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WATER SECURITY COMPREHENSIVE EVALUATION MODEL BASED ON COMPREHENSIVE WEIGHT AND IMPROVED MATTER-ELEMENT

Modelo de evaluación integral de la seguridad del agua basado en el peso integral y la mejora de la materia-elemento

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ABSTRACT

As a multi-objective decision-making system, water security evaluation is suitable for the evaluation with a matter-element model. However, in the traditional matter-element model, the eigenvalue of matter-element cannot be calculated when it is beyond the range of nodes, and the calculation process is complex and error-prone. In this paper, improved analytic hierarchy process with entropy weight were combined to calculate the water security comprehensive evaluation index weight, avoiding the over-subjective or over-objective weight value. The normalization of matter-element improves the rationality of the matter-element correlation function and expands the application scope of the model, while the standardization of comprehensive proximity improves the accuracy of model results. Guangdong Province was taken as an example to verify the practicability of the model in the evaluation of the water security comprehensive index. The results show that from 2004 to 2019, the overall water security of Guangdong Province showed a trend rising from deteriorated grade to safe grade and the model results were in line with the facts. As a result, the water security comprehensive evaluation model based on comprehensive weight and improved matter-element is simple, practical, and suitable for the multi-level and multi-factor regional water security comprehensive evaluation.

Palabras clave: proceso jerárquico analítico modificado por peso de entropía, elemento-materia mejorado, evaluación comprensiva de la seguridad del agua

RESUMEN

Como sistema de adopción de decisiones multiobjetivo, la evaluación de la seguridad del agua es adecuada para la evaluación con un modelo de elemento-materia. Sin embargo, en el modelo tradicional de elemento-materia, el valor propio no se puede calcular cuando está más allá del rango de nodos, y el proceso de cálculo es complejo y propenso a errores. En este trabajo, se combinó un proceso de jerarquía analítica mejorado con peso de entropía para calcular el peso del índice de evaluación integral de seguridad del agua, evitando el valor de peso demasiado subjetivo o excesivamente objetivo. La normalización del elemento-materia mejora la racionalidad de la función de correlación elemento-materia y amplía el ámbito de aplicación del modelo, mientras que la estandarización de la proximidad integral mejora la precisión de los resultados del modelo. La provincia de Guangdong se tomó como ejemplo para verificar la viabilidad del modelo en la evaluación del índice general de seguridad del agua. Los resultados muestran que de 2004 a 2019, la seguridad hídrica general de la provincia de Guangdong mostró una tendencia al aumento de grado deteriorado a grado seguro y los resultados del modelo estaban en línea con los hechos. Como resultado, el modelo de evaluación integral de la seguridad hídrica basado en el peso integral y el modelo elemento-materia mejorado es simple, práctico y adecuado para la evaluación integral de la seguridad hídrica regional de múltiples niveles y factores.

INTRODUCTION

According to the system theory, the large-scale system of human development consists of economy, society, resources, ecology, and other subsystems. Only the coordinated and unified development of all subsystems can ensure the sustainable and stable development of the large-scale system. As the basic natural resources and strategic economic resources of human development, water resources security may affect the sustainable development of human beings. With the rapid development of the economy and society, there is a huge deviation between the limited supply and unlimited demand of water resources, which challenges regional water resources security. Water security has become a hot topic for governments and international organizations. Combined with the theory of the large-scale system, water security is the harmonious development of regional water resource endowment, development and utilization with human society, economy, and ecology at a certain technical level. To accurately grasp the regional water resources endowment and development, water security, as a multi-objective decision-making system reflecting the regional water resources endowment, development and utilization and human society, economy, and ecology, has an important practical significance for regional water security evaluation and regional water resources planning.

Ecological security was put forward in the 1940s (Whitford et al. 1999). Water security, as an important component of ecological security, was proposed at Stockholm Water Forum in 2000 (Fang 2001). After that, scholars at home and abroad carried out a lot of theoretical methods and case studies on the definition of water resources security (Jia et al. 2002), water resources security evaluation index system (Ohlsson 2000, Cheng and Zhao 2006), water environment quality evaluation (Ferrier et al. 2001, Zhang and Li 2013), effectively improving the attention of the whole society on water security (Peng et al. 2016). As for the water security comprehensive evaluation, scholars mainly used the comprehensive index method (Jensen and Wu, 2018), analytic hierarchy process (Jin et al. 2007, Fan et al. 2004), fuzzy comprehensive evaluation method (Zhang et al. 2010), projection pursuit method (Wei et al. 2015, Cao et al. 2010), system dynamics model (Ren et al. 2017), multi-objective decision-making analysis (Slobodan P et al. 2005), bp neural network model (Jin et al. 2012), cloud theory (Tran Thi et al. 2017, Xue and Du, 2020) and other methods to evaluate regional water security. However, in most studies, the water security comprehensive evaluation value was firstly got by quantitative method, the water security comprehensive evaluation value was assigned in a range of 0-100 or 0-1 in general, and then the range was equally or subjectively divided into several grades. The evaluation result often deviated from reality. The matter-element model was founded by Chinese scholar and professor Cai Wen in the early 1980s (Cai 1994), which mainly solves the problem of multi-factor evaluation. Then the matter-element model was used by scholars in a variety of fields. Some scholars applied the matter-element model to the study of water security (Liu et al. 2003, Li 2005, Oi et al. 2006, Chen et al. 2007, Huang et al. 2010, Yang and Guo 2010, Jia et al. 2011, Lu and Xu 2011, Li et al. 2012, Liu et al. 2015, Wang et al. 2019). However, in the traditional matter-element model, the irregular design of the correlation function leads to the fact that the eigenvalue of the matter-element to be evaluated cannot be calculated when it exceeds the range of the section, and the matter-element model cannot be used. In this paper, based on calculating the index weight by the comprehensive weighting method which combines the subjective and objective evaluation methods of entropy and AHP, the matter-element of water security comprehensive evaluation was standardized, avoiding that the comprehensive proximity cannot be calculated when the eigenvalue of the matter-element to be evaluated exceeds the range of segment field, simplifying the calculation process and ensuring the accuracy of model results.

METHOD

Weight of each evaluation index determined by improved analytic hierarchy process with entropy weight

The idea of improved analytic hierarchy process with entropy weight

The index system weight assignment method mainly includes subjective weight assignment and objective weight assignment. The subjective weight assignment is based on experts' subjective experience and judgment to assign the weight of the evaluation index, including the analytic hierarchy process (AHP). The calculated index weight value has absolute subjectivity, and the same index will result in different index weights due to different subjective experiences of evaluators. The objective weight assignment calculates the weight value of each index according to the information reflected by the sample data, including entropy weight method, correlation coefficient method, etc. The determined index value has absolute objectivity, and the weight value is easy to fluctuate with the change of the sample data. Therefore, in this paper, the objective value of the indexes in each scheme was fully used to modify the weight vector obtained in the analytic hierarchy process, and the expert's professional judgment was fully combined with the information of each data so that the modified weight vector could not only reflect the subjective will but also combine with the objective information, avoiding the absolute subjectivity and objectivity of the index weight.

Specific steps of improved analytic hierarchy process with entropy weight

(1) Construct decision matrix D with an index value. Suppose that there are m evaluation objects, and each object has n evaluation indexes, the order decision matrix D is constructed with the eigenvalues of each index V_{ij}.

(2) Calculate index weight by improved analytic hierarchy process with entropy weight:

① The original decision-making matrix D is standardized to get the standardized matrix $R = (r_{ij})_{m\times n}$. The calculation method is as follows:
Positive indicator:

$$r_{ij} = \frac{\max \mathrm{v}_j - \mathrm{v}_{ij}}{\max \mathrm{v}_j - \min \mathrm{v}_j} \tag{1}$$

Negative index:

$$r_{ij} = \frac{\mathrm{v}_{ij} - \min \mathrm{v}_j}{\max \mathrm{v}_j - \min \mathrm{v}_j} \tag{2}$$

② The projection of index J is $P_{ij} = \frac{r_{ij}}{\sum_{i=1}^{m} r_{ij}}$, and the entropy is $E_j = -\frac{1}{\ln m}\sum_{i=1}^{m} p_{ij}\ln(p_{ij})$.
In order to make $1\mathrm{n}(p_{ij})$ sense, assume $p_{ij}1\mathrm{n}(p_{ij}) = 0$ when $p_{ij} = 0$. But $p_{ij}1\mathrm{n}(p_{ij}) = 0$ is not practical when $p_{ij} = 1$, which is contrary to the connotation of entropy. Therefore, p_{ij} is modified and defined as:

$$f_{ij} = \frac{1 + p_{ij}}{\sum_{i=1}^{n}\left(1 + p_{ij}\right)} \tag{3}$$

③ Define the deviation degree $d_j = 1 - E_j$ and the weight of index J after correction.

$$\lambda_j = \frac{d_j}{\sum_{j=1}^{n} d_j}\left(j = 1, 2, \mathrm{L}\ \ , n\right) \tag{4}$$

Using λ_j improved analytic hierarchy process to get the index weight value q_j, and get the comprehensive weight value ω_j.
Take the modified weight vector $W = (\omega_1, \omega_2, \cdots, \omega_3)$ as the final weighted average weight vector.

$$\omega_j = \frac{\lambda_j \omega_j}{\sum_{j=1}^{n} \lambda_j \omega_j}\left(j = 1, 2, \mathrm{L}\ \ , n\right) \tag{5}$$

Water security evaluation model based on improved matter-element

As a multi-objective decision-making system, water security evaluation is suitable for the application of the matter-element model. The matter-element model calculates the proximity function between a single index and each level interval, which can better reveal the influence degree of a single index on the water security comprehensive evaluation index. The level of the evaluation object was divided into J levels, and the value range of each level was determined in combination with the relevant national standards and literature. The entropy method was used to modify AHP to determine the weight of each evaluation index; then the value of each evaluation index was substituted into each grade set to calculate the proximity, and the weight was used to get the comprehensive proximity. The greater the comprehensive proximity, the greater the degree of compliance with the level set. Then, the grade of the evaluation object could be determined. The water security matter-element matrix R is composed of evaluation object N, water security evaluation index C and corresponding index value V, in which the number of index C is i.

$$R = \left(N, C_i, V_i\right) = \left|\begin{array}{ccc} N & c_1 & v_1 \\ & c_2 & v_2 \\ & M & M \\ & c_i & v_i \end{array}\right| \tag{6}$$

Steps of water security evaluation model based on improved matter-element

(1) Determine the matrix of classical field and segment field matter-elements and the matter-element to be evaluated

The matrix of the classical field matter-elements of water security R_o can be expressed as

$$R_o = \left(N_{oj}, C_i, V_o\right) = \left|\begin{array}{ccc} N_{oj} & c_1 & \left(a_{oj1}, b_{oj1}\right) \\ & c_2 & \left(a_{oj2}, b_{oj2}\right) \\ & M & M \\ & c_n & \left(a_{oji}, b_{oji}\right) \end{array}\right| \tag{7}$$

N_o is the classical field matter-element; R_{oj} is the evaluation grade j (j = 1, 2,···, n) of water security, which is determined according to the national environmental quality standards, national related ecological environmental protection evaluation standards, and the actual average level of water security at home and abroad; c_i is the evaluation index i; and $V_o = (a_{oji}, b_{oji})$ is the value range of index grade J.

The matrix of the segment field matter-elements of water security assessment is expressed as follows:

$$R_x = (N_x, C_i, V_i) = \left|\begin{array}{ccc} N_x & c_1 & v_1 \\ & c_2 & v_2 \\ & M & M \\ & c_i & v_i \end{array}\right| \tag{8}$$

R_p is the segment field matter-element; $V_p = (a_{pi}, b_{pi})$ is the range of the segment field values of the index c_i, which is determined by the value range or actual level of regional water security matter-element; P is the overall level of water security assessment.

The matter-element of water security to be assessed N_x is expressed as R_x follows:

$$R_p = \left(N_p, C_i, V_p\right) = \left|\begin{array}{ccc} N_p & c_1 & \left(a_{p1}, b_{p1}\right) \\ & c_2 & \left(a_{p2}, b_{p2}\right) \\ & M & M \\ & c_i & \left(a_{pi}, b_{pi}\right) \end{array}\right| \tag{9}$$

(2) Normalize the classical field and segment field matter-elements and the matter-element to be evaluated

In the traditional matter-element model, if the eigenvalue of the matter-element to be evaluated is beyond the range of the segment field, the denominator in the comprehensive proximity formula cannot be calculated, it will be impossible to calculate the comprehensive proximity, so it is necessary to improve the matter-element extension method. In this paper, normalization was used to improve the matter-element, that is, all the quantity values of matter-element are divided by the maximum value of segment field V_p, so that when the eigenvalues of matter-element to be evaluated exceed the range of segment field, reasonable results can be obtained, and the calculation process can be simplified.

The normalized classical field matter-element is:

$$R_o' = \left(N_{oj}', C_i, V_o'\right) = \left(N_{oj}', C_i, V_o/V_p\right) = \left|\begin{array}{ccc} N_{oj} & c_1 & \left(a_{oj1}', b_{oj1}'\right) \\ & c_2 & \left(a_{oj2}', b_{oj2}'\right) \\ & M & M \\ & c_n & \left(a_{oji}', b_{oji}'\right) \end{array}\right| = \left|\begin{array}{ccc} N_{oj} & c_1 & \left(a_{oj1}/V_p, b_{oj1}/V_p\right) \\ & c_2 & \left(a_{oj2}/V_p, b_{oj2}/V_p\right) \\ & M & M \\ & c_n & \left(a_{oji}/V_p, b_{oji}/V_p\right) \end{array}\right| \tag{10}$$

The normalized segment field matter-elements are as follows

$$R_p' = \left(N_p', C_n, V_p'\right) = \left|\begin{array}{ccc} N_p' & c_1 & \left(0,1\right) \\ & c_2 & \left(0,1\right) \\ & M & M \\ & c_n & \left(0,1\right) \end{array}\right| \tag{11}$$

The normalized matter elements to be evaluated are as follows:

$$R_x' = (N_x', C_i, V_i') = (N_x', C_i, V_i / V_p) = \begin{vmatrix} N_x & c_1 & v_1 \\ & c_2 & v_2 \\ & \vdots & \vdots \\ & c_i & v_i \end{vmatrix} \quad (12)$$

(3) Calculate the correlation degree of the normalized matter-element to be evaluated with respect to the value range of the normalized classical field matter-element matrix D_{ij}.

$$D_{ij} = \left| V_i' - \frac{1}{2}\left(a_{oji}' + b_{oji}'\right) \right| - \frac{1}{2}\left(b_{oji}' - a_{oji}'\right) \quad (13)$$

a_{oji}' and b_{oji}' are the normalized value range of index grade J.

In the traditional matter-element model, it is necessary to calculate whether the matter-element to be evaluated is at a certain level of the classical domain. At the same time, when the matter-element to be evaluated exceeds the node domain, the closeness formula will be invalid. Compared with the traditional matter-element model, the improved matter-element model directly uses the distance between the matter-element to be evaluated and the classical domain to represent the comprehensive closeness, which is more convenient to calculate. It not only avoids whether the matter-element to be evaluated is distinguished within the interval of a certain level of classical matter-element but also avoids the problem that the closeness formula is invalid since the matter-element to be evaluated exceeds the segment.

(4) Calculate the comprehensive correlation degree K_j (N_x').

$$K_j\left(N_x'\right) = 1 - \frac{1}{n*(n+1)} \sum_{i=1}^{n} a_i D_{ij} \quad (14)$$

The comprehensive proximity degree of water security was calculated by using proximity function. Comprehensive proximity degree K_j (N_x') represents the degree of proximity between the regional water security object to be evaluated and grade standard. The greater the degree of proximity, the closer the object to be evaluated is to this grade.

(5) Calculate and improve the comprehensive proximity to determine the evaluation grade.

Generally, the following formula is used to determine the evaluation grade:

$$K_j = max\left[K_j\left(N_x'\right)\right], j = 1, 2, \ldots n \quad (15)$$

In extenics, the extension set uses (-1 ,1) real numbers to express the degree of certain properties of a thing. A positive number indicates the degree to which it has the property, a negative number indicates the degree to which it does not have the property, and zero means that it has the property, and it does not have the property. Therefore, the positive and negative signs of comprehensive proximity degree K_j (N_x') cannot be used as the basis for comparison. In view of the applicable limit of the evaluation criterion, the standardization improvement is carried out:

$$\overline{K_j\left(N_x\right)'} = \frac{K_j - \min_j K_j}{\max_j K_j - \min_j K_j} \quad (16)$$

The improved evaluation grade is calculated by the following formula

$$\overline{K_j}' = max\left[\overline{K_j\left(N_x\right)'}\right], j = 1, 2, \ldots n \quad (17)$$

$$j^* = \frac{\sum_{j=1}^{n} j \times \overline{K_j\left(N_x\right)'}}{\sum_{j=1}^{n} \overline{K_j\left(N_x\right)'}} \quad (18)$$

$\overline{K_j'}$ is the grade of N_x, and j^* is the eigenvalue of N_x, indicating that the evaluation object X is of grade J.

Construction of water security comprehensive index system and determination of evaluation grade

Construction of water security evaluation index system

The water security system is a composite system with water as the carrier and composed of subsystems such as water resources, water environment, society, economy, and ecology. The behavior of any subsystem will cause the overall function of the water safety system to play. In this paper, regional water security is regarded as two subsystems of the water system and socio-economic system. There is a dialectical relationship of cooperation and mutual restriction between water resources subsystem and socio-economic system which contains economy, society, and ecological environment. Therefore, based on the principle of availability of index data and operability of methods, the complex relationship of various evaluation factors of regional water security and the water security evaluation index system at home and abroad were fully considered. The evaluation index system of the water security comprehensive index was constructed as shown in **table I**. The index attribute “+” represents that the larger the index, the better; and the index attribute “-” represents that the smaller the index, the better.

TABLE I. REGIONAL WATER SECURITY COMPREHENSIVE EVALUATION INDEX SYSTEM.

Target layer	Criterion layer	Index layer	Index No.	Index trend
Full evaluation (A)	Water resourcesç subsystem (B1)	Rainfall (mm)	x_1	+
		Surface water resources (10^8m^3)	x_2	+
		Groundwater resources (10^8m^3)	x_3	+
		Total water supply (10^8m^3)	x_4	+
		Water resources per capita (m^3/person)	x_5	+
	Society subsystem (B2)	Comprehensive water consumption per capita (m^3/person)	x_6	-
		Population density (person/square kilometer)	x_7	-
		Urbanization rate (%)	x_8	+
		Per capita domestic water consumption of urban residents (L/D)	x_9	-
		Per capita domestic water consumption of rural residents (L/D)	x_{10}	-
	Economy subsystem (B3)	GDP per capita (yuan/person)	x_{11}	+
		Consumption level of residents (yuan)	x_{12}	+
		Water consumption per 10,000-yuan GDP (m^3)	x_{13}	-
		Water consumption per 10,000 yuan of industrial GDP added value (m^3/10,000 yuan)	x_{14}	-
		Irrigation water consumption per area (m^3/hm^2)	x_{15}	-
	Ecology subsystem (B4)	Total wastewater discharge (10^8t)	x_{16}	-
		Daily treatment capacity of urban sewage (10^4m^3)	x_{17}	+
		COD discharge in industrial wastewater (10^4t)	x_{18}	-
		Discharge of ammonia nitrogen in industrial wastewater (10^4t)	x_{19}	-
		Total factor evaluation of water function area compliance rate (%)	x_{20}	+

Determination of water security comprehensive index evaluation grade

According to the connotation of water security, water security is divided into five grades. Grade I indicates that the regional water security is at the safe stage; Grade II indicates that the regional water security is at a good stage; Grade III indicates that the regional water security is at the average stage; Grade IV indicates that the regional water security is at the deterioration stage. Refer to the national environmental quality standards, relevant national ecological and environmental protection assessment standards, advanced level at home and abroad and the average level at home to determine the grading standards of indexes as shown in **table II**. Among them, the first to fifth-grade eigenvalues of water security is assigned as 5, 4, 3, 2, and 1 respectively. The better the water security grade is, the smaller the grade eigenvalue is.

Example application

Overview of the study area and data sources

Guangdong Province is in the south of China. The abundant water resource stock has provided great power for the social and economic development of Guangdong Province. However, with the rapid development of the social economy, the rapid growth of population, water pollution and frequent floods in recent years, water security has become an important factor restricting the sustainable and stable development of the social economy of Guangdong Province. Therefore, in this paper, the water security

TABLE II. THE COMPREHENSIVE EVALUATION STANDARD OF WATER SAFETY.

	Grade I (safety)		Grade II (better)		Grade III (medium)		Grade IV (poor)		Grade V (deterioration)	
	Lower limit	Upper limit	Lower limit	Upper limit	Lower limit	Upper limit	Lower limit	Upper limit	Lower limit	Upper limit
x_1	2210	2450	1970	2210	1730	1970	1490	1730	1250	1490
x_2	2266	2570	1962	2266	1658	1962	1354	1658	1050	1354
x_3	552	620	484	552	416	484	348	416	280	348
x_4	462	480	444	462	426	444	408	426	390	408
x_5	2240	2500	1980	2240	1720	1980	1460	1720	1200	1460
x_6	340	386	386	434	434	482	482	530	530	578
x_7	446	492	492	538	538	584	584	630	630	676
x_8	72.6	77	68.2	72.6	63.8	68.2	59.4	63.8	55	59.4
x_9	167	184	184	201	201	218	218	235	235	252
x_{10}	115	124.4	124.4	133.8	133.8	143.2	143.2	152.6	152.6	162
x_{11}	8.48	10.5	6.46	8.48	4.44	6.46	2.42	4.44	0.4	2.42
x_{12}	24600	30000	19200	24600	13800	19200	8400	13800	3000	8400
x_{13}	18	84.4	84.4	150.8	150.8	217.2	217.2	283.6	283.6	350
x_{14}	10	56	56	102	102	148	148	194	194	240
x_{15}	658	706.4	706.4	754.8	754.8	803.2	803.2	851.6	851.6	900
x_{16}	50	60	60	70	70	80	80	90	90	100
x_{17}	2100	2500	1700	2100	1300	1700	900	1300	500	900
x_{18}	5	10.4	10.4	15.8	15.8	21.2	21.2	26.6	26.6	32
x_{19}	0.1	0.42	0.42	0.74	0.74	1.06	1.06	1.38	1.38	1.7
x_{20}	78	95	61	78	44	61	27	44	10	27

of Guangdong Province was selected as the research object, and it is intended to trace the main influencing factors of water security by analyzing the temporal and spatial vertical changes of water security of Guangdong Province in recent 15 years, to find out the breakthrough to improve the regional water security. The research data were mainly from Guangdong Statistical Yearbook (2004-2019), Guangdong Environmental Statistical Yearbook (2004-2019) and Guangdong Water Resources Statistical Bulletin (2004 - 2019).

Index weight determined based on improved analytic hierarchy process with entropy weight

The questionnaires were designed with the water security and comprehensive evaluation index system. Experts from the Ministry of Water Resources and in water resources management were invited to score according to the importance of the index system, and the weight of the index system was determined by AHP. Then, according to Formulas 1 to 5, in combination with entropy weight, the weight of AHP was improved to calculate the comprehensive weight of each index in the water security evaluation of Guangdong Province. The results are shown in **table III**.

Construct matrix of classical field, segment field and matter-element to be evaluated

The classical field matrix N_{oj} and segment field matrix with Grade I, Grade II, Grade III, Grade IV, and Grade V were constructed according to the data in **table II**. With the normalization of N_{oj} and R_p according to Formula 10 and Formula 11, the new classical field matrix N_{oj} and the segment field matter-element matrix R_p' of the water security composite index were got.

$$N_{oj}' = \left(N_{oj}', C_i, V_o'\right)$$
$$= \begin{vmatrix} N_{oj}' & c_1 & (0.902,1) & (0.804,0.902) & (0.706,0.804) & (0.608,0.0.706) & (0.510,0.608) \\ & c_2 & (0.882,1) & (0.763,0.882) & (0.645,0.763) & (0.527,0.645) & (0.409,0.527) \\ & c_3 & (0.890,1) & (0.781,0.890) & (0.671,0.781) & (0.561,0.671) & (0.452,0.561) \\ & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ & c_{20} & (0.821,1) & (0.642,0.821) & (0.463,0.642) & (0.284,0.463) & (0.105,0.284) \end{vmatrix}$$

$$R_p' = \left(N_p', C_n, V_p'\right) = \begin{vmatrix} N_p' & c_1 & (0,1) \\ & c_2 & (0,1) \\ & \vdots & \vdots \\ & c_n & (0,1) \end{vmatrix}$$

TABLE III. WATER SECURITY COMPREHENSIVE INDEX WEIGHT OF GUANGDONG PROVINCE.

	Revised AHP weight	Deviation degree	Coefficient of difference	AHP weight	Entropy of evaluation index ω_j
x_1	0.9517	0.0483	0.0588	0.0272	0.0254
x_2	0.9517	0.0483	0.0588	0.0878	0.0819
x_3	0.9517	0.0483	0.0587	0.0878	0.0819
x_4	0.9514	0.0486	0.0591	0.0472	0.0443
x_5	0.9517	0.0483	0.0588	0.1334	0.1245
x_6	0.9517	0.0483	0.0588	0.1208	0.1127
x_7	0.9517	0.0483	0.0587	0.0221	0.0206
x_8	0.9516	0.0484	0.0588	0.0392	0.0366
x_9	0.9514	0.0486	0.0591	0.0679	0.0637
x_{10}	0.9517	0.0483	0.0588	0.0434	0.0405
x_{11}	0.9517	0.0483	0.0588	0.0295	0.0276
x_{12}	0.9517	0.0483	0.0588	0.1133	0.1057
x_{13}	0.9516	0.0484	0.0589	0.0654	0.0611
x_{14}	0.9516	0.0484	0.0588	0.0418	0.0390
x_{15}	0.9516	0.0484	0.0588	0.0295	0.0276
x_{16}	0.9517	0.0483	0.0587	0.0420	0.0391
x_{17}	0.9517	0.0483	0.0588	0.0727	0.0678
x_{18}	0.9517	0.0483	0.0588	0.0677	0.0631
x_{19}	0.9517	0.0483	0.0588	0.0677	0.0631
x_{20}	0.9516	0.0484	0.0589	0.1259	0.1178

Took the data of 2019 as an example. The matrix R_{2019} of the matter-element to be evaluated was normalized with Formula 12.

$$R_{2019} = \left(R_{2019}, C_i, V_o'\right) = \begin{vmatrix} N_{2018} & c_1 & 0.814 \\ & c_2 & 0.801 \\ & \vdots & \vdots \\ & c_{20} & 0.511 \end{vmatrix}$$

Calculate the distance between the normalized water security matter-element of Guangdong in 2019 and the normalized classical field matter-element matrix with Formula 13.

$$D_{ij} = \begin{vmatrix} 0.088 & -0.010 & 0.010 & 0.108 & 0.206 \\ 0.081 & -0.037 & 0.037 & 0.156 & 0.274 \\ 0.701 & -0.039 & 0.039 & 0.149 & 0.258 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0.311 & 0.132 & -0.047 & 0.047 & 0.226 \end{vmatrix}$$

Calculate the comprehensive proximity between the water security matter-element and the value in the normalized classical field matter-element matrix of Guangdong Province in 2019 with Formula 14.

$$K_j^{'} = (0.064 \quad 0.082 \quad 0.150 \quad 0.283 \quad 0.439)$$

Calculate and improve the comprehensive proximity and determine the evaluation grade with Formula 16.

$$\overline{K_j(N_x)}' =$$
$$(0.99985 \ 0.99981 \ 0.99964 \ 0.99923 \ 0.99895)$$

According to Formula 17, the water security comprehensive proximity of Guangdong Province in 2019 was Grade I.

Calculate the eigenvalue of the water security comprehensive evaluation index of Guangdong Province in 2019 with Formula 18.

$$j^* = 2.192$$

The eigenvalue of the water security comprehensive evaluation index of Guangdong Province in 2019 was 2.192, which indicates that the water security comprehensive evaluation status of Guangdong Province in 2019 was closer to Grade II, and the water security status will be worse in the future.

RESULTS

All the data of water security of Guangdong Province from 2004 to 2018 can be calculated according to the same method to get the water security comprehensive evaluation index grade of Guangdong Province from 2004 to 2018. In addition, with the four subsystems including water resources, society, economy, and ecology as a single system, in combination with the weight of each index in the subsystems, the grades of the four subsystems of the water security of Guangdong Province from 2004 to 2019 can be obtained as shown in **Table IV**.

DISCUSSION

The above measurement results show that:

1) From the overall development trend, the water security of Guangdong Province was upgraded from Grade V in 2004 to Grade I in 2019. The water security comprehensive evaluation results of Guangdong Province showed a benign change trend, which shows that Guangdong Province has played a relatively significant role in the technical input, policy guarantee and social support effect for improving water security, and it has achieved good results in water resources management in recent years. However, the water security of Guangdong Province was still not optimistic, especially in 2011, 2007, 2005, and 2004, the water security indexes were below the "safe" grade, and the changing trend continued to change to the "medium" grade, indicating that there is still a large space for optimization of water security regulation and control of Guangdong Province.
2) From the perspective of the sub-dimension situation, the water resources subsystem fluctuated greatly from 2004 to 2019, and the water resources subsystem reached Grade I in 2015 and 2016, which is closely related to the abundant rainfall and water resources in the past two years. In 2004, it reached Grade V because the rainfall in 2004 was the lowest among that from 2004 to 2019, and the regional water resources were relatively exhausted. That of other years fluctuated from Grade II to Grade IV, which is strongly correlated with the rainfall in those years. Overall, natural conditions are closely related to the security grade of the water resources subsystem, but human intervention has little impact on the security grade of the water resources subsystem. The society subsystem reached Grade V in 2004, Grade IV from 2005 to 2007, Grade III from 2008 to 2011, Grade IV from 2012 to 2018, and Grade I in 2019, that was maintained for a long time, reflecting that

TABLE IV. WATER SECURITY SUBSYSTEMS AND COMPREHENSIVE EVALUATION RESULTS OF GUANGDONG PROVINCE.

	Water resource	Society	Economy	Ecology	Grade I proximity	Class II proximity	Grade III proximity	Grade IV proximity	Grade V proximity	Comprehensive grade	Characteristic value
2019	3	1	1	1	0.99895	0.99981	0.99964	0.99933	0.99985	1	2.192
2018	3	2	1	2	0.99910	0.99983	0.99974	0.99946	0.99976	2	2.297
2017	3	2	1	4	0.99931	0.99994	0.99988	0.99977	0.99969	2	2.547
2016	1	2	2	2	0.99880	0.99994	0.99974	0.99939	0.99983	2	2.297
2015	1	2	2	4	0.99935	0.99980	0.99988	0.99969	0.99951	3	2.705
2014	4	2	2	4	0.99897	0.99973	0.99987	0.99977	0.99942	3	2.704
2013	2	2	3	4	0.99931	0.99983	0.99984	0.99964	0.99956	3	2.575
2012	3	2	3	4	0.99942	0.99977	0.99989	0.99975	0.99945	3	2.931
2011	4	3	3	4	0.99961	0.99958	0.99980	0.99986	0.99925	4	3.541
2010	3	3	3	3	0.99942	0.99979	0.99994	0.99979	0.99945	3	2.954
2009	4	3	4	3	0.99956	0.99968	0.99994	0.99991	0.99931	3	3.396
2008	2	3	4	3	0.99942	0.99976	0.99986	0.99975	0.99945	3	2.951
2007	4	4	4	4	0.99971	0.99953	0.99983	0.99997	0.99916	4	3.640
2006	2	4	4	3	0.99951	0.99965	0.99980	0.99972	0.99936	3	3.300
2005	3	4	4	3	0.99971	0.99952	0.99985	0.99988	0.99915	4	3.627
2004	5	5	5	3	0.99987	0.99930	0.99964	0.99985	0.99895	5	3.837

the sustainable development level of the society subsystem is relatively stable, and the overall trend is getting better and better. The economy subsystem reached Grade V in 2004, Grade IV from 2005 to 2009, Grade III from 2008 to 2013, Grade IV from 2014 to 2016, and Grade I from 2017 to 2019, and the overall change trend has been improving in recent years, indicating that the economic development of Guangdong Province is rapid, and the sustainable development ability of the economy subsystem has been also greatly improved. The ecology subsystem fell into Grade III and IV in more than 80% of years, fluctuated between Grade III and IV from 2004 to 2015, and even maintained at Grade IV from 2011 to 2015, indicating the deterioration of the water security ecosystem in recent years. In 2016, the ecology was improved to Grade II, but it deteriorated to Grade IV in 2017. In 2018, it was improved to Grade II, and then to Grade I in 2019. Overall, the relevant policies for water pollution control of Guangdong Province played a certain effect from 2004 to 2019. The pollution of Guangdong Province was effectively controlled, the ecology quality and urban appearance were significantly improved, and the water security ecology subsystem showed a trend of improvement. However, there were still repeated problems in the process, and the improvement effect was not stable.

3) From the perspective of the application of the model, the results of the water security quantitative evaluation of Guangdong Province with the water security index evaluation model based on comprehensive weight and improved matter-element model, are basically consistent with the analysis of water resources and utilization trend in the *Guangdong Water Resources Statistical Bulletin* (2004 – 2019), and consistent with the historical and actual development of water resources and their management of Guangdong Province, which shows that the model is reasonable and operable.

CONCLUSION

In this paper, based on the matter-element model, the regional water security comprehensive evaluation index system was constructed with the integration of the regional water resources, society, economy, ecology, and other indexes, and the water security comprehensive evaluation model based on comprehensive weight and improved matter-element was constructed too. Moreover, the vertical time measurement and future trend of the water security index of Guangdong Province were discussed in combination with the actual data of Guangdong Province. According to the measurement results, the model overcomes the defects of absolute subjectivity and objectivity of index weight; after consideration of the actual data of water security and the national standards, the comprehensive evaluation grade standard of water security is more reasonable; in addition, the application scope of the normalized matter-element model is wider, and the obtained grade of water security comprehensive evaluation index is more accurate than that with the conventional method, which can better reflect the actual situation and future development trend of regional water security. As a result, the algorithm of the water security comprehensive evaluation model based on comprehensive weight and improved matter-element is simple, practical, and suitable for the multi-level and multi-factor regional water security comprehensive evaluation.

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AUTHOR CONTRIBUTIONS

Conceptualization: Ying juan YANG, Hui feng XUE. Data curation: Ying juan YANG. Model analysis: Ying juan YANG, Haiqing HU. Investigation: Ying juan YANG, Hui feng XUE. Methodology: Ying juan YANG, Haiqing HU, Hui feng XUE. Project administration: Haiqing HU. Resources: Hui feng XUE. Visualization: Ying juan YANG. Writing – original draft: Ying juan YANG Haiqing HU. Writing – review and editing: Haiqing HU

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