



# Comprehensive evaluation on water resources carrying capacity based on improved AGA-AHP method

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Received: 5 July 2021 / Accepted: 8 March 2022 / Published online: 10 April 2022  
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## Abstract

The combined weight method (CWM) for comprehensive water resources carrying capacity evaluation is proposed in this paper to evaluate the regional water resources carrying capacity. Firstly, the accelerating genetic algorithm based on analytic hierarchy process (AGA-AHP) method is improved to optimize the expert evaluation matrix and determine the subjective weight, in which entropy weight method is used to determine objective weight, and the combined weight formula is put forward to get the combined weight of evaluation index. Secondly, the certainty degree is calculated by using the multi-dimensional normal cloud model. The obstacle factors of evaluation index are diagnosed. Finally, taking Henan Province as an example, the regional water resources carrying capacity is evaluated by using CWM method. The comparison between single cloud model, AHP-TOPSIS and CWM is made. It is proved that CWM method takes the fuzziness and randomness into account in the evaluation process, and the efficient and intuitive results can be obtained through evaluation. The obstacle degree and the time changing pattern of the index can be clearly diagnosed, which can provide a new idea for the evaluation method of water resources carrying capacity.

**Keywords** Improved AGA-AHP method · Entropy weight · Multi-dimensional normal cloud model · Obstacle degree diagnose · Water resources carrying capacity · Henan province

## Introduction

With the rapid development of social-economy and the expansion of population, human demand for water resources is increasing (Bogardi et al. 2003). Water resources carrying capacity refers to the maximum amount of water resources availability to meet the ecological water demand and realize the development goal of population, production and environment in a certain stage of economic and social development (Bender Simonovic 2000, Chang, Chen 1996). The scientific and reasonable evaluation on the regional water resources carrying capacity is of great significance for identifying the current situation of regional water resources and for ensuring regional social and economic development. During recent years, a lot of research methods have been

carried out to evaluate water resources carrying capacity, such as multi-objective analysis models (Esogbue et al. 1992, Fu 2008, Ouma, Tateishi 2014), multi-index comprehensive evaluation model (Rezaei et al. 2013, Adhikari et al. 2016, Asgari et al. 2016), and simulation model of system dynamics (Borgomeo et al. 2018, Hajkowicz, Collins 2007). During recent years, many researchers have put forward improved evaluation models, which provide new ideas for the study of water resources carrying capacity evaluation (Zou et al. 2020, Celeste et al. 2004).

Cloud model is a multi-index comprehensive evaluation model, which can be transformed between qualitative and quantitative expressions. Cloud model has been applied to water quality evaluation, power network safety evaluation, rock mass stability evaluation, etc. In recent years, the application of cloud model in water resources carrying capacity evaluation has been increased due to water shortage both in home and abroad. On one hand, the cloud model takes the randomness and fuzziness in the evaluation process into account. On the other hand, the certainty degree can be adopted not only directly to judge the grade of carrying capacity, but also to judge the water resources carrying

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capacity at the same evaluation level (Nicklow et al. 2010, Al-Jawad et al. 2019).

At the present, most of researchers use single cloud model to evaluate the carrying capacity of water resources. The multi-dimensional normal cloud model (MNCM) is an extension of the single cloud model (Chen et al. 2018, Kumar et al. 2019). Compared with the single cloud model, the multi-dimensional normal cloud model has the advantages of less number of models and fast calculation speed (Kundzewicz et al. 2018).

Among the different water resources carrying capacity evaluation models, a prominent problem is the determination of weight coefficient (Li et al. 2018). This is because that the weight of different parameters in the model is very important to the evaluation results. Therefore, a combined weight method (CWM) for comprehensive evaluation on water resources carrying capacity is proposed in this paper. Firstly, we consider the weight both from the subjective identification and the objective law on certain problems. The objective function of accelerating genetic algorithm based on analytic hierarchy process (AGA-AHP) was improved to realize simplification of the objectives (Lin et al. 2020). An improved AGA-AHP method was used to calculate the subjective weight, the entropy weight method was used to calculate the objective weight, and the combined weight of the evaluation index was achieved by using the combined weight formula. Secondly, the combined weights are assigned to the measured data. The certainty degree was calculated by using multi-dimensional normal cloud model; then, evaluation grade of water resources carrying capacity can be determined. Finally, the obstacle diagnosis method is used to diagnose the obstacle factors affecting the carrying capacity of regional water resources.

## Methods and materials

### Improved AGA-AHP method

The evaluation matrix constructed by AHP should meet the requirement of consistency index,  $CR < 0.1$ . The matrix that does not pass the consistency test should be optimized and adjusted (Molinos-Senante et al. 2014). In order to raise the optimizing ability of evaluation matrix, the AGA-AHP method is improved in this paper. The improved AGA-AHP method takes the consistency ratio CR as an optimization goal, which can desirably meet the goal of reducing CR in traditional AHP, and the improved model could achieve better results in optimizing the consistency rate. The improved AGA-AHP method retains the limit of the searching range of the solution in the constraint conditions; therefore, it can obtain higher consistency and more reasonable evaluation

matrix and weights under the premise of ensuring the similarity between the original and optimized matrix.

The improved AGA-AHP calculation method is as follows:

$$\min CR = CI/RI \quad (1)$$

$$s.t. y_{ii} = 1 (i = 1 \sim n) \quad (2)$$

$$1/y_{ji} = y_{ij} \in [b_{ij} - db_{ij}, b_{ij} + db_{ij}] (i = 1 \sim n, j = i + 1 \sim n) \quad (3)$$

$$w_i > 0 \quad (4)$$

$$\sum_{i=1}^n w_i = 1 \quad (5)$$

where  $y_{ij}$  is the elements in the evaluation matrix obtained by the improved AGA-AHP method;  $b_{ij}$  is the elements in the evaluation matrix of AGA-AHP method,  $d$  is a non-negative parameter with a range of  $[0, 0.5]$ , and  $w_i$  is the combined weight of the  $i$ th component. CI is a consistency index, and RI is a stochastic consistency index of evaluation matrix.

### Entropy weight method

The basic idea of entropy weight method is to use the discrete degree of index, i.e., information entropy, to measure the importance of index. Usually, the smaller the information entropy  $E_i$  for an index, the greater the variation of the index value, the more information it would provide, the greater the role it can play in the comprehensive evaluation, and the greater the weight of the index value will be (Nematian, Movahhed 2019, Pishvae, Khalaf 2016).

The information entropy and entropy weight for an index are calculated using Eq. (6) and Eq. (7).

$$E_i = - \sum_{i=1}^n p_i \log p_i \quad (6)$$

$$w_i = \frac{1 - E_i}{k - E_i} (i = 1, 2, \dots, k) \quad (7)$$

where  $p_i$  is index,  $w_i$  is the entropy weight.

### Multi-dimensional normal cloud model method

Cloud model is a kind of uncertainty transformation model between qualitative description and qualitative concept which was proposed by Li Deyi academician in 1995. Multi-dimensional normal cloud model is an extension of one-dimensional cloud model. The certainty of  $m$  dimension normal cloud model can be calculated by using Eq. (8).

$$\mu(x(x_1, x_2, \dots, x_m)) = \exp\left(-\sum_{j=1}^m w_j \frac{(x_j - Ex_j)^2}{2(En'_j)^2}\right) \tag{8}$$

In cloud model, the index of expectation  $E_x$ , entropy  $E_n$  and hyper-entropy  $H_e$  are generally used to express entire population. Researchers have proposed index calculation methods for different cloud models (Roach et al. 2018, Uprety et al. 2019, Xu, et al. 2020). The cloud model index calculation method is shown in Table 1, in which  $s_{i\max}$ ,  $s_{i\min}$  refers to the upper and lower bounds of the values in the  $i$ th evaluation grade, respectively.

**The diagnosis method of obstacle degree**

The obstacle degree diagnosis method can diagnose the obstacle factors that affect the evaluation result of water resources carrying capacity (Alamanos et al. 2020, Carayannis et al. 2016). This method mainly includes three basic variables, i.e., factor contribution degree  $F_i$ , index bias  $I_i$ , and obstacle degree  $O_i$ . The factor contribution degree  $F_i$  refers to the contribution of a single evaluation index to the overall evaluation results, which generally takes the weight of the index. The deviation degree of index  $I_i$  is the distance between the index actual value and the optimal target value, which can be expressed by the difference between 1 and the standardized index value. The obstacle degree  $O_i$  refers to the index influence degree on water resources capacity; the larger the value  $O_i$ , the greater the obstacle to realize the optimal evaluation results would be.

The calculation method of obstacle degree  $O_i$  is shown as follows:

$$O_i = \frac{I_i \cdot F_i}{\sum_{i=1}^m I_i \cdot F_i} \tag{9}$$

**Combined weight method (CWM)**

The evaluation flowchart of the combined weight method (CWM) is shown in Fig. 1, in which evaluation process includes three main modules: weight calculation, water

resources carrying capacity evaluation and obstacle diagnosis analysis. Firstly, subjective and objective weights are substituted into the combined weight formula to obtain the combined weight of evaluation system. Secondly, the measured data after weighting are substituted into the multi-dimensional normal cloud model to calculate the certainty degree, and the evaluation grade of water resources carrying capacity is obtained. Finally, the post-evaluation is carry out for the model by using obstacle degree diagnosis method, and the influence of each evaluation index on the evaluation results of regional water resources carrying capacity is studied.

**Combined weight calculation**

The evaluation index includes subjective and objective weight (Chen et al. 2017). Subjective weight refers to the important degree of the index according to human subjective judgment and expert experience. Objective weight can be calculated through analyzing the objective rule of the relevant data. In this paper, the subjective weight was calculated by using the improved AGA-AHP method, and the objective weight was calculated by using the entropy weight method after standardizing the index data. The combined weight of the evaluation system is calculated by using Eq. (6), and the results are applied into the comprehensive evaluation.

$$w_i = \frac{w_{ai} \times w_{si}}{\sum_{i=1}^N w_{ai} \times w_{si}} \tag{10}$$

where  $w_{ai}$  represents the calculated weight for the  $i$ th indicator by using the improved AGA-AHP method,  $w_{si}$  represents the calculated weight for the  $i$ th index by using the entropy weight method, and  $w_i$  represents the combined weight for the  $i$ th indicator. The combined weight methods synthetically take the subjective and objective influence of the index into consideration and make the weight determination of the evaluation model more reasonable.

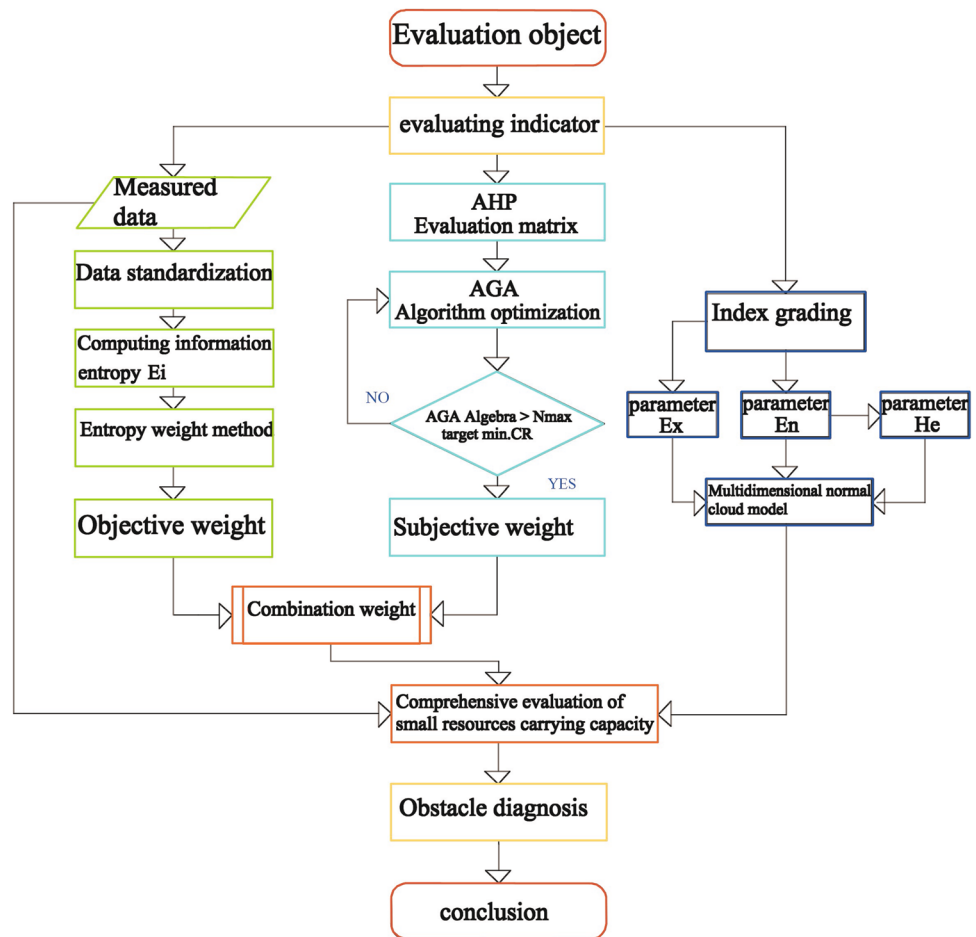
**Water resources carrying capacity evaluation**

The parameters (expectation  $E_x$ , entropy  $E_n$  and super-entropy  $H_e$ ) in the multi-dimensional normal cloud model

**Table 1** Calculation methods of cloud model index

Grade	Positive indicators (X1, X4, X6, X7)		Negative indicators(X2, X3, X5, X8)		$H_e$
	$Ex$	$En$	$Ex$	$En$	
I	$(S_{1\min} + S_{1\max})/2$	$(S_{1\max} - S_{1\min})/3$	$(S_{1\min} + 2S_{1\max})/2$	$(2S_{1\max} - S_{2\min})/3$	$En/10$
II	$(S_{2\min} + S_{2\max})/2$	$(S_{2\max} - S_{2\min})/3$	$(S_{2\min} + S_{2\max})/2$	$(S_{2\max} - S_{2\min})/3$	$En/10$
III	$(S_{3\min} + S_{3\max})/2$	$(S_{3\max} - S_{3\min})/3$	$(S_{3\min} + S_{3\max})/2$	$(S_{3\max} - S_{3\min})/3$	$En/10$
IV	$(S_{4\min} + S_{4\max})/2$	$(S_{4\max} - S_{4\min})/3$	$(S_{4\min} + S_{4\max})/2$	$(S_{4\max} - S_{4\min})/3$	$En/10$
V	$(S_{5\min} + 2S_{5\min})/2$	$(2S_{5\min} - S_{1\min})/3$	$(S_{5\min} + S_{5\max})/2$	$(S_{5\max} - S_{5\min})/3$	$En/10$

**Fig. 1** The flowchart of water resources carrying capability evaluation based on CWM



are calculated according to the grade of the index, which are substituted into Eq. (6) to construct the new multi-dimensional normal cloud model. The evaluation index data are assigned by using the combined weights. The certainty of each evaluated grades is calculated by substituting the weighted data into Eq. (6). The certainty degree determined by using the new multi-dimensional normal cloud model is the membership degree for the evaluated grade. The relative certainty degree of each evaluated grade is calculated by using Eq. (11).

$$\mu'_i = \frac{\mu_i}{\sum_{i=1}^n \mu_i} \tag{11}$$

The highest relative certainty degree is selected as the evaluated grade of water resources carrying capacity determined by multi-dimensional normal cloud model.

**Obstacle degree diagnosis**

Firstly, the obstacle degree is calculated by the obstacle degree diagnosis method (Ek, Persson 2020), and the influence degree of each evaluation index on the overall

evaluation result of water resources carrying capacity is obtained. Secondly, according to the obstacle degree, the main obstacle factors affecting the evaluation of water resources carrying capacity are analyzed, and the variation of the main obstacle factors with time is studied.

**Case study**

**Background**

In this paper, Henan province of China was selected to carry out water resources carrying capacity. Henan Province is located in the middle plain of China and the middle and downstream reaches of the Yellow River, with the total area about  $16.7 \times 10^4 \text{ km}^2$ . The province spans four large water systems from north to south, i.e., the Haihe River, the Yellow River, the Huaihe River and the Yangtze River, including more than 1500 main and branch rivers (Fig. 2). The annual average precipitation is 500–900 mm, the total water resources is 41.3 billion  $\text{m}^3$ , and the water resources per capita is only 440  $\text{m}^3$ . The temporal-spatial distribution of water resources in Henan

**Fig. 2** Distribution of major river systems in Henan Province



Province is uneven, and the precipitation is mainly concentrated from June to September. The distribution of water resources shows that it is larger in the south than that in the north, and it is larger in the mountain area than that in the plain. With the rapid development of local economy and the growth of population, the water demand for industrial, agricultural and domestic sectors is increasing, which intensifies the carrying burden of water resources. Although a lot of scholars have carried out a large number of related studies on the water resources carrying capacity in Henan Province, the algorithms are simple and the evaluation indexes are scattered; it is difficult to meet the requirements of systematic evaluation on water resources carrying capacity. Therefore, it is of great importance to use the combined weight method to analyze the grade of water resources carrying capacity in Henan Province.

**Screening of evaluation indicators**

The selection of indicators should be conformed to the principles of systematization, objectivity and representativeness. In this paper, considering the economy, ecology and water resources, 8 factors are selected as the evaluation index. According to the classification standard of water resources carrying capacity and the actual situation of Henan Province, the selected indexes are divided into five grades, as shown in Table 2.

In Table 2, if the regional water resources carrying capacity is evaluated as grade I, it shows that the water resources carrying capacity is excellent, and the regional water resources can carry more economic development and larger population scale. If the regional water resources carrying capacity is evaluated as V, which indicates that the water resources carrying capacity is very poor and the regional water resources are facing great stress.

**Table2** Evaluation index and classification of water resources capacity in Henan Province

Evaluation	Index no	Index meaning	I	II	III	IV	V
Economy	$X_1$	GDP (10 <sup>4</sup> Yuan)/per capita	> 7.4	[3.4,7.4]	[2.5,3.4]	[0.66,2.5]	< 0.66
	$X_2$	Water use (m <sup>3</sup> )/10 <sup>4</sup> Yuan GDP	< 40	[40,130]	[130,170]	[170,200]	> 200
	$X_3$	Popu. Density (persons/km <sup>2</sup> )	< 300	[300,500]	[500,700]	[700,900]	> 900
Ecology	$X_4$	Ecological water use ratio (%)	< 1	[1,2]	[2,3]	[3,5]	> 5
	$X_5$	COD/per capita (m <sup>3</sup> )	[0,2]	[2,5]	[5,10]	[10,15]	[15,20]
Water resources	$X_6$	Runoff modulus (m <sup>3</sup> /km <sup>2</sup> )	> 60	[35,60]	[20,35]	[10,20]	< 10
	$X_7$	Water resources (m <sup>3</sup> )/per capita	> 3000	[1700,3000]	[1000,1700]	[500,1000]	< 500
	$X_8$	Water consumption ratio (%)	< 10	[10,25]	[25,40]	[40,60]	> 60

### Evaluation on water resources carrying capacity

Firstly, the initial evaluation matrix was obtained by expert scoring. An improved AGA-AHP method was used to calculate the subjective weight of the index system. In order to expand the searching scope, let the parameter  $d$  to be equal to 0.5. The optimized evaluation matrix consistency ratio  $CR$  is 0.012, which is well below the 0.1. Secondly, the entropy weight method was used to calculate the objective weight of the index, and finally, the combined weight of the index was calculated by the combination weight Eq. (6). The evaluation index weight of water resources carrying capacity in Henan Province is shown in Table 3.

The multi-dimensional normal cloud model was set up corresponding to each evaluation grade, which is used to calculate the certainty of water resources carrying capacity. Finally, the evaluated grade with the highest certainty degree is considered as the evaluation result. The certainty degree of water resources carrying capacity evaluation grade in Henan Province is shown in Fig. 3.

The evaluation results show that the high certainty degrees of the water resources carrying capacity in Henan Province (grade I and grade II) have the increasing trend during recent years, which is due to the fact that Henan Province has paid great attention to water saving and the water use structure has been continuously improved.

In order to verify the effectiveness of the combined weight method (CWM), both single cloud model method

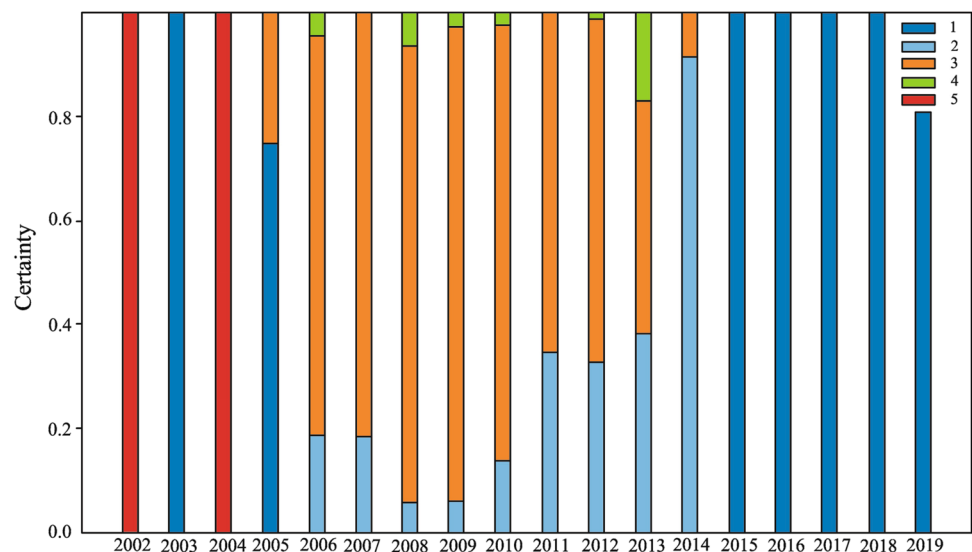
and AHP-TOPSIS method were selected for comparative analysis. The results of the model calculation and comparison between two methods are shown in Table 4.

It can be seen from Table 4 that the similar consistent results were obtained by using different models, but compared with other methods, CWM has the following advantages; (1) CWM uses certainty degree to express the membership degree for a evaluated grade, and considers the subjectivity and fuzziness in the evaluation grade division. (2) The certainty degree for a evaluation grade is determined by the weighted different indexes, which reduces the fuzziness influence of single evaluation index on the overall evaluation grade. For instance, in the evaluation of water resources carrying capacity in 2013, the index value per capita GDP is near the boundary of grade I and II, and the index value per capita COD emission is near the boundary of grade IV and grade V, which is difficult to judge the final evaluation grade. In this case, the comprehensive certainty degree of evaluation grade can be intuitively calculated by using CWM, and the final evaluation grade of water resources carrying capacity can be determined as grade III according to the principle of maximum certainty degree. (3) In this evaluation, only 5 models need to be established by using CWM, and 40 models need to be established if single cloud model was used, which reduces the number of models and simplifies the calculation process.

**Table 3** The evaluation index weight of water resources carrying capacity in Henan Province

	$X_1$	$X_2$	$X_3$	$X_4$	$X_5$	$X_6$	$X_7$	$X_8$
Subjective	0.08	0.14	0.04	0.02	0.04	0.25	0.31	0.12
Objective	0.12	0.19	0.06	0.34	0.09	0.08	0.05	0.06
Combined weight	0.11	0.28	0.03	0.08	0.04	0.22	0.16	0.08

**Fig. 3** The certainty degree of water resources carrying capacity evaluation grade in Henan Province



**Table 4** Comparison between different methods

Years	2002	2003	2004	2005	2006	2007	2008	2009	2010
AHP-TOPSIS							III	III	III
Single cloud model	V	II	V	III	III	III	III	III	III
CWM	V	II	V	II	III	III	III	III	III
Years	2011	2012	2013	2014	2015	2016	2017	2018	2019
AHP-TOPSIS	III	III	III	III	II	II	II	II	II
Single cloud model	III	III	IV	III	II	II	II	II	II
CWM	III	III	III	II	II	II	II	II	II

### Diagnosis of obstacle degree

Taking the combined weight  $w_i$  as the factor contribution degree  $F_i$ , then, the obstacle degree  $O_i$  can be calculated by using Eq. (5). The calculated obstacle degree of water resources carrying capacity evaluation index in Henan Province is shown in Table 5.

According to the results of obstacle diagnosis, the runoff modulus and water resources per capita rank at the highest level during recent years, which has a great influence on water resources carrying capacity. It shows that raising runoff modulus and water resources per capita are the main tasks to raise water resources carrying capacity in Henan province. The Mann–Kendall trend test method was used to analyze the obstacle degree variation of the indexes. It was discovered that some of index obstacle degree are significantly decreased during recent years, such as water use/per capita, which is closely related to the economic development and water use efficiency. The raising trend for some of the index obstacle degree was discovered, such as population density, ecological water use and water consumption rate. It shows that Henan Province should pay more attention to the problems of population density, ecological water consumption and high water consumption in the future. It also shows that the index obstacle degree can provide the basis for the weight determination in evaluation of water resources

carrying capacity. For the indexes with large obstacle degree and upward trend (for example, the water use ratio of ecological environment), the weight can be increased appropriately, otherwise, the index weight can be reduced appropriately.

### Conclusion

In this paper, the combined weight method (CWM) was put forward, which includes the entropy weight method, multi-dimensional normal cloud model and obstacle degree diagnosis. The improved AGA-AHP method was formed to evaluate the regional water resources carrying capacity.

The combined weight method (CWM) takes the subjective cognition of experts and the objective law of the events into consideration to make combined weight factors more scientific and reasonable. The combined weight method (CWM) simplified the model construction. For instance, in Henan province water resources carrying capacity evaluation, only 5 models need to be established by using CWM, but 40 models need to be established if single cloud model was used, which greatly reduces the number of models and simplifies the calculation process.

The multi-dimensional normal cloud model takes the randomness and fuzziness into account in the water resources carrying capacity evaluation, and the certainty

**Table 5** The obstacle degree of water resources carrying capacity evaluation index in Henan Province

Years	$X_1$	$X_2$	$X_3$	$X_4$	$X_5$	$X_6$	$X_7$	$X_8$
2010	0.13	0.11	0.04	0.13	0.02	0.27	0.16	0.13
2011	0.14	0.10	0.05	0.16	0.09	0.23	0.13	0.10
2012	0.11	0.08	0.05	0.14	0.07	0.29	0.18	0.08
2013	0.08	0.06	0.04	0.12	0.06	0.32	0.19	0.12
2014	0.09	0.06	0.02	0.15	0.06	0.29	0.17	0.15
2015	0.11	0.04	0.03	0.22	0.08	0.19	0.12	0.20
2016	0.15	0.05	0.06	0.37	0.03	0.01	0.01	0.32
2017	0.04	0.01	0.03	0.18	0.01	0.34	0.21	0.17
2018	0.02	0.01	0.04	0.17	0.00	0.36	0.22	0.17
20,019	0.00	0.01	0.03	0.13	0.00	0.42	0.26	0.15

degree can reflect the evaluation results more intuitively, reduce the number of modeling and improve the calculation efficiency.

The obstacle degree diagnosis method can effectively identify the obstacle degree and the changing trend of the obstacle factors, which has an important role in the determination of the index weight in water resources evaluation.

In order to verify the effectiveness of the combined weight method (CWM), both single cloud model method and AHP-TOPSIS method were selected for comparative analysis. It can be concluded through comparison that although the similar consistent results were obtained by using different models, compared with other methods, CWM has the advantages of comprehensive consideration for the subjectivity and fuzziness in the evaluation grade division, reducing the fuzziness and increasing the certainty degree, and realizing model simplification.

It can be concluded that compared with other methods, CWM has the advantages of reducing fuzziness influence on the overall evaluation, intuitively calculating the comprehensive certainty degree, simplifying the model numbers in construction and operation, etc. It shows that the index obstacle degree can provide the basis for the weight determination in evaluation on water resources carrying capacity.

It shows through study that the raising trend for some of the index obstacle degree was discovered, such as population density, ecological water use and water consumption rate. Therefore, Henan Province should pay more attention to the problems of population density, ecological water consumption and high water consumption in the future.

**Acknowledgements** The study was supported by the Natural Science Fund of China (No.50579020).

**Authors contribution** The study conception and design, material preparation, data collection and analysis were performed by KZ.

**Funding** The study was supported by the National Natural Science Fund of China (No.50579020).

## Declarations

**Conflict of interest** There is no conflict of interest in this manuscript.

**Data availability** All the data and materials in the current study are available from the corresponding author on reasonable request.

**Ethical approval** The author declares that there are no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**Human or animal rights** This article does not contain any studies with human participants or animals performed by any of the authors.

**Consent to participate** The author consents to participate in the works under the Ethical Approval and Compliance with Ethical Standards.

**Consent to publish** All the data in the paper can be published without any competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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