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Comprehensive Assessment of Water Supply Benefits for South-to-North Water Diversion in China from the Perspective of Water Environmental Carrying Capacity

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ABSTRACT

The South-to-North Water Diversion Project in China is an important measure to promote the ecological civilization construction in the receiving areas. Since the operation of the east and middle routes, the comprehensive benefits are more and more remarkable. It is very significant to quantitatively evaluate the comprehensive benefits of the South-to-North Water Diversion Project. The idea of quantitative evaluation by the improved degree of the carrying capacity of regional water environment after water diversion is put forward in this paper. On the basis, combining with variable fuzzy set and cloud theory, a new comprehensive assessment model is established. According to the evaluation index system of water environmental carrying capacity and the index values of research area, the linear difference function value is generated randomly by triangular forward cloud generator, and then the variable fuzzy comprehensive evaluation is carried out. Taking Haihe River Basin and Beijing City as typical research areas respectively, the comprehensive benefits of water supply from the diversion project in 2030 are analysed. The comprehensive evaluation method with variable cloud model considers both “good” and “bad” aspects and considers both randomness and fuzziness. Results show that the model is feasible and efficient. It is worth popularizing and applying.

INTRODUCTION

Water is the basis of ecology and the basic resource for the construction of ecological civilization. The South-to-North Water Diversion Project is an important measure to promote the construction of ecological civilization in the receiving area. The project that is planned east, middle, and west three lines is a major strategic infrastructure to relieve the severe water shortages in northern China, and promote the optimal allocation of water resources. In November 2013 and December 2014, the East Route Project and the Middle Route Project were put into operation respectively. Since the operation of the East and Middle Routes of the South-to-North Water Diversion Project, the total amount of water transported has been nearly 24 billion m^3, and the beneficiary population has exceeded 100 million. The guarantee rate of water supply of cities along the route has been improved, the regional sustainable development has been promoted, and the social, economic and ecological comprehensive benefits have become increasingly prominent. It is of great significance to scientifically evaluate the comprehensive benefits of the South-to-North Water Diversion Project. At present, many people have carried out preliminary studies on the water supply benefits of the South-to-North Water Diversion Project and obtained some achievements, but most of the researches are only statistical analysis for some aspects. The comprehensive evaluation system has not been established and the quantitative calculation of the comprehensive benefits has not been realized. Benefits assessment of South-to-North Water Diversion Project is a complex system. The following aspects should be considered.

Firstly, it is necessary to establish a scientific evaluation index system. Select indicators reflect social, economic, ecological and other aspects. Based on the principle of sustainable development and on the premise of maintaining the virtuous development of ecological environment, the critical value of evaluation grade for individual indicators is determined. Secondly, there are many factors to promote regional development, and the effect of water resources is affected by the optimal allocation of regional water resources, industrial structure, science and technology, etc. Studies on the contribution of water diversion to the receiving area should be based on certain technical level and conditions. Thirdly, benefits evaluation involves many indexes and belongs to multiple objective comprehensive assessments, which generally involve fuzziness and randomness. A comprehensive evaluation model established should reflect these characteristics to realize quantitative analysis scientifically. At last, in order to facilitate practical application, index selection should consider achieving index data easily.

The main research results about water resources carrying capacity and water environmental carrying capacity were completed by Chinese scholars. Pan et al. (2007) studied the evaluation method for water resources carrying capacity based on GIS techniques. Cheng et al. (2015) evaluated the capacity of water resources in Heilongjiang Province based on entropy weight and cloud model. Dong et al. (2010) studied population carrying capacity of Beijing in China by dynamic simulation. Duan et al. (2010) made preliminary research on regional water resources carrying capacity conception and method. Sun et al. (2006) proposed a quantification and appraisal method for carrying capacity of water resources. Wang et al. (2017) studied on index system and judgment criterion of water resources carrying capacity. Zhao et al. (2008) analysed the evolution of water resources carrying capacity of Haihe River Basin in China. Li et al. (2017) simulated dynamically the policy implications for water resources carrying capacity of megacities. At present, there is no completely unified understanding and definition, but they all emphasize the supporting capacity of water environment to the socio-economic system and ecological system, reflect the principle of sustainable development, and take into account all aspects of society, economy and ecological environment. Over the past decades, abundant achievements have been made in the research of water environmental carrying capacity. The evaluation index system has been also established and applied to practice. Therefore, the comprehensive benefits of water diversion can be analysed from the point of view of improving the carrying capacity of water environment in the receiving area.

At present, there are many comprehensive evaluation methods, each of which has its own characteristic. Chen et al. (2007, 2008) proposed variable fuzzy set considering “good” and “bad” two aspects of things to apply optimum decision making for flood control dispatch, land suitability evaluation and so on. Li (2000) suggested cloud models by combining randomness and fuzziness. Chen et al. (2008) applied cloud model into making of the medium and long term irrigation schedule. Sun et al. (2015) established the cloud model based on entropy weight method to study the capacity evaluation of flood disaster prevention and reduction in Chaohu Basin in China. Zhang et al. (2017) suggested the cloud theory-based regional water resources carrying capacity evaluation model. In this paper, the improvement of regional water environmental carrying capacity by water diversion is taken as the standard to quantify the comprehensive benefits of water supply. A comprehensive evaluation model based on variable cloud model is established by combining the basic ideas of variable fuzzy set theory and cloud theory.

EVALUATION INDEX SYSTEM OF WATER SUPPLY BENEFITS

Evaluation of comprehensive benefits of water supply is transformed into evaluation of water environmental carrying capacity before and after regional water diversion. Water environmental carrying capacity refers to the maximum supporting capacity of water environment for social and economic development under a specific historical development condition, based on the level of technology, economic and social development, the principle of sustainable development, and the condition of maintaining the virtuous cycle of ecological system. After the development of more than several decades, the research results have gradually matured, and some representative definitions and methods have been formed. The analysis methods of water environmental carrying capacity can be divided into two categories. One is to evaluate comprehensively the water environmental carrying capacity of the study area according to the established evaluation index system, and to evaluate the saturation degree or potential of water environmental carrying capacity under given social, economic and technological conditions. The other is to calculate the population size, social and economic scale that can be carried by water environment after optimizing the allocation of water resources, under certain conditions of water resources development and utilization. Considering the simplicity of calculation and the accessibility of data, this paper uses the method of evaluation to analyse the carrying capacity of water environment.

Determine the evaluation index system of regional water environmental carrying capacity with the existing research results. The grade of comprehensive evaluation of water environmental carrying capacity is divided into five grades. The smaller the grade value is, the greater the carrying capacity of water environment is, and the larger the grade value is, the closer the carrying capacity of water environment is to saturation. Considering the economy, water resources, ecology and other factors, as well as the easy access to data, the evaluation index is selected, and the threshold of the classification of each index is determined. Among them, some indicators belong to the “bigger is better” type, while

Fig. 1: Sketch of relative position.

others are the opposite. The specific evaluation index system is given in Table 1 and Table 2.

According to the index system suggested, water environmental carrying capacity of receiving area in typical year can be evaluated respectively under water diversion and without water diversion conditions. Suppose that the grade value of water environmental carrying capacity in the area before water diversion is D_0, and after water diversion, the carrying capacity of water environment is D_1. The comprehensive benefit of water diversion can be defined by the following formula:

$$B = \frac{D_0 - D_1}{D_0} \quad \ldots(1)$$

Table 1: Evaluation index system of water environmental carrying capacity.

Category	Evaluation index	Number
Socio-economic conditions	GDP per capita (Yuan/person)	1
	Proportion of the tertiary industry (%)	2
	Population density (person/km^2)	3
	Urbanization rate (%)	4
	Water consumption of 10 thousand Yuan GDP ($m^3/10^4$ Yuan)	5
Water resources conditions	Annual per capita water resources (m^3)	6
	Utilization rate of water resources development (%)	7
	Water supply modulus of other sources (10^4 m^3/km^2)	8
	Annual water shortage rate (%)	9
Ecological environment conditions	Water quality standard rate of rivers and lakes (%)	10
	Sewage treatment rate (%)	11
	Forest coverage rate (%)	12
	Ecological environment water consumption rate (%)	13

Table 2: Criteria for evaluating water environmental carrying capacity.

Grade 1	Grade 2	Grade 3	Grade 4	Grade 5
50000~35000	35000~21000	21000~7000	7000~4000	4000~0
70~60	60~50	50~30	30~20	20~0
0~10	10~100	100~200	200~400	400~600
70~60	60~50	50~30	30~15	15~0
0~80	80~110	110~250	250~600	600~700
3000~2200	2200~1700	1700~1000	1000~500	500~0
0~10	10~40	40~50	50~60	60~100
30~20	20~10	10~5	5~1	1~0
0~10	10~20	20~30	30~40	40~100
100~70	70~50	50~30	30~10	10~0
100~80	80~60	60~40	40~20	20~0
40~30	30~25	25~20	20~10	10~0
50~40	40~30	30~20	20~10	10~0

Where, B is the comprehensive benefit of water diversion; D_1 is the quantitative value of water environmental carrying capacity evaluation after water diversion; D_0 is the quantitative value of regional water environmental carrying capacity evaluation without water diversion.

COMPREHENSIVE EVALUATION MODEL BASED ON VARIABLE CLOUD

Variable Fuzzy Set Theory

The theory of variable fuzzy set is a dynamic variable theory, model and method of fuzzy set about things, phenomena and concept membership. Based on relative difference function and considering advantages and disadvantages, the theory of variable fuzzy set has been widely applied into hydrology and water resources fields.

Suppose that $\tilde{A}$ and $\tilde{A}_c$ are a pair of concepts (things or phenomena) in discourse domain U, $u \in U$. As for the point on the reference continuum axis of the relative membership function, the relative membership degree of u to $\tilde{A}$ is $\mu_{\tilde{A}}(u)$, and the degree of u to $\tilde{A}_c$ is $\mu_{\tilde{A}_c}(u)$, $\mu_{\tilde{A}}(u) \in [0,1]$, $\mu_{\tilde{A}_c}(u) \in [0,1]$. Let

$$D_{\tilde{A}}(u) = \mu_{\tilde{A}}(u) - \mu_{\tilde{A}_c}(u) \quad \ldots(2)$$

$D_{\tilde{A}}(u)$ is called the relative difference degree of u to $\tilde{A}$.

Because $\mu_{\tilde{A}}(u) + \mu_{\tilde{A}_c}(u) = 1$, the relation between $\mu_{\tilde{A}}(u)$ and $\mu_{\tilde{A}_c}(u)$ can be described as follows:

$$\mu_{\tilde{A}}(u) = (1 + D_{\tilde{A}}(u))/2 \quad \ldots(3)$$

The mapping

$$\begin{cases} D_{\tilde{A}} : D \to [-1,1] \\ u \mapsto D_{\tilde{A}}(u) \in [-1,1] \end{cases} \quad \ldots(4)$$

is called the relative difference function of u to $\tilde{A}$. Let

$$\tilde{V} = \{(u,D)|u \in U, D_{\tilde{A}}(u) = \mu_{\tilde{A}}(u) - \mu_{\tilde{A}_c}(u), D \in [-1,1]\} \quad \ldots(5)$$

$$A_+ = \{u|u \in U, 0 < D_{\tilde{A}}(u) \le 1\} \quad \ldots(6)$$

$$A_- = \{u|u \in U, -1 \le D_{\tilde{A}}(u) < 0\} \quad \ldots(7)$$

$$A_0 = \{u|u \in U, D_{\tilde{A}}(u) = 0\} \quad \ldots(8)$$

$\tilde{V}$ is called variable fuzzy set. A_+, A_-, A_0 are the attraction domain, exclusion domain and gradual qualitative change boundary.

Set the attraction domain of variable fuzzy set $\tilde{V}$ is (a, b), the exclusion domain is $[c, a)$ and $(b, d]$. $D_{\tilde{A}}(u) = 1$ at the point M. Let x be any point in interval $[c, d]$, the relative difference function can be calculated by the relative position of the points on the real axis, as shown in Fig. 1.

When x is on the left side of point M, the relative difference function can be calculated by the following formula:

$$D_{\tilde{A}}(u) = \left(\frac{x-a}{M-a}\right)^{\beta}, x \in [a, M] \quad \ldots(9)$$

$$D_{\tilde{A}}(u) = -\left(\frac{x-a}{c-a}\right)^{\beta}, x \in [c, a] \quad \ldots(10)$$

When x is on the right side of point M, the relative difference function can be computed as follows:

$$D_{\tilde{A}}(u) = \left(\frac{x-b}{M-b}\right)^{\beta}, x \in [M, b] \quad \ldots(11)$$

$$D_{\tilde{A}}(u) = -\left(\frac{x-b}{d-b}\right)^{\beta}, x \in [b, d] \quad \ldots(12)$$

Where, β is non-negative exponent. Generally, let $\beta = 1$.

Cloud Theory

Cloud theory is formed on the basis of probability statistics and fuzzy mathematics to realize the uncertainty transformation between qualitative and quantitative concepts. The cloud model uses numerical characteristics of expectation, entropy and hyper entropy to describe fuzziness and randomness. The fuzziness is used to describe by membership degree based on expectation and entropy and the randomness of membership degree is described by hyper entropy.

Let U={u} be the domain of discourse described numer-

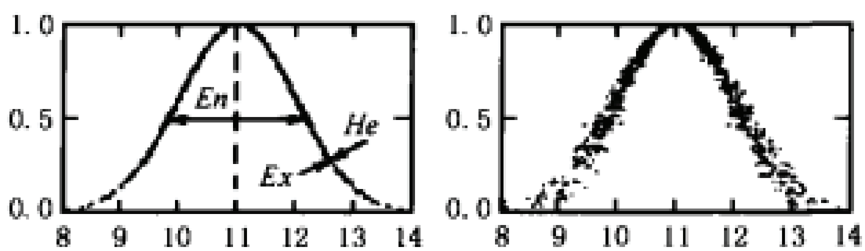

Fig. 2: Sketch of one-dimensional Normal Cloud.

ical value, and C be the qualitative conception associated with U. The membership degree of u to U for the conception C, $\mu(u)$, is a random number generated in the interval [0, 1]. That is,

$$\mu: U \to [0,1] \quad \forall u \in U \; u \to \mu(u) \qquad ...(13)$$

The mapping from the universe U to the interval [0, 1] is called a compatibility cloud, and each u is called a cloud drop.

Normal cloud described by expectation E_x, entropy E_n and hyper entropy H_e is the most widely used cloud model at present. It is based on normal distribution function. Set x submit to normal distribution, taking E_x as expectation, E_n' as standard deviation. E_n' is also a random variable that obeys normal distribution of expectation E_n and standard deviation H_e. The certainty degree of x, $\mu(u)$, is calculated by the following formula:

$$\mu(x) = \exp\left\{-\frac{(x-E_x)^2}{2E_n'^2}\right\} \qquad ...(14)$$

The distribution of x is called normal cloud (Fig. 2).

Normal distribution function is universal and widely used, but linear distribution is often used in practice. For example, membership functions of triangle style or linear style that can be taken as a side of triangle are often used in evaluation. Based on the idea of cloud theory, the cloud model with triangle distribution is deduced in this paper. The method of generating random numbers subjecting to triangle distribution density is introduced.

Let the probability density function of triangle distribution be an isosceles triangle, as shown in Fig. 3.

The probability distribution function can be calculated by distribution density function.

$$F(x) = \begin{cases} 0 & x \le E_x - E_n \\ \frac{1}{2(E_n)^2}x^2 - \frac{E_x - E_n}{(E_n)^2}x + \frac{(E_x - E_n)^2}{2(E_n)^2} & E_x - E_n < x \le E_x \\ -\frac{1}{2(E_n)^2}x^2 + \frac{E_x + E_n}{(E_n)^2}x - \frac{(E_x)^2 + 2E_xE_n - (E_n)^2}{2(E_n)^2} & E_x < x \le E_x + E_n \\ 1 & x > E_x + E_n \end{cases} \qquad ...(15)$$

The inverse function of distribution function is shown as follows:

$$F^{-1}(x) = \begin{cases} (E_x - E_n) + E_n\sqrt{2x} & 0 \le x \le 1/2 \\ (E_x + E_n) - E_n\sqrt{2(1-x)} & 1/2 < x \le 1 \end{cases} \qquad ...(16)$$

According to the inverse function, take a series of random numbers submitting to uniform distribution in interval [0, 1] into equation (16), and achieve random numbers subjecting to triangle distribution with the numerical characters E_x and E_n.

Let three numerical characters of cloud based on triangle distribution density be (E_x, E_n, H_e). The steps of triangular cloud generator are as follows:

(1) According to the method of generating random number of triangle distribution, produce random samples E_n' that are based on the numerical characters (E_n, H_e). H_e can be selected by experience.

(2) According to the parameters (E_x, E_n'), generate the random number x obeying triangle distribution density.

(3) The certainty degree of x, $\mu(x)$, can be calculated by the following equation:

$$\mu(x) = \begin{cases} \frac{x - E_x + E_n'}{E_n'} & E_x - E_n' \le x \le E_x \\ \frac{E_x + E_n' - x}{E_n'} & E_x < x \le E_x + E_n' \end{cases} \qquad ...(17)$$

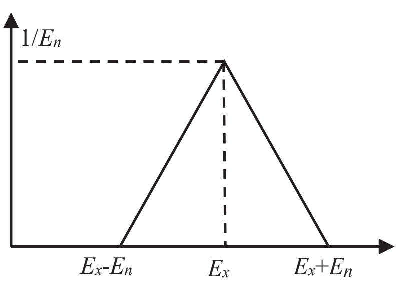

Fig. 3: Probability density function submitting to triangle distribution.

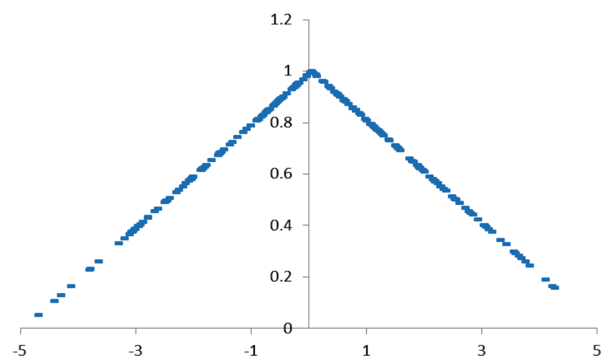

Fig. 4: One-dimensional triangular cloud map.

(4) x_i with the certainty degree μ_i is called the cloud drop. Repeat the above steps to create n cloud drops, and form the triangular cloud.

Giving a number a, the corresponding certainty degree can be calculated by forward cloud generator as follows:

(1) According to the numerical characters (E_n, H_e), generate random number $E_n^{'}$ subjecting to triangle distribution.

(2) According to the given number a, compute the corresponding certainty degree by the formula (17).

Let E_x=0, E_n=5, H_e=0.01. Generate 200 cloud drops, and form the cloud map as given in Fig. 4.

Evaluation Method Based on Variable Cloud Model

The comprehensive evaluation method with variable cloud is established by combining variable fuzzy set with cloud theory. According to the evaluation index system, the triangular cloud model is used to generate the difference degree randomly, and then the variable fuzzy comprehensive evaluation is carried out by difference degree. The specific steps are as follows:

(1) According to the above evaluation index system and classification criteria, the relative difference function of each evaluation grade is established for each index. Taking the population density index as an example, the corresponding grade 3 difference functions can be seen in Fig. 5.

(2) According to the graph of relative difference function, the expectation and entropy digital characteristics of each index for different grades are determined, and the hyper entropy value is determined according to experience. On the basis of the relative difference function corresponding to each grade, according to each index value of the evaluated object, the corresponding difference degree is randomly generated by the forward triangular cloud generator.

(3) According to the relative difference degree, the relative membership degree of each grade can be calculated.

(4) Suppose that the number of evaluation indicators is m and the number of evaluation grade is c. According to the relative membership degree generated above, the comprehensive grade of the evaluated object is calculated according to the following formula:

$$u_h^{'} = \frac{1}{\left[1+\left(\frac{d_{hg}}{d_{hb}}\right)^{\alpha}\right]} \qquad h = 1,2,\cdots,c \qquad ...(18)$$

$$d_{hg} = \{\sum_{i=1}^{m}[w_i(1-\mu_{\tilde{A}}(u_{ih}))]^p\}^{1/p} \qquad ...(19)$$

$$d_{hb} = [\sum_{i=1}^{m} w_i\mu_{\tilde{A}}(u_{ih}))^p]^{1/p} \qquad ...(20)$$

Where, $u_h^{'}$ is the membership degree corresponding grade h; p is the distance parameter. Generally, let p=2; a is the parameter of optimization criterion. Let a=1; w_i is the weight of the i^{th} evaluation index; $\mu_{\tilde{A}}(u_{ih})$ is the relative membership degree of the i^{th} evaluation index to the h^{th} grade.

Take the normalized membership degrees as weights, and calculate the comprehensive grade as follows:

$$D = \sum_{h=1}^{c} u_h \cdot h \qquad ...(21)$$

$$u_h = \frac{u_h^{'}}{\sum_{h=1}^{c} u_h^{'}} \qquad ...(22)$$

Where D is the comprehensive grade of evaluated object.

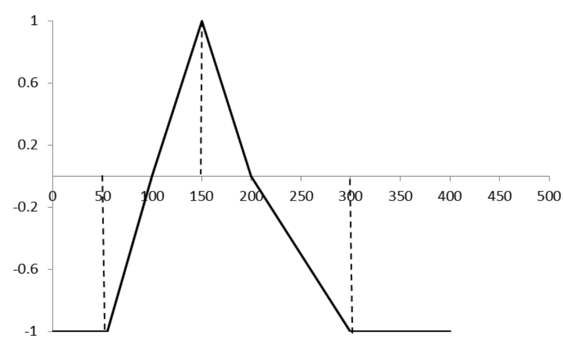

Fig. 5: Relative difference function.

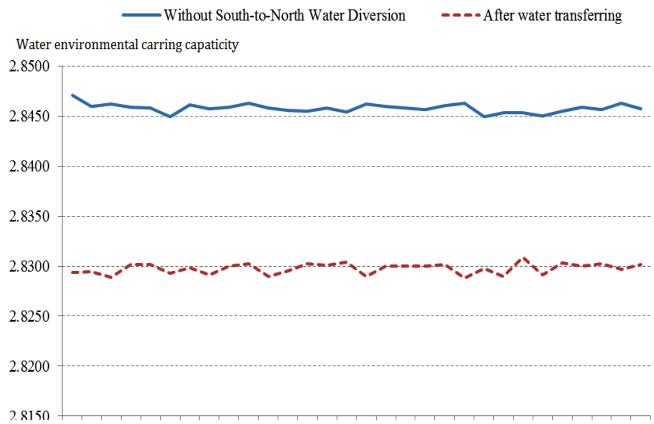

Fig. 6: Water environmental carrying capacity under different conditions in Haihe River Basin.

APPLICATION OF THE VARIABLE CLOUD MODEL

Evaluation of Comprehensive Benefits for Haihe River Basin

The Haihe River Basin is taken as a typical research area. The basin is bordered by the Mongolian Plateau in the north, the Yellow River in the south, the Bohai Sea in the east and Shanxi in the west. The total area of the basin is 318,200 km^2, accounting for about 3.3% of the total area of the country. The administrative areas of Haihe River Basin include Beijing, Tianjin, most of Hebei Province, eastern part of Shanxi Province, northern part of Shandong and Henan Province, and parts of Liaoning Province and Inner Mongolia Autonomous Region. The Haihe River Basin has a rapid economic development, and many large and medium sized cities, but the total amount of water resources is small, and the spatial and temporal distribution is uneven. The shortage of water resources is restricting the sustainable development of regional social economy. The South-to-North Water Diversion Project is a strategic project to alleviate the shortage of water resources in northern China. The East Route Project and the Middle Route Project have begun to operation since December 2013 and December 2014, respectively. By the end of March 2019, the cumulative water supply to the receiving area along the line exceeded 24 billion m^3, and the comprehensive benefits of the project are remarkable. According to relevant planning and information, by 2030, on the basis of diverting water

Table 3: Evaluation index value of Haihe River Basin in 2030.

Evaluation index	Without South-to-North Water Diversion	After water transferring
GDP per capita (Yuan/person)	81000	81000
Proportion of the tertiary industry (%)	53	53
Population density (person/km^2)	497	497
Urbanization rate (%)	60	60
Water consumption of 10 thousand Yuan GDP (m^3/10^4 Yuan)	95	95
Annual per capita water resources (m^3)	266	342
Utilization rate of water resources development (%)	96	96
Water supply modulus of other sources (10^4 m^3/km^2)	1.57	5.34
Annual water shortage rate (%)	30	9.5
Water quality standard rate of rivers and lakes (%)	40	40
Sewage treatment rate (%)	82	82
Forest coverage rate (%)	18	18
Ecological environment water consumption rate (%)	12.1	12.1

Table 4: Evaluation index value of Beijing City in 2030.

Evaluation index	Without South-to-North Water Diversion	After water transferring
GDP per capita (Yuan/person)	215983	215983
Proportion of the tertiary industry (%)	82.43	82.43
Population density (person/km^2)	1402	1402
Urbanization rate (%)	88.8	88.8
Water consumption of 10 thousand Yuan GDP (m^3/10^4 Yuan)	11	11
Annual per capita water resources (m^3)	149	210
Utilization rate of water resources development (%)	100	100
Water supply modulus of other sources (10^4 m^3/km^2)	0	8.53
Annual water shortage rate (%)	38.79	13.37
Water quality standard rate of rivers and lakes (%)	90	90
Sewage treatment rate (%)	99	99
Forest coverage rate (%)	45	45
Ecological environment water consumption rate (%)	14.58	14.58

about 5 billion m^3 from the Yellow River each year, about 12 billion m^3 of water will be diverted to the Haihe River Basin through the South-to-North Water Diversion Project. Taking 2030 as a typical year, by relevant research results and data, according to the above evaluation index system and variable cloud model, the impact of South-to-North Water Diversion on water environmental carrying capacity of Haihe River Basin is analysed. In 2030, without considering the South-to-North Water Diversion and after water transferring, the index values of water environmental carrying capacity under the two kinds of conditions are indicated as given in Table 3.

Using analytic hierarchy process, the weight of each index is determined as follows: (0.127, 0.089, 0.111, 0.057, 0.155, 0.073, 0.047, 0.021, 0.023, 0.036, 0.051, 0.095, 0.116).

Based on the above evaluation system and index values, the carrying capacity of water environment in Haihe River Basin is calculated and analysed by using variable cloud model. Set hyper entropy equal 0.1. Thirty calculations have been made in this paper, and the results are as shown in Fig. 6.

According to the Fig. 6, there is certain randomness in the calculation results using the variable cloud model, that is, the results are not exactly the same each time, but results have a stable tendency value. The cloud model reflects the fuzzy uncertainty and random uncertainty. Without considering the water conveyance from South-to-North Water Diversion Project, the average value of water environmental carrying capacity in Haihe River Basin in 2030 is 2.8458. After water diversion, the average grade of water environmental carrying capacity is 2.8298. It is considered that the carrying capacity of water environment in Haihe River Basin will be increased by 0.5625% by water diversion from the South-to-North Water Diversion Project. According to the calculation results, the analysis is as follows:

(1) In 2030, with the advancement of technology, the improvement of water use efficiency and the optimization of industrial structure, the carrying capacity of water environment in Haihe River Basin will be basically at the middle level. Water environment could bear the social and economic scale at that time, but still at the general level.

(2) To a certain extent, the carrying capacity of regional water environment can be improved through water diversion, but it is more important that the region itself should vigorously save water, optimize the industrial structure, improve the utilization rate of water resources, improve the ecological environment and implement green development.

(3) The benefits of water diversion are not only related to the total amount of water diversion, but also to the degree of local social and economic development, technological level and optimal allocation of water resources. Therefore, the evaluation of water diversion benefits is dynamic.

(4) This paper takes Haihe River Basin as an example, and the scope of the research object is large. If a small area is chosen for research, such as province or city, the proportion of water diversion in the total water supply is larger, and the contribution of water diversion to the improvement of water environmental carrying capacity in the local area is greater. Therefore, the evaluation results of water diversion benefits are also related to the study object.

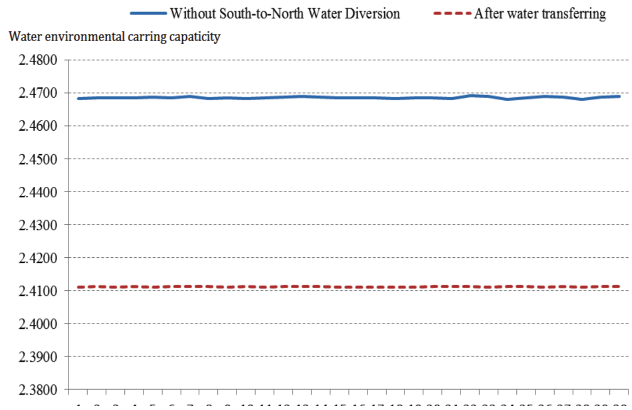

Fig. 7: Water environmental carrying capacity under different conditions in Beijing City.

Evaluation of Comprehensive Benefits for Beijing City

Taking Beijing as an example, which is the main receiving area of South-to-North Water Diversion Middle Route Project, the model can be validated. Beijing is located at the north-west end of the North China Plain, adjacent to Tianjin in the east, surrounded by Hebei Province in the west, south and north. The total area of the city is about 16410 km^2, of which the mountainous area accounts for about 60% and the plain area accounts for about 40%. The seasonal variation of precipitation in Beijing is great, and the precipitation is mostly concentrated in summer. The average annual precipitation in Beijing is about 585 mm. The shortage of water resources in Beijing is very serious. The per capita water resources are less than 9% of the national level. In order to alleviate the shortage of water resources in Beijing, from September 2008 to April 2014, the Middle Route Project diverted water from reservoirs in Hebei Province by using the pre-built Beijing-Shijiazhuan section project, and implemented four emergency water supplies to Beijing, with a total water supply of 1.6 billion m^3. Since December 2014, the Middle Route Project has been in operation, and by the end of March 2019, about 4.4 billion m^3 of water from Dajiankou reservoir has been transported to Beijing. Taking 2030 as a typical year, by relevant research results and development plan, on basis of the above evaluation index system and variable cloud model, the impact of South-to-North Water Diversion on water environmental carrying capacity of Beijing is analysed. In 2030, without considering the South-to-North Water Diversion and after water transferring, the index values of water environmental carrying capacity under the two kinds of conditions are indicated as given in Table 4.:

The weight is the same as the previous example. Let hyper entropy be 0.1. Thirty calculations have been made. The results calculated with the variable cloud model have certain randomness, and each result is not completely the same, but the calculated results have a stable tendency value. Without considering the water conveyance from South-to-North Water Diversion Project, the average value of water environmental carrying capacity of Beijing in 2030 is 2.4685. After water diversion, the average grade of water environmental carrying capacity is 2.4112. It is considered that the carrying capacity of water environment in Beijing will be increased by 2.32% by water diversion from the South-to-North Water Diversion Project. The carrying capacity of water environment in Beijing is basically in the middle level. Water environment can bear the social and economic scale at that time, but it is still at the general level. Although water transfer can improve the carrying capacity of water environment in water receiving areas, it mainly depends on local efforts to save water and improve the utilization rate of water resources. The calculated results under different conditions for Beijing are as shown in Fig. 7.

CONCLUSIONS

Considering the uncertainty and multiple criteria feature of the comprehensive benefits evaluation of the South-to-North Water Diversion Project, the idea of benefits evaluation based on the improvement of water environmental carrying capacity in the receiving area is put forward. On this basis, combined with variable fuzzy set theory and cloud theory, a new comprehensive evaluation model based on variable cloud model is established. The model not only considers the membership degree of "good" and "bad" in comprehensive evaluation, but also takes into account the fuzziness and randomness in evaluation. Examples show that the method based on variable cloud model is reasonable and easy to use. It provides a new idea for the quantitative evaluation of the benefits produced by the South-to-North Water Diversion Project.

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