

Article

An Evaluation of the Coalbed Methane Mining Potential of Shoushan I Mine Based on the Subject–Object Combination Weighting Method

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Abstract: The parameters of coalbed methane reservoirs have large differences, and the precise values cannot represent the resource and production characteristics of the whole block. In order to address these problems, an index system for evaluating the production potential of coalbed methane blocks was constructed, the weights of evaluation parameters were determined, and a model for the preferential selection of coalbed methane blocks based on the subjective–objective combination of weights method was established. The main coal seams (No. 2-1 and No. 4-2) of the Pingdingshan-Shoushan I Mine Block were taken as the research objects to rank the development potential of CBM blocks in a preferential way. The results show that the six resource and production parameters of No. 2-1 coal are gas content, top and bottom rock properties, coal seam thickness, coal seam depth, coal body structure, and tectonic conditions, in descending order of importance, and the parameters of No. 4-2 coal are gas content, coal body structure, coal seam thickness, top and bottom rock properties, coal seam depth, and tectonic conditions, in descending order of importance. It is predicted that the favorable CBM gas development sweet spot areas of the No. 2-1 coal seam and No. 4-2 coal seam will be located along the exploration wells W15–W29 and W31, respectively. This paper aims to make a multi-dimensional and more comprehensive evaluation of coalbed methane mining potential in the Shoushan I mine, and provide a technical basis for the next step of coalbed methane mining in the study area.

Keywords: coalbed methane; Shoushan I mine; exploitation potential; FEAHP; entropy weighting



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1. Introduction

In recent years, with the deepening of CBM exploration and development, the evaluation of CBM production potential has become increasingly important. In the existing quantitative evaluations of CBM production potential, the weights of evaluation indicators are mostly determined by subjective factors, and their values are fixed [1–4]. Coalbed methane constituency evaluation is the basic work in coalbed methane exploration, which is related to exploration results and development benefits [5]. At present, most of the evaluation methods of coal reservoirs are mainly based on gas content and permeability. However, coal reservoirs buried deep below the ground surface are actually part of a complex environmental system with multiple factors acting together [6,7]. In China, the formation conditions for coalbed methane and the history of reservoir tectonic evolution are relatively complex, resulting in large regional differences in geological parameters [8]. Even in the same stratum in the same region, each parameter still shows strong anisotropy [9]. Therefore, the question of how to select a suitable approach to determine the weights of indicators and avoid subjectivity and objective randomness is a prerequisite for establishing

a practical and accurate preference model. The subjective assignment method is mainly based on the experience of subjective judgement to obtain the weight, but the subjective randomness of the decision maker is difficult to quantify. The objective assignment method is based on the characteristics and interrelationships of the indicator values of the evaluation object, and the use of statistical methods to calculate the weights, but the evaluation of the weights is too objective, and may be biased away from actual indicators [10,11].

The Pingdingshan coal mine area in Henan Province is a typical coal seam development zone in China, with rich coal seam reserves, large total thickness, large spacing between seams, high gas content in coal seams, tectonic coal development, and strong heterogeneity [12,13]. However, it also faces problems of complicated geological conditions and difficult target area preference. Therefore, based on previous research, the Shoushan I Mine in the Pingdingshan mine area was taken as the research object. This study puts forward a coalbed methane potential evaluation index system of the constituency based on multi-level and multi-type indicators of the gas source conditions, reservoirs' physical properties, and preservation conditions. In this system, the triangular fuzzy hierarchical analysis method and the entropy weight method that combines the subjective and objective weights were used to design the indicator weight [14–16]. This practice can enable the multi-dimensional evaluation of coalbed methane mining potential in the Shoushan I mine. It can provide a technical basis for the priority and construction ratio of coalbed methane exploration and development in the subsequent Shoushan I mine area. It can provide a better solution for the exploration and development of the project, and provide the direction for the next step of coalbed methane exploration and development in the area. Therefore, this study has certain theoretical significance and important application value.

2. Method and Material

After constructing the index system, it is necessary to choose an appropriate evaluation model. Determining the weights of the index and choosing the evaluation methods are fundamental for objective and rational assessment. In order to obtain accurate and objective index weights, relatively mature and widely recognized model combinations or methods should be used first when selecting evaluation methods. Secondly, evaluation methods should be adapted to the evaluation purposes. According to specific evaluation objectives, adaptive and rational evaluation methods should be chosen. Finally, qualitative methods should be combined with quantitative methods. In complex evaluation problems where obtaining quantitative data for many indicators is challenging, qualitative analysis becomes particularly crucial. Thus, it is essential in relevant evaluations to thoroughly explore the selected indicators, appropriately combine qualitative and quantitative methods, and achieve a comprehensive and unbiased evaluation of the objects under assessment.

The analytic hierarchy process is the most commonly used method for determining the weights of indicators, but its weight allocation is not objective enough. The entropy weight method is a method for determining the evaluation weights based on the sample data, and does not contain the subjective opinion of the evaluator, but its defect is that the evaluation weights are too objective and may be biased away from the indicator's actuality [17,18]. Therefore, to improve the rationality of the evaluation, this paper proposed an integrated method of the two evaluation methods, which uses the triangular fuzzy hierarchical analysis method FEAHP (Fuzzy Extend Analytic Hierarchy Process) to improve the traditional hierarchical analysis method and the entropy weight method to correct the weights determined by the hierarchical analysis method.

2.1. Indicator Weights Based on Fuzzy Extend AHP

The traditional hierarchical analysis method can unify and quantify qualitative and quantitative indicators of different dimensions into one dimension, which is very practical for multi-objective decision-making problems in various fields. However, it is difficult for some experts to accurately assign weights to multiple parameters simply based on the "1–9" scale [19]. Therefore, the concept of triangular fuzzy numbers is introduced when

determining the score. The improved hierarchical analysis method proposes the theory of fuzzy triangular numbers for the drawbacks of the “1–9” scale in the hierarchical analysis method, i.e., the triangular fuzzy hierarchical method FEAHP (Fuzzy Extend Analytic Hierarchy Process). When determining the relative importance of indicators, the degree of affiliation in fuzzy mathematics is used instead [20]. The calculation steps in the FEAHP method are as follows:

2.1.1. Application of Fuzzy Triangular Numbers to Build a Two-by-Two Judgement Matrix

The fuzzy triangular number takes the form of an affiliation function, denoted as (l, m, u) , where l denotes the value of the smallest possible value, m takes the value of the most likely value, and u denotes the maximum possible value. For the two-by-two factor comparison matrix, the values are taken as shown in Table 1.

Table 1. Triangular fuzzy number conversion table.

Linguistic Scale	Triangular Fuzzy Scale	Triangular Fuzzy Reciprocal Scale
Equally preferred (EP)	(1, 1, 1)	(1, 1, 1)
Equally important (EI)	(1/2, 1, 3/2)	(2/3, 1, 2)
Weakly more important (WMI)	(1, 3/2, 2)	(1/2, 2/3, 1)
Strongly more important (SMI)	(3/2, 2, 5/2)	(2/5, 1/2, 2/3)
Very strongly more important (VSMI)	(2, 5/2, 3)	(1/3, 2/5, 1/2)
Absolutely more important (AMI)	(5/2, 3, 7/2)	(2/7, 1/3, 2/5)

According to the basic principle of the FEAHP method, combined with the research results of former experts and the geological background of the study area [3,5,21–23], through the evaluation system of coalbed methane potential indexes established above (Figure 1) and the analysis of the controlling factors of the coalbed methane potential indexes, the triangular scale method was used to obtain the judgement matrix of pairwise fuzzy comparisons.

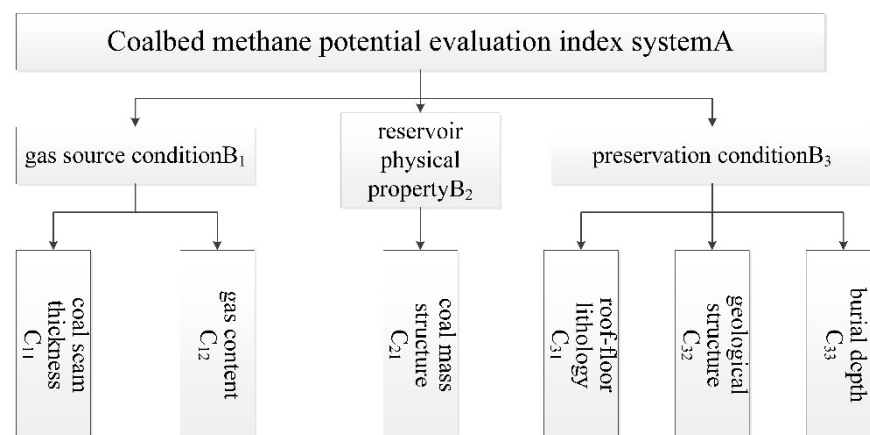


Figure 1. Coalbed methane potential evaluation index system.

2.1.2. Consistency Test

Using the triangular fuzzy number defuzzification method, the pairwise fuzzy comparison judgement matrix is transformed into a clear matrix as shown in Equation (1). Additionally, the consistency test is carried out as shown in Equation (2).

$$M_{crisp} = (4m + l + u) / 6 \quad (1)$$

$$C.I. = (\lambda_{max} - n) / (n - 1) \quad (2)$$

$$C.R. = C.I. / R.I. \quad (3)$$

where λ_{max} is the maximum characteristic root of the matrix; n is the number of matrix orders; $R.I.$ is the average random consistency index, which is determined by Table 2; and $C.I.$ is the deviation from the full consistency index, and the closer the judgement matrix is to full consistency, the smaller the value is. When $C.R. < 0.10$ (which can be obtained from Equation (3)), it is necessary to re-adjust the fuzzy judgement matrix and clarify it to obtain the $C.R.$ value again.

Table 2. The value of random index ($R.I.$).

Determining Matrix Order	1	2	3	4	5	6	7	8	9
$R.I.$	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45

The fuzzy judgment matrix is transformed into a clear matrix according to Equations (1) and (2), and the clear matrix of the A–B layer can be obtained. Similarly, the pairwise fuzzy comparison judgment matrix and the defuzzification clarity matrix of B–C layer indicators can be obtained, as well as the consistency test results (Table 3).

Table 3. Hierarchical indicator fuzzy comparison judgement matrix.

Hierarchical Indicator Fuzzy Comparison Judgement Matrix				Maximum Characteristic Root (λ_{max})	Consistency Ratio ($C.R.$)/%
A	B ₁	B ₂	B ₃		
B ₁	(1, 1, 1)	(3/2, 2, 5/2)	(1, 3/2, 2)	3.0352	0.0303
B ₂	(2/5, 1/2, 2/3)	(1, 1, 1)	(1/2, 2/3, 1)		
B ₃	(1/2, 2/3, 1)	(1, 3/2, 2)	(1, 1, 1)		
B ₁	C ₁₁		C ₁₂	2.0203	0
C ₁₁	(1, 1, 1)		(1/2, 2/3, 1)		
C ₁₂	(1, 3/2, 2)		(1, 1, 1)		
B ₂		C ₂₁		1.0000	0
C ₂₁		(1, 1, 1)			
B ₃	C ₃₁	C ₃₂	C ₃₃	3.0302	0.1056
C ₃₁	(1, 1, 1)	(1/2, 1, 3/2)	(1/2, 2/3, 1)		
C ₃₂	(2/3, 1, 2)	(1, 1, 1)	(1, 3/2, 2)		
C ₃₃	(1, 3/2, 2)	(1/2, 2/3, 1)	(1, 1, 1)		

2.1.3. Compute Weight Vectors for Each Level of the Target Hierarchy

1. The formula for calculating the synthetic fuzzy number for each indicator in the dominance layer is as per Equation (4):

$$S_i = \sum_{j=1}^m X_i^k \otimes \left[\sum_{i=1}^n \sum_{j=1}^m X_i^k \right]^{-1} \quad (4)$$

where $\sum_{j=1}^m X_i^k$ denotes the total fuzzy importance of a single element in the matrix in comparison with other elements in its dominant layer, which can be obtained by a fuzzy addition operation, and the calculation formula is shown in Equations (5)–(7).

$$\sum_{j=1}^n X_i^k = \left(\sum_{j=1}^n l_j, \sum_{j=1}^n m_j, \sum_{j=1}^n u_j \right) \quad (5)$$

$$\sum_{i=1}^n \sum_{j=1}^m X_i^k = \left(\sum_{i=1}^m \sum_{j=1}^n l_{ij}, \sum_{i=1}^m \sum_{j=1}^n m_{ij}, \sum_{i=1}^m \sum_{j=1}^n u_{ij} \right) \quad (6)$$

$$\left[\sum_{i=1}^m \sum_{j=1}^n X_i^k \right]^{-1} = \left(\frac{1}{\sum_{i=1}^m \sum_{j=1}^n u_{ij}}, \frac{1}{\sum_{i=1}^m \sum_{j=1}^n m_{ij}}, \frac{1}{\sum_{i=1}^m \sum_{j=1}^n l_{ij}} \right) \quad (7)$$

2. The probability that $S_i \geq S_k$ and $S_k \geq S_i$ can be calculated from the following.

Denote $V(S_k \geq S_i)$ as the possibility of $S_k \geq S_i$, and m_2 is the triangular fuzzy number of S_k , m_1 is the triangular fuzzy number of S_i , which is calculated as follows (Equation (8)):

$$V(S_k \geq S_i) = \text{hgt}(S_k \cap S_i) = \mu_{S_k}(d) = \begin{cases} 1, & m_2 \geq m_1 \\ 0, & l_1 \geq u_2 \\ \frac{(l_1 - u_2)}{(m_2 - u_2) - (m_1 - l_1)}, & \text{otherwise} \end{cases} \quad (8)$$

3. Measure the likelihood of the synthetic value S_i of indicator x_i , which is, on average, greater than the synthetic values of all other indicators (Equation (9)):

$$V(S_i \geq S_1, S_2, \dots, S_{i-1}, S_{i+1}, \dots, S_n) = \min_{V(S_i \geq S_k)} = d'(A_n) \quad (i, k = 1, 2, \dots, i \neq k) \quad (9)$$

Then, the weight vector is $W' = (d'(A_1), d'(A_2), \dots, d'(A_n))^T$.

4. Normalize the weight vectors (Equation (10)):

$$W = (d(A_1), d(A_2), \dots, d(A_m))^T \quad (10)$$

where W is a vector of non-fuzzy numbers, which determines the subjective weights of the elements in the evaluation system.

Table 4 can be obtained according to the above calculation process.

Table 4. Summary of the calculation process of the FEAHP method.

Indicator Level	Index	S_i	$d'(A_n)$	$d(A_n)$
B_i	B_1	(0.30, 0.46, 0.70)	1.00	0.50
	B_2	(0.16, 0.22, 0.28)	0.19	0.10
	B_3	(0.22, 0.32, 0.51)	0.80	0.40
C_{1i}	C_{11}	(0.30, 0.40, 0.58)	0.47	0.16
	C_{12}	(0.40, 0.60, 0.87)	1.00	0.34
C_{2i}	C_{21}	(0.40, 0.60, 0.87)	1.00	0.10
C_{3i}	C_{31}	(0.16, 0.29, 0.49)	0.79	0.12
	C_{32}	(0.21, 0.39, 0.70)	1.00	0.14
	C_{33}	(0.20, 0.35, 0.56)	0.95	0.14

2.2. Indicator Weights Based on Entropy Weighting

The entropy method is a mathematical method for determining the weights of evaluation parameters based on the degree of data discrepancy of each parameter. In a system with evaluation indicators and n evaluation objects, the evaluation matrix is constructed from the raw data of the corresponding indicators m of the evaluated objects $X = (x_{ij})_{m \times n}$.

2.2.1. Dimensionless Processing of the Original Data

For positive indicators, a half-liter trapezoidal fuzzy affiliation function was used for quantification (Equation (11)).

$$a_{ij} = \begin{cases} 1; & x_{ij} = \max(x_{ij}), \\ \frac{x_{ij} - \min(x_{ij})}{\max(x_{ij}) - \min(x_{ij})}; & \min(x_{ij}) < x_{ij} < \max(x_{ij}) \\ 0; & x_{ij} = \min(x_{ij}) \end{cases} \quad (11)$$

where $1 \leq i \leq m, 1 \leq j \leq n$.

For the reverse indicator, a half-descending trapezoidal fuzzy affiliation function was used for quantification (Equation (12)):

$$a_{ij} = \begin{cases} 1; & x_{ij} = \min(x_{ij}), \\ \frac{\max(x_{ij}) - x_{ij}}{\max(x_{ij}) - \min(x_{ij})}; & \min(x_{ij}) < x_{ij} < \max(x_{ij}) \\ 0; & x_{ij} = \max(x_{ij}) \end{cases} \quad (12)$$

where $1 \leq i \leq m, 1 \leq j \leq n$. x_{ij} is the original value of the j th evaluation object on indicator i , n is the number of evaluated objects, m represents the number of evaluation indicators, and a_{ij} represents the dimensionless value.

2.2.2. Correction of a_{ij} Values Using the Efficacy Coefficient Method

Because the logarithmic function is imperative in the calculation of the entropy weight method, the dimensionless value a_{ij} cannot take zero. For this reason, it is necessary to use the efficacy coefficient method to correct a_{ij} , to ensure that the final result of each operation is greater than 0, as shown in Equation (13):

$$y_{ij} = a_{ij} \times 0.4 + 0.6 \quad (13)$$

Finally, a new evaluation matrix with m evaluation indicators and n samples as the evaluation system, and the dimensionless value of the evaluated object as y_{ij} , can be obtained and written as follows:

$$Y = (y_{ij})_{m \times n} = \begin{pmatrix} y_{11} & y_{12} & \cdots & y_{1n} \\ y_{21} & y_{22} & \cdots & y_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ y_{m1} & y_{m2} & \cdots & y_{mn} \end{pmatrix}_{m \times n}$$

2.2.3. Calculation of the Entropy Value of the i th Indicator e_i (Equation (14))

$$e_i = -k \sum_{j=1}^n p_{ij} \cdot \ln p_{ij}; k = 1 / \ln n \quad (14)$$

where $p_{ij} = y_{ij} / \sum_{j=1}^n y_{ij}$, $i = 1, \dots, m$; $j = 1, 2, \dots, n$, denotes the calculation of the weight of the j th sample indicator under the i th indicator.

2.2.4. Calculation of the Coefficient of Variation for the i th Indicator ∂_i (Equation (15))

$$\partial_i = 1 - e_i; (i = 1, 2, \dots, m) \quad (15)$$

2.2.5. Calculation of the Entropy Weight of the i th Indicator $w_i^{(e)}$ (Equation (16))

$$w_i^{(e)} = \frac{\partial_i}{\sum_{i=1}^m \partial_i}; (i = 1, 2, \dots, m) \quad (16)$$

For the qualitative indicators, the fuzzy comprehensive evaluation method in fuzzy mathematics is used to portray the parameters using the affiliation function and the degree of affiliation. Based on the above analysis of geological control factors of the CBM-rich area in the Shoushan I Mine and the actual situation of the study area, the determination of tectonic complexity combines the determination of Zhang Xiaodong (2017) [24] in the Changzhi block with four indicators, namely, fault density, extension length, and fault inclination and fault distance, are selected for the qualitative evaluation of tectonic complexity for block stacking (Table 5). The prediction and qualitative evaluation criteria of CBM-rich areas were established, and the assignment results of the membership degree of the index are shown in Tables 5 and 6.

Table 5. Determination of tectonic complexity.

Index	Evaluation Result		
	Simpler	More Complex	Complex
Fault density	1/4 km ²	1~3/4 km ²	≥3/4 km ²
Fault extension length	≤2 km	2~4 km	≥4 km
Fault displacement	≤20 m	20~40 m	≥40 m
Dip of fault	≤35°	35°~45°	≥45°

Table 6. Assignment of qualitative indicators of affiliation.

Tectonic Condition	Simple	Simpler	More Complex	Complex
number of affiliations	0.8	0.6	0.4	0.2
roof-floor lithology	mudstone	Sandy mudstone with siltstone	Sandstone in sandstone and carbonaceous mudstone is interbedded with fine-grained sandstone	
number of affiliations	1	0.7	0.3	
coal mass structure	primary structure coal	cataclastic coal	Broken-mylonite coal	
number of affiliations	1	0.7	0.3	

For the quantitative index, the forward index and the reverse index are dimensionlessly processed by Equation (11) and Equation (12), respectively. After the above calculation of the original data in the study area (Tables 7 and 8), the value of $w_i^{(e)}$ can be obtained; the calculation results are shown in Tables 9 and 10.

Table 7. The original data of No. 2-1 coal reservoir in an exploration well of Shoushan I Mine.

CBM Well	B ₁		B ₂		B ₃		
	C ₁₁	C ₁₂	C ₂₁	C ₃₁	C ₃₂	C ₃₃	
W1	6.40	14	III	more complex	sandy mudstone	post office box stone	824.10
W2	5.62	25	III	simpler	sandy mudstone	carbon mudstone	917.84
W3	6.45	15	II	simpler	post office box stone	carbon mudstone	878.18
W4	4.21	5	I	more complex	Mudstone	post office box stone	645.75
W5	6.17	20	II	simpler	Mudstone	post office box stone	870.03
W6	7.93	12	III	simpler	Siltstone	mudstone	782.09
W7	4.61	8	III	simpler	Mudstone	mudstone	758.23
W8	4.23	15	II	simple	Siltstone	post office box stone	829.22
W9	4.65	9	III	simple	sandy mudstone	mudstone	743.54
W10	5.94	30	III	simpler	Siltstone	siltstone	983.57
W11	0.84	30	II	simple	Mudstone	mudstone	970.33
W12	7.58	26	II	simple	Siltstone	mudstone	885.20
W13	8.02	12	I	simpler	Siltstone	carbon mudstone	761.13
W14	7.78	7	I	simpler	sandy mudstone	mudstone	731.69
W15	6.73	40	II	more complex	Mudstone	mudstone	1136.40
W16	2.93	10	II	more complex	post office box stone	sandy mudstone	766.55
W17	5.02	23	II	simple	mudstone	carbon mudstone	899.77
W18	7.44	20	III	simpler	mudstone	mudstone	843.09
W19	6.67	10	II	more complex	carbon mudstone	mudstone	768.96
W20	4.53	30	III	simple	siltstone	siltstone	947.35
W21	4.71	16	III	simpler	sandy mudstone	sandy mudstone	791.38
W22	5.63	20	I	simple	sandy mudstone	sandy mudstone	815.40
W23	7.08	35	II	more complex	mudstone	mudstone	1047.91
W24	2.76	15	III	more complex	medium grained sandstone	mudstone	882.90
W25	5.82	20	III	simple	siltstone	post office box stone	791.35
W26	5.38	33	II	simpler	mudstone	mudstone	1029.93
W27	6.72	8	III	simple	carbon mudstone	mudstone	899.60
W28	0.84	7	II	more complex	sandy mudstone	sandy mudstone	1305.35
W29	5.03	37	III	simple	sandy mudstone	siltstone	985.30
W30	4.23	32	III	complex	sandy mudstone	mudstone	1002.80
W31	5.19	38	II	complex	mudstone	mudstone	1131.55
W32	5.52	39	II	more complex	mudstone	mudstone	1133.55

Table 8. The original data of No. 4-2 coal reservoir in an exploration well of Shoushan I Mine.

CBM Well	B ₁		B ₂		B ₃		
	C ₁₁	C ₁₂	C ₂₁	C ₃₁	C ₃₂	C ₃₃	
W1	1.97	0.5	III	more complex	carbon mudstone	mudstone	637.89
W2	1.17	0.2	II	simpler	mudstone	mudstone	751.67
W3	1.04	3	II	more complex	post office box stone	sandy mudstone	691.20
W4	0.90	15	I	simple	mudstone	mudstone	445.11
W5	2.07	2	I	simple	mudstone	mudstone	685.32
W6	2.29	0.2	I	simpler	mudstone	mudstone	590.99
W7	2.46	0.3	II	simpler	mudstone	mudstone	572.09
W8	0.94	2	II	simpler	post office box stone	sandy mudstone	667.26
W9	1.18	1	II	simple	mudstone	sandy mudstone	529.47
W10	2.26	3	III	simpler	mudstone	mudstone	782.54
W11	2.45	4.5	I	simple	sandy mudstone	sandy mudstone	783.54
W12	2.20	2	II	simpler	sandy mudstone	mudstone	705.16
W13	2.31	1	II	simpler	sandy mudstone	sandy mudstone	567.46
W14	2.04	1	I	simple	sandy mudstone	mudstone	553.75

Table 8. Cont.

CBM Well	B ₁		B ₂		B ₃		
	C ₁₁	C ₁₂	C ₂₁	C ₃₁	C ₃₂		C ₃₃
W15	2.35	7	II	more complex	mudstone	mudstone	946.04
W16	2.54	4	II	more complex	mudstone	mudstone	562.62
W17	2.27	5	I	simpler	mudstone	mudstone	726.75
W18	2.27	2	III	simple	mudstone	mudstone	665.76
W19	1.89	0.42	I	simpler	sandy mudstone	mudstone	569.77
W20	3.39	0.2	III	simple	mudstone	mudstone	767.65
W21	3.70	0.8	II	more complex	mudstone	mudstone	611.46
W22	2.08	1.5	I	simple	mudstone	mudstone	646.32
W23	2.41	0.2	I	simpler	mudstone	mudstone	867.20
W24	2.65	0.3	III	more complex	mudstone	mudstone	688.00
W25	3.30	0.2	I	simple	medium grained sandstone	mudstone	610.64
W26	3.49	0.2	I	simple	sandy mudstone	sandy mudstone	845.36
W27	3.46	0.4	III	simpler	mudstone	sandy mudstone	697.42
W28	2.44	1.2	III	simpler	sandy mudstone	mudstone	1130.09
W29	5.15	15	III	simpler	sandy mudstone	mudstone	809.00
W30	2.64	18	III	simpler	mudstone	mudstone	825.63
W31	2.40	20	II	simple	mudstone	mudstone	949.60
W32	2.97	10	II	simple	sandy mudstone	mudstone	950.80

Table 9. Summary of entropy weighting method calculation process for No. 2-1 coal reservoir.

Indicator Level	Index	$-k$	e_i	∂_i	w_i
C _{1i}	C ₁₁	−0.288539008	0.997990003	0.002009997	0.1449
	C ₁₂	−0.288539008	0.996449207	0.003550793	0.2560
C _{2i}	C ₂₁	−0.288539008	0.997897274	0.002102726	0.1516
C _{3i}	C ₃₁	−0.288539008	0.998874497	0.001125503	0.0812
	C ₃₂	−0.288539008	0.996780208	0.003219792	0.2322
	C ₃₃	−0.288539008	0.998141042	0.001858958	0.1340

Table 10. Summary of entropy weighting method calculation process for No. 4-2 coal reservoir.

Indicator Level	Index	$-k$	e_i	∂_i	w_i
C _{1i}	C ₁₁	−0.288539008	0.998287154	0.001712846	0.1395
	C ₁₂	−0.288539008	0.996414986	0.003585014	0.2920
C _{2i}	C ₂₁	−0.288539008	0.997678877	0.002321123	0.1891
C _{3i}	C ₃₁	−0.288539008	0.999154221	0.000845779	0.0689
	C ₃₂	−0.288539008	0.997990176	0.002009824	0.1637
	C ₃₃	−0.288539008	0.998197809	0.001802191	0.1468

2.3. Subjective-Objective Combination Weight

In this paper, the additive integration method was used. The comprehensive weight vector obtained using the subjective and objective combination weighting method is expressed as $W = \alpha W_s + \beta W_o$, where α and β are the undetermined coefficients of the combination of the main and objective phases. The values of α and β can be determined using the subjective and objective weight values obtained from each index. Let $\alpha_i = \frac{W_{si}}{W_{si} + W_{oi}}$, $\beta_i = (1 - \alpha_i)$, obtain $\bar{w}_i = \alpha_i \omega_{si} + \beta_i \omega_{oi}$, $\bar{W} = [\bar{w}_1, \bar{w}_2, \dots, \bar{w}_i]$, and then normalize them, and the obtained $W = [\omega_1, \omega_2, \dots, \omega_n]$ will be the final weight vector based on FEAHP and the entropy weight method. The application results of each parameter weight are shown in Tables 11 and 12. The comprehensive evaluation results of the mining potential of the main coal seam in Shoushan I Mine are shown in Tables 13 and 14:

Table 11. Main parameters and weight coefficient of No. 2-1 coal reservoir.

A	Index	Weight Coefficient	Relative Total Target Weight
B ₁ (0.4403)	C ₁₁	0.3346	0.1489
	C ₁₂	0.6654	0.2960
B ₂ (0.1264)	C ₂₁	1.0000	0.1277
B ₃ (0.4333)	C ₃₁	0.2634	0.1016
	C ₃₂	0.4315	0.1923
	C ₃₃	0.3050	0.1335

Table 12. Main parameters and weight coefficient of No. 4-2 coal reservoir.

A	Index	Weight Coefficient	Relative Total Target Weight
B ₁ (0.4572)	C ₁₁	0.3213	0.1458
	C ₁₂	0.6787	0.3080
B ₂ (0.1545)	C ₂₁	1.0000	0.1534
B ₃ (0.3928)	C ₃₁	0.2876	0.1130
	C ₃₂	0.3583	0.1407
	C ₃₃	0.3541	0.1391

Table 13. Comprehensive evaluation of No. 2-1 coal reservoir in an exploration well of Shoushan I Mine.

CBM Well	B ₁ /0.4449		B ₂ /0.1277		B ₃ /0.4274		Evaluation Result
	Coal Thickness	Gas Content	Coal Mass Structure	Tectonic Conditions	Roof/Floor Rocks	Burial Depth	
	C ₁₁ /0.1489	C ₁₂ /0.2960	C ₂₁ /0.1277	C ₃₁ /0.1016	C ₃₂ /0.1923	C ₃₃ /0.1335	
W1	0.7744	0.2571	0.3	0.4	0.21	0.2704	0.3468
W2	0.6657	0.5714	0.3	0.6	0.21	0.4125	0.4630
W3	0.7813	0.2857	0.7	0.6	0.09	0.3524	0.4156
W4	0.4694	0.0000	1	0.4	0.3	0.0000	0.2959
W5	0.7423	0.4286	0.7	0.6	0.3	0.3400	0.4908
W6	0.9875	0.2000	0.3	0.6	0.7	0.2067	0.4677
W7	0.5251	0.0857	0.3	0.6	1	0.1705	0.4179
W8	0.4721	0.2857	0.7	0.8	0.21	0.2782	0.4031
W9	0.5306	0.1143	0.3	0.8	0.7	0.1483	0.3868
W10	0.7103	0.7143	0.3	0.6	0.49	0.5122	0.5791
W11	0.0000	0.7143	0.7	0.8	1	0.4921	0.6401
W12	0.9387	0.6000	0.7	0.8	0.7	0.3630	0.6711
W13	1.0000	0.2000	1	0.6	0.21	0.1749	0.4605
W14	0.9666	0.0571	1	0.6	0.7	0.1303	0.5015
W15	0.8203	1.0000	0.7	0.4	1	0.7439	0.8398
W16	0.2911	0.1429	0.7	0.4	0.21	0.1831	0.2805
W17	0.5822	0.5143	0.7	0.8	0.3	0.3851	0.5187
W18	0.9192	0.4286	0.3	0.6	1	0.2992	0.5952
W19	0.8120	0.1429	0.7	0.4	0.3	0.1868	0.3759
W20	0.5139	0.7143	0.3	0.8	0.49	0.4572	0.5628
W21	0.5390	0.3143	0.3	0.6	0.49	0.2208	0.3963
W22	0.6671	0.4286	1	0.8	0.49	0.2572	0.5637
W23	0.8691	0.8571	0.7	0.4	1	0.6097	0.7868
W24	0.2674	0.2857	0.3	0.4	0.3	0.3595	0.3090
W25	0.6936	0.4286	0.3	0.8	0.21	0.2207	0.4196

Table 13. Cont.

CBM Well	B ₁ /0.4449		B ₂ /0.1277	B ₃ /0.4274			Evaluation Result
	Coal Thickness	Gas Content	Coal Mass Structure	Tectonic Conditions	Roof/Floor Rocks	Burial Depth	
	C ₁₁ /0.1489	C ₁₂ /0.2960	C ₂₁ /0.1277	C ₃₁ /0.1016	C ₃₂ /0.1923	C ₃₃ /0.1335	
W26	0.6323	0.8000	0.7	0.6	1	0.5824	0.7513
W27	0.8189	0.0857	0.3	0.8	0.3	0.3849	0.3760
W28	0.0000	0.0571	0.7	0.4	0.49	1.0000	0.3747
W29	0.5836	0.9143	0.3	0.8	0.49	0.5148	0.6401
W30	0.4721	0.7714	0.3	0.2	0.7	0.5413	0.5641
W31	0.6058	0.9429	0.7	0.2	1	0.7365	0.7696
W32	0.6518	0.9714	0.7	0.4	1	0.7395	0.8056

Table 14. Comprehensive evaluation of No. 4-2 coal reservoir in an exploration well of Shoushan I Mine.

CBM Well	B ₁ /0.4538		B ₂ /0.1534	B ₃ /0.3928			Evaluation Result
	Coal Thickness	Gas Content	Coal Mass Structure	Tectonic Conditions	Roof/Floor Rocks	Burial Depth	
	C ₁₁ /0.1458	C ₁₂ /0.3080	C ₂₁ /0.1534	C ₃₁ /0.1130	C ₃₂ /0.1407	C ₃₃ /0.1391	
W1	0.2518	0.0152	0.3	0.4	0.3	0.2814	0.2140
W2	0.0635	0.0000	0.7	0.6	1	0.4475	0.3874
W3	0.0329	0.1414	0.7	0.4	0.21	0.3593	0.2805
W4	0.0000	0.7475	1	0.8	1	0.0000	0.6147
W5	0.2753	0.0909	1	0.8	1	0.3507	0.5014
W6	0.3271	0.0000	1	0.6	1	0.2130	0.4392
W7	0.3671	0.0051	0.7	0.6	1	0.1854	0.3968
W8	0.0094	0.0909	0.7	0.6	0.21	0.3243	0.2792
W9	0.0659	0.0404	0.7	0.8	0.7	0.1232	0.3355
W10	0.3200	0.1414	0.3	0.6	1	0.4926	0.4132
W11	0.3647	0.2172	1	0.8	0.49	0.4941	0.5015
W12	0.3059	0.0909	0.7	0.6	0.7	0.3796	0.3991
W13	0.3318	0.0404	0.7	0.6	0.49	0.1786	0.3298
W14	0.2682	0.0404	1	0.8	0.7	0.1586	0.4159
W15	0.3412	0.3434	0.7	0.4	1	0.7313	0.5505
W16	0.3859	0.1919	0.7	0.4	1	0.1716	0.4325
W17	0.3224	0.2424	1	0.6	1	0.4112	0.5408
W18	0.3224	0.0909	0.3	0.8	1	0.3221	0.3969
W19	0.2329	0.0111	1	0.6	0.7	0.1820	0.3824
W20	0.5859	0.0000	0.3	0.8	1	0.4709	0.4280
W21	0.6588	0.0303	0.7	0.4	1	0.2429	0.4325
W22	0.2776	0.0657	1	0.8	1	0.2937	0.4861
W23	0.3553	0.0000	1	0.6	1	0.6162	0.4994
W24	0.4118	0.0051	0.3	0.4	1	0.3546	0.3429
W25	0.5647	0.0000	1	0.2	0.3	0.2417	0.3342
W26	0.6094	0.0000	1	0.8	0.49	0.5843	0.4829
W27	0.6024	0.0101	0.3	0.6	0.7	0.3683	0.3545
W28	0.3624	0.0505	0.3	0.6	0.7	1.0000	0.4198
W29	1.0000	0.7475	0.3	0.6	0.7	0.5312	0.6622
W30	0.4094	0.8990	0.3	0.6	1	0.5555	0.6684
W31	0.3529	1.0000	0.7	0.8	1	0.7365	0.8004
W32	0.4871	0.4949	0.7	0.8	0.7	0.7383	0.6224

3. Case Study

3.1. Tectonic Setting

The Pingdingshan mine is located at the eastern extension of the latitudinal tectonic belt of the Qinling Mountains and at the top of the reflecting arc of the western flank of the Huayangshan zigzag tectonics, which are a composite of latitudinal tectonics and Huayangshan zigzag tectonics [25–27]. Shoushan I Mine is located in the eastern section of the northern flank of the Likou dyke in the Pingdingshan mine, and the main tectonics consist of a broad and gentle dorsal slope with an axial direction of 320° , i.e., the Baishishan dyke, whose north and south flanks are the north flanks and south flanks of the Likou and Lingwushan dykes, respectively (Figure 2) [27].

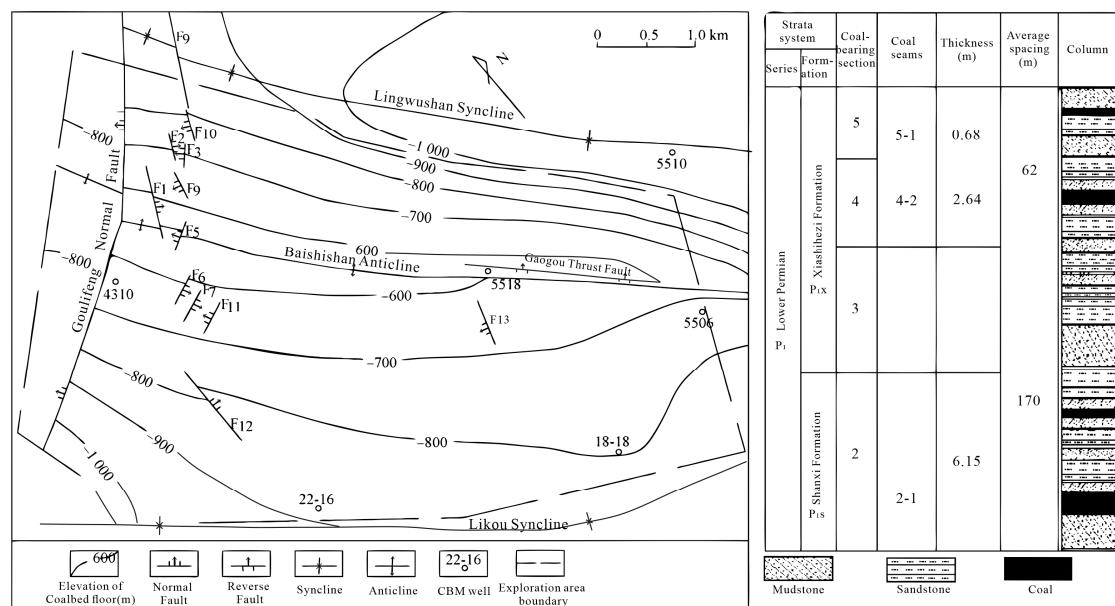


Figure 2. Tectonic position and coal seam composite histogram of Shoushan I Mine, Pingdingshan, China.

3.2. Coal-Bearing Formations and Coal Seams

The main strata developed in the region are Pre-Aurignian (Anz), Aurignian, Cambrian, Upper Carboniferous, Permian, Triassic, Cretaceous, Palaeoproterozoic, Neoproterozoic, and Quaternary. The coal-bearing strata in this area consist of the Taiyuan Formation of the Upper Carboniferous and Lower Permian, the Shanxi Formation of the Lower Permian, the Lower Xiashihezi Formation, and the Upper Xiashihezi Formation of the Upper Permian. The total thickness of the coal-bearing strata is 795 m. The total thickness of the coal beds is 22.85 m, and the coal content coefficient is 2.77% [27]. The recoverable coal seams in the whole area are the No. 2-1 coal seam of the Shanxi Group and the No. 4-2 coal seam of the Lower Stone Box Group, and the distribution of coal seams is stable. Most of the coal reservoirs in this area have experienced complex tectonic effects, and the coal seams have been abraded and compressed, resulting in the deformation of the coal body structure and serious tectonic damage. In particular, the coal body structure of the No. 4-2 seam features mainly crushed coal and is dominated by Permian strata, and that of the No. 2-1 coal seam is mainly dominated by cracked coal and crushed coal, with a local distribution of ergocene. In general, the coal body structure of the No. 4-2 seam is poorer than that of the No. 2-1 coal seam (Figure 1) [12].

In the whole Pingdingshan mining area, the No. 2-1 coal seam is located in the lower part of the Shanxi Formation, with a coal thickness ranging from 2.76 to 10.22 m, generally 5.00 to 7.00 m, and on average 6.15 m. The local branch features No. 2-1 and No. 2-2 coal, and the coal seam structure is relatively simple, with zero to two layers of interbedded gangue and a thickness ranging from 0.03 to 0.65 m—on average, 0.27 m. The lithology is

composed of charcoal mudrock and mudstone, indicating a stable or relatively stable coal seam. The average gas content of the air-dried basis in the No. 2-1 coal seam is $3.50 \text{ m}^3/\text{t}$. The No. 4-2 coal seam is located in the lower part of the No. 4 coal section of the Lower Stone Box Group, with a coal thickness of 0.90–5.15 m and an average of 2.64 m. The coal seam has a relatively simple structure, containing 0–3 layers of dirt band with a thickness of 0.08–0.79 m, and the lithology is mudstone and charcoal mudstone, which suggests that it is a more stable coal seam and the average gas content of the air-dried basis in the No. 4-2 coal seam is $5.64 \text{ m}^3/\text{t}$. [12].

3.3. Evaluation Index Analysis of CBM Potential in Study Area

To evaluate the CBM mining potential, it is necessary to construct a potential evaluation index system suitable for the study area. The determination of the factors affecting CBM production can be regarded as a multi-criteria decision-making problem, and the importance of each evaluation index in the final evaluation system varies, so it is necessary to first screen out the main controlling factors affecting the potential of CBM in the study area [28]. By comprehensively analyzing the geological conditions of coalbed methane formation, storage, and cap combinations, the weighted evaluation index system established by the previous research could be summarized. Finally, the three key factors affecting CBM enrichment and high production, namely, gas source conditions, reservoir physical properties, and preservation conditions, were comprehensively selected. Each key control factor was further subdivided into several major qualitative and quantitative sub-indicators affecting CBM survival and output.

3.3.1. Coal Thickness

The coal seam not only produces gas, but also stores gas. A coal seam with a large thickness is a prerequisite for a high yield of coalbed methane (CBM) storage, and the thicker the coal seam is, the larger the corresponding effective reservoir space is and the richer the gas reserves are [29]. Therefore, the thickness of coal beds is considered as a benefit-based indicator. In the study area, the main coal seams for CBM exploration and development are the No. 2-1 coal seam and the No. 4-2 coal seam. The contour maps of the coal thicknesses of No. 2-1 coal and No. 4-2 coal were plotted according to the data on CBM exploratory wells (Tables 7 and 8), as shown in Figure 3. From the statistical data of 32 wells, the thickness of the No. 2-1 coal seam is 0.84–8.02 m, and the average thickness of the coal seam is 5.4 m. A thick coal seam over 6 m is concentrated in the northwestern part, and the coal seam located near the southern well area is thin. The thickness of the coal seam is less than 1 m. The thickness of the No. 4-2 coal seam is 0.90–5.15 m, and the average thickness of the coal seam is 2.4 m. The coal seam over 3 m is concentrated in the southwestern part, and the coal seam located near the southwestern well area is thin. The coal seams near the well area in the northwest are thin, and the thickness of the coal seams is 0–1.6 m. The coal seams in the thick coal seam areas generally have good horizontal continuity, high resource abundance, and a stable coal structure [5]. Therefore, the thick coal seam area in the western part of the Shoushan I Mine study area is favorable for the development of coalbed methane in multi-branch horizontal wells.

3.3.2. Gas Content

Gas content is a key parameter in reflecting the abundance of coalbed methane. The critical desorption pressure rises as the gas content of the coal reservoir increases, and the larger the effective desorption area becomes, the shorter the gas breakthrough time becomes, thus increasing the gas production of a single well [30]. In the evaluation, gas content is considered to be a benefit-based indicator. The gas content of the No. 2-1 coal seam in the study area is $5\text{--}40 \text{ m}^3/\text{t}$ (Tables 7 and 8). The gas content contour maps of No. 2-1 coal and No. 4-2 coal were plotted based on the gas content data, as shown in Figure 4. The gas content of the No. 2-1 coal seam is relatively high ($>26 \text{ m}^3/\text{t}$) in the northern part (near wells W10, W15, and W23) and the southern part of the Shoushan I Mine (near wells

W32, W30, and W29), while in the central part of the block, the gas content is low ($<10 \text{ m}^3/\text{t}$). The gas content of the No. 4-2 seam ranges from 0.2 to $20 \text{ m}^3/\text{t}$. The gas content of the No. 4-2 seam in the southern part of the Shoushan I Mine (near the shafts W30 and W31) is relatively high ($>15 \text{ m}^3/\text{t}$), while in the northeastern and central parts of the block, the gas content is low ($<1 \text{ m}^3/\text{t}$).

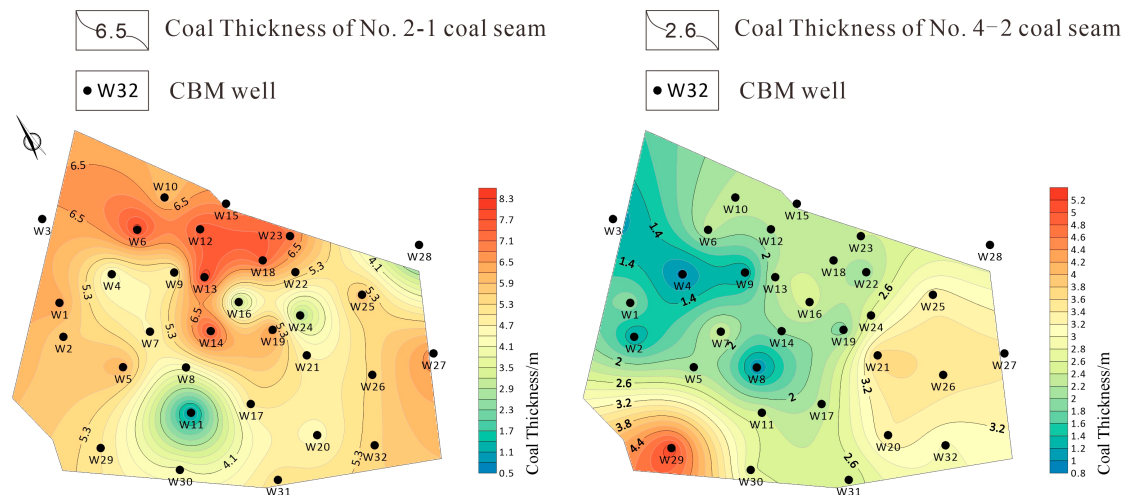


Figure 3. Contour map of coal thickness of No. 2-1 coal and No. 4-2 coal in Shoushan I Mine.

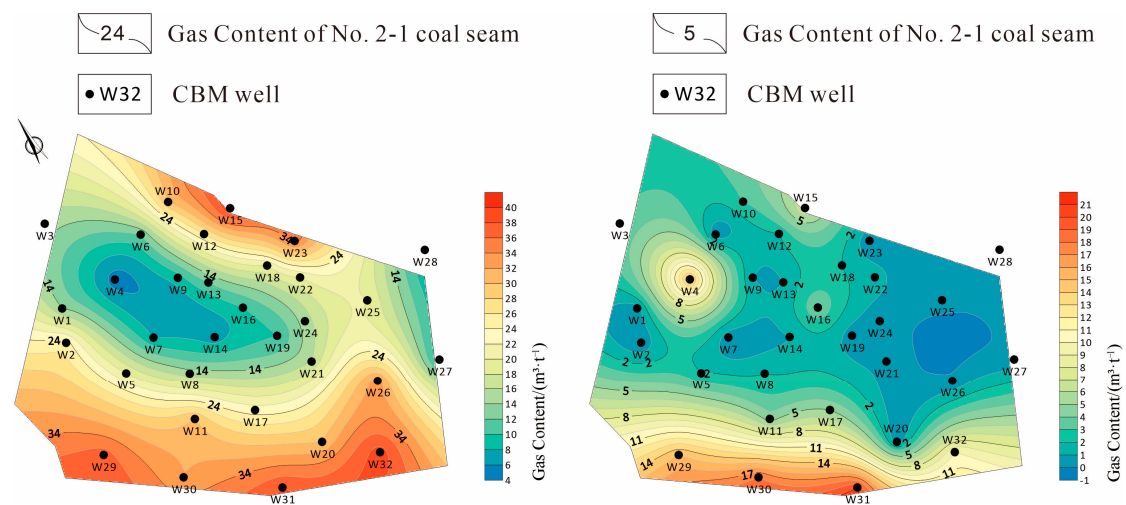


Figure 4. Contour map of gas content of No. 2-1 coal and No. 4-2 coal in Shoushan I Mine.

3.3.3. Burial Depth

From the perspective of commercial development value, there is a critical threshold for the increase in burial depth. The permeability of a coal seam decreases with increasing burial depth, which is not conducive to drainage and pressure reduction in CBM wells or to the seepage output of CBM, indirectly affecting the development cost of CBM. Therefore, weighing the recoverable reserves of CBM and the economic rationality of engineering technology, the maximum recoverable burial depth of CBM reservoirs is generally set at 2000 m as the lower limit of the resource calculation range [31]. In reservoir evaluation, it is considered that the burial depth of a coal bed is a cost-based indicator. According to the data table of CBM exploratory wells (Tables 7 and 8), the burial depth of No. 2-1 coal ranges from 645.75 m to 1305.35 m, with an average of 898.75 m, and that of No. 4-2 coal ranges from 445.11 m to 1130.09 m, with an average of 713.55 m. From the contour plots of the depths of burial of No. 2-1 and No. 4-2 coals (Figure 5), the burial depth of the

No. 2-1 coal seam generally decreases from northwest to southeast. Overall, the depths of both Seam 2-1 and Seam 4-2 increase from northwest to southeast and are shallower in the central northwest area, increasing from the center towards the edge of the mine.

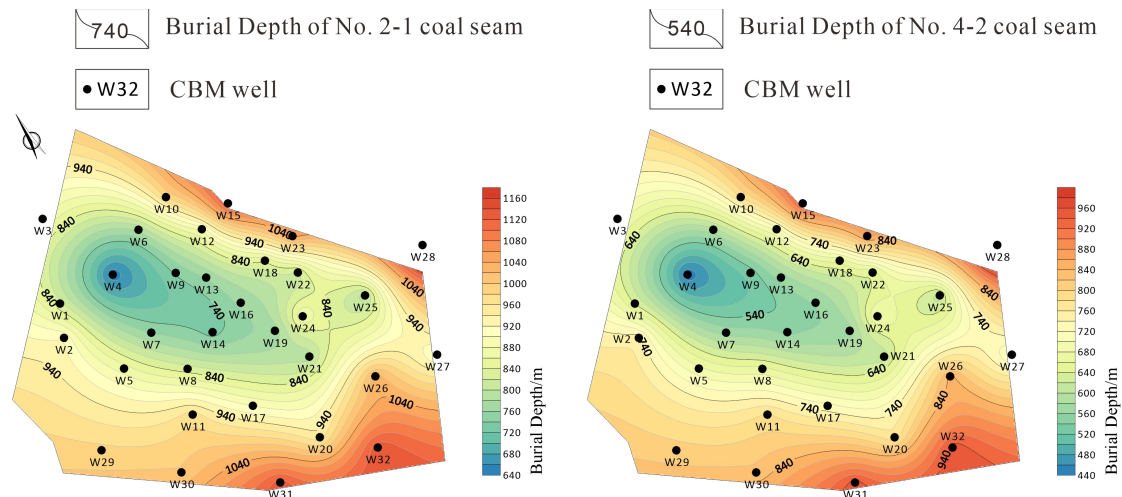


Figure 5. Contour map of burial depth of No. 2-1 coal and No. 4-2 coal in Shoushan I Mine.

3.3.4. Roof/Floor Rocks

The existence of a rock layer with certain confinement properties above the coal seam can block and slow down the escape of free gas through water solubility, percolation, and diffusion so that more free gas can be preserved. The closure performance of the cap seam is controlled by two factors: the lithology of the top slab and its thickness [32]. The lithology of the top and bottom slabs of the No. 2-1 coal seam and No. 4-2 coal seam includes six kinds of lithologies: sandy mudstone, fine-grained sandstone, mudstone, siltstone, charcoal mudstone, and medium-grained sandstone. The lithological assemblage characteristics of coal-bearing rock systems in various regions of China can be divided into five types as a whole: oil shale type, mudstone type, sandy mudstone interbedded type, limestone type, and sandstone type. Under the condition that the reservoir is not damaged by tectonic stress, the enclosing rock types of these five lithological combinations have a decreasing effect on closure according to the above ordering. The oil shale type is the best, followed by mudstone and sandstone–mudstone interbedded types, while the limestone and sandstone types are poor. On this basis, the cover conditions (Tables 7 and 8) in the study area were divided and quantified, and the contour maps of the cover conditions of No. 2-1 coal and No. 4-2 coal were drawn, as shown in Figure 6. The cover conditions are considered to be benefit-based indicators in the reservoir evaluation.

3.3.5. Tectonic Conditions

The influence of geological formations on CBM reservoirs is comprehensive and important, and it can be quantified in terms of geological formation burial history, folding, and fracturing in general terms [33].

Shoushan I Mine is located in Xiangcheng County, northeast of Pingdingshan City, and the folds and fractures in the minefield are relatively developed, with the main structure of the Baishishan anticline. Its northeast-oriented Lingwushan syncline and its southwest-oriented Likou syncline belong to the longitudinal folds, with the axial direction of about 320° and an inclination angle of the two flanks ranging from 10° to 20°. There are 14 major faults identified in the minefield which have NEE and NNE strike directions, including the Goulifeng normal fault, and the Gaogou thrust fault. The Goulifeng normal fault and Gaogou thrust fault have the largest extension lengths in the wellfield, and the Goulifeng normal fault is located on the west side of the wellfield, cutting into the Baishishan anticline and Lingwushan syncline with a drop of about 150 m. The extension length of the wellfield

is 5500 m. The Gaogou thrust fault is located in the eastern part of the wellfield near the Baishishan anticline, with a drop of about 40 m, and the extension length of the wellfield is 2070 m. The rest of the faults are located on the eastern side of the Goulifeng normal fault, with a drop of 3–10 m, and their extension lengths are less than 1000 m [34]. In addition to this, there are 352 small faults catalogued in the roadway of the No. 2-1 coal, most of which are positive faults with a drop of 0.5 m, and the strike directions are mostly in the NEE direction and the NWW direction. The geological structure outline of the No. 2-1 coal seam and No. 4-2 coal seam of Shoushan I Mine is shown in Figure 7.

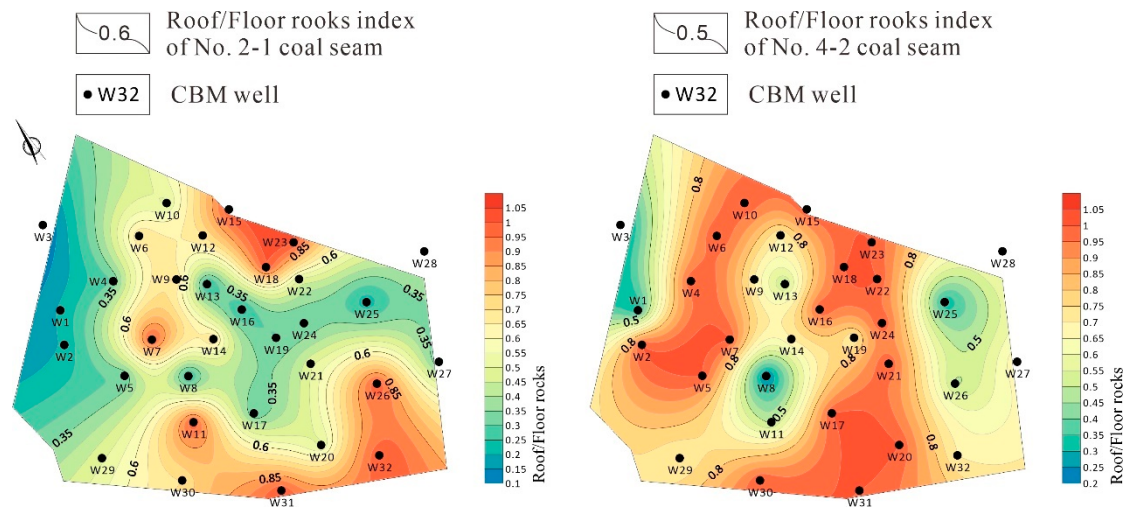


Figure 6. Contour map of roof/floor rocks index of No. 2-1 coal and No. 4-2 coal in Shoushan I Mine.

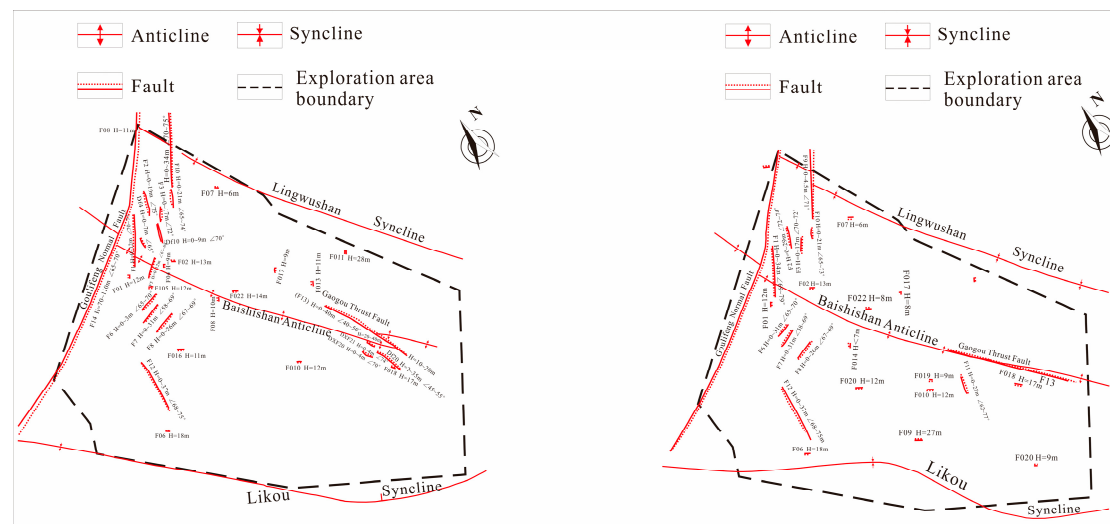


Figure 7. Schematic diagram of tectonic conditions of No. 2-1 coal and No. 4-2 coal in Shoushan I Mine.

3.3.6. Coal Body Structure Index

Based on the analysis of the coal core logging response, the geophysical identification criteria of the coal body structure in the study area were established, and the coal body structure was classified into Class I (primary structural coal), Class II (fractured coal), and Class III (fractured granular mineral coal) [35]. As the main mining seam in the study area (Tables 7 and 8), the coal body structure of the No. 2-1 coal seam is generally complete, and the coal samples are lumpy, with a small amount of them being granular and powdery. The coal body structure of the No. 4-2 coal seam is more fractured than that of the No. 2-1 coal

seam, and the coal body structure is fractured and has broken grains. The distribution of different types of coal structures is shown in Figure 8.

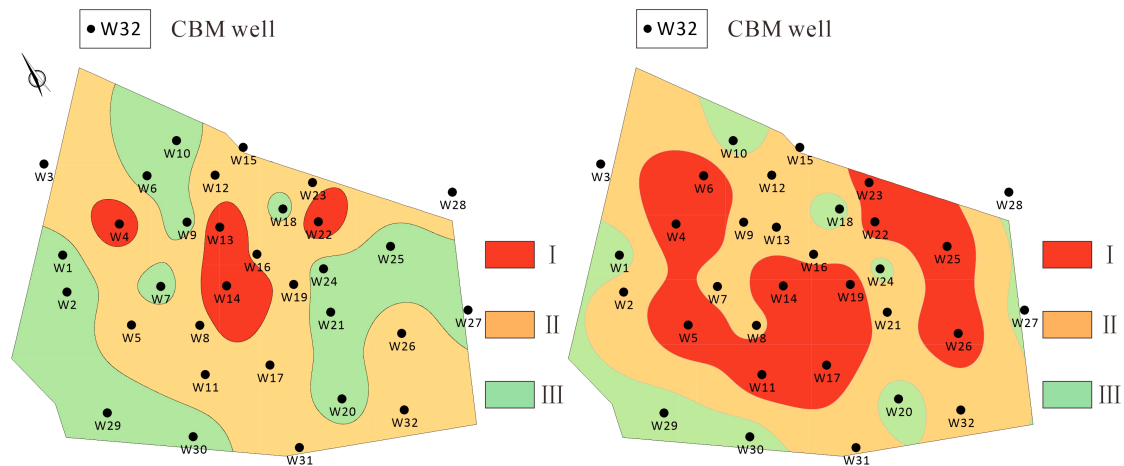


Figure 8. Contour map of coal body structure index of No. 2-1 coal and No. 4-2 coal in Shoushan I Mine.

3.4. Model Application

According to the evaluation index system and evaluation model established above, the specific data of 34 wells of coalbed methane evaluation parameters of No. 2-1 coal and No. 4-2 coal in Shoushan I Mine area were counted, and a quantitative prediction map of coalbed methane mining potential in Shoushan I Mine was drawn after a comprehensive calculation and analysis (Figure 9). The comprehensive evaluation results of coalbed methane predicted its enrichment and recoverable potential. According to the size of the evaluation value, it was divided into a desert area (type I, evaluation score [0.8, 1.0]), a sub-desert area (type II, evaluation score [0.6, 0.8]), a sub-unfavorable area (type III, evaluation score [0.4, 0.6]), and an unfavorable area (type IV, evaluation score [0, 0.4]).

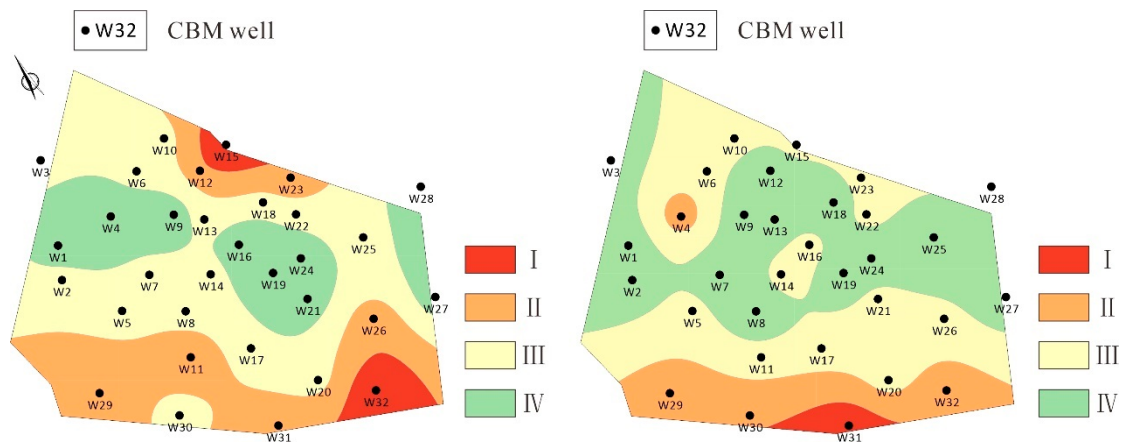


Figure 9. The distribution of comprehensive scores of CBM system in Shoushan I Mine blocks. Left is No. 2-1 coal seam, and right is No. 4-2 coal seam.

4. Results Analysis and Discussion

1. The coalbed methane formation conditions of No. 2-1 coal in the study area of Shoushan I Mine are simpler than those of No. 4-2 coal: from the data of 32 wells, the thickness of the No. 2-1 coal seam is 0.84–8.02 m, with an average thickness of 5.4 m; the gas content of the coal seam is 5–40 m³/t; and the depth of burial of the coal reservoir is 645.75 m–1305.35 m, with an average of 898.75 m. The coal body structure

is dominated by Class I primary structural coal and Class II fractured coal, and the top and bottom lithology are dominated by mudstone. At 898.75 m, the structure of the coal body is dominated by Class I primary structural coal and Class II fractured coal, the lithology of the top and bottom plates is dominated by mudstone, and the overall gas content is good; the thickness of the No. 4-2 coal seam is 0.90~5.15 m, the average thickness of the seam is 2.4 m, the gas content of the seam is $0.2\sim 20\text{ m}^3/\text{t}$, and the depth of burial of the seam is 445.11 m~1130.09 m, with an average of 713.55 m. The structure of the coal body is dominated by Class II primary structural coal and Class III crushed grain–mineral coal, the lithology of the top and bottom plates is also dominated by mudstone, and the overall gas content is lower than that of No. 2-1 coal.

2. Using the subjective and objective combination weight method of the triangular fuzzy analytic hierarchy process and entropy weight method, the weight distribution proportion of each index can be carried out, and the weight value of the evaluation index can be determined by synthesizing the subjective experience of the experts and the objective deviation law of the data. The importance of evaluation indexes of No. 2-1 coal is ranked from high to low regarding gas content, roof–floor lithology, coal thickness, burial depth, coal body structure index, and tectonic conditions, and the weight values are 0.2960, 0.1923, 0.1489, 0.1335, 0.1277, and 0.1016, respectively. The order of importance of the evaluation indexes of No. 4-2 coal from high to low is as follows: gas content, coal body structure index, coal thickness, roof–floor lithology, burial depth, and tectonic conditions, and the weight values are 0.3080, 0.1534, 0.1458, 0.1407, 0.1391, and 0.1130.
3. Based on the systematic theory of triangular fuzzy hierarchical analysis and the entropy weighting method, a multi-level and multi-indicator preferential model for selective CBM blocks applicable to the Shoushan I Mine in Pingdingshan was established, and the mining potentials of the main coal seams in the study area, i.e., the No. 2-1 coal seam and the No. 4-2 coal seam, were evaluated and classified into the sweet spot area (Type I), the sub-sweet spot area (Type II), the sub-unfavorable area (Type III), and the unfavorable area (Type IV), respectively. The Type I sweet spot zone of the No. 2-1 coal seam is mainly located near well W15 in the north and well W29 in the southeast of the block, and the Type I sweet spot zone of No. 4-2 coal seam is mainly located near well W31 in the south of the block.

5. Conclusions

1. The No. 2-1 coal seam has more advantages in coalbed methane mining potential than the No. 4-2 coal seam. The thickness of the No. 2-1 coal seam ranges from 0.84 to 8.02 m, the average thickness of the seam is 5.4 m, and the depth of the seam ranges from 645.75 m to 1305.35 m. The average depth of the seam is 898.75 m, and the gas content is $5\sim 40\text{ m}^3/\text{t}$.
2. In this paper, FEAHP and the entropy weight method were used to quantify the weight of each parameter, and fuzzy mathematical analysis was supplemented to unify the qualitative data and quantitative data. On this basis, the evaluation model of coalbed methane exploitation potential in the geological background of the Shoushan I coal mine was established. Four types of CBM enrichment blocks were delineated, namely, the sweet zone (type I), the sub-sweet zone (type II), the sub-unfavorable zone (type III), and the unfavorable zone (type IV). The Class I blocks of coal seams 2-1 and 4-2 were located near well W15 in the north, well W29 in the southeast, and well W31 in the south of the study area, respectively.
3. Taking the Shoushan I mine as an example, the optimal model of the sweet spot area on the plane was established. The evaluation results were in good agreement with the actual development situation. The evaluation results of this study have important theoretical significance for the exploration and development of the Shoushan I mine and the locations of coalbed methane wells.

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