



Assessment on water resources carrying capacity in karst areas under a novel multi-dimensional cloud model—a case study

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Abstract

The contradiction of water supply and demand has increased in China recently due to rapid economic and social development. Lacking of water has become one of problems that need to be improved and solved urgently. So assessment on water resources carrying capacity (WRCC) is an important basis for maintaining the sustainable development of water resources. In allusion to the uncertainty in the evaluation process, this study put forward an assessment method for WRCC based on the multi-dimensional cloud model after referring to the one-dimensional cloud model theory. Each evaluation index is regarded as a one-dimensional variable of the multi-dimensional cloud model. According to the cloud theory and WRCC assessment standards, appropriate cloud model digital characteristics were selected. After considering the information amount and correlation of indicators, and by using the sum of deviation square method to determine weights of all evaluation indicators, then a multi-dimensional cloud model corresponding to each evaluation level that integrated all evaluation indexes was generated. Then measured values of all indicators were entered to obtain the comprehensive certainty degree that belonged to each evaluation level, and WRCC level was determined under the principle of maximum certainty. To verify the rationality and effectiveness of the model, this study took a typical karst area (Guiyang) as an example, and compared assessment results with that of the one-dimensional cloud model and Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) method. Results showed that the multi-dimensional cloud model is effective in the assessment on WRCC. It can intuitively and quickly determine the carrying level of water resources, and provide a new method for the assessment on WRCC. Moreover, based on assessment results of the study area, some reasonable policies and measures were put forward to ensure the effective utilization of water resources and improve the bearing capacity of regional water resources.

Keywords Karst area · Sustainable development · Water resources carrying capacity (WRCC) · Combination weighting method · Multi-dimensional cloud model · Assessment

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Introduction

Water resource is the basic element of socioeconomic development and ecological system. With the rapid economic development and the increase of population, human activities have had an effect on the natural water cycle, and the natural water cycle has evolved into a natural-social dual water cycle. From the perspective of human society, the transformation of natural water cycle has increasingly deepened the contradiction between supply and demand of water resources (Wang and You 2016). Nowadays, water resource shortage has become the key to restricting the sustainable development of many cities (Tan and Liu 2021). Solving the contradiction of water resources supplies and demands, and realizing the high efficient utilization of water resources are the important link in realizing the sustainable

development of water resources. “Water resources carrying capacity” (WRCC) is a key indicator for judging the sustainable development of water resources (Wu et al. 2018). Therefore, scientific evaluations on WRCC are very important to promote the social and economic development and ecological environmental protection.

In the field of resources and the environment, the concept of carrying capacity is derived from the ecology capacity and applied to evaluate the maximum amount of bionts of a species which could be supported within a particular district (Sun 2000; Wu et al. 2020). Subsequently, the notion of carrying capacity was diffused and used to specify the capacity of ecotope or unartificial resources to maintain social and economic actions (Feng 2000; Zheng et al. 2020), such as water environment-carrying capacity (Zhu et al. 2010; Li and Wang 2011; Wang et al. 2019), water resources carrying capacity (Feng and Huang 2008; Li and Jin 2009; Meng et al. 2009; Peng and Deng 2020b), soil-carrying capacity (Johnson et al. 2011; Das and Dey 2020), and population-carrying capacity (Shi et al. 2013; Archer 2021). Researchers across the world gave different definitions on WRCC (Xu et al. 2002; Peng and Deng 2020d). Few researchers have defined WRCC on the basis of the ability to maintain a functioning and sustaining society (Lopes and Theisohn 2003; Clarke 2002; Ubels et al. 2010; Harris and Kennedy 1999; Ofoezie 2002; Ahmadi et al. 2020), while others have regarded it as a threshold of water supplies for activities of humankind (Hunter 1998; Kuykendtierna et al. 1997; Rijsberman and Ven 2000; Li et al. 2000; Falkenmark and Lundqvist 1998; Yu et al. 2020).

China is one of 21 countries with severe water shortage in the world (Jin et al. 2018). China’s water resources are scarce, the temporal spatial distribution of which is not uniform, and land and water resources distribution is not concerted (Liu et al. 2018). Water resources have become the important restriction element for economic and social sustainable development (Wang et al. 2000; Sun et al. 2016). WRCC, the basic content of strategy researches on the sustainable development and water resources security, has become the hot point and key question in current water resources researches (Zhu et al. 2002; Yang et al. 2021), and it has become an obstacle to the population and development, especially in areas where water resources are scarce (Tang and Zhang 2001; Liu et al. 2016).

In fact, WRCC is of great significance for sustainable social and economic development of a country or a region (Li et al. 2014). Great attentions have been paid to studies on WRCC in the past 20 years and these studies have become the important approaches of measuring water safety to achieve sustainability in China, especially in regions with serious water resources shortage (Xia et al. 2002; Dai et al. 2019). Considering the interplay between physical surroundings and mankind world, carrying capacity tries to build the

sustainable development path of harmony between humankind and nature (Yang et al. 2019).

In terms of previous studies on WRCC, researchers outside China have summarized WRCC in the research of sustainable development, and there are fewer studies on individual WRCC (Ren et al. 2016). Researches on WRCC in China mostly focused on evaluation methods and evaluation index systems. Zhang and Guo (2006) summarized the concept of WRCC in detail. Daily and Ehrlich (1996) proposed the relationship between socio-economic quality and sustainable development and the carrying capacity of the earth. Fu et al. (2005) analyzed and evaluated WRCC from aspects of population and economic carrying capacities by forecasting water demands of various industries in the study area. Zhang (2011) combined AHP method with fuzzy mathematical membership method to analyze water ecological carrying capacity in Jiangxi province. Dai et al. (2016) built a fuzzy comprehensive evaluation model by using the entropy weight method to evaluate and compare carrying capacities of water resources in various cities of Guangxi province. Su et al. (2017) combined the projection pursuit method with the matter-element’s extension theory to establish an evaluation model, eliminating the influence of subjective judgment on evaluation results. Yang et al. (2019) carried out a study on Xi’an’ WRCC by using the analytic hierarchy process (AHP) and system dynamics (SD) models. Yin et al. (2020) assessed and simulated the safety sensitivity of water resources in karst regions under hydroclimatological change conditions. Sun et al. (2017) used a system dynamics model to evaluate the sustainable use of water resources in China and find out influence factors. Wang et al. (2020) put forward a novel water resources ecological footprint (WEF) model to study WRCC of Hubei province from regional characteristics and spatiotemporal patterns of water utilization. Peng and Deng (2020b) proposed a DPESBR framework to carry out assessment on WRCC in karst regions, and used it to conduct a case study.

The study of WRCC has become the foundational content of sustainability and strategic research on water resources safety (Xia and Zhu 2002). The study of WRCC has put major concentrations in evaluation methodologies and indicator systems in the past 20 years (Duan et al. 2010; Peng and Deng 2020b; Li et al. 2014). The study of WRCC is relatively rare in the background of special water hydrology in karst regions (Dai et al. 2016). Water resources of karst regions in southwest of China have traditionally been abundant, but surface water resources are scarce and groundwater resources are abundant, resulting in a peculiar binary aquatic ecosystem with great ecological importance (Zhou and Liang 2006). Because of the impact of special geological environment and activities of humankind, water resources safety of karst regions in southwest of China has been under all kinds of challenges,

such as nonperennial water resources depletion, frequent alternation of water disasters, and water contamination (Li and Wang 2021). Water resources are the determining element for the ecological equilibrium, environmental conservation, economy growth and poverty elimination in karst regions. As relief karstique in Guiyang has a wide distribution and various categories, with the society great development of economy, its WRCC has been given a lot of attention (Lv et al. 2017a). For instance, there are abundant ground water resources and water quality is comparatively superior (Su 2008), while the low exploitation rate is between 8 and 15% (Lu et al. 2006). Therefore, in contrast to non-karst regions, there are substantial differences in the bearing capacity of water resource system to population, socioeconomic growth and eco-environment in karst regions (Kong et al. 2007), and groundwater resource is highly susceptible to contamination due to unconscionable activities of humankind (Zhang et al. 2014).

To have a better management programming on water resources in karst regions rationally, the most important thing is to learn more about WRCC, which could offer guidance for the regulation on rock desertification and eco rehabilitation. This study aims at the uncertainty of WRCC, the complexity under the combined action of multiple factors, and the correlation between factors. Firstly, based on the theory of uncertain artificial intelligence, a multi-dimensional cloud model was used to solve the problem of evaluation on WRCC. At the same time, the combination weight was used to obtain comprehensive weights by merging weights which were calculated through the improved analytic hierarchy process and improved CRITIC (Criteria Importance Though Intercriteria Correlation) method respectively. Secondly, a combination weighting-multi-dimension cloud model was established, and the model was used in an example of a certain area to test the validity of the model. Thirdly, this study could also offer the theory instruction and guidance for studies on WRCC of other cities deficient of water resources.

Methods

Theory of cloud model

Based on stochastic and fuzzing mathematics, Li and Du (2014) put forward a cloud model, which is a mathematical tool to implement processing of the uncertainty knowledge from the qualitative analysis to the quantitative analysis. It has been much more successful in the following fields: picture processing, DM (data mining), grade assessment on adjoining rock, decision-making analysis, and other areas (Yao et al. 2019; Peng and Deng 2020c).

Cloud and cloud droplets

Cloud is a two-way cognitive model between a qualitative concept expressed by a linguistic value and its quantitative representation, which could reflect uncertainties of concepts in natural languages, that is, the randomness and the fuzziness. The related definition is as follows (Li and Du 2014):

Let U be a quantitative domain characterized by an exact number, and C is a qualitative concept on U . If the quantitative value $x \in U$ and x is a random implementation of C , there is a steady random digit $\mu(x) \in [0,1]$, which is named as certainty degree of x on C , and the certainty degree distribution on U is named as *cloud* (Li et al. 2017; Yao et al. 2019). Each x is called a cloud droplet (Guo et al. 2018).

$$\mu : U \rightarrow [0,1], \forall x \in U, x \rightarrow \mu(x) \tag{1}$$

Multi-dimensional forward normal cloud

The multidimensional forward normal cloud is generalized from one-dimensional forward normal cloud, which could reflect the multidimensional qualitative concept. The related definition is as follows:

Setting $U\{X_1, X_2, \dots, X_n\}$ be a n -dimensional quantitative domain represented by exact numerical values, and C is a qualitative concept on $U\{X_1, X_2, \dots, X_n\}$. If the quantitative value $x(x_1, x_2, \dots, x_n)$ ($x \in U$) is a random implementation of C , and x obeys a normal distribution $x(x_1, x_2, \dots, x_n) \sim N(Ex(Ex_1, Ex_2, \dots, Ex_n), .En'(En'_1, En'_2, \dots, En'_n)^2)$ Among them, En' also obeys a normal distribution $En'(En'_1, En'_2, \dots, En'_n) \sim N(En(En_1, En_2, \dots, En_n), He(He_1, He_2, \dots, He_n)^2)$. Therefore, the degree of certainty $W_1 = (a_j)_{1 \times n}, W_2 = (b_j)_{1 \times n}$ on C meets:

$$\mu(x(x_1, x_2, \dots, x_n)) = \exp - \left[\sum_{j=1}^n \frac{(x_j - Ex_j)^2}{2(En'_j)^2} \right] \quad (j = 1, 2, \dots, n) \tag{2}$$

Then, the distribution of $x(x_1, x_2, \dots, x_n)$ on domain U is called *n-dimensional normal cloud*.

The algorithm of multidimensional forward normal cloud generator is as follows:

Input: digital characteristics of multidimensional cloud model $(Ex_1, Ex_2, \dots, Ex_n, En_1, En_2, \dots, En_n, He_1, He_2, \dots, He_n)$, the number of cloud drops N is generated.

Output: $drop(x_{1i}, x_{2i}, \dots, x_{ni}, \mu_i)(i = 1, 2, \dots, N)$.

Algorithm steps are as follows:

- (1) n -dimensional normal random number $En'(En'_1, En'_2, \dots, En'_n)$ is generated, the expectation

and variance of which are $En(En_1, En_2, \dots, En_n)$ and $He(He_1, He_2, \dots, He_n)^2$, respectively.

- (2) n-dimensional normal random number $x(x_1, x_2, \dots, x_n)$ is generated, the expectation and variance of which are $Ex(Ex_1, Ex_2, \dots, Ex_n)$ and $En'(En'_1, En'_2, \dots, En'_n)^2$, respectively.

- (3)
$$\mu_i[x(x_1, x_2, \dots, x_n)] = exp\left[-\sum_{j=1}^n \frac{(x_j - Ex_j)^2}{2(En'_j)^2}\right] (j = 1, 2, \dots, n)$$
 is calculated.

- (4) Setting $drop(x_{1i}, x_{2i}, \dots, x_{ni}, \mu_i)$ as a cloud droplet, it is a specific implementation of language values in quantity, which is expressed by the cloud. Among them, $(x_{1i}, x_{2i}, \dots, x_{ni})$ is the corresponding value of the qualitative concept in the domain, μ_i is a measure of the language value degree that includes $(x_{1i}, x_{2i}, \dots, x_{ni})$.

- (5) Steps (1) to (4) are repeated until N cloud droplets are generated.

One-dimensional and two-dimensional cloud models generated by the above algorithm are shown in Fig. 1a and b (Peng et al. 2021; Guo et al. 2018). The digital characteristic and expectancy Ex of the cloud model are 10, entropy En are both 10/3, hyperentropy He are 0.1, and the number of cloud droplet N is 15 000.

Digital characteristic of the multi-dimensional cloud model

The cloud model adopts the three digital characteristics of expectation Ex , entropy En , and super-entropy He to represent the qualitative concept as a whole. Expectation Ex is the mathematical expectation of cloud drops in the spatial distribution of the domain. Entropy En is the uncertainty measure of the qualitative concept, which reflects the dispersion degree of cloud droplets on the one hand, and determines the certainty degree of cloud droplets that could be accepted by the concept in the domain space on the other hand. Super-entropy He is an uncertain measure of entropy (Zhou et al. 2019a, b). There are corresponding formulas to determine three digital characteristics of one-dimensional cloud model, while the determination of digital characteristics of multi-dimensional cloud model has not been conclusive. With reference to results of studies by Guo and other scholars (Guo et al. 2010, 2018; Du et al. 2008; Peng and Deng 2020b), this study determined cloud digital characteristics of predictive indicators of WRCC for a certain level standard by using the following methods:

$$Ex = (C_{min} + C_{max})/2 \tag{3}$$

In Formula (3), C_{max} and C_{min} are the upper and lower edge values of the corresponding standard for grade respectively. With

regard to variables with a unilateral edge, such as $[C_{min}, +\infty)$ or $(-\infty, C_{max}]$, default edge parameters can be determined based on top and bottom limitations of measured values.

Because the multi-dimensional cloud model comprehensively considers each grade standard of each predictive indicator, the digital characteristic En is determined according to the maximum range of each predictive indicator value, and the entropy of each grade standard of each index is unchanged. According to “3En rule” of the normal cloud (Liu et al. 2005), the following formula can be obtained:

$$En = Ex_{max}/3 \tag{4}$$

In Formula (4), Ex_{max} is the maximum value of certain indicators corresponding to the expectation of each grade standard.

Superentropy He can weaken the randomness constraint of the indicator value x into some kind of “pan-normal distribution,” which is the uncertainty measure of entropy En . Therefore, a suitable constant for He can be chosen according to the size of En , and the larger the value of

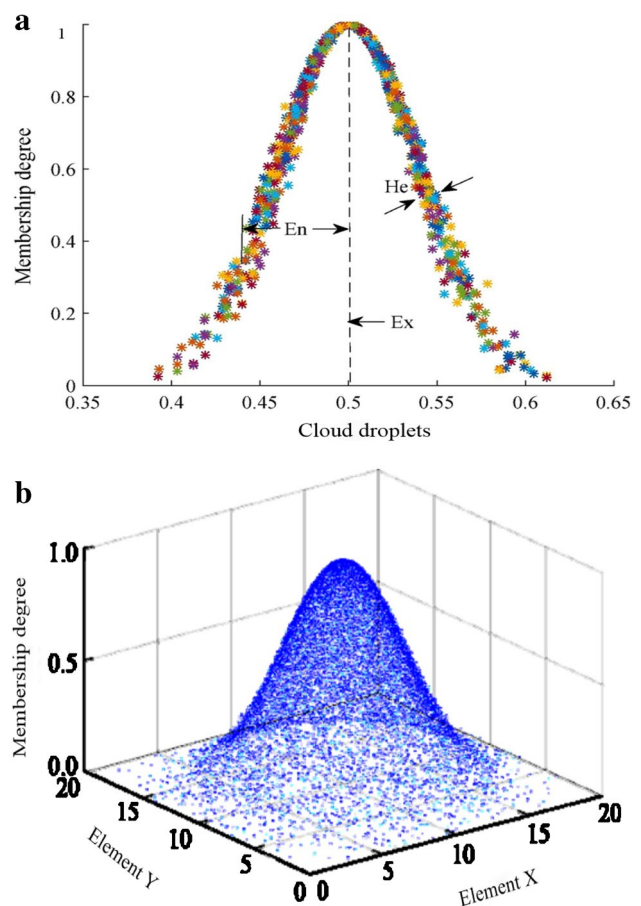


Fig. 1 a A one-dimensional cloud model of a certain concept affected by element X. b A two-dimensional cloud model of a certain concept affected by elements X and Y

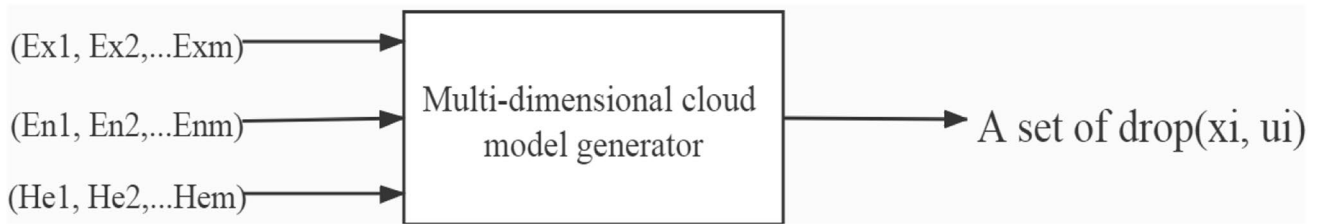


Fig. 2 Principles of the multi-dimensional forward cloud model generator

E_n is, the larger the corresponding He value is, generally $0.01 \leq He \leq 0.1$ (Li and Du 2014). This study takes He as 0.1 all together (Fig. 2).

Multi-dimensional cloud model for WRCC assessment

Model framework for WRCC assessment

The basic framework of the multi-dimensional cloud model method for WRCC evaluation proposed in this study is as follows:

- (1) Based on previous studies on WRCC (Zhang et al. 2020; Cheng et al. 2018; Elsheikh et al. 2011; Juanah et al. 2013), this study established an evaluation index system for WRCC and its evaluation grade standards.
- (2) According to evaluation standards of water resource carrying capacity, combined with the theory of multi-dimensional cloud model, 3 digital characteristics of cloud models with m evaluation levels of n indicators are determined.

$$[Ex_k(Ex_1, Ex_2, \dots, Ex_n), En_k(En_1, En_2, \dots, En_n), He_k(He_1, He_2, \dots, He_n)], k = 1, 2, \dots, m.$$
- (3) The formula for the sum of squares of deviation was used to calculate index weights.
- (4) Digital characteristics of the cloud model and the weight of each indicator were entered, then the multi-dimensional forward normal cloud generator generated m n -dimensional cloud models that took n prediction indicators into consideration corresponding to m evaluation levels.
- (5) Actual measured values of n indicators of WRCC were entered, and the formula of comprehensive certainty degree (see below) was used to calculate the certainty degree, then the assessment level of carrying capacity was determined based on the maximum certainty principle.

The detailed implementation process of WRCC evaluation based on the multi-dimensional cloud model is shown in Fig. 3.

Evaluation standards

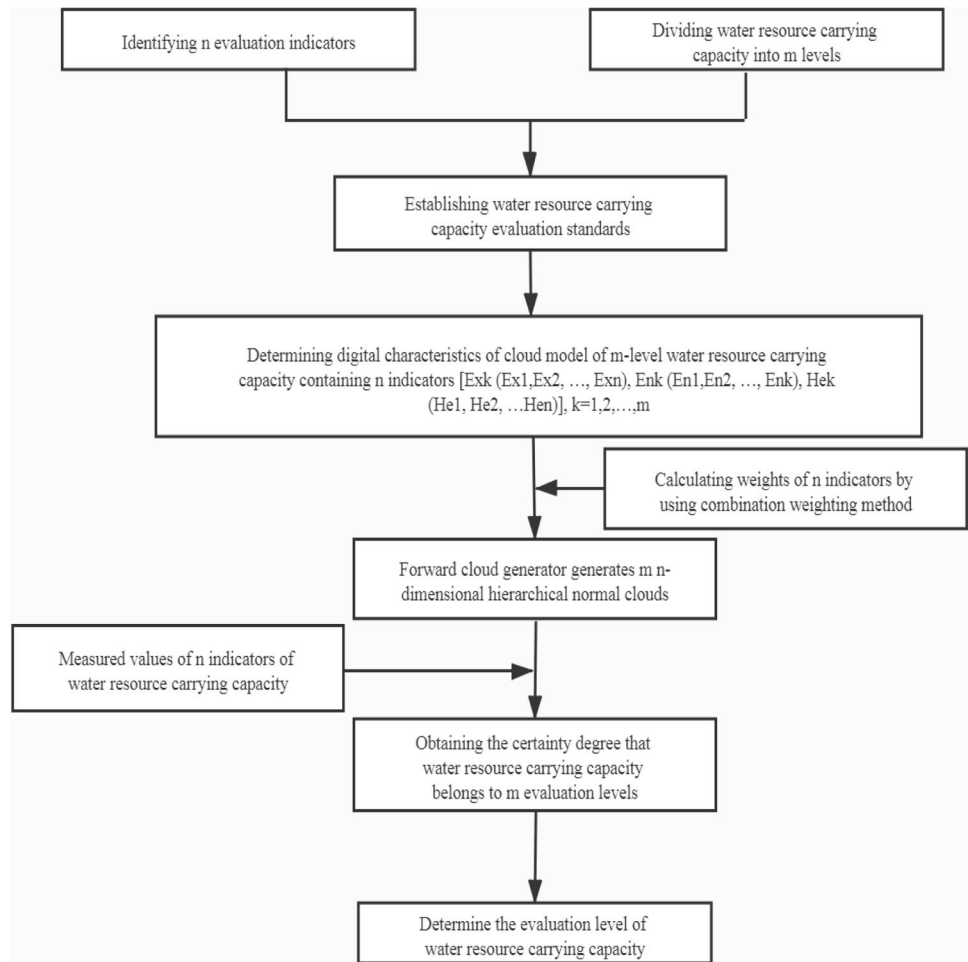
The identification of WRCC evaluative criteria should precisely and impersonally judge whether the population and the economy are coordinated with resources and the environment in an area. On the basis of water resources situation in karst regions and the whole nation, referring to widely recognized evaluation criteria of WRCC (Peng et al. 2021a; Jin et al. 2019; Zhang et al. 2017; Hao et al. 2018), this study selected targeted indicators from three aspects: water resources carrying supporting capacity, water resources carrying controlling capacity, and water resources carrying pressure, and determined classification standards of indicators for evaluating WRCC in the study area. Then, WRCC was divided into 3 grades (see Tables 1 and 2): grade I indicated a higher level of WRCC, richer water resources, and greater potential for development and utilization. Water resources were in a carrying state and could meet the coordinated development of population-economy-resources-environment. Grade II indicated an ordinary level of WRCC, water resources being in a balanced state, and the basic saturation state for development and utilization. Water resources and regional development needs were in a basically coordinated state. Grade III indicated a poor level of WRCC, water resources have become a serious limiting factor for the regional development, there was no room for development and utilization, and water resources were in an overloaded state.

Determining weights of evaluation indicators for WRCC

Improved analytic hierarchy process

Analytic hierarchy process (AHP) is a kind of decision analysis approach combining the quantitative analysis and the qualitative analysis, which has advantages of a simple operation and a brief calculation process. Traditional analytic

Fig. 3 Flow chart of the evaluation on WRCC



hierarchy process (AHP) adopts the scale method of 1~9 (Li et al. 2018; Zhou et al. 2019a, b). In contrast, the improved analytic hierarchy process (IAHP) adopts the scale method of 1~3. There is no need to judge the specific importance difference between indicators, only the relative importance between indicators needs to be determined. Therefore, it is convenient to build the comparison matrix and improve the evaluation efficiency in view of no needs for the consistency check. The improved analytic hierarchy process (IAHP) establishes a comparison matrix by the pairwise comparison between indicators, and determines the relative importance and the weight of each indicator. Specific steps are as follows:

(1) Building the comparison matrix A

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \tag{5}$$

Among them, $a_{ij} = \begin{cases} 1, & \text{denoting } i \text{ is more important than } j, \\ 0, & \text{denoting } i \text{ is as important as } j, \\ -1, & \text{denoting } i \text{ is less important than } j. \end{cases}$

(2) Building the optimal transfer matrix R

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1j} \\ r_{21} & r_{22} & \cdots & r_{2j} \\ \vdots & \vdots & \ddots & \vdots \\ r_{i1} & r_{i2} & \cdots & r_{ij} \end{bmatrix} \tag{6}$$

Among them, $r_{ij} = \frac{1}{n} \sum_{n=1}^n (a_{in} + a_{nj})$.

(3) Building the synthetic judgment matrix

$$D = \begin{bmatrix} d_{11} & d_{12} & \cdots & d_{1n} \\ d_{21} & d_{22} & \cdots & d_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ d_{n1} & d_{n2} & \cdots & d_{nn} \end{bmatrix} \tag{7}$$

Table 1 Evaluation index system of WRCC

Subsystem	Serial number	Evaluation indicators	Computational methods
Carrying supporting capacity	X ₁	Per capita water resources; (unit: m ³ /person)	Total amount of water resources/total resident population
	X ₂	Water yielding modulus; (unit: 10 ⁴ m ³ /km ²)	Average total amount of water resources/region areas
	X ₃	Water supply per capita per year; (unit: m ³ /person·Y)	Annual total amount of water supply/total resident population
	X ₄	Forest coverage rate; (unit: %)	Forest areas/total areas of land
Carrying controlling capacity	X ₅	Development utilization rate of surface water resources; (unit: %)	Total surface water supply/total amount of water resources
	X ₆	Development utilization rate of ground water resources; (unit: %)	Total ground water supply/total amount of water resources
	X ₇	GDP per capita; (unit: 10 ⁴ yuan/person)	Total GDP/total population
	X ₈	Ecological water use ratio; (unit: %)	Amount of ecological and environmental water use/Total water use
Carrying pressure	X ₉	Mean daily water consumption of per urban resident; (unit: L/D·P)	Total daily water consumption of residents/total resident population
	X ₁₀	Water consumption per 10,000 Yuan of GDP; (unit: m ³ /10000 yuan)	Total socio-economic water use/total GDP
	X ₁₁	Water consumption per 1,0000 Yuan of industrial output; (unit: m ³ /10 ⁴ yuan)	Total industrial water use/industrial added value
	X ₁₂	Population density; (unit: person/km ²)	Total resident population/region areas
	X ₁₃	Urbanization rate; (unit: %)	Urban population/total population
	X ₁₄	Farmland irrigation quota; (unit: m ³ /hm ²)	Irrigation water capacity/irrigation areas

Among them, $d_{in} = \exp(r_{in})$.

Improved criteria importance through intercriteria correlation

Criteria importance through intercriteria correlation (CRITIC) method was proposed by Diakoulaki and his

colleagues in 1995 (Diakoulaki et al. 1995). Its basic idea is to combine the information volume and relevance of indicators to allocate weights. The information volume and relevance of indicators are reflected by the variability of indicators and the conflict between indicators. Index variability indicates the difference in the value of the same index for each prediction object, which is measured by the

Table 2 Evaluation indicators classification criteria of WRCC

Evaluation indicators	I Grade (carrying state)	II Grade (critical state)	III Grade (overloaded state)
Per capita water resources; (unit: m ³ /person)	> 1670	1000 ~ 1670	< 1000
Water yielding modulus; (unit: 10 ⁴ m ³ /km ²)	> 80	50 ~ 80	< 50
Water supply per capita per year; (unit: m ³ /person·Y)	> 450	350 ~ 450	< 350
Forest coverage rate; (unit: %)	> 40	25 ~ 40	< 25
Development utilization rate of surface water resources; (unit: %)	< 20	20 ~ 30	> 30
Development utilization rate of ground water resources; (unit: %)	< 1	1 ~ 2	> 2
GDP per capita; (unit: 10 ⁴ yuan/person)	> 24,840	6624 ~ 24,840	< 6624
Ecological water use ratio; (unit: %)	> 5	1 ~ 5	< 1
Mean daily water consumption of per urban resident; (unit: L/D·P)	< 70	70 ~ 180	> 180
Water consumption per 10,000 Yuan of GDP; (unit: m ³ /10000 yuan)	< 100	100 ~ 400	> 400
Water consumption per 1,0000 Yuan of industrial output; (unit: m ³ /10 ⁴ yuan)	< 50	50 ~ 200	> 200
Population density; (unit: person/km ²)	< 200	200 ~ 500	> 500
Urbanization rate; (unit: %)	< 50	50 ~ 80	> 80
Farmland irrigation quota; (unit: m ³ /hm ²)	< 250	250 ~ 400	> 400

standard deviation of the index. The larger the standard deviation, the greater the difference between the objects. The greater the amount of information provided by the index, the greater the weight of the index. The magnitude of the conflict between indicators is measured by the correlation coefficient between indicators. The larger the correlation coefficient, the stronger the positive correlation between indicators and the lower the conflict. The more repetitive the amount of information provided by the two indicators, the smaller the weight of the indicator.

CRITIC method not only considers the information volume of indicators but also considers the correlation between indicators, which has significant advantages. However, dimensions and magnitudes of indicators are often different, and the standard deviation is insufficient to measure the variability of indicators. Therefore, this study adopts the variation coefficient method to improve CRITIC method. Main steps are as follows (Wang et al. 2014; Guo et al. 2018):

- (1) The value x_{ij} of the j th index of the i th object among m predicted objects and n predicted indicators constitute the original predictive index numerical matrix $X = (x_{ij})_{m \times n}$.
- (2) Z-score method is adopted to standardize each index value in matrix X:

$$x_{ij}^* = \frac{x_{ij} - \bar{x}_j}{s_j} (i = 1, 2, \dots, m; j = 1, 2, \dots, n) \tag{8}$$

In Formula (8), $\bar{x}_j = \frac{1}{m} \sum_{i=1}^m x_{ij}$, $s_j = \sqrt{\frac{1}{m-1} \sum_{i=1}^m (x_{ij} - \bar{x}_j)^2}$.

And \bar{x}_j and s_j are the mean and standard deviation of the j th index, respectively.

- (3) The variation coefficient of indicators could be found by Formula (9):

$$v_j = \frac{s_j}{\bar{x}_j} (j = 1, 2, \dots, n) \tag{9}$$

In formula (10), v_j is the variation coefficient of the j th index.

- (4) The standardized matrix X^* obtained in step (2) is used to calculate the correlation coefficient, so the correlation coefficient matrix could be obtained:

$$R = (r_{kl})_{n \times n} (k = 1, 2, \dots, n; l = 1, 2, \dots, n) \tag{10}$$

In Formula (10), r_{kl} is the correlation coefficient between the k th index and the l th index.

- (5) The quantization coefficient of the independence degree of each index could be found by Formula (11):

$$\eta_j = \sum_{k=1}^n (1 - r_{kj}) (j = 1, 2, \dots, n) \tag{11}$$

- (6) Quantitative coefficients of the comprehensive information and the independence degree of each index could be found by Formula (12):

$$C_j = v_j \sum_{k=1}^n (1 - r_{kj}) (j = 1, 2, \dots, n) \tag{12}$$

- (7) The weight of each indicator could be determined:

$$\omega_j = \frac{C_j}{\sum_{j=1}^n C_j} (j = 1, 2, 3, \dots, n) \tag{13}$$

Combination of subjective and objective weights based on the formula for sum of deviation square

After calculating subjective and objective weights, the formula for sum of deviation square was used to get the comprehensive weight. The formula for sum of deviation square refers to the sum of squares of differences between each item and the average of all items. The main idea of this method is to achieve the optimization based on the coefficient vector calculated by the performance evaluation index and the comprehensive evaluation on the target. The key to achieving the optimization is to keep all solutions away from the average term, thus facilitating the ranking and comparison of various solutions. And this remoteness can be used to evaluate the sum of squared deviations of each plan through a comprehensive evaluation method. According to the idea of the formula for sum of deviation square, the relevant calculation

$$\left[\begin{array}{cccc} \sum_{i=1}^m \sum_{i_1=1}^m (a'_{i1} - a'_{i_1 1})(a'_{i1} - a'_{i_1 1}) & \sum_{i=1}^m \sum_{i_1=1}^m (a'_{i1} - a'_{i_1 1})(a'_{i1} - a'_{i_1 1}) & \dots & \sum_{i=1}^m \sum_{i_1=1}^m (a'_{i1} - a'_{i_1 1})(a'_{i1} - a'_{i_1 n}) \\ \sum_{i=1}^m \sum_{i_1=1}^m (a'_{i2} - a'_{i_1 2})(a'_{i2} - a'_{i_1 2}) & \sum_{i=1}^m \sum_{i_1=1}^m (a'_{i2} - a'_{i_1 2})(a'_{i2} - a'_{i_1 2}) & \dots & \sum_{i=1}^m \sum_{i_1=1}^m (a'_{i2} - a'_{i_1 2})(a'_{i2} - a'_{i_1 n}) \\ \vdots & \vdots & \ddots & \vdots \\ \sum_{i=1}^m \sum_{i_1=1}^m (a'_{in} - a'_{i_1 n})(a'_{in} - a'_{i_1 n}) & \sum_{i=1}^m \sum_{i_1=1}^m (a'_{in} - a'_{i_1 n})(a'_{in} - a'_{i_1 n}) & \dots & \sum_{i=1}^m \sum_{i_1=1}^m (a'_{in} - a'_{i_1 n})(a'_{in} - a'_{i_1 n}) \end{array} \right]$$

process for the implementation of the combination weighting on indicators is as follows (Wang and Deng 2020):

- (1) Based on the original predictive index numerical matrix X , the non-negative definite matrix A' can be obtained by matrix A , that is
- (2) Let the weight vector of the subjective weight and the objective weight calculated by the improved analytic hierarchy process and the improved CRITIC be $W_1 = (a_j)_{1 \times n}$, $W_2 = (b_j)_{1 \times n}$, then the weight vector matrix composed of W_1 and W_2 is expressed as $W = (W_1, W_2)$. According to W and A' , a 2nd order symmetry matrix can be obtained:

$$W^T S' W = \begin{bmatrix} \omega_{11} & \omega_{12} \\ \omega_{21} & \omega_{22} \end{bmatrix} \quad (15)$$

According to the above formula, the maximum eigenvalue λ_{max} of the second-order symmetric matrix can be calculated, and the eigenvector corresponding to the symmetric matrix can be expressed as $\zeta = (\zeta_1, \zeta_2)^T$, then the final combination weighting coefficient vector $W^* = W\zeta$ can be obtained, and W^* was normalized to get $W^{**} = (\omega'_j)_{1 \times n}$, which can get the comprehensive weight of each index.

Determining digital characteristics of the multi-dimensional cloud model

According to evaluation indicators classification criteria of WRCC in Table 2 and the method described in the “Digital characteristic of the multi-dimensional cloud model” section, digital characteristics of the multi-dimensional cloud model for WRCC evaluation were calculated. Specific numerical values of the three digital characteristics for the multi-dimensional cloud model were listed in Table 3.

Table 3 Digital characteristics of the multi-dimensional cloud model for WRCC

Evaluation grade	Digital characteristic	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}	X_{14}
I	Ex	1735	90	475	50	10	0.5	24,920	7.5	35	50	25	100	25	125
	En	578.33	30	158.33	16.67	13.33	0.83	8306.67	2.5	63.33	150	83.33	200	30	150
	He	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
II	Ex	1335	65	400	32.5	25	1.5	15,732	3	125	250	125	350	65	325
	En	578.33	30	158.33	16.67	13.33	0.83	8306.67	2.5	63.33	150	83.33	200	30	150
	He	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
III	Ex	500	25	175	12.5	40	2.5	3312	0.5	190	450	250	600	90	450
	En	578.33	30	158.33	16.67	13.33	0.83	8306.67	2.5	63.33	150	83.33	200	30	150
	He	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

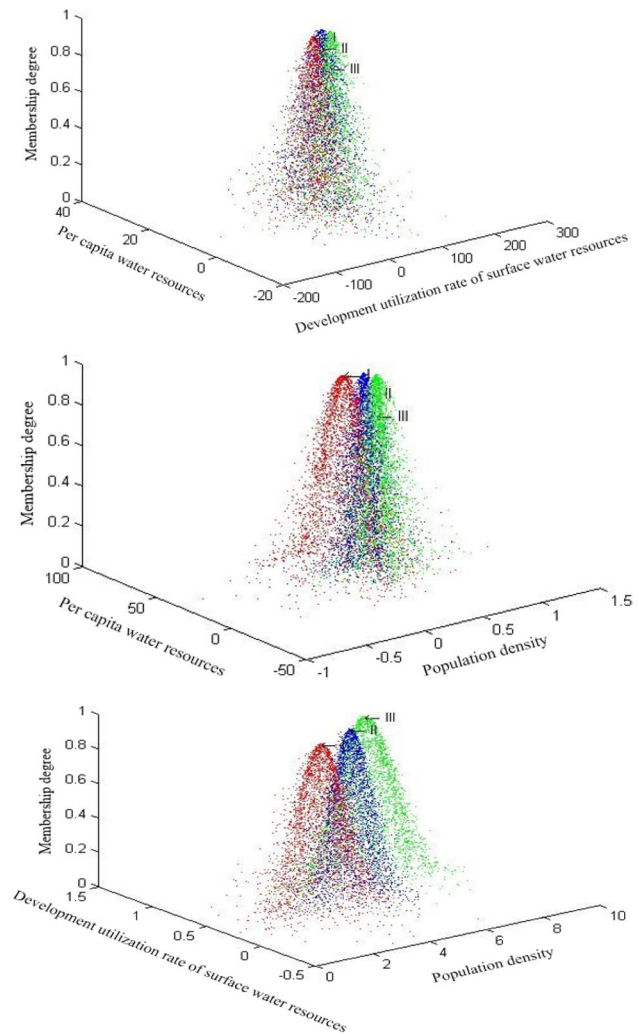


Fig. 4 Three-dimensional normal cloud model maps with three indicators belonging to three grades

Table 4 Raw data and combination weight of each evaluation indicator from 2009 to 2018 in Guiyang

Indicators	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Combina- tion weight
Per capita water resources; (unit: m ³ /person)	1076	770	616	1128	743	1275.2	1044.6	693.0	1096.4	984.9	0.35
Water yielding modulus; (unit: 10 ⁴ m ³ /km ²)	49.17	35.7	33.7	62.5	41.8	72.3	60.1	40.5	65.5	59.8	0.32
Water supply per capita per year; (unit: m ³ /person·Y)	278.42	275.22	231.03	226.88	231.32	232.22	227.40	232.71	224.28	228.60	0.12
Forest coverage rate; (unit: %)	41.78	41.78	41.78	43.20	44.2	45	45.50	46.5	48.66	52.2	0.21
Development utilization rate of surface water resources; (unit: %)	22.71	31.58	32.95	18.36	28.74	17.32	20.70	31.98	19.92	22.63	0.26
Development utilization rate of ground water resources; (unit: %)	1.86	1.76	1.62	1.48	1.35	1.26	1.37	1.87	0.9	1.21	0.25
GDP per capita; (unit: yuan/person)	23,240	26,210	31,700	38,670	46,480	55,020	63,000	67,770	74,490		
Ecological water use ratio; (unit: %)	1.37	1.36	1.87	2.38	1.34	1.19	1.49	1.59	1.81	2.56	0.23
Mean daily water consumption of per urban resident; (unit: L/D·P)	124.64	124.08	140.31	112.01	105.42	111.73	114.47	115.03	115.88	134	0.24
Water consumption per 10 ⁴ Yuan of GDP; (unit: m ³ /10000 yuan)	105.15	91.55	73.39	59.40	50.16	42.4	36.4	34.6	30.4	29.4	0.24
Water consumption per 10 ⁴ Yuan of industrial output; (unit: m ³ /10 ⁴ yuan)	172.68	119.54	119.54	72.55	67.98	60.2	53.3	50.2	43.9	45.6	0.27
Population density; (unit: person/km ²)	452.99	456.91	419.67	468.16	466.18	564.31	574.61	583.93	597.01	606.95	0.10
Urbanization rate; (unit: %)	65.20	68.13	69.20	70.53	72.10	73.20	73.25	74.16	74.80	75.43	0.11
Farmland irrigation quota; (unit: m ³ /hm ²)	4657.0	3688.1	3336.0	3153.7	4394.1	4756.4	4781.0	4860.4	4404.2	4333.2	0.04

According to three digital characteristics of the multi-dimensional cloud model and the concept of the forward cloud generator, this study selected three indicators (Per capita water resources, Development utilization rate of surface water resources and Population density) from three subsystems (carrying supporting capacity, carrying controlling capacity, and carrying pressure) to draw three three-dimensional cloud model maps, as shown in Fig. 4.

Comprehensive certainty degree

On the basis of actual measured values of WRCC, as well as the weight of each assessment index, comprehensive certainty degree μ_k was calculated based on formulas (1) and (16):

$$\mu_k[x(x_1, x_2, \dots, x_n)] = \exp\left(-\sum_{j=1}^n \frac{\omega_j(x_j - Ex_{jk})^2}{2(En'_j)^2}\right) \quad (16)$$

$j = 1, 2, \dots, n; k = 1, 2, \dots, m$

In Formula (17), $\mu_k[x(x_1, x_2, \dots, x_n)](k = 1, 2, \dots, m)$ is the certainty degree of every index, w_j is the weighting of each index.

According to the calculated value of the comprehensive certainty degree and the maximum membership principle, WRCC level could be determined.

Case study

Study area

Guiyang is located in the central part of Guizhou Plateau and the core area of Central Guizhou Economic Zone. It is the provincial capital and regional political, economic, and transportation center of Guizhou Province. The national territory area is about 8034 km², occupying 4.56% of the total area of the province. And the population was 5.99 million in 2020. The terrain is relatively undulating, with high north–south and low center, extending from east to west. The elevation of Guiyang is about 916–1720 m, with hills, valleys, basins, depressions, and other landforms distributing alternately. The climate belongs to the subtropical monsoon climate, with an average annual precipitation of 1200 mm and an average annual temperature of 15.3 °C. It has characteristics of rain and heat in the same period and distinct seasons. As of 2020, the resident population reached 5.987 million, with an urbanization rate of about 73.25%. Total GDP was 379.845 billion yuan, and the proportion of primary, secondary, and tertiary industries were 4.03%, 37.22%, and 58.75%, respectively. The built-up area was 299

km² and per capita residential land area was 15.86 m² (Peng and Deng 2020a).

Due to the pressure of the increasing population and the economic growth, the problem of water shortage has become more and more serious. On the one hand, located in a typical karst region, Guiyang is incredibly sensitive to variations of water resources and is also an ecologically fragile area. On the other hand, Guiyang is an economic less-developed region, it has obvious and huge development potential in terms of the resource exploitation and the economic growth. A strong appeal for development overlaps with maturing conditions for the economic growth, and there is an urgent need to increase the city's water supplies for meeting a dramatic increase in the scope of population, making the contradiction between developmental requirements for water resources in a city and the carrying threshold of water resources become increasingly outstanding (Lv et al. 2017b). The gross amount of water resources in China is large, but the average available water resources volume is low and the distribution of water resources is irregular temporally and spatially (Xia and Chen 2001). Hence, natural factors and social factors are both contributing to Guiyang's severe shortage of water resources, having brought looming challenges for the government. Studying the spatiotemporal pattern of WRCC is helpful for local government to make regional development of relevant policy recommendations, to ameliorate living standards of urban residents and give provisions of references for the eco rehabilitation of karst regions (Peng and Deng 2020b).

Assessment on WRCC of Guiyang by using the multi-dimensional cloud model

According to the evaluation index system established above, raw data of all indicators from 2009 to 2018 were obtained mainly from China Statistical Yearbook (2009–2019), Guizhou Statistical Yearbook (2009–2019), Guiyang Statistical Yearbook (2009–2019), Guizhou Province Water Resources Bulletin (2009–2019), Guiyang City Water Resources Bulletin (2009–2019), and field data. Specific raw data of all indicators can be seen in Table 4 (Peng and Deng 2020c). Then the combination weight could be calculated by using Formula (5) to Formula (16), which can be seen in Table 4.

Results and discussion

Results and analysis

Based on the established index system of regional WRCC, the normal multi-dimensional cloud model after the specification transformation represents the evaluation level

corresponding to each evaluation index, super-entropy uniform value is 0.1, and the calculation process is performed by MATLAB software writing model. This assessment selected 2009 to 2018 as the evaluation year. Original data of indicators were shown in Table 4, and assessment results were shown in Table 5 and Fig. 5.

It can be seen from Table 5 and Fig. 5 that Guiyang's WRCC in 2009, 2010 and 2016 were in an overloaded state, 2011, 2012 and 2013 were in a critical state, and 2014, 2015, 2017 and 2018 were in a carrying state. While WRCC of Guiyang had been increased from the overload state in 2009 to the carrying state in 2018. The situation of WRCC had gradually improved, the safety performance of water resources ecosystem had gradually increased, and the degree of damage due to external shocks had been declining day by day. In recent decades, Guiyang has increased investments in urban and rural water conservancy constructions by carrying out a series of measures such as the soil erosion control, industrial structure optimization, and ecological restoration construction, and introduced advanced water-saving irrigation technologies to enhance WRCC. It has a positive significance for the future planning and development of the region.

During the study period, some key indicators decreased year by year, for example, water consumption per 10⁴ yuan of GDP fell from 105.15m³/10⁴ yuan in 2009 to 29.4m³/10⁴ yuan in 2018, water consumption per 10⁴ Yuan of industrial output decreased from 172.68m³/10⁴ yuan in 2009 to 45.6m³/10⁴ yuan in 2018, reflecting the significant increase in regional industrial water levels. But with the economic and social development and the rapid population growth, the population density of Guiyang had increased from 452.99 person/km² in 2009 to 606.95 person/km² in 2018, the urbanization rate also increased from 65.2% in 2009 to 75.43% in 2018. Although scores of various evaluation indicators such as per capita water resources, water yielding modulus and forest coverage rate were increasing year by year, this area is a typical karst area, and the problem of engineering water shortage is serious.

In recent years, population growth, urban and rural development have led to the pressure on the contradiction between supplies and demands of water resources, presenting an increasing state. When the pressure reaches a critical level, WRCC and water ecosystem in the region will decline rapidly, and the ability to withstand external shocks will gradually weaken. Therefore, measures such as controlling desertification, solving engineering water shortages and increasing industrial water reuse, forest coverage, and water investment ratios are important prerequisites for protecting Guiyang's future WRCC.

Figure 5 shows that assessment results of the model proposed in this study are basically consistent with assessment results of several other models, indicating that the combination weighting method-multi-dimensional cloud model

Table 5 Assessment results of WRCC and comparisons with related methods

Year	Comprehensive certainty degree			Assessment results of this study	Entropy and one-dimensional cloud model	TOPSIS
	I	II	III			
2009	0.1877	0.2792	0.4112	III	III	II I
2010	0.154	0.2418	0.4240	III	III	III
2011	0.1272	0.4516	0.2125	II	III	III
2012	0.1878	0.3517	0.2604	II	II	II
2013	0.1411	0.3992	0.2243	II	II	II
2014	0.3051	0.2464	0.2042	I	I	I
2015	0.3395	0.2360	0.1702	I	I	I
2016	0.1279	0.1990	0.3754	III	II	II
2017	0.3230	0.2326	0.1759	I	I	I
2018	0.3488	0.2259	0.1605	I	I	I

proposed in this study is reasonable and effective for the evaluation on WRCC. In the weighting process of combination weighting method, the information quantity and the correlation between indicators are comprehensively considered, improving the reliability of weight calculation results. As a cognitive model that realizes the bidirectional conversion of qualitative concepts and quantitative data, the cloud model can convert the ambiguity and randomness during the evaluation process of WRCC into the quantitative data (certainty degree), which accurately reflects the uncertainty of WRCC evaluation. That's what makes it so much better than other methods. Multi-dimensional cloud model uses various factors as its one-dimensional variables to generate a comprehensive cloud model. Compared with the one-dimensional cloud model, the establishment process is more convenient. The comprehensive cloud model generated by all indicators in this study takes into account the correlation between indicators and reflects characteristics of multi-factors of WRCC. In addition, the digital feature En of multi-dimensional cloud model has a larger value, that is, the range of indicators covered by each level is more wider, which reduces the sensitivity of cloud model to the mean interval and can more objectively reflect the complexity of WRCC, and prediction results are more credible.

Discussion

Evaluation of WRCC is one of main influencing factors of water resources safety in karst areas. Factors that have a greater impact on WRCC in karst areas are the proportion of groundwater supply, the degree of groundwater development and utilization, the utilization rate of water resources, and water yielding modulus. Due to special topographical conditions in karst areas, although the total amount of natural water resources is large, the available amount is seriously insufficient. The construction of controlled water conservancy projects in mountain areas lags behind, and the problem

of engineering water shortage is serious. The control capacity of surface water resources is weak, the development and utilization of surface water is insufficient, and the method of development and utilization is single (Liu et al. 2017).

The rapid economic development has a significant impact on WRCC in karst areas. It can be obtained from model results that, although WRCC has gradually improved in recent years, the contradiction between the supply and demand of water resources is still prominent. When it comes to reasons, at this stage, Guiyang's leading industries are mostly resource-intensive industries that consume a lot of resources and environment, mainly labor-intensive industries and traditional industries, while high-tech industries and light industries have a small proportion. The rapid development of industrial production has increased the amount of sewage discharged, and the amount of industrial water used is increasing, which has a negative impact on WRCC.

Comprehensive evaluation of WRCC is the necessary foundation and the most difficult problem for the

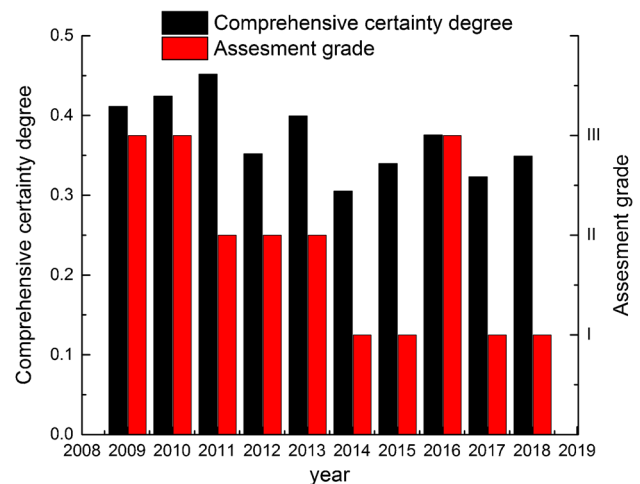


Fig. 5 Assessment results of WRCC in Guiyang based on the multi-dimensional cloud model from 2009 to 2018

construction of water resources evaluation index system. At present, domestic and foreign scholars' research on the evaluation of WRCC mainly focuses on water resources, socio-economics, and ecological environment. Existing research methods are mainly based on research ideas of sustainable development for water resources, including pressure-state-response model (Zhang et al. 1999), water footprint method (Zhang et al. 2012), expert system method (Wu et al. 2008), multi-level structure analysis method (Han and Ruan 2003), inductive summary method (Wang and Liang 2001), "composite system method of social-economic-environment," (Xia 2002) and so on. From different research perspectives, the establishment of evaluation index system for WRCC is different (Guo et al. 2018). Overall, the research on the evaluation index system of WRCC has achieved rich theoretical results, but there are also some problems: (1) The theory itself has defects, which cannot accurately reflect the biggest characteristic of uncertainty during the evaluation process of WRCC. For example, the expert system method ignores the randomness of the system, the water footprint method has a slow convergence rate, and the expert system method relies heavily on expert opinions. The cloud model is proposed to describe the phenomenon of uncertainty. Its use in assessment on WRCC has certain advantages. However, current one-dimensional cloud model for evaluation cannot reflect characteristics of WRCC affected by multiple factors, not reflecting the correlation of factors in the process. (2) At present, many evaluation methods evaluate WRCC from the perspective of multi-factor comprehensive evaluation, which inevitably involves the problem of factor weight allocation. The rationality of weight allocation is the key to the credibility of results for WRCC. The weighting method is mainly divided into subjective weighting method and objective weighting method. Due to the lack of perfect theory for WRCC mechanism, the subjective weighting method based on expert opinions has obvious defects. While from existing researches on WRCC evaluation, CRITIC method is more commonly used in objective weighting method. CRITIC method is a method to determine the variability of evaluation indicators based on sample data and calculate the amount of information contained in indicators, to give corresponding weights according to the size of indicators' information, but there is no subjective factor of experts. Therefore, it is necessary to introduce a relatively more comprehensive evaluation model of WRCC.

Based on the theory of uncertain artificial intelligence, this study aims at the uncertainty of WRCC evaluation, the complexity under the influence of multiple factors, and the correlation between factors, using the multi-dimensional cloud model to solve the problem of WRCC evaluation. Index weights are determined by combination weighting method, a combined weighting method-multi-dimensional cloud model for WRCC is established, and this model is

used in a concrete evaluation example for WRCC to test the effectiveness of the model in this study.

Suggestions and conclusions

Suggestions

First, Guiyang has been suffering from seasonal and engineering water shortage for a long time. It is necessary to adjust the supply and demand structure of water resources and improve WRCC. As the main type of water use, industrial water plays a leading role in water resources utilization. To ensure the sustainable utilization of water resources, the industrial land structure should be adjusted based on current land types, and the demand of different land use industries for water resources should be analyzed, to realize the orderly optimization of industrial structure (Lv et al. 2017a).

Second, in consideration of actual situation in the study area, it is necessary to control water use from the source, and the government should pay special attention to strengthening industrial water conservation, implementing urban water conservation, and developing water conservation in agriculture. In terms of industry, it is suggested to carry out technological transformation of existing high-water-use industries such as chemical industry, metallurgy and steel industry, to establish and consummate a system for recycling water, and improve the repetitive use rate of industrial water. The government should adjust the industrial structure, strictly restrict the construction of high-water-consumption industrial projects, and transfer high-water-consumption industrial projects to areas with relatively rich water resources in a planned and focused way. The government should also strengthen water management through economic and administrative means. In terms of water conservation in cities and towns, importance should be attached to the role of planning in water conservation. The government should reduce the leakage rate of water supply network, accelerate the construction of water-saving public infrastructure, and carry out the pipe network transformation actively, prudently and scientifically. It is suggested to set up a professional leakage detection team, equipped with advanced detection equipment, to effectively carry out the leakage detection and leakage repairment of urban water supply network. In the field of agriculture, it is suggested to collect and store rainwater, build water diverting and water lifting projects, and improve the efficiency of water resources utilization from water sources. Efficient water transmission and distribution projects should be constructed to improve water resources use efficiency during the process of water transmission. Advanced saving water technique should be adopted to improve the utilization efficiency of water resources in the process of water utilization. Farmers should adjust the plant

structure and select plant breeding of the new cultivar, to improve the utilization efficiency of water resources from the way of irrigation.

Third, it is necessary to take outside water diversion into consideration. With full consideration of water conservation and rational allocation of local water resources, the contradiction between supply and demand of water resources is still prominent with the continuous development of social economy. Therefore, the outside water diversion scheme should be taken into consideration.

Fourth, water rights should be defined, water markets should be established gradually, and rational water price should be set. To realize sustainable utilization of water resources, it is urgent to bring up and develop water market during the process of saving water, to transfer water resources from low-benefit use to high-benefit use. Its economic means are mainly reflected in the establishment of a reasonable water price system, so that the water price can really play the role of economic leverage, curb the growth of total water use, and alleviate the contradiction between supply and demand of water resources. Therefore, it is suggested that the government take effective measures to promote the establishment of water market as soon as possible, and improve the water price management system and adjustment mechanism.

Fifth, comprehensive promotion of water rights reform should fully consider characteristics of regional differences. Nationwide reform of water rights system should be implemented according to local conditions. Whether the registration of water rights, water rights transactions, or water rights supervision and management should be based on factors such as water resources conditions, socioeconomic conditions, and ecological and environmental conditions in different regions. Especially for karst areas, the reform model of water rights should be suitable for economic development and achievable of the region, so that water resources can be used reasonably and efficiently, which in turn contributes to the development of water-saving industries in karst areas and the construction of water-saving society, thereby promoting the sustainable development of economy and society.

Primary conclusions of this study

Water resource is not only the basic natural resource, but also the strategic economic and social resource. Therefore, assessment on WRCC is not only an ecological environmental issue, but also an economic, social, and political issue related to national security (Guo et al. 2007; Peng and Deng 2020d), especially in karst areas. In this study, the multi-dimensional cloud model is used to carry out assessment on regional WRCC, and the model is applied into a typical karst

area (Guiyang city) for assessing WRCC to test the effectiveness. The following conclusions are drawn:

Firstly, considering the systematicity and availability of indicators' parameters, carrying supporting capacity of water resources, carrying controlling capacity of water resources, and carrying pressure of water resources are selected as index factors of WRCC classification, and the three levels and classification standards for index factors of WRCC are determined. A classification system for WRCC is established.

Secondly, in allusion to the uncertainty of WRCC assessment, the complexity under the influence of multiple factors, and the correlation between factors, the multi-dimensional cloud model is applied in assessing WRCC. Index weights are determined by combination weighting method, a combined weighting method-multi-dimensional cloud model for WRCC is established, and this model is used in a typical karst area for assessing WRCC to test the effectiveness of the model in this study.

Thirdly, compared with the one-dimensional cloud model, the establishment process of multi-dimensional cloud model is more concise, each level for WRCC covers measured values of indicators more extensively, the model is more comprehensive, and can further reflect the complexity of WRCC. So the reliability of assessment results is higher. Compared with other prediction methods, the multi-dimensional normal cloud model can better reflect the uncertainty in the evaluation of WRCC, and the assessment process is more intuitive and comprehensive.

Fourthly, by applying the multi-dimensional cloud model in assessing WRCC of Guiyang, showing that Guiyang's WRCC in 2009, 2010, and 2016 were in an overloaded state, 2011, 2012 and 2013 were in a critical state, and 2014, 2015, 2017, and 2018 were in a carrying state. While WRCC of Guiyang had been increased from the overload state in 2009 to the carrying state in 2018. Assessment results of the model proposed in this study are basically consistent with that of several other models, indicating that the combination weighting method-multi-dimensional cloud model proposed in this study is reasonable and effective for the evaluation on WRCC. According to evaluation results, the government can have a more objective understanding of the relationship between water resources and economic development, and can appropriately slow down the urbanization process, adjust industrial structure and develop water-saving economic model.

Fifthly, the selection of multi-dimensional normal cloud model parameters is currently inconclusive, especially the selection of entropy En . This study uses the common method of selecting En . The application of multi-dimensional cloud model theory to WRCC evaluation is only a preliminary attempt. How to select cloud model parameters more reasonably and effectively to make

multi-dimensional normal cloud model more accurate in evaluating WRCC is a work that needs to be done in the future. The evaluation of WRCC involves ambiguity and randomness, and it is difficult to study thoroughly using a single theory. The cloud model is good at dealing with ambiguity and randomness. How to better couple the multi-dimensional normal cloud model with other theories is a subject worthy of further investigation.

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Declarations

Conflict of interest The authors declare no competing interests.

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