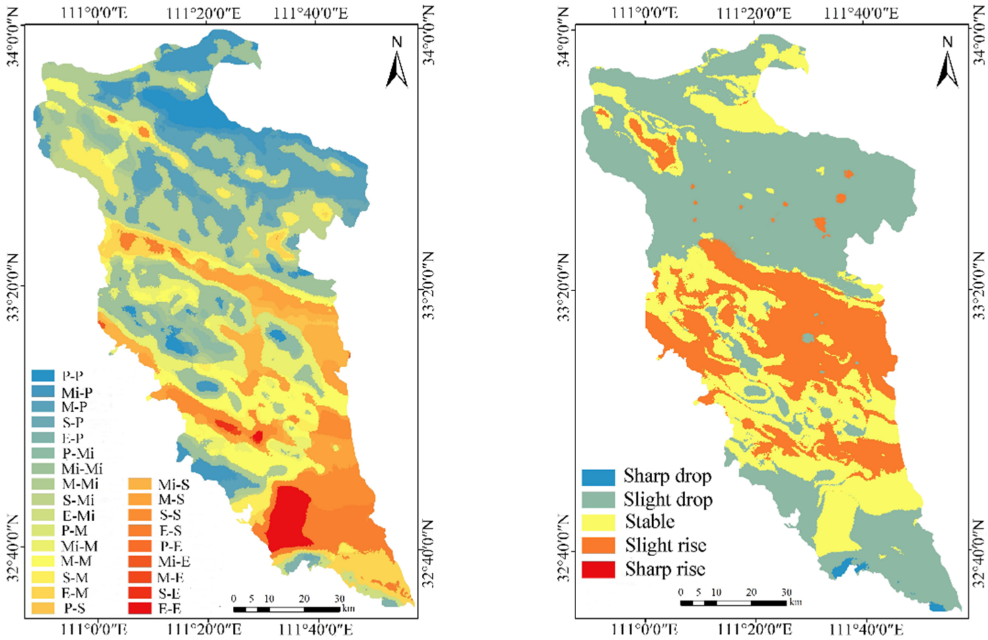


Figure 5. Distribution map of changes in ecological vulnerability levels in the study area from 2010 to 2020 (P = potentially vulnerable; Mi = mildly vulnerable; M = moderately vulnerable; S = significantly vulnerable; E = extremely vulnerable).

Table 7. Transition matrix of different ecological fragility levels from 2010 to 2020 (km^2).

Year		2020					
	Vulnerability Level	**Potentially Vulnerable**	**Mildly Vulnerable**	**Moderately Vulnerable**	**Significantly Vulnerable**	**Extremely Vulnerable**	**Total**
2010	Potentially vulnerable	22.81	657.13	38.01	1.00	2.00	720.95
	Mildly vulnerable	818.70	283.44	889.68	89.80	4.71	2086.33
	Moderately vulnerable	305.18	950.26	763.83	893.53	55.22	2968.03
	Significantly vulnerable	1.00	588.47	504.04	438.47	169.88	1701.86
	Extremely vulnerable	1.00	238.03	339.71	147.75	208.76	935.26
	Total	1148.70	2717.33	2535.26	1570.55	440.58	8412.42

As can be seen from Figure 5 and Table 7, diversity was identified in the conversion types of ecological vulnerability in the DRB (Henan section) from 2010 to 2020. Among the changes in ecological vulnerability types, the ecological vulnerability in the DRB (Henan section) was shown to have increased sharply from 2010 to 2020, accounting for 0.09% of the total area, which scarcely differed from the percentage found in 2000–2010. The surface with increased vulnerability amounted to 2793.25 km^2, accounting for 33.20% of the total study area, which was lower than that for 2000–2010; the area with stable vulnerability amounted to 1717.31 km^2, accounting for 20.41% of the total area, which was significantly lower than that for 2000–2010; the area with reduced vulnerability amounted to 3654.12 km^2, accounting for 43.44% of the total area, which was significantly higher than that for 2000–2010; the area with a sharp decline in vulnerability amounted to 240.03 km^2, accounting for 2.85% of the total area, which was not significantly different from the figure for 2000 and 2010. When considering the changes overall, the area of decreasing ecological fragility was greater than that of rising vulnerability, while the stable state surface had reduced. Globally, the ecological fragility of the DRB (Henan section) showed a downward trend from 2010 to 2020, matched with an improved ecological status compared to the previous decade.

From the perspective of regional changes, the area with a sharp increase in ecological fragility was relatively small, distributed discretely over the middle of the study area—that is, part of Xixia County. The areas with increasing ecological fragility were mostly found scattered among the southern and northern regions of the study area—namely, the southern and northern parts of Xixia County, Xichuan County, and Dengzhou City. This was believed mainly to be due to the gentle topography, reduced surfaces of woodland and grassland, and high population density, which coincided with an expansion in ecological fragility from 2000 to 2010. In contrast, the southern part of Xixia County showed a downward trend for the same period, which was deemed to be mainly related to the rapid industrial and economic growth in Xixia County over recent years. The area showing a sharp decline in ecological fragility was small and mainly distributed in the northwest of the study area—that is, the northern part of Lushi County. The areas with decreasing ecological fragility were primarily distributed in the northern and southern parts of the study area—namely, the northern part of Xixia County, the southern part of Lushi County, and some areas of Luanchuan County, Xichuan County, and Dengzhou City—which was assumed to have primarily been a result of the completion of the Dam Heightening Project of Danjiangkou Reservoir and the formal opening of the watercourse in the first phase of the South-to-North Water Diversion Project. Among them, the greening rate of barren hills and wasteland suitable for forestation in Xichuan County reached 95%, which arrested any further ecological deterioration. The areas with stable ecological fragility were mainly distributed in the southern part of Xichuan County.

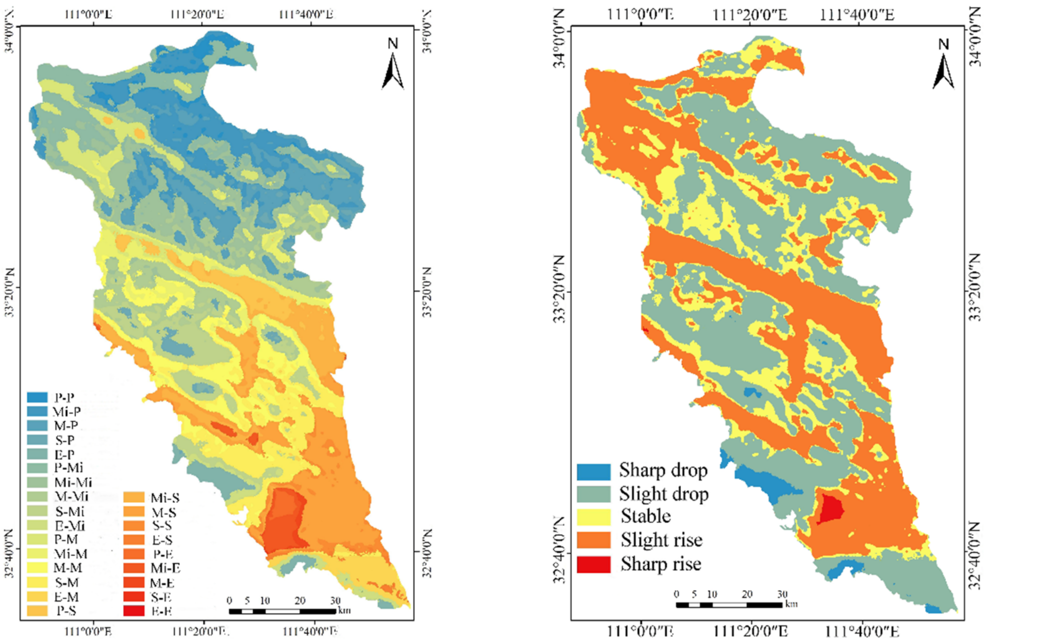


Figure 6. Distribution map of changes in ecological vulnerability levels in the study area from 2000 to 2020 (P = potentially vulnerable; Mi = mildly vulnerable; M = moderately vulnerable; S = significantly vulnerable; E = extremely vulnerable).

Table 8. Transition matrix of different ecological fragility levels from 2000 to 2020 (km^2).

Year	2020						
	Vulnerability Level	**Potentially Vulnerable**	**Mildly Vulnerable**	**Moderately Vulnerable**	**Significantly Vulnerable**	**Extremely Vulnerable**	**Total**
2000	Potentially vulnerable	672.42	530.38	263.09	57.55	9.52	1532.96
	Mildly vulnerable	471.92	1262.77	733.57	263.56	31.04	2762.86
	Moderately vulnerable	2.36	345.21	898.67	932.07	112.49	2290.80
	Significantly vulnerable	1.00	506.04	287.75	181.17	205.68	1181.64
	Extremely vulnerable	1.00	72.93	352.19	136.20	81.84	644.16
	Total	1148.70	2717.33	2535.26	1570.55	440.58	8412.42

As can be seen from Figure 6 and Table 8, diversity in the conversion types of ecological vulnerability was also identified in the DRB (Henan section) from 2000 to 2020. The changes in ecological vulnerability types indicated that the area of ecological vulnerability had increased sharply, accounting for 1.17% of the total area, or 3040.84 km^2, accounting for 36.15% of the total area. The area with stable vulnerability amounted to 3096.88 km^2, accounting for 36.81% of the total area; the area with reduced vulnerability amounted to 2101.66 km^2, accounting for 24.98% of the total area; and the area with a sharp decline in vulnerability amounted to 74.93 km^2, accounting for 0.89% of the total area. When considering the changes as a whole, the area of increasing ecological fragility was larger than the decreasing area, while the area that was in a stable state was the largest. Overall, from 2000 to 2020, the ecological fragility of the DRB (Henan section) was found to have decreased at first and then increased, reflected by an initial reduction in ecological vulnerability followed by a rise; nonetheless, the general ecological status in 2020 was found to be better than that in 2010, but poorer than in 2000.

From the perspective of regional changes, the areas revealing a sharp increase in ecological fragility were small and mainly distributed in the southern part of the study area, in the southern part of Xichuan County—namely, the scattered areas of Xixia County, Xichuan County, Neixiang County, and Dengzhou City; the area with a sharp decline in ecological fragility was small, mainly distributed in the northwest of the study area—that is, the western part of Lushi County. The areas with steadily declining ecological fragility were mainly distributed in the north of the study area—that is, most parts of Xixia County, Luanchuan County, and Lushi County. In order to promote water sourcing along the middle section of the South-to-North Water Diversion Project and further prioritize greater environmental protection measures, Henan Province has launched and implemented a series of sewage treatment policies since 2004 to enhance water quality. To ensure that the water quality of the reservoir in the source area of the middle route of the South-to-North Water Diversion Project met the required standards, a range of environmental protection policies were formulated to effectively protect the ecological environment of the DRB. The areas with stable ecological fragility were mainly distributed in the central and northern parts of the study area, including Xixia County and Xichuan County.

3.4. Identification of Driving Factors of Ecological Vulnerability

This study was based on the ArcGIS platform, with a selected grid spacing of 30 m and a total of 9,343,510 grid points matching the ecological vulnerability (Y) and driving factors (X) of the DRB (Henan section) from 2000 to 2010. Eighteen indicators, including topographic factors, surface factors, meteorology, hydrology, vegetation, population activity, and economy, were selected as driving factors (X). Once the data had been standardized, it was necessary to classify the driving factors of ecological vulnerability in the DRB

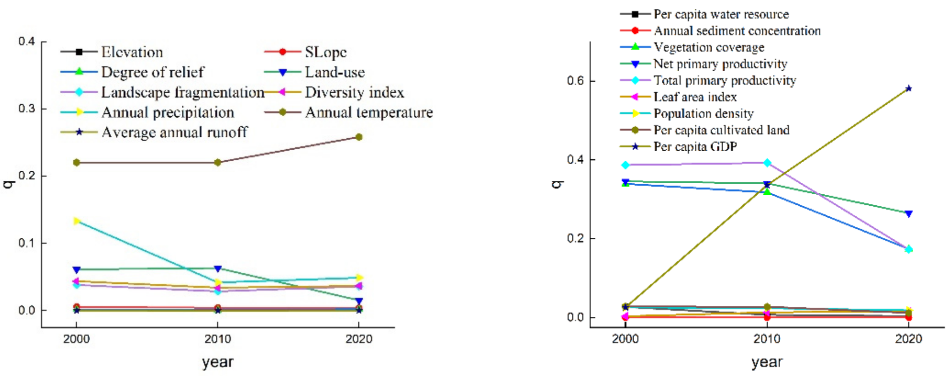
(Henan section). Lastly, GeoDetector was used to analyze the driving factors of ecological vulnerability (Y) in the study area from 2000 to 2010.

As can be seen from Table 9 and Figure 7, the q values of per capita GDP, total primary productivity, net primary productivity, vegetation coverage, average temperature, and land use type were the largest from 2000 to 2020, with explanatory power exceeding 4%, indicating that per capita GDP, total primary productivity, net primary productivity, vegetation coverage, average annual temperature, and land use type were the main factors affecting ecological vulnerability. The explanatory power of per capita GDP relative to ecological vulnerability was found to have gradually increased, indicating that human factors had progressively replaced meteorological factors to become the dominant drivers of ecological vulnerability. Secondly, the explanatory power of annual precipitation, the diversity index, landscape fragmentation, per capita density, and per capita cultivated land was greater than 2%. Thirdly, the explanatory power of elevation, per capita water resources, and the leaf area index was above 1%. Fourthly, the explanatory power of slope, topographic fluctuation, average annual runoff, and the annual sediment concentration was below 1%, indicating that slope, topographic variations, average annual runoff, and annual sediment concentrations have little impact on ecological vulnerability. Among the key influential factors from 2000 to 2020, the power q values determined for per capita GDP, average annual temperature, and land use type showed an upward trend, indicating that the influence of GDP, air temperature, and land use type on ecological vulnerability in the DRB (Henan section) may increase in the future, while the power q values determined for total primary productivity, net primary productivity, and vegetation coverage showed a downward trend. This suggested that the influence of total primary productivity, net primary productivity, and vegetation coverage on the ecological vulnerability of the DRB (Henan section) may decrease in the future.

Table 9. Factor q values for the period 2000–2020.

q	C1	C2	C3	C4	C5	C6	C7	C8	C9
	Elevation	**Slope**	**Degree of Relief**	**Land Use**	**Landscape Fragmentation**	**Diversity Index**	**Annual Precipitation**	**Annual Temperature**	**Average Annual Runoff**
2000	0.0145	0.0056	0.0018	0.0615	0.0384	0.0438	0.1334	0.2206	0.0003
2010	0.0140	0.0043	0.0012	0.0634	0.0289	0.0340	0.0419	0.2206	0.0001
2020	0.0182	0.0039	0.0022	0.0653	0.0362	0.0369	0.0490	0.2584	0.0005

q	C10	C11	C12	C13	C14	C15	C16	C17	C18
	Per Capita Water Resources	**Annual Sediment Concentration**	**Vegetation Coverage**	**Net Primary Productivity**	**Total Primary Productivity**	**Leaf Area Index**	**Population Density**	**Per capita Cultivated Land**	**Per Capita GDP**
2000	0.0271	0.0004	0.3394	0.3457	0.3869	0.0035	0.0259	0.0281	0.0260
2010	0.0071	0.0001	0.3178	0.3405	0.3929	0.0133	0.0238	0.0275	0.3360
2020	0.0037	0.0001	0.1740	0.2650	0.1730	0.0167	0.0186	0.0119	0.9814



(**a**) (**b**)

Figure 7. Changes in the q value of each factor. (**a**) represents the first nine indicator factors. (**b**) represents the last nine indicator factors.

4. Discussion

(1) It was found that the ecological vulnerability of the DRB (Henan section) had initially decreased and then increased over the past 20 years, and was overall diminishing. The present authors consider that all parties involved in future urbanization planning and economic development along the DRB (Henan section) should imperatively prioritize the protection of any areas of high ecological fragility, and, in particular, enhance water treatment works' productivity and soil erosion control measures for the water source of the middle route of the South-to-North Water Diversion Project, in order to prevent any further ecological deterioration and adverse effects on the water quality of the reservoir. In addition, the ecology of cultivated land, grassland, and construction land was found to be fragile and strongly disturbed by human activities, calling for reasonable safeguarding measures to be implemented to optimize the impact of land use and reduce any further ecological deterioration.

(2) According to the analysis of the driving factors of ecological vulnerability in the DRB (Henan section), it was found that, from 2000 to 2020, its resilience index for the vegetation factor significantly influenced ecological vulnerability, while the influence of economic pressure and surface factors on ecological vulnerability had gradually increased, as primarily reflected by the per capita GDP, land use type, total primary productivity, vegetation coverage, and so on. Among these factors, the explanatory power of per capita GDP, characterizing socioeconomic development, was observed to have risen from 2000 to 2020, being in excess of 90% in 2020. The adverse interference of human and socioeconomic factors in the ecological environment cannot, in the present authors' view, be ignored.

5. Conclusions

Taking the ecological sensitivity/ecological resilience/ecological pressure model as the core tool, a vulnerability evaluation index system was constructed, and a mathematical model for the fuzzy synthesis/catastrophe series method was established to facilitate a comprehensive evaluation of ecological vulnerability. The temporal and spatial evolutionary law of ecological vulnerability in the DRB (Henan section) from 2000 to 2020 was systematically expounded, and the driving factors of ecological vulnerability were analyzed. A range of measures and suggestions for the protection of the ecological environment in this region were put forward based on the analysis results. The conclusions of this study are as follows.

(1) Through the use of the fuzzy comprehensive evaluation/catastrophe progression method to evaluate the ecological vulnerability of the DRB (Henan section), its fragility was found to be primarily moderate and mild in 2000, 2010, and 2020. The degree of ecological fragility increased at first and then decreased, with average overall

ecological quality. From the perspective of regional distribution, the overall ecological vulnerability intensity of the study area displayed characteristics of "low in the north and high in the south". Among these features, the degree of ecological vulnerability of built land and bare land was greater, that of woodland was lower, while that of other different land use types was found to have gradually increased, calling for more stringent ecological management measures for built land.

(2) According to the evaluation results regarding ecological vulnerability in the study area, an analytical method based on the spatiotemporal evolution law of ecological vulnerability was implemented, and the spatiotemporal evolution law of ecological vulnerability in the study area was analyzed quantitatively. The results showed that the comprehensive indices of ecological vulnerability in the DRB (Henan section) in 2000, 2010, and 2020 were 0.56, 0.61, and 0.58, respectively, showing a trend of initial reduction and then a rise, while the ecological quality decreased at first and then increased. The areas with declining ecological quality were primarily distributed over the southern plain of the study area, notably in Xichuan County, Neixiang County, and Dengzhou City. The areas with improving ecological quality were mainly distributed in the north of the study area—that is, most areas of Xixia County, Luanchuan County, and Lushi County—and the areas of high ecological vulnerability were found to have been gradually transferred from the northern mountainous areas to the southern plains. This was chiefly attributed to the implementation and water access of the middle route of the South-to-North Water Diversion Project, facilitating the development of improved, more comprehensive water treatment installations and soil erosion control measures along the Danjiang River Basin, in turn restraining further ecological deterioration to some extent.

(3) According to the evaluation results regarding ecological vulnerability and the research results regarding the spatial evolution law in the study area, the spatial differentiation of the study area was examined, and the driving factors were revealed using GeoDetector technology. The results showed that among the influencing factors from 2000 to 2020, the q values of per capita GDP, total primary productivity, net primary productivity, vegetation coverage, average annual temperature, and land use type were the largest, with explanatory power exceeding 4%. The results furthermore indicated that these were the main factors affecting ecological vulnerability. Among them, the determining power of per capita GDP, average annual temperature, and land use type showed an upward trend, indicating that the influence of GDP, temperature, and land use type on the ecological vulnerability of the DRB (Henan section) may increase in the future.

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