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# Suitability evaluation of shallow geothermal energy development model based on variable weight theory

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## ABSTRACT

With the rapid development of ground-source heat pump (GSHP), it is necessary to evaluate the suitability zoning of shallow geothermal energy, which is in order to avoid the waste of resources and the restriction of popularization of GSHP. However, due to the difference between geology and hydrogeology, the conventional evaluation method of shallow geothermal energy suitability is prone to the poor accuracy of index weight and non-accuracy and does not conform to the objective facts. Therefore, this paper takes Chengde area as the research area to construct the evaluation system of vertical ground source heat pump (VGSHP). Based on the variable weight theory, combined with analytic hierarchy process and fuzzy C-cluster analysis, ArcGIS is used to evaluate the suitability of VGSHP in Chengde area, and the zoning map of variable weight and constant weight suitability evaluation is obtained. Combined with the actual conditions for shallow geothermal energy (SGE) development, the accuracy of the suitability evaluation of shallow geothermal energy development based on the theory of variable weight is verified by comparing and analyzing the variable weight diagram and the constant weight diagram.

## 1. INTRODUCTION

Shallow geothermal energy (SGE) is a green, low-carbon, clean and renewable energy with the advantages of wide distribution, large reserves and high economy (Ma et al., 2015) which has been developed rapidly. As a technology to develop SGE, vertical ground source heat pump (VGSHP) is favored for its stable operation, high efficiency, low initial investment, simple design and construction, and has been widely developed in practical projects. With the rapid development of this technology in the development and utilization of SGE, the phenomenon of blind development of SGE without exploration, planning and design appears in this field, which not only fails to achieve green mining, but also causes waste of resources. Therefore, to carry out the suitability evaluation research of SGE developing mode, scientifically and reasonably plan the development and utilization of SGE, delimit the accurate suitability zoning of development mode, and grasp its applicability from a macro perspective (Yin et al.,) green and efficient exploitation of SGE is the key problem to be solved at present.

Therefore, domestic and foreign scholars have done a lot of research on the suitability evaluation of shallow geothermal energy and achieved fruitful results. Foreign researchers mainly use various software to evaluate the suitability of shallow geothermal energy, and discuss the thermal properties of soil, types of heat exchangers and influencing factors of heat transfer (Bertermann et al., 2015; Gemelli et al., 2011; Erol et al., 2012; Santilano et al.;

2016). Chinese researchers have evaluated the suitability of SGE by using analytic hierarchy process (AHP), fuzzy comprehensive method and entropy weight method (Goodchild et al., 2004; Rybach et al., 2000; Lund et al., 2003) from the aspects of geology, hydrogeological conditions, economy, environmental protection and project development mode, which made certain achievements (Wang et al.; 2017; Wang et al.; 2020; Wang et al.; 2017). The previous studies on the suitability evaluation of the exploitation and utilization of SGE are mainly based on the analytic hierarchy process (AHP), combined with some methods to determine the constant weight, which are used to analyze and study from the overall macro perspective. The objective role of each main controlling factor is viewed at a macro level, lacking the consideration of areas with large differences between geological conditions and hydrogeological conditions. It is easy to cause the phenomenon of low accuracy and does not accord with the objective facts. While, the variable weight theory can reflect the abrupt change of the index value of the suitability control factor and the influence of different index combinations on the suitability evaluation (Li et al., 2004), which can also flexibly adjust the weight of each factor of each evaluation unit. In this paper, Chengde area is taken as the research area. Based on the variable weight theory and combined with the AHP, the weight contribution of each main control factor index to influencing the suitability evaluation is determined by establishing the main control index system. ArcGIS is used to realize the integration of main control factors, and the suitability evaluation model for the development of SGE by VGSHP is established. The reasonable evaluation model is determined by model identification test. Fuzzy C-means clustering was used to improve the classification method of the variable weight interval of the suitability of SGE, and the evaluation zone threshold was determined. Finally, the evaluation zone map of the suitability of the VGSHP for the development of SGE was obtained.

## 2. BASIC PRINCIPLE OF VARIABLE WEIGHT

The variable weight theory was proposed by Chinese scholars. The essence of variable weight theory is that factor weight will be adjusted according to the corresponding factor status index value, which can better make the weight serve the role of corresponding factors in the evaluation system. In this way, the fixed weight in the traditional constant weight evaluation can be changed, so as to make the comprehensive decision more reasonable and scientific, which can also better reflect the influence of the state changes of corresponding factors on the decision system. The variable weight vector is based on the factors of the constant weight vector, and the state variable weight vector is used to properly readjust and allocate the weight, so as to obtain the weight value in line with the decision maker's attitude (Li, 1996). At present, variable weight theory is mainly divided into three types of decision models: incentive variable weight, penalty variable weight and mixed variable weight (Li et al., 2004). The high value of incentive index plays a role in promoting suitability. The low value of the penalty index that hinders the suitability is not incentivized or punished for the general value.

### 2.1 Variable weight model

Based on the variable weight theory, the state vector should be constructed on the basis of meeting the requirements of comprehensive evaluation of suitability. The appropriate parameter values in the state vector conforming to the expected weight should be back calculated. To determine the parameters of the state variable weight vector, the mathematical function of the state variable weight vector studied by predecessors (Duan, 2003) is used to determine the variable weight vector of the penalty zone, the non-excitation non-punishment zone, the initial excitation zone and the strong excitation zone. The variable weight vector is synthesized into the piecewise function as follows:

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

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 the $J_{TH}$ factor variable weight interval. As shown in Figure 1, it is divided into four different intervals according to the interval threshold of state variable weight vector-based variable weight.

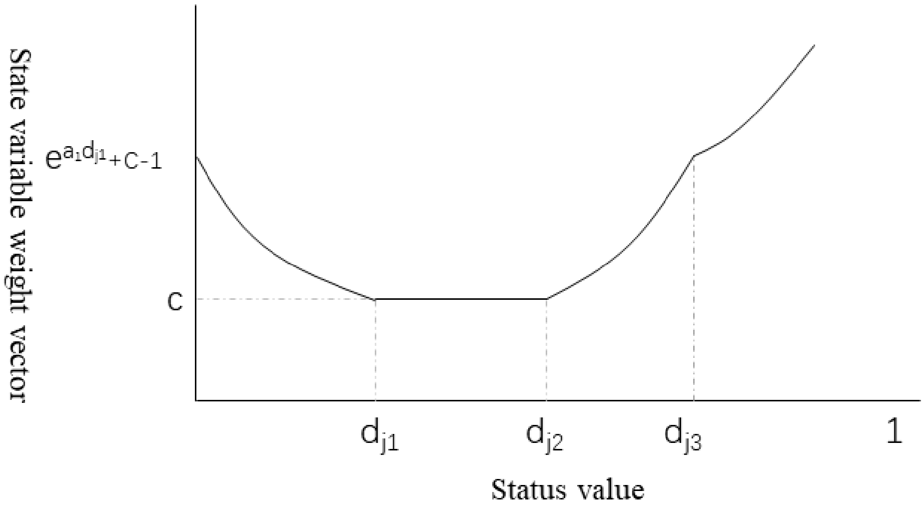


**Figure 1: State variable weight vector variable weight function diagram (Li Bo, 2014)**

Based on the variable weight theory, the shallow geothermal energy suitability evaluation model is constructed. Considering the geological conditions, hydrogeological conditions, drilling difficulty and other factors affecting the suitability evaluation, the mathematical model reflecting the interaction of multiple factors is established, which can directly reflect the SGE suitability evaluation zone of a certain location. The final variable weight model is as follows:

$$W(x)=\sum_{i=1}^{n}\frac{w_i^{(0)}S_i(x)}{\sum_{j=1}^{n}w_j^0 s_i(x)}f_i(x,y)=\frac{w_1^{(0)}S_1(x)}{\sum_{j=1}^{n}w_j^0 s_i(x)}f_i(x,y)+\frac{w_2^{(0)}S_2(x)}{\sum_{j=1}^{n}w_j^0 s_i(x)}f_i(x,y)+$$

$$\frac{w_3^{(0)}S_3(x)}{\sum_{j=1}^{n}w_j^0 s_i(x)}f_i(x,y)+\frac{w_4^{(0)}S_4(x)}{\sum_{j=1}^{n}w_j^0 s_i(x)}f_i(x,y)+\ldots+\frac{w_n^{(0)}S_n(x)}{\sum_{j=1}^{n}w_j^0 s_i(x)}f_i(x,y) \quad (2)$$

Where: W(x)- variable weight suitability evaluation value, $w_i^{(0)}$-any constant weight vector; $f_i(x,y)$-single factor influence function; S(x)-n dimension partition state variable weight vector; n is the number of influencing factors.

## 3. EVALUATION METHOD OF THE SUITABILITY OF VGSHP BASED ON VARIABLE WEIGHT THEORY

### 3.1. Determination of main control factors for suitability evaluation of VGSHP

Based on the variable weight theory, the suitability evaluation of the VGSHP for the exploitation and utilization of SGE is carried out. On the basic of the characteristics of the VGSHP for the exploitation of SGE, the suitability evaluation is carried out by affecting the mining conditions, operating conditions and economy of the VGSHP. Therefore, combined with the general situation of geology, hydrogeology and geothermal energy occurrence conditions in research area, the relevant data and literature are collected (Li et al., 2012; Yuan and Chen, 2013). The following aspects should be considered:

1) Geological and hydrological conditions: the geological conditions and hydrogeological conditions determine the characteristics of SGE resources. The water-abundance capacity of aquifer and the groundwater depth determine the groundwater flow, which has a great impact on the heat exchange performance of borehole heat exchangers. The thickness of the Quaternary system not only affects the thermal conductivity and thermal storage performance of the formation, but also is a part of the difficulty in evaluating drilling construction. Therefore, the three indexes of the Quaternary system thickness, the groundwater depth and the aquifer thickness are used as the main factors to affect the evaluation of its suitability.

2) Temperature field and thermophysical properties: The temperature field and thermophysical properties determine the heat exchange performance of borehole heat exchangers. The heat exchange of a single hole and the heat exchange per linear meter have a certain impact on the design, number of holes, and initial investment of the borehole heat exchangers. The thermal conductivity of rock and soil directly reflects the rate of heat transfer and exchange, and directly affects the heat transfer capacity of VGSHP. Specific heat capacity can reflect the ability to release or absorb heat when the temperature of rock and soil mass changes. Geothermal gradient intuitively shows the characteristics of underground rock and soil heat occurrence. Therefore, geothermal gradient, average specific heat capacity and thermal conductivity are used as the index factors for evaluating the suitability of VGSHP.

3) Construction conditions: The construction difficulty not only affects the construction difficulty and initial investment of drilling, but also has a certain impact on the effective depth of heat exchange hole. Formation lithology and particle size affect the difficulty of drilling and increase the initial investment cost and construction time cost. According to the economic conditions of Chengde urban and rural areas, the initial investment cost affects the promotion and implementation of the buried pipe ground source heat pump technology.

To sum up, the VGSHP suitability evaluation system constructed in this paper is mainly considered from three aspects: geological and hydrological conditions, temperature field and thermal properties, and construction conditions. There are seven indexes in total: Quaternary thickness, groundwater depth, aquifer thickness, geothermal gradient, average specific heat capacity, thermal conductivity and drilling difficulty.

### 3.2. Establishment of thematic map of main control factors

Based on the variable weight theory, to evaluate the suitability of VGSHP in Chengde rural areas, it is necessary to use SUFER software for interpolation calculation and processing of the collected original data. And it is imported into ArcGIS for processing, generate thematic maps of main control factors and establish attribute database. Thematic maps of main control factors are established as follows. Among them, the data of quaternary thickness, groundwater depth, aquifer thickness, geothermal gradient and thermal conductivity were collected by means of drilling data, thermal physical properties experiment, pumping experiment and thermal response experiment. The average specific heat capacity is the data of borehole, borehole histogram and thermal physical property test. The proportion of exposed layers and the specific heat capacity of different lithologies are weighted to calculate the average specific heat capacity of borehole as a whole. The drilling difficulty is based on the drilling progress per hour (Li, 2017; Hu, 2021), and the weighted average method is used to obtain data to represent the drilling difficulty of different holes, and the drill ability (m/h) is used to show its difficulty.

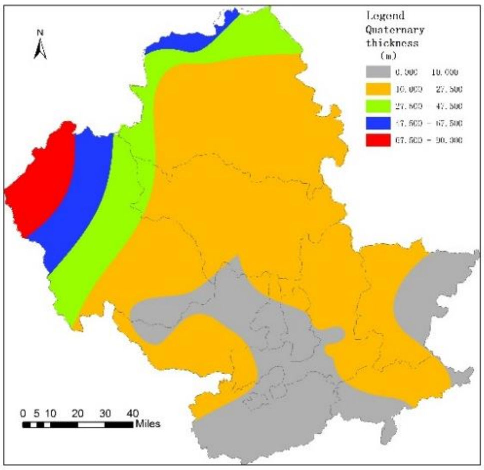


**Figure 2: Thematic map of Quaternary thickness**

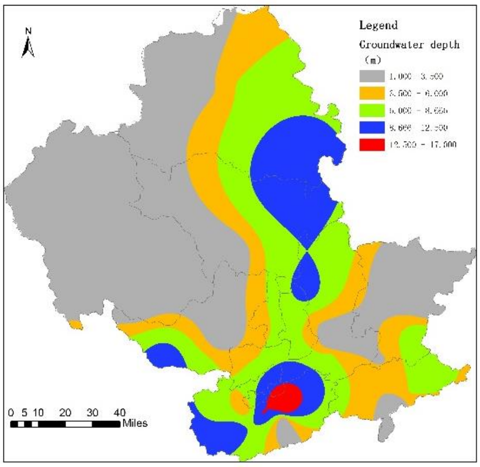


**Figure 3: Thematic map of groundwater depth**

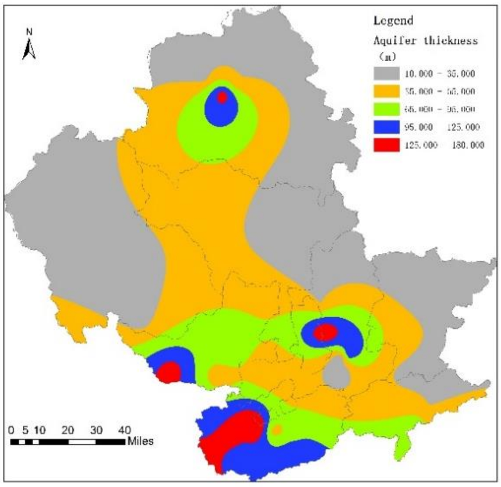


Figure 4: Thematic map of aquifer thickness

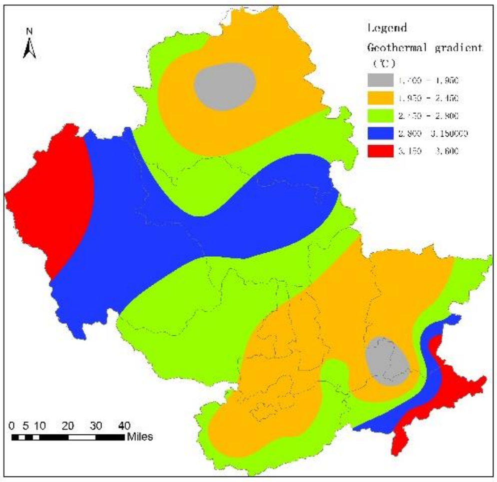


Figure 5: Thematic map of geothermal gradient

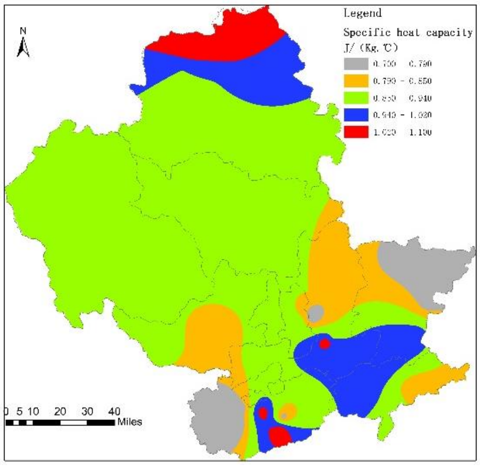


Figure 6: Thematic map of specific heat capacity

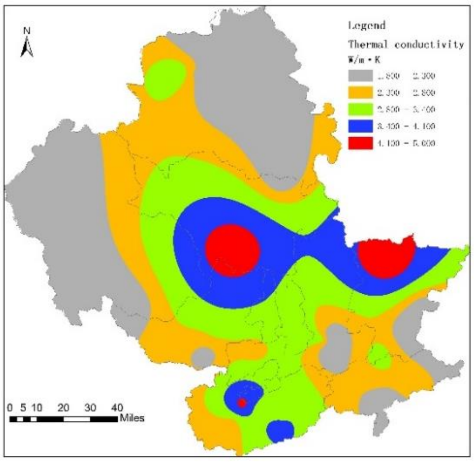


Figure 7: Thematic map of thermal conductivity

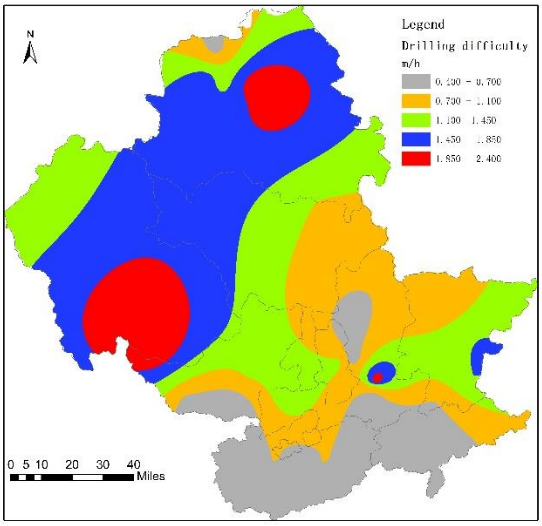


Figure 8: Thematic map of drilling difficulty

### 3.3. Normalization of thematic maps

The unit and magnitude of each main control factor in the suitability evaluation of VGSHP are different, which cannot be directly compared. The normalization method is used to make dimensionless treatment of each main control factor. The main normalization methods are minimum value method and maximum value method.

(1) Minimum method

$$A_{ij}=\frac{X_{maxj}-X_{ij}}{X_{maxj}-X_{minj}} \tag{3}$$

(2) Maximum method

$$A_{ij}=\frac{X_{ij}-X_{minj}}{X_{maxj}-X_{minj}} \tag{4}$$

Where: $A_{ij}$ - normalized quantized value; $X_{ij}$ minimum value in quantized data; $X_{maxj}$ - the maximum value in the quantized data; $X_{minj}$ - The minimum value in the quantized data.

Among the selected main controlling factors, the normalization of the maximum value method was adopted including the thickness of the quaternary system, aquifer thickness, specific heat capacity, thermal conductivity, geothermal gradient and drilling difficulty, which are were all positively correlated with the adaptability evaluation. The groundwater level depth is negatively correlated with the suitability evaluation, which carried out by minimum value normalization. In the normalization process, the maximum and minimum values of each main control factor in the suitability evaluation of VGWHP were taken from the actual data of the thematic map, which did not change before and after normalization. ArcGIS was used to establish the normalized thematic map of each main control factor, as shown in Figure 9 to 15.

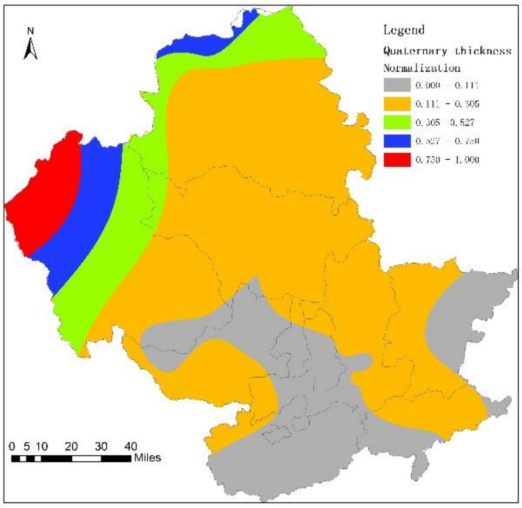


**Figure 9: Thematic map of quaternary thickness normalization**

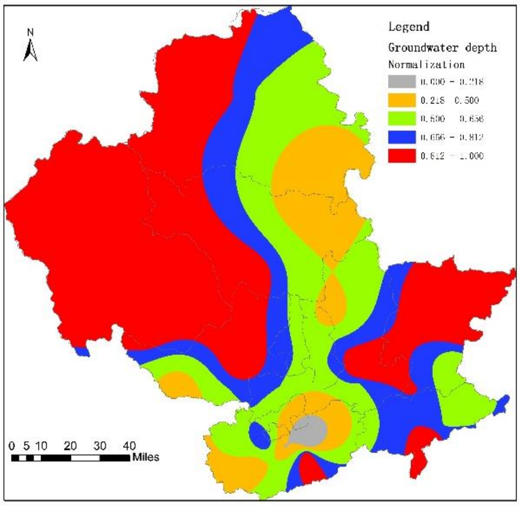


**Figure 10: Thematic map of groundwater depth normalization**

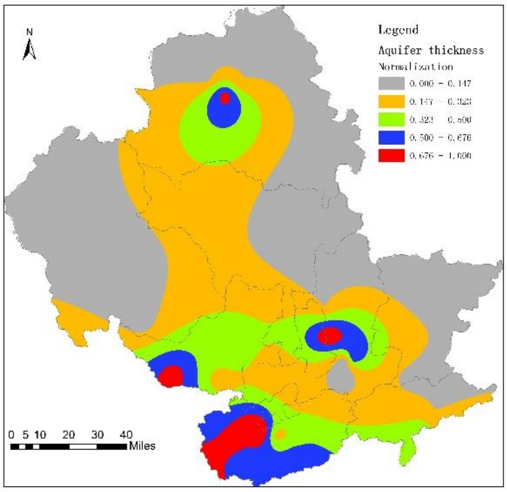


**Figure 11: Thematic map of aquifer thickness normalization**

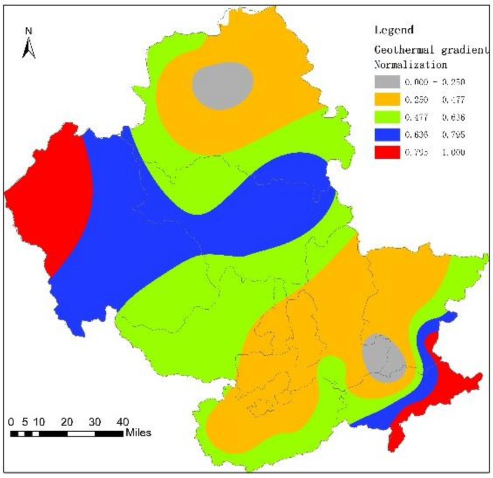


**Figure 12: Thematic map of geothermal gradient normalization**

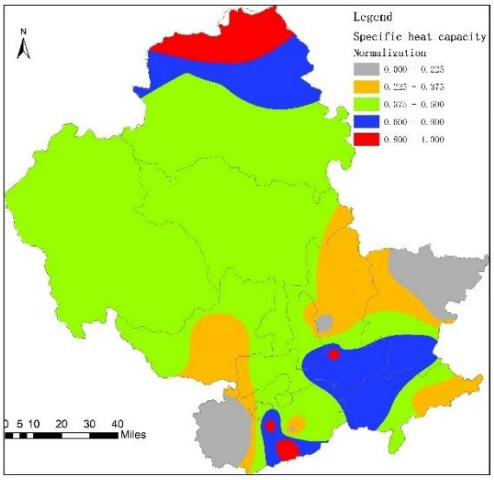


**Figure 13: Thematic map of specific heat capacity normalization**

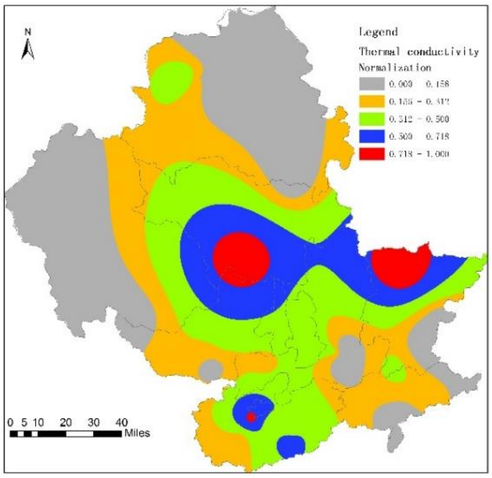


**Figure 14: Thematic map of thermal conductivity normalization**

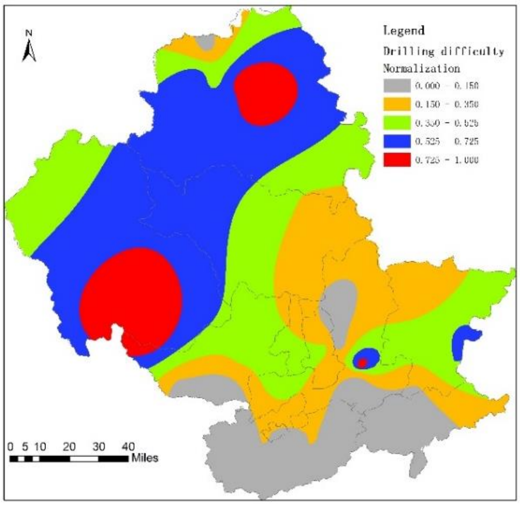


**Figure 15: Thematic map of drilling difficulty normalization**

### 3.4. Determination of constant weight

The suitability evaluation of VGWHP is a multi-index comprehensive evaluation method. The basic process is to determine the scientific evaluation index, carry out dimensionless processing, calculate the weight of each index and finally get the evaluation result. In this paper, the suitability evaluation essence is to rank the indexes of each main control factor, combined with the weight of the contribution to the suitability evaluation of VGWHP, to obtain a comprehensive ranking. Among them, the evaluation of the suitability of VGSHP development and utilization of SGE mainly uses the analytic hierarchy process (AHP) to obtain the index weight.

### 3.5. Weight determination

By analyzing the main controlling factors of VGWHP, the evaluation architecture model is divided into three levels, which are target layer A, attribute layer B and factor index layer C (Zhao, 2010). A is the suitability evaluation of VGWHP. Attribute target B is composed of geological and hydrological conditions, temperature field, thermal properties and construction conditions. Factor index C is composed of 7 indexes including quaternary thickness, groundwater depth, aquifer thickness, geothermal gradient, average specific heat capacity, thermal conductivity and drilling difficulty, as shown in Figure 16.

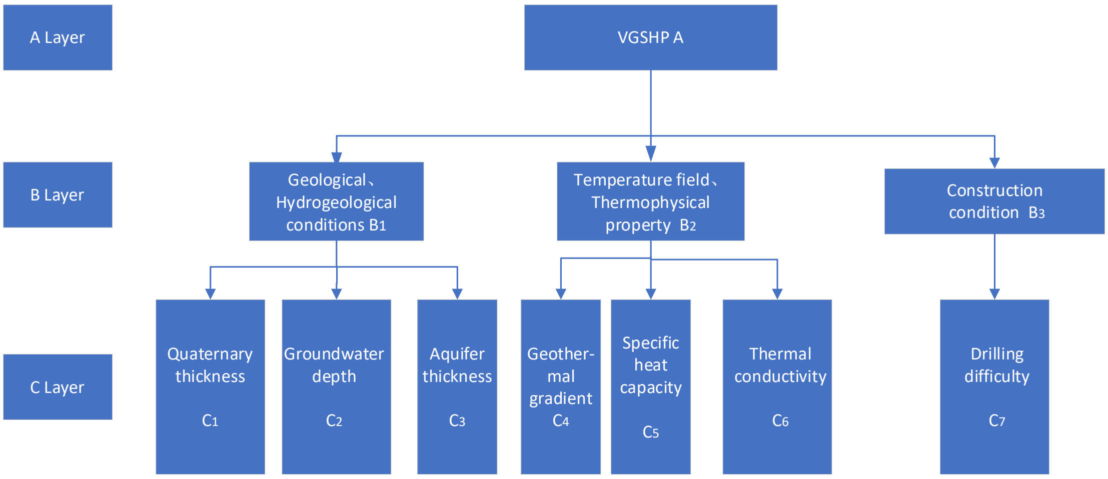


**Figure 16: AHP model for suitability evaluation of VGWHP**

In accordance with the requirements of AHP, on the basis of the determination of the staggered subordination and subordination of the evaluation system, the 1-9 scale method is adopted to evaluate the relative importance of each element in the factor layer respectively by consulting experts and relevant literature. The more important the score is, the larger the score is. Thus, the comparison matrix is constructed (Luo and Yang, 2004).

Table 1 Judgment matrix A～$B_i$ (i=1～3)

| A | $B_1$ | $B_2$ | $B_3$ | W(A/B) |
|---|---|---|---|---|
| $B_1$ | 1 | 1/2 | 2/3 | 0.2239 |
| $B_2$ | 2 | 1 | 4/5 | 0.3778 |
| $B_3$ | 3/2 | 5/4 | 1 | 0.3983 |

$\lambda_{max}$=3.0291; CR=0.0279<0.1; CI=0.0145<0.1

Table 2 Judgment matrix $B_1$～$C_i$ (i=1～3)

| $B_1$ | $C_1$ | $C_2$ | $C_3$ | W(B/Ci) |
|---|---|---|---|---|
| $C_1$ | 1 | 3 | 2 | 0.5499 |

| | | | | |
|---|---|---|---|---|
| $C_2$ | 1/3 | 1 | 1 | 0.2098 |
| $C_3$ | 1/2 | 1 | 1 | 0.2402 |

λmax=3.0183； CR=0.0176<0.1； CI=0.0091<0.1

Table 3 Judgment Matrix $B_2$～$C_i$(i=4-6)

| $B_2$ | $C_4$ | $C_5$ | $C_6$ | W(B/Ci) |
|---|---|---|---|---|
| $C_4$ | 1 | 7/3 | 7/5 | 0.4667 |
| $C_5$ | 3/7 | 1 | 3/5 | 0.2 |
| $C_6$ | 5/7 | 5/3 | 1 | 0.3333 |

λmax=3； CR=0<0.1； CI=0<0.1

Table 4 Judgment Matrix $B_3$～$C_i$(i=7)

| $B_3$ | $C_7$ | W(B/Ci) |
|---|---|---|
| $C_7$ | 1 | 1 |

λmax=1； CR=0<0.1； CI=0<0.1

It can be seen from each table that the calculated CR of each matrix is less than 0.1, which can pass the consistency test.

Table 5 The weight of each index to the target at the same level

| $C_i$ | Peer weight | $B_i$ weight | $B_i$ |
|---|---|---|---|
| $C_1$ | 0.5499 | | |
| $C_2$ | 0.2098 | 0.2239 | $B_1$ |
| $C_3$ | 0.2402 | | |
| $C_4$ | 0.4667 | | |
| C5 | 0.2 | 0.3778 | $B_2$ |
| $C_6$ | 0.3333 | | |
| $C_7$ | 1 | 0.3983 | $B_3$ |

Table 6 weight of main control factors affecting suitability evaluation of VGSHP

| Influencing factor | Quaternary thickness | Groundwater depth | Aquifer thickness | Geothermal gradient | Average specific heat capacity | Thermal conductivity | Drilling difficulty |
|---|---|---|---|---|---|---|---|
| Weight Wi | 0.1232 | 0.047 | 0.0538 | 0.1763 | 0.0756 | 0.1259 | 0.3983 |

### 3.6. Determination of variable weight interval of main control factors

Based on the variable weight theory, it is necessary to determine the parameters in the variable weight model to establish and apply the variable weight model when evaluating the suitability of buried pipes. Before determining the variable weight parameters, it is necessary to divide the weight adjustment range of each main control factor, which is used to define the weight adjustment range of the main control factor index value. Therefore, it is necessary to conduct hierarchical processing on each index value of VGSHP, which is to correspond to the weight adjustment mechanism of each index. Fuzzy C-means clustering method (FCM) is commonly used to grade evaluation indicators. Based on the ordinary C-means clustering method, FCM makes further fuzzy classification. It can describe the mediation of sample genus and determine the transaction membership relationship through membership function, and indicates the degree to which a sample belongs to a certain class, so as to achieve classification (Zhou, 2014).

FCM divides the data into four levels. By extracting clustering samples from ArcGIS database, fuzzy-C (number of clustering levels), weighted index "m" and key parameter iteration error "e" are determined. The FCM is implemented by input Python, and the index of each main control factor is classified by calculation. On this basis, the index value classification threshold fi is determined, as shown in Table 7.

Table 7 classification critical values of index values of each main control factors (normalization)

| Classification critical value | $f_1$ | $f_2$ | $f_3$ | $f_4$ | $f_5$ | $f_6$ |
|---|---|---|---|---|---|---|
| Quaternary thickness | 0.1111 | 0.1527 | 0.2500 | 0.3055 | 0.52778 | 0.5833 |
| Groundwater depth | 0.4063 | 0.4375 | 0.625 | 0.6563 | 0.7813 | 0.8125 |
| Aquifer thickness | 0.1765 | 0.2059 | 0.3235 | 0.3725 | 0.5588 | 0.5882 |
| Geothermal gradient | 0.2955 | 0.341 | 0.5000 | 0.5227 | 0.6818 | 0.7045 |
| Specific heat capacity | 0.3250 | 0.375 | 0.5250 | 0.5500 | 0.6833 | 0.7250 |
| Thermal conductivity | 0.2188 | 0.25 | 0.2969 | 0.4063 | 0.5938 | 0.6563 |
| Drilling difficulty | 0.1750 | 0.225 | 0.3750 | 0.4000 | 0.6250 | 0.6333 |

On the basis of determining the classification critical value, combined with formula (1), we calculated the weight threshold of variable weights according to formula (5):

$$d_1=( f_{j1}+ f_{j2})/2,\ \ d_2=( f_{j3}+ f_{j4})/2;\ \ d_3=(f_{j5}+ f_{j6})/2 \tag{5}$$

Where, $f_j$ is the classification critical value of the index value of the jth factor; $d_j$ is the variable weight interval threshold of the jth index. Therefore, the variable weight threshold interval of each main control factor is obtained as shown in Table 8.

Table 8 Variable weight interval based on fuzzy C-means clustering

| Interval property / Main control factor | Penalty interval | No incentive and no punishment interval | Initial incentive interval | Strong incentive range |
|---|---|---|---|---|
| Quaternary thickness | 0≤x≤0.1319 | 0.1319≤x≤0.2778 | 0.2778≤x≤0.5556 | 0.5556≤x≤1 |
| Groundwater depth | 0≤x≤0.4219 | 0.4219≤x≤0.6406 | 0.6406≤x≤0.7969 | 0.7969≤x≤1 |
| Aquifer thickness | 0≤x≤0.1912 | 0.1912≤x≤0.3480 | 0.3480≤x≤0.5735 | 0.5735≤x≤1 |
| Geothermal gradient | 0≤x≤0.3182 | 0.3182≤x≤0.5114 | 0.5114≤x≤0.6932 | 0.6932≤x≤1 |
| Specific heat capacity | 0≤x≤0.3500 | 0.3500≤x≤0.5375 | 0.5375≤x≤0.7042 | 0.7042≤x≤1 |
| Thermal conductivity | 0≤x≤0.2344 | 0.2344≤x≤0.3516 | 0.3516≤x≤0.6250 | 0.6250≤x≤1 |
| Drilling difficulty | 0≤x≤0.2000 | 0.2000≤x≤0.3875 | 0.3875≤x≤0.6292 | 0.6292≤x≤1 |

### 3.7. Parameter determination of variable weight model

In the variable weight model constructed for the VGSHP suitability evaluation, on the basis of determining the variable weight threshold interval, it is necessary to determine the adjustment weight parameters c, $a_1$, $a_2$ and $a_3$. These four groups of parameters can adjust and control the weight changes and characteristics of different main control factors. Where "c" can control and adjust the weight of the variable weight model; $a_1$, $a_2$ and $a_3$ can adjust the weight change amplitude of the three intervals of no incentive and no punishment, initial incentive and strong incentive respectively (Li, 2014). To determine the parameters of the model, it is necessary to reverse calculate the mathematical model. An evaluation unit is constructed from the evaluation system, including different main control factors, among which four main control factors should meet the basic requirements of being in the penalty interval, not stimulating and not punishing interval, initial excitation interval and strong excitation interval, and then a main control factor located in the penalty interval is selected. On the basis of the determined evaluation units, it is necessary to use the analytic hierarchy process to determine the weight value of the main control factors and the ideal variable weight of the main control factors to satisfy the objective facts and the preference of the decision maker. Among them, according to the constructed evaluation unit, the constant weight that meets the basic requirements of parameter evaluation is shown in Table 9.

Table 9 Construction of new evaluation constant weight value

| Main control factor | Specific heat capacity | Drilling difficulty | Thermal conductivity | Aquifer thickness | Quaternary thickness | Geothermal gradient | Groundwater depth |
|---|---|---|---|---|---|---|---|
| Weight | 0.0756 | 0.3983 | 0.1259 | 0.0538 | 0.1232 | 0.1763 | 0.0470 |

The index values of the average specific heat capacity, drilling difficulty, thermal conductivity and aquifer thickness in the newly constructed evaluation unit are located in different intervals. The Quaternary thickness is located in the penalty interval, while other values are located in the non-penalty and non-incentive interval. The index values are shown in Table 10:

Table 10 Index value of new construction unit

| Main control factor | Specific heat capacity | Drilling difficulty | Thermal conductivity | Aquifer thickness | Quaternary thickness | Geothermal gradient | Groundwater depth |
|---|---|---|---|---|---|---|---|
| Normalized value | 0.3167 | 0.2250 | 0.4063 | 0.6176 | 0.0741 | 0.4242 | 0.5938 |

According to the parameter determination method, it is necessary to determine the ideal variable weight of the average specific heat capacity, drilling difficulty, thermal conductivity and aquifer thickness distribution in the newly constructed unit. The ideal variable weight of the above four main control factors is determined as shown in Table 11 by consulting literature and experts, taking into account the role of each factor index value.

Table 11 Ideal weight values of evaluation units

| Main control factor | Specific heat capacity | Drilling difficulty | Thermal conductivity | Aquifer thickness |
|---|---|---|---|---|
| Ideal weight | 0.0836 | 0.3410 | 0.1200 | 0.1014 |

Table 12 Variable weight parameters

| Variable weight parameter | c | $a_1$ | $a_2$ | $a_3$ |
|---|---|---|---|---|
| Numerical | 0.73 | 5.75 | 1.45 | 8.98 |

**3.8. Study area variable weight model**

According to the parameter values determined by the evaluation unit, the variable weight model of the study area is determined:

$$W(x)=\sum_{i=1}^{n}\frac{w_i^{(0)}s_i(x)}{\sum_{j=1}^{n}w_j^0 s_i(x)}f_i(x,y)=\frac{w_1^{(0)}s_1(x)}{\sum_{j=1}^{n}w_j^0 s_i(x)}f_1(x,y)+\frac{w_2^{(0)}s_2(x)}{\sum_{j=1}^{n}w_j^0 s_i(x)}f_2(x,y)\frac{w_3^{(0)}s_3(x)}{\sum_{j=1}^{n}w_j^0 s_i(x)}f_3(x,y)+\frac{w_4^{(0)}s_4(x)}{\sum_{j=1}^{n}w_j^0 s_i(x)}f_4(x,y)+\frac{w_5^{(0)}s_5(x)}{\sum_{j=1}^{n}w_j^0 s_i(x)}f_{i5}(x,y)+\frac{w_6^{(0)}s_6(x)}{\sum_{j=1}^{n}w_j^0 s_i(x)}f_6(x,y)+\frac{w_7^{(0)}s_7(x)}{\sum_{j=1}^{n}w_j^0 s_i(x)}f_7(x,y) \quad (6)$$

$$Sj(X)=\begin{cases} e^{5.75(d_{j1}-x)}+0.73-1, & x\in[0,\ d_{j1}) \\ 0.73, & x\in[d_{j1},\ d_{j2}) \\ e^{1.45(x-d_{j2})}+0.73-1, & x\in[d_{j2},\ d_{j3}) \\ e^{1.45(x-d_{j3})}+e^{8.98(d_{j3}-d_{j2})}+0.73-2, & x\in[d_{j3},\ 1] \end{cases} \quad (7)$$

Where: J=1,2,3...7.$d_{j1}$, $d_{j2}$ and $d_{j3}$ are the thresholds of the variable weight interval of the jth main control factor. $w_i^0$ is the constant weight of the factor.

## 4. RESULTS AND DISCUSSION

### 4.1. Suitability evaluation zoning of VGSHP

The parameters and clustering data were obtained according to the above parameters and formulas, and the variable weights of each main control factor were calculated by MATLAB. The calculation was completed in ArcGIS according to formula 6, and the data in the attribute table was classified using the natural interrupt method in ArcGIS. And the suitability evaluation of the VGSHP was divided into five areas. They are respectively unfit area, low suitability area, suitable area, more suitable area and most suitable area, as shown in Figure. 17.

Most areas of Shuangluan District and Shuangqiao District of Chengde City are suitable areas with low suitability of VGSHP in Figure. 17. It is caused that the Quaternary system in this area has a small thickness, and the lithology is mainly pebble layer. In most areas of Longhua County in rural areas of Chengde, Kuancheng Manchu Autonomous County and Yingshou Yingzi mining area are unfit areas. Based on the variable weight theory, for the suitability evaluation area of buried pipes in Chengde, the most suitable area is 2722.14km$^2$, the more suitable area is 7749.33km$^2$, the suitable area is 11001.3km$^2$, the low suitable area is 9325.08km$^2$, and the unsuitable area is 8671.22km$^2$.

As shown in Figure. 17, in the suitability zone of rural VGSHP in Chengde, the suitable area, more suitable area and the most suitable area account for 54.4% of Chengde area, among which the most suitable area is relatively small and dispersed. The proportion of unsuitable area and low suitable area is 45.6%. The main reasons for this phenomenon are closely related to the climatic characteristics, geological structure characteristics and shallow thickness of the fourth series in Chengde. Therefore, Chengde City has a great potential for the development and utilization of shallow geothermal energy for VGSHP system, and it is highly feasible to promote clean energy to replace coal burning.

Table 13 Classification interval of variable weight suitability of VGSHP

| Most suitable area | More suitable area | Suitable area | Low suitable area | Unsuitable area |
|---|---|---|---|---|
| 0.6620-0.9591 | 0.5244-0.6620 | 0.4224-0.5244 | 0.3232-0.4224 | 0.1287-0.3232 |

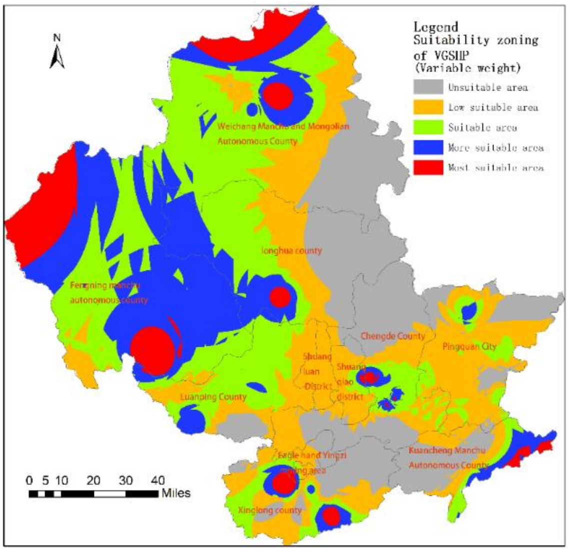


**Figure 17: The zoning diagram for suitability evaluation of VGSHP in Chengde area**

### 4.2. Suitability evaluation of constant weight model

The weights of the main controlling factors determined by the above chapters and the weights of the main controlling factors for the suitability evaluation of the VGSHP are as follows: the Quaternary thickness ($W_1$), the groundwater level ($W_2$), the aquifer thickness ($W_3$), the geothermal gradient ($W_4$), the specific heat capacity ($W_5$), the thermal conductivity ($W_6$) and the drilling difficulty ($W_7$), respectively.0.1232, 0.047, 0.0538, 0.1763, 0.0756, 0.1259, 0.3983.

The above data were substituted into the suitability evaluation model of constant weight respectively:

$$VI = \sum_{i=1}^{n} w_i f_i(x, y) \quad (8)$$

Where: *VI* is the suitability evaluation; $w_i$ is the influence factor constant weight; $f_i(x,y)$ is the single factor influence value function. The suitability results of VGSHP are calculated according to Eqs. 8.

Table 14 Classification interval of common weight suitability of VGSHP

| Most suitable area | More suitable area | Suitable area | Low suitable area | Unsuitable area |
|---|---|---|---|---|
| 0.5145-0.6244 | 0.4352-0.5145 | 0.3603-0.4352 | 0.2897-0.3603 | 0.1726-0.2897 |

According to the calculation of the subarea of the VGSHP suitability constant weight evaluation, it can be known that the most suitable area is 11789km$^2$, the more suitable area is 8288.48km$^2$, the suitable area is 7905.1km$^2$, the low suitable area is 6204.6km$^2$, and the unsuitable area is 5272.15km$^2$.

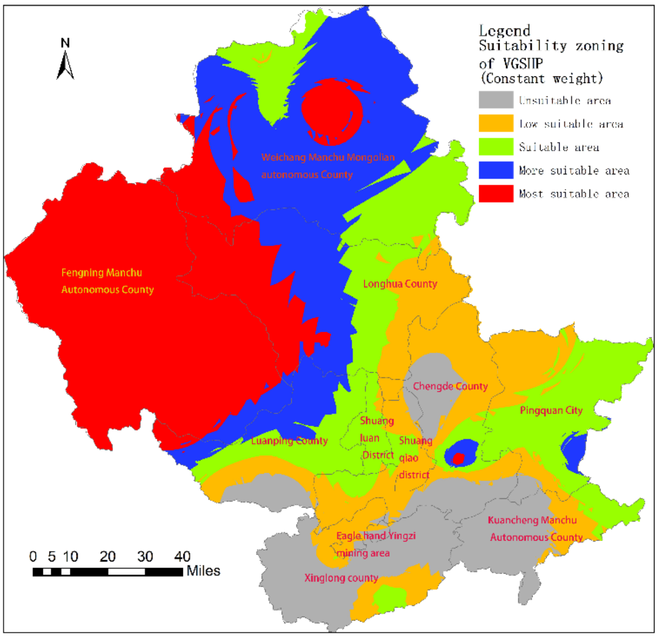


**Figure 18: The zoning map of suitability constant weight evaluation of VGSHP in Chengde area**

### 4.3. Comparison and analysis of constant weight and variable weight suitability evaluation zoning map

Through the evaluation of the suitability of VGSHP in the above chapters, variable weight evaluation zoning map and constant weight evaluation zoning map are obtained. Now, the results obtained by the two methods are compared and analyzed as shown in Figure.17 and 18.

It shows that the variable weight result diagram has good dispersion in Figure. 17, which accords with the characteristics of wide distribution of geological and hydrogeological conditions in rural areas. While the constant weight diagram shows a relatively clustered result with good integrity, but does not accord with the characteristics of rural distribution. For example, in the normal weight diagram of Fengning Manshu Autonomous County, the VGSHP is the most suitable area. The variable weight results show that the suitability distribution of VGSHP in this county is relatively discrete and the zoning is relatively complete.

By contrast, the suitable area, suitable area and the most suitable area of the VGSHP system with variable weight evaluation account for 54.4% in Chengde region, while the proportion of the most suitable area, suitable area and suitable area with constant weight is 70.9%, which is reduced by 16.5%. It is cause that the variable weight chooses the quaternary thickness and specific heat capacity as the penalty interval. It can be seen from the above normalized figure that the suitability of the two index values is relatively large, so the variable weight comprehensive weight will reduce the weight of the penalty interval, so as to conform to the objective fact.

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