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Sustainability evaluation of limestone geothermal reservoirs with extended production histories in Beijing and Tianjin, China

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ABSTRACT

Sustainable development of geothermal resources is the key to prolong the commercial life of geothermal fields. This paper uses two well-known geothermal fields in China, with long histories of production, to demonstrate how sustainability can be quantitatively evaluated, and to highlight the essential differences between sustainable and non-sustainable development schemes. After examining the complex nature of sustainability evaluation, fuzzy synthetic evaluation is applied as a tool for the quantitative sustainability rating of geothermal reservoirs. The evaluation procedures include systemic criteria selection, weighing, individual criterion evaluation and finally final multi-criterion decision analysis evaluation. The sustainability of a limestone reservoir in the urban sector of Tianjin is rated rather low because of insufficient levels of water injection. On the contrary, the carbonate rock reservoirs of the Xiaotangshan geothermal field in suburban Beijing have a strong sustainability rating, mainly due to high injection rates.

1. Introduction

With the rapidly growing demand for energy, and increasing concern for climate change, utilization of geothermal energy is becoming more desirable (Bertani, 2005; Bilgen et al., 2008; Lund et al., 2005). As renewable, environmentally friendly energy sources, geothermal fluids have been used for electricity production, space heating and industrial purposes (Brophy, 1997; Barbier, 2002; Rybach, 2003). Using these resources in a sustainable manner is important to geothermal operators and decision-makers, and also contributes to environmental protection and sustainable development. Geothermal water can be replenished, but overexploitation may cause resource depletion and other environmental problems such as land subsidence and even surface water pollution (Allis et al., 2009; Barker, 2000; Hole et al., 2007; Sanyal et al., 2000).

Sustainability of geothermal resources has long been the concern of geothermal researchers (Axelsson et al., 2005; Stefansson, 2000; Wright, 1995). Several geothermal fields have been analyzed and different aspects of their utilization, such as geothermal potential, exploitation strategy, and environmental impacts have been evaluated (Bodvarsson et al., 1987; Erdogdu, 2009; Kristmannsdottir and Armannsson, 2003; Pang et al., 2010; Satman, 2010; Ungemach, 2003).

If sustainability is judged based on only one criterion (e.g. longevity of the resource), it may lead to a potentially biased conclusion. As Ketilsson et al. (2010) noted, sustainability relates to several indicators including environmental, social, and institutional themes, as well as relevant sub-themes. Therefore, sustainability evaluation is a multi-criterion problem and a multi-criterion decision analysis (MCDA) should be applied (Chang et al., 2008; Lahdelma et al., 2000; Ma et al., 2010; Wang et al., 2009).

Another problem is that geothermal sustainability may be characterized by ill-defined objectives and standards. In the evaluation process, it is usually difficult to use one single crisp number for ranking due to the vagueness of evaluation standards. It has been proposed that fuzzy sets theory and methods should be applied to such a problem (Azadia et al., 2007; Gong, 2004; McKone and Deshpande, 2005). Fuzzy synthetic evaluation (FSE) has been widely applied in decision-making and environmental-evaluation processes (Dahiya et al., 2007; Fisher, 2003; Icaga, 2007; Lv et al., 2008; Onkal-Engin et al., 2004; Wang et al., 2008; Yu and Yao, 2002). Herein, the essential difference is highlighted between sustainable and non-sustainable development schemes and the FSE, a kind of MCDA, is applied to quantitatively evaluate geothermal sustainability.

The present study is concerned with geothermal projects where our attention is only focused on the environmental impact and exploitation strategies; no economic and social attributes are considered because of the unavailability of experts with the required knowledge.

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Nomenclature

$\circ$	fuzzy composite operator which determines the fuzzy algorithm
C	criterion set
C_i	the ith criterion
C_i/C_j	the comparison of criterion C_i to criterion C_j
D	matrix of pairwise comparisons
d_{ij}	the relative importance of criterion C_i with respect to criterion C_j
E	integrated evaluation set
e_j	element of E
G	evaluation matrix of single criterion
GCI	geometric consistency index
G_i	evaluation vector
g_{ij}	element of matrix G
Q_{rec}	the rate of natural recharge to the geothermal system [$L^3 T^{-1}$]
Q_{PRO}	the production rate [$L^3 T^{-1}$]
Q_{INJ}	the injection rate [$L^3 T^{-1}$]
R	rank set
r	the sustainability score
R_j	the jth rank
W	weight set
w_i	weight of C_i
α	ratio determined by $\alpha = Q_{REC}/(Q_{PRO} - Q_{INJ})$
$\mu(x)$	membership function

2. Methodology

The distinct advantage of the FSE methods is the capability to reach an integrated decision-making solution when multiple criteria are involved. The FSE process includes the following four main stages (Sadiq et al., 2004; Liang et al., 2006): (1) definition of rank and criteria selection, (2) criterion weighting, (3) single criterion evaluation, and (4) integrated evaluation and final treatment.

2.1. Sustainability ranks and criteria selection

Sustainable development is defined as *development that meets the needs of the present without compromising the ability of future generations to meet their own needs* (WCED, 1987). Sustainability of geothermal resources involves consideration of two issues, i.e., (1) the nature of a resource, and (2) the manner of utilization.

The Bellagio Principles for Assessment provide guidelines for evaluating progress toward sustainable development (Hardi and Zdan, 1997). They summarize the entire assessment process including the choice and design of indicators and their interpretation, as well as communication of the results. Ketilsson et al. (2010) proposed a series of sustainability goals for geothermal utilization, which include resource renewability, utilization efficiency, environmental impacts, economical, and societal issues, etc.

Based on the operational experience from geothermal fields and some previous work (Axelsson et al., 2005; Erdogdu, 2009; Pang, 2007; Ungemach, 2003; Wright, 1995), the evaluation criteria can be categorized into five main groups: resource, technological, environmental, economical, and social attributes. The criteria for evaluating geothermal sustainability are shown in Table 1.

When evaluating sustainability, criteria should be selected to form the criterion set C.

$$C = (C_1, C_2, \ldots, C_i, \ldots, C_n) \quad (1)$$

where C_i represents the ith criterion. The selection of criteria depends on our concerns and the actual situation. Note that our analysis is only concerned with the environmental impact and exploitation strategies of geothermal projects and that no social and economic attributes will be considered.

Table 1
Typical criterion for geothermal sustainability.

Aspects	Main criteria
Resource	Exploitation potential
	Geothermal water temperature
	Reservoir permeability
Technology	Injection/production ratio
	Return water temperature
	Geothermal well distribution
	Data availability and integrity
Environment	Water level decline
	Changes in water quantity, quality and temperature
	Ground surface subsidence
	Surface water pollution
Economy	Investment costs
	Operation and maintenance costs
	Payback period
Society	Social acceptability
	Job creation
	Social benefits

Geothermal sustainability can be assigned several evaluation ranks, i.e., very low (R_1), . . ., and very high (R_m). These linguistic ranks are used as the rank set R:

$$R = (R_1, R_2, \ldots, R_j, \ldots, R_m) \quad (2)$$

Each rank corresponds to a fuzzy subset. Generally, the total number of ranks (m) is an integer between 3 and 7. If m is too large, it is difficult to describe the ranks. On the other hand, if it is too small, it may not be possible to precisely define the outcome. Usually, m is an odd number, and intermediate ranks (between very low and very high) can be specified.

2.2. Assigning weights to criteria

In the evaluation process, a weight set W is used to represent the relative importance of each criterion. Different weights directly influence the result of the evaluation. Consequently, it is necessary to ensure the validity of the criteria weights. Wang et al. (2009) summarized the most widely used weighing methods in the MCDA. Here the analytic hierarchy process (AHP), proposed by Saaty (1977, 1980) is applied to obtain the weight set.

The AHP method builds on the pairwise comparison to determine the relative importance of one criterion over another. The matrix of pairwise comparisons for n criteria can be written as:

$$D = [d_{ij}] = \begin{pmatrix} C_1/C_1 & C_1/C_2 & \cdots & C_1/C_n \\ C_2/C_1 & C_2/C_2 & \cdots & C_2/C_n \\ \vdots & \vdots & C_i/C_j & \vdots \\ C_n/C_1 & C_n/C_2 & \cdots & C_n/C_n \end{pmatrix}_{n\times n} \quad (3)$$

where C_i/C_j represents the comparison of criterion C_i to criterion C_j, and d_{ij} denotes the relative importance of criterion C_i with respect to criterion C_j.

To make the comparisons, a numerical scale is needed to indicate the magnitude of the importance of one criterion over another. The classical 1–9 scale (Saaty, 1978) is applied here because of its advantage of good original order-keeping, uniformity of scale and perceptibility (Luo and Yang, 2004); the scale is shown in Table 2.

Next, the row geometric mean method (RGMM) is used to obtain the weight of C_i (Crawford and Williams, 1985),

$$w_i = \sqrt[n]{\prod_{j=1}^{n} d_{ij}} \quad (4)$$

Table 2
The 1–9 pairwise comparison scale.

Intensity of weight	Definition	Explanation
1	Equal importance	Two criteria contribute equally to objectives
3	Weak/moderate importance of one over another	Experience and judgment slightly favored one criteria over another
5	Essential or strong importance	Experience and judgment strongly favor one criteria over another
7	Very strong or demonstrated importance	One criteria is favored very strongly over another; its dominance demonstrated in practice
9	Absolute importance	Evidence favoring one criteria over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent scale values	Used to represent compromise between the priorities listed above
Reciprocals of above non-zero numbers		If criteria i has one of the above non-zero numbers assigned to it when compared to criteria j, then criteria j has the reciprocal value when compared with criteria *i*

The weight set $W=(w_1, w_2, \ldots, w_i, \ldots, w_n)$ is normalized according to:

$$W=\left(\frac{w_1}{\sum w_i}, \frac{w_2}{\sum w_i}, \ldots, \frac{w_n}{\sum w_i}\right) \quad (5)$$

From this normalized set of weights, the priority or importance of the criteria of interest is obtained.

Because the relative importance judgment of criteria depends on each expert's own knowledge and may not agree perfectly, consistency verification should be carried out to guarantee that the judgments are reasonable. The geometric consistency index (*GCI*) (Aguaron and Moreno-Jimenez, 2003) is given by:

$$GCI=\frac{2}{(n-1)(n-2)}\sum_{i<j}\left(\log\frac{d_{ij}w_j}{w_i}\right)^2 \quad (6)$$

where n is the matrix order.

The thresholds of *GCI* are $GCI = 0.31$ for $n = 3$; $GCI = 0.35$ for $n = 4$; and $GCI = 0.37$ for $n > 4$. When *GCI* is less than its threshold, the comparison matrix D can be considered to be completely consistent. If *GCI* is larger, the matrix should be modified to satisfy the consistency check.

2.3. Single criterion evaluation and analysis

The evaluation of sustainability involves some uncertainties. The evaluation ranks are usually described by words like 'strong' and 'low'. It is usually hard to clearly define the boundary between them. So they are a source of uncertainty and it is difficult to use one single crisp number. Here we take the criterion 'injection ratio' as an example to explain the problem. When injection ratio is about 50% (i.e. half of the volume of water being extracted is injected back into the reservoir), the water level stops declining in Tianjin. If we define that the sustainability is R_3 *(medium)* when the injection ratio is 0.5, does it mean that the R_3 *(medium)* is exactly 0.5 and cannot be 0.49 or 0.51? Here fuzzy set theory is applied to solve the problem.

The respective value of each rank should be identified first. Then, our work is to judge which rank the actual condition is close to. This is achieved by the membership function and membership degree in fuzzy set theory.

The membership function applied here is shown in Fig. 1. When the actual value of C_i is equal to the respective value of R_j, the membership degree of C_i to R_j is 1. It means that the probability that C_i belongs to R_j is 100%. In this study the membership function of the first and last ranks is a semi-trapezoid distribution, while others have a triangular distribution. Their equations are as follows:

$$\mu_1(x)=\begin{cases}1 & (x\le a_1)\\ \dfrac{a_2-x}{a_2-a_1} & (a_1<x\le a_2)\\ 0 & (x>a_2)\end{cases} \quad (7)$$

$$\mu_j(x)=\begin{cases}0 & (x\le a_{j-1}, x>a_{j+1})\\ \dfrac{x-a_{j-1}}{a_j-a_{j-1}} & (a_{j-1}<x\le a_j) \qquad (j\in[2, m-1])\\ \dfrac{a_{j+1}-x}{a_{j+1}-a_j} & (a_j<x\le a_{j+1})\end{cases} \quad (8)$$

$$\mu_m(x)=\begin{cases}0 & (x\le a_{m-1})\\ \dfrac{a_m-x}{a_m-a_{m-1}} & (a_{m-1}<x\le a_m)\ ,\\ 1 & (x>a_m)\end{cases} \quad (9)$$

where x is the actual value, a_1, a_{j-1}, a_j and a_{j+1} are the representative values of ranks R_1, R_{j-1}, R_j and R_{j+1}, respectively. Note that $g_{ij} = \mu_j(x)$ is the membership degree of criterion C_i to rank R_j. It means that the probability that criterion C_i can be ranked as R_j is g_{ij}. The evaluation vector G_i of criterion C_i is as follows:

$$G_i=(g_{i1}, g_{i2}, \ldots g_{ij}, \ldots, g_{im}) \quad (10)$$

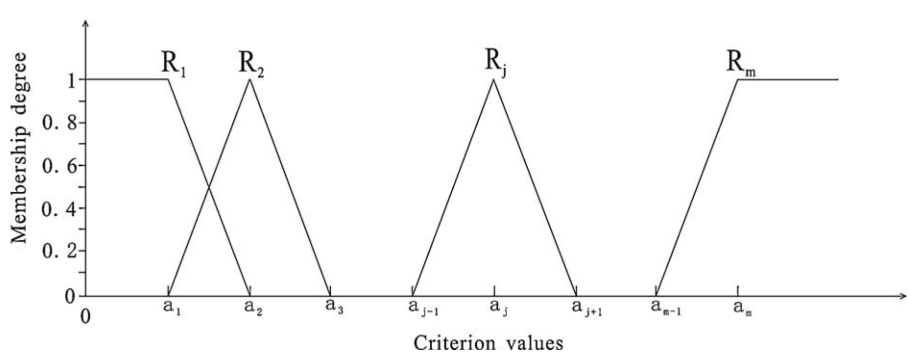

Fig. 1. Graph illustrating the membership function.

Taken the evaluation vector of each criterion as the row vector, the evaluation matrix G is obtained as follows:

$$G=\begin{pmatrix} G_1 \\ G_2 \\ \vdots \\ G_i \\ \vdots \\ G_n \end{pmatrix}=\begin{pmatrix} g_{11} & g_{12} & \cdots & g_{1j} & \cdots & g_{1m} \\ g_{21} & g_{22} & \cdots & g_{2j} & \cdots & g_{2m} \\ \vdots & \vdots & \ddots & \vdots & \therefore & \vdots \\ g_{i1} & g_{i2} & \cdots & g_{ij} & \cdots & g_{im} \\ \vdots & \vdots & \therefore & \vdots & \ddots & \vdots \\ g_{n1} & g_{n2} & \cdots & g_{nj} & \cdots & g_{nm} \end{pmatrix}_{n\times m} \tag{11}$$

From the evaluation vector G_i of criterion C_i we can determine the most likely rank of C_i. But it does not give us a straightforward way to show the sustainability of C_i.

Since g_{ij} denotes the probability that criterion C_i is ranked as R_j we can use the evaluation vector G_i as the weight to get the weight average of the ranks. This value can show the sustainability score of criterion C_i. First, the language ranks are represented by digital quantities. Here the ranks are translated as follows:

$$\{R_1\ \ (\text{very}\ \ \text{low}), R_2\ \ (\text{low}), \ldots, R_j, \ldots, R_m\ \ (\text{very}\ \ \text{high})\} \\ = \{1, 2, \ldots j, \ldots m\}.$$

Then, the following equation is used to get the sustainability score of criterion C_i (Hu et al., 2008):

$$r=\sum_{j=1}^{m}\left(g_{ij}\times j/\sum_{j=1}^{m}g_{ij}\right), \tag{12}$$

where j is the digital quantity of rank R_j. Eq. (12) implies that the sustainability score of C_i is r while the highest score is m.

In Section 3 we evaluate the sustainability of the Wumishan geothermal reservoir in Tianjin. The sustainability is classified using five ranks; i.e. R_1 (very low), R_2 (low), R_3 (medium), R_4 (high), and R_5 (very high). For criterion C_3, the 'injection ratio', the respective values a_j of these five ranks are: 0.2, 0.3, 0.5, 0.7 and 0.8. By substituted these values into Eqs. (7)–(9), the membership functions of C_3 are as follows:

$$\mu_1(x)=\begin{cases} 1 & (x\le 0.2) \\ \dfrac{0.3-x}{0.1} & (0.2<x\le 0.3) \\ 0 & (x>0.3) \end{cases}$$

$$\mu_2(x)=\begin{cases} 0 & (x\le 0.2, x>0.5) \\ \dfrac{x-0.2}{0.1} & (0.2<x\le 0.3) \\ \dfrac{0.5-x}{0.2} & (0.3<x\le 0.5) \end{cases}$$

$$\mu_3(x)=\begin{cases} 0 & (x\le 0.3, x>0.7) \\ \dfrac{x-0.3}{0.2} & (0.3<x\le 0.5) \\ \dfrac{0.7-x}{0.2} & (0.5<x\le 0.7) \end{cases}$$

$$\mu_4(x)=\begin{cases} 0 & (x\le 0.5, x>0.8) \\ \dfrac{x-0.5}{0.2} & (0.5<x\le 0.7) \\ \dfrac{0.8-x}{0.1} & (0.7<x\le 0.8) \end{cases}$$

$$\mu_5(x)=\begin{cases} 0 & (x\le 0.7) \\ \dfrac{0.8-x}{0.1} & (0.7<x\le 0.8) \\ 1 & (x>0.8) \end{cases}.$$

Monitoring data show that the actual injection ratio of the reservoir is 0.334. Substituting $x = 0.334$ into the membership functions above the evaluation vector of C_3 is obtained as follows:

$$G_3 = (0.00, 0.83, 0.17, 0.00, 0.00)$$

Thus, the probability that C_3 belongs to R_2 is 0.83, and that it belongs to R_3 is 0.17.

Based on Eq. (12), the sustainability score for the Wumishan reservoir is 2.17 (the highest score is 5).

2.4. Multi-criterion integrated evaluation

Using the fuzzy algorithm, the integrated evaluation set E can be obtained through the fuzzy composition of the evaluation matrix G and weight set W,

$$E = W\circ G = (w_1, w_2, \ldots, w_i, \ldots, w_n)\circ \\ \begin{pmatrix} g_{11} & g_{12} & \cdots & g_{1m} \\ g_{21} & g_{22} & \cdots & g_{2m} \\ \vdots & \vdots & g_{ij} & \vdots \\ g_{n1} & g_{n2} & \cdots & g_{nm} \end{pmatrix}_{n\times m} = (e_1, e_2, \ldots, e_j, \ldots, e_m) \tag{13}$$

The fuzzy composite operator "∘" determines the fuzzy algorithm that would affect the final evaluation result. Here the multiplication-summation operator is applied (Liu, 1998):

$$e_j=\sum_{k=1}^{n} w_k\times g_{kj} \tag{14}$$

This method can show the influences of all criteria, avoiding the loss of information (Song et al., 2006; Wang et al., 2008). e_i represents the probability that a site can be evaluated to rank of R_j when all criteria are considered.

The weighted average method (see Section 2.3) is also used here to get the integrated sustainability score.

3. The Wumishan geothermal reservoir, Tianjin

The Tianjin geothermal field is located in the north-eastern part of the North China Basin, 130 km SE of Beijing, and extends over an area of about 8700 km^2 (Fig. 2). The geothermal reservoirs are found in Neogene sandstones and in Mesoproterozoic fractured and karstic limestones. The temperature of geothermal water ranges from 42 °C (in the Neogene Minghuazhen Group reservoir) to 117 °C (in the Mesoproterozoic Jixian Wumishan Group reservoir). These thermal waters are being used for space heating, bathing, and agriculture (Axelsson and Dong, 1998; Wang, 2008).

The Wumishan geothermal reservoir consists mostly of Mesoproterozoic dolomitic limestones that are widely found in the Tianjin area. Geothermal wells are mostly located in the regional structural high known as the Cangxian Uplift (Fig. 2; Minissale et al., 2008). Average well water production rates are in the 100–200 m^3/h range, with wellhead temperatures between 79 and 105 °C (Fan, 2006).

By the end of 2008, 77 wells producing from the Wumishan reservoir were in operation; 52 of these wells are located in the Tianjin urban area. A total of 12,500,000 m^3 were extracted in 2008. The water level in the reservoir has rapidly declined due to this exploitation. Since 1997, the water level has been falling 6–9 m per year (Fig. 3) and a regional cone of depression has formed (Cheng et al., 2010), indicating that fluid recharge to the reservoir is limited. Therefore, water injection was started in 2001 to maintain reservoir pressure and to prolong production well lifetimes.

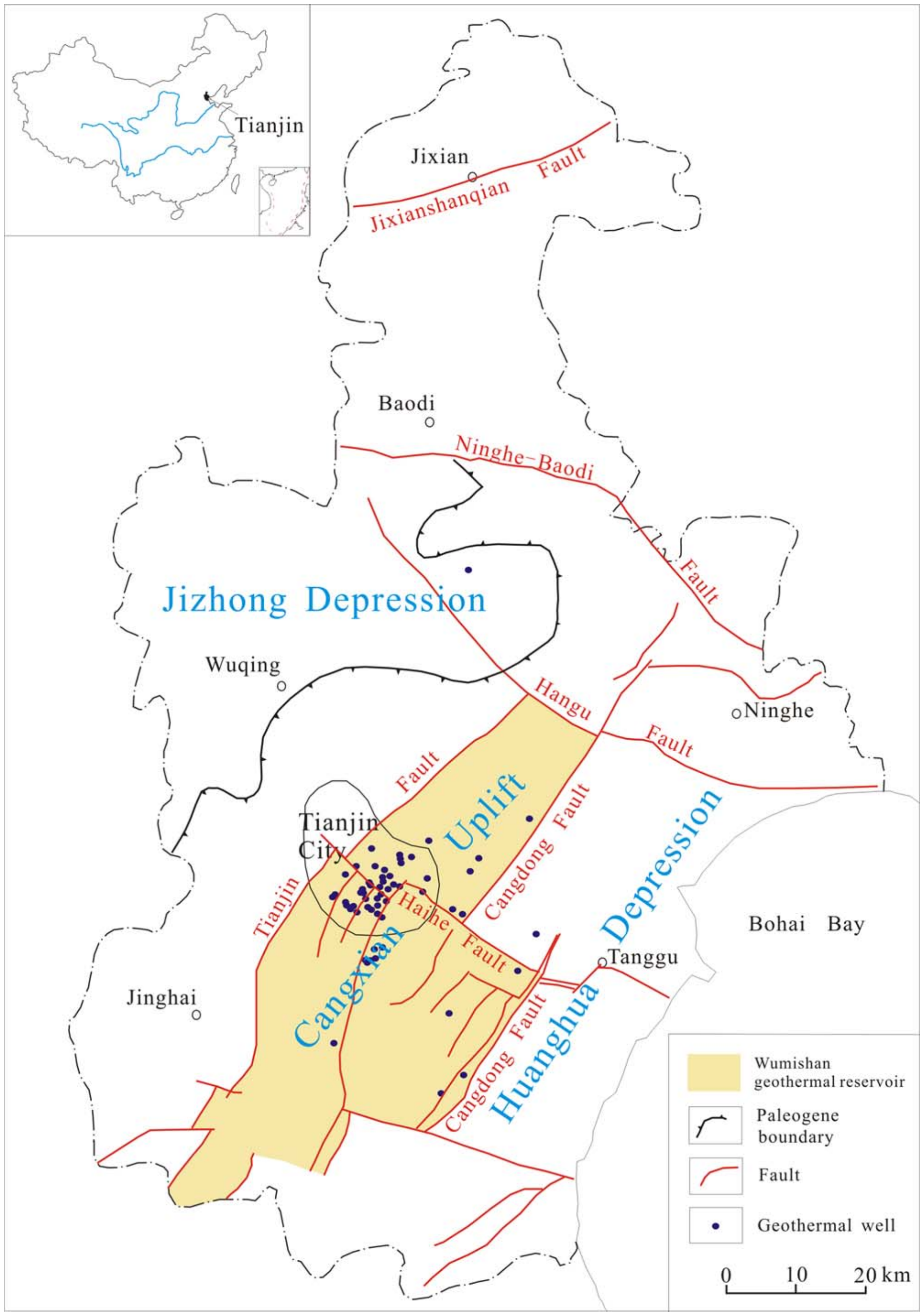

Fig. 2. Location of the Wumishan geothermal reservoir, Tianjin, China.

Between 2001 and 2008 the total injection volume was gradually increased (Table 3) (Zeng and Tian, 2010). By 2008 24 injection wells were in operation, and the injection rate was about 33.4% of the produced volume (Wang et al., 2010). Fig. 3 shows how the annual rate of water level decline decreased in response to injection (Cheng et al., 2010; Lin, 2006).

The temperature of return water from space heating in Tianjin is generally between 30 and 50 °C, with a minimum of 15 °C. The ratio of thermal energy uti-

Table 3
Production and injection data (2001–2008) for the Wumishan reservoir, Tianjin ($\times 10^4$ m^3).

Year	2001	2002	2003	2004	2005	2006	2007	2008
Production	886.4	1200	1200	887	891.9	1361.3	1285.2	1250
Injection	118.4	124	96	118.6	118.6	227.5	289.4	417.4
Injection (%)	13.4	10.3	8.0	13.4	13.3	16.7	22.5	33.4

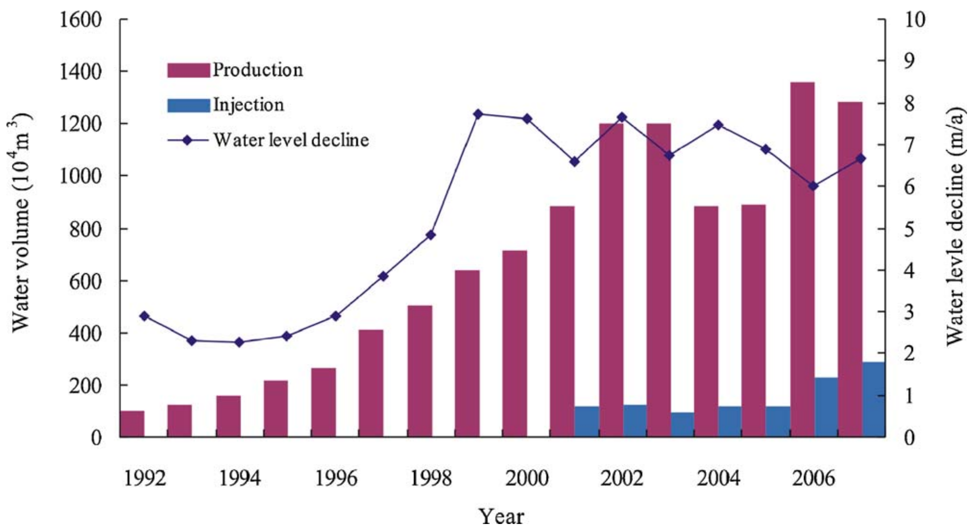

Fig. 3. Exploitation history for the Wumishan geothermal reservoir in Tianjin.

lization was about 64% in 2008 (Lin et al., 2010). The relatively high injection temperature leads to aquifer thermal pollution and to a considerable waste in geothermal resources.

3.1. Selection of rank, criterion and weight sets

Geothermal sustainability is classified into five ranks: R_1 (very low), R_2 (low), R_3 (medium), R_4 (high), and R_5 (very high). These linguistic ranks are used as the rank set R.

$$R = (R_1, R_2, R_3, R_4, R_5)$$

The establishment of a proper evaluation criterion system is the basis for the geothermal sustainability assessment. Generally, the synthetic sustainability evaluation is affected by many factors as shown in Table 1. Seven evaluation criteria are chosen, based on exploitation conditions at the Tianjin geothermal field and suggestions from geothermal operators and specialists (Table 4), and form the criterion set C.

$$C = (C_1, C_2, C_3, C_4, C_5, C_6, C_7)$$

The AHP method introduced in Section 2.2 is applied to obtain the weight set. Table 5 summarizes the results of the pairwise comparison, which is based on the knowledge of geothermal experts.

The geometric consistency index (*GCI*) is calculated from Eq. (6) to be 0.23. Thus, the comparison matrix D meets consistency requirements.

Consequently, the weight set of the criteria is established according to Eqs. (4) and (5) as follows:

$$W = (0.270, 0.105, 0.031, 0.045, 0.024, 0.139, 0.386).$$

It shows that criterion C_7 is thought to be the most significant, with C_1 and C_2 next in importance.

3.2. Single criterion evaluation

In this step of the analysis each criterion is evaluated separately. The key is to identify the respective value of each rank, i.e., a_j in Eqs. (7)–(9). The respective value of Rank 3 (medium) should be defined first. Then the respective values of ranks on either side of R_3 are defined. The rating of each criterion depends on the knowledge of the experts involved in the analysis.

As indicated by Axelsson et al. (2001), there exists a maximum level of energy production E_0 for each geothermal reservoir; E_0 is controlled by the recharge t (natural plus man-made injection). If production is below (or equal to) this level it will be possible to exploit the reservoir for a very long time (100–300 years). This status is called "*sustainable production*", and the exploitation strategy would correspond to 'strong sustainability' as defined by Bosselmann (2002). It takes the health of the environment (natural resources) as the primary limit.

The criterion C_1 (exploitation potential) is described by the following ratio:

$$\alpha = \frac{Q_{REC}}{(Q_{PRO} - Q_{REI})} \tag{15}$$

where Q_{REC} is the rate of natural recharge to the geothermal system, Q_{PRO} the production rate, and Q_{REI} the injection rate. When $\alpha > 1$, it means that production is below or equal to the maximum allowable production, and the geothermal field development is strongly sustainable.

Geothermal water production can increase natural recharge into the system (Stefansson, 2000). According to the results of numerical models of geothermal fields in Tianjin and Beijing (Duan, 2007; Lin, 2006), water levels can be maintained for a long time when the ratio is 0.6. Hence 0.6 corresponds to rank R_3 (medium).

Criterion C_2 (reservoir permeability) is represented by the water yield of a geothermal well. In Tianjin, a geothermal well is consid-

Table 4
Criteria selected in this study to determine geothermal sustainability.

Aspects	Criteria		Description
Resource	Exploitation potential	C_1	Calculated by $\alpha = Q_{REC}/(Q_{PRO} - Q_{INJ})$
	Reservoir permeability	C_2	Indicated by the water yield of the geothermal well
Technology	Injection/production ratio	C_3	Ratio between injection and production volumes
	Geothermal well distribution	C_4	Percentage of wells between which the distance is larger than the well radius of influence R.
	Data availability and integrity	C_5	Percentage of wells that have monitoring data
	Return water temperature	C_6	Reflects the thermal energy utilization efficiency
Environment	Water level decline	C_7	Reflects the response of the reservoir to exploitation

Table 5
Pairwise comparison of criteria.

		C_1	C_2	C_3	C_4	C_5	C_6	C_7
C_1	Exploitation potential	1	4	3	5	7	3	1/2
C_2	Reservoir permeability	1/4	1	1/3	3	5	1/3	1/5
C_3	Injection/Production ratio	1/3	3	1	4	6	1	1/4
C_4	Geothermal well distribution	1/5	1/3	1/5	1	4	1/4	1/6
C_5	Data availability and integrity	1/7	1/5	1/6	1/4	1	1/6	1/8
C_6	Return water temperature	1/3	3	1	4	6	1	1/4
C_7	Water level decline	2	5	4	6	8	4	1

Table 6
Rank values of each criterion for the Wumishan geothermal reservoir, Tianjin.

Criteria		R_1	R_2	R_3	R_4	R_5
C_1	Exploitation potential (α)	0.4	0.5	0.7	0.8	0.9
C_2	Reservoir permeability (water yield, m^3/h)	60	80	100	140	160
C_3	Injection ratio	0.2	0.3	0.5	0.7	0.8
C_4	Geothermal well distribution (%)	60	70	80	90	95
C_5	Data availability and integrity (%)	10	30	40	70	80
C_6	Return water temperature (°C)	55	45	35	25	15
C_7	Water level decline (m/a)	6	5	4	3	2

ered barely successful if it produces less than 60 m^3/h of hot water. Hence, 60 m^3/h is set to correspond to rank R_3 (medium).

The injection ratio C_3 is defined as the ratio between injection and production volumes. A numerical model of the study area (Duan, 2007) has showed that, when injection ratio is about 0.5, the water level stops declining. So, the value of C_3 corresponding to R_3 (medium) is set to 50%.

Geothermal well distribution, C_4, is quantified by the radius of well influence which is defined as the radial distance from a geothermal wellbore to the nearest point where there is no lowering of water level. If the distance between two wells is smaller than the sum of their radii of influence, their production may affect each other. In a geothermal field, we must ensure that over 80% of the wells are sited at distances greater than the sum of radius of influence between neighboring wells. Hence 0.8 is the respective value to R_3 (medium) for C_4.

Data availability and integrity, C_5, is quantified by the percentage of wells that are being monitored; i.e. there is information on their water level depths, temperatures, production rates. Based on the experiences of Taijin geothermal operators and researchers, field exploitation conditions can be evaluated if 40% of the geothermal wells are monitored.

The R_3 (medium) level value for the injection water temperature, C_6, is defined as the temperature at which the thermal energy utilization ratio is about 60%. In Tianjin, that temperature is calculated to be 35 °C.

Because mass recharge to a geothermal system is limited, water level decline is inevitable when the reservoir is produced at a commercial scale. The maximum allowable decline (i.e. pressure drawdown) was suggested by Kang (2010). When the actual drop does not exceed that maximum within a given time period, the rate of production can be considered to be in a sustainable status. Compared to 'strong sustainability', this kind of exploitation strategy is called 'weak sustainability'. It gives consideration to both economic factors and to environmental safety (Bosselmann, 2002). Most geothermal fields in China are in a weak sustainability status.

The water level decline criterion, C_7, corresponds to a weak sustainable development. The maximum annual allowable water level (or pressure) decline is defined as the value corresponding to R_3 (medium), which usually depends on government regulations. According to the 2004–2030 Development and Utilization Plan on Geothermal Resources of Tianjin the maximum allowable water level decline is 4 m per year.

The index values for all criteria are summarized in Table 6, and their estimated values for the Wumishan reservoir are shown in Table 7. Using these data each criterion is evaluated by using Eqs. (7)–(9); the results are shown in Table 8. The sustainability score for each criterion is calculated by Eq. (11). On the basis of these criteria the following can be concluded for the Wumishan reservoir utilization: (1) water extraction has exceeded the maximum allowable production value (Rank 2); (2) the distribution of geothermal wells is reasonable (Rank 5), but there is a cone of depression in the urban areas which is obviously related to an excessive well density in that region. So, this criterion needs to be reconsidered; (3) the injection ratio is still low (Rank 2); (4) monitoring of the reservoir and its utilization is comprehensive (Rank 4) and provides detailed data for geothermal resource management; and (5) water levels are declining too fast (Rank 1), therefore even the weak sustainable development cannot be achieved.

3.3. Integrated evaluation

Using the fuzzy algorithm, the integrated evaluation set E can finally be obtained. Applying the multiplication-summation operator, that set is obtained based on Eqs. (13) and (14).

$$E = W \circ G = (0.270, 0.105, 0.031, 0.045, 0.024, 0.139, 0.386) \circ \begin{pmatrix} 0 & 0.9 & 0.1 & 0 & 0 \\ 0 & 0 & 0.75 & 0.25 & 0 \\ 0 & 0.83 & 0.17 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0.33 & 0.67 & 0 \\ 0 & 0 & 0.6 & 0.4 & 0 \\ 1 & 0 & 0 & 0 & 0 \end{pmatrix} = (0.386, 0.269, 0.202, 0.098, 0.045)$$

Table 7
Estimated values of all criteria for the Wumishan geothermal reservoir, Tianjin.

Criteria	C_1	C_2	C_3	C_4	C_5	C_6	C_7
Value	0.52	110	0.334	98	60	36	6

Table 8
Evaluation matrix G of Wumishan geothermal reservoir, Tianjin.

G		R_1	R_2	R_3	R_4	R_5	Sustainability score
C_1	Exploitation potential	0.00	0.90	0.10	0.00	0.00	2.1
C_2	Reservoir permeability	0.00	0.00	0.75	0.25	0.00	3.25
C_3	Injection rate	0.00	0.83	0.17	0.00	0.00	2.17
C_4	Geothermal well distribution	0.00	0.00	0.00	0.00	1.00	5
C_5	Data availability and integrity	0.00	0.00	0.33	0.67	0.00	3.67
C_6	Return water temperature	0.00	0.00	0.60	0.40	0.00	3.4
C_7	Water level decline	1.00	0.00	0.00	0.00	0.00	1

The integrated sustainability score is given by:

$$r = \sum_{j=1}^{5} \left(e_j \times j / \sum_{j=1}^{5} e_j \right) = 1.997$$

The integrated score of 1.997 is close to Rank 2 (low). Thus the overall sustainability status for the Wumishan geothermal reservoir is evaluated to be low.

4. Xiaotangshan geothermal field, Beijing

Beijing is rich in low-temperature geothermal resources. The identified geothermal area covers over 2760 km^2 with ten geothermal fields (Liu et al., 2010). For nearly 40 years geothermal waters have been used intensively (e.g. for space heating, bathing, swimming pools, health spas, recreation, greenhouses, fish farming) bringing significant social, economical, and environmental benefits to the region (Wang, 2007).

Xiaotangshan (about 30 km north of the city center) is the best known geothermal field in the Beijing area (Fig. 4; Ke, 2009). Its thermal waters have been used for bathing for more than 700 years. The geothermal resources are mainly found in Cambrian limestones, and in Mesoproterozoic Jixian dolomites. Water production for single wells is in the 35–125 m^3/h range, with wellhead temperature between 46 and 70 °C (Liu, 2008).

Over 90 geothermal wells had been drilled by the end of 2008, one with a depth of over 3500 m. The temperature of the return water is about 25–38 °C. The overall thermal utilization ratio is about 53.2%. Because of ever increasing demands, the geothermal

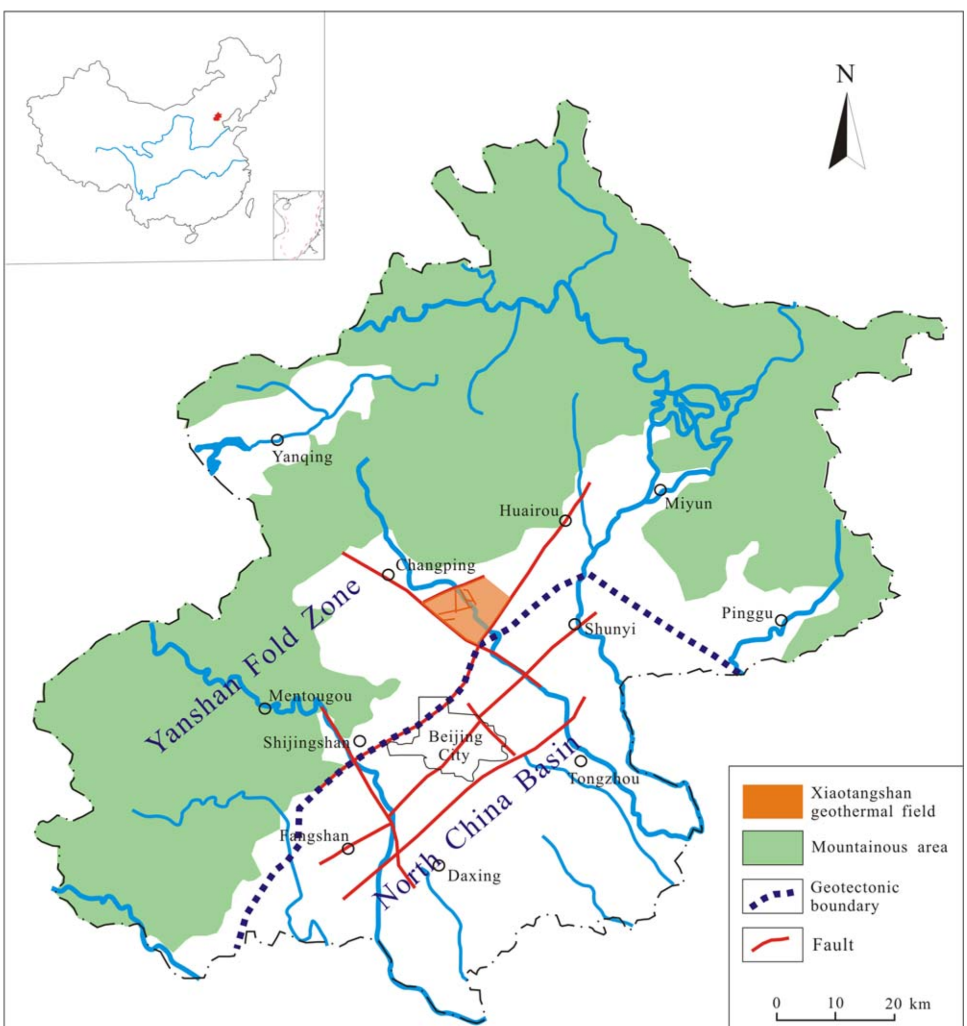

Fig. 4. Location of the Xiaotangshan geothermal field, Beijing, China.

Table 9
Production and injection data (2001–2008) for the Xiaotangshan geothermal field, Beijing ($\times 10^4$ m^3).

Year	2001	2002	2003	2004	2005	2006	2007
Water produced (10^4 m^3)	408.55	290.22	326.43	280.75	233.39	199.48	231.94
Water injected (10^4 m^3)	7.0	10.0	24.8	102.7	132.3	127.0	123.2
Water level depth (m)	32.79	32.67	33.45	35.86	34.68	33.84	33.47

Table 10
Rank values of each criterion for Xiaotangshan geothermal field, Beijing.

Criteria		R_1	R_2	R_3	R_4	R_5
C_1	Exploitation potential (α)	0.4	0.5	0.7	0.8	0.9
C_2	Reservoir permeability (water yield, m^3/h)	60	80	100	140	160
C_3	Injection rate	0.2	0.3	0.5	0.7	0.8
C_4	Geothermal well distribution (%)	60	70	80	90	95
C_5	Data availability and integrity (%)	10	30	40	70	80
C_6	Return water temperature (°C)	50	40	30	20	15
C_7	Water level decline (m/a)	2.5	2	1.5	1	0.5

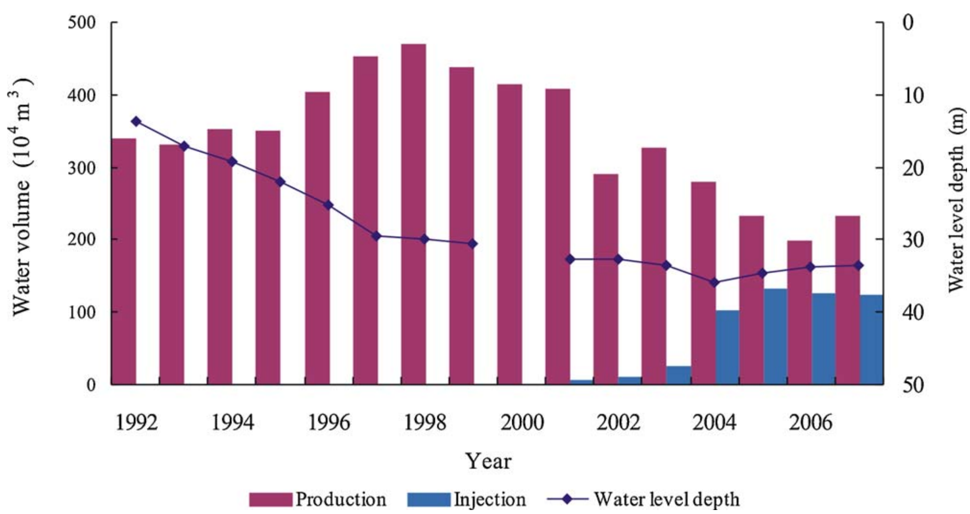

Fig. 5. Exploitation history for the Xiaotangshan geothermal field in Beijing.

resource has long been overexploited. Since the 1980s in most parts of the geothermal field, water levels in the wells have declined by 1–2.5 m per year (Fig. 5; Che, 2004).

To improve conditions for the sustainable use of the geothermal resources, injection has been carried out in the Xiaotangshan geothermal field since 2001. Return water from the geothermal heating systems, with temperatures of 24–37 °C, is injected back into the reservoir. In 2007, there were seven injection wells in operation with a total injection of 1.232×10^6 m^3, accounting for 53.3% of the annual production (Table 9; Pan, 2010). Since 2005, the water level in the geothermal reservoir has begun to gradually recover, showing that injection is effective in aiding the sustainable use of the Xiaotangshan geothermal resource.

4.1. Sustainability evaluation

The FSE method is also used for the sustainability evaluation of the Xiaotangshan field. The rank set R, criterion set C, and weight set W are the same as for the Wumishan geothermal reservoir in Tianjin. However, there are considerable differences in the values of each rank.

The value of criterion C_6 (return water temperature) is site-specific, and depends on the desired geothermal energy utilization efficiency. In Beijing, the return water temperature is about 30 °C for a utilization efficiency of 60%.

For criterion C_7 (water level decline), rank R_3 equals the maximum allowable value. In Beijing the maximum allowable annual water level decline is 1.5 m, which is smaller than in Tianjin.

The index values for the Xiaotangshan geothermal field are summarized in Table 10 based on the data from the geothermal operator and the experience of experts. The estimated values for the different criteria are shown in Table 11, while Table 12 presents the evaluation of each criterion according to Eqs. (7)–(9). The integrated evaluation set E is obtained using Eqs. (13) and (14).

$$E = W \circ G = (0.270, 0.105, 0.031, 0.045, 0.024, 0.139, 0.386) \circ \begin{pmatrix} 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0.84 & 0.16 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0.2 & 0.8 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} = (0.000, 0.028, 0.242, 0.005, 0.701)$$

Table 11
Estimated values of all criteria for the Xiaotangshan geothermal reservoir, Beijing.

Criterion	C_1	C_2	C_3	C_4	C_5	C_6	C_7
Value	1.38	100	0.533	100	95	32	−0.37

Table 12
Evaluation matrix *G* for the Xiaotangshan geothermal reservoir, Beijing.

G		R_1	R_2	R_3	R_4	R_5	Sustainability score
C_1	Exploitation potential	0.00	0.00	0.00	0.00	1.00	5
C_2	Reservoir permeability	0.00	0.00	1.00	0.00	0.00	3
C_3	Injection rate	0.00	0.00	0.84	0.17	0.00	3.2
C_4	Geothermal well distribution	0.00	0.00	0.00	0.00	1.00	5
C_5	Data availability and integrity	0.00	0.00	0.00	0.00	1.00	5
C_6	Return water temperature	0.00	0.20	0.80	0.00	0.00	2.8
C_7	Water level drop	0.00	0.00	0.00	0.00	1.00	5

The integrated sustainability score, *r*, is 4.41,

$$r = \sum_{j=1}^{5}\left(e_j \times j / \sum_{j=1}^{5} e_j\right) = 4.41$$

In other words, the sustainability of the Xiaotangshan field is close to Rank 5 (very high), an encouraging result. Even though the production in 2007 was greater than the recharge (about 150×10^4 m^3) (Sun et al., 2005), the water level rose as a result of increased injection levels, indicating that the present exploitation of the Xiaotangshan geothermal field is strongly sustainable.

5. Conclusions

The sustainability of two Chinese geothermal reservoirs has been evaluated using the fuzzy synthetic evaluation (FSE) method. Based on the geology and groundwater dynamics of the systems, as well as on temperature monitoring data, in conjunction with comments from geothermal experts and governmental officials, evaluation criteria were established, and the rating index of each criterion was developed.

Results show that the sustainability of the utilization of the limestone geothermal reservoir in urban Tianjin is rated rather low because of insufficient injection. The volume of water injection will have to be increased in order to achieve sustainable production. In contrast, the utilization of the geothermal reservoir in the Beijing area is ranked as a strongly sustainable development. This is mainly due to its high injection to production ratio.

The FSE and AHP methods provide new insights into the analysis of sustainable development of geothermal resources, and may serve as practical tools for decision making in geothermal resources management. However, some aspects of the sustainability analysis by these methods need to be improved. In particular, the standardization of evaluation criteria is a challenging task, especially if economical and societal aspects are to be considered in the evaluation process.

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