Groundwater assessment based on analytic hierarchy process and the normal cloud model in Weinan, China

Wengang Qu¹,², Panpan Xu¹,², Hui Qian¹,²,³ and Qiying Zhang¹,²

¹ School of Water and Environment, Chang’an University, No. 126, Yanta Road, Xi’an 710054, Shaanxi, China;
² Key Laboratory of Subsurface Hydrology and Ecological Effects in Arid Region of the Ministry of Education, No. 126, Yanta Road, Chang’an University, Xi’an 710054, Shaanxi, China
³ Email: qianhui@chd.edu.cn

Abstract. Groundwater quality is facing a grim challenge due to the development of Weinan city. A multi-index comprehensive evaluation method—analytic hierarchy process and normal cloud model are proposed to evaluate the groundwater quality of Weinan city. Seven parameters including TH (total hardness), TDS (total dissolved solids), SO₄²⁻, Cl⁻, COD, NO₂⁻, Mn were selected to characterize the groundwater quality. The results show that the groundwater quality level of W6 and B557 are excellent water quality (I), H32, W15, W23, and W14 are good water quality (II), only B24 is medium or average water quality (III). Compared with other methods, the results obtained by the proposed method are in good agreement with the NI method but far from SFI method. This study confirms the suitability of the Analytic hierarchy process and Normal cloud model method in groundwater quality evaluation in Weinan city, and provides a reasonable basis for decision-makers of groundwater protection and utilization in Weinan city.

1. Introduction

Weinan is a political and economic center in the east of Guanzhong Basin, China [1]. With the rapid development of the economy and society, groundwater quality in Weinan is facing increasingly serious challenges [2]. Hence, accurate assessment method has become a top priority for groundwater quality evaluation in this area.

There are many methods that have been proposed to evaluate water quality in past decades. Such as projection pursuit method [3], weight coefficient of variation method [4], fuzzy set-based model [5], Bayesian model [6] and normal cloud model [7]. The normal cloud model is developed on the basis of fuzzy set theory, which combines the characteristics of ambiguity and randomness [8]. It has been applied to a lot of fields [9-12]. For example, Fu et al. [13] introduced the normal cloud method to regional sustainable water resource utilization schemes. Gou et al. [14] proposed a Superiority Weakness Opportunity Threats (SWOT) Analysis and Normal Cloud Model for water resource sustainable utilization assessment and strategy development.

The water quality index is one of the most common methods to evaluate water quality. However, the influence degree of each index on water quality is different [15], so it is very important to determine the reasonable weight of evaluation indexes for the accuracy of evaluation results. The methods of estimating index weight are as follows: PCA/PFA [16], the revised Simos’ procedure [17],
Delphi method [18], and analytic hierarchy process (AHP) method [19]. The AHP is a multi-criteria decision analysis method used to determine the relative weights of available alternatives. Based on these weights, the AHP can make priorities choices among those alternatives effectively [20]. The AHP is easily implemented, understandable, and it is a better multi-attribute decision criteria used to derive weights. The normal cloud model is more advantageous than other models, due to not only quantifying both randomness and fuzziness by means of three fixed parameters, but also traveling from qualitative concept to quantitative characteristics. Therefore, the AHP and the normal cloud model were chosen.

In this study, the data of major wells were collected for seven parameters at seven sites in Weinan city. A multi-index comprehensive evaluation method analytic hierarchy process and the normal cloud model were chosen to evaluate the groundwater quality in Weinan city. And it aims to supply the accurate groundwater quality levels for decision maker of the city to make the policy of groundwater utilization.

2. Study area

Weinan city is located in the east of the Guanzhong Basin (Figure 1), and it is an emerging medium-sized industrial city, a political and economic center and transportation hub in the eastern part of Guanzhong. It is distinguished by an N-S length of 8 km, an E-W length of 16 km with an area of 135 km², approximately [2]. The climate in Weinan is warm temperate continental monsoon semi-humid climate, with average annual temperature of 13 °C and average annual precipitation of 558 mm, respectively [1]. The sample sites distributed in the study area are presented in Figure 1.

![Figure 1. Study area and sample sites location.](image)

3. Materials and assessment methods

3.1. Materials

| Table 1. Monitoring data of groundwater quality in Weinan city in 2011. |
|-----------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Index | H32 | W15 | W23 | W14 | W6 | B24 | B557 |
|-------|-----|-----|-----|-----|----|-----|-----|
| TDS  | 404 | 634 | 632 | 576 | 400 | 816 | 140 |
| TH   | 85.1 | 100.1 | 215.2 | 197.7 | 105.1 | 387.8 | 90.1 |
| SO₄²⁻ | 84.1 | 134.5 | 141.7 | 100.9 | 26.4 | 220.9 | 48 |
| Cl⁻  | 53.2 | 147.1 | 81.5 | 79.8 | 72.7 | 54.9 | 8.9 |
| COD  | 1.5 | 0.8 | 1.9 | 1.6 | 1.9 | 0.7 | 2.7 |
| NO₂⁻ | 0.262 | 0.003 | 0.047 | 0.017 | 0.177 | 0.015 | 0.003 |
| Mn   | 0.153 | 0.05 | 0.764 | 0.05 | 0.05 | 0.17 | 0.05 |
Seven groundwater samples were collected from wells in Weinan city in 2011. Depending on the standard for groundwater quality (GB14848-2017) [21], seven indexes including TH (total hardness), TDS (total dissolved solids), $\text{SO}_4^{2-}$, Cl, COD, $\text{NO}_2^-$, Mn were selected to evaluate the groundwater quality (as shown in Table 1). TDS presents total dissolved solids, is the mostly direct response of water quality. TH presents total hardness, is important for drink water. $\text{SO}_4^{2-}$, Cl, COD and $\text{NO}_2^-$ represent industrial pollution. Mn represent heavy metal pollution. So these indexes were selected to represent the quality of water.

3.2. Analytic hierarchy process

3.2.1. Construction of the pairwise comparison matrix. The pairwise comparison matrix used in this study was shown in Eq (1), using the 1-9 point scale to assess the relative importance among parameters [22]. When constructing the pairwise comparison matrix, the $a_{ij}$ must satisfy the following situation: (1) $a_{ij}=1$, as $i=j$; (2) $a_{ij}=1/a_{ji}$.

$$A = \begin{bmatrix} a_{11} & a_{12} & \ldots & a_{1N} \\ a_{21} & a_{22} & \ldots & a_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ a_{N1} & a_{N2} & \ldots & a_{NN} \end{bmatrix} \quad (1)$$

3.2.2. Calculation of the weights and consistency evaluation. Firstly, the principal eigenvector is determined from matrix $A$ by matrix algebra, and then the weights are estimated by normalization [19]. The principle eigenvector was calculated by Eq (2) using MatLab software.

$$A w = \lambda_{\text{max}} w \quad (2)$$

where $\lambda_{\text{max}}$ is the largest eigenvalue, and $w$ is the corresponding eigenvector.

Consistency is the best way to evaluate whether the judgment is consistent with the respondent. The closer $\lambda_{\text{max}}$ is to $N$, the more consistent the judgment is [16]. To measure the consistency, $\lambda_{\text{max}}$ was used as a validating parameter in Eq (3):

$$\text{CI} = \frac{\lambda_{\text{max}} - N}{N - 1} \quad (3)$$

where CI is the consistency index, $N$ is the dimension of the matrix.

Finally, Eq (3) is used to measure the consistency of the pairwise comparison matrix.

$$\text{CR} = \frac{\text{CI}}{\text{RI}} \quad (4)$$

where CR is consistency ratio, RI is a random index and its values are shown in Table 2. The pairwise comparison matrix has an acceptable consistency with the value of CR less than 0.1.

### Table 2. Random Index (RI) values for different values of $N$.  

| $N$ | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 |
|-----|----|----|----|----|----|----|----|----|----|----|
| RI  | 0  | 0  | 0.58 | 0.9 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 | 1.49 |

3.3. Normal cloud model

The cloud model proposed by professor Li is constructed on the probability concepts and fuzzy sets theory [8]. It has three numerical characteristics: $E_x$, $E_n$, $H_e$. $E_x$ is the expectation parameter, $E_n$ is the entropy parameter and $H_e$ is hyper entropy parameter [23].

3.3.1. Calculation of numerical characteristics of groundwater quality assessment. The numerical parameters are calculated as follow Eq (5) - Eq (7):
\[
E_w = \frac{B^\text{max}_i + B^\text{min}_i}{2}
\]
\[
E_w = \frac{B^\text{max}_i - B^\text{min}_i}{2.355}
\]
\[
H_e = k
\]

Where \(B^\text{max}_i\) and \(B^\text{min}_i\) are the boundaries of the specific evaluation criteria, \(k\) is a constant (\(k \leq 1\)).

Based on the standard for groundwater quality in China [21], groundwater quality was classified into five levels shown in Table 3.

### Table 3. Classification standards of groundwater quality.

| Evaluation   | I                   | II                  | III                 | IV                  | V                   |
|--------------|---------------------|---------------------|---------------------|---------------------|---------------------|
|              | Excellent water     | Good water quality  | Medium or average   | Poor water quality  | Extremely poor      |
|              | quality             | quality             | water quality       | quality             | water quality       |

3.3.2. The normal cloud model process of groundwater assessment. The normal cloud model generator algorithm can be induced in the algorithm as follow:

1. Generate a random number \(E^\prime_i\): \(E^n_i \sim N(En, He^2)\); the expectation of \(E^\prime_i\) is \(En\), the standard deviation is \(He\), and it is a normal random number.

2. Generate a random number \(x_i\): \(x_i \sim N(E_x, E^n_x)\), the expectation of \(x_i\) is \(E_x\), the standard deviation is \(E^n_x\), and it is a normal random number.

3. Calculate certainly degree: \(\mu(x_i) = \exp\left(-\left(x_i - E^n_x\right)^2 / 2\left(E^n_x\right)^2\right)\);

4. Repeat steps (1) to (3), and generate enough drops (3000 times in this study).

According to the method described above, the three characteristics of the normal cloud model at different levels can be calculated (in Table 4).

### Table 4. Normal cloud model characteristic parameters \((E_x, En, He)\).

| Evaluation index | I          | II         | III        | IV         | V          |
|------------------|------------|------------|------------|------------|------------|
| \(\text{SO}_4^{2-}\) | (25,21.23,1) | (100,42.46,1) | (200,42.46,1) | (300,42.46,1) | (400,42.46,1) |
| Cl               | (25,21.23,1) | (100,42.46,1) | (200,42.46,1) | (300,42.46,1) | (400,42.46,1) |
| COD              | (0.5,0.425,0.01) | (1.5,0.425,0.01) | (2.5,0.425,0.01) | (6.5,2.97,0.1) | (15,4.25,0.1) |
| \(\text{NO}_2^-\) | (0.05,0.0425,0.001) | (0.1,0.0425,0.01) | (0.55,0.382,0.01) | (2.9,1.61,0.1) | (7.2,2.04,0.1) |
| Mn               | (0.025,0.021,0.001) | (0.05,0.021,0.001) | (0.075,0.021,0.001) | (0.8,0.59,0.01) | (2.25,0.64,0.1) |
| TDS              | (150,127.39,1) | (400,84.93,1) | (750,212.31,1) | (1500,424.63,1) | (2500,424.63,1) |
| TH               | (75,63.69,1) | (225,63.69,1) | (375,63.69,1) | (500,42.46,1) | (825,63.69,1) |

4. Result and discussions

4.1. The weights of evaluation index

According to the analytic hierarchy process described before, the pairwise comparison matrix constructed was shown in Table 5. The largest eigenvalue \((\lambda_{\text{max}})\) and the corresponding eigenvector \((w)\) of matrix were calculated by MatLab software.

\[ w = (0.7846, 0.4877, 0.3024, 0.1863, 0.1147, 0.0715, 0.0448)^T, \lambda_{\text{max}} = 7.629. \]

The \(w\) was obtained by normalizing \(w\), and \(w = (0.3939, 0.2448, 0.1518, 0.0935, 0.0576, 0.0359, 0.0225)^T\). And then CR was calculated by Eq (3) and Eq (4): CR=0.0794 < 0.1. Hence, the pairwise comparison matrix can be considered as having an acceptable consistency. The weights of TDS, TH, \(\text{SO}_4^{2-}\), Cl, COD, \(\text{NO}_2^-\) and Mn were 0.3939, 0.2448, 0.1518, 0.0935, 0.0576, 0.0359 and 0.0225, accordingly.
Table 5. The pairwise comparison matrix used in AHP.

|     | V  | TDS | TH | SO₄²⁻ | Cl⁻ | COD | NO₂⁻ | Mn |
|-----|----|-----|----|-------|-----|-----|------|----|
| TDS | 1  | 3   | 4   | 5     | 6   | 7   | 9    |    |
| TH  | 1/3| 1   | 3   | 4     | 5   | 6   | 7    |    |
| SO₄²⁻| 1/4| 1/3 | 1   | 3     | 4   | 5   | 6    |    |
| Cl⁻ | 1/5| 1/4 | 1/3 | 1     | 3   | 4   | 5    |    |
| COD | 1/6| 1/5 | 1/4 | 1/3   | 1   | 3   | 4    |    |
| NO₂⁻| 1/7| 1/6 | 1/5 | 1/4   | 1/3 | 1   | 3    |    |
| Mn  | 1/9| 1/7 | 1/6 | 1/5   | 1/4 | 1/3 | 1    |    |

4.2. The certainty degree of evaluation index

According to the normal cloud model, the certainty degree of evaluation index at different levels can be obtained. Taking H32 as an example, after 3000 times of calculation with MatLab software, the mean value was considered to represent the certainty degree, and the certainty degree of different evaluation index in different levels was shown in Table 6. Combined with the weights of evaluation index, the final certainty degree of H32 at different levels could be confirmed.

Table 6. Certainty degree of H32 groundwater sample evaluation index.

| Evaluation index | I   | II  | III | IV  | V  |
|------------------|-----|-----|-----|-----|----|
| TDS              | 0.14| 1.00| 0.27| 0.04| 0.00|
| TH               | 0.99| 0.09| 0.00| 0.00| 0.00|
| SO₄²⁻            | 0.02| 0.93| 0.02| 0.00| 0.00|
| Cl⁻              | 0.41| 0.54| 0.00| 0.00| 0.00|
| COD              | 0.06| 1.00| 0.06| 0.24| 0.01|
| NO₂⁻             | 0.00| 0.00| 0.75| 0.26| 0.00|
| Mn               | 0.00| 0.00| 0.00| 0.55| 0.01|

Applying the same method to other samples, final evaluation results of seven samples are presented in Table 7. To verify the feasibility of the normal cloud model method in this study, the single factor index (SFI) method [24] and the Nemerow index (NI) method [25] were also selected to evaluate the quality of groundwater in Weinan city (Table 7).

In Table 7, the water quality evaluation results of each well can be classified in five levels from low to high. The final quality levels in the normal cloud model of W6 and B557 are excellent water quality (I), H32, W15, W23, and W14 are good water quality (II), only B24 is medium or average water quality (III). It can be seen from Table 7 that the evaluation results by normal cloud model method and NI method are basically the same. Six out of seven results are the same as those of the NI method. By contrast, the results of SFI method have big difference with other two methods. Nearly all results assessed by SFI are medium or average water quality (III) or Poor water quality (IV). Which may be due to that the SFI method is one-sided and only emphasizes the most serious pollution indicator [26], the grade of the most serious indicator was selected as the grade of groundwater. The normal cloud model is a comprehensive method, it can avoid the influence of individual serious pollution indicator effectively and give a more objective and comprehensive water quality results. Thus, the normal cloud model method is suitable for groundwater quality assessment in Weinan city.
Table 7. The final evaluation results of the wells.

| Well | Final Certainty Degrees | The Normal Cloud Model Method | SFI | NI |
|------|--------------------------|-------------------------------|-----|----|
|      | I   | II   | III  | IV  | V   |     |     |    |
| H32  | 0.7347 | 0.7700 | 0.1531 | 0.0497 | 0.0007 | II  | IV  | I  |
| W15  | 0.3111 | 0.5843 | 0.5017 | 0.0758 | 0.0005 | II  | III | II |
| W23  | 0.0703 | 0.8202 | 0.4940 | 0.0962 | 0.0024 | II  | IV  | II |
| W14  | 0.1291 | 0.8705 | 0.3660 | 0.0689 | 0.0006 | II  | III | II |
| W6   | 0.8410 | 0.7131 | 0.1707 | 0.0497 | 0.0008 | I   | IV  | I  |
| B24  | 0.1117 | 0.4557 | 0.8710 | 0.1705 | 0.0007 | III | III | III|
| B557 | 0.8192 | 0.1440 | 0.0845 | 0.0449 | 0.0011 | I   | III | I  |

5. Conclusions

In this study, a multi-index comprehensive evaluation method combing the Analytic hierarchy process and the Normal cloud model is proposed. The conclusions can be drawn as follow:

(1) It can be seen that AHP and the normal cloud model have a high accuracy and are suitable for groundwater evaluation. Based on that, the groundwater quality of Weinan city is evaluated reasonably. The groundwater quality mostly are I and II grade in Weinan city, only one well is III. In most part, the groundwater has not been polluted.

(2) The method can evaluate the quality of groundwater qualitatively and quantitatively and avoid the randomness and blindness of water quality index weighting. Compared with the single SFI method the results calculated by Normal cloud model is more acceptable.

(3) Considering the successful application of this method in Weinan city, it can be applied to other similar areas in the world. This method can also be used in other fields, such as surface water quality assessment, air quality assessment and soil pollution assessment. When apply this method, please pay attention to that the method is a one-dimensional model, and multi-dimensional cloud model need to be explored in the future.

References

[1] Liu JG, Savenije, H. H. G., Xu JX 2002 Forecast of water demand in Weinan City in China using WDF-ANN model Physics & Chemistry of the Earth. 28(4-5) 219–224
[2] Zhang MA 2004 Study on the optimization of watwer resources of Weinan city M.S. Thesis Xi'an University of Technology, Xi'an, China (in Chinese)
[3] Zhang C, Dong SH 2009 A new water quality assessment model based on projection pursuit technique Journal of Environmental Sciences 21 S154-S157
[4] Li Q, Meng X, Liu Y, Pang L 2019 Risk assessment of floor water inrush using entropy weight and variation coefficient model Geotechnical and Geological Engineering 37(3) 1493-1501
[5] Azimi S, Moghaddam MA., Monfared SH 2019 Prediction of annual drinking water quality reduction based on Groundwater Resource Index using the artificial neural network and fuzzy clustering Journal of contaminant hydrology 220 6-17
[6] Sperotto A, Molina JL, Torresan S, Critto A, Pulido-Velazquez M, Marcomini A 2019 Water Quality Sustainability Evaluation under Uncertainty: A Multi-Scenario Analysis Based on Bayesian Networks Sustainability 11(17) 4764
[7] Yao J, Wang G, Xue B, Wang P, Hao F, Xie G, Peng Y 2019 Assessment of lake eutrophication using a novel multidimensional similarity cloud model Journal of environmental management. 248 109259
[8] Zhong L, Yan L 2010 Single rule reasoning mapping for the two dimensional normal cloud model. CAAI Transactions on Intelligent Systems 5
[9] Wang X, Li S, Xu Z, Hu J, Pan D, Xue Y 2019 Risk assessment of water inrush in karst tunnels
excavation based on normal cloud model *Bulletin of Engineering Geology and the Environment* 78(5) 3783-3798

[10] Cui CQ, Wang B, Zhao YX, Wang Q, Sun ZM 2019 China's regional sustainability assessment on mineral resources: Results from an improved analytic hierarchy process-based normal cloud model *Journal of cleaner production* 210 105-120

[11] Wang X, Yang W, Xu Z, Hu J, Xue Y, Lin P 2019 A Normal Cloud Model-Based Method for Water Quality Assessment of Springs and Its Application in Jinan *Sustainability* 11(8) 2248

[12] Qi YL 2009 Classification for trademark image based on normal cloud model *Paper presented at the 2009 International Conference on Information Management, Innovation Management and Industrial Engineering*

[13] Fu Q, Meng FX, Li TX, Liu D, Gong FL, Osman A, Li YT 2016 Cloud model-based analysis of regional sustainable water resource utilization schemes *International Journal of Agricultural and Biological Engineering* 9(5) 67-75

[14] Gao X, Chen L, Sun B, Liu Y 2017 Employing SWOT analysis and normal cloud model for water resource sustainable utilization assessment and strategy development *Sustainability* 9(8) 1439

[15] Sutadian AD, Muttil N, Yilmaz AG, Perera B 2016 Development of river water quality indices - a review *Environmental monitoring and assessment* 188(1) 58

[16] Mohd Ali Z, Ibrahim NA, Mengersen K, Shitan M, Juahir H 2013 The Langat River water quality index based on principal component analysis *Paper presented at the AIP Conference Proceedings*

[17] Fontana ME, Morais DC, Almeida AT 2011 A MCDM model for urban water conservation strategies adapting simos procedure for evaluating alternatives intra-criteria *Paper presented at the International Conference on Evolutionary Multi-Criterion Optimization*

[18] Cheng M, Liu TK, Olenin S, Su PX 2019 Risk assessment model based on expert's perspective for ballast water management *Ocean & coastal management* 171 80-86

[19] Sutadian, A. D., Muttil, N., Yilmaz, A. G., & Perera, B 2017 Using the Analytic Hierarchy Process to identify parameter weights for developing a water quality index *Ecological indicators* 75 220-233

[20] LaValle IH, Bard JF 1991 The analytic hierarchy process: applications and studies:M.S. JSTOR.

[21] Bureau of Quality and Technical Supervision of China 1994 National Standard of the People’s Republic of China: Quality Standard for Groundwater GB/T 14848-93 (in Chinese)

[22] Harker PT, Vargas, LG 1987 The theory of ratio scale estimation: Saaty's analytic hierarchy process *Management science* 33(11) 1383-1403

[23] Li J, Wang M, Xu P, Xu P 2014 Classification of stability of surrounding rock using cloud model *Chinese Journal of Geotechnical Engineering* 36(1) 83-87

[24] Luo X, Zhang Q, Chen L, Meng Q, Zhao M 2016 Namning river upstream region comprehensive quality evaluation in guiyang based on the single factor index method *Ground Water* 38 80-82

[25] Jie C, Qing L, Hui Q 2012 Application of improved Nemerow index method based on entropy weight for groundwater quality evaluation *International Journal of Environmental Sciences* 2(3) 1284-1290

[26] Wang Y, Jing H, Zhang Q, Yu L, Xu Z 2015 A normal cloud model-based study of grading prediction of rockburst intensity in deep underground engineering *Rock and Soil Mechanics* 36(4) 1190-1193