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Research on Agricultural Drought Vulnerability in Henan Province

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Abstract: In order to systematically evaluate the vulnerability of agricultural drought in Henan Province, based on the meteorological, agricultural, water resources and socio-economic data of Henan Province from 2007 to 2023, 15 indicators were selected from the two dimensions of sensitivity and recovery, through quantitative qualitative indicators and entropy weight method Determine the weight, build weighted comprehensive evaluation models and fuzzy comprehensive evaluation models respectively, and conduct comparative analysis on the vulnerability of agricultural drought in 18 cities in the province. The result shows that the evaluation result of fuzzy comprehensive evaluation model is more reasonable. During the study period, the overall agricultural drought vulnerability of the province showed a downward trend, but the regional differences were significant, especially in southern and eastern Henan, the regional vulnerability continued to be high. Finally, rationalization suggestions and countermeasures are put forward according to the evaluation results, in order to improve the regional agricultural drought resistance capacity.

Keywords: Entropy Weight Method; Vulnerability to Drought in Agriculture; Fuzzy Comprehensive Evaluation Model.

1. Introduction

As a vulnerable sector, agriculture faces significantly higher drought disaster risks than other industries. Statistics show that between 2007 and 2023, China's annual average agricultural drought-affected area exceeded 10 million hectares, accounting for approximately 40% of the total area affected by natural disasters and ranking first among all disaster types. As China's core grain-producing region, Henan Province accounts for approximately 9% of the nation's annual crop planting area. Yet it bears about 13% of the country's annual agricultural drought-affected area. Its unique geographical location and climatic conditions make Henan a high-risk zone for drought disasters. To ensure the stability and sustainable development of Henan's agricultural economy, it is imperative to strengthen agricultural drought risk analysis and related research, providing scientific basis for the government to formulate drought prevention and mitigation measures.

Agricultural drought vulnerability reflects the extent of losses incurred by agriculture due to drought disasters. It directly manifests the resilience of agriculture to drought disasters, the severity of losses sustained, and the level of risk. Early research centered on constructing indicator systems, such as the systematic review of vulnerability assessment theoretical frameworks by Biedejin et al. [4], which emphasized the coupled effects of natural, economic, and social factors. In recent years, research has focused on revealing the vulnerabilities of agricultural systems to drought risks at regional or global scales through multidimensional indicator systems and model analysis. Approaches often adopt a coupled natural-economic-social perspective, integrating multi-source data including remote sensing, statistical yearbooks, and disaster bulletins to construct evaluation frameworks encompassing sensitivity and resilience. For instance, Chen Jia [2] selected indicators from both sensitivity and resilience dimensions to establish an evaluation system covering natural, economic, and social dimensions, providing a unified and feasible indicator reference for national agricultural drought vulnerability research. Guo et al. [3] selected indicators from sensitivity and drought resilience, employing entropy weighting, weighted composite scoring, K-means clustering, and contribution models to assess agricultural drought vulnerability while analyzing its spatial heterogeneity and influencing factors; Luo et al.[17] addressed agricultural drought in Henan Province by employing a Random Forest (RF) model combined with SHAP value interpretation. They identified irrigation rates and farmer income as key drivers of vulnerability, achieving a model prediction error below 3.0457%. Xie Jiazhi et al. [5] introduced a BP neural network model to dynamically evaluate agricultural drought vulnerability in Chongqing using four-dimensional indicators (natural, economic, social, and technological), revealing the disaster mitigation effects of economic development and technological progress. In recent years, research has increasingly focused on dynamics and uncertainty. Li Jing [1] proposed a grey C-type association and normal grey cloud clustering model, combined with panel data, to study agricultural drought vulnerability in 18 cities of Henan Province. The study indicated that high-vulnerability areas are concentrated in the west, while low-vulnerability areas are concentrated in the south.

However, existing research still faces certain limitations in constructing indicators and applying models for assessing agricultural drought vulnerability: On one hand, indicator selection often focuses on macro dimensions such as natural conditions (e.g., precipitation) and socioeconomic factors (e.g., per capita GDP), while paying less attention to crop-specific attributes (e.g., variety drought resistance, differing disaster sensitivity between cash crops and food crops). This results in discrepancies between assessment outcomes and actual agricultural production. On the other hand, while models like grey clustering and random forests perform well with explicit quantitative data, their ability to characterize features with fuzzy boundaries—such as crop water requirement thresholds and drought resistance grading—remains limited. Based on this, This study examines 18 prefectures in Henan Province. Integrating the province's crop planting structure and climatic characteristics, it establishes regionally tailored quantitative standards based on crop water requirements, economic value, and drought resistance. A comprehensive agricultural drought vulnerability assessment system is constructed to systematically reveal the spatial distribution patterns and evolution trends of agricultural drought vulnerability in Henan. This provides scientific basis for advancing differentiated, precision-oriented regional drought prevention and control strategies, thereby enhancing agricultural resilience and sustainable development capacity.

2. Overview of the Study Area

Henan Province is situated in the middle and lower reaches of the Yellow River, with a topography that slopes from west to east. Influenced by a temperate monsoon climate, precipitation exhibits uneven spatial and temporal distribution, showing distinct seasonal and regional variations in annual rainfall. Spring and summer droughts occur frequently, following a spatial pattern of "more severe in the west than in the east," posing a serious threat to agricultural production and food security. Therefore, scientifically assessing the vulnerability of Henan's agriculture to drought can facilitate effective prevention and control of drought risks.

3. Selection of Indicators and Determination of Weights

The vulnerability of agriculture to drought is jointly influenced by natural environments, crop and planting structures, socio-economic factors, water resource management, and policies and institutions. Guided by principles of comprehensiveness, scientific rigour, data accessibility, and feasibility, and considering the practical context of agricultural production in Henan Province, an evaluation framework for agricultural drought vulnerability has been developed. This framework encompasses two dimensions: sensitivity and resilience. Sensitivity characterises the agricultural system's degree of response to drought impacts, while resilience reflects the socio-economic system's comprehensive capacity for drought prevention, response during the disaster, and post-disaster recovery [6].

3.1. Selection of Indicators

Drawing upon the indicator selection principles outlined in relevant literature [1][2][7][9]and considering the practical requirements for assessing agricultural drought vulnerability in Henan Province, a total of 15 indicators were selected (Table 1). Research data were sourced from the Henan Statistical Yearbook and the Henan Water Resources Bulletin covering the period 2007–2023, with certain indicator values derived through indirect calculations. Following existing research [3], the direction of each indicator's influence on agricultural drought vulnerability was categorised as positive (+) or negative (-). Positive indicators exhibit a direct correlation with vulnerability, while negative indicators demonstrate an inverse relationship.

Table 1. Indicators for Assessing Agricultural Drought Vulnerability in Henan Province

	Indicator	Source	Direction of Influence
Sensitivity	Crop Rotation Index(X_1)(%)	Crop Sown Area/Arable Land Area	+
	Population Density(X_2)(persons/km^2)	Total Population / Land Area	+
	Agriculture's Share(X_3)(%)	Primary Industry Output Value/GDP	+
	Annual Mean Temperature(X_4)(°C)	Statistical Yearbook	+
	Precipitation(X_5)(mm)	Statistical Yearbook	-
	Surface Water Resource Density(X_6)(10,000m^3/km^2)	Water Resources Bulletin	-
	Groundwater Resource Density(X_7)(10,000m^3/km^2)	Water Resources Bulletin	-
	Crop Structure(X_8)	Statistical Yearbook	Qualitative
Restorative	Irrigation Index(X_9)(%)	Effectively Irrigated Area / Arable Land Area	-
	Fertiliser Application Rate per Unit Area(X_{10})(kg/mu)	Fertiliser Application (Converted to Pure Nutrients) / Total Sown Area	-
	Grain Yield per Unit Area(X_{11})(t/hm^2)	Total Grain Output/Grain Crop Sown Area	-
	GDP per Capita(X_{12})(yuan)	Statistical Yearbook	-
	Net Income per Capita of Farmers(X_{13})(yuan)	Statistical Yearbook	-
	Greening Rate(X_{14})(%)	Statistical Yearbook	-
	Total Agricultural Machinery Power per Unit Area(X_{15})(KW/hm^2)	Statistical Yearbook	-

3.2. Sub-section Headings

To ensure the objectivity and validity of vulnerability assessment results, qualitative indicators are first quantified in accordance with the characteristics of agricultural drought vulnerability evaluation metrics.

3.2.1. Quantification of Qualitative Indicators

The crop structure within the agricultural drought vulnerability assessment indicators constitutes a qualitative metric. A region's crop structure exerts significant influence upon its comprehensive agricultural benefits, food security, and the sustainable development of agricultural production. The crop diversification index reflects the variety of cultivated crops within a region, thereby embodying its resilience to drought. This paper employs an area-weighted crop diversity index to quantify the annual crop structure across prefecture-level cities, following these specific steps:

(1)Select crop types: Based on data availability, all relevant crop types listed in statistical yearbooks are selected (e.g., summer grain, autumn grain, rice, wheat, maize, soybeans, oilseeds, peanuts, rapeseed, cotton, hemp, sugar crops, tobacco, Chinese medicinal herbs, vegetables and edible fungi, melons and fruits, flowers).

(2)Calculate the annual area proportion for each crop: Divide the area of each crop by the total sown area [18].

(3)Calculate the annual crop diversity index: Employ the Shannon Diversity Index, calculated using the formula:

$$H = -\sum (p_i \times \ln(p_i)) \tag{1}$$

Where p_i denotes the proportion of area occupied by the i-th crop.

3.2.2. Determination of Indicator Weights

Given the characteristics of agricultural drought, the vulnerability to such disasters is often caused by isolated extreme factors. The core advantage of the entropy weight method lies in its strong objectivity, where weights are entirely determined by the degree of data variation. It can automatically identify and amplify indicators with strong discriminatory power, whilst maintaining a transparent calculation process. Therefore, this method is employed to determine the weights of each evaluation indicator.

The computational steps are as follows [10]:

(1)Standardisation is performed using the range standardisation method: For positive indicators, processing is conducted according to Equation (2):

$$X_{ij}=\frac{x_{ij}-\min(x_j)}{\max(x_j)-\min(x_j)} \tag{2}$$

For negative indicators, apply treatment according to formula (3):

$$X_{ij}=\frac{\max(x_j)-x_{ij}}{\max(x_j)-\min(x_j)} \tag{3}$$

Where x_{ij}(i=1,2, …,18;j=1,2,…,14)denotes the observed value for indicator j in region i. $\max(x_j)$ represents the maximum value of indicator j across all regions; $\min(x_j)$ denotes the minimum value of indicator j across all regions; $X_{ij}\in[0,1]$, with values closer to 1 indicating a greater influence on drought vulnerability [9].

(2)Constructing the indicator judgement matrix P:

$$P_{ij}=\frac{X_{ij}}{\sum_{i=1}^{18} X_{ij}} \tag{4}$$

(3)Calculate the information entropy E_{ij} of the indicator:

$$E_{ij}=-\frac{1}{\ln 18}\sum_{i=1}^{18} P_{ij}\ln P_{ij} \tag{5}$$

(4)Calculate the coefficient of variation D_{ij} for the indicator value:

$$D_{ij}=1-E_{ij} \tag{6}$$

(5)Calculate weight Z_j:

$$Z_j=\frac{D_{ij}}{\sum_{j=1}^{15} D_{ij}} \tag{7}$$

4. Assessment of Agricultural Drought Vulnerability in Henan Province

The issue of agricultural drought vulnerability is complex in nature and ill-defined in scope. To effectively enhance the accuracy and reliability of vulnerability assessments, two distinct models were developed to address the problem's characteristics: a weighted comprehensive evaluation model and a fuzzy comprehensive evaluation model. These models were applied to evaluate agricultural drought vulnerability across 18 prefecture-level cities in Henan Province from 2007 to 2023. The weighted model aims to quantify the relative vulnerability levels across prefectures, whilst the fuzzy model employs fuzzy mathematical theory. By constructing membership functions and fuzzy relational matrices, it seeks to capture the fuzzy characteristics of vulnerability grades. Finally, through comparative analysis of the evaluation results from both models, the accuracy and reliability of vulnerability assessments are effectively enhanced, providing scientific decision support for agricultural drought risk management.

4.1. Weighted Integrated Evaluation Model

The weighted composite scoring method is a widely employed multi-criteria assessment technique in vulnerability evaluations. The specific calculation formula is as follows:

$$S=\sum_{j=1}^{15} Z_j X_j \tag{8}$$

In the formula: S denotes the composite score; X_j represents the standardised value of indicator j for a given region; Z_j denotes the weight assigned to indicator j.

4.2. Fuzzy Comprehensive Evaluation Model

Fuzzy Comprehensive Evaluation is a multi-criteria assessment methodology grounded in fuzzy mathematics theory. Its specific steps are as follows:

(1)Define evaluation grades: Following the classification framework established by Wang Ying et al.[9] in their study of agricultural drought vulnerability in northern China, vulnerability is categorised into four grades: V={High, Moderately High, Moderately Low, Low};

(2) Establish the fuzzy evaluation matrix (membership matrix) R: After obtaining the weights assigned to each indicator, quantify the membership degrees for each evaluation indicator. This involves determining the membership degree of each indicator for each level within the indicator set[11] (i.e., the extent to which the indicator belongs to a particular level, with values ranging from 0 to 1, and the sum of the membership degrees for the same indicator across all levels equalling 1).

$$R=\begin{pmatrix} r_{11} & r_{12} & \cdots & r_{1j} \\ r_{21} & r_{22} & \cdots & r_{2j} \\ \vdots & \vdots & \ddots & \vdots \\ r_{i1} & r_{i2} & \cdots & r_{ij} \end{pmatrix} \tag{9}$$

(3)Calculate the comprehensive evaluation vector B: Perform ‘fuzzy synthesis’ between the weight vector Z_j and the evaluation matrix R to obtain the comprehensive membership vector B, representing the overall degree of membership of the evaluation object across each grade.

$$B=Z_j\cdot R \tag{10}$$

5. Results and Analysis

5.1. Analysis of the Results from the Assessment of Agricultural Drought Vulnerability in Henan Province

The Shannon diversity index was employed to quantify the qualitative indicator of crop structure (Table 2). Subsequently, the entropy weighting method was applied to assign weights to the agricultural drought vulnerability indicators for Henan Province (Table 1) (Table 3). Subsequently, the agricultural drought vulnerability of 18 prefecture-level cities in Henan

Province during 2007–2023 was assessed using both the weighted comprehensive evaluation model (Equation 8) and the fuzzy comprehensive evaluation model (Equations 9–10). Finally, comparative analysis of the evaluation outcomes from these two models provides scientific decision support for agricultural drought risk management.

Table 2. Annual Quantified Values of Cropping Patterns by Prefecture

Municipality	Year	Quantitative Value of Cropping Structure
Zhengzhou	2007	2.2236
Kaifeng	2007	2.3058
Luoyang	2007	2.1310
Pingdingshan	2007	2.2285
Anyang	2007	2.1427
…	…	…
Shangqiu	2023	2.1829
Xinyang	2023	2.3133
Zhoukou	2023	2.2057
Zhumadian	2023	2.1844
Jiyuan	2023	2.0025

Table 3. Weighting of Agricultural Drought Vulnerability Indicators in Henan Province

Indicator	Weighting	Indicator	Weighting	Indicator	Weighting
X_1	0.0507	X_6	0.0085	X_{11}	0.0033
X_2	0.1429	X_7	0.0164	X_{12}	0.0568
X_3	0.1934	X_8	0.0734	X_{13}	0.0554
X_4	0.0697	X_9	0.1437	X_{14}	0.1122
X_5	0.0039	X_{10}	0.0659	X_{15}	0.0039

5.1.1. Vulnerability Grading Based on a Weighted Integrated Evaluation Model

Given the minimal overall variation in the composite agricultural drought vulnerability scores across the 18 prefecture-level cities (Figure 1), to avoid bias from subjective threshold setting, the percentile method was employed to categorise agricultural drought vulnerability within the study area. This approach was selected based on the data distribution characteristics and drawing upon the classification methods outlined in relevant literature [19][20] (Table 4). This approach not only ensures balanced sample sizes across categories but also provides dual assurance of objectivity and statistical validity in the classification process.

Table 4. Percentile Method for Classifying Vulnerability Levels

Grade	Low	Moderately Low	Moderately High	High
Overall Score	≤25^{th}	25^{th}~50^{th}	50^{th}~75^{th}	>75^{th}

By examining the overall distribution of composite scores, quantitative thresholds were established for classifying agricultural drought vulnerability levels (Table 5). Analysis of weighted composite scores and vulnerability classifications across 18 prefecture-level cities in Henan Province from 2007 to 2023 (Figure 1) reveals a pronounced dynamic shift in vulnerability distribution throughout the province. Furthermore, composite scores across all prefecture-level cities exhibit an overall downward trend over time, reflecting a gradual strengthening of the agricultural system's resilience to disasters.

Table 5. Threshold for determining vulnerability classification levels

Grade	Low	Moderately Low	Moderately High	High
Overall Score	≤0.4116	0.4116~0.4614	0.4567~0.5125	>0.5125

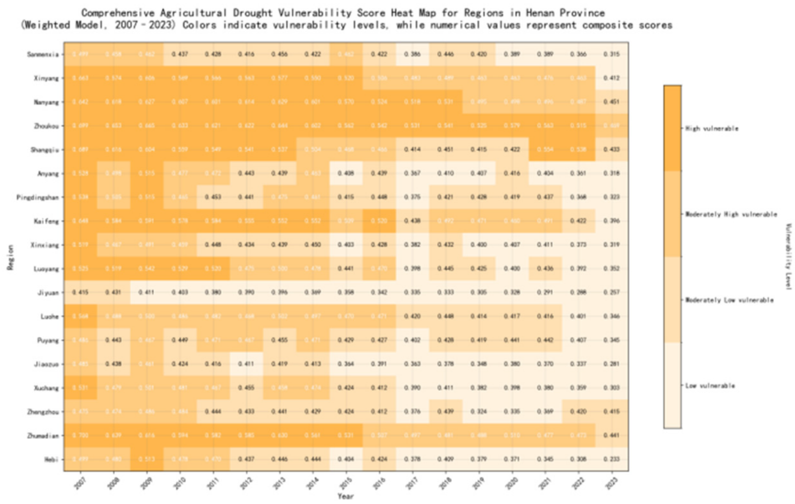

Figure 1. Comprehensive Vulnerability Assessment Results for All Municipalities in Henan Province, 2007–2011

5.1.2. Vulnerability Grading Based on a Fuzzy Comprehensive Evaluation Model

Based on the results of the fuzzy comprehensive evaluation (Figure 2), an analysis of agricultural drought vulnerability across 18 prefecture-level cities in Henan Province from 2007 to 2023 reveals a distinct dynamic pattern in the distribution of vulnerability levels. The overall number of high-vulnerability zones has shown a declining trend, reflecting the gradual strengthening of the agricultural system's resilience to disasters. Specifically, in 2007, 12 regions were classified as highly vulnerable. Over time, the number of highly vulnerable areas fluctuated while decreasing, falling to zero by 2023. Concurrently, the number of moderately vulnerable and low-vulnerability areas increased significantly. This trend clearly demonstrates that Henan Province's agricultural drought vulnerability exhibited an overall gradual decline between

2007 and 2023.

5.1.3. Model Consistency Comparison

A consistency comparison of the results from the two aforementioned evaluation models (Table 6) reveals certain discrepancies in their assessment outcomes. These differences primarily stem from divergent modelling principles: the weighted comprehensive evaluation model employs fixed thresholds for classification, offering clear boundaries but limited flexibility;

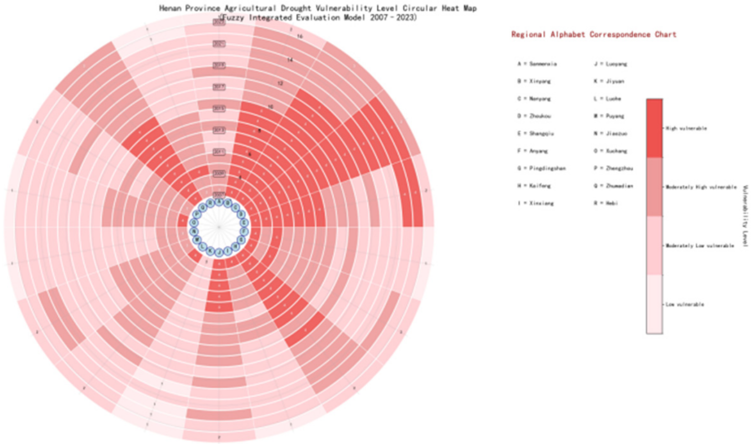

Figure 2. Fuzzy Comprehensive Vulnerability Assessment Results for Municipalities in Henan Province, 2007–2015

whereas the fuzzy integrated evaluation model employs triangular membership functions to handle boundary values, permitting a single data point to belong to multiple vulnerability grades simultaneously. This approach better aligns with the inherent fuzziness and uncertainty of agricultural drought vulnerability, thereby demonstrating superior theoretical rationality and practical applicability. Actual data confirms that the latter model's evaluation results more accurately reflect real-world conditions. Taking 2007 as an example: Hebi City recorded annual precipitation of 505.3mm, significantly lower than Xinyang City, with a medium population density, leading to its classification as a moderately high vulnerability zone. Xinxiang City, with both per capita GDP and net per capita income of farmers at relatively high levels, should be categorised as a high vulnerability zone. Conversely, Jiaozuo and Luohe, where multiple socio-economic indicators were below average, were more appropriately classified as moderately high vulnerability zones. Similarly, in 2019, although Zhengzhou City exhibited high population density, its per capita GDP significantly exceeded that of regions such as Zhoukou City, leading to its classification as a low vulnerability zone. These instances collectively demonstrate that the fuzzy comprehensive evaluation model possesses greater rationality and explanatory power in its assessments.

Table 6. Model comparison consistency rate

Year	Consistency Rate	Year	Consistency Rate	Year	Consistency Rate
2007	100.00%	2013	61.11%	2019	66.67%
2008	88.89%	2014	83.33%	2020	50.00%
2009	94.44%	2015	66.67%	2021	44.44%
2010	83.33%	2016	77.78%	2022	50.00%
2011	77.78%	2017	33.33%	2023	55.56%
2012	66.67%	2018	44.44%		

5.2. Spatiotemporal Distribution Characteristics of Agricultural Drought Vulnerability in Henan Province

Based on the aforementioned evaluation results, spatial distribution maps of agricultural drought vulnerability in Henan Province from 2007 to 2023, along with trend charts for each prefecture-level city, have been compiled (Figures 3 and 4). These comprehensively reveal the spatiotemporal evolution of agricultural drought vulnerability across the province. From a temporal perspective, agricultural drought vulnerability across prefectures exhibited an overall gradual decline throughout the study period. Spatially, vulnerability displayed marked regional differentiation: Eastern and Southern Henan consistently remained high-vulnerability zones, with levels significantly exceeding other areas; most regions in Central and Western Henan showed moderate vulnerability with a sustained decreasing trend; while Northern Henan exhibited generally low vulnerability. This spatial differentiation is closely linked to regional imbalances in natural conditions and socio-economic systems. Despite being part of the Huang-Huai-Hai Plain with relatively favourable water resources, southeastern Henan still faces seasonal droughts and water use pressures, resulting in persistently high vulnerability. In contrast, areas in western Henan such as Sanmenxia and Luoyang have successfully mitigated drought stress through measures like irrigation district water diversion and artificial rainfall enhancement, demonstrating effective vulnerability control.

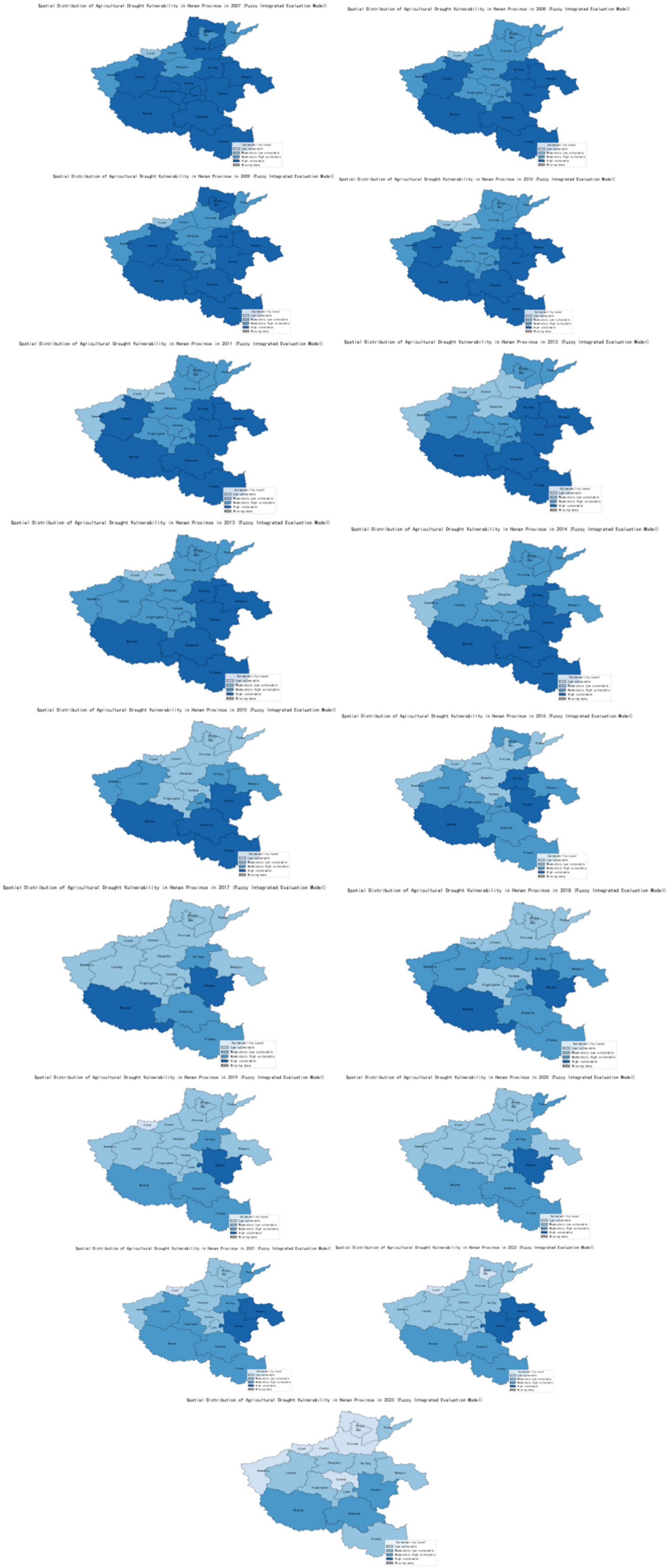

Figure 3. Distribution of Agricultural Drought Vulnerability Levels in Henan Province, 2007–2023

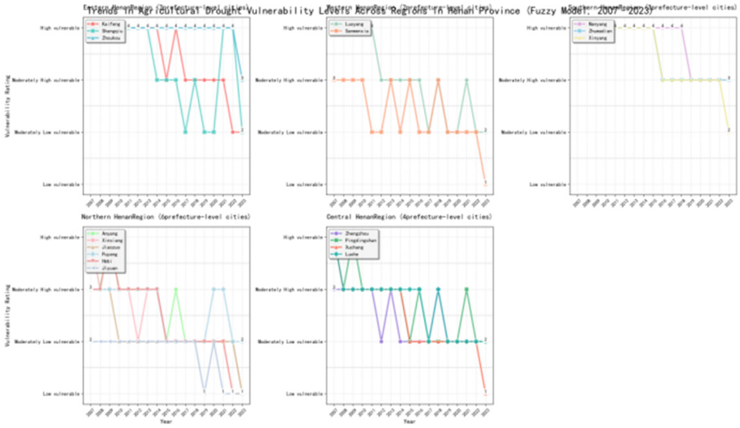

Figure 4. Trends in Agricultural Drought Vulnerability Across 18 Regions in Henan Province

From a provincial perspective, the overall decline in agricultural drought vulnerability correlates closely with Henan's sustained efforts during this period to advance drought-resilience legislation, invest in water infrastructure, and promote water-saving technologies. The significant enhancement of regional drought-resilience capabilities has markedly improved the adaptability and resilience of the agricultural system.

6. Conclusion

Through the construction of two distinct evaluation models, a systematic analysis of agricultural drought vulnerability in Henan Province was conducted. Key conclusions are as follows: (1) Model comparisons demonstrate that the fuzzy comprehensive evaluation model significantly outperforms the weighted comprehensive model in overall performance. This model does not entirely replace traditional methods but serves as a crucial supplement, more effectively addressing ambiguity and uncertainty inherent in agricultural drought vulnerability assessments. Together, they provide more comprehensive and reliable evaluation outcomes.(2)Between 2007 and 2023, the number of high-vulnerability zones for agricultural drought in Henan Province gradually decreased from 12 to 0 (with minor fluctuations during the period), reflecting a pronounced overall downward trend in the province's agricultural drought vulnerability.(3)Although agricultural drought vulnerability fluctuated across various prefectures, an overall diminishing trend was evident. Spatially, the eastern and southern regions of Henan exhibited comparatively higher levels of agricultural drought vulnerability.

As a populous province with significant agricultural output, Henan continues to face acute water scarcity. To progressively reduce agricultural vulnerability to drought, the following measures are recommended: Firstly, rationally regulate population density and optimise demographic structure to alleviate resource pressures and enhance water utilisation efficiency; secondly, strengthen the construction and maintenance of water conservancy infrastructure, prioritising the upgrading of existing facilities and refurbishment of ageing systems to tangibly improve water storage and supply capacity; Thirdly, optimise agricultural cropping patterns by reducing the cultivation area of high-water-consumption, low-yield crops, promoting drought-resistant and water-saving varieties, developing water-efficient agriculture, and fostering the coordinated and efficient utilisation of natural and social resources.

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