Renewable Energy 184 (2022) 564–576

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Suitability evaluation system for the shallow geothermal energy implementation in region by Entropy Weight Method and TOPSIS method

Zhao Li [a], Zujiang Luo [a,*], Yan Wang [b], Guanyu Fan [c], Jianmang Zhang [c]

[a] School of Earth Sciences and Engineering, Hohai University, Nanjing, Jiangsu, 210 098, China
[b] Jilin Jianzhu University, Changchun, Jilin, 130 118, China
[c] Environmental Geology Exploration Institute of Jiangsu Province, Nanjing, Jiangsu, 211 102, China

ARTICLE INFO

Article history:
Received 11 May 2021
Received in revised form
31 October 2021
Accepted 28 November 2021
Available online 2 December 2021

Keywords:
Suitable evaluation
Shallow geothermal energy
Entropy weight method
TOPSIS Method

ABSTRACT

Shallow geothermal energy suitability map presents the potential for implementation in a region. The potential for implementation depends on hydrogeology, geotechnical, geology environment, and geothermal characteristics. Plenty of scholars evaluate shallow geothermal energy by the algorithm combined Analytic Hierarchy Process and Index Overlap. But Analytic Hierarchy Process and Index Overlap, as knowledge driven methods, rely on the experts' experience. This research presents a data driven algorithm based on Entropy Weight Method and TOPSIS Method. The weights are calculated by the Entropy Weight Method and assigned to the TOPSIS model. The closeness coefficient could be calculated by TOPSIS model. The suitability potential is analysed by comparing the closeness coefficient. The algorithm is accomplished by coding a program using Matlab. The algorithm is also applied to Nantong, China. Depending on the principle of ground source heat pump system, the suitability evaluation system of the open loop system and the closed loop system are established, respectively. Hydrogeology, geotechnical, geothermal, and geology environmental investigations are carried out to obtain the measured data and parameters for suitability analysis. The suitability maps are drawn in according with closeness coefficient. The algorithm is able to overcome the subjectivity of experts' experience. Compared with knowledge driven methods, the proposed algorithm tends to compare the relative potential in a region, rather than assess whether the site is suitable for SGE implementation. Consequently, it is more suitable for selecting the best field-site.

1. Introduction

Greenhouse gas emissions, climate change, and the rising energy demand are currently seen as most crucial environmental concerns. Renewable energy use is claimed to be at least a partial solution in order to reduce fossil energy consumption and related environmental impact as well as capital and operating and maintenance costs [1]. Shallow Geothermal Energy (SGE) is a kind of renewable energy. It has become popular to achieve space heating and cooling for the purpose of thermal comfort by SGE implementation all over the world, especially in Europe [2–4], North America [5–7], and Southeast Asia [8–10]. However, the potential for SGE implementation depends on field-site conditions, i.e. hydrogeology, geotechnical, and geothermal characteristics. Different field-site conditions would be resulted in the different economic value. It is important to evaluate the suitability in a region and select a high-potential field-site to exploit SGE.

Suitability analysis is used to establish the suitability of the process and procedures of some activity [11–13]. And it has been applied in a wide variety of situations, especially in suitability of land for agricultural activities [14,15]. The best field-site selection for SGE and the regional planning could be achieved by suitability analysis. Potential for SGE implementation is usually in relation to several attributes, such as hydrogeology, geotechnical and

* Corresponding author.
E-mail address: luozujiang@sina.com (Z. Luo).

https://doi.org/10.1016/j.renene.2021.11.112
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geothermal characteristics, etc. The essence of suitability evaluation is multi-criteria decision analysis.

The common method to assess the suitability is achieved by Analytic Hierarchy Process (AHP) and Index Overlap (IO) [16–18]. Tinti et al. presented a method to assess the suitability of SGE by Multi-criteria decision analysis using the AHP [19]. The method was applied to map the suitability zones in Europe. Sadeghi and Khalajmasoumi analysed the acidic volcanic and intrusive rocks, volcanoes, faults, hot springs, geothermal alterations in Northwestern Iran and studied the geothermal potential by binary IO and Fuzzy Logic methods [20]. The study presented that the central parts of the study area have more potential for detailed exploration in the future. But previous research indicated that the weight of the factors is important in the process of suitability evaluation. AHP, as knowledge driven methods, are based on the experts' experience. However, experts' experience will lead to subjective results. If the study area is large, it is nearly impossible to expect from the experts to obtain the detailed knowledge about every single locality in the study area.

Noorollahi et al. developed Boolean Logic and IO models for geothermal site selection [21]. The results were combined with environmental suitability analysis for final selection of well sites. Tüfekçi identify potential geothermal areas in western Anatolia, Turkey, using IO method and Weights of Evidence method, respectively [22]. The results were demonstrated by Aydın and Denizli, Turkey [23,24]. Aydın and Denizli, Turkey have been explored and exploited geothermal resources, and thus found to be favourable. Kiavarz and Jelokhani-Niaraki attempted to incorporate the concept of risk into the GIS-based analysis for suitability evaluation with different pessimistic or optimistic strategies via Ordered Weighted Averaging approach [25]. The approach was applied in Akita and Iwate provinces, Japan. Boolean Logic, Weights of Evidence, and Ordered Weighted Averaging, as data driven methods, could calculate the weight objectively. It demonstrates that data driven methods could eliminate weight problem. It is meaningful to get objective weight in the process of suitability evaluation.

Casasso and Sethi developed G.POT model, a quantitative method, to assess the SGE potential by a set of analytical heat transfer simulation [26]. The method was applied to the province of Cuneo, Italy [27]. Fujii et al. established a numerical model and simulated the heat exchange performance at different locations. The suitability maps for ground-coupled heat pump systems of Chikushi Plain, Japan were presented by the numerical simulation [28]. The quantitative calculation method is able to present suitability map objectively. But a large amount of calculation workload is required.

This paper presents an algorithm to evaluate the suitability for SGE implementation in the region by the Entropy Weight (EW) Method and the TOPSIS Method. The algorithm was coded using MATLAB. The algorithm could obtain the weight and rank suitable zones without experts' experience. The principle is simple and the calculation workload is small. We first identify the factors of suitability evaluation for SGE development by analysis of Ground Source Heat Pumps (GSHP) principle and successful exploiting SGE projects. And a series of factors will be selected to represent the criteria. Secondly, the weight of each factor will be calculated quantitatively by the EW Method. Thirdly, the exploitation potential of SGE will be calculated quantitatively by TOPSIS Method. Lastly, the proposed algorithm will be implemented to evaluate suitability potential for SGE implementation in Nantong, China.

2. Methodology

Aim at evaluating potential for SGE implementation in a region quantitatively, the algorithm mainly contains six steps. The steps are presented below:

- Step 1 : Establish a suitability evaluation system by the principle of GSHP implementation. The attributes that have an effect on the suitability system are determined, i.e. hydrogeology, geotechnical, geology environment, and geothermal characteristics. In addition, a series of factors which could present attributes characteristics are determined.
- Step 2 : Discretize the study area into grids. Each node would present a field-site.
- Step 3 : Investigate the hydrogeology, geotechnical, geology environment, and geothermal characteristics. Collect the measured data and parameters from field tests as factors. Insert and assign the factors to the grids.
- Step 4 : Calculate the weight of each factor by EW Method.
- Step 5 : Assign the weight to the factors. Calculate the closeness coefficient of each node. The potential will be determined by comparing the closeness coefficient.
- Step 6 : Map the suitability in a region.

2.1. Suitability evaluation system

The exploitation of SGE requires GSHP to transfer the heat. The GSHP can be classified generally as open loop system and closed loop system depending on the nature of the ground heat exchanger. The open loop system uses natural groundwater as a heat carrier. The closed loop system requires pipes to be placed in the ground. And the mixture of water and anti-freeze as a heat carrier circulation in the pipes, is separated from soil and groundwater. The schematic diagrams of GSHP system type and principle are shown in Fig. 1.

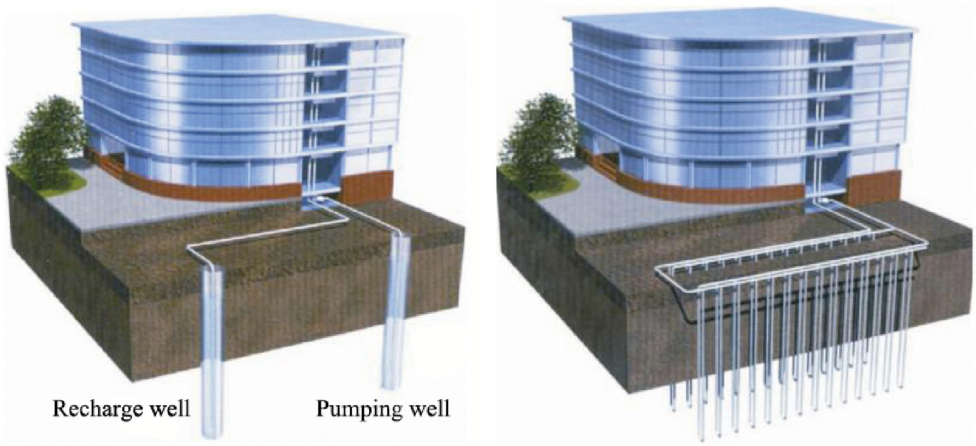
The applicable conditions of the open loop system and the closed loop system are different, due to the different principles. It is necessary to identify the factors for GSHP. Successfully exploiting SGE with the combined use of the GSHP technologies described above depends on the attributes as hydrogeology, geotechnical, geology environment, and geothermal characteristics. The suitability evaluation system for the open loop system and the closed loop system is established, respectively [29].

The open loop system requires pumping and recharging groundwater from the aquifer. The heat transport in the aquifer is dominated by heat convection. Heat transport is mainly influenced by hydrodynamic parameters, while thermal conductivity has a minor impact on the heat diffusion into the aquifer [30]. The ability of pumping and recharging groundwater is important. But groundwater abstraction would cause land subsidence. Consequently, seven factors are identified to evaluate the suitability of the open loop system. The suitability evaluation system of the open loop system is shown in Fig. 2.

The closed loop system is linked to Borehole Heat Exchangers (BHE) to capture or dissipate heat from the ground. A limit is therefore imposed on the thermal alteration of the heat carrier fluid, which mostly depends on the thermal parameters of the ground [31]. Consequently, seven factors are defined to evaluate the suitability for the closed loop system. The suitability evaluation system of the closed loop system is shown in Fig. 3.

2.2. EW method

EW Method is a branch of information theory. It can capture the implied interactions among factors and be commonly used to measure value dispersion in decision-making. The weight of each factor could be determined. The EW Method is mainly divided into the following steps [32–34]:



(a) the open loop system (b) the closed loop system

Fig. 1. Schematic diagrams of GSHP system type and working principle.

Step 1 : Construction of the initial decision matrix

The initial decision matrix is constructed as follows:

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \tag{1}$$

Where X is the initial decision matrix, m is the number of nodes for suitability evaluation, n is the number of factors, x_{ij} is the analysed values of each sample parameter, $i = 0, 1, 2, \ldots, m$, and $j = 0, 1, 2, \ldots, n$.

Step 2 : Normalization of the initial decision matrix

It is necessary to normalise the matrix, since dimension and metric of the data are not uniform. The normalised decision matrix can be expressed as following:

$$Y = \begin{bmatrix} y_{11} & y_{12} & \cdots & y_{1n} \\ y_{21} & y_{22} & \cdots & y_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ y_{m1} & y_{m2} & \cdots & y_{mn} \end{bmatrix} \tag{2}$$

$$\begin{cases} y_{ij} = \dfrac{x_{ij} - (x_{ij})^j_{min}}{(x_{ij})^j_{max} - (x_{ij})^j_{min}}, & (\textit{efficiency type}) \\ y_{ij} = \dfrac{(x_{ij})^j_{max} - x_{ij}}{(x_{ij})^j_{max} - (x_{ij})^j_{min}}, & (\textit{cost type}) \end{cases} \tag{3}$$

Where Y is the normalised decision matrix.

Step 3 : Calculation of the entropy

The entropy of each factor can is calculated as following:

$$e_j = -\frac{1}{\ln m} \sum_{i=1}^{m} p_{ij} \ln p_{ij} \tag{4}$$

$$p_{ij} = y_{ij} \Big/ \sum_{i=1}^{m} y_{ij} \tag{5}$$

Where e_j is the entropy of each factor.

Step 4 : Calculation of the weight

The weight of each factor can is calculated as following:

$$w_j = (1 - e_j) \Big/ \sum_{i=1}^{n} (1 - e_j) \tag{6}$$

Where w_j is the weight of each factor.

2.3. TOPSIS

TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) is used for solving multi-criteria decision analysis problems [35,36]. TOPSIS is based on the concept that the chosen alternative should have the shortest geometric distance from the positive ideal solution and the longest geometric distance from the negative ideal solution. The specific steps can be expressed as following:

Step 1 : Construction of the normalised decision matrix.

The normalised decision matrix is constructed as Eqs. (1) ~ (3).

Step 2 : Construction of the weighted decision matrix.

The calculated weight above is assigned to the normalised decision matrix as

$$Z = \begin{bmatrix} z_{11} & z_{12} & \cdots & z_{1n} \\ z_{21} & z_{22} & \cdots & z_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ z_{m1} & z_{m2} & \cdots & z_{mn} \end{bmatrix} \tag{7}$$

$$z_{ij} = w_j \times y_{ij} \tag{8}$$

Where Z is weighted decision matrix.

Step 3 : Determination of the positive and negative ideal reference points

The positive and negative ideal reference points can be outlined as follows:

$$Z^{+} = \{Z_1^{+}, Z_2^{+}, \ldots, Z_n^{+}\} = \{\max Z_{ij} | j = 1, 2, \ldots, m\} \tag{9}$$

$$Z^{-} = \{Z_1^{-}, Z_2^{-}, \ldots, Z_n^{-}\} = \{\min Z_{ij} | j = 1, 2, \ldots, m\} \tag{10}$$

Step 4 : Calculation of the distances to the positive and negative ideal reference points

$$S_i^{+} = \sqrt{\sum\nolimits_{i=1}^{n} (Z_{ij} - Z_j^{+})}, \qquad (i = 1, 2, \ldots, n) \tag{11}$$

$$S_i^{-} = \sqrt{\sum\nolimits_{i=1}^{n} (Z_{ij} - Z_j^{-})}, \qquad (i = 1, 2, \ldots, n) \tag{12}$$

Step 5 : Calculation of the closeness coefficient

The closeness coefficient can be calculated as follows:

$$C_i = \frac{S_i^{-}}{S_i^{-} + S_i^{+}} \tag{13}$$

Where C_i is closeness coefficient.

A schematic view of the workflow is shown in Fig. 4. The workflow contains the specific steps of evaluation suitability.

3. Application

3.1. Background

The proposed algorithm of suitability evaluation will be applied in Nantong, China. Nantong is located in the coastal regions of China. The geographic location is shown in Fig. 5. The study area is 800 km^2. The Quaternary deposit in coastal regions of China composed of clay, silt, sand, and gravel can be characterised by an alternating multi-aquifer-aquitard system (MAAS) [37]. The thickness of Quaternary sediments is approximately 200–360 m in Nantong [38]. Four aquifers are identified: phreatic aquifer, confined aquifer I, confined aquifer II, and confined aquifer III. Aquitards that separate the aquifers are, with increasing depth, referred to as aquitard I, aquitard II, and aquitard III [39]. The lithology of the phreatic aquifer is silt and sandy loam. The hydraulic head of the phreatic aquifer is 1 ~3 m depth approximately. And the thickness of is 20 ~30 m. The lithology of the confined aquifer I is fine-medium-grained sand. The roof depth of the aquifer is 50 ~60 m. The hydraulic head of confined aquifer I is 1 ~3 m depth approximately. The lithology of the confined aquifer II is fine sand, medium-coarse sand, and gravel. The roof depth of the aquifer is 130 ~140 m. The hydraulic head of the confined aquifer II is 3 ~5 m depth approximately. The lithology of the confined aquifer III is medium-fine sand. The depth of the aquifer is 187 ~270 m. The hydraulic head of the confined aquifer III is 30 ~40 m depth approximately. The hydrogeology profile is shown in Fig. 6.

3.2. Discretize grids

The whole study area was subdivided into rectangular grids with resolution 200 × 200 m^2 on the plane dimension. The size of the grids was determined by considering the field-site is 200 × 200 m^2 approximately in reality. There are 20 089 nodes on the plane dimension.

3.3. Collection of factors

The SGE within 100 m depths is planned to be exploited in Nantong. Consequently, the investigation range is also within 100 m depths, which means the open loop system will make use of

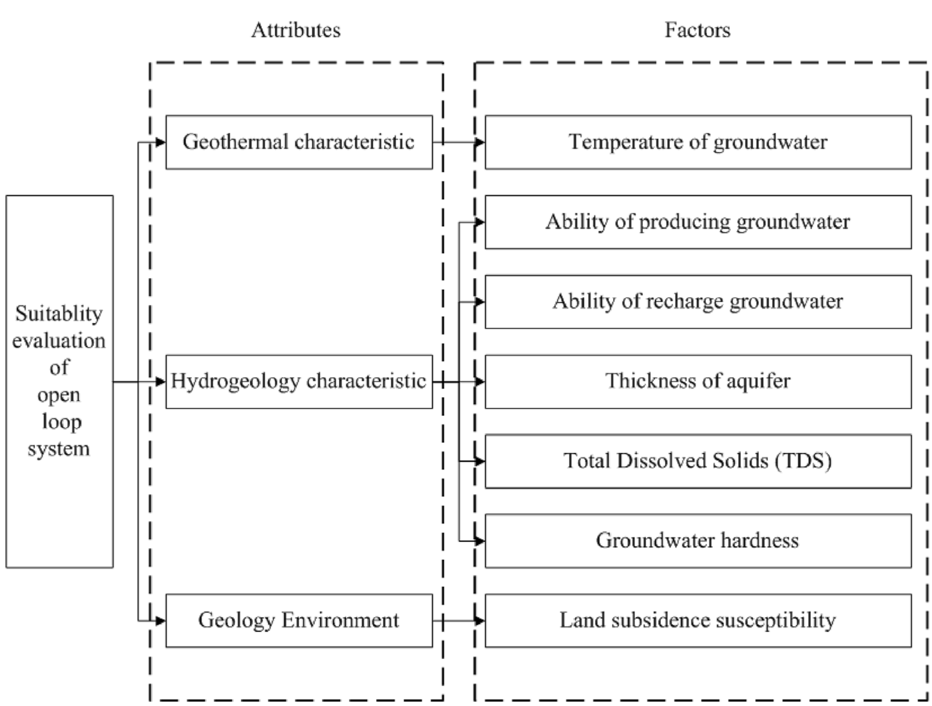


Fig. 2. Suitability evaluation system of the open loop system.

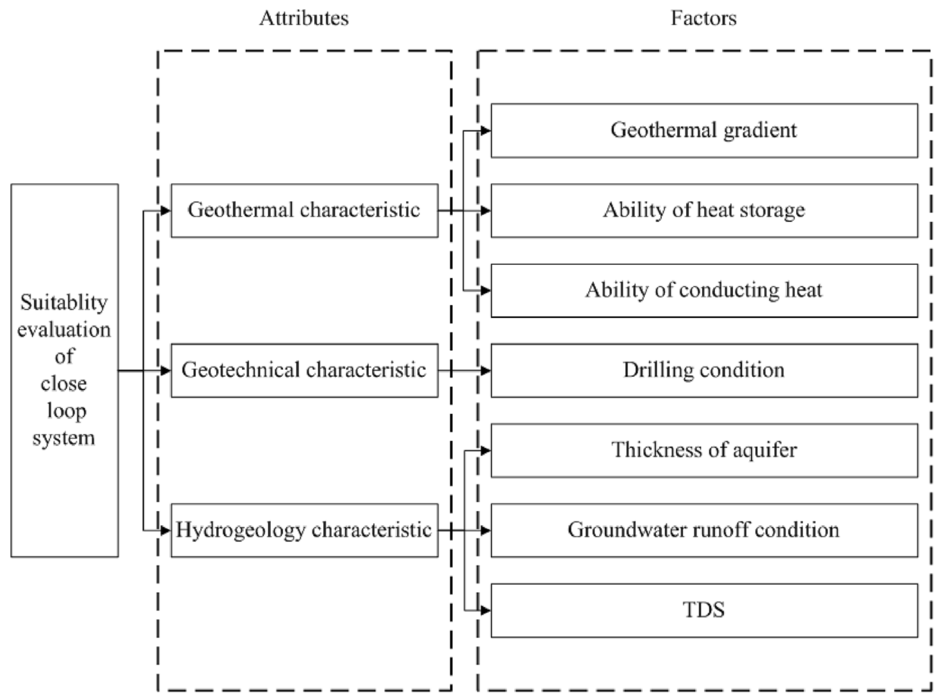


Fig. 3. Suitability evaluation system of the closed loop system.

the natural groundwater from confined aquifer I as heat carrier. A series of quantitative factors are identified to present the degrees of criteria. The factors are shown in Tables 1 and 2. The factors will be collected by field tests in the process of investigation. In according to the measured value and parameters from field tests, the decision data of each node are interpolated by Kriging method.

As is shown in Tables 1 and 2, the hydrogeology characteristics would affect the potential for SGE implementation, including seepage capacity, recharge capacity, and groundwater quality. But there are two aquifers within 100 m, i.e. phreatic aquifer and confined aquifer I. The permeability and thickness of confined aquifer I is better than that of the phreatic aquifer. So confined aquifer I is selected to present the hydrogeology characteristics. Fourteen wells are carried out for pumping and recharge field tests. Screens of the wells locate at confined aquifer I. In the process of pumping tests, groundwater samples are collected for hydrochemical analysis. The hydraulic conductivity which would present the ability of producing groundwater is calculated by the graphical method [40]. The unit discharge of recharge well would present the ability of recharge groundwater. The seepage velocity which would present the groundwater runoff condition could be calculated in according with hydraulic head and hydraulic conductivity. The factors of hydrogeology characteristics are shown in Fig. 7.

Geothermal characteristics would affect the potential for SGE implementation. Twenty-one thermal response tests are carried out to calculate specific heat capacity and thermal conductivity. The temperature gradient and the average temperature of the aquifer (mainly confined aquifer I) are measured by the borehole of the thermal response tests. The factors of geothermal characteristics are shown in Fig. 8.

The degree of land subsidence presents the sensitivity of geological hazards, which indicates the impact of the open loop system operation on the geological environment. The thickness of sand and gravel strata represents the difficulty of drilling, which indicates the impact of geotechnical conditions on the construction of boreholes for the closed loop system. The thickness of sand and gravel is measured in the process of borehole of well and thermal response tests. The thickness of aquifer and the accumulative land subsidence (2016–2018) are collected by GIS-data. The factors of geotechnical and geology environmental characteristics are shown in Fig. 9.

Note that the soil within 100 m depths in Nantong is Quaternary. The thickness of Quaternary is assigned 100 m to the entire study area in the process of suitability evaluation. There are two aquifers within 100 m, i.e. phreatic aquifer and confined aquifer I. But the permeability of confined aquifer I is quite better than that of the phreatic aquifer. Consequently, the thickness of aquifer and the seepage velocity are only considered those of the confined aquifer I. The thickness of aquifer for evaluating potential of the closed system is the thickness of confined aquifer I within 100 m depths, and the thickness of aquifer for evaluating potential of the open system is the whole thickness of confined aquifer I.

4. Results and discussion

4.1. Calculated weight

The factors described in the previous chapter were used to evaluate the SGE potential in Nantong. The weight should be determined at first. The calculated weight is shown in Table 3.

In the process of evaluating the open loop system potential, the hydraulic conductivity and the unit discharge of recharge well have a major impact on the heat transport. And In the process of evaluating the closed loop system potential, the seepage velocity has a major impact on the heat transport. Generally, the greater the difference among attribute values, the greater the amount of information it contains. So the smaller the entropy value, the greater the weight is [41]. It could also be indicated that the difference in hydrogeological characteristics is far greater than others, especially in seepage velocity.

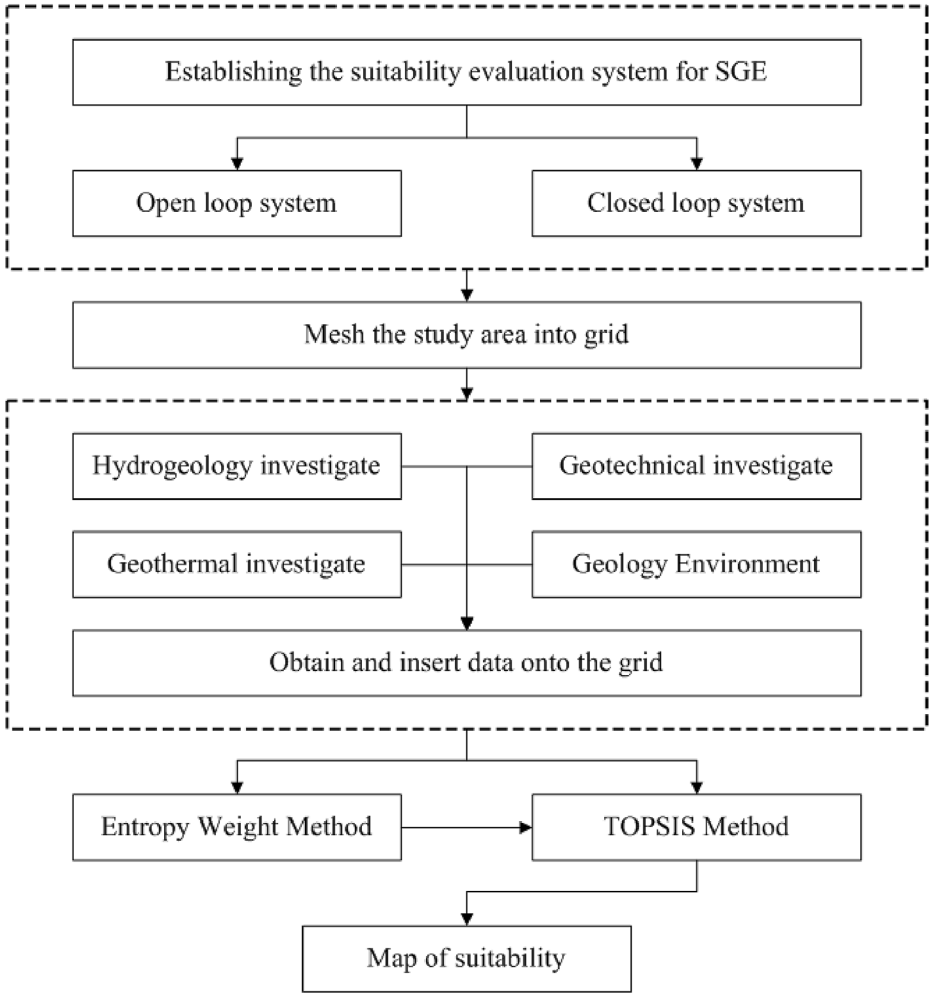


Fig. 4. Schematic view of the workflow.

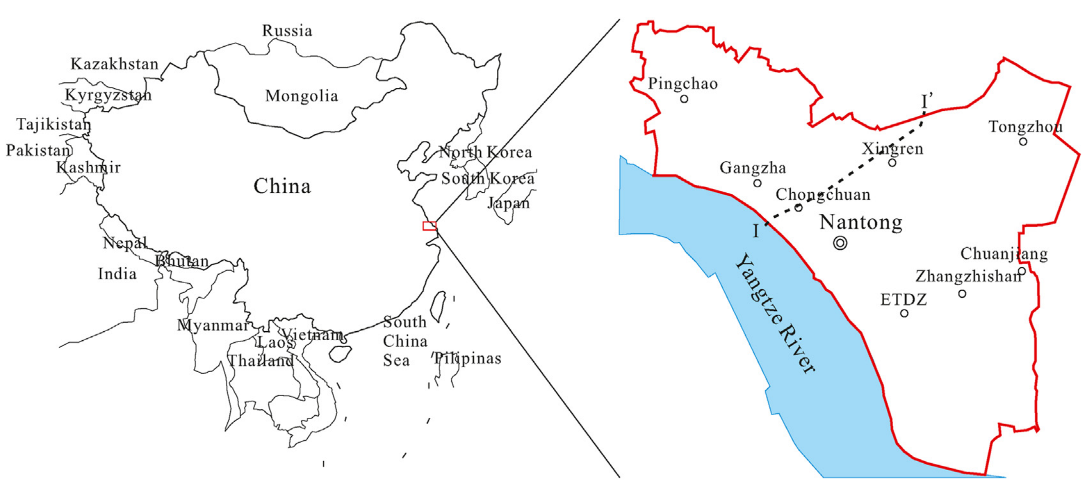


Fig. 5. The geographic location of Nantong.

4.2. Potential for SGE

The weight was assigned to the TOPSIS model, and the closeness coefficient could be calculated. The frequency of closeness coefficient is shown in Table 4. Histograms of relative frequency are shown in Fig. 10. As is shown in Table 4 and Fig. 10, the closeness coefficient of the open loop system is mainly distributed in the range of 0.2 ~ 0.7. And the closeness coefficient of the open loop system conforms to the normal distribution. However, the closeness coefficient of the closed loop system is mainly distributed in the range of 0.0 ~ 0.1. The closeness coefficient of the closed loop system conforms to skewed distribution.

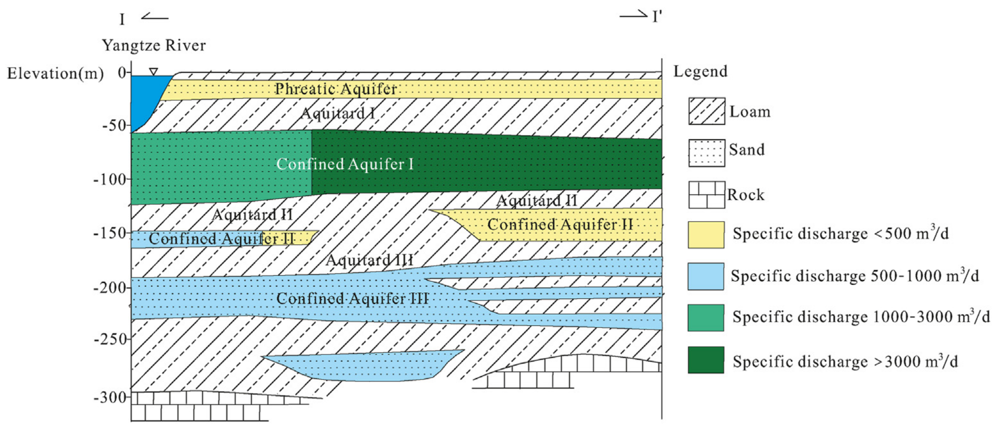


Fig. 6. Hydrogeology profile of Nantong (line I–I′ in Fig. 5).

Table 1
Suitability evaluation system of the open loop system.

Attributes	Criteria	Factors
Hydrogeology Characteristics	Ability of producing groundwater	Hydraulic Conductivity
	Ability of recharge groundwater	Unit Discharge of Recharge Well
	Thickness of aquifer	Thickness of aquifer
	Total Dissolved Solids (TDS)	TDS
	Groundwater Hardness	Groundwater Hardness
Geothermal Characteristic	Groundwater Temperature	Average temperature aquifer
Geology Environment	Land subsidence susceptibility	Accumulative land subsidence

The evaluation potential could be obtained by comparing the closeness coefficient of nodes. The suitability maps were shown in Fig. 11. The SEG potential distribution characteristics of the open loop system and the closed loop system in Nantong are different. Generally, the potential of the open loop system in the south is better than that in the north. But the distribution characteristic of exploitation potential of the closed loop system is opposite to that of the open loop system.

As is shown in Fig. 11(a), the best field-site for the open loop system locates at the north of Zhangzhishan and the northeast of Nantong. The worst field-site for the open loop system locates at south of ETDZ and Pingchao. The relatively low potential in the north Zhangzhishan is mainly caused by low ability of producing groundwater and recharge.

As is shown in Fig. 11(b), the best field-site for the closed loop system locates at Zhangzhishan. The worst field-site for the closed loop system locates at north of Nantong. The relatively low potential in the north is mainly caused by low ability of seepage velocity.

4.3. Discussion

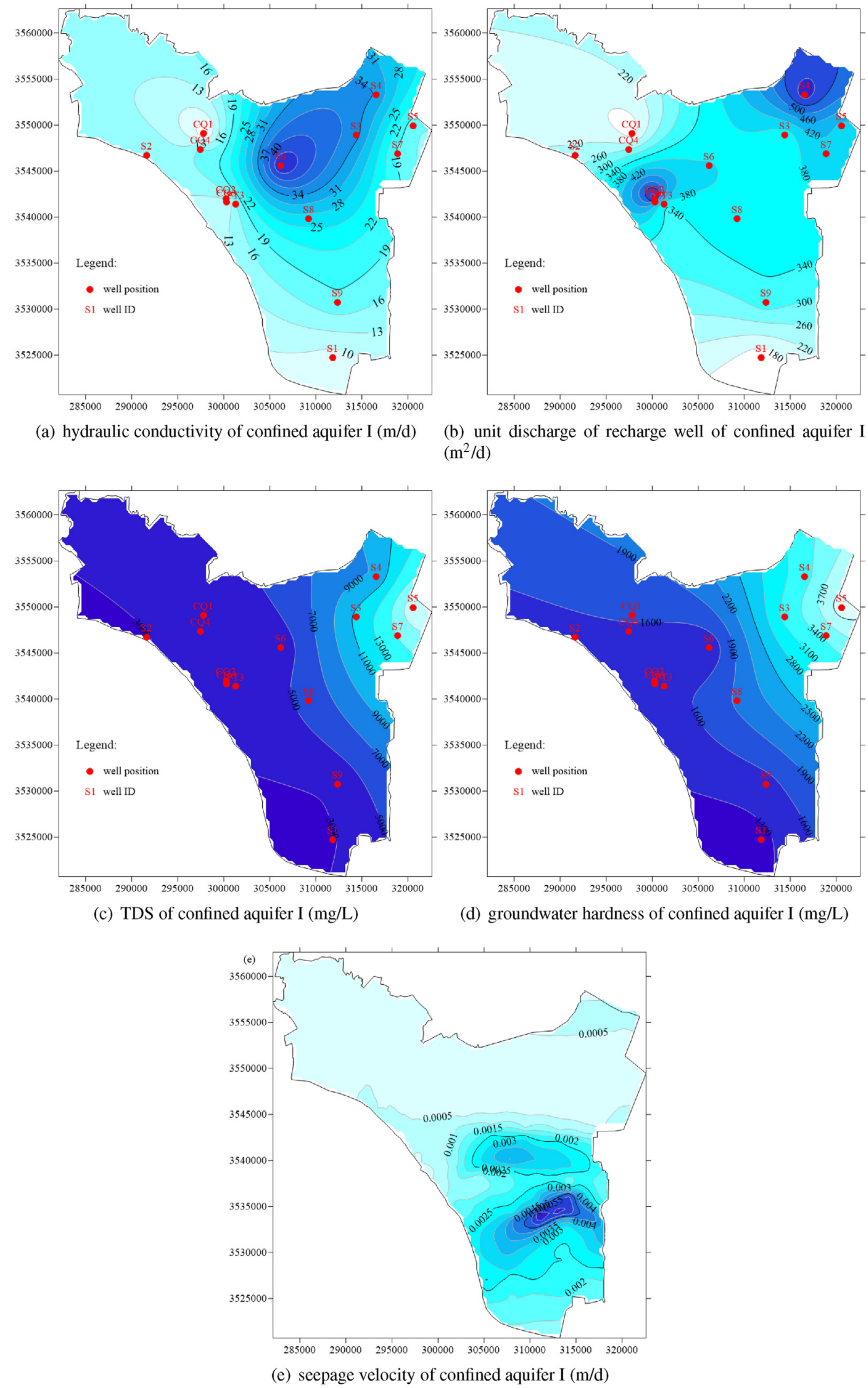
The suitability evaluation algorithm is based on the EW Method and the TOPSIS Method. The algorithm is able to overcome the dimension and metric inconsistencies by normalization of factors. The calculated data come from measured value and parameters of field tests rather than experts' experience. Compared to studies in the previous section, the presented algorithm overcomes the subjectivity of experts.

As shown in Table 3, the ability of producing and recharging groundwater plays an important role in suitability evaluation of open looped system. It indicates a high variability of the aquifer in the region. The weight of TDS and groundwater hardness is low. Hydrochemical characteristics have a small impact on open looped system. These features are consistent with experts' experience [42].

The potential of the closed loop system in Nantong is also evaluated by AHP and IO Method [43]. The comparison of the weights calculated by AHP and EW Method is shown in Table 5. The weight calculated by the EW Method shows that groundwater runoff condition has the greatest impact on SGE implementation in Nantong. The weight of groundwater runoff condition calculated by EW is 3.67 times higher than that calculated by AHP. The main reason for the large difference is the wide variation in seepage velocity of confined aquifer I in Nantong. However, the weight of TDS, temperature gradient, specific heat capacity, and thermal conductivity calculated by the EW Method less than that by AHP. The main reason for the difference is that the experts' experience suggests that temperature gradient, specific heat capacity, and

Table 2
Suitability evaluation system of the closed loop system.

Attributes	Criteria	Factors
Hydrogeology Characteristics	Thickness of Aquifer	Thickness of Aquifer
	Groundwater runoff condition	Seepage Velocity
	TDS	TDS
Geothermal Characteristics	Geothermal gradient	Geothermal gradient
	Ability of heat storage	Specific Heat Capacity
	Ability of heat transfer	Thermal Conductivity
Geotechnical Characteristic	Drill Condition	Thickness of Sand and Gravel



(a) hydraulic conductivity of confined aquifer I (m/d)

(b) unit discharge of recharge well of confined aquifer I (m^2/d)

(c) TDS of confined aquifer I (mg/L)

(d) groundwater hardness of confined aquifer I (mg/L)

(e) seepage velocity of confined aquifer I (m/d)

Fig. 7. The factors of hydrogeology characteristics.

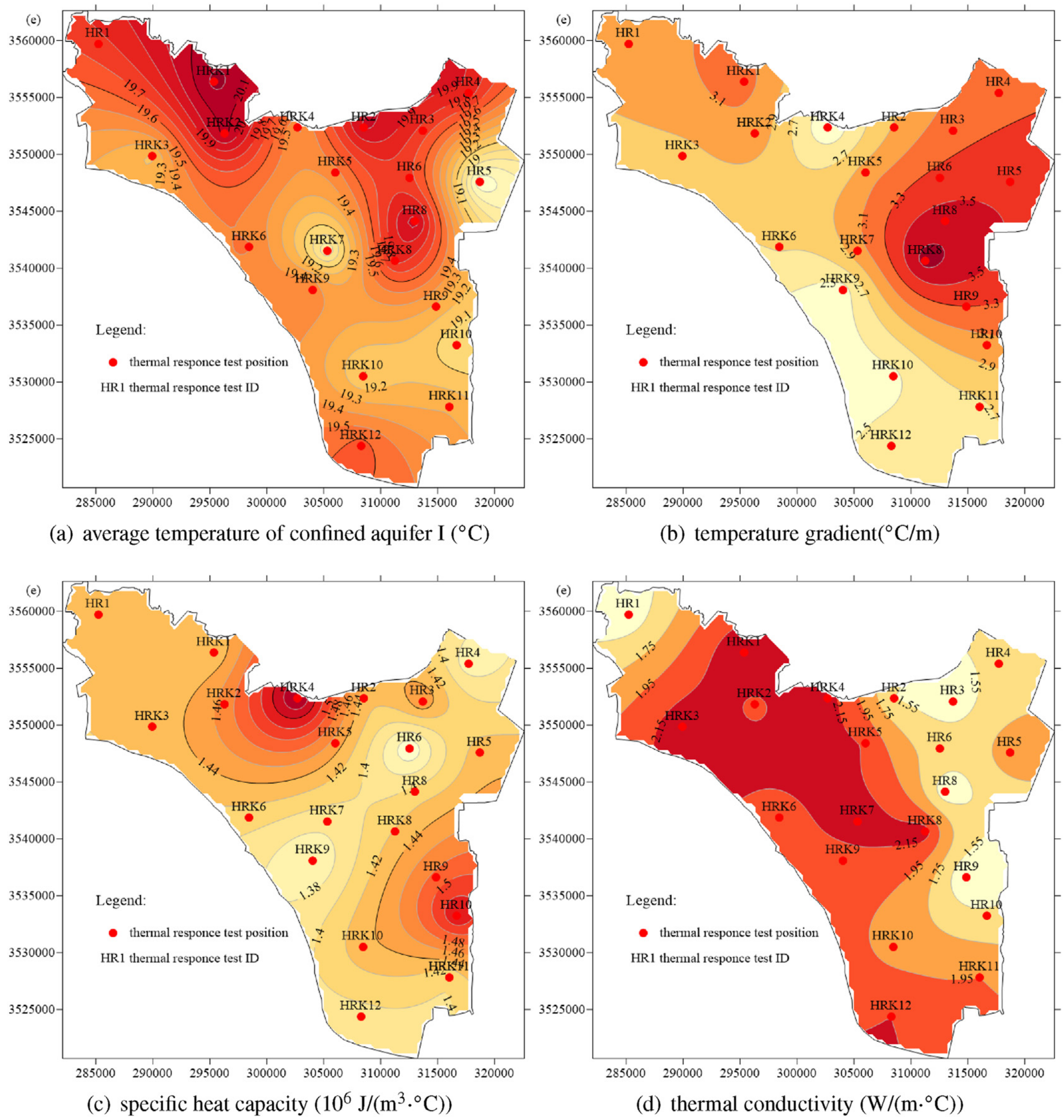
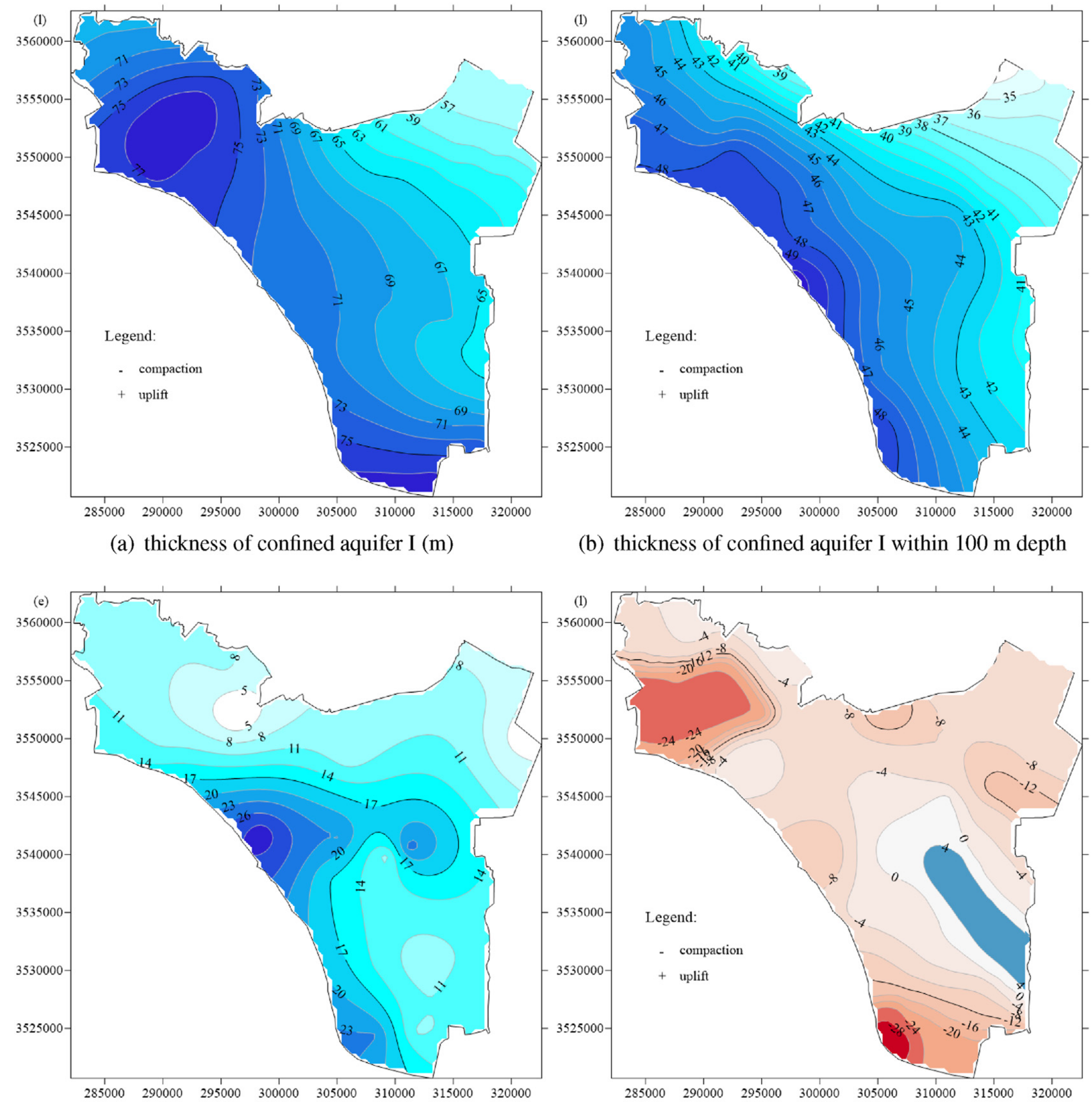


Fig. 8. The factors of geothermal characteristics are shown.

thermal conductivity have an impact on SGE implementation in Nantong. But the difference of temperature gradient, specific heat capacity, and thermal conductivity is small in Nantong. Fig. 7(e) shows that the seepage velocity of confined aquifer I in the south of Nantong is two orders of magnitude larger than that in the north. And Fig. 8(b) ~ 8(d) show that the temperature gradient, specific heat capacity, and thermal conductivity are of the same order of magnitude in Nantong.

The potential of the closed loop system evaluated by AHP and IO Method is shown in Fig. 12 [43]. The result of the potential evaluation shows that almost the whole of Nantong is suitable for the closed loop system based on the experts' experience. Previous study also evaluated the suitability of SGE based on geological conditions and expert' experience subjectively, such as suitability map for Iran [20] or Europe [19]. But it is difficult to compare the potential differences of different places in Nantong.

Fig. 11(b) shows that the south of Nantong is more suitable for the closed loop system implementation than the north. The algorithm based on EW and TOPSIS Method tends to compare the relative potential in region, rather than assess whether the site is appropriate for SGE implementation. Consequently, it is more suitable for selecting the best field-site. The main reason contains two components. On one hand, the EW Method obtains the weight by measuring value dispersion. It only considers the numerical discrimination degree of the factors and ignores rank discrimination. Consequently, the immense dispersion of seepage velocity leads to immense weight in the closed loop system. On the other hand, the suitability map is drawn in accordance with closeness coefficient of TOPSIS. The alternative will be ranked by comparing the distance and closeness coefficient. The closeness coefficient



(a) thickness of confined aquifer I (m)

(b) thickness of confined aquifer I within 100 m depth

(c) thickness of sand and gravel (m)

(d) 2016~2018 accumulative land subsidence(mm)

Fig. 9. The factors of geotechnical and geology environmental characteristics.

Table 3
Calculated weight of factors.

Open loop system		Closed loop system	
Factors	Weight	Factors	Weight
Hydraulic Conductivity	0.245 3	Thickness of Aquifer	0.065 7
Unit Discharge of Recharge Well	0.271 6	Seepage Velocity	0.529 1
Thickness of Aquifer	0.142 8	TDS	0.038 5
TDS	0.059 7	Geothermal Gradient	0.131 2
Groundwater Hardness	0.081 6	Specific Heat Capacity	0.080 4
Average temperature aquifer	0.086 6	Thermal Conductivity	0.106 6
Accumulative land subsidence	0.112 4	Thickness of Sand and Gravel	0.048 4

Table 4
The frequency of closeness coefficient.

closeness coefficient range	0 ~0.1	0.1 ~0.2	0.2 ~0.3	0.3 ~0.4	0.4 ~0.5	0.5 ~0.6	0.6 ~0.7	0.7 ~0.8	0.8 ~0.9	0.9 ~1.0
open loop system	0	0	0.143 9	0.127 6	0.275 7	0.236 3	0.178 9	0.037 6	0	0
closed loop system	0.512 6	0.104 4	0.077 0	0.108 7	0.092 6	0.058 7	0.018 7	0.012 6	0.008	0.006 7

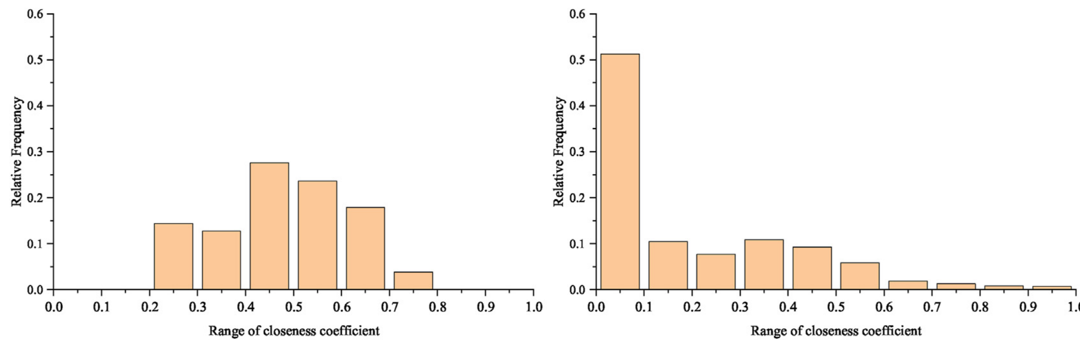
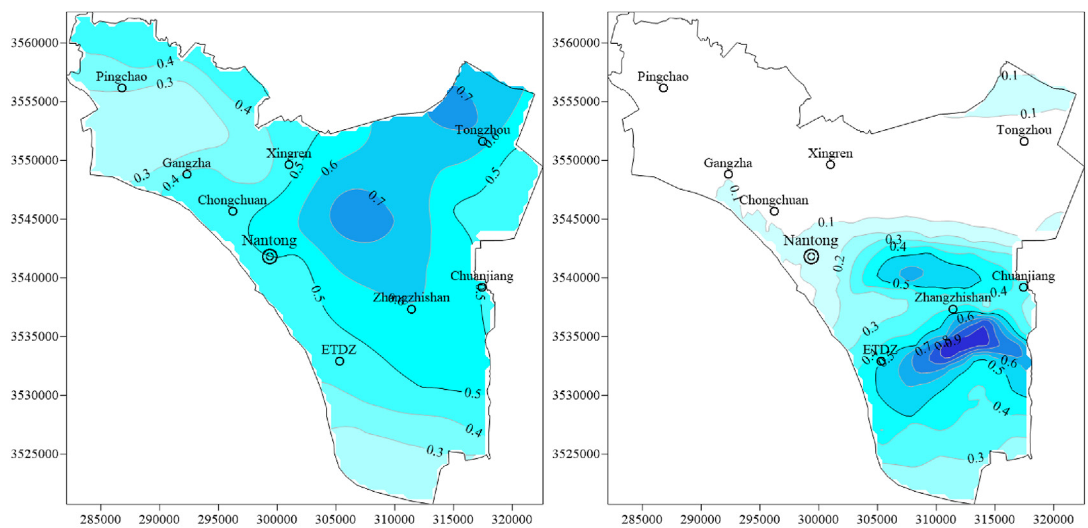


Fig. 10. Histograms of relative frequency of closeness coefficient(a: open loop system; b: closed loop system).



(a) the open loop system

(b) the closed loop system

Fig. 11. Maps of the geothermal potential calculated with TOPSIS method.

Table 5
Comparison of the weight calculated by AHP and EW Method.

Method	Thickness of Quaternary	Thickness of aquifer	Groundwater runoff condition	TDS	Temperature gradient	Specific heat capacity	Thermal conductivity	Drill condition
AHP [43]	0	0	0.143 9	0.127 6	0.275 7	0.236 3	0.178 9	0.037 6
EW	0	0.065 7	0.529 1	0.038 5	0.131 2	0.080 4	0.106 6	0.048 4

presents the relative distance to the ideal solution.

5. Conclusion

In this study, we present an algorithm to evaluate potential for SGE implementation in the region. On the basis of EW Method and TOPSIS Method, the presented algorithm overcomes the inconsistency of dimension and metric. Subsequently, the algorithm is applied to Nantong, China. The main conclusions that can be drawn from this study are as following:

(1) The suitability evaluation systems of the open loop system and the closed loop system are established, respectively. Hydraulic conductivity, unit discharge of recharge well, thickness of the aquifer, TDS, groundwater hardness, the average temperature aquifer, and the accumulative land subsidence are identified as factors in the suitability evaluation systems of the open loop system. Thickness of aquifer, seepage velocity, TDS, geothermal gradient, specific heat capacity, thermal conductivity, thickness of sand and gravel are identified as factors in the suitability evaluation systems of the closed loop system.

(2) The EW Method is able to calculate the weight quantitatively by measuring value dispersion. The greater the degree of dispersion, the higher weight should be given to the factors. The advantage of the EW Method is that the numerical discrimination degree of the index is considered without experts' experience.

(3) The TOPSIS Method is able to measure the relative performance of each alternative quantitatively. The larger closeness coefficient, the better performance of the potential is. The

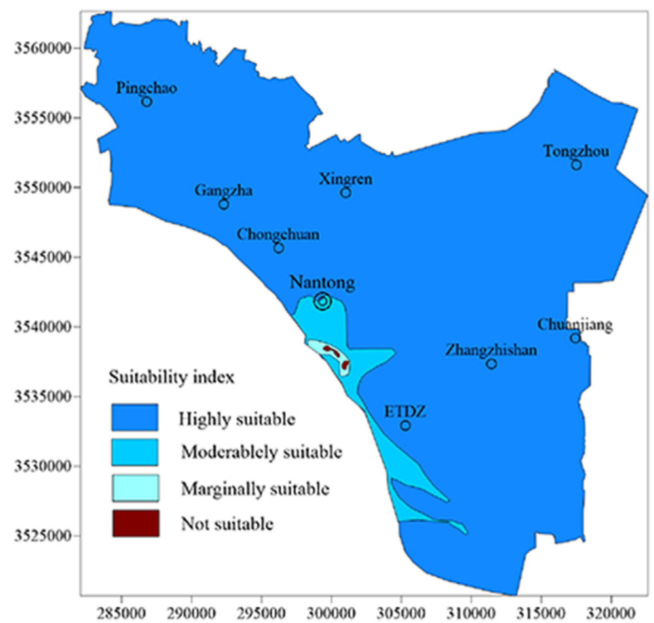


Fig. 12. The potential of the closed loop system evaluated by AHP and IO Method (modified from Ref. [43]).

advantage of the TOPSIS Method is simplicity, rationality, comprehensibility, good computational efficiency.

(4) The algorithm overcomes the subjectivity of experts. However, the algorithm tends to compare the relative potential in region, rather than assess whether the site is suitable for SGE implementation. Consequently, it is more suitable for selecting the best field-site.

CRediT authorship contribution statement

Zhao Li: Conceptualization, Methodology, Writing – original draft. **Zujiang Luo:** Supervision. **Yan Wang:** Visualization, Writing - review & editing. **Guanyu Fan:** Investigation. **Jianmang Zhang:** Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research is financially supported by the National Natural Science Foundation of China (Grant No. 42002263). The authors would also gratefully acknowledge Jiangsu Department of Land and Resources for support of this work under Nantong Urban Geological Survey Program. The first author acknowledges the support of China Scholarship Council. We acknowledge the anonymous reviewers for their constructive comments, which helped us in improving the quality of this manuscript.

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报告编号：2023-1633

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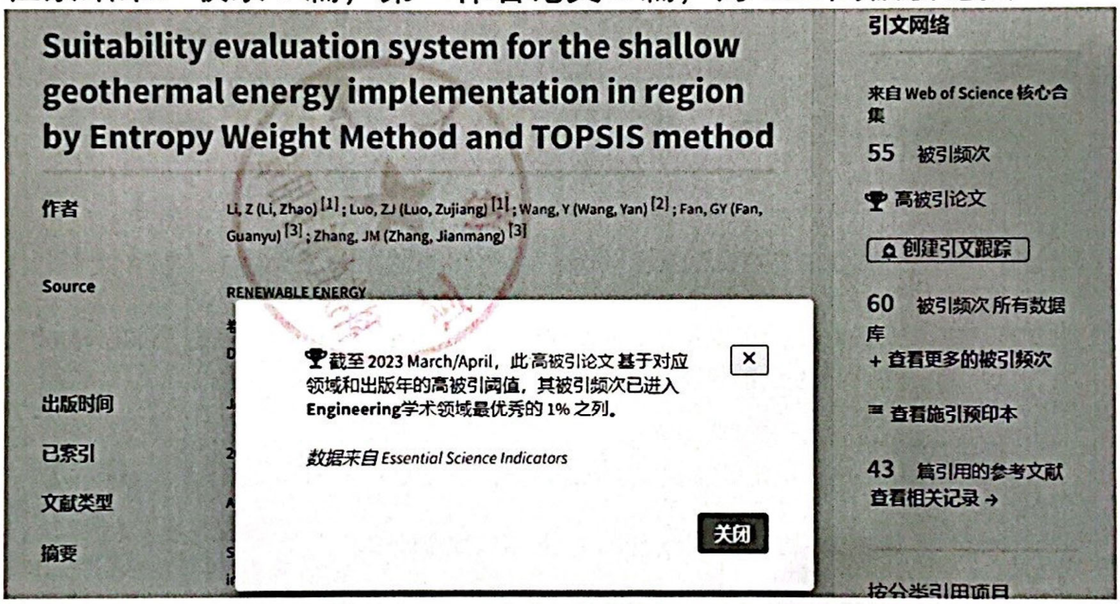

Suitability evaluation system for the shallow geothermal energy implementation in region by Entropy Weight Method and TOPSIS method

作者 Li, Z (Li, Zhao) [1]; Luo, ZJ (Luo, Zujiang) [1]; Wang, Y (Wang, Yan) [2]; Fan, GY (Fan, Guanyu) [3]; Zhang, JM (Zhang, Jianmang) [3]

Source RENEWABLE ENERGY

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序号	题名	刊名	ISSN	年份
1	Suitability evaluation system for the shallow geothermal energy implementation in region by Entropy Weight Method and TOPSIS method	RENEWABLE ENERGY	0960-1481	2022
	类别	学科		分区
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1	Article	1	1

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文献标题: Suitability evaluation system for the shallow geothermal energy implementation in region by Entropy Weight Method and TOPSIS method

作者: Li, Z;Luo, ZJ;Wang, Y;Fan, GY;Zhang, JM

文献类型: Article

出版物名称:RENEWABLE ENERGY　**出版年:**JAN 2022　**卷:**184　**页数:**564-576

DOI:10.1016/j.renene.2021.11.112

Web of Science 核心刊的"被引频次":59　**被引频次合计:**2

入藏号:WOS:000773708900012

作者地址:[Li, Zhao; Luo, Zujiang] Hohai Univ, Sch Earth Sci & Engn, Nanjing 210098, Jiangsu, Peoples R China. [Wang, Yan] Jilin Jianzhu Univ, Changchun 130118, Jilin, Peoples R China. [Fan, Guanyu; Zhang, Jianmang] Environm Geol Explorat Inst Jiangsu Prov, Nanjing 211102, Jiangsu, Peoples R China. C3 Hohai University; Jilin Jianzhu University

通讯作者地址: Luo, ZJ (通讯作者)，Hohai Univ, Sch Earth Sci & Engn, Nanjing 210098, Jiangsu, Peoples R China.

电子邮件地址:luozujiang@sina.com　**语种:**English

Web of Science 类别: Green & Sustainable Science & Technology; Energy & Fuels

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基金资助机构和授权号

基金资助机构	授权号
National Natural Science Foundation of China	**42 002 263**

基金资助正文: This research is financially supported by the National Natural Science Foundation of China (Grant No. 42 002 263). The authors would also gratefully acknowledge Jiangsu Department of Land and Resources for support of this work under Nantong Urban Geological Survey Program. The first author acknowledges the support of China Scholarship Council. We acknowledge the anonymous re-viewers for their constructive comments, which helped us in improving the quality of this manuscript.

作者全名: Li, Zhao;Luo, Zujiang;Wang, Yan;Fan, Guanyu;Zhang, Jianmang

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附件

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（各等级内排名不分先后）

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9	军事地质理论、方法与应用研究成果	中国地质调查局自然资源综合调查指挥中心、中国人民解放军 31016 部队、河北地质大学、中国科学院空天信息创新研究院、国防大学联合作战学院、新疆大学、中国科学院地理科学与资源研究所	刘晓煌、郗笃刚、孙兴丽、刘玉、王洪波、丁建丽、葛良胜、刘玖芬、李平、麻洪川、刘晓洁、沈睿文、王梁、戚冉、方梦阳	中国地质调查局自然资源综合调查指挥中心	中国地质学会评审组
10	深层海相碳酸盐岩建造-改造成储理论技术创新及其应用	中国地质大学（北京）、中国石油化工股份有限公司西北油田分公司、中国石油化工股份有限公司石油勘探开发研究院	高志前、樊太亮、李开开、李传新、吴俊、耿锋、李一凡、闫相宾、卫端、张福顺、张元福、王宏语、张军涛、石巨业、王海荣	中国地质大学（北京）	中国地质学会评审组

11	高煤阶煤层气高效开发地质保障技术及示范应用	中国地质大学（北京）、山西蓝焰煤层气集团有限责任公司、中联煤层气国家工程研究中心有限责任公司、太原理工大学	刘大锰、姚艳斌、徐凤银、田永东、常锁亮、蔡益栋、王勃、郭盛强、张生、闫霞、邱勇凯、聂志宏、孙晓晓、徐博瑞、王虹雅	院士推荐	中国地质学会评审组
12	南海北部海域天然气水合物地质科学重大创新及找矿突破	广州海洋地质调查局	梁金强、陆敬安、匡增桂、郭依群、苏丕波、康冬菊、方允鑫、龚跃华、何玉林、尚久靖、张伟、尉建功、赵庆献、文鹏飞、付少英	广州海洋地质调查局	中国地质学会评审组
13	长三角典型地区地热资源勘查评价关键技术研究与高效利用示范	江苏省地质调查研究院、河海大学	杜建国、骆祖江、邹鹏飞、王丽娟、杨林、范迪富、鄂建、闵望、喻永祥、曹曜、王彩会、李朗、时国凯、尚通晓、左丽琼	江苏省地质学会	中国地质学会评审组
14	黄土丘陵区浅埋厚煤层开采诱发地表塌陷防控关键技术及工程应用	中国地质大学（北京）、河南理工大学、天地科技股份有限公司、中国矿业大学（北京）	武雄、梅钢、穆文平、杨红磊、闫伟涛、徐能雄、孙凯华、刘宏磊、张彬、张中俭、白中科、秦严、朱阁、李生生、赵坤阳	中国地质大学（北京）	中国地质学会评审组
15	秦巴山区滑坡成因机理与监测预警技术	长安大学、陕西省地质环境监测总站（陕西省地质灾害中心）、陕西核工业工程勘察院有限公司	范文、熊炜、曹琰波、于宁宇、郝光耀、柴小庆、邓龙胜、魏心声、李永红、李培、宋宇飞、姬怡微、吝哲峰、吕佼佼、郑文博	陕西省自然资源厅	中国地质学会评审组
16	海洋生物活性物质高效挖掘技术体系的构建与应用	上海交通大学、烟台新药创制山东省实验室、山东省科学院生物研究所、中国科学院上海药物研究所、威海紫光生物科技开发有限公司、青岛聚大洋藻业集团有限公司、烟台东宇海珍品有限公司、苏州颐华生物医药技术股份有限公司、上海其胜生物制剂有限公司	林厚文、刘可春、郭跃伟、王淑萍、孙凡、李晓彬、靳梦、焦伟华、杨帆、易杨华、王文风、程跃谟、蒋毅、蒋丽霞	上海交通大学	中国海洋学会和中国太平洋学会评审组
17	南海深水及超深水钻完井关键技术创新与工业推广	中海油研究总院有限责任公司、中海石油（中国）有限公司湛江分公司、东北石油大学、中国石油大学（北京）	李中、黄熠、李占东、刘和兴、张海翔、孟文波、文敏、任冠龙、武胜男、殷志明、余意、王殿举、于毕成、刘淑芬、肖英建	院士推荐	中国海洋学会和中国太平洋学会评审组
18	海洋二号卫星厘米级精密定轨系统关键技术及工程应用	国家卫星海洋应用中心、武汉大学	彭海龙、李敏、赵齐乐、林明森、王晓梅、蒋科材、王友存、郭靖、李文文、慕仁海、胡志刚、方荣新、张宇、秦格尔、王煜斌	国家卫星海洋应用中心	中国海洋学会和中国太平洋学会评审组