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Original Research

An AHP-Fuzzy Comprehensive Evaluation Model for Mining Geo-Environmental Assessment: A Case Study of the Huainan Coal Mine Area, China

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Abstract

Mining activities have caused severe ecological and environmental problems worldwide. Accurate and reliable assessment methods are essential for identifying ecological changes in mining areas and for supporting effective preventive and mitigation measures to reduce environmental damage, improve ecosystem quality, and maintain suitable living conditions for humans. However, significant challenges remain in the precise evaluation of environmental changes in mining regions. Huainan City, located in Anhui Province, is one of China's most intensively exploited coal-mining areas, where decades of extraction have led to pronounced geological instability and ecological degradation. Taking the Huainan mining area as a case study, this paper applies the Analytic Hierarchy Process (AHP) combined with a fuzzy comprehensive evaluation model to systematically assess environmental quality from multiple perspectives. The evaluation results are highly consistent with field observations and provide reliable scientific evidence to support ecological restoration planning and risk mitigation. Furthermore, this assessment framework demonstrates strong applicability and scalability, and can be extended from local and regional levels to broader environmental assessment of other coal-mining regions in China and worldwide.

Keywords: coal mine, geological environment quality, fuzzy comprehensive evaluation, china

Introduction

The exploitation of mineral resources presents a dual-edged scenario. On one hand, it serves as a driving force for socioeconomic development; on the other hand, it poses substantial threats to the geo-environment, thereby exerting an impact on human safety and ecological sustainability [1, 2]. Consequently, the exploration and assessment of the mining geo-environment have become a crucial focal point of global research.

Since the 1970s, early investigations have utilized geographic information systems (GIS), remote sensing (RS), and comprehensive evaluation techniques to assess specific environmental elements, such as

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geological disasters, groundwater quality, and landform destruction, within natural units. These efforts have provided a fundamental basis for ecological restoration [3-5].

In China, research in this field has gathered momentum since 2000. The pioneering work of [6] introduced a comprehensive indicator system for mining geo-environmental assessment and applied the Fuzzy Comprehensive Evaluation (FCE) method. Subsequently, studies by [7] and [8] refined the objective indicators and established evaluation models for coal mines and sulfur-iron ore concentrated mining areas, respectively, laying a theoretical foundation. Although these studies have made significant contributions to the establishment of evaluation models and indicator systems, the high variability of geological settings across different mining regions necessitates continuous research on the selection and weighting of appropriate evaluation factors [9].

Multi-Criteria Decision-Making (MCDM) methods, which are well-known for dealing with complex problems involving multiple conflicting criteria, have increasingly been applied in environmental assessments. The integration of the Analytic Hierarchy Process (AHP) for weight determination and FCE for handling ambiguity has proven to be particularly effective. For example, recent international research has successfully applied hybrid Fuzzy AHP approaches for site-specific remediation strategy selection, such as for mercury contamination in Musa Bay [10], and for the socio-economic risk assessment of land use systems [11]. Similarly, FCE has been employed in specialized fields like rock joint strength modeling, where [12] developed a roughness classification system based on fuzzy evaluation. However, the application of an integrated AHP-FCE framework for the comprehensive geo-environmental assessment of large-scale, mature coal mining areas, which are characterized by cumulative and interconnected environmental impacts, remains relatively underexplored. Many existing models tend to focus on single environmental issues or lack the spatial explicitness required for targeted restoration planning.

The Huainan coalfield in Anhui Province, a significant energy base in China, is a prime example of a region that has experienced intensive and long-term mining. This mining activity has given rise to a range of intertwined geo-environmental problems, including land subsidence, geological hazards, water resource depletion, and pollution from waste materials [13-16]. Therefore, a holistic and spatially explicit assessment is essential to inform effective environmental management and restoration strategies.

In response to this research gap, this study develops and applies an integrated AHP-FCE model to conduct a comprehensive geo-environmental assessment of the Huainan mining area. The main contributions of this research are threefold:

Novel Model Integration: It establishes a robust AHP-FCE framework specifically designed for the complex and multi-faceted nature of geo-environmental impacts in mature coal mining regions, building upon the advancements in MCDM methods as demonstrated in studies such as [10] and [12].

Comprehensive Indicator System: It constructs a holistic evaluation indicator system that captures the synergistic effects of various environmental stressors, moving beyond single-issue assessments and incorporating insights from socio-economic risk frameworks such as [11].

Spatially Explicit Analysis for Decision-Support: It employs GIS-based spatial analysis to visualize assessment results, clearly identifying priority areas for intervention and providing a scientifically-grounded decision-making tool for geo-environmental restoration and sustainable land-use planning in Huainan and similar mining areas.

This approach not only addresses the limitations of previous models but also integrates contemporary international methodologies to enhance the relevance and applicability of the findings.

Materials and Methods

Study Area Overview

Natural Geographical Conditions

The Huainan coal-mining concentrated area stretches eastward from the Tan–Lu Fault to Fuyang in the west. It is demarcated by the Minglongshan and Shangyao mountains in the north and the Shungengshan and Bagongshan ranges in the south (115°50′-117°45′ E, 32°25′-33°10′ N). It incorporates the Huainan, Panxie, Dingyuan, and Xinji mining districts [17], covering an area that is approximately 180 km in the east-west direction and 15-20 km in the north-south direction, with a total area of approximately 3240 km². The regional details are presented in Fig. 1.

The coalfield is located in a transitional zone between the Jianghuai Hills and the Huaibei Plain. The surface geology is predominantly composed of Cenozoic strata (Qp, Qn, E_2t, N_1x), with typical thicknesses ranging from 200 to 300 m. Limited outcrops of older units, including Cambrian ($\in_{1-3}$), Proterozoic (Pt_1b), Archaean (Ar_3w), Cretaceous (K_2z), and Ordovician (O_{1-2}), are mainly distributed in the eastern part of Dingyuan and the central sectors of the field (Fig. 1).

Structurally, the coalfield is positioned along the southeastern margin of the North China Craton and is characterized by a fan-shaped synclinorium trending NWW-EW [18]. The major bounding structures encompass the Shungengshan thrust nappe to the south, the Laorencang fault to the southwest, the Shangyao–Minglongshan fault to the north, the Changfeng fault to the east, and the Kouziji fault to the west. The regional fault system demonstrates hierarchical control: large-scale faults determine the orebody architecture, while

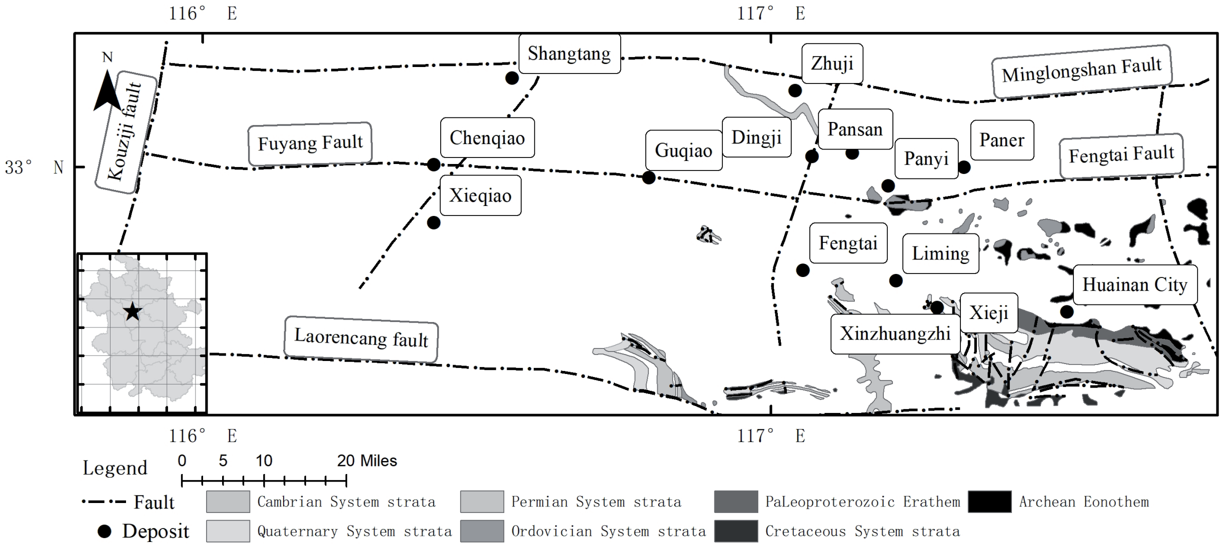

Fig. 1. Regional geological structures and mineral distributions of the Huainan coal-mining area. The map illustrates major fault systems, synclinal features, and bounding mountain ranges, as well as the spatial extent of key mining districts (Huainan, Panxie, Dingyuan, and Xinji). Coordinate grid (115°50′-117°45′ E, 32°25′-33°10′ N) delineates the study area's location within the transitional zone between the Jianghuai Hills and the Huaibei Plain.

smaller subsidiary structures conform to the orientations dictated by these primary features.

Socioeconomic Context

Huainan, a prefecture-level city in Anhui Province, covers an area of approximately 5,571 km^2 and is administratively composed of five urban districts and two counties. As of 2023, the city's total population amounted to 3.016 million, with 1.909 million residents (63.3%) residing in urban areas. The local economy is primarily propelled by coal mining, which has exerted a significant influence on both industrial development and regional infrastructure. Huainan benefits from well-developed transportation networks, including the Shu–Zhang and Fu–Huai railway lines, multiple national highways, and the navigable Huai River. Collectively, these elements form an integrated logistics system that facilitates coal distribution and broader economic activities.

Primary Geological Environmental Issues

The study area is faced with a complex array of environmental challenges, including regional water pollution, groundwater depletion, hydrological disturbance, air pollution, accumulation of industrial solid waste, and extensive mining-induced land subsidence. Industrial solid wastes, primarily coal gangue and fly ash, have accumulated to an estimated 25 million metric tons, occupying approximately 620 hectares of land. These materials are mainly stored in surface stockpiles. Long-term accumulation has resulted in the formation of large gangue hills, which intensify air pollution, degrade water quality, and severely hinder vegetation regeneration.

Mining activities have also caused widespread land subsidence. Currently, the confirmed subsidence zones cover approximately 4,700 hectares. Among these areas, permanent waterlogging affects about 1,400 hectares, nearly one-third of the total subsided land [19]. Major subsidence basins are concentrated in key mining districts such as Jiulonggang–Datong, Panji, Xieji–Liyingzi, Xinzhuangzi–Lizuizi, Xinji, and Zhangji–Xieqiao [15]. Projections suggest that if mining operations continue at the current rate, the total subsidence area could expand to approximately 370 km^2 by 2040 [16], underscoring the urgent need for targeted mitigation and ecological restoration strategies.

Data and Methodology

In the assessment of the mining geo-environment, the selection of the methodology is of crucial importance owing to the complexity and uncertainty intrinsic to environmental impacts. This research employs an integrated model of the Analytic Hierarchy Process (AHP) and Fuzzy Comprehensive Evaluation (FCE), chosen for their complementary advantages. The AHP offers a systematic means of determining the weights of indicators through pairwise comparisons by experts, and it reduces subjectivity via consistency checks [20]. Simultaneously, the FCE effectively manages fuzzy and imprecise data, such as qualitative environmental grades, by utilizing membership functions to quantify uncertainties [21]. The integration of these two methods guarantees a balanced evaluation: the weight outputs of the AHP serve as inputs for the FCE, facilitating a comprehensive assessment that is both objective and adaptable to real-world ambiguities.

In comparison with alternative methods, such as neural networks, which demand large datasets and lack interpretability, or Principal Component Analysis (PCA), which may oversimplify through dimensionality reduction, the AHP-FCE framework provides greater transparency and relevance for multi-criteria decision-making in environmental scenarios. This approach is in line with recent advancements in hybrid Multiple-Criteria Decision-Making (MCDM) applications [10] and [12], highlighting its scientific rigor and innovation in addressing the specific challenges of large-scale coal mining areas, such as the Huainan coalfield.

Geological Environment Monitoring Data Source

To attain a comprehensive characterization of the mine geological environment, this research adopted a multisource data acquisition strategy that incorporated remote-sensing monitoring, in-depth field investigations, and on-site collection of hydro-atmospheric samples. High-resolution satellite imagery (Beijing-2, with a spatial resolution of 0.8 m) was utilized as the primary remote-sensing dataset. Leveraging the ENVI software platform, the imagery was subjected to standardized pre-processing procedures, including: (i) multispectral-panchromatic fusion, (ii) orthorectification, (iii) geometric correction, and (iv) radiometric and color calibration. These operations generated high-precision base maps, which were then imported into ArcGIS for geological and environmental interpretation.

In addition to the remote-sensing data, representative water and atmospheric samples were systematically gathered across key mining areas. Laboratory analyses of these samples offered quantitative evaluations of surface-water contamination and atmospheric pollutant concentrations. Consequently, field-based observations were integrated with spatial datasets to conduct a robust environmental assessment.

Evaluation Methodology

The evaluation methodology is designed to address the complex and uncertain nature of mining geo-environmental assessment. This section details the integrated Analytic Hierarchy Process (AHP) and Fuzzy Comprehensive Evaluation (FCE) framework, including its rationale, implementation steps, and advantages over alternative methods.

Rationale for Method Selection

The selection of an integrated AHP-FCE model is grounded in its ability to handle multi-criteria decision-making (MCDM) under uncertainty, which is critical for geo-environmental assessments. Traditional single-method approaches (e.g., statistical models or standalone AHP) often fail to capture the fuzzy transitions in environmental quality, such as gradual pollution spread or subjective expert judgments. The AHP-FCE combination leverages complementary strengths:

AHP provides a structured approach for determining indicator weights through pairwise comparisons and consistency checks (CR<0.1), reducing subjectivity in weight assignment [20].

FCE employs membership functions to quantify qualitative data (e.g., “Good” or “Poor” environmental grades), effectively managing imprecision and ambiguity [21].

This integration is particularly suited to the Huainan case study, where cumulative impacts (e.g., land subsidence, water pollution) require a holistic and nuanced evaluation. Compared to alternatives like neural networks (which require large datasets and lack interpretability) or Principal Component Analysis (PCA) (which may oversimplify via dimensionality reduction), the AHP-FCE framework offers greater transparency, adaptability, and practicality for dynamic mining environments [10, 12].

Overview of AHP and FCE

Analytic Hierarchy Process (AHP): AHP decomposes the complex evaluation problem into a hierarchy of criteria and sub-criteria. The process involves:

- constructing a hierarchy: The goal (geo-environmental assessment) is broken into criteria (e.g., geological issues, mining operations) and indicators (e.g., water pollution, subsidence).
- pairwise comparisons: Experts rate the relative importance of indicators using a 1-9 scale, forming a judgment matrix.
- weight calculation: Eigenvectors are computed to derive weights, and consistency is verified (CR<0.1).
- sensitivity analysis: Weights are adjusted based on expert feedback to ensure robustness.

Fuzzy Comprehensive Evaluation (FCE): FCE handles fuzzy and uncertain data through:

- defining evaluation grades: e.g., V = {Good, Moderate, Fair, Poor} with corresponding scores {90, 65, 35, 10}.
- membership functions: Piecewise linear functions map indicator values to membership degrees. For instance, the “Good” grade membership function is defined as:

$$\mu_{\mathrm{Good}}(x)=\begin{cases}1, & x \le S_1 \\ \dfrac{S_1-x}{S_1-I_1}, & S_1 < x < I_1 \\ 0, & x \ge I_1\end{cases} \tag{1}$$

where S_1 and I_1 are thresholds derived from environmental standards.

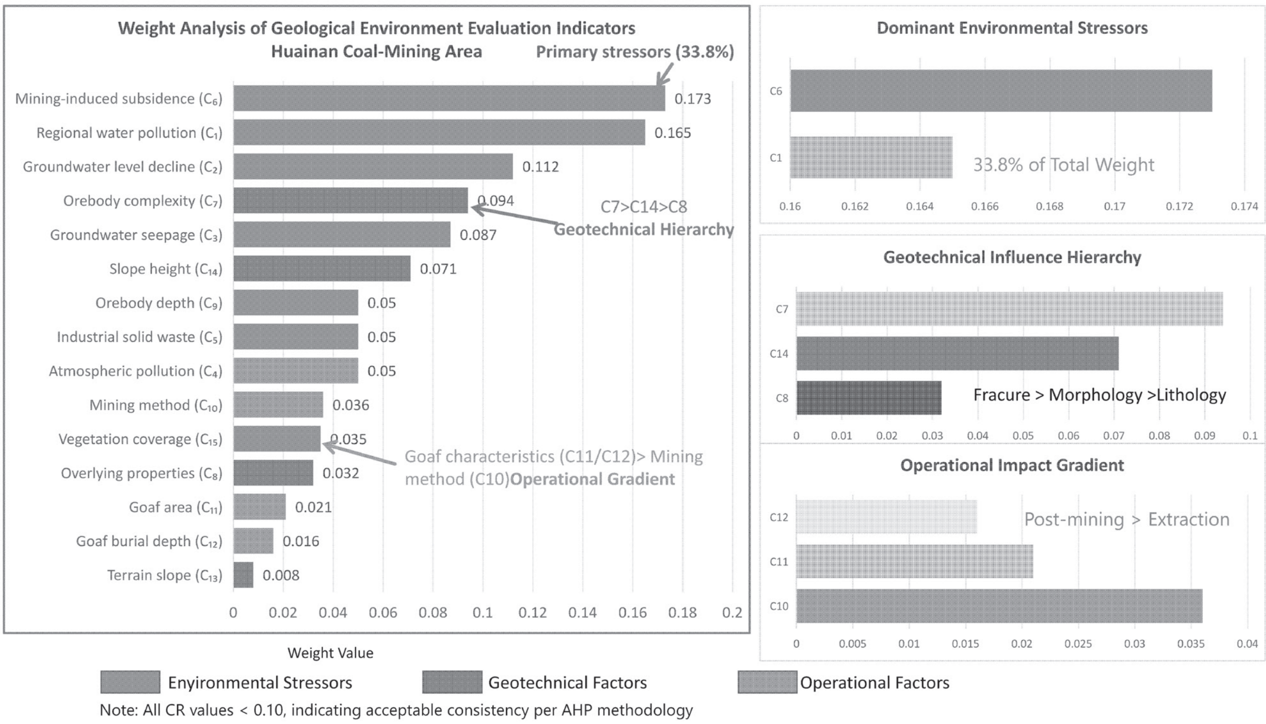

Fig. 2. Distribution of indicator weights for the geological environment evaluation framework. Indicators are grouped by dimension (Environmental Stressors, Geotechnical Factors, Operational Factors) and sorted by weight. Key findings highlight the dominant stressors (C_1 and C_6, contributing 33.8% total weight), the hierarchy within geotechnical factors (C_7 and C_{14} > C_8), and the operational impact gradient (post-mining factors C_{11}/C_{12} > mining method C_{10}). (Note: All CR values < 0.10, indicating acceptable consistency).

- Fuzzy synthesis: The membership matrix R is combined with AHP weights W to compute the evaluation vector B = W×R, resulting in a comprehensive score.

Integration Framework

The AHP-FCE integration follows a sequential process:

(1) AHP for weight determination: Indicator weights are calculated using AHP (as summarized in Table 2 and Fig. 2), ensuring objective prioritization based on expert input.

(2) FCE for evaluation: Weights from AHP are input into FCE, where membership functions convert raw data (e.g., pollution concentrations) into fuzzy grades.

(3) Spatial visualization: Results are mapped using GIS (e.g., ArcGIS) to produce zoning maps (Fig. 3), enabling spatially explicit decision-support.

Advantages over Alternative Methods

The AHP-FCE framework offers distinct advantages for mining geo-environmental assessment:

(1) Handling subjectivity and uncertainty: AHP's consistency checks reduce expert bias, while FCE's membership functions capture environmental gradations (e.g., threshold effects in water quality).

(2) Flexibility and transparency: Unlike black-box models (e.g., neural networks), the process is interpretable and adaptable to regional variations (e.g., Huainan's high groundwater table).

(3) Comprehensive assessment: It integrates multiple dimensions (e.g., geological, social, economic), as demonstrated in recent applications like mercury contamination remediation [10] and rock joint strength modeling [12].

This methodology not only addresses the limitations of prior models but also provides a scalable tool for sustainable resource management in similar mining regions.

Experimental

Construction of Evaluation Index System

The hierarchical evaluation framework encompasses four key dimensions that collectively characterize the mine geological environment: geological environmental issues (U_1), mine engineering geological conditions (U_2), mining operation status (U_3), and topographic characteristics (U_4). Within these dimensions, fifteen diagnostic indicators were systematically selected based on field investigations and expert consultation to ensure both representativeness and applicability to the study area. Each indicator was further stratified into four environmental quality grades, with scientifically derived threshold values established according to regional geological characteristics and national evaluation

Table 1. Evaluation index system and hierarchical structure of factors used for geological environment assessment in the Huainan coal-mining area. The framework encompasses four primary dimensions – geological environmental issues, mine engineering geological conditions, mining operation status, and topographic characteristics – each subdivided into specific diagnostic indicators.

Objective Layer	Criterion Layer	Indicator Layer	Good (≥80)	Moderate (50-80)	Fair (20-50)	Poor (≤20)
Geological Environment Evaluation	Geological Environment Issues (U_1)	Regional water pollution (C_1)	6.0≤pH≤9.0; BOD≤3	pH<6.0 or >9.0; 3<BOD≤4	pH<6.0 or >9.0; 4<BOD≤6	pH<6.0 or >9.0; 6<BOD≤10
		Groundwater level decline (C_2)	No decline	Minor decline	Moderate decline	Severe decline
		Groundwater seepage (C_3)	No seepage	Minor seepage	Moderate seepage	Severe seepage
		Atmospheric pollution (C_4)	SO_2≤0.05 mg/m³; TSP≤0.12 mg/m³	SO_2≤0.15 mg/m³; TSP≤0.30 mg/m³	SO_2≤0.25 mg/m³; TSP≤0.50 mg/m³	SO_2>0.25 mg/m³; TSP>0.50 mg/m³
		Industrial solid waste accumulation (C_5)	0 km²	0-100 km²	100-200 km²	>300 km²
		Mining-induced subsidence (C_6)	0 km²	0-5 km²	5-10 km²	>10 km²
	Mine Engineering Geological Conditions (U_2)	Orebody structural complexity (C_7)	Simple structure; no fractures/joints	Simple structure; minor fractures	Moderately complex structure	Highly complex structure
		Overlying rock/soil properties (C_8)	Hard volcanic bedrock	Carbonate-dominated	Clastic-dominated	Unconsolidated soil
		Orebody depth (C_9)	<10 km	10-15 km	15-20 km	>20 km
	Mining Operations (U_3)	Mining method (C_{10})	No mining	Underground only	Underground + Surface	Surface only
		Goaf area (C_{11})	<500 m²	500-1000 m²	1000-2000 m²	>2000 m²
		Goaf burial depth (C_{12})	>250 m	250-150 m	150-50 m	<50 m
	Topographic Conditions (U_4)	Terrain slope (C_{13})	<10°	10-15°	15-20°	>20°
		Slope height (C_{14})	<10 m	10-15 m	15-20 m	>20 m
		Vegetation coverage rate (C_{15})	>30%	30-20%	20-10%	<10%

standards. An overview of the evaluation index system and hierarchical framework is provided in Table 1.

Determination of Evaluation Indicator Weights

The Analytic Hierarchy Process (AHP) was employed to determine the relative weights of the evaluation indicators through three sequential phases: (i) construction of the pairwise judgment matrix using Saaty's 1-9 scale; (ii) derivation of eigenvectors via the geometric mean method to obtain preliminary weight coefficients; and (iii) consistency verification using the consistency index (CI) and consistency ratio (CR). All calculated CR values were less than 0.10, indicating satisfactory consistency and validating the reliability of the weight assignments. The finalized weights for the fuzzy comprehensive evaluation indicators are summarized in Table 2.

Dominant Environmental Stressors

Among all indicators, mining-induced subsidence (C_6, weight = 0.173) and regional water pollution (C_1, weight = 0.165) together contribute 33.8% of

Table 2. Weights of indicators used in the fuzzy comprehensive evaluation framework for assessing the geological environment in the Huainan coal-mining area.

Evaluation Indicator	Weight	CI	CR	Evaluation Indicator	Weight	CI	CR
Regional water pollution (C_1)	0.165	0.0125	0.0171	Orebody depth (C_9)	0.050	-	-
Groundwater level decline (C_2)	0.112	0.0084	0.0090	Mining method (C_{10})	0.036	0.0506	0.0306
Groundwater seepage (C_3)	0.087	0.0066	0.0066	Goaf area (C_{11})	0.021	0.0030	0.0463
Atmospheric pollution (C_4)	0.050	0.0038	0.0052	Goaf burial depth (C_{12})	0.016	0.0017	0.0148
Industrial solid waste (C_5)	0.050	0.0038	0.0052	Terrain slope (C_{13})	0.008	0.0128	0.0176
Mining-induced subsidence (C_6)	0.173	0.0131	0.0179	Slope height (C_{14})	0.071	0.0113	0.0562
Orebody complexity (C_7)	0.094	0.0098	0.0870	Vegetation coverage (C_{15})	0.035	0.0560	0.0770
Overlying properties (C_8)	0.032	0.0033	0.0296				

Note: The key findings from the weight analysis are presented in the following section, while the main results are illustrated in Fig. 2 through statistical analysis. The three primary indicators of Environmental Stressors, Geotechnical Factors, and Operational Factors are highlighted in Fig. 2, with their relative importance and corresponding explanations also summarized.

the total weighting, identifying them as the primary environmental stressors in the Huainan coal-mining area. These factors represent the most critical targets for ecological management and mitigation strategies.

Geotechnical Influence Hierarchy

Within the geotechnical dimension, structural complexity (C_7, weight = 0.094) and slope height (C_{14}, weight = 0.071) exert a more pronounced influence compared to lithological properties (C_8, weight = 0.032). This weighting pattern underscores the dominant role of fracture networks and slope morphology in controlling geological stability across the mining districts.

Operational Impact Gradient

In terms of operational factors, extraction methods (C_{10}, weight = 0.036) rank lower in significance than goaf-related characteristics (C_{11}-C_{12}, weights = 0.021-0.016). This suggests that post-mining geomechanical alterations exert greater environmental impact than the mining techniques themselves, emphasizing the importance of post-extraction monitoring and remediation.

Interpretation of Weight Results

The weight analysis revealed critical insights into the geo-environmental dynamics of the Huainan mining area:

(1) Dominant stressors: Mining-induced subsidence (C_6, weight = 0.173) and regional water pollution (C_1, weight = 0.165) collectively accounted for 33.8% of the total weighting, identifying them as primary concerns for mitigation.

(2) Geotechnical hierarchy: Structural complexity (C_7, weight = 0.094) and slope height (C_{14}, weight = 0.071) outweighed lithological properties (C_8, weight = 0.032), emphasizing the role of fracture networks in stability control.

(3) Operational gradient: Post-mining factors (e.g., goaf area C_{11}) held higher weights than extraction methods (C_{10}), underscoring the importance of long-term monitoring.

Results and Discussion

Results and Analysis

Fuzzy Comprehensive Evaluation

The evaluation process began by defining a comprehensive factor set $U = \{U_1, U_2, U_3, U_4\}$ representing the four core dimensions of geological environment assessment: geological environmental issues, mine engineering geological conditions, mining operations, and topographic characteristics. This factor set formed the mathematical basis for subsequent analytical procedures.

A corresponding evaluation grade set $V = \{V_1, V_2, V_3, V_4\}$ was then established to categorize environmental quality into four levels: Good (>80 points), Moderate (50-80 points), Fair (20-50 points), and Poor (<20 points). To facilitate computation within the fuzzy evaluation framework, representative numerical values V = {90, 65, 35, 10} were assigned to these grades.

Central to the fuzzy evaluation methodology was the construction of a membership matrix, which quantifies the degree of association between observed parameter values and defined quality grades. This relationship was characterized using specialized piecewise membership functions for each grade. Four customized functions governed this relationship:

For the Good grade classification:

$$\mu_{Good}(x)=\begin{cases}1, & x\le S_1\\ \dfrac{S_1-x}{S_1-I_1}, & S_1<x<I_1\\ 0, & x\ge I_1\end{cases} \tag{2}$$

The Moderate grade membership followed a distinct transitional pattern:

$$\mu_{Mod}(x)=\begin{cases}\dfrac{x-I_1}{I_1-S_1}, & S_1<x<I_1\\ 1, & I_1\le x\le S_2\\ \dfrac{I_2-x}{I_2-S_2}, & S_2<x<I_2\\ 0, & otherwise\end{cases} \tag{3}$$

Specifically, for the membership functions, we adopted piecewise linear forms (as shown in Equations (2) and (3)) rather than simple linear or binary functions due to their superior ability to model the continuous transitions in environmental quality. For instance, piecewise functions allow for smooth gradients at critical thresholds (e.g., between "Good" and "Fair" water quality), avoiding abrupt jumps that could misrepresent real-world scenarios like gradual pollution spread. This choice aligns with findings from recent studies, such as Zhao Yanlin et al. (2020), who successfully applied similar functions in rock joint strength modeling to handle fuzzy roughness classifications [12], and Alishirazi Melika et al. (2023), who used them in mercury contamination assessments to optimize remediation strategies [10]. Compared to alternatives like neural networks – which require large datasets and lack interpretability – or Principal Component Analysis (PCA) – which may oversimplify by reducing dimensionality – the AHP-FCE framework offers greater transparency, adaptability, and practicality for multi-criteria decision-making in dynamic mining environments. This integrated approach not only enhances the scientific validity of the assessment but also provides a scalable tool for sustainable resource management, as demonstrated in applications like socio-economic risk evaluations [11]. Ultimately, this methodology supports robust, evidence-based decision-making for geo-environmental restoration in regions like the Huainan coalfield, where cumulative impacts demand a holistic and nuanced evaluation.

For example, the "Good" classification employed a specific functional form capturing high-quality thresholds, whereas the "Moderate" classification was described by a transitional function reflecting intermediate conditions. To ensure smooth transitions between adjacent grades, threshold values were defined using:

$$I_k=S_k+0.5(S_{k+1}-S_k) \tag{4}$$

where S_k and S_{k+1} denote successive grade boundaries. The resulting membership matrix R mathematically formalized these relationships, serving as the basis for subsequent fuzzy synthesis.

For spatial implementation, the 3240 km² study area was systematically partitioned into 360 standardized evaluation units (3 km × 3 km), establishing a grid-based framework compatible with GIS analytical platforms. This approach ensured both spatial continuity and statistical robustness across the geologically heterogeneous mining landscape.

Evaluation Case Study and Result Analysis

The evaluation workflow was demonstrated using Unit 122 as a representative case. For the critical indicator of orebody structural complexity (C_7), expert scoring produced a membership vector of (0, 0.13, 0.60, 0.27) across the four environmental quality grades. The complete membership matrix for this unit was mathematically represented as:

$$R=\begin{pmatrix}0 & 0.10 & 0.11 & 0.79\\ 0 & 0.26 & 0.30 & 0.44\\ 0 & 0.42 & 0.35 & 0.23\\ \vdots & \vdots & \vdots & \vdots\\ 0 & 0.24 & 0.36 & 0.40\end{pmatrix} \tag{5}$$

Applying the weighted fuzzy synthesis:

$$B=W\times R \tag{6}$$

The resulting evaluation vector was (0,0.173,0.173,0.173), corresponding to a normalized composite score of 29.96. This score placed Unit 122 within the "Fair" environmental quality category, providing a benchmark for subsequent spatial analysis and classification across the entire study area.

Spatial Evaluation Results and Classification

Building on the case analysis of Unit 122, the fuzzy comprehensive evaluation was applied to all 360 grid units across the 3240 km² study area. The composite scores derived from the weighted synthesis were mapped using ArcGIS to visualize spatial variations in geological environmental quality. In particular, four

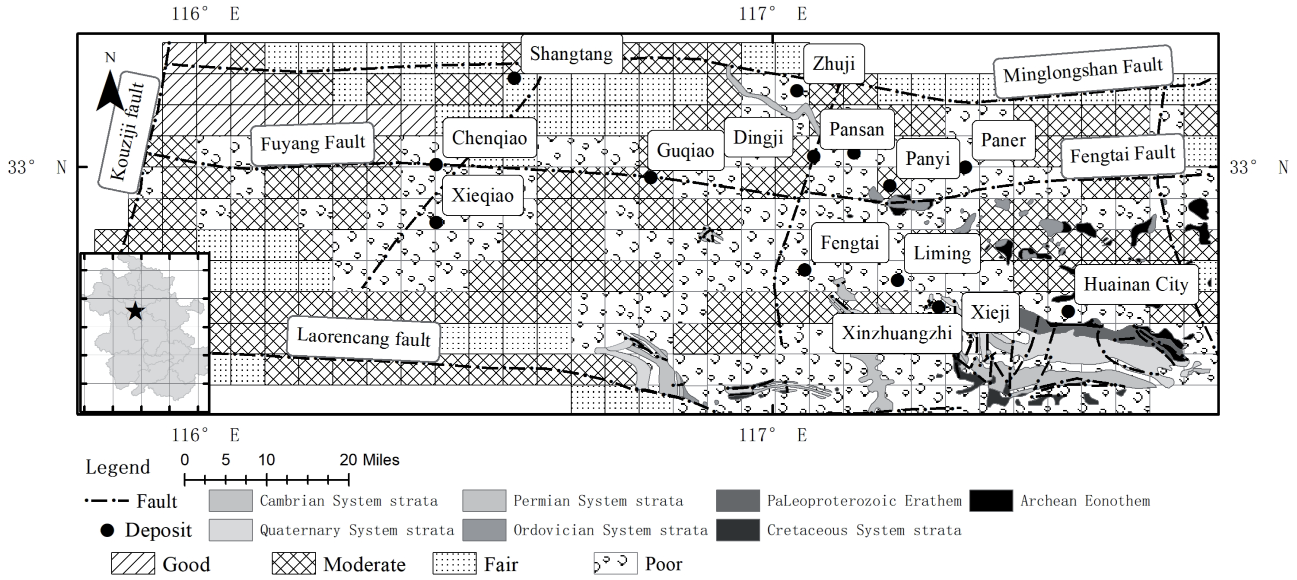

Fig. 3. Geological–environmental quality zoning map of the Huainan coal-mining area. The map delineates four environmental quality categories – Poor, Fair, Moderate, and Good – derived from the integrated AHP–FCE evaluation, highlighting the spatial clustering of degradation relative to mining intensity and geological features.

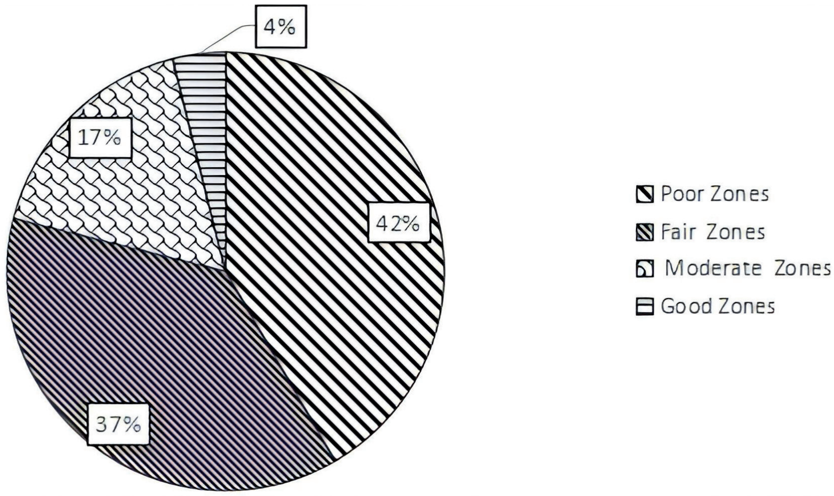

Fig. 4. Proportional distribution of geological environment quality zones in Huainan Coal Mine area.

distinct environmental quality zones were examined, and the results are summarized in Fig. 4.

The classification results reveal four distinct environmental quality zones:

Poor (<20 points) – 1,350 km² (41.7%)

Fair (20-50 points) – 1,206 km² (37.3%)

Moderate (50-80 points) – 558 km² (17.2%)

Good (>80 points) – 126 km² (3.8%)

Poor-grade and fair-grade areas are concentrated in the central and western coalfield zones, where intensive mining, high subsidence rates, and extensive gangue deposition have severely degraded environmental conditions. In contrast, moderate- and good-grade areas occur primarily along the peripheral eastern and northern margins, characterized by less intensive extraction and relatively intact hydro-geological systems.

Spatial patterns of geological environmental quality were mapped using advanced geo-spatial analysis in ArcGIS 10.7, producing a definitive zoning map that delineates distinct clusters of environmental conditions across the Huainan coal-mining area (Fig. 3). The results reveal that high-intensity mining districts – including Xieqiao, Panji, and Dingji – constitute the core concentration zones of Poor environmental quality, collectively covering approximately 1,350 km² (41.7%) of the study area. Surrounding the active mining zones and extending westward, Fair quality conditions dominate, encompassing 1,206 km² (37.3%). In contrast, the northern uplands and southwestern margins exhibit more localized Moderate quality zones totaling 558 km²

(17.2%), while good quality conditions are confined to 126 km² (3.8%) in relatively undisturbed northwestern sectors.

A pronounced spatial correlation between mining intensity and environmental degradation was observed, confirming the robustness of the AHP–FCE evaluation model through comparison with field survey data. The delineated zoning framework provides a scientifically grounded basis for tiered ecological management strategies:

Poor zones: prioritized geohazard mitigation and large-scale ecological rehabilitation.

Fair zones: comprehensive land reclamation and preparation for controlled redevelopment.

Moderate zones: selective remediation paired with regulated land use.

Good zones: conservation-oriented measures to preserve remaining high-quality environments.

Discussion

Advantages and Validation of the Integrated AHP-FCE Method in Environmental Assessment

The effectiveness of the AHP-FCE integrated model employed in this study is demonstrated not only through the strong correspondence between final evaluation results and field observations, but more importantly through its inherent advantages in addressing the complexity and fuzzy characteristics of coal mine geological environment systems. Compared to using singular deterministic index methods or subjective scoring approaches [6, 7], this integrated framework offers dual advantages: Firstly, the AHP method scientifically quantifies the subjective expertise of domain experts in determining indicator weights through consistency tests (all CR<0.1), effectively reducing the arbitrariness in weight allocation and enhancing the objectivity of the evaluation system. Secondly, the FCE method skillfully transforms precise measured values of indicators into membership degrees of fuzzy quality grades through membership functions, thereby objectively characterizing the transitional states between fuzzy concepts such as "high pollution" and "low pollution", which better reflects the continuous nature of environmental quality variations.

This advantage was particularly evident in the evaluation of unit 122, where the evaluation vector (0, 0.173, 0.173, 0.173) does not represent a deterministic value but clearly indicates that the environmental quality of this unit has an equal probability of belonging to "General," "Medium," and "Poor" grades. This probabilistic characterization aligns more accurately with the essential continuous variation characteristics of environmental quality.

Our findings are consistent with previous research by Xu Dan et al. [6] and He Fang et al. [7], but through methodological integration and optimization, we have addressed the issue of excessive subjectivity in weight determination present in the former and the problem of overly rigid indicators in the latter. Compared with the study by Liu Yanguang et al. [8] in the Heshan coal mining area, our weight analysis reveals the dominant roles of mining-induced subsidence (C_6) and water pollution (C_1), highlighting the unique chain environmental effects of "mining-subsidence-water accumulation" characteristic of high-groundwater-level mining areas like Huainan. This demonstrates that the construction of evaluation indicator systems must fully consider regional geological and geographical characteristics, emphasizing the importance of developing context-specific assessment frameworks that account for local environmental conditions and mining impacts.

The integrated approach presented in this study provides a more comprehensive and nuanced understanding of environmental quality assessment in mining areas, offering valuable insights for both academic research and practical environmental management applications.

Driving Mechanisms of Spatial Heterogeneity in Geological Environmental Quality

The spatial heterogeneity pattern of "poor in central and western regions, better in eastern and northern regions" revealed in this study is an inevitable result of the coupling effects of geological background, mining activities, and regional geographical characteristics under specific socio-economic conditions. Based on the evaluation results (Fig. 3) and weight analysis (Fig. 2) of this study, the driving mechanism can be deconstructed into the following progressively in-depth and interconnected hierarchical system:

Core Driving Force: Spatial Control Effects of Mining Engineering Activities

Spatial analysis indicates that units with "Poor" and "Fair" environmental quality are highly concentrated in the central and western regions characterized by high-intensity mining activities. As shown in Figure 4, the areas evaluated as "Poor" almost completely overlap spatially with known high-intensity mining centers such as Xieqiao, Panji, and Dingji, providing the most intuitive spatial evidence for the assertion that "mining activity is the decisive driving force". The weight analysis results (Fig. 2) of this study further confirm this mechanism, showing that mining-induced subsidence (C_6, weight 0.192) and regional water pollution (C_1, weight 0.146) dominate among the 15 evaluation indicators, with a combined contribution of 33.8%, significantly higher than other factors.

This weight distribution is not coincidental but rather a direct mathematical representation of mining activities as the primary driving force. This pattern demonstrates global applicability while manifesting differently depending on mining methods: compared to the Appalachian open-pit mining areas in the United States where "mountaintop removal" represents the primary environmental concern [22], the underground mining methods in Huainan directly lead to distinct environmental effects centered on "subsidence-water accumulation", highlighting the crucial role of mining methods as a key variable controlling the types of environmental issues. The spatial concentration of environmental degradation correlates strongly with specific mining technologies and geological conditions, suggesting that mitigation strategies must be tailored to both the extraction methods and local hydrogeological characteristics. This understanding provides valuable insights for developing targeted environmental management policies in mining-affected regions worldwide.

Regional Amplifier: Cascade Environmental Effects Triggered by High Groundwater Table

The Huainan mining area is situated within the Huaihe River Plain, where its unique geological and hydrological conditions – characterized by a high groundwater table with burial depths ranging from 1.5 to 3.0 m [23, 24] – act as a critical geographical factor that dramatically amplifies the effects of mining disturbances. Results from this study reveal that the waterlogged areas have expanded to approximately 1,400 hectares, and GIS-based spatial overlay analysis demonstrates a strong correlation between these waterlogged zones and regions evaluated as "Poor" in the environmental quality assessment. The high groundwater table exacerbates environmental impacts through two primary mechanisms:

First, it facilitates the formation of a "mining-subsidence-waterlogging" disaster chain. Unlike arid mining areas, the subsidence depressions in Huainan are highly susceptible to spontaneous inundation by groundwater, forming permanent waterlogged areas that lead to fundamental alterations in land ecological functions. This transformation renders traditional reclamation strategies aimed at "recreating arable land" ineffective, necessitating a shift in the restoration approach towards "aquatic ecological restoration and utilization".

Second, the high groundwater table exacerbates the "expressway effect" of pollutant migration. The ground fissure system induced by subsidence damages the natural protective function of the vadose zone, providing a direct pathway for surface pollutants (such as gangue leachate) to rapidly reach shallow aquifers. Simultaneously, the waterlogged areas act as "sinks" for regional pollution, characterized by poor water mobility and weak self-purification capacity, resulting in long-term accumulation of pollutants and the formation of recalcitrant complex pollution. Compared to mining areas in the German Ruhr region or Poland's Upper Silesia [25], the high groundwater table conditions in Huainan make subsidence areas more prone to transform into permanent water bodies. This not only causes fundamental changes in land function but also significantly exacerbates environmental risks of water pollution through mechanisms such as the destruction of the vadose zone structure and the formation of pollution "sinks". This unique hydrogeological background means that under similar mining intensity, the Huainan mining area exhibits more complex and severe composite environmental problems compared to arid and semi-arid mining regions.

Socioeconomic Catalyst: The Profound Impact of Historical Development Patterns

The spatial heterogeneity of environmental patterns also reflects the profound influence of socioeconomic drivers. The central and western sectors of the study area, being the focus of early-stage intensive development, have long been subject to a "production-prioritized, remediation-neglected" developmental approach. This has resulted in the protracted accumulation of environmental governance deficits. The persistent existence of substantial solid waste accumulation (reaching 25 million metric tons) and extensive subsidence areas (covering 4,700 hectares) serves as spatial evidence of this developmental paradigm.

The spatial disparity in policy orientation has, to some extent, exacerbated the environmental pattern characterized by "more severe degradation in the west and relatively better conditions in the east". When compared to the successful transformation achieved through systematic planning in Germany's Ruhr region, the challenges confronting our study area extend beyond technical remediation. They fundamentally reside in establishing effective cross-sectoral collaborative governance mechanisms and ensuring sustainable financing schemes. This comparative analysis provides a critical socioeconomic perspective for understanding the formation mechanisms of the current environmental configuration, highlighting that institutional and financial dimensions are equally as crucial as technological solutions in achieving meaningful environmental restoration.

The enduring legacy of historical policy choices continues to shape the region's environmental trajectory, suggesting that comprehensive remediation strategies must address not only technical challenges but also the underlying institutional and economic drivers that perpetuate environmental degradation.

Methodological Support and Technical Prospects: from Static Assessment to Dynamic Simulation

The integrated AHP-FCE framework employed in this study has effectively identified the dominant environmental factors, though its static assessment nature presents certain limitations. It is noteworthy that the static evaluation results established a crucial foundation for future dynamic simulation research. For instance, the dominant factors identified in this study (C_1, C_6, C_7, etc.) can be directly utilized as feature variable inputs for machine learning models, while the assessment results can serve as validation benchmarks for time-series monitoring technologies like SBAS-InSAR. This integration of "static-to-dynamic" research paradigms will advance mining area environmental studies from current state assessment to process simulation and early warning prediction, thereby providing more powerful scientific tools for precise environmental management.

In summary, the driving mechanism behind the spatial heterogeneity of environmental quality in the Huainan coal mining area constitutes a multi-level, composite coupled system. Mining activities provide the initial driving force, the geographical condition of a high groundwater table acts as an effect amplifier, while historical policies and governance models determine the accumulation degree of environmental issues. The establishment of this multi-level driving framework not only deepens the mechanistic understanding of environmental problems in the study area but also provides important theoretical references for environmental assessment and remediation in similar mining regions worldwide. This comprehensive analytical approach offers valuable insights for developing targeted management strategies that account for both natural geological constraints and sociohistorical influences on environmental degradation patterns.

Practical Implications and Differentiated Management Strategies Based on Research Findings

The value of this study lies not only in "diagnosing" environmental issues, but also in providing a spatially explicit decision-making basis for "targeted treatment". Based on the evaluation results, we propose differentiated and implementable environmental management strategies:

Key Remediation Zones (Areas with "Poor" Quality)

These zones represent the absolute core of ecological restoration and risk management. Measures should focus on: (1) Priority treatment of geological hazards: conducting continuous monitoring and engineering stabilization in areas with unstable subsidence; (2) Systematic restoration of the water environment: implementing water resource utilization (such as constructed wetlands) and water quality purification in waterlogged areas; (3) Resource utilization of solid wastes like coal gangue to reduce pollution sources at their origin. These areas require rescue strategies with primary allocation of funding and technical resources.

Comprehensive Improvement Zones (Areas with "Fair" Quality)

These zones are crucial for preventing further environmental degradation and reserving space for future development. Implementation should include: (1) Large-scale land reclamation, transforming stable subsidence areas into arable land, forest land, or construction land; (2) Establishing ecological corridors to connect fragmented habitats. The strategy for these zones emphasizes comprehensive improvement and preparatory planning.

Prevention and Conservation Zones (Areas with "Good/Moderate" Quality)

For such areas, the primary task is preventive protection. Strict restrictions should be imposed on new mining expansion, establishing ecological redlines, strengthening protection of existing vegetation and water systems, and implementing conservation-oriented regulatory strategies. These areas should serve as benchmarks for sustainable mining practices and ecological preservation.

The proposed differentiated management framework enables precise allocation of resources based on environmental quality gradients, ultimately forming a systematic governance pattern that integrates "emergency remediation-comprehensive improvement-preventive conservation". This approach provides both theoretical guidance and practical solutions for achieving sustainable environmental management in mining areas.

Research Limitations and Future Prospects

Although this study has achieved meaningful results, certain limitations remain, which also represent potential directions for future research:

Limitations in Indicator Dynamics

This study is based on a static assessment at a single time point. However, the coal mining environment is a dynamically evolving system. Future research should incorporate time-series remote sensing data and multi-temporal monitoring data to construct dynamic evaluation models. This would enable the revelation of evolutionary patterns in environmental quality and facilitate predictive early warning systems.

Consideration of Socioeconomic Factors

The evaluation indicator system primarily focuses on natural geological and environmental elements. In practice, the effectiveness of environmental governance is closely related to socioeconomic factors (such as investment in remediation funds, policy implementation capacity, and community participation). Future studies could attempt to integrate socioeconomic indicators into the evaluation system, thereby enhancing the comprehensiveness and management relevance of the results.

Higher Precision Spatial Analysis

While the 3 km × 3 km grid used in this assessment can reflect macroscopic patterns, it lacks sufficient detail for characterizing specific local key engineering projects (such as individual gangue hills or wastewater discharge outlets). Utilizing higher-resolution remote sensing imagery and more refined assessment units would allow for precise micro-scale evaluations.

Conclusions

This study demonstrates the robustness of an integrated evaluation methodology that combines the Analytic Hierarchy Process (AHP) with Fuzzy Comprehensive Evaluation (FCE) to assess geological environments in coal-mining regions. The three-tiered framework – comprising objective, criterion, and indicator layers – incorporates four critical dimensions: geological environmental issues, mine engineering geological conditions, mining operations, and topographic characteristics, operationalized through fifteen rigorously calibrated indicators. This multi-criteria system successfully classifies environmental quality into four distinct categories (Good, Moderate, Fair, and Poor), effectively capturing the complex geological realities of the Huainan coal concentration area.

Spatial implementation via grid-based GIS analysis produced high-resolution environmental zoning maps that exhibit strong agreement with field survey data. Quantitative results reveal that 1,350 km² (41.7%) of the area is classified as Poor, 1,206 km² (37.3%) as Fair, 558 km² (17.2%) as Moderate, and 126 km² (3.8%) as Good. These findings validate the reliability of the evaluation framework and provide actionable intelligence for targeted ecological restoration strategies – prioritizing hazard mitigation in severely degraded zones while supporting conservation and controlled development in less-impacted areas.

Despite its demonstrated effectiveness, two key considerations warrant attention in future applications. First, pronounced geological heterogeneity across mining regions necessitates context-specific adjustment of evaluation indicators, especially those related to structural complexity and hydrological dynamics. Second, differences in extraction methodologies (e.g., underground versus surface mining) require recalibration of AHP weightings to accurately reflect site-specific operational impacts. Addressing these factors will enhance the framework's transferability and scalability to diverse mining contexts worldwide.

The proposed AHP–FCE framework provides a scientifically rigorous yet operationally feasible tool for environmental assessment in mining regions. Its integration with GIS supports evidence-based decision-making for:

Targeted restoration planning, allocating resources to the most degraded zones.

Risk-informed land-use management, aligning reclamation priorities with regional development strategies.

Regulatory compliance and monitoring, offering quantitative benchmarks for environmental performance evaluations.

Global adaptation, enabling comparative assessments across coalfields with similar geotechnical and ecological challenges.

By bridging methodological rigor with practical applicability, this approach contributes directly to the advancement of sustainable mining practices and ecological restoration policies at both regional and national scales.

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AI Usage Disclosure Statement

During Preperation of this manucript, the authors used "Tencent. (2025). Yuanbao (Version 2.0) [AI language model]" solely for language polishing and gramar correction to improve the readability of the manuscript. The authors reviewed and edited all AI-generated suggestions and take full responsibility for the final content. No AI tools were used for data generation, analysis, or the creation of scientific results.

Conflict of Interest

The authors declare no conflict of interest.

References

1. XU J.X., ZHAO H., PENG C.Y., LI X.W., GANG L. Landscape ecological quality assessment and its dynamic change in coal mining area: a case study of Peixian,

Environmental Earth Sciences 78, 708, **2019**.
2. ELMIRA T.A., REZA K., MOHAMMAD A., MOHAMMAD R.T.M. A review of studies on sustainable development in mining life cycle. *Journal of Cleaner Production*. **229,** 213, **2019.**
3. WISCHMEIER W. H., SMITH D.D. Rainfall energy and its relationship to soil loss. *Transactions American Geophysical Union*, 39 (2), 285, **1958**.
4. JOHN C. P. Land surface temperature measurements from the split window channels of the NOAA 7 Advanced Very High Resolution Radiometer. *Journal of Geophysical Research: Atmospheres*, **89** *(D5)*, 7231, **1984**.
5. DU Y., TEILLET P. M., CIHLAR J. Radiometric normalization of multitem poral high-resolution satellite images with quality control for land cover change detection. *Remote Sensing of Environment*, **82** (1), 123, **2002**.
6. ZHAOY. L. Study and application of analytic hierarchy process of mine geological environment: A case study in Hainan Island. Remote Sensing for Lan and Resources, **32** (01), 148, **2020**.
7. SONG G.J., HUANG J.C., ZHANG G., WANG S. Zoning evaluation of Mine Geological Environment in Xuchang City, Henan Province. Geology and Resources, **31** (02), 221, **2022**.
8. WANG N.Q., LI R.W. Evaluation of mine geological environment quality in Shangnan county, Shaanxi province. China Mining Magazine, **27** (12), 83, **2018.**
9. JIA H., LIU J.X., YIN X.Y., WANG C.G., GENG H., CHI H. X., TANG S.J. Ecological evalution of teh Tongling pyrite mining district in Anhui province. Earth Science Frontiers, **28** (4), 131, **2021**.
10. MELIKA A., SABA S., SAEID G. A comprehensive assessment to offer optimized remediation method for mercury contamination in Musa Bay by using hybrid Fuzzy AHP-VIKOR approach. Environmental Geochemistry and Health. 45 (11), 8685, **2023**.
11. LYU H. M., WU Y. X., SHEN J. S., ZHOU A. N. Assessment of Social-Economic Risk of Chinese Dual Land Use System Using Fuzzy AHP. Sustainability, **10** (7), 2451, **2018**.
12. ZHAO Y., ZHANG C., WANG Y., LIN H. Shear-related roughness classification and strength model of natural rock joint based on fuzzy comprehensive evaluation. International Journal of Rock Mechanics and Mining Sciences, **137**, 104550, **2021**.
13. JI W. Evaluation and optimization of the effectiveness of ecological restoration projects in coal mining subsidence areas-A case study of Huainan City Master's thesis, Anhui University of Science and Technology. **2020**. [In Chinese].
14. LI X.H.Characteristics of heavy metal pollution and health risk assessment in subsidence ponds of Huainan coal mining area. Master's thesis, Anhui Jianzhu University, **2017**.
15. LI J.C. Research on Deformation Disaster Monitoring in Huainan Mining Area Based on InSAR and Sentinel-1A. Doctoral thesis, Hefei University of Technology, **2021**.
16. YANG G., CHEN Z.X., LU X.S., ZHANG Y.Q. Mechanics and analog modeling of the Huo-Ma-Tu thrust sheet in the southern Junggar Basin fold andthrust belt, Journal of Geomechanics, **31** (1), 8, **2025**.
17. WANG K.J., ZHAI X.R., TANG M., ZHANG Z.Q. Exploration and evaluation of roof weathering zone in 1410(3) working face of Zhangji Coal Mine, Huainan mining area. Coal Technology, **43** (5), 180, **2024**. [In Chinese].
18. WANG G.S. Structural features and genetic analysis of the Dingji coal mine in the huainan coalfield. Geology of Anhui, 26 (4), 256, 2016 [In Chinese].
19. YANG H. Research of Benefit Assessment and Promotion Strategy of Ecological Restoration Project in Coal Mining Subsidence Area-Take Xiejiaji District Ecological Restoration Project of Huainan City As an Example. Anhui University of Science and Technology, **2020**. [In Chinese].
20. SAATY T.L. The Analytic Hierarchy Process. McGraw-Hill, New York. **1980**.
21. ZADEH L. A. Fuzzy sets as a basis for a theory of possibility. Fuzzy Sets and Systems, **100** (1), 9, **1999**.
22. NASLUND L.C., GERSON J.R., BROOKS A.C., ROSEMONDA.D., WALTERS D.M., BERNHARDT E.S. Ecosystem modification and network position impact insect-mediated contaminant fluxes from a mountaintop mining-impacted river network. Environmental Pollution, **291**, 118, **2021**.
23. Zhang W.X. Water quality characteristics and changing trend of coal mining subsidence area with high underground water in Huainan. Anhui University, **2019**. [In Chinese].
24. HU L., CHEN Y.C., XU Y.F., LI B., WANG J., AN S.K., CHEN C., H.J., MIAO W., Evaluation of water quality and identification of pollution factors in mining subsidence area with high phreatic water level. Coal Geology & Exploration, **51** (11), 83, **2023**.
25. ZIMMERMANN K., LEE D. Environmental Justice and Green Infrastructure in the Ruhr. From Distributive to Institutional Conceptions of Justice. Frontiers in Sustainable Cities, **3**, 670190, **2021**