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Evaluation of Favorable Area for Coalbed Methane Development Based on Local Variable Weight Theory

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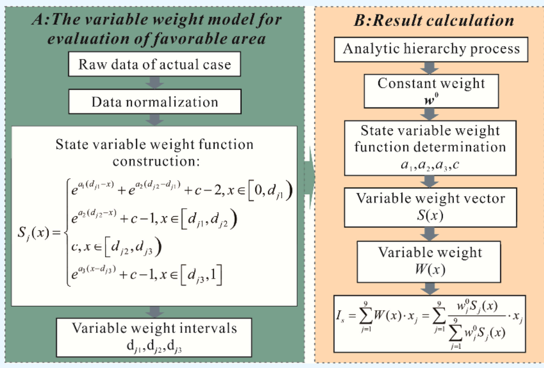
ABSTRACT: The evaluation of a favorable area is crucial for the exploration and exploitation of coalbed methane (CBM) resources. In traditional evaluation methods, the weight of controlling factors for the evaluation of favorable area is often obtained from different models and calculation methods, and the constant weight is commonly used in the entire target area. The influence of the index value of controlling factors and the combination state of these values on the weight is consistently overlooked during the evaluation process. In view of this phenomenon, a new evaluation method based on variable weight theory was introduced to enhance the accuracy of the result from evaluation (i.e., favorable area for CBM development) in this paper. Based on the raw data of controlling factors, the evaluation area was divided into a finite number of regular grids; each grid could be seen as an evaluation unit, and different attribute values were assigned to them. The constant weights are determined by the analytic hierarchy process (AHP), while the variable weight of controlling factors in each unit was calculated by a partitioned variable weight model (VWM) which constructed based on variable weight theory. Finally, the VWM for the evaluation of favorable area was constructed and applied in the Weibei CBM field. The influence of variability in index values on the weight was taken into consideration in this model, which can complement the disadvantage of the constant weight model (CWM). The accuracy of the result from the evaluation of favorable areas for CBM development could be improved by using this VWM, which provides a reasonable idea and method for the selection of target areas in CBM fields.



1. INTRODUCTION

Coalbed methane (CBM) is an efficient, clean, and high-quality unconventional natural gas source.[1,2] The development of CBM could not only improve the security of coal mine production but also optimize the structure of energy consumption and is more conducive to the reduction of carbon emission which could promote the achievement of carbon peaking and carbon neutrality.[3,4] The CBM resource within a burial depth of less than 2000 m in China accounts for 30.05×10^{12} m^3, while 18.47×10^{12} m^3 in the depth of 2000−3000 m.[5−8] After the exploration and development of CBM in recent decades, two industrial bases of CBM were gradually formed in China (i.e., the southern part of Qingshui Basin and the eastern margin of Ordos Basin).[9−13] By the end of 2023, more than 20,000 CBM wells had been completed in China, and CBM production reached 117.7×10^8 m^3 per year. The rapid development of the CBM industry requires the support of advanced theory and technology.[14,15]

The selection of target area, which involves numerous influence factors and complex controlling mechanisms, is crucial for CBM exploration and development.[16,17] Many research studies on the system and methods for evaluation of favorable area have been completed continuously. The evaluation methods, commonly used in the evaluation process, mainly encompass the analytic hierarchy process (AHP),[18] expert scoring, main factor one-vote veto, principal component analysis (PCA),[19] gray relational analysis,[20] fuzzy mathematics,[21,22] and hierarchical optimization of key elements,[23] among others. These methods could provide a degree of guidance for the evaluation of a favorable area for CBM development. However, the weight of each controlling factor remains constant in these methods (i.e., regardless of changes in the index value of controlling factors), which brings some inaccuracy to the evaluation result. The constant weight reflects the overall superiority of controlling factors in the evaluation of the favorable area and represents the relative importance of each single factor to the output of the evaluation, which has a degree of scientific validity and applicability. Nevertheless, the

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comprehensive evaluation result of the favorable area is linked not only to the fundamental importance of each controlling factor but also to its corresponding index value. The influence of variability in index values on the evaluation result was neglected in the constant weight model (CWM), which brings some limitations to the utilization of these constant weight methods for the selection of favorable area. Meanwhile, the change in the relative importance of controlling factors, which was caused by the differentiation of the index value, was also neglected.

In view of these shortcomings, a series of models based on variable weight theory were proposed in several research works.[24−28] The relative importance of controlling factors and the influence of the variability in index value on the result of evaluation were taken into consideration in the variable weight model (VWM). The constant weight of controlling factors was compensated throughout the evaluation process, which could significantly improve the accuracy of the evaluation result (i.e., favorable area for CBM development). The result of evaluation by using VWM had shown to be more relevant to the actual situation. These research works mainly focus on the aspect of quality evaluation of geological engineering,[29,30] risk assessment,[31−35] comprehensive evaluation,[36] among others. However, to the best of the authors' knowledge, the variable weight theory has never been utilized in the evaluation of favorable area for fossil fuel resources.

In this paper, a comprehensive evaluation model based on variable weight theory was proposed and applied to evaluate the favorable area for CBM development in the Weibei CBM field. The adaptability of this model in the evaluation of energy sources has also been discussed.

2. GEOLOGY SETTING

The Weibei CBM field is located in the southeast margin of the Ordos Basin (Figure 1), which has shown great potential for CBM exploitation with a total gas-bearing area of up to 1530 km^2.[37,38]

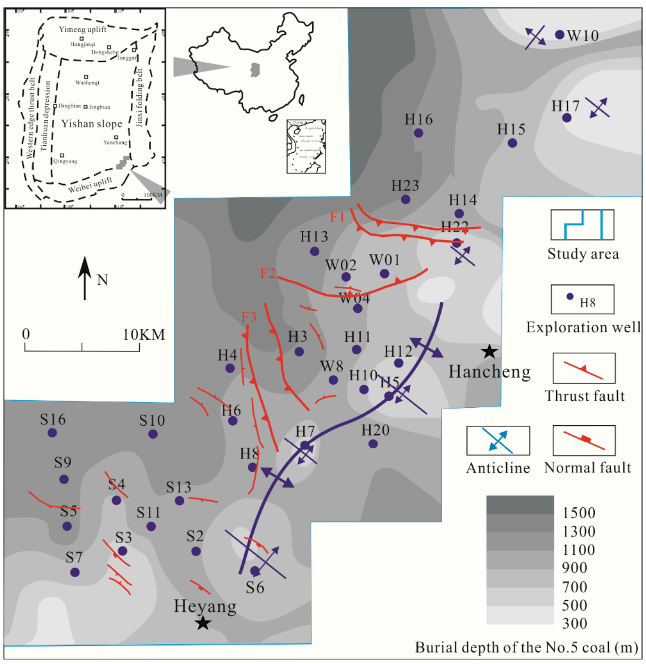

Figure 1. Location and burial depth of the No. 5 coal seam in the Weibei CBM field.

Tectonically, the Weibei CBM field is a monoclinic tectonic structure, which gently tilted to the northwest as a whole (i.e., from the basin margin to the center). Three overthrust faults of F1, F2, and F3 (Figure 1) developed in the center part, which runs across the study area in W-E to NW-SE direction, and divided the Weibei CBM field into several structural domains.[39]

The strata preserved in this area are rocks of the Archaeozoic, Proterozoic, Cambrian, Ordovician, Carboniferous, Permian Paleozoic, Triassic Mesozoic, and Quaternary Cenozoic from the oldest to the newest (Figure 2). The main coal-bearing strata are the Taiyuan Formation of Carboniferous and Shanxi Formation of Permian with multicoal seams (No. 1 to No. 11) developed in this area. The Nos. 5 and 11 coal seams deposited at the top and bottom of the Taiyuan Formation, which are thick and stably distributed in this area, are the main target seams for CBM commercial exploitation.

3. PRELIMINARIES

3.1. Variable Weight Theory. The idea of variable weight was first introduced by Wang.[40] Li makes an in-depth analysis of the variable weight principle.[41,42] In his research, the axiomatic definition of variable weight and state variable weight vector was defined. Then, three types of variable-weight axiomatic definitions for different applications were given. Meanwhile, an important conclusion (i.e., the variable weight vector is the product of the constant weight vector and the state variable weight vector) was also summarized. Based on the previous research works, Yao proposed the idea that different variable weight strategies should be given according to the index value, i.e., local variable weight theory.[43] After that, additional research studies were performed to make it more systematic.[44,45] The following definitions must be satisfied in the established VWM:

Definition 1: Let $W_0 = (w_1^{(0)}, w_2^{(0)},..., w_m^{(0)})$ be constant weight vector, $\forall i \in \{1,2,..., m\}$, $w_i^{(0)} \in (0,1]^m$ and satisfy: $\sum_{i=1}^{m} w_i^{(0)} = 1$.

Definition 2: Let W: $[0,1]^m \rightarrow (0,1]^m$, $W_i(X) = (W_1(X), W_2(X),..., W_m(X))$ be a set of m-dimensional variable weight vector and meet the following conditions:

1: $\sum_{i=1}^{m} W_i(X_1, \ldots, X_m) = 1$.

2: For each $i \in \{1,2,..., m\}$, α_i, $\beta_i \in [0,1]$ and $\alpha_i \leq \beta_i$. $W_i(X_1,..., X_m)$ monotonically decreasing and increasing with X_i in range of $[0, \alpha_i]$ and $[\beta_i,1]$, respectively.

Definition 3: Let S: $[0,1]^m \rightarrow (0, +\infty)^m$, $S(X) = (S_1(X), S_2(X),..., S_m(X))$ be a set of m-dimensional state variable weight vector. For each $i \in \{1,2, ..., m\}$, α_i, $\beta_i \in [0,1]$ and $\alpha_i \leq \beta_i$, $S(X)$ should also meet the following conditions:

1: For each $i \in \{1,2,..., m\}$, $W_0 = (w_1^{(0)}, w_2^{(0)},..., w_m^{(0)})$, $W_i(X) = \frac{W_i^0 \cdot S_i(X)}{\sum_{k=1}^{m} W_k^{(0)} S_k(X)}$ for X_i, it monotonically decreasing at $[0, \alpha_i]$ and monotonically increasing at $[\beta_i,1]$.

2: When $0 \leq X_j \leq X_k \leq \alpha_j \wedge \alpha_k$, $S_j(X) \geq S_k(X)$; When $\beta_j \vee \beta_k \leq X_j \leq X_k \leq 1$, $S_j(X) \leq S_k(X)$.

3: Let $S(X)$ be a set of m-dimensional state variable weight vector and $W_0 = (w_1^{(0)}, w_2^{(0)}, ..., w_m^{(0)})$ be a constant weight vector, then a set of m-dimensional state variable weight vector can be expressed by

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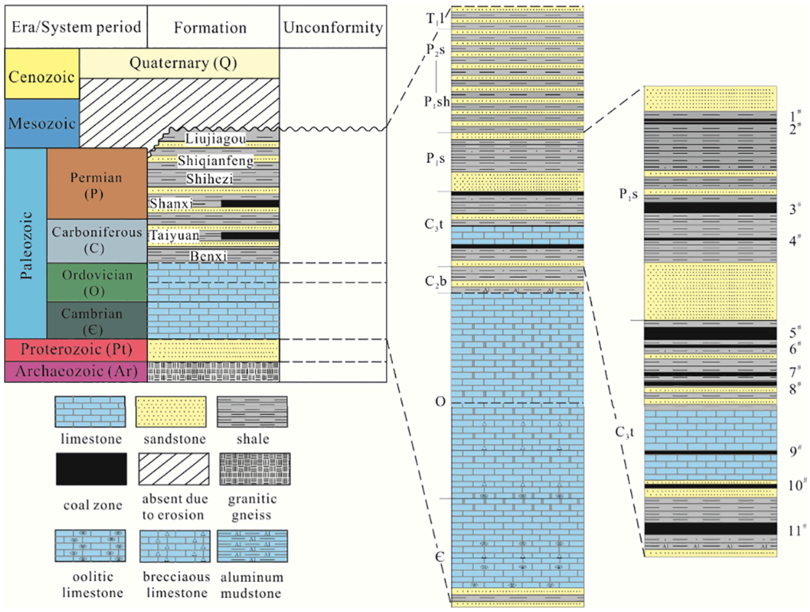

Figure 2. Histogram of stratigraphic lithology in the Weibei CBM field.

$$W(X) = \frac{W_i^{(0)} \cdot S_i(X)}{\sum_{i=1}^{m} W_i^{(0)} S_i(X)} = \left(\frac{W_1^{(0)} S_1(X)}{\sum_{i=1}^{m} W_i^{(0)} S_i(X)}, \frac{W_2^{(0)} S_2(X)}{\sum_{i=1}^{m} W_i^{(0)} S_i(X)}, \ldots, \frac{W_m^{(0)} S_m(X)}{\sum_{i=1}^{m} W_i^{(0)} S_i(X)} \right)$$

3.2. Construction of the State Variable Weight Function.

3.2.1. Characteristics of VWM for Evaluation of Favorable Area. The extreme value (too large or too small) of the controlling factors will neutralize the influence of other factors during the evaluation of a favorable area. As a result, the evaluation result would be inconsistent with the actual situation, i.e., lose objectivity. Therefore, the impact of variability in index value on the result of evaluation should be able to be accurately reflected in the VWM. The original weight of controlling factors could also be adjusted by VWM, which may increase or decrease the level of the evaluation result for each evaluation unit.

For the evaluation of a favorable area for CBM development, the VWM should meet the following requirements: In each evaluation unit, even if there is only one factor that has a small weight with an extreme index value, the final level of the evaluation result would significantly change to avoid a neutralizing effect. In an actual evaluation system of favorable area, the degree of favorability would not significantly increase while a single factor has an extremely large index value but will significantly decrease as the occurrence of an extremely small value. Therefore, the magnitude of the penalty should be stronger than that of the incentive in the VWM.

3.2.2. State Variable Weight Function. The state variable weight function was constructed based on the analysis above. Four intervals (i.e., "strong penalty interval", "penalty interval", "no incentive and no penalty interval", and "incentive interval") were included in the constructed function. The corresponding mathematical function and curve are shown in eqn 1 and Figure 3, respectively.

$$S_j(x) = \begin{cases} e^{a_1(d_{j1}-x)} + e^{a_2(d_{j2}-d_{j1})} + c - 2, & x \in [0, d_{j1}) \\ e^{a_2(d_{j2}-x)} + c - 1, & x \in [d_{j1}, d_{j2}) \\ c, & x \in [d_{j2}, d_{j3}) \\ e^{a_3(x-d_{j3})} + c - 1, & x \in [d_{j3}, 1] \end{cases} \tag{1}$$

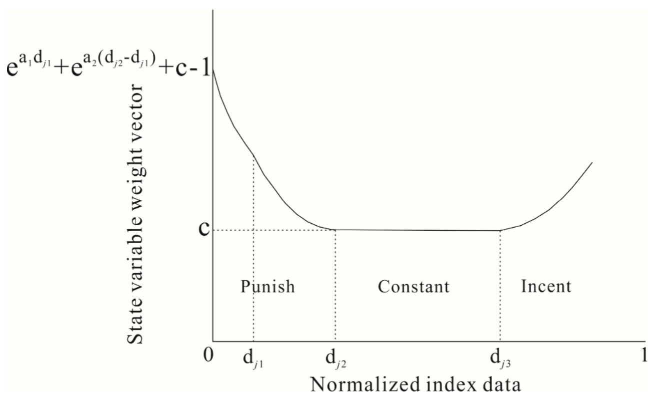

Figure 3. Schematic diagram of the state variable weight function.

where $S_j(x)$ is the state variable weight vector; d_{j1}, d_{j2}, and d_{j3} are thresholds of variable weight interval; c, a_1, a_2, and a_3 are adjustment parameters, which represent the adjustment degree of the weight.

4. EVALUATION METHOD OF FAVORABLE AREA BASED ON VWM

4.1. Determination of Main Controlling Factors. During the evaluation of favorable area for CBM development, the selection of main controlling factors must follow the principle of 'selecting the main geological parameters, and each parameter is independent of others'.[37] Geological parameters utilized in the evaluation of favorable areas for CBM development include direct parameters (e.g., gas content, permeability, burial depth,

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reservoir pressure, critical desorption pressure, etc.) and indirect parameters (e.g., hydrogeological condition, crustal stress, and tectonic characteristics, etc.), which indirectly affect the evaluation result by influencing the direct parameters.

Based on the production conditions and the degree of geological exploration in the study area, combined with the results of our previous research,[37] the following nine factors were selected as the main controlling factors (Table 1).

Table 1. Raw Data of Selected Main Controlling Factors

controlling factor	min	max	average
intensity of tectonic movement	0.74	1.25	1.01
gas content (m^3/t)	0.33	24.42	11.02
thickness of muddy cover (m)	1.4	10.8	5.44
gas saturation	3%	100%	56.7%
groundwater mineralization (mg/L)	814	4335	2285
mineral content in coal	0.3%	24.55%	6.6%
permeability (mD)	0.005	0.904	0.25
burial depth (m)	531.6	1347.1	886.7
P_d/P_r	0.02	1.68	0.485

The intensity of tectonic movement was introduced to reflect the effect of tectonic action on CBM enrichment. P_d/P_r is the ratio of the critical desorption pressure to reservoir pressure.

4.1.1. Raw Data Processing. Consider the spatial distribution characteristics of the main controlling factors and requirements of accuracy for evaluation. The study area was divided into about 10,930 grids with grid cell of 400 m × 400 m by using square regular grid generation (Figure 4).

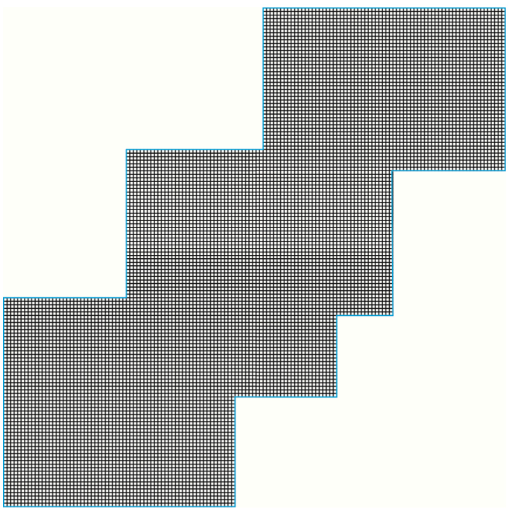

Figure 4. Grid generation map of the study area.

The quantification of the main controlling factors was accomplished by the interpolation calculation of raw data. The quantitative contours are shown in Figure 5.

4.1.2. Data Normalization. The normalization of data, which makes the data comparable, statistically significant, and easy to systematically analyze, could eliminate the influence of main controlling factors' data with different scales on the evaluation result. The formula for normalization is as follows:

$$A_i = a + \frac{(b - a)\cdot(x_i - \min(x_i))}{\max(x_i) - \min(x_i)} \tag{2}$$

where A_i is the normalization result; a and b are the minimum and maximum values for the normalization range, in this evaluation, take 0 and 1; $\min(x_i)$ and $\max(x_i)$ are the minimum and maximum values of each main controlling factor.

The normalization process is different for each of the main controlling factor. Minimum value normalization (i.e., the minimum value is 1, and the maximum value is 0) was adopted for the normalization of factors that negatively correlated with the evaluation of favorable area for CBM development (e.g., intensity of tectonic movement and mineral content in coal), and maximum value normalization (i.e., the maximum value is 1 and the minimum value is 0) was utilized for the normalization of factors that positively correlated with the evaluation result.

4.2. Determination of VWM. Currently, there is no unified method for the determination of variable weight interval thresholds and adjustment parameters. According to research of predecessors, a method for determining that is presented by Wu.[46] In this research, a similar research strategy was used in the construction of VWM.

First, cluster analysis based on the K-means algorithm was used to classify the quantitative data of each main controlling factor. Then, the threshold value of the variable weight interval (d_{j1}, d_{j2}, and d_{j3}) was determined based on the obtained classification threshold of each factor. The variable weight intervals of each main controlling factor are shown in Table 2. After that, for the determination of adjustment parameters (c, a_1, a_2, and a_3), the formula of these parameters can be derived based on the determined interval threshold and assumed ideal variable weight of controlling factors in an evaluation unit. For this selected unit, it should satisfy that the index values of four factors are in four different intervals while one other factor is in penalty or incentive interval, and the rest factors in nonpenalty and nonincentive interval. The ideal variable weights were established using the AHP in this paper. The formulas of the adjustment parameters are derived as follows.

Suppose that there are n factors in the evaluation system, five factors were used to establish the formula of adjustment parameters. For an evaluation unit, first, set the factor with index value that x_1 is located in the strong penalty interval, x_2 is located in the penalty interval, x_3 is located in the nonpenalty and nonincentive interval, x_4 is located in the incentive interval, and x_5 is located in the penalty interval. To facilitate the calculation process, other factors are selected to be located in the nonpenalty and nonincentive interval. The interval thresholds for the n factors are set as d_{11}, d_{12}, and d_{13}; d_{21}, d_{22}, and d_{23}; and ···, d_{n3}, respectively. Based on the state variable weight function constructed above, a series of formulas for parameters (c, a_1, a_2, and a_3) can be derived:

$$w_1 = \frac{w_1^0[e^{a_1(d_{11}-x_1)} + e^{a_2(d_{12}-d_{11})} + c - 2]}{\sum_{j=1}^{n} w_j^0 S_j(x)} \tag{3}$$

$$w_2 = \frac{w_2^0[e^{a_2(d_{22}-x_2)} + c - 1]}{\sum_{j=1}^{n} w_j^0 S_j(x)} \tag{4}$$

$$w_3 = \frac{w_3^0 c}{\sum_{j=1}^{n} w_j^0 S_j(x)} \tag{5}$$

$$w_4 = \frac{w_4^0[e^{a_3(x_4-d_{43})} + c - 1]}{\sum_{j=1}^{n} w_j^0 S_j(x)} \tag{6}$$

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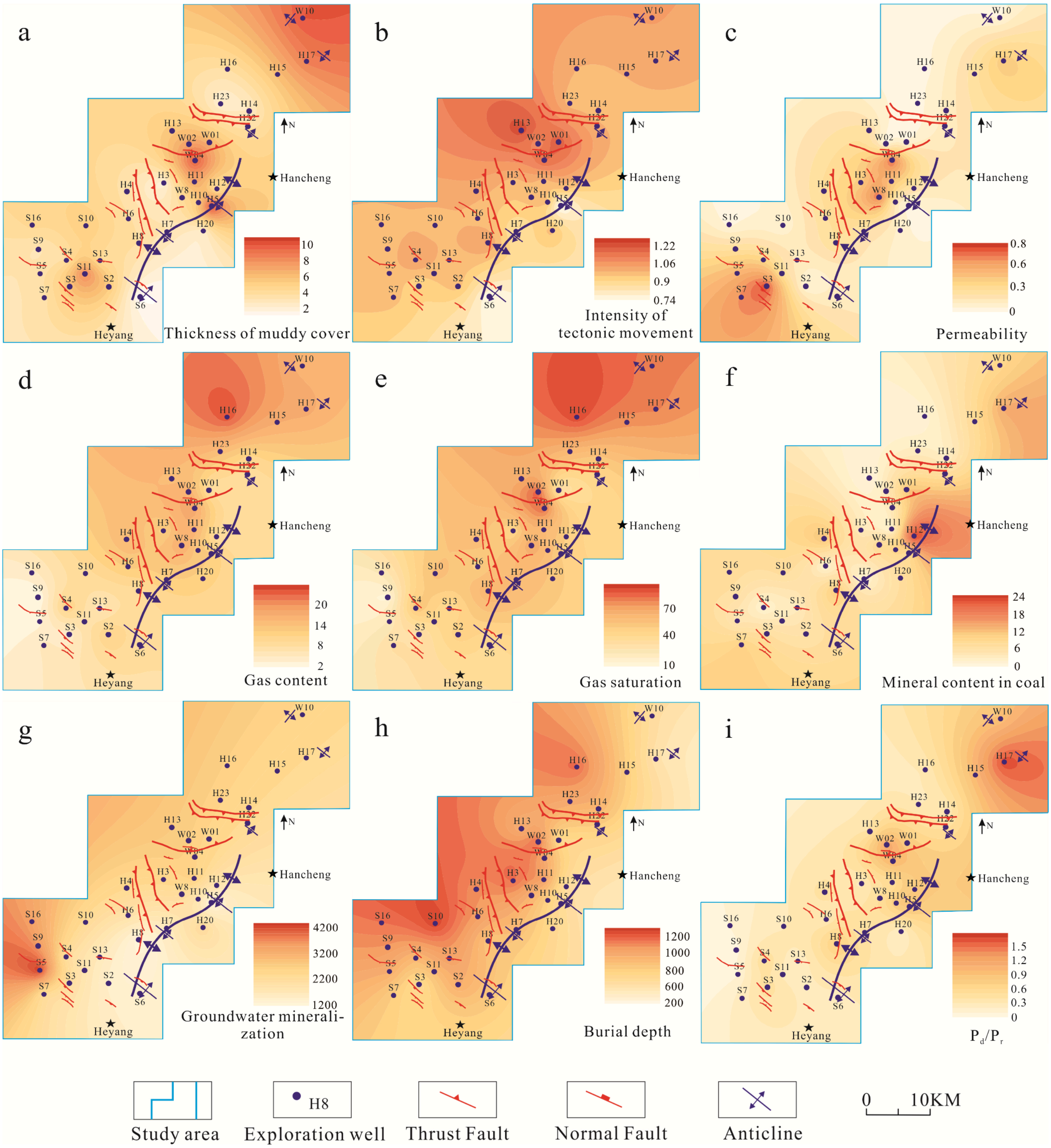

Figure 5. Thematic maps of the main controlling factors: (a) thickness of muddy cover, (b) intensity of tectonic movement, (c) permeability, (d) gas content, (e) gas saturation, (f) mineral content in coal, (g) groundwater mineralization, (h) burial depth, and (i) ratio of the critical desorption pressure and reservoir pressure.

Then, the ratio of w_1 to w_3 can be expressed as

$$\frac{w_1}{w_2} = \frac{w_1^0[e^{a_1(d_{11}-x_1)} + e^{a_2(d_{12}-d_{11})} + c - 2]}{w_1^0 c} \tag{7}$$

which in turn leads to an expression for the parameter a_1:

$$a_1\frac{1}{d_{11} - x_1}\ln = \frac{w_3^0 w_1 - w_3 w_1^0}{w_3 w_1^0}c + 2 - \left(\frac{w_3^0 w_2 - w_3 w_2^0}{w_3 w_2^0}c + 1\right)^{d_{12}-d_{11}/d_{22}-x_2} \tag{8}$$

The ratio of w_2 to w_3 can be expressed as

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Table 2. Variable Weight Interval of Each Main Controlling Factor

	variable weight interval			
controlling factor	strong penalty	penalty	nonpenalty and nonincentive	incentive
gas content	$0 < x < 0.262$	$0.262 < x < 0.565$	$0.565 < x < 0.868$	$0.868 < x < 1$
intensity of tectonic movement	$0 < x < 0.176$	$0.176 < x < 0.438$	$0.438 < x < 0.804$	$0.804 < x < 1$
permeability	$0 < x < 0.189$	$0.189 < x < 0.478$	$0.478 < x < 0.910$	$0.910 < x < 1$
burial depth	$0 < x < 0.236$	$0.236 < x < 0.530$	$0.530 < x < 0.822$	$0.822 < x < 1$
gas saturation	$0 < x < 0.174$	$0.174 < x < 0.495$	$0.495 < x < 0.804$	$0.804 < x < 1$
thickness of muddy cover	$0 < x < 0.234$	$0.234 < x < 0.479$	$0.479 < x < 0.846$	$0.846 < x < 1$
mineral content in coal	$0 < x < 0.211$	$0.211 < x < 0.607$	$0.607 < x < 0.796$	$0.796 < x < 1$
groundwater mineralization	$0 < x < 0.315$	$0.315 < x < 0.663$	$0.663 < x < 0.897$	$0.897 < x < 1$
P_d/P_r	$0 < x < 0.125$	$0.125 < x < 0.372$	$0.372 < x < 0.857$	$0.857 < x < 1$

$$\frac{w_2}{w_3} = \frac{w_2^0[e^{a_2(d_{22}-x_2)} + c - 1]}{w_3^0 c} \tag{9}$$

which in turn leads to an expression for the parameter a_2:

$$a_2 = \frac{1}{(d_{22} - x_2)}\ln\left[\frac{w_3^0 w_2 - w_3 w_2^0}{w_3 w_2^0}c + 1\right] \tag{10}$$

The ratio of w_4 to w_3 can be expressed as

$$\frac{w_4}{w_3} = \frac{w_4^0[e^{a_3(x_4-d_{43})} + c - 1]}{w_3^0 c} \tag{11}$$

which in turn leads to an expression for a_3:

$$a_3 = \frac{1}{(x_4 - d_{43})}\ln\left[\frac{w_3^0 w_4 - w_3 w_4^0}{w_3 w_4^0}c + 1\right] \tag{12}$$

The following formula can be derived based on the index values of the factors and their constant weights:

$$\begin{aligned}\sum_{j=1}^{n} w_j^0 S_j(x) &= w_1^0[e^{a_1(d_{11}-x_1)} + e^{a_2(d_{12}-d_{11})} + c - 2] \\ &\quad + w_2^0[e^{a_2(d_{22}-x_2)} + c - 1] + w_3^0 c \\ &\quad + w_4^0[e^{a_3(x_4-d_{43})} + c - 1] + w_5^0[e^{a_2(d_{52}-x_5)} + c - 1] + w_6^0 c \\ &\quad + w_7^0 c + w_8^0 c + \ldots + w_n^0 c\end{aligned} \tag{13}$$

Then bring eqns 8, 10, and 12 were then brought into eqn 13, which could obtain

$$\begin{aligned}\sum_{j=1}^{n} w_j^0 S_j(x) &= \frac{w_1}{w_3}w_3^0 c + \frac{w_2}{w_3}w_3^0 c + w_3^0 c + \frac{w_4}{w_3}w_3^0 c \\ &\quad + w_5^0[e^{a_2(d_{52}-x_5)} + c - 1] \\ &\quad + w_6^0 c + w_7^0 c + w_8^0 c + \ldots + w_n^0 c \\ &= \frac{w_3^0}{w_3}(w_1 + w_2 + w_3 + w_4)c \\ &\quad + (w_6^0 + w_7^0 + w_8^0 + \ldots + w_n^0)c \\ &\quad + w_5^0\left[\left(\frac{w_3^0 w_2 - w_3 w_2^0}{w_3 w_2^0}c + 1\right)^{d_{52}-x_5/d_{22}-x_2} + c - 1\right]\end{aligned} \tag{14}$$

Bringing eqn 14 into eqn 5 yields

$$w_3 = \frac{w_3^0 c}{\frac{w_3^0}{w_3}(w_1 + w_2 + w_3 + w_4)c + (w_6^0 + w_7^0 + w_8^0 + \ldots + w_n^0)c + w_5^0\left[\left(\frac{w_3^0 w_2 - w_3 w_2^0}{w_3 w_2^0}c + 1\right)^{d_{52}-x_5/d_{22}-x_2} + c - 1\right]} \tag{15}$$

Eqn 15 could also be expressed as follows:

$$k_1 c = (k_2 c + 1)^{k_3} - 1 \tag{16}$$

where $k_1 = \frac{w_3^0 - w_3^0(w_1 + w_2 + w_3 + w_4) - w_3(w_5^0 + w_6^0 + w_7^0 + w_8^0 + \ldots + w_n^0)}{w_3 w_5^0}$; $k_2 = \frac{w_3^0 w_2 - w_3 w_2^0}{w_3 w_2^0}$; and $k_3 = \frac{d_{52} - x_5}{d_{22} - x_2}$.

4.2.1. Calculation of Constant Weights. According to the analyses above, the constant weight of the main controlling factors needs to be determined first. The analytical hierarchy process was adopted to determine the constant weight in this paper. First, a hierarchical analysis structure model was established (Figure 6). Then, the constant weight of each main controlling factor was calculated by using a commercial computer software program "YAAHP". The calculated constant weights of the main controlling factors are shown in Table 3.

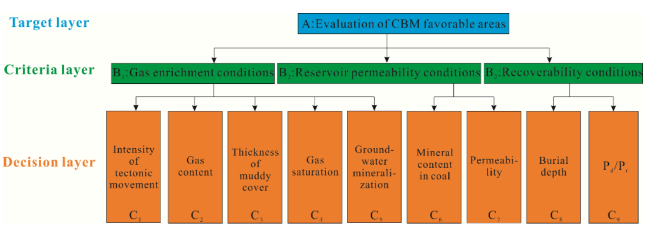

Figure 6. Hierarchical analysis model for evaluation of a favorable area.

4.2.2. Calculation of the Adjustment Parameters. Based on the calculation of eqns 8, 10, 12, and 16, combined with the constant weight and ideal variable weight (Table 4) of each main controlling factor in the selected evaluation unit, the value of parameters c, a_1, a_2, and a_3 (i.e., $c = 0.52$, $a_1 = 0.22$, $a_2 = 0.81$, and $a_3 = 0.62$) could be obtained by using a commercial computer software program "MATLAB".

4.3. Determination of Evaluation Model. On the basis of the state variable weight function and the determined adjustment parameters, the VWM for evaluation of favorable area for CBM development was established.

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Table 3. Constant Weight of Each Main Controlling Factor

controlling factor	constant weight	controlling factor	constant weight	controlling factor	constant weight
intensity of tectonic movement	0.0369	groundwater mineralization	0.0492	P_d/P_r	0.1637
thickness of muddy cover	0.0215	gas saturation	0.1215	mineral content in coal	0.0325
gas content	0.1835	burial depth	0.1637	permeability	0.2274

Table 4. Variable Weight of Each Controlling Factor in the Selected Evaluation Unit

controlling factor	variable weight	controlling factor	variable weight	controlling factor	variable weight
intensity of tectonic movement	0.0347	groundwater mineralization	0.0429	P_d/P_r	0.1585
thickness of muddy cover	0.0186	gas saturation	0.105	mineral content in coal	0.0297
gas content	0.2511	burial depth	0.1561	permeability	0.2077

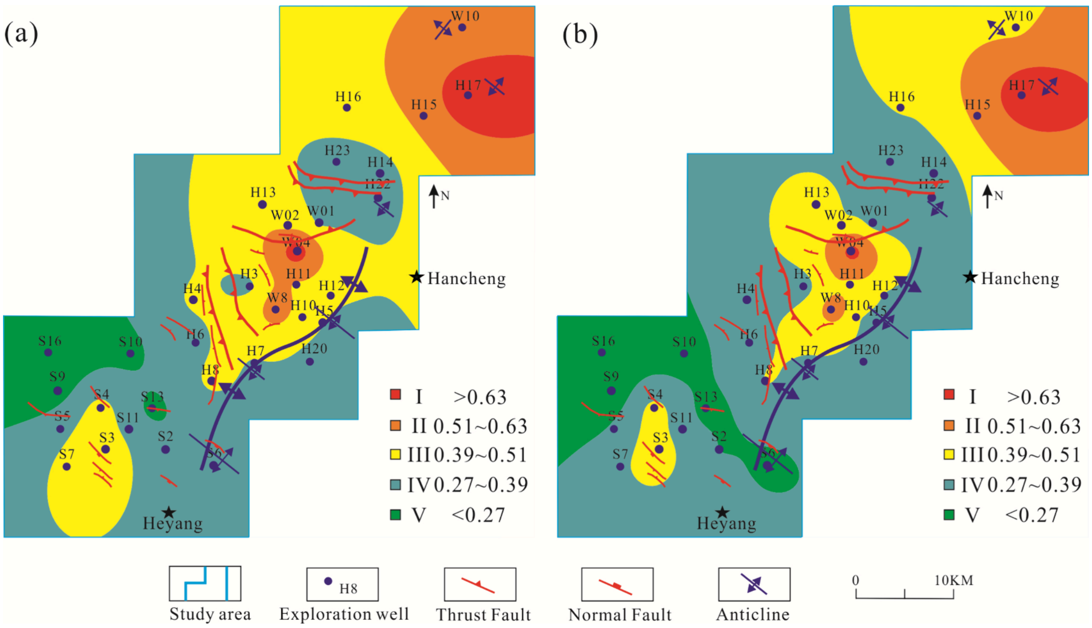

Figure 7. Zoning evaluation result of favorable area based on (a) CWM and (b) VWM.

$$W(x) = \frac{w_j^0 S_j(x)}{\sum_{j=1}^{9} w_j^0 S_j(x)} = \left(\frac{w_1^0 S_1(x)}{\sum_{j=1}^{9} w_j^0 S_j(x)}, \frac{w_2^0 S_2(x)}{\sum_{j=1}^{9} w_j^0 S_j(x)}, \frac{w_3^0 S_3(x)}{\sum_{j=1}^{9} w_j^0 S_j(x)}, \dots, \frac{w_9^0 S_9(x)}{\sum_{j=1}^{9} w_j^0 S_j(x)} \right) \tag{17}$$

$$S_j(x) = \begin{cases} e^{0.22(d_{j1}-x)} + e^{0.81(d_{j2}-d_{j1})} + 0.52 - 2, \ x \in [0, d_{j1}) \\ e^{0.81(d_{j2}-x)} + 0.52 - 1, \ x \in [d_{j1}, d_{j2}) \\ 0.52, \ x \in [d_{j2}, d_{j3}) \\ e^{0.62(x-d_{j3})} + 0.52 - 1, \ x \in [d_{j3}, 1] \end{cases} \tag{18}$$

Where $W(x)$ is the variable weight; $j = 1, 2, 3 \cdots 9$; d_{j1}, d_{j2} and d_{j3} are the thresholds of variable weight interval; $w_1^{(0)}$, $w_2^{(0)}$, $w_3^{(0)}$..., $w_9^{(0)}$ are the constant weights of each main controlling factor.

Based on the quantitative data of each main controlling factor, the variable weights of the main controlling factors for each evaluation unit could be calculated by using VWM. Then, the evaluation result of favorable area could be obtained from the variable weight and comprehensive index evaluation method. The calculation formula is as follows:

$$I_s = \sum_{j=1}^{9} W(x) \cdot x_j = \sum_{j=1}^{9} \frac{w_j^0 S_j(x)}{\sum_{j=1}^{9} w_j^0 S_j(x)} \cdot x_j \tag{19}$$

where I_s is the comprehensive value of evaluation; $W(x)$ is the variable weight of controlling factors; x_j is the index value of controlling factors; w^0 is the constant weight of controlling factors; and $S_j(x)$ is the state variable weight vector.

5. RESULTS AND DISCUSSION

Based on the variable weight evaluation model, the comprehensive evaluation values of all evaluation units could be calculated by eqns 17, 18, and 19. The comprehensive value of evaluation for each evaluation unit based on CWM was also calculated for comparison. The value of the constant-weighted comprehensive evaluation is in the range of 0.17079−0.71332, while the value of the variable-weighted comprehensive evaluation is in the range of 0.14881−0.71109. The value of variable-weighted comprehensive evaluation has shown a stronger discreteness. Nonequal spacing method is adopted to classify the evaluation result, with 0.12 as the intermediate grade

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division spacing. Based on the evaluation result, the coal reservoir in the Weibei CBM field could be divided into five grades, from good to poor in order: >0.63(I), 0.51−0.63(II), 0.39−0.51(III), 0.27−0.39(IV), <0.27(V). Adjacent evaluation units, which belong to the same favorable grade, were merged to obtain the distribution of favorable area for CBM development by using the CWM and VWM, respectively (Figure 7).

The distribution characteristics of favorable area evaluation based on the VWM and CWM are generally consistent, with some differences in the acreage and shape of the district for each grade. For zones of Class I, II, and III, the results from VWM are smaller, while for zones of Class IV and V, they show a strong inconsistency. This is due to that the influences of some factors with low index values were neglected in CWM but reflected in the evaluation process of VWM. In detail, take the area in the west of Well H23 and east of Well H22 as an example, the grade of result from evaluation has changed from III (based on CWM) to IV (based on VWM). This is due to the "strong punishment" of the weight based on the VWM, which significantly reduced the value of the comprehensive evaluation, as a response to the low index value of permeability and P_d/P_r. The evaluation result could effectively reflect the controlling effects of the index value in the evaluation of a favorable area for CBM development.

Generally, the weights of the controlling factors could be appropriately adjusted in the VWM. Then, the relationship between the internal variability of factors and the result of evaluation could be adequately reflected in this VWM. Thus, this newly provided method has great application potential in the evaluation of energy sources (e.g., CBM, shale gas, tight sandstone gas, etc.).

6. CONCLUSIONS

In this paper, the concept of variable weight was introduced into the evaluation of a favorable area for CBM development. Nine controlling factors were selected to evaluate the favorable area for the CBM development. A "strong penalty-incentive" type of state variable weight function was constructed, and a method for the determination of the parameters in this function was also proposed. Based on these, a VWM for the evaluation of favorable area is established and applied in the Weibei CBM field. "Punish" negative indices and "incent" positive ones, make the result of evaluation more closely to the actual situation. The comparison of results from VWM and CWM verified that the VWM could better reflect the variability in index values of the main controlling factors and their influence on the evaluation result.

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Notes

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