

Article

Application of Variable Weight Theory in the Suitability Evaluation of Regional Shallow Geothermal Energy Development

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Abstract: Blindly developing shallow geothermal energy (SGE) may lead to difficulties in reinjection, a low coefficient of performance (COP), and the waste of funds. In order to avoid these problems and improve development efficiency, it is necessary to scientifically conduct a development suitability evaluation and classify the suitability levels before development. This article takes Chengde City, Hebei Province, China as an example and constructs an evaluation index system based on the analysis of regional basic conditions. The Analytic Hierarchy Process (AHP) was used to calculate the constant weight. A Fuzzy C-means Clustering (FCM) analysis was used to determine the critical value of evaluation index classification and the interval threshold of variable weights. The parameters of the variable-weight model were calculated using the method of model backcalculation. Based on the constructed variable-weight model, the suitability of SGE development for groundwater sources in the study area was evaluated, and it was divided into five levels: most suitable area, suitable area, relatively suitable area, less suitable area, and unsuitable area. Through a verification analysis of engineering examples and a comparison with the evaluation results under traditional constant-weight models, it was found that the evaluation results based on variable weight theory have better data discreteness and a higher accuracy. Research has shown that variable-weight models can adjust the weight of each index based on its state value. Through this study, the accuracy of the suitability evaluation for regional SGE development can be improved. This can provide a certain reference for the suitability evaluation of SGE development in other regions.

Keywords: variable weight theory; shallow geothermal energy (SGE); development suitability; evaluation method



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1. Introduction

Shallow geothermal energy (SGE) refers to the energy that exists within a depth range of 200 m below the Earth's surface, including in the rock, soil, groundwater, and surface water. It mainly comes from solar energy, which radiates from the Earth's surface. Surface soil and rocks absorb heat and conduct it downwards, forming SGE [1]. This is significantly different from deep geothermal energy, which is renewable thermal energy from deep within the Earth, originating from molten magma and the decay of radioactive materials [2]. The development and utilization of SGE can be divided into three modes: buried-pipe

ground source heat pump system, groundwater ground source heat pump system, and surface-water ground source heat pump system [3]. This article mainly discusses the development suitability of groundwater ground source heat pump systems. As a kind of clean and renewable energy, SGE has the characteristics of a wide distribution, large reservoirs, high efficiency, energy saving, and no pollution [4]. It can serve as an important energy source for promoting clean heating or cooling worldwide. In addition, it can also contribute to China's achievement of the "30 carbon peak" and "60 carbon neutrality" goals [5]. It is well-known that the initial investment in the development of SGE is high; the blind development of ground source heat pump technology to develop SGE can not only not achieve the energy-saving effect, but also cause high operating costs due to the lower COP [6]. Taking Chengde City of Hebei Province as an example (Figure 1), according to the survey statistics, there are more than 70 SGE development and utilization projects in the urban planning area, and the groundwater ground source heat pump system is the main one. Due to the lack of scientific site selection based on a suitability evaluation in the early stage, there was no targeted development and utilization plan design based on different suitability levels. As a result, some projects are built in less suitable or unsuitable areas; the development and utilization design does not match the hydrogeological conditions. After the project was put into operation, there were problems such as the poor operational efficiency, difficulty in recharging, and even inability to operate. These seriously constrain the development and utilization of SGE. Therefore, in the early stage of developing SGE, it is necessary to establish a suitability evaluation index system and model according to regional characteristics, delimit suitability zones, and macroscopically grasp the suitability of regional SGE development [7]. The suitability of SGE development is a complex nonlinear problem. It is related to basic conditions such as the aquifer water-richness, hydraulic conductivity, groundwater mineralization, average groundwater temperature, recharge capacity, and aquifer thickness [8]. In addition, it is closely related to the economy. In order to scientifically evaluate the suitability of SGE development, it is necessary to consider these factors comprehensively and use systematic methods and theories for a comprehensive evaluation [9].

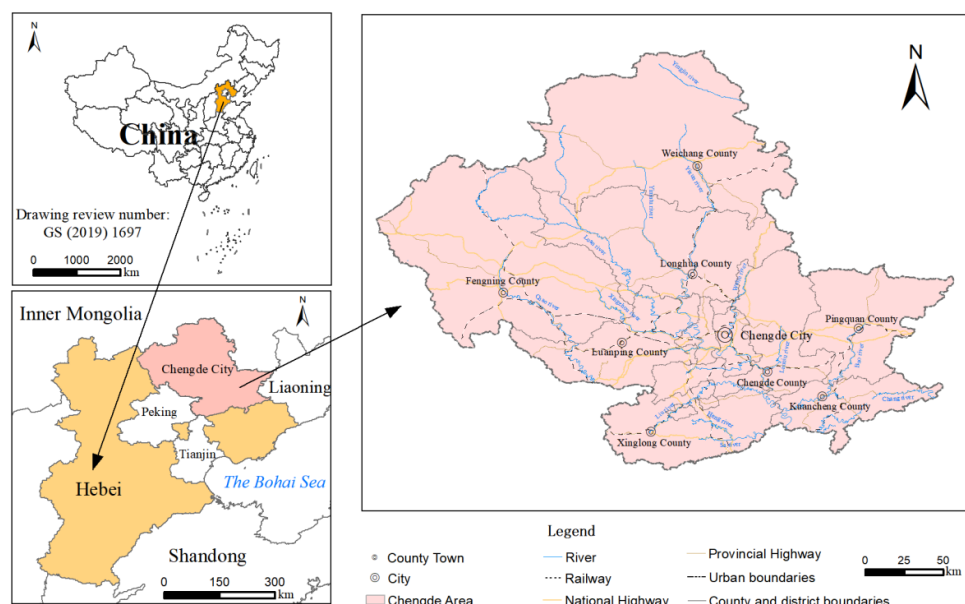


Figure 1. Location of the study area [10].

At present, there are many studies on the suitability evaluation methods for the development of SGE in China. The evaluation method first involves constructing evaluation indices tailored to local conditions. Then, evaluation methods such as the AHP, Fuzzy Comprehensive Method, Entropy Weight Method, Grey Relational Degree Method, and

Expert Questionnaire Method are used to calculate weights. On the basis of determining the weights, the spatial information fusion function of the GIS platform is utilized, and then the development suitability is determined by the weighted superposition method [11–15]. A series of research achievements have also been made in the suitability evaluation of SGE development abroad. For example, developing a computational program in a GIS environment to derive a regional model that can combine physical and economic variables to analyze the potential for SGE development in the Marche region of central Italy [16]. By developing a method called G.POT, the suitability of developing SGE in a region for building heating and cooling is evaluated [17]. An evaluation was conducted on the appropriate areas for introducing closed-loop ground source heat pump (GSHP) systems in standard independent residences in Akita Plain, Japan, using the drilling depth required for the GSHP system as a suitability index [18]. We then assess the installation potential of different types of GSHP systems in the Aizu Basin (Japan) based on groundwater conditions [19]. Based on the specific actual situation in each region, experimental research and the establishment of index systems are carried out to determine the influencing factors and use various research methods to determine relevant indices. Suitable evaluations for SGE development are carried out [20,21]. On the basis of meeting the requirements for the suitability evaluation of SGE and saving mining capital, the evaluation results are more focused on practical applications. Especially in the evaluation process, future urban development planning, regional development, and local funding and technical support were considered [22–24]. It can be seen that a series of achievements have been made in the evaluation of the suitability of SGE development. However, the current evaluation method is mainly based on the constant-weight evaluation method. If the value of a certain index within a certain evaluation unit is too low, its final evaluation value may be neutralized by the high value of other indices, causing the evaluation result to be inconsistent with reality. On the contrary, if a certain index value is too high, its final evaluation value may be neutralized by the low values of other indices, which can also cause the evaluation results to be inconsistent with reality. It can be seen that the use of fixed and unchanging weights to reflect the different state values of evaluation indices has certain limitations on the suitability of SGE development. This is mainly manifested in the inability to highlight the impact of changes in evaluation index values on evaluation results, regardless of the use of any constant-weight model. Especially when there is a significant change or mutation in the status value of evaluation indices, the limitations of the constant-weight evaluation become more prominent [25,26].

In order to overcome the limitations caused by fixed weights, the weight values can be adjusted based on the state values of each evaluation index within each evaluation unit, thus highlighting the impact of excessively high or low evaluation index values on the evaluation results, achieving more realistic evaluation results and improving the evaluation accuracy. This article introduces the theory of variable weights for the first time. We then systematically study the suitability evaluation method for SGE development based on variable weight theory from the aspects of establishing evaluation indices, quantifying indices, calculating constant-weight weights, and constructing variable-weight models. Taking Chengde City (Figure 1), Hebei Province as the research object, this study compares the differences in results between the constant-weight evaluation and variable-weight evaluation methods. We then analyze the advantages of variable-weight evaluation models in terms of data discretization and evaluation accuracy. I hope to provide some reference for the research on the suitability evaluation of SGE development and a scientific basis for its development and utilization through conducting this research.

The study area is located in the northeast of Hebei Province, with an area of approximately 39,500 km². It is situated in the transitional zone between North China and Northeast China, adjacent to Beijing and Tianjin to the south, Inner Mongolia to the north, and Liaoning Province to the east (Figure 1). The study area belongs to the temperate semi-humid and semi-arid continental monsoon mountain climate, which is a transitional area from the temperate zone to the warm temperate zone. It has the characteristics of four

distinct seasons, synchronous rain and heat, and a large temperature difference between day and night. The average annual rainfall is 648 mm, the average temperature is 9.5 °C, and the annual frost-free period is about 160 days.

The study area has well-developed faults and fold structures, which have gone through three main stages: basement formation, cap rock development, and strong activity. The exposed strata in the study area are relatively complete, ranging from the Archean to the Proterozoic, and also from the Mesozoic to the Cenozoic. Only the Paleozoic lacks the Silurian and Devonian strata, as well as the adjacent Upper Ordovician and Lower Carboniferous strata (Figure 2). The groundwater in the study area is strictly controlled by the geotectonic and geomorphic units. From north to south, it is divided into two hydrogeological regions: the Inner Mongolian Plateau and the northern Hebei mountainous region. According to the type of groundwater and its storage medium, the aquifer in the study area can be divided into four different types: loose rock pore water, clastic rock fracture pore water, bedrock fracture water, and carbonate rock fracture cave water (Figures 3 and 4). Among them, the first three types are widely developed in this area, while the fourth type has a relatively small distribution range. Within a depth range of 200 m, the aquifer has a thickness of 16–149.17 m, a hydraulic conductivity of 0.0132–13.03 m/d, a groundwater mineralization degree of 150.07–1593 mg/L, and an average groundwater temperature of 4.6–15.1 °C.

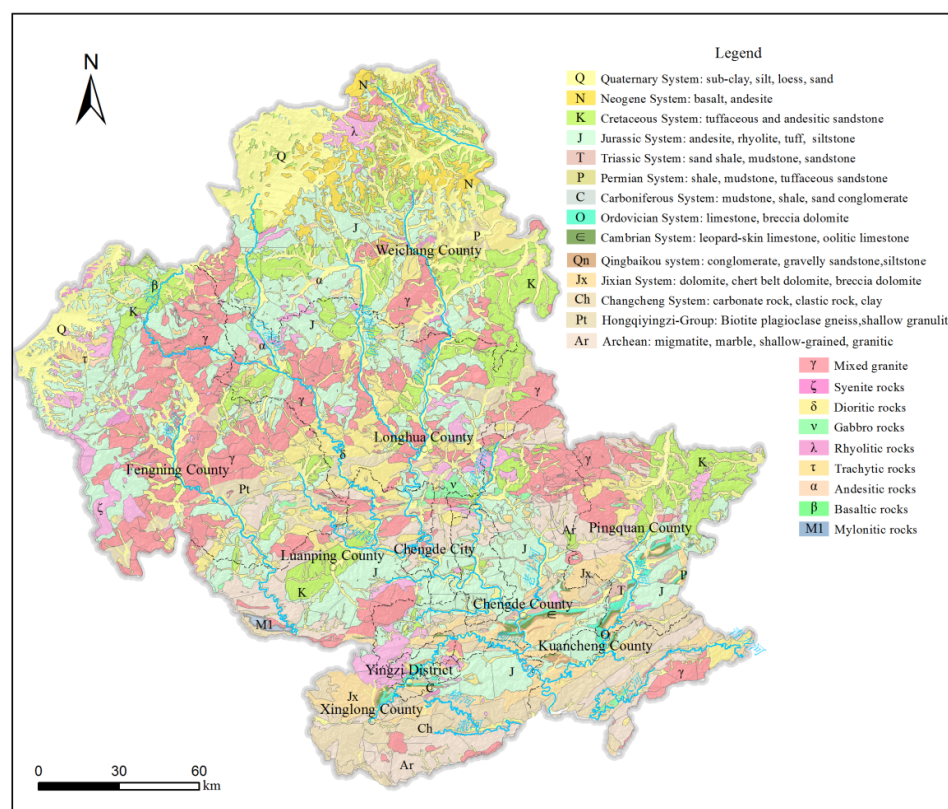


Figure 2. Brief geological map of the study area [27].

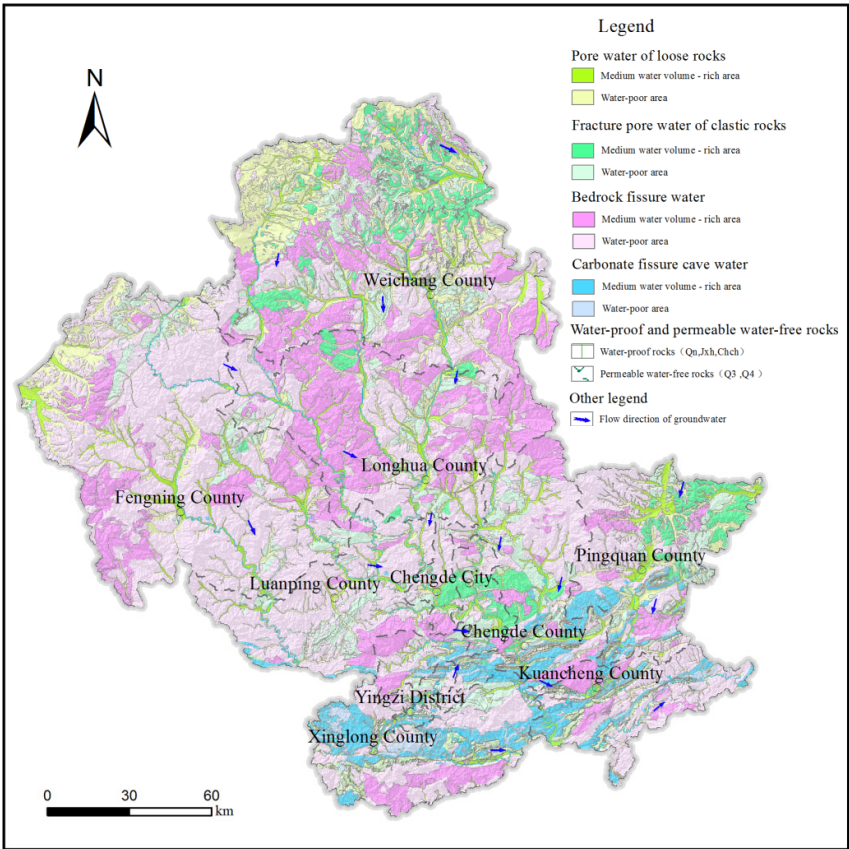


Figure 3. Brief hydrogeological map of the study area [28].

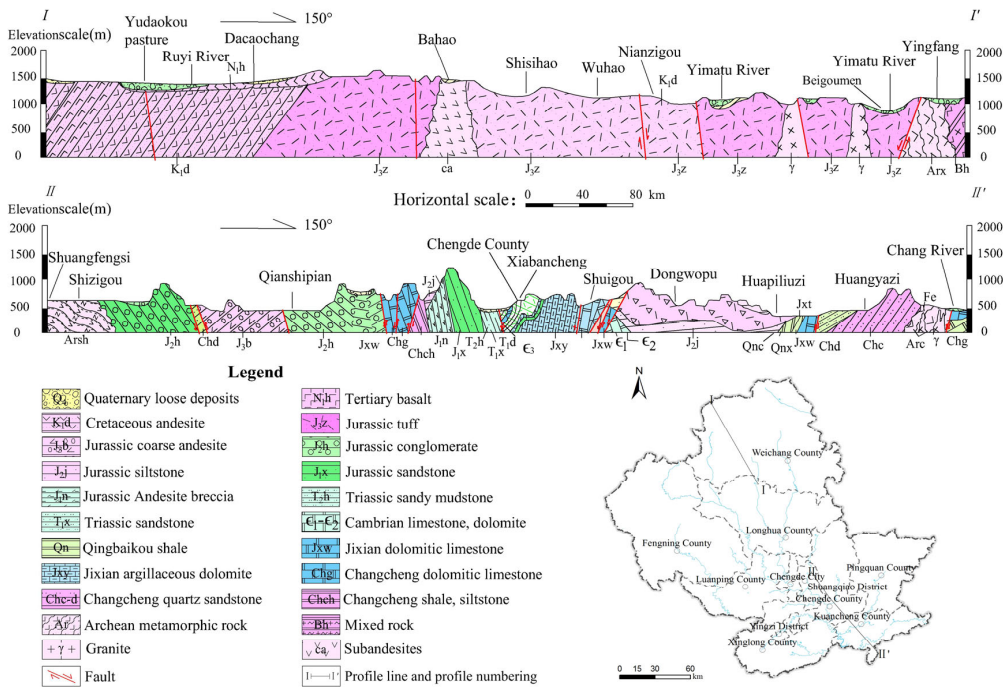


Figure 4. Hydrogeological profile map of the study area [28].

2. Evaluation Method

2.1. Evaluation Index System Construction

The suitability of regional SGE development is a huge and complex system, which is composed of many relatively independent and interrelated parts; reasonable evaluation index is very important to the evaluation result [29,30]. On the basis of the comprehensive research results of experts and scholars in the field of SGE development in recent years, the evaluation index system is determined through the analysis and research of the existing basic data in the study area and the characteristics of the regional geological environment. The evaluation index system is divided into two levels. The first-level indices are divided into geological and hydrogeological conditions, groundwater conditions and drilling conditions; the second-level indices included in each first-level index are shown in Table 1.

Table 1. The main controlling factors affecting the suitability of shallow geothermal energy (SGE) development.

Primary Index	Secondary Index	Quantitative Basis
Geological ¹ and hydrogeological conditions ²	The water-richness of aquifers	Based on the degree of regional water-richness
	Hydraulic conductivity	Based on the value of hydraulic conductivity
	Recharge capacity	Based on the regional stratigraphic lithology
	Aquifer thickness	Based on the value of aquifer thickness
Groundwater condition	Mineralization of groundwater	Based on the value of groundwater mineralization
	Average temperature of groundwater	Based on the value of regional groundwater temperature
Drilling condition	Drilling difficulty	Based on the regional drilling difficulty

Notes: ¹ This refers to various factors that affect the geological phenomena on the Earth's surface, including stratigraphic lithology, geological structure, magmatic activity, etc. This article mainly involves stratigraphic lithology. ² This refers to the general term for conditions related to the formation, distribution, and variation of groundwater, including groundwater recharge, burial, runoff, discharge, water quality, and quantity. This article mainly involves the water-richness, hydraulic conductivity, and thickness of the aquifer.

For the definition or related description of geological and hydrogeological conditions and their secondary indices, please refer to Appendix A. For the definition or related description of groundwater conditions and their secondary indices, please refer to Appendix B. For the definition or related description of drilling conditions, please refer to Appendix C.

2.2. Quantification of Evaluation Index

After the establishment of the evaluation index system, it is necessary to conduct scientific and reasonable quantification of each evaluation index. Among all the indices, the hydraulic conductivity, aquifer thickness, mineralization of groundwater, average temperature of groundwater, and drilling difficulty are directly collected measured data or calculated data, without quantitative processing. For the water-richness of aquifers and recharge capacity, in order to facilitate later evaluation and calculation, the same quantified value interval is adopted for each of these two evaluation indices. Combined with the actual situation in the study area, the grading standard and quantified value of the evaluation indices are proposed in this article. The details are shown in Table 2.

After the evaluation index quantization, in order to eliminate the influence of each evaluation index dimension, it is necessary to normalize the quantization value of each evaluation index. The six evaluation indices of the water-richness of aquifers, recharge capacity, hydraulic conductivity, average temperature of groundwater, aquifer thickness, and drilling difficulty are positively correlated with the suitability of SGE development. In this article, the maximum value method (Formula (1)) was adopted for normalization. As for the mineralization of groundwater, it is negatively correlated with the suitability

of SGE development; the minimum method (Formula (2)) is adopted for normalization treatment.

$$A_{ij} = \frac{X_{\max j} - X_{ij}}{X_{\max j} - X_{\min j}}, \quad (1)$$

$$A_{ij} = \frac{X_{ij} - X_{\min j}}{X_{\max j} - X_{\min j}}, \quad (2)$$

where A_{ij} is the normalized quantized value; X_{ij} is the index value before normalization; $X_{\max j}$ is the maximum value in the quantized data before normalization; and $X_{\min j}$ is the minimum value in the quantized data before normalization.

After the evaluation indices are quantified and normalized, thematic layers of each evaluation index are constructed by using ArcGIS spatial interpolation function (Figure 5).

Table 2. Evaluation index grading and evaluation criteria.

No.	Evaluation Index	Quantitative Grading Standard				
1	The water-richness of aquifers	Impermeable rock layer ¹	Permeable and non-aqueous rock layers ²	Non-water-rich rock layers ³	Medium-water-rich rock layers ⁴	Water-rich rock layer ⁵
		1	3	5	7	9
2	Recharge capacity	Impermeable rock layer	Weathering zone fissure water in metamorphic or intrusive rocks	Pore water in loose rocks	Fissure or pore water in clastic rocks, and fissure or karst water in clastic or carbonate rocks	Fissure water, karst cave water, and bedrock structural fissure water in carbonate rocks
		1	3	5	7	9

Notes: ¹ This refers to a relatively impermeable rock layer that separates groundwater. It cannot provide water, nor can water pass through it. ² This refers to water that can pass through it, but its water holding capacity is poor and it cannot provide water. ³ This refers to $q \leq 0.1$ L (s.m); q is a unit water inflow, with a unit water inflow based on a diameter of 91 mm and a pumping depth of 10 m. ⁴ This refers to $0.1 < q \leq 1$ L (s.m). ⁵ This refers to $q > 1$ L (s.m).

2.3. Calculation of Constant Weight

Based on the evaluation index system of SGE development suitability, the AHP is used to calculate and determine the weight of each main control factor. The specific calculation process is as follows. Firstly, the evaluation system structure model is divided into three levels (Figure 6), namely, target layer A (suitability for SGE development), attribute layer B (including geological and hydrogeological conditions, groundwater conditions, and drilling conditions), and element index layer C (aquifer richness, recharge capacity, hydraulic conductivity, average groundwater temperature, groundwater mineralization, aquifer thickness, and drilling difficulty). Secondly, the importance of the indices in this layer compared pairwise with those in the previous layer was evaluated using expert scoring methods, and a judgment matrix was constructed (Tables 3–6). Again, we calculate the maximum eigenvalue of each judgment matrix ($\lambda_{\max}$), consistency index (CI), and consistency coefficient (CR). Here, the calculation process of these parameters is as follows. Firstly, we calculate the product (M_i) of each row element in the judgment matrix according to Formula (3). Secondly, we calculate the n -th root of M_i according to Formula (4). Thirdly, we construct the vector w according to Formula (5) and normalize the vector according to Formula (6). Fourthly, we calculate $\lambda_{\max}$ according to Formula (7). On this basis, we calculate CI according to Formula (8) and CR according to Formula (9). If $CR < 0.1$, it is considered that the judgment matrix has passed the consistency test; otherwise, it does not have satisfactory consistency [31]. Taking the judgment matrix $A \sim B_i$ as an example, with a matrix order of 3, we calculate it according to the above formula $\lambda_{\max} = 3.0735$; the index weight are shown in Table 7, with a CI of 0.0368. When the matrix order is 3, the corresponding RI is 0.58, and the CR is 0.0707. According to this method, the final weight

calculation results of each index are shown in Table 7. The CR is less than 0.1; that is, it passes the consistency test.

$$M_i = \prod_{j=1}^n b_{ij}, i = 1, 2, \dots, n \quad (3)$$

where M_i is the product of the i -th row elements in the matrix, b_{ij} is the j -th column element in the i -th row, and n is the matrix order.

$$\overline{W}_i = \sqrt[n]{M_i} \quad (4)$$

where $\overline{W}_i$ is n -th root of M_i , M_i is the product of the i -th row elements in the matrix, and n is the matrix order.

$$w = [\overline{W}_1, \overline{W}_2, \dots, \overline{W}_n] \quad (5)$$

where, w is a vector, $\overline{W}_i$ is n -th root of M_i , and n is the matrix order.

$$w_i = \overline{W}_i / \sum_{i=1}^n \overline{W}_i \quad (6)$$

where w_i is the weight value of the evaluation index, $\overline{W}_i$ is n -th root of M_i , and n is the matrix order.

$$\lambda_{max} = \frac{1}{n} \sum_{i=1}^n \frac{(AW)_i}{w_i} \quad (7)$$

where λ_{max} is the maximum eigenvalue of the judgment matrix, A is the judgment matrix, and W is the eigenvector corresponding to λ_{max} . w_i is the weight value of the evaluation index, and n is the matrix order.

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (8)$$

where CI is the consistency index, λ_{max} is the maximum eigenvalue of the judgment matrix, and n is the matrix order.

$$CR = \frac{CI}{RI} \quad (9)$$

where CR is the consistency coefficient, and RI is the average random consistency index, which can be obtained by consulting relevant data tables.

2.4. Construction of Variable-Weight Evaluation Model

The basic principle of variable weight theory is that the weight of evaluation index will be adjusted based on the evaluation index status value of each evaluation unit. Therefore, the weights can better serve the role of corresponding evaluation indices in the evaluation system. It can change the fixed weight in traditional constant-weight evaluation, making comprehensive decision-making more reasonable and scientific [32]. Based on the theory of variable weight, it is necessary to first construct a state vector and determine the variable-weight vectors for the penalty interval, non-incentive and non-penalty interval, initial incentive interval, and strong incentive interval. The segmented function of the variable-weight vector used in this study is shown in Formula (10). Secondly, the critical value and variable-weight interval of the evaluation index classification are calculated. Finally, on the basis of meeting the requirements of comprehensive suitability evaluation, the appropriate parameter values in the state vector that meet the expected weights are calculated in reverse. For the determination of the parameters of the state variable-weight vector, this article cites previous research to determine the mathematical function of state variable-weight vectors [33].

$$S_f(X) = \begin{cases} e^{a_1(d_{j1}-x)} + c - 1, & x \in [0, d_{j1}) \\ C, & x \in [d_{j1}, d_{j2}) \\ e^{a_2(x-d_{j2})} + c - 1, & x \in [d_{j2}, d_{j3}) \\ e^{a_3(x-d_{j3})} + e^{a_2(d_{j3}-d_{j2})} + c - 2, & x \in [d_{j3}, 1], \end{cases} \quad (10)$$

where c , a_1 , a_2 , and a_3 are the weight adjustment parameters of the state variable-weight vector; and d_{j1} , d_{j2} , and d_{j3} are the threshold of variable-weight interval for the j -th factor.

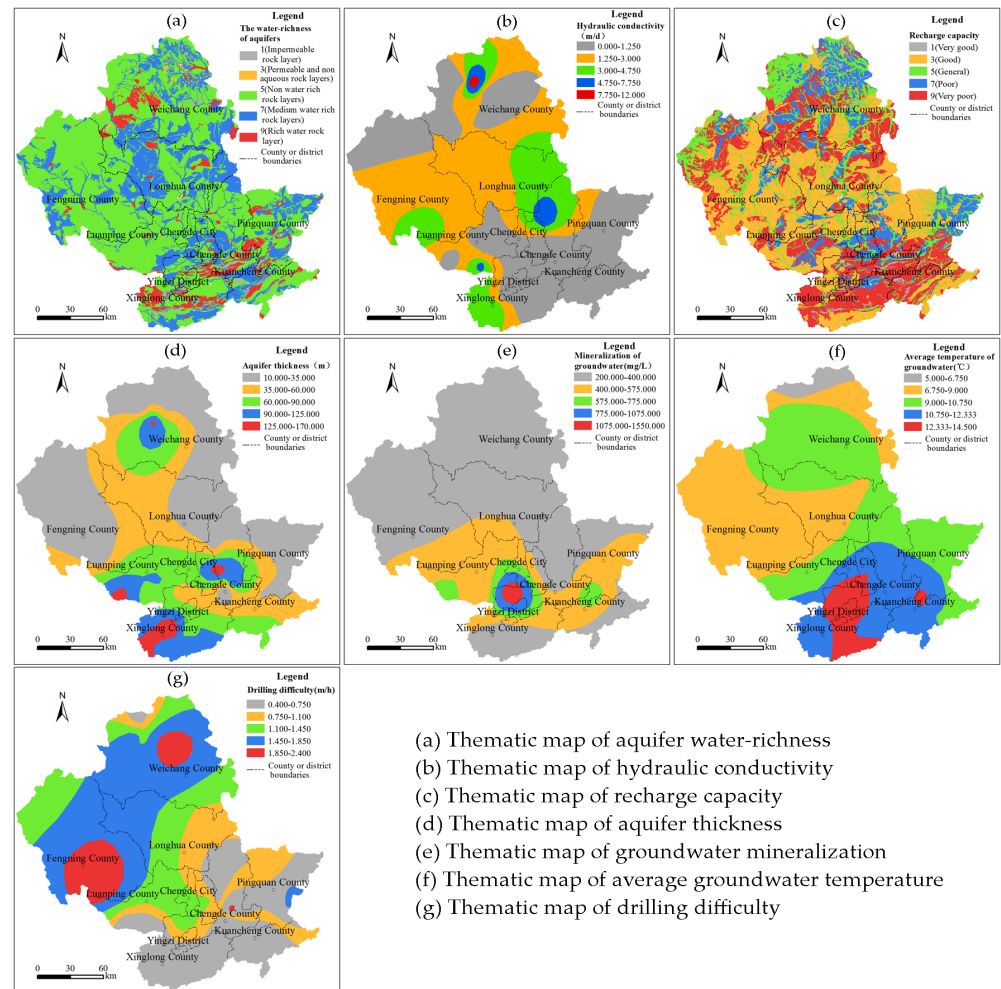


Figure 5. Thematic map of suitability evaluation indices for shallow geothermal energy (SGE) development.

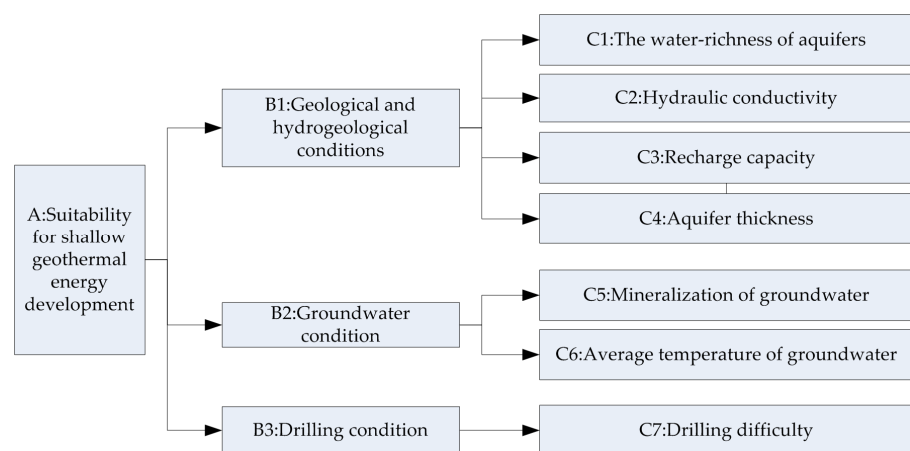


Figure 6. The AHP structural model based on evaluation index system.

Table 3. Judgment matrix $A \sim B_i$ ($i = 1 \sim 3$).

A	B ₁	B ₂	B ₃	W (A/B _i)
B ₁	1	2	3	0.5499
B ₂	1/2	1	2/3	0.2099
B ₃	1/3	3/2	1	0.2402

Note: $\lambda_{\max} = 3.0735$; $CR = 0.0707 < 0.1$; and $CI = 0.0368 < 0.1$.

Table 4. Judgment matrix $B_1 \sim C_i$ ($i = 1 \sim 4$).

B ₁	C ₁	C ₂	C ₃	C ₄	W (B ₁ /C _i)
C ₁	1	5/2	1	3/2	0.3324
C ₂	2/5	1	1/2	4/3	0.1717
C ₃	1	2	1	1	0.3144
C ₄	2/3	3/4	2/3	1	0.1815

Note: $\lambda_{\max} = 4.0641$; $CR = 0.024 < 0.1$; and $CI = 0.02141 < 0.1$.

Table 5. Judgment matrix $B_2 \sim C_i$ ($i = 5 \sim 6$).

B ₂	C ₅	C ₆	W (B ₂ /C _i)
C ₅	1	1/2	0.3333
C ₆	2	1	0.6667

Note: $\lambda_{\max} = 2$; $CR = 0 < 0.1$; and $CI = 0 < 0.1$.

Table 6. Judgment matrix $B_3 \sim C_i$ ($i = 7$).

B ₃	C ₇	W (B ₃ /C _i)
C ₇	1	1

Note: $\lambda_{\max} = 1$; $CR = 0 < 0.1$; and $CI = 0 < 0.1$.

Table 7. Evaluation index weight.

No.	Primary Index	Primary Index Weight	Secondary Index	Secondary Index Weight
1	Geological and hydrogeological conditions	0.5499	The water-richness of aquifers	0.1828
2			Hydraulic conductivity	0.0944
3			Recharge capacity	0.1729
4			Aquifer thickness	0.0998
5	Groundwater condition	0.2098	Mineralization of groundwater	0.0699
6			Average temperature of groundwater	0.1399
7	Drilling condition	0.2402	Drilling difficulty	0.2402

2.4.1. The Determination of Variable-Weight Intervals

Before determining the variable-weight parameters, it is necessary to divide the weight adjustment range of each evaluation index, which is used to define the weight adjustment amplitude of the main control factor index value. There are three steps required here. Firstly, it is necessary to use statistical analysis methods to determine the classification threshold values for each index. Secondly, it is necessary to calculate the threshold of the variable-weight interval for each index based on the calculation of the classification threshold. Finally, the variable-weight interval of each index can be determined based on the threshold of the variable-weight interval [34]. For the calculation of critical values for each index classification, the FCM was used in this study. Firstly, we extract clustering sample data from the ArcGIS database. Secondly, we determine the fuzziness C (number of clustering layers) as 4, the weighted index m as 2, and the iteration error ϵ as 1×10^{-4} . Thirdly, FCM is implemented by input Python, and each evaluation index value is classified by calculation. Finally, determine the classification threshold f_i for index values, as shown in Table 8.

Table 8. Evaluation index classification critical value (normalized processing).

Classification Critical Value	f_1	f_2	f_3	f_4	f_5	f_6
The water-richness of aquifers	0.25	0.5	0.52	0.68	0.73	0.87
Hydraulic conductivity	0.0833	0.1042	0.2083	0.2292	0.3958	0.4375
Recharge capacity	0.15	0.25	0.55	0.65	0.75	0.85
Aquifer thickness	0.1875	0.2186	0.3958	0.4063	0.625	0.6563
Mineralization of groundwater	0.3519	0.3889	0.7037	0.7222	0.8519	0.8704
Average temperature of groundwater	0.3947	0.4211	0.579	0.6053	0.7719	0.7895
Drilling difficulty	0.225	0.275	0.5	0.525	0.75	0.775

In this table, “ $f_1, \dots, f_6$ ” represents the classification threshold values of each index after normalization, rather than the actual values of each index. Taking the hydraulic conductivity as an example, its actual value ranges from 0.0132 to 13.03 m/d, and, after normalization, its range is 0 to 1. The FCM analysis was used to determine its classification critical values as 0.0833, 0.1042, 0.2083, 0.2292, 0.3958, and 0.4375, respectively, which are the data shown in Table 8.

On the basis of determining the classification critical value, we calculate the weight threshold of variable weights according to Formula (11):

$$d_1 = (f_{j1} + f_{j2})/2, d_2 = (f_{j3} + f_{j4})/2, d_3 = (f_{j5} + f_{j6})/2 \quad (11)$$

where f_j is the classification critical value of the index value of the j -th factor; and d_j is the variable-weight interval threshold for the j -th index. Therefore, as shown in Table 9, variable-weight threshold intervals for each master control factor are obtained [35].

Table 9. Variable-weight interval based on FCM clustering.

Evaluation Index	Penalty Interval	Non-Incentive and Non-Punishment Interval	Initial Incentive Interval	Strong Incentive Interval
The water-richness of aquifers	$0 \leq x < 0.2$	$0.2 \leq x < 0.6$	$0.6 \leq x < 0.8$	$0.8 \leq x \leq 1$
Hydraulic conductivity	$0 \leq x < 0.0938$	$0.0938 \leq x < 0.2188$	$0.2188 \leq x < 0.4167$	$0.4167 \leq x \leq 1$
Recharge capacity	$0 \leq x < 0.2$	$0.2 \leq x < 0.6$	$0.6 \leq x < 0.8$	$0.8 \leq x \leq 1$
Aquifer thickness	$0 \leq x < 0.2031$	$0.2031 \leq x < 0.401$	$0.401 \leq x < 0.6406$	$0.6406 \leq x \leq 1$
Mineralization of groundwater	$0 \leq x < 0.3704$	$0.3704 \leq x < 0.713$	$0.713 \leq x < 0.8611$	$0.8611 \leq x \leq 1$
Average temperature of groundwater	$0 \leq x < 0.4079$	$0.4079 \leq x < 0.5921$	$0.5921 \leq x < 0.7807$	$0.7807 \leq x \leq 1$
Drilling difficulty	$0 \leq x < 0.25$	$0.25 \leq x < 0.5125$	$0.5125 \leq x < 0.7625$	$0.7625 \leq x \leq 1$

2.4.2. The Determination of Variable-Weight Parameters

After determining the variable-weight intervals for different indices, it is necessary to calculate the adjustment parameters c , a_1 , a_2 , and a_3 of the constructed variable-weight vector. The calculation of these parameters mainly adopts the method of model backcalculation, and the specific process includes three steps. Firstly, selecting an evaluation unit requires that the four index values should be located in four different variable-weight intervals. In addition, one of the remaining index values needs to be within the penalty interval. Secondly, based on objective facts and the preferences of decision-makers, the AHP is used to calculate the ideal variable weights of each evaluation index within the evaluation unit. Finally, we substitute the values of various indices, constant-weight values, and ideal variable-weight values within the evaluation unit into the variable-weight vector. Based on this, we establish an equation system about the parameters to be solved, and then calculate the parameter values [36]. The parameter values are shown in Table 10.

Table 10. Adjustment parameters of state variable-weight vectors.

Variable-Weight Parameters	c	a ₁	a ₂	a ₃
value	0.2428	0.0442	0.0974	0.1245

2.4.3. The Construction of Variable-Weight Models

On the basis of determining the variable-weight interval and variable-weight parameters, the constructed variable-weight evaluation model is as follows [37]:

$$W(X) \triangleq \frac{W_0 \cdot S(X)}{\sum_{j=1}^7 W_j^{(0)} S_j(X)} \triangleq \left\{ \frac{W_1^{(0)} S_1(X)}{\sum_{j=1}^7 W_j^{(0)} S_j(X)}, \frac{W_2^{(0)} S_2(X)}{\sum_{j=1}^7 W_j^{(0)} S_j(X)}, \dots, \frac{W_7^{(0)} S_7(X)}{\sum_{j=1}^7 W_j^{(0)} S_j(X)} \right\} \quad (12)$$

$$S_j(X) = \begin{cases} e^{0.0442(d_{j1}-x)} + 0.2428 - 1, x \in [0, d_{j1}) \\ 0.2428, x \in [d_{j1}, d_{j2}) \\ e^{0.0974(x-d_{j2})} + 0.2428 - 1, x \in [d_{j1}, d_{j3}) \\ e^{0.1245(x-d_{j3})} + e^{0.0974(d_{j3}-d_{j2})} + 0.2428 - 2, x \in [d_{j3}, 1) \end{cases} \quad (13)$$

where $j = 1, 2, 3, 4 \dots 7$; d_{j1} , d_{j2} , and d_{j3} are the thresholds for the variable-weight interval of the j -th main control factor; and $W_i^{(0)}$ is the constant weight of the evaluation index.

3. Results

3.1. The Evaluation Results

Based on the obtained variable-weight parameter values, we substitute them into the MATLAB program, and, finally, obtain the suitability index values within each evaluation unit according to Formulas (13) and (14). The suitability index calculation data are linked to the layer attribute table through the attribute library. Based on the ArcGIS platform, the classification threshold is determined according to the natural classification method. The suitability of SGE development for groundwater sources in the study area is divided into five levels: most suitable area, suitable area, relatively suitable area, less suitable area, and unsuitable area. Based on the above evaluation methods, the suitability evaluation of SGE development in the study area was completed, and an evaluation subarea layer was formed (Figure 7). The statistical results of the evaluation are shown in Table 11.

From the evaluation results, it can be seen that, within the study area, the most suitable area for the development of SGE with underground water sources is 5848.1 km², accounting for 14.82%; the suitable area is 9794.5 km², accounting for 24.82%; the relatively suitable area is 16,775.9 km², accounting for 42.50%; the low-suitability area is 6809.3 km², accounting for 17.25%; and the unsuitable area is 241.3 km², accounting for 0.61%. The proportion of less suitable and unsuitable areas is about 17.86%, and the proportion of the most suitable and suitable areas is about 39.64%.

3.2. The Result Analysis

According to the evaluation results, the most suitable areas for the development of SGE in the study area are mainly distributed in the central and western parts of Xinglong County, the western part of Kuancheng County, the southwestern part of Pingquan City, the southern part of Shuangqiao District, the southwestern part of Weichang County, and the northwestern part of Fengning County. This area has a good water-richness, large aquifer thickness, and strong recharge capacity, making it an ideal area for the development of SGE based on groundwater sources.

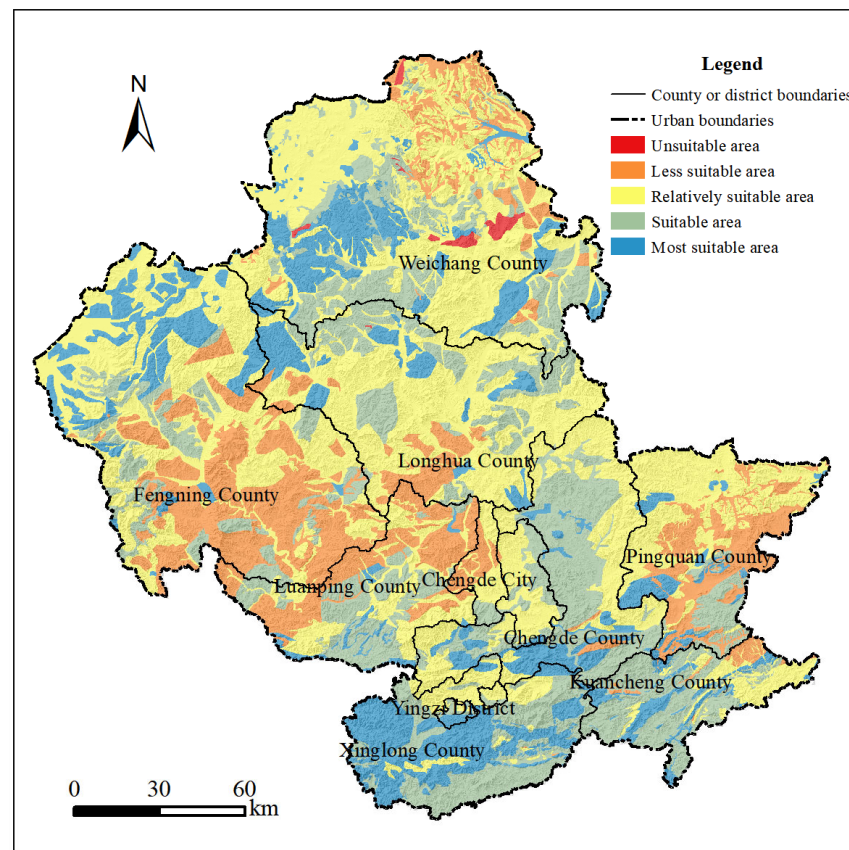


Figure 7. Suitability evaluation map for SGE development in the study area based on variable-weight model.

Table 11. Statistical table for suitability evaluation of SGE development in the study area based on variable-weight model.

Suitability Level	Area (km ²)	Proportion (%)
Most suitable area	5848.1	14.82
Suitable area	9794.5	24.82
Relatively suitable area	16,775.9	42.50
Less suitable area	6809.3	17.25
Unsuitable area	241.3	0.61

According to the evaluation results, the suitable areas for the development of SGE based on groundwater sources in the study area are distributed in the southern and eastern parts of Xinglong County, the central and southern parts of Luanping County, Chengde County, Kuancheng County, the northeastern part of Shuangqiao District, the southern part of Shuangluan District, the northeastern and northwestern parts of Longhua County, the southeastern part of Pingquan City, and the central part of Weichang County. These areas have a good recharge capacity, high average groundwater temperature, and easy drilling, making them suitable for the development of SGE based on groundwater sources.

According to the evaluation results, the relatively suitable areas for the development of SGE based on groundwater sources in the study area are distributed in the northwest and southeast of Weichang County, central and northern parts of Fengning County, southwest and eastern parts of Longhua County, northern parts of Shuangluan District, northern parts of Shuangqiao District, eastern and northern parts of Chengde County, western and northern parts of Pingquan City, southwestern and southeastern parts of Luanping County, Yingzi District, and northern parts of Xinglong County. These areas have a moderate difficulty in drilling, average groundwater temperature, and water-richness, and belong

to the more suitable areas for the development of SGE based on groundwater sources. Feasibility studies need to be conducted before development, and development plans should be designed according to local conditions.

According to the evaluation results, the less suitable areas for the development of SGE based on groundwater sources in the study area are distributed in the northeast of Weichang County, the central and southern parts of Fengning County, the western and northern parts of Luanping County, the western parts of Shuangluan District, the southern parts of Longhua County, and the central and eastern parts of Pingquan City. These areas have a high groundwater mineralization, poor recharge capacity, and difficult drilling, and belong to the less suitable areas for the development of SGE based on groundwater sources. Before development, a detailed hydrogeological exploration is required in the engineering construction area to fully demonstrate the feasibility of development and minimize development risks.

According to the evaluation results, the unsuitable areas for the development of SGE based on groundwater sources in the study area are mainly distributed in the central part of Pingquan City and Weichang County, while other areas have smaller distribution areas. These areas are not suitable for the development of SGE based on groundwater sources, and should be avoided during the site selection stage of the project.

4. Discussion

4.1. The Comparison of Evaluation Results

Based on the calculated constant weight, a constant-weight evaluation model (Formula (14)) is used to evaluate the suitability of SGE development in the study area. We determine the classification threshold based on the natural breakpoint classification method on the ArcGIS platform. The suitability of SGE development is divided into five levels: most suitable area, suitable area, relatively suitable area, less suitable area, and unsuitable area (Figure 8). The evaluation results are shown in Table 12 and compared with the evaluation results of the variable-weight model in Table 13 and Figure 9.

$$V = \sum_{j=1}^m (W_j \cdot X_j) \quad (14)$$

where V is the suitability index for SGE development (the larger the value is, the more suitable it is for development), which is the weighted total score of all evaluation factors. W_j is the weight of the evaluation indices, X_j is the standardized value of the indices, and m is the number of evaluation indices.

By comparison, it can be concluded that the area of the low-suitability area has the largest change, followed by the relatively suitable area, while the area of the suitable area has the smallest change, followed by the most suitable area. The evaluation results based on the variable-weight model show that the most suitable area, suitable area, and relatively suitable area are all larger than the evaluation results of the constant-weight model, while the less suitable area and unsuitable area are smaller than the evaluation results of the constant-weight model. It can be seen that the evaluation results based on the variable-weight model are more inclined towards suitability.

By comparing the main distribution areas of the results based on the two evaluation models, it can be seen that there is a significant difference in their distribution areas (Table 14). Taking the most suitable area as an example, the evaluation results based on the constant-weight model show that it is mainly distributed in Xinglong County, Kuancheng County, and Chengde County. The evaluation based on the variable-weight model shows that it is mainly distributed in Weichang County, Xinglong County, and Fengning County. It can be seen that, for the spatial distribution of the most suitable area, the results of the two models are completely different. Similarly, the same applies to the main spatial distribution of unsuitable areas. The evaluation results based on the constant-weight model show that it is mainly distributed in Fengnian County, Weichang County, and Longhua County.

The evaluation based on the variable-weight model shows that it is mainly distributed in Weichang County, Longhua County, and Chengde County. This is also a big difference.

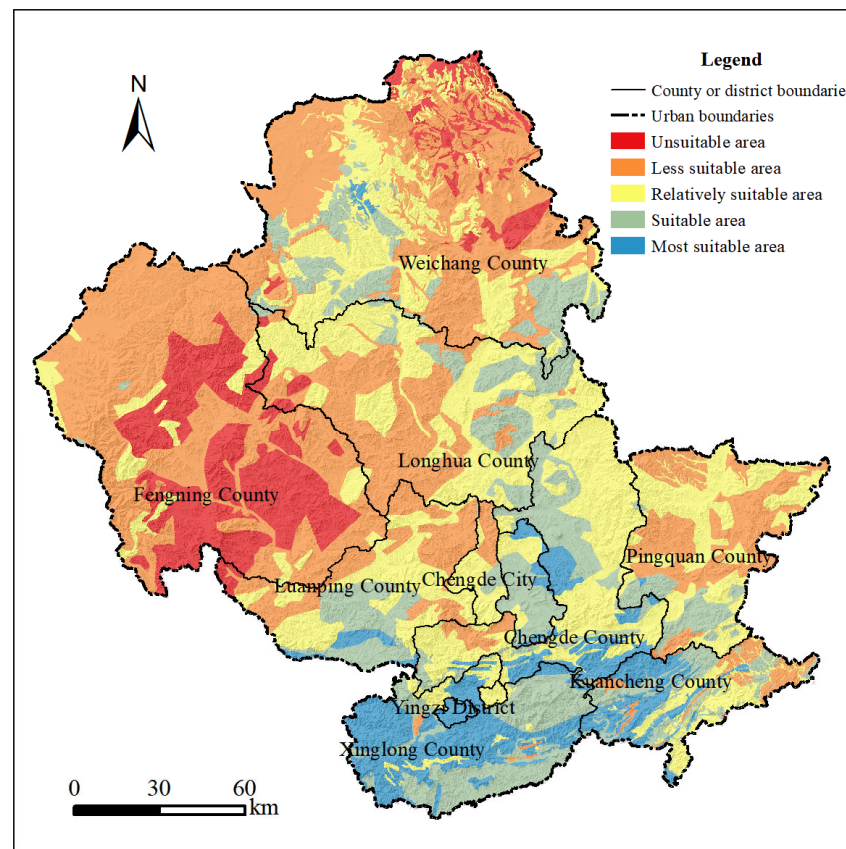


Figure 8. Suitability evaluation map for SGE development in the study area based on constant-weight model.

Table 12. Statistical table for suitability evaluation of SGE development in the study area based on constant-weight model.

Suitability Level	Area (km ²)	Proportion (%)
Most suitable area	2944.67	7.46
Suitable area	6934.32	17.57
Relatively suitable area	10,713.2	27.15
Less suitable area	14,157.3	35.88
Unsuitable area	4710	11.94

Table 13. Comparison and statistical table of suitability evaluation results for the development of SGE based on groundwater sources in the study area.

Suitability Level	Area (km ²)			Proportion (%)		
	Based on Constant-Weight Model	Based on Variable-Weight Model	Area Difference	Based on Constant-Weight Model	Based on Variable-Weight Model	Proportion Difference
Most suitable area	2944.67	5848.1	2903.43	7.46	14.82	7.36
Suitable area	6934.32	9794.5	2860.18	17.57	24.82	7.25
Relatively suitable area	10,713.2	16,775.9	6062.7	27.15	42.50	15.35
Less suitable area	14,157.3	6809.3	−7348	35.88	17.25	−18.63
Unsuitable area	4710	241.3	−4468.7	11.94	0.61	−11.33

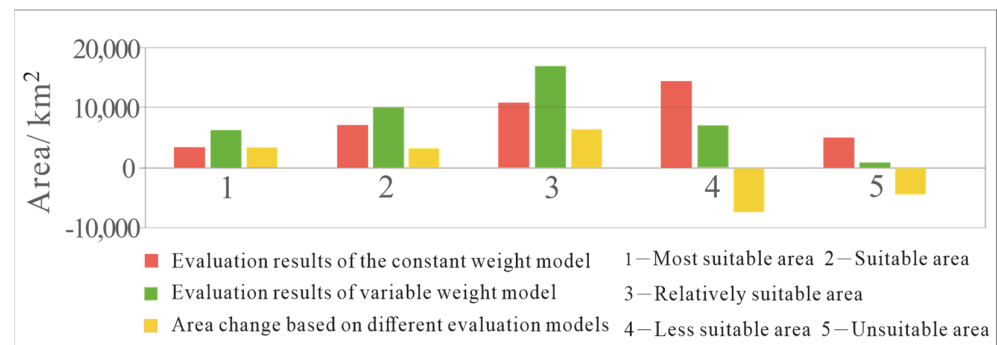


Figure 9. Comparison chart of evaluation results based on constant-weight evaluation model and variable-weight evaluation model.

Table 14. Comparison table of main distribution regions of evaluation results for different models in the study area.

Suitability Level	The Top Three Counties and Districts in Terms of Distribution Area (Area from Large to Small)	
	Based on Constant-Weight Model	Based on Variable-Weight Model
Most suitable area	Xinglong County, Kuancheng County, Chengde County	Weichang County, Xinglong County, Fengning County
Suitable area	Xinglong County, Weichang County, Longhua County	Weichang County, Chengde County, Xinglong County
Relatively suitable area	Weichang County, Longhua County, Chengde County	Weichang County, Fengning County, Longhua County
Less suitable area	Fengning County, Weichang County, Longhua County	Fengning County, Luanping County, Pingquan County
Unsuitable area	Fengning County, Weichang County, Longhua County	Weichang County, Longhua County, Chengde County

4.2. The Discrepancy Analysis of Evaluation Results

This article uses the standard deviation ellipse tool in ArcGIS to analyze the discreteness of evaluation results. This tool can analyze the directionality and discreteness of data, where the long axis of the ellipse represents the directionality of the data, and the short axis represents the discreteness of the data. The longer the short axis, the better the discreteness of the data, and vice versa. From Figure 10 and Table 15, it can be seen that among the five evaluation levels, the elliptical short axis lengths of the most suitable, suitable, and less suitable areas based on the variable-weight model are all longer than those based on the constant-weight model. The elliptical short axis lengths of the more suitable areas are relatively close, while the elliptical short axis lengths of the unsuitable areas differ greatly. However, due to the small unsuitable area of the variable-weight evaluation results (only 0.61%). Therefore, from an overall analysis, it is found that the evaluation results based on the variable-weight model have better discrete data. This is because the variable-weight model starts from the whole to the local, fully considering the changes in various parameters within a certain evaluation unit, and allocates different evaluation index weights for each evaluation unit based on the evaluation nature and purpose, which is more in line with reality.

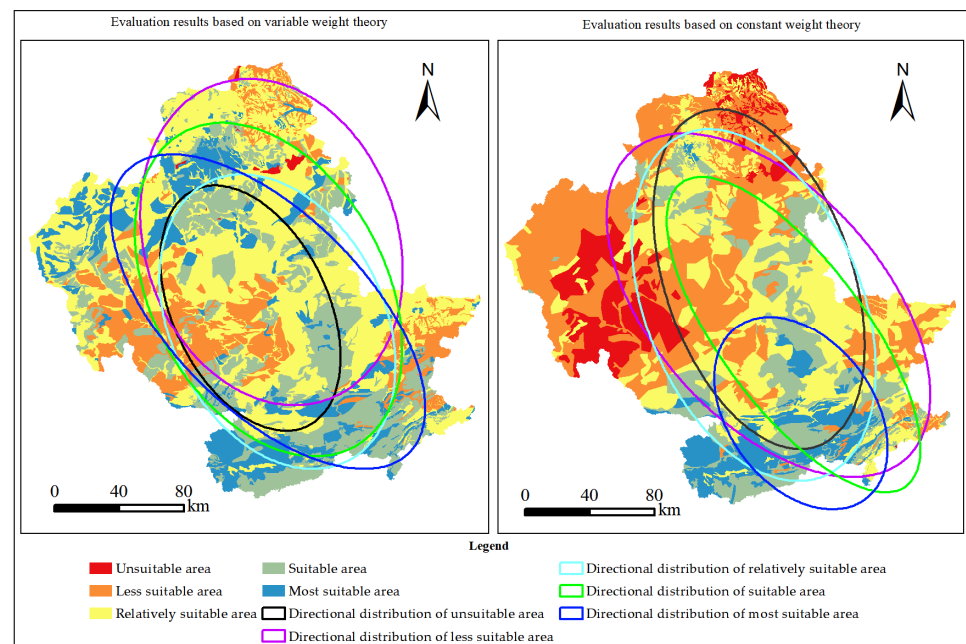


Figure 10. Comparison of standard deviation ellipses of evaluation results based on constant-weight evaluation model and variable-weight evaluation model.

Table 15. Comparison table of short axis length based on different evaluation models.

Suitability Level	The Length of the Short Axis of the Standard Deviation Ellipse		The Difference in Length of the Short Axis
	Based on Constant-Weight Model	Based on Variable-Weight Model	
Most suitable area	44,741.63	60,549.27	15,807.64
Suitable area	45,044.06	72,243.92	27,199.86
Relatively suitable area	66,783.83	65,734.70	−1049.13
Less suitable area	71,200.12	77,957.52	6757.4
Unsuitable area	57,793.17	47,902.11	−9891.06

4.3. The Accuracy Analysis of Evaluation Results

In order to verify the accuracy of the evaluation results, this article compares and analyzes the operational effectiveness of existing projects with the evaluation result layer. Based on expert analysis and judgment, this article proposes to evaluate the operational effectiveness of the project from two aspects: the power consumption and recharge rate. The classification threshold for power consumption is mainly based on the heating and cooling costs of about 30 RMB/m² in the study area under centralized heating in winter and air-conditioning cooling in summer, which is equivalent to a power consumption of about 50 kWh/m². Considering the high initial investment cost of SGE, if the energy consumption of SGE engineering is greater than 50 kWh/m², its operating effect will be judged as poor from the perspective of energy consumption. If the energy consumption is less than 30 kWh/m², equivalent to a cost of about 18 RMB/m², which is less than 60% of the average cost, it is considered to have a good operating effect. If the energy consumption is between the two, it is considered that its operating effect is average. The grading threshold for the recharge rate is mainly determined based on expert experience. Therefore, based on the collected data of the existing SGE development and utilization projects with underground water sources, the operational effects of the following four projects were investigated and interviewed from two aspects: the recharge rate and power consumption. According to the judgment matrix (Table 16), their operational effects were determined as shown in Table 17. Through investigation and analysis, among the existing four projects, there is one project with a good operating effect, two projects with a moderate operating effect, and one project with a poor operating effect.

Table 16. Engineering operation effect judgment matrix.

Annual Power Consumption (kWh/m ²)	Recharge Rate (%)		
	>80	>50 and ≤80	≤50
≤30	Good operating effect	Moderate operating effect	Poor operating effect
>30 and ≤50	Moderate operating effect	Moderate operating effect	Poor operating effect
>50	Moderate operating effect	Poor operating effect	Poor operating effect

Table 17. Statistical table of existing engineering operation effects.

Project Number	Recharge Rate (%)	Annual Power Consumption (kWh/m ²)	Operating Effect
1#	100%	28.37	Good operating effect
2#	80%	34.28	Moderate operating effect
3#	80%	36.70	Moderate operating effect
4#	30%	72.99	Poor operating effect

We verify and analyze the evaluation effect based on the variable-weight model based on the operational performance of existing engineering points. From Figure 11 and Table 18, the following can be seen: In the evaluation result layer based on the variable-weight model, the one project with a good operating effect is located in the suitable area, the two projects with a moderate operating effect are located in the relatively suitable area, and the projects with a poor operating effect are also located in the relatively suitable area. It can be seen that, except for the one project with a poor operating effect, the suitability areas of the other three projects are in good agreement with the evaluation results of the operating effect. In the evaluation result layer based on the constant-weight model, all the projects are located in the suitable area. Except for one project with good operating effects, the suitability areas of the other three projects do not match the evaluation results of the operating effects. It can be seen that the evaluation results based on the variable-weight model are more accurate and in line with reality.

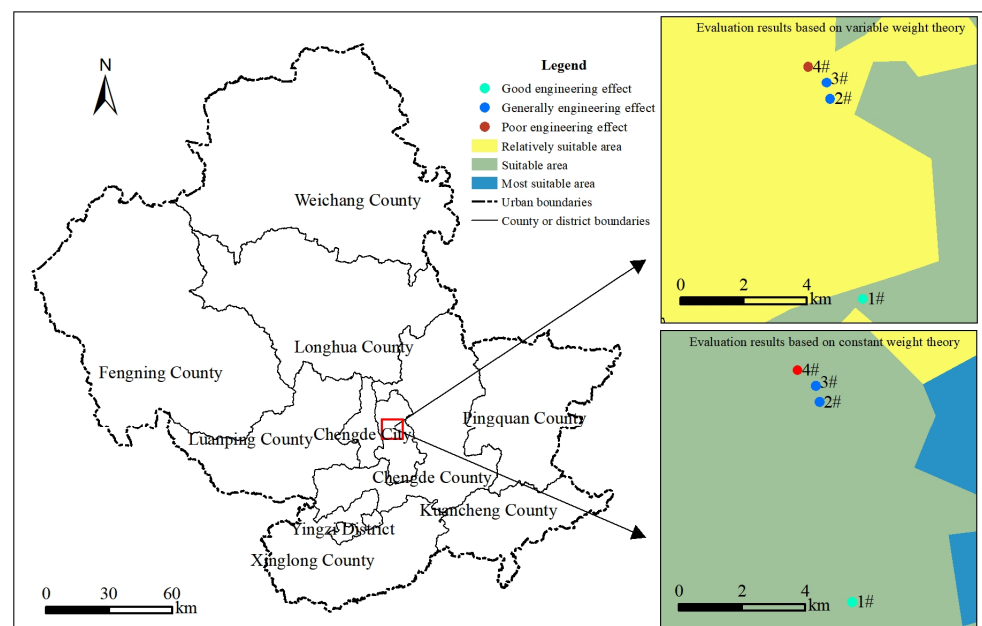
**Figure 11.** Local comparison of evaluation results based on constant-weight evaluation model and variable-weight evaluation model.

Table 18. Comparison table of existing engineering evaluation results based on different evaluation models.

Project Number	Operating Effect	Based on Constant-Weight Model	Matching with Evaluation Results	Based on Variable-Weight Model	Matching with Evaluation Results
1	Good operating effect	Suitable area	Matched	Suitable area	Matched
2	Moderate operating effect	Suitable area	Mismatched	Relatively suitable area	Matched
3	Moderate operating effect	Suitable area	Mismatched	Relatively suitable area	Matched
4	Poor operating effect	Suitable area	Mismatched	Relatively suitable area	Mismatched

5. Conclusions

This article takes Chengde City, Hebei Province as the research object, analyzes the basic conditions, and constructs an evaluation index system and quantitative methods. AHP, FCM, and model inverse algorithms were used to calculate relevant parameters and establish a variable-weight evaluation model to evaluate and partition the suitability of SGE development. The main conclusions were as follows:

- (1) Compared with the evaluation results of the constant-weight model, the evaluation graph based on the variable-weight model has relatively good discreteness, and the variable-weight evaluation model can adjust the weights of each evaluation index based on the index state values. It can meet the preferences of decision-makers for evaluation indices in different combination states, thus overcoming the limitations of fixed weights in traditional constant-weight evaluation models.
- (2) Through the verification and analysis of existing projects, the evaluation results based on the variable-weight model have a higher accuracy. The evaluation method based on the variable-weight theory can accurately reflect the suitability of SGE development in different regions of the study area, and provide a reference for its scientific development and utilization.

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Appendix A

The geological conditions mainly include the stratigraphic lithology and geological structure. This article mainly considers the impact of the stratigraphic lithology on the recharge capacity. Hydrogeological conditions refer to the general term for conditions related to the formation, distribution, and variation of groundwater. This article mainly considers the water-richness, hydraulic conductivity, and thickness of aquifers related to the development of SGE.

1. The water-richness of aquifers

The water-richness of an aquifer represents its water output capacity and is a measure of the water output of the aquifer during groundwater extraction. It is generally expressed as the maximum water inflow of a specified diameter wellbore. This article mainly discusses the suitability of developing groundwater source heat pumps. The water-richness determines the performance of the water source heat pump system to extract heat for building heating and cooling. If the water content of the aquifer is poor, it will affect the use of it. To ensure the required water volume for the heat pump system, it may be necessary to drill more holes. If so, it will increase the initial investment cost, which is not conducive to the development of SGE. Therefore, from the perspective of aquifer water-richness, the better the regional water-richness is, the more suitable it is for developing SGE. This article classifies the water-richness of the study area on the basis of a 1:200,000 hydrogeological survey in the early stage.

2. Hydraulic conductivity

The hydraulic conductivity is an index that comprehensively reflects the permeability of the rock and soil, indicating the difficulty of fluid passing through the pore skeleton. It determines the water yield and recharge efficiency, and also affects the flow aggregation of groundwater. If it is too small, groundwater cannot flow in the soil or the flow rate is very slow. This will affect the flow and convergence of groundwater, as well as reduce the water output and recharge capacity. These impacts are not conducive to the development of SGE. Therefore, from the perspective of hydraulic conductivity, the larger it is, the more suitable it is for developing SGE, and vice versa. The hydraulic conductivity in this article is derived from the data collected from the hydrologic exploration holes in the study area.

3. Recharge capacity

The recharge capacity is a measure of the ability to inject water from other sources into the ground through artificial measures. It determines the conditions of recharge, and the lack of a recharge capacity may lead to difficulty in recharging, a decrease in groundwater level, and geological environment problems such as surface subsidence. The better the recharge capacity is, the more suitable it is for developing SGE, and, when it is the reverse case, the less suitable it is [38,39]. The recharge capacity is greatly affected by geological conditions, and the recharge capacity is different in different rock strata. On the basis of a 1:200,000 hydrogeological survey in the early stage, this article classifies the recharge capacity of different rock formations by consulting experts and the literature.

4. Aquifer thickness

The thickness of the aquifer refers to the total thickness of the aquifer in the soil layer or rock layer. It mainly affects the water yield of a single well. The greater the aquifer thickness is, the more suitable it is for exploiting the SGE of an underground water source, and, when it is the reverse case, the less suitable it is. The aquifer thickness data in this article are collected from the hydrologic exploration boreholes in the study area.

Appendix B

The groundwater conditions mainly include the sources of groundwater recharge, burial conditions, runoff, discharge, water quality, and quantity. This article mainly considers the mineralization degree of groundwater and the average temperature of groundwater.

1. Mineralization of groundwater

The mineralization degree of groundwater is the mass of soluble salts in a unit volume of groundwater. If the mineralization is high, the number of ions in groundwater will be higher, and reactions between ions will cause an increase in the tendency for scaling. This will accelerate the scaling rate of equipment and pipelines. Scaling can cause pipeline blockage, and studies have shown that, when the mineralization degree of groundwater is less than 10 g/L, there is a linear relationship between the mineralization degree and

the corrosion rate of pipelines [40]. The blocking and corrosion of pipelines can affect the service life and heat exchange efficiency of water source heat pump units, and also increase maintenance costs in the later stage. Therefore, from the perspective of groundwater mineralization, the lower the groundwater mineralization is, the more suitable it is for developing SGE, and vice versa. The data of groundwater mineralization in this article are collected from the groundwater quality test report in the study area.

2. Average temperature of groundwater

This article mainly involves the average temperature of groundwater within a depth range of 200 m below the surface. It determines the energy efficiency ratio of the groundwater source heat pump; the lower temperature in winter will cause the heat pump unit to consume more electricity and extract less heat, and the energy efficiency ratio is lower. The high temperature in summer will also reduce its energy efficiency ratio, and cannot meet the building load. The average temperature of underground water is relatively high, which is suitable for the development of SGE of an underground water source, but not suitable in the opposite case. The average groundwater temperature data in this article are derived from the groundwater monitoring data collected in the study area.

Appendix C

Drilling conditions refer to the difficulty of drilling, mainly related to the cost of drilling. The economy is the main restriction factor of the promotion and development of the ground source heat pump; different geological conditions and a different drilling difficulty will cause the early investment cost difference. The difficulty of drilling in the loose soil layer of the Quaternary system differs greatly from that in other formations. If it is hard rock and soil, it will increase the construction period and cost. In this article, based on the collected drilling data and the hourly drilling progress, the weighted average method is used to express the drilling difficulty of different holes, and the drillability (m/h) is used to characterize the drilling difficulty. The calculation formula is as follows:

$$P = L/T \quad (A1)$$

where P is the drillability, L is the hole depth (m), and T is the effective drilling time (h).

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