Debris Flow Risk Assessment in Wudongde Reservoir Area Based on Analytic Hierarchy Process and Fuzzy Comprehensive Evaluation

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Abstract: The outbreak of debris flow is a threat to human life and property, especially so in reservoir areas. Hence, it is critical to evaluate the risk of debris flow in the reservoir area. In this study, data were obtained through remote-sensing imagery interpretation and field survey. By using analytic hierarchy process, determined the weight of each evaluation factor was determined. Fuzzy comprehensive evaluation was applied for the debris flow risk assessment of Wudongde reservoir in China. The evaluation results show that the reservoir area has 20 mildly dangerous mudslides, 200 moderately dangerous mudslides, and 18 severely dangerous mudslides; only one debris flow ditch is extremely dangerous. Thus, the risk of debris flow in Wudongde reservoir area is relatively small and will not have a great impact on the construction and operation of hydropower stations here.

Key words: debris flow; debris flow risk assessment; AHP; FSE

1. Introduction
The risk of debris flow indicates the magnitude of possibility that all people or objects within a debris flow on a watershed scale will suffer damage. Study on debris flow has been extensively studied worldwide\textsuperscript{11}. In the 1970s, Japan scholars\textsuperscript{1,2} studied and graded the risk of debris flow. Alexander\textsuperscript{3} and Eldeen\textsuperscript{4} and other western scholars too explored this topic. The earliest work on the risk of debris flow in China was that of Liu\textsuperscript{5}. With advances in the study of debris flow in recent years, many scholars judged the risk of debris flow from the viewpoints of its occurrence conditions, background factors, parameter characteristics, and numerical simulation.

Historical data and literature show that the vulnerability to debris flow may depend on the formation conditions of debris flow, such as the basin area, river slope, loose surface material, and rainfall characteristics. The various debris flow sensitivity evaluation methods, from qualitative to quantitative analyses, can be roughly classified into statistical and dynamic methods. Statistical methods, such as logistic regression\textsuperscript{6}, analytic hierarchy process (AHP)\textsuperscript{7} and improvement\textsuperscript{8}, fuzzy comprehensive evaluation (FSE)\textsuperscript{9} and neural networks\textsuperscript{10}, evaluate debris flow indicators determined by experts\textsuperscript{11}. Meanwhile, in dynamic methods, physical models are used to obtain the best solution, and this process may require a highly compiled dataset for practical validation\textsuperscript{12}. The scope of application of statistical and dynamic methods too differ greatly as the former type of methods is usually used on a country or regional scale, while the latter type of methods are used to describe
processes within a basin. In the past decade, as multi-source and high-resolution geographic data have become available, debris flow vulnerability assessments based on dynamic methods are being more widely used to realize detailed descriptions of complex rainfall-triggered debris flow events\textsuperscript{[13]}.\n
Through physical models and corresponding numerical methods, the dynamic processes of the debris flows and the affected areas in gullies can be quantitatively evaluated\textsuperscript{[4]}. The actual debris flow is characterized by a large outflow area and long duration. Hence, the calculation involved in modeling is very time-consuming\textsuperscript{[15]}. The depth integral continuum method has been widely used to simulate the dynamic process of a debris flow\textsuperscript{[16]}. The foundation friction model and the selected parameters greatly influence the calculated debris flow velocity and deposition area. Generally, the parameters of extreme debris flow are used to evaluate the dangerous area conservatively.\n
Traditionally, debris flow information is obtained through field surveys, which are time-consuming and labor-intensive. With the development of remote-sensing technology, satellite remote-sensing imagery has been of great assistance in obtaining information on geological disasters. In this study, SPOT-5 remote-sensing imagery and a digital elevation model (DEM) were used, and data of debris flow were obtained through the comprehensive method of remote-sensing imagery interpretation and field survey. The weight of each evaluation factor was determined by the AHP; finally, FSE was applied for the debris flow risk assessment of the Wudongde reservoir area in China.\n
2. Study area\n
The Wudongde Hydropower Station is located in the lower reaches of the Jinsha River in China. The proposed dam sites are in Wudongde, Luquan County, Yunnan Province and in the Jisha River reaches of Leijijawan, Huidong County, Sichuan Province. The water surface elevation of the Jinsha River at the dam site area of the Wudongde Hydropower Station is about 810 m, and the normal storage water level is 975 m. The back water of the reservoir is upstream at Panzhuhua City, and the entire reservoir area extends about 209 km. There are 239 debris flow ditches in the reservoir area, with 135 on the left bank and 104 on the right bank. In this study, all of these debris flow ditches were considered as the research object.\n
The reservoir area of the hydropower station is located at the transition zone between the southeast edge of the Qinghai–Tibet Plateau, the mountainous area of southwest Sichuan, and the Yunnan–Kweichow Plateau. The lowest elevation of about 800 m is in Jinsha River itself; the highest elevation is 3600 m. The general terrain is high in the east and low in the west. According to the classification standard of mountains proposed by the Institute of Geography, CAS, the Wudongde reservoir area belongs to middle- and high-mountain areas. Located in the famous dry–hot valley of Jinsha River, the study area is located in the low-latitude plateau monsoon climate zone. This climate is characterized by more sunshine, strong evaporation, concentrated rainfall, and distinctly dry and wet seasons; small annual temperature difference and large daily temperature differences; no frostiness in winter; and torridity in summer. Ample rain is received in the months May–October, and the average annual rainfall is 834–1309 mm. The maximum daily rainfall is 110 mm. The vegetation in the research area is sparse, and the vegetation coverage rate is less than 30%. The typical debris flow gullies are shown in Figure 1.
3. Data and method

The influencing factors of debris flow risk include geological conditions, terrain conditions, hydrology, and meteorological conditions. Extracting the data of the influencing factors is the key step in debris flow risk assessment. In this study, these data were obtained through a combination of remote-sensing imagery interpretation and field survey.

3.1 Remote-sensing imagery interpretation

SPOT5, which was launched in May 2002, provides remote-sensing imagery that have been widely used in geological disaster assessment\[17-18\]. The data have a multi-spectrum resolution of 10 m and a panchromatic resolution of 2.5 m. In SPOT-5 imagery, we can clearly identify the debris flow sink water boundary, gullies, and the debris accumulation region. To magnify and observe the debris flow gullies to be studied, to delimit the scope of the debris flow, and to draw drainage maps of the forming region of the debris flow gullies, some essential parameters have to be determined. These parameters include the drainage area, length of main gully, the cutting density of the drainage area, debris-
accumulation area, and characteristics of the plane shapes of debris flow. The normalized vegetation index can be calculated from multi-spectrum remote-sensing imagery to obtain the vegetation coverage rate.

The abovementioned remote-sensing imagery only provides two-dimensional (2D) information, and many challenges are encountered in the actual interpretation process. First, the elevation of a point cannot be obtained from the 2D imagery. Therefore, it is crucial to use a DEM for the interpretation. Therefore, the 1:10000 topographic base map is vectorized to build a numerical elevation model (i.e., the DEM), which can be combined with remote-sensing imagery to obtain the three-dimensional (3D) imagery of the debris flow gully. Using this 3D imagery, we can obtain the spatial evaluation parameters, such as the maximum relative elevation of the drainage area, average slope of main gullies, and average gradient of slopes in the formation area, for debris flow assessment.

3.2 Field survey
It is difficult to estimate some debris flow evaluation factors, such as the sediment supply length ratio and the frequency of debris flow, by using remote-sensing imagery. Therefore, debris flow surveys are also necessary. Debris flows near the dam reservoir area of the hydropower stations are more dangerous to the stability of the dam and should be surveyed in detail. Hence, debris flows near the dam reservoir area were the focus of the survey. Photographs taken during the survey are shown in Figure 2 and Figure 3.

![Figure 2: Gully bottom (a) and deposits (b) in Xiabai gully](image)

![Figure 3: Transportation area in Xiushuihe gully](image)
3.3 Introduction to the algorithm

3.3.1 Analytic hierarchy process (AHP)

The AHP can deal with the relationship between the factors and is an effective method to
determine the weight of factors. The procedure of determining weights by AHP is as follows:

(1) Construct a judgment matrix

d = [d_{ij}]

\[ d = \frac{C_1}{C_2}, \frac{C_1}{C_3}, \ldots, \frac{C_1}{C_n}, \frac{C_2}{C_1}, \frac{C_2}{C_3}, \ldots, \frac{C_2}{C_n}, \ldots, \frac{C_n}{C_1}, \frac{C_n}{C_2}, \ldots, \frac{C_n}{C_n} \]

\( d_{ij} \) is the result of comparing factor \( C_i \) with factor \( C_j \) and represents the importance of factor \( C_i \) relative to factor \( C_j \). The values of the elements of the judgment matrix reflect people's understanding of the relative importance of each factor. The comparison scale 1–9 (Table 1) is generally used to construct the judgment matrix.

Table 1 Scale of the judgment matrix and its meaning

| Scale | Meaning                              |
|-------|--------------------------------------|
| 1     | two factors are of equal importance in comparison |
| 3     | the former is slightly more important than the latter in comparison |
| 5     | the former is obviously more important than the latter in comparison |
| 7     | the former is intensively more important than the latter in comparison |
| 9     | the former is extremely more important than the latter in comparison |
| 2, 4, 6, 8 | the intermediate value of the above adjacency judgment in comparison |

(2) Calculate the factor weight aggregate

The weight of factor \( C_i \) is calculated by the following formula:

\[ w_i = \frac{1}{\sqrt{\prod_{j=1}^{n} d_{ij}}} \]  

(2)

The weight aggregate is normalized by using the following formula:

\[ W = \left( \frac{w_1}{\sum w_i}, \frac{w_2}{\sum w_i}, \ldots, \frac{w_n}{\sum w_i} \right) \]  

(3)

(3) Test the consistency

The quantitative index to measure the degree of inconsistency of the judgment matrix is the consistency index, which is obtained from the following formula:

\[ CI = \frac{\lambda_{\text{max}}}{n-1} \]  

(4)

where \( \lambda_{\text{max}} \) is the maximum eigenvalue of the judgment matrix, and \( n \) is the order of the judgment matrix.

The consistency criterion of the judgment matrix is as follows:

\[ CR = \frac{CI}{RI} < 0.1 \]  

(5)

\( RI \) can be obtained by from the table of consistency index. When \( CR < 0.1 \), the consistency of the judgment matrix is regarded acceptable; when \( CR > 0.1 \), the judgment matrix does not meet the consistency requirement and needs to be revised until it satisfies the consistency requirements.

3.3.2 Fuzzy Comprehensive Evaluation (FSE)

FSE allows the overall evaluation of a phenomenon influenced by multiple factors, including fuzzy factors. The steps are as follows:

(1) Construct factor aggregate: \( U = \{ u_i \}, i = 1, 2, \ldots, n \). Here, \( u_i \) represents the \( i \)-th impact factor.
(2) Construct assessment aggregate: \( V = \{ v_j \} , j = 1,2, \cdots , m \). Here, \( v_j \) represents the \( j \)-th assessment grade. In this study, the risk assessment of debris flow was divided into four grades: mild, moderate, severe, and extreme.

(3) Determine the fuzzy relation matrix by the degree of membership function: The degree of membership of each evaluation index for each evaluation category is calculated by the degree of membership function. In this study, the risk assessment of debris flow was divided into four grades, and each grade is determined as follows:

\[
\begin{align*}
\hat{f}_{ij}(x_i) &= \begin{cases} 
0 & x_i > v_{i(j+1)} \\
\frac{v_{i(j+1)}-x_i}{v_{i(j+1)}-v_{ij}} & v_{ij} \leq x_i \leq v_{i(j+1)}j = 1 \\
1 & x_i < v_{ij}
\end{cases} \\
\hat{f}_{ij}(x_i) &= \begin{cases} 
0 & x_i > v_{i(j+1)}, x_i < v_{i(j+1)} \\
\frac{x_i-v_{i(j+1)}}{v_{ij}-v_{i(j+1)}} & v_{i(j-1)} \leq x_i \leq v_{ij}j = 2,3 \\
\frac{v_{ij}-x_i}{v_{ij}-v_{i(j+1)}} & v_{ij} < x_i \leq v_{(j+1)} \\
1 & x_i < v_{i(j-1)}
\end{cases} \\
\hat{f}_{ij}(x_i) &= \begin{cases} 
0 & x_i > v_{ij} \\
\frac{x_i-v_{i(j-1)}}{v_{ij}-v_{i(j-1)}} & v_{ij} \leq x_i \leq v_{i(j+1)}j = 4
\end{cases}
\]

(9)

where \( i \) represents the \( i \)-th evaluation factor; \( j \), the \( j \)-th evaluation category; and \( x_i \), the actual value of \( i \)-th evaluation factor. Further, \( v_{ij} \), \( v_{i(j+1)} \), and \( v_{i(j+1)} \) represent the thresholds of the \( j \)-th evaluation category for the \( i \)-th evaluation factor. A fuzzy relation matrix can be constructed by calculating the degree of membership of each evaluation factor to each evaluation category, as follows:

\[
R = \begin{bmatrix}
R_{11} & R_{12} & \cdots & R_{1m} \\
R_{21} & R_{22} & \cdots & R_{2m} \\
\vdots & \vdots & \ddots & \vdots \\
R_{n1} & R_{n2} & \cdots & R_{nm}
\end{bmatrix} \tag{9}
\]

where \( r_{ij} = f_{ij}(x_i) \) represents the degree of membership of the \( i \)-th factor to the \( j \)-th evaluation category.

(4) Determine the final assessment grade

Vector \( B \) is calculated from the weight aggregate of factors and fuzzy relation matrix:

\[
B = W \ast R = (b_1, b_2, \cdots, b_m) \tag{10}
\]

The category to which the maximum value of vector \( B \) belongs is the final assessment grade.

4. Results and discussion

The risk of debris flow is determined based on various influencing factors, and the selection of the evaluation factors is critical to the assessment result. Liu used gray statistical analysis to analyze the results of an expert communication survey to determine the one-time flow rate of debris flow \( M \) and the frequency of debris flow \( F \) as the main influencing factors of debris flow. The drainage area \( S_1 \), length of mail gully \( S_2 \), relative elevation of the drainage basin \( S_3 \), cutting density of the drainage area \( S_4 \), main-gully bending coefficient \( S_5 \), sediment supply length \( S_6 \), maximum daily rainfall \( S_7 \), and population density \( S_8 \) were used as the secondary influencing factors. The importance ranking of the 10 influencing factors was determined by gray incidence analysis. The ranking is as follows: the one-time flow rate of debris flow \( M \) > frequency of debris flow \( F \) > the drainage area \( S_1 \) > the cutting density of the drainage area \( S_4 \) > the length of the main gully \( S_2 \) > the relative elevation of the drainage basin \( S_3 \) > the sediment supply length \( S_6 \) > the maximum daily rainfall \( S_7 \) > the population density \( S_8 \) > the main-gully bending coefficient.

In this study, the above 10 factors were selected as the evaluation factors for debris flow risk assessment. Based on Liu's work, AHP was used to calculate the weight aggregate of each evaluation
factor, and the judgment matrix was constructed. The weight aggregate of the evaluation factors was calculated by using formula (2) and formula (3). The result is as follows:

\[ W = (0.239, 0.239, 0.167, 0.081, 0.056, 0.116, 0.015, 0.039, 0.028, 0.020) \]

The value of the consistency index \( CR \) is 0.035, which is less than 0.1 and hence satisfies the consistency test.

Data were obtained through remote-sensing imagery interpretation and field survey. Owing to space limitation, the data of all evaluation factors of the debris flow gullies are not provided in this paper. Table 2 lists the data of each evaluation factor of 10 debris flow gullies. The risk assessment of debris flow is divided into four grades: mild, moderate, severe, and extreme. The assessment aggregate \( V = \{v_1, v_2, v_3, v_4\} \) was determined according to previous studies. The threshold values of each evaluation factor for each evaluation category are listed in Table 3.

### Table 2 Evaluation index values of debris flows

| Gully      | M (×10⁶m³) | F (time/100year) | S1 (km²) | S2 (km) | S3 (km) | S4 (km³) | S5 | S6 | S7 (mm) | S8 (person/km²) |
|------------|-------------|------------------|----------|---------|---------|----------|-----|-----|---------|-----------------|
| Xiabai     | 7.04        | 54               | 3.1      | 3.08    | 1.26    | 5.51     | 1.19| 0.22| 110     | 110             |
| Shangbai   | 5.7         | 74               | 0.91     | 1.87    | 0.67    | 10.29    | 1.08| 0.59| 110     | 110             |
| Zhugongdi  | 6.89        | 23               | 6.5      | 4.98    | 1.34    | 6.24     | 1.15| 0.5  | 110     | 50              |
| Yindigou   | 23.6        | 35               | 60.5     | 20.17   | 2.25    | 5.08     | 1.23| 0.24| 110     | 20              |
| Shenyuhe   | 25.73       | 23               | 256      | 29.63   | 1.48    | 2.26     | 1.47| 0.26| 110     | 4               |
| Xiushuine  | 3.9         | 5                | 8.58     | 2.2     | 1.67    | 6.9      | 1.2  | 0.35| 110     | 5               |
| Menggugou  | 31.4        | 102              | 37.1     | 10.52   | 1.74    | 6.73     | 1.13| 0.46| 110     | 10              |
| Jiachehe   | 68.7        | 599              | 15.6     | 5.07    | 1.33    | 7.4      | 1.22| 0.56| 110     | 6               |
| Pingdicuo  | 11.5        | 110              | 24.2     | 9.9     | 1.47    | 5.9      | 1.14| 0.73| 110     | 30              |
| Fangshuang| 47.9        | 27               | 98       | 20.2    | 1.39    | 4.63     | 1.38| 0.67| 110     | 30              |

### Table 3 Threshold values of single evaluation index for the assessment grade

| Evaluation index | Threshold values of grade | Evaluation index | Threshold values of grade |
|------------------|---------------------------|------------------|---------------------------|
| M (×10⁶m³)       | mild 10 100 200           | S4 (km³)         | mild 5 10 20 50           |
| F (time/100year) | 0.5 10 35 50             | S5 (mm)          | 1.1 1.25 1.4 1.6         |
| S1 (km²)         | 0.5 10 35 50             | S6 (mm)          | 0.1 0.3 0.6 1            |
| S2 (km)          | 0.2 0.5 1 2              | S7 (mm)          | 25 50 100 200            |
| S3 (km)          | 0.2 0.5 1 2              | S8 (person/km²)  | 50 150 250 350           |

### Table 4 Results of debris flow risk assessment

| Gully    | Xiabaitan | Shangbai | Zhugongdi | Yindigou | Shenyuhe |
|----------|-----------|----------|-----------|----------|----------|
| Risk     | moderate  | moderate | moderate  | moderate | mild     |

| Gully    | Xiushuine | Menggugou | Jiachehe | Pingdicuo | Fangshuang |
|----------|-----------|-----------|----------|-----------|------------|
| Risk     | mild      | severe    | moderate | severe    | extreme    |

According to the degree of membership function of formulas (6), (7), and (8), the fuzzy relation matrix is calculated and multiplied by the weight aggregate to calculate vector B; finally, the evaluation grade is determined. Table 4 lists the evaluation results for 10 debris flow gullies.

There exist 239 debris flow gullies in Wudongde reservoir area. Among them, 20 mudslides are mildly dangerous, accounting for 8.4% of the total; 200 mudslides are moderately dangerous, accounting for 83.7%, and 18 mudslides are severely dangerous, accounting for 7.5%. Only one debris flow gully is extremely dangerous. Thus, according to the risk assessment result, the risk of most debris flow gullies in the reservoir area is low, and only a few debris flow gullies have high risk. The only extremely dangerous debris flow gully is 74 km away from the dam site, and is sufficiently far from the dam to have much effect on the stability of the dam. Thus, overall, the risk of debris flow in this reservoir area is relatively small and will not have a great impact on the construction and operation of hydropower stations here.

### 5. Conclusion

A large-scale debris flow in the reservoir area of a hydropower station will cause river stoppage and
swells, directly affecting the stability of the dam and posing a threat to human life and property downstream. Hence, it is crucial to evaluate the risk of debris flow in such reservoir areas. The traditional method is to obtain the required information through field surveys, which are tedious, time-consuming, and labor-intensive. In this study, remote-sensing imagery was used to acquire the information of debris flow gullies. A combination of remote-sensing imagery interpretation and field survey was employed. The results show that the remote-sensing imagery is very helpful to acquire the information of evaluation factors effectively in less time and is suitable for assessing debris flow disasters. The one-time flow rate of debris flow, frequency of debris flow, drainage area, cutting density of the drainage area, length of main gully, relative elevation of the drainage basin, sediment supply length, maximum daily rainfall, population density, and the main-gully bending coefficient were selected as the evaluation factors of the debris flow risk assessment; The weights of these 10 evaluation factors were determined by AHP as follows: 0.239, 0.239, 0.167, 0.081, 0.056, 0.116, 0.015, 0.039, 0.028, and 0.02, respectively. The risk of all debris flow in reservoir area was calculated by FSE. In all, the reservoir has 20 mildly dangerous mudslides, 200 moderately dangerous mudslides, 18 severely dangerous mudslides, and 1 extremely dangerous debris flow ditch. Thus, overall, the risk of debris flow in the reservoir area is relatively small and will not have a great impact on the construction and operation of hydropower stations in the studied reservoir.

Reference

[1] Liu, XL, Tang C. Risk Assessment on Debris Flow [M]. Beijing: Science Press, 1995.
[2] Ashitake, Adachi, Katsuji, Tokuyama, Hisao, Nakamura, Shoji, etc. Research on Debris Flow Hazard Assessment [J]. Journal of the Japan Society of Erosion Control Engineering, 1977, 30:7-16.
[3] D.A lexander. Natural Disaster Framework for Research[J]. Disasters, 1991,15(3):209-226.
[4] Eldeen. M. T, Predisaster Physical Planning: Integration of Disaster Risk Analysis into Physical Planning- A Case Study in Tunisia[J]. Disasters, 1980, 4(2):211-222.
[5] Liu, XL. Research on Debris Flow Hazard Assessment [J]. Journal of Catastrophology. 1988, 3(3):10-15.
[6] Heckmann, T.; Gegg, K.; Gegg, A.; Becht, M. Sample size matters: Investigating the effect of sample size on a logistic regression debris flow susceptibility model. Nat. Hazards Earth Syst. Sci. Discuss. 2013, 1, 2731-2779.
[7] Yong-Bo, T.; Tang, C. Application of AHP in single debris flow risk assessment. Chin. J. Geol. Hazard Control 2006, 17, 79–84.
[8] Liu, G.; Li, G.; Yang, L. Risk assessments of debris flow based on improved analytic hierarchy process and efficacy coefficient method. Glob. Geol. 2012, 15, 231-236.
[9] Ning, N.; Shu, H.P.; Liu, D.F.; Jin-Zhu, M.A. Hazard assessment of debris flow based on the entropy weight method and fuzzy evaluation method. J. Lanzhou Univ. 2014, 3, 369–375.
[10] Liang,W.-J.; Zhuang, D.-F.; Jiang, D.; Pan, J.-J.; Ren, H.-Y. Assessment of debris flow hazards using a Bayesian Network. Geomorphology 2012, 171, 94–100.
[11] Tiranti, D.; Cremonini, R.; Asprea, I.; Marco, F. Driving factors for torrential mass-movements occurrence in the Western Alps. Front. Earth Sci. 2016, 4, 16.
[12] Pudasaini, S.P. A general two-phase debris flow model. J. Geophys. Res. Earth Surf. 2012, 117, F03010.
[13] Kean, J.W.; Mccoy, S.W.; Tucker, G.E.; Staley, D.M.; Coe, J.A. Runo-generated debris flows: Observations and modeling of surge initiation, magnitude, and frequency. J. Geophys. Res. Earth Surf. 2013, 118, 2190–2207.
[14] van Asch, Th.W.J., Tang, C., Alkema, D., Zhu, J., Zhou, W., 2014. An integrated model to assess critical rainfall thresholds for run-out distance of debris flows. Nat. Hazards 70 (1), 299–311.
[15] Rickenmann, D., Laigle, D., Mcardell, B.W., Hübl, J., 2006. Comparison of 2D debris-flow simulation models with field events. Comput. Geosci. 10 (2), 241–264.

[16] Iverson, R.M., Ouyang, C.J., 2015. Entrainment of bed material by Earth-surface mass flows: review and reformulation of depth-integrated theory. Rev. Geophys. 53 (1), 27–58.

[17] Li CK, Goldstein RM. Studies of multibaselinespaceborne interferometric synthetic aperture radars[J]. IEEE Trans Geosci Remote Sensing. 1990,28:88–97.

[18] Antrop M, Eetvelde VV. Changing patterns in the urbanized countryside of Western Europe[J]. Landscape Ecol. 2004,15:257–270.

[19] Duan ZF, Pang ZH, Wang XY. Sustainability evaluation of limestone geothermal reservoirs with extended production histories in Beijing and Tianjin, China[J]. Geothermics. 2011,40:125–135.

[20] Lu XW, Loretta Y Li, Lei K, Wang LJ, Zhai YX, Zhai M, Water quality assessment of Wei River, China using fuzzy synthetic evaluation[J]. Environ Earth Sci. 2010, 60:1693–1699.