Genetic algorithm based combined evaluation model for regional water security evaluation: a case study

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Abstract The water security crisis is one of the most serious challenges facing sustainable water development in the world. The North River basin in Guangdong Province of China is one such area facing a water security crisis. The case study in the North River basin applied a novel Combined Evaluation Model based on Genetic Algorithm (CEM-GA) developed for regional water security evaluation. The study method considered the pros and cons of both the subjective and objective weighting evaluation methods, and integrated four single evaluation methods with the Minimizing Difference Degree Model based on Nash Equilibrium in Game Theory and Genetic Algorithm as the coordinated objective function. The case study of the North River basin illustrated the results of this methodology. The results suggest that CEM-GA, as a practical method, can be widely used for the quantitative evaluation and comparison of water security status in different regions.

Key words water security; combined evaluation model; genetic algorithm; Nash equilibrium; Minimization Difference Degree Integration Model

INTRODUCTION

Water, one of the most important natural resources, is widely considered as the key to human health and wealth (Johnson *et al.*, 2001; Brown, 2002). Water security, affected by natural factors as well as human actions, has increasingly become a major threat to food security, human health, economic development and natural ecosystems on a global level (Rockström, 2000; Xia *et al.*, 2006). Water security evaluation bridges water security scenario analysis and water strategic decision-making. Hence the study of precise and practical regional water security evaluation methods is the foundation of regional water resources management and planning (Lundqvist *et al.*, 2000).

The crux of water security evaluation is to determine the weights of the evaluation indicators. The existing weighting methods mainly consist of two categories: (1) the subjective weighting methods and (2) the objective weighting methods (Gu, 1990). The limitation of each weighting method, as well as each single comprehensive evaluation method, can not be neglected. Under this backdrop, a combined evaluation concept was conceived. This novel method mainly focuses on the reinforcement of the merits of each single evaluation method to fully explore the feature information of the evaluation objective from different angles (Gregory, 1996; Tang, 2001).

The purpose of this study is to set up a combined model for regional water security evaluation based on Nash Equilibrium in Game Theory and Genetic Algorithm to solve problems of subjective and objective weighting methods, as well as defects of single evaluation methods. Further, stability and sensibility analysis on this combined model, significant for water security evaluation in ungauged basins, is also discussed.

METHODOLOGY OF THE CEM-GA

The standard processing of the evaluation indicator sample data

Define $\{x^*(i,j)\}$ (i ranges from 1 to m, j ranges from 1 to n) as the evaluating object vector sample set, where $x^*(i,j)$ is the jth evaluation indicator value of the ith evaluating object vector, m and n are the numbers of the evaluating object vector and indicators, respectively.

The standard processing of the original evaluation sample series should be implemented to eliminate the influences of the units and dimension of the evaluation sample series. Use equation (1) for the effective-type evaluation indicators (the bigger the better), and equation (2) for the cost-type evaluation indicators (the smaller the better).

$$x(i,j) = x^*(i,j) / x^*_{\max}(j) \tag{1}$$

$$x(i,j) = x^*_{\min}(j) / x^*(i,j) \tag{2}$$

where, $x^*_{\min,j}$ and $x^*_{\max,j}$ are the minimum and maximum of the jth indicator in sample series, and $x^*(i,j)$ is the unified effective-type indicator value.

Selecting the comparable evaluation method set *M*

Several comparable comprehensive evaluation methods should be selected. Weights of indicators, on the one hand, reflect the bias of the decision-maker (the subjective aspect), and on the other hand, present the various importance of each indicator value during decision-making (the objective facet). Therefore, the Genetic Algorithm improved Projection Pursuit (GAPP), Ideal Solution Point Method (TOPSIS), Fuzzy Comprehensive Evaluation (FCE) and Analytic Hierarchy Process (AHP) evaluation methods are selected as the comparable evaluation method set. The former two methods, belonging to objective weighting method, can explore the whole information diversity of the evaluation indicators of different evaluating object vectors; and the latter two methods, belonging to subjective weighting method, can reflect the local diversity information of the evaluation indicators of the same evaluating object vector:

$$M = \{m_1, m_2, \cdots, m_l\} \tag{3}$$

where l is the number of compatible evaluation methods, and l equals 4 in this research.

The determination of the compatible evaluation method set M_1

(a) Implement the four selected comparable evaluation methods within the comparable evaluation method set M to evaluate the relative evaluation indicator values of each evaluating object vector $x(i,j)$, and the comprehensive indicator value vector of each evaluating object vector $Z(i,p)$ (where i ranges from 1 to m, and p ranges from 1 to l), can be calculated by equation (4). The detailed calculation process can be referred in the literature concerned (Friedman & Turkey, 1974; Saaty, 1980; Chen & Hwang, 1992; Ozernoy, 1992).

$$Z(i,p) = \sum_{j=1}^{n} w(j,p)x(i,j) \quad i = 1 \sim m, j = 1 \sim n, p = 1 \sim l \tag{4}$$

where $Z(i,p)$ is the comprehensive indicator value of the ith evaluating object vector with the pth method, $w(j,p)$ is the weight of the jth indicator with the pth method and l is the number of the selected comparable methods.

(b) Apply Fuzzy Clustering Analysis (FCA) to the evaluation comprehensive indicator value vector, $Z(i,p)$; then divide the comparable evaluation method set M into two groups with the fixed threshold value ξ: the first group is only one vector $Z(i,k)$ (where k belongs to the interval of $[1,l]$), and the other group is the remaining other methods except $Z(i,k)$.

(c) Calculate the mean vector of the second evaluation group $MZ(i)$, by equation (5):

$$MZ(i) = \left[\sum_{p=1, p\neq k}^{l} Z(i,p) \right] / (l-1) \quad i = 1 \sim m, p = 1 \sim l \tag{5}$$

Then calculate the correlation coefficient of $Z(i,k)$ and $MZ(i)$ by equation (6):

$$r_{z,mz} = \frac{\sum_{i=1}^{n}(Z(i,k)-\overline{Z(i,k)})(MZ(i)-\overline{MZ(i)})}{[\sum_{i=1}^{n}(Z(i,k)-\overline{Z(i,k)})^2\sum_{i=1}^{n}(MZ(i)-\overline{MZ(i)})^2]^{0.5}} \quad (6)$$

And the compatibility between the kth evaluation method and the other remaining methods can be obtained through testing the correlation of $Z(i,k)$ and $MZ(i)$ using equation (6) with the required significance level.

(d) If the testing result presents significant correlation between $Z(i,k)$ and $MZ(i)$, the selected l comparable methods are compatible with each other, that is to say, M is the compatible method set M_l; otherwise, the kth evaluation method is the incompatible method from M, and should be excluded from the group. Then implement these steps narrated above to the remaining methods, and the compatible method set M_l can be obtained as equation (7).

$$M_l = \{m_1, m_2, \ldots, m_q\} \quad (7)$$

where q is the number of selected compatible evaluation methods.

The establishment of the combined comprehensive evaluation indicator function

The combined comprehensive evaluation indicator function can be set up as equation (8).

$$ZZ(i) = \sum_{p=1}^{q} a(p)Z(i,p) \quad i = 1 \sim m, p = 1 \sim q \quad (8)$$

where $ZZ(i)$ is the combined comprehensive evaluation indicator of the ith evaluating object vector, $a(p)$ is the weight of the pth evaluation method, and q is number of selected compatible evaluation methods.

The establishment of the minimizing difference degree integration model based on Nash equilibrium of game theory

The competitive and yet coordinative relationship between different evaluation methods can be analysed through Game Theory, and Nash Equilibrium can be applied into the integration model of single evaluation methods as the coordinative objective. Hence the optimal value of $a(p)$ can be solved from equation (9). The optimization objective for this problem is to minimize the Difference Degree of the results of selected single evaluation methods within the M_l set and the combined comprehensive evaluation indicator value.

$$\begin{cases} Minf(a) = \sum_{i=1}^{n}\sum_{p=1}^{q}\|Z(i,p)-ZZ(i)\|_2 \\ s.t.\sum_{p=1}^{q}a(p)=1, a(p)\geq 0, \end{cases} \quad (9)$$

This is a complicated nonlinear optimal problem with $a(p)$ as the optimal variables, and it is difficult to be solved by general approaches. Real coding Accelerating Genetic Algorithm (RAGA), as an overall optimal method, can easily solve this optimal problem (Jin & Ding, 2000).

The ranking evaluating results of the combined evaluation model

Apply the optimal weight vector $a^*(q)$ into equation (8), and the combined evaluation indicator values of evaluating object vector $ZZ^*(m)$ can be obtained. Then rank the $ZZ^*(m)$ values, and the ranking results of the evaluating object vector sample can be obtained.

A CASE STUDY

The lower reaches and the delta region of the North River, with an area of 32 000 km^2 and a population of 835 940 000, is one of the socio-economically robust regions in Guangdong Province in China. Water security, reflecting water availability in terms of quality and quantity, has become one of the key factors challenging the sustainable socio-economic development in this region.

The indicator system for water security evaluation in the North River basin is established based on the Pressure-State-Response (P-S-R) framework and its application in selecting indicators for sustainability assessment (OECD, 1993). The P-S-R mechanism for regional water security assessment can be obtained and is shown in Fig. 1. The indicator system and the indicator values of the status quo and the planning level years are presented in Table 1.

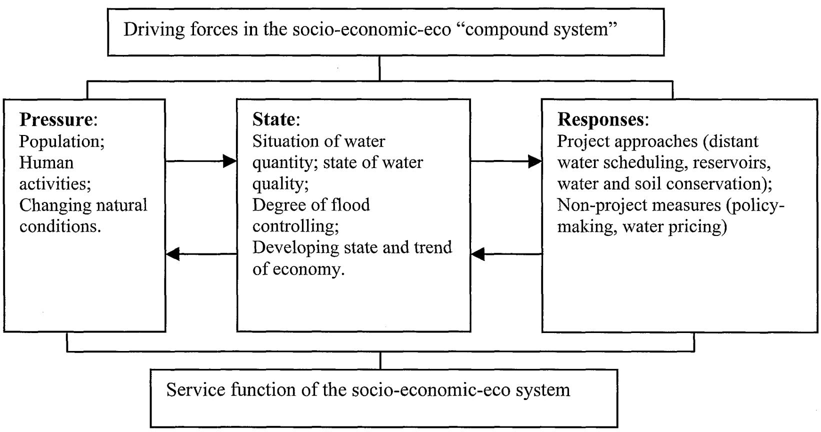

Fig. 1 The Pressure-State-Response (P-S-R) framework for regional water security assessment.

Table 1 the evaluation indicator values of water security situation in North River basin of the year of the status quo and the planning level years.

Time Indicator	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
I_1	1	0.9678	0.9485	1	1	1	1	1	1	0.9808	0.9763
I_2	1	0.9347	0.893	1	1	1	1	1	1	0.9565	0.9454
I_3	1	1	1	1	1	1	1	1	1	1	1
I_4	0.0188	0.0181	0.0168	0.0156	0.0147	0.0137	0.0112	0.0085	0.0075	0.0066	0.0063
I_5	0.4906	0.5553	0.6832	0.9369	1	1	1	1	1	1	1
I_6	0.3092	0.3194	0.3449	0.3513	0.3522	0.355	0.3672	0.3879	0.4141	0.4484	0.492
I_7	0.1079	0.0894	0.0835	0.0854	0.0655	0.0602	0.0551	0.0513	0.0516	0.0472	0.0466
I_8	0.0059	0.0077	0.0082	0.0046	0.0023	0.0031	0.0040	0.0047	0.0046	0.0055	0.0056

I_1: ratio of industrial water supply (%); I_2: ratio of agricultural water supply (%);
I_3: ratio of ecological water supply (%); I_4: ratio of flood disaster loss (%);
I_5: over-standard ratio of released water (%); I_6: utilization ratio of water resources (%);
I_7: GDP ratio of increase (%); I_8: proportion of investment on water resources construction (%).

Implement the selected four comparable comprehensive evaluation methods to the water security evaluation indicator sample series in Table 1, and the comprehensive indicator value vector $Z(11,4)$ and the ranking results are shown in Table 2.

Then carry out Fuzzy Clustering Analysis to the four evaluation vectors in Table 2, then with the required threshold value of ξ (ξ equals to 0.95), divide it into two groups. The first group is

Table 2 the comprehensive indicator value vector of water security situation in North River basin of the year of the status quo and the planning level years with four comparable evaluation methods.

year	GAPP		TOPSIS		FCE		AHP	
	Indicator values	Ranking results	Indicator values	Ranking results	Indicator values	Ranking results	Indicator values	Ranking results
2000	0.5350	11	0.3635	10	0.1621	11	0.6725	10
2005	0.5600	10	0.3620	11	0.4352	8	0.6695	11
2010	0.6130	9	0.3665	9	0.3368	10	0.6870	9
2015	0.7425	8	0.4231	6	0.4251	9	0.7405	1
2020	0.7590	6	0.3895	8	0.4668	7	0.7155	8
2025	0.7570	7	0.3925	7	0.5986	5	0.7165	7
2030	0.7695	5	0.4365	5	0.6125	4	0.7201	5
2035	0.7710	3	0.532	4	0.5698	6	0.7265	2
2040	0.7735	1	0.9951	2	0.7521	3	0.7175	6
2045	0.7700	4	0.754	3	0.9421	1	0.7245	3
2050	0.7720	2	0.9963	1	0.8655	2	0.7225	4

the evaluation vector of GAPP, $Z(11,1)$ equals to (0.5350, 0.5600, 0.6130, 0.7425, 0.7590, 0.7695, 0.7710, 0.7735, 0.7700, 0.7720, 0.7710), and the second group is the remaining three evaluation vectors. Then through equation (5), calculate the mean vector of the second evaluation group MZ (11), MZ (11) equals to (0.4302, 0.5067, 0.5008, 0.4751, 0.5827, 0.6157, 0.6347, 0.6498, 0.8096, 0.8391, 0.8381); and then apply equation (6) to calculate $r_{z,mz}$, the correlation coefficient of $Z(11,1)$ and MZ (11). In this case study, $r_{z,mz}$ equals to 0.869 and is larger than $r_{0.01}$ ($r_{0.01}$ equals to 0.735 with the sample volume of 11); hence the GAPP evaluation method is compatible with the three other methods, and the compatible evaluation method set M_1 contains PP, TOPSIS, FCA and AHP.

Then the Minimizing Difference Degree Integration Model of evaluation methods can be defined as follows:

$$\begin{cases} Minf(a) = \sum_{i=1}^{11} \sum_{p=1}^{4} \left\| Z(i,p) - ZZ(i) \right\|_2 \\ s.t. \sum_{p=1}^{4} a(p) = 1, a(p) \geq 0 \end{cases}$$

Apply RAGA to solve this optimization problem, and the optimal weight vector $a^*(4)$ can be obtained: $a^*(4)$ equals to (0.3120, 0.2963, 0.1952, 0.1965); then put $a^*(4)$ into equation (8), and the combined comprehensive evaluation indicator values of water security situation in North River basin from 2000 to 2050, $ZZ^*(11)$, can be obtained. The comprehensive evaluation indicators results, as well as the final ranking results of the water security situation in the North River basin from 2000 to 2050, are presented in Table 3.

The result in Table 3 shows that the water security level after implementation of water resources planning gradually increases in the course of the planning level years. Therefore, it proves that CEM-GA can be effectively used for qualitative analysis and quantitative evaluation of water security level of a single region, as well as for comparison of different regions.

Table 3 The Combined Comprehensive Evaluation Indicator (CCEI) values and the final rank of water security situation in North River basin of the status quo and the planning level years.

Time (year)	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
CCEIV	0.4627	0.5600	0.5356	0.5580	0.6374	0.6595	0.6765	0.6770	0.6881	0.7973	0.8183
Final rank	11	8	10	9	7	6	5	4	3	2	1

CCEIV: Combined Comprehensive Evaluation Indicator Value.

DISCUSSIONS

About the selection of regional water security comprehensive evaluation indicators

Selection of regional water security evaluation indicators is the first and also one of the key steps of the whole modelling process. The P-S-R framework was applied in setting up an indicator system in the case study of the North River basin. However, the selection process of the eight indicators was still quite qualitative, due in part to the limitations of the available data.

A large quantity of indicators from various driving forces can be available if full-scale and detailed data material is accessible. Hence it could be a demanding job to establish an optimal evaluation indicator system, since this involves both qualitative and quantitative "evaluation" of each indicator. Theoretical research and case studies of this problem require further study.

About the sensitivity of standardization method of the evaluation sample series

In theory, standardization processing for the evaluation indicator sample series is very important; however, it is more or less neglected in practice. Three common linear standardization methods are Maximum-and-Minimum method, Difference of Maximum and Minimum method and Mean value method, and the calculation expressions are presented in equation (10), (11) and (12), respectively.

$$\begin{cases} x(i,j) = x^*(i,j)/x^*_{\max}(j) \\ x(i,j) = 1.0 - x^*(i,j)/x^*_{\max}(j) \end{cases} \tag{10}$$

$$\begin{cases} x(i,j) = (x^*(i,j) - x^*_{\min}(j))/(x^*_{\max}(j) - x^*_{\min}(j)) \\ x(i,j) = 1.0 - (x^*(i,j) - x^*_{\min}(j))/(x^*_{\max}(j) - x^*_{\min}(j)) \end{cases} \tag{11}$$

$$\begin{cases} x(i,j) = x^*(i,j)/\overline{x}(j) \\ x(i,j) = 1.0 - x^*(i,j)/\overline{x}(j) \end{cases} \tag{12}$$

In the case study of the North River basin, the sensitivity of the indicator standardization procedures is influential to the evaluation precision for Genetic Algorithm improved Projection Pursuit method (GAPP). The three standardization methods mentioned above were applied into the Projection Pursuit evaluation method to further study of the regulation of this problem, and the experimental error results of the three methods are shown in Table 4.

Table 4 Comparison error results of the three general standardization methods on GAPP.

	PEAV (%)				PERV (%)				AAE	ACE
	[0~0.1]	[0~0.2]	[0~0.25]	[0~0.3]	[0~0.04]	[0~0.07]	[0~0.09]	[0~0.15]		(%)
Equation(10)	42.01	61.52	71.12	100	40.42	61.65	86.04	99.63	0.17	4.13
Equation(11)	5.63	15.96	36.85	40.21	3.65	10.53	22.63	30.36	0.45	17.85
Equation(12)	12.65	43.35	58.21	71.32	13.65	32.63	42.30	61.85	0.33	9.63

PEAV: Percentage of Absolute Error Values within the intervals;
PERV: Percentage of Relative Error Values within the intervals;
AAE: Average Absolute Error; ACE: Average Relative Error.

In analysis, equation (11) enlarges the comparative differences among the original indicator sample series. Therefore, it greatly changes the data structure feature of the indicator sample series, hence resulting in lower precision of the evaluation model than the other two equations.

About the stability of the integration method for the Combined Evaluation Model

The stability experimental study on the result of this integration model was designed as follows: choose four major indicators, namely, GDP ratio of increase, over-standard ratio of released water, utilization ratio of water resources and flood disaster loss ratio, to implement the result of sensitivity with the designed change rate of ±10% of each indicator sample series. Table 5 presents the results.

Table 5 The stability experimental results on the result of CEM-GA.

Indicator Selected	Change (%)	Change rate of the comprehensive indicator values *ZZ*(*i*) of 11 evaluation years of North River basin (%)										
		2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
IS_1	10	−1.32	−3.20	−1.63	0.96	−2.85	−2.74	−1.96	−1.32	−1.85	−2.63	−1.08
	−10	2.01	1.36	2.12	1.63	2.63	1.78	1.96	0.85	1.36	1.64	1.29
IS_2	10	1.22	1.36	1.88	1.02	1.74	1.66	1.59	1.89	2.01	2.03	1.65
	−10	−1.01	−1.36	−1.42	−1.50	−2.18	0.99	−2.09	−1.85	−1.47	−1.63	−2.07
IS_3	10	2.63	2.85	3.01	2.45	2.87	1.99	2.46	3.05	2.03	3.12	3.78
	−10	−2.78	−2.60	−2.11	−3.01	−2.96	−2.17	−3.00	−1.99	−2.65	−2.18	−2.09
IS_4	10	−5.56	−3.96	−4.56	−4.01	−3.01	−4.12	−2.96	−5.56	−2.64	−4.87	−3.65
	−10	4.63	3.78	3.41	3.10	3.85	4.14	4.69	2.99	3.18	3.89	4.67

IS_1: GDP ratio of increase; IS_2: over-standard ratio of released water;
IS_3: utilization ratio of water resources; IS_4: flood disaster loss ratio.

As shown in Table 5, the biggest change rate of the comprehensive indicator value ZZ(*i*) is 4.69%, and the smallest is 0.96%, with the designed change rate of ±10% of each indicator sample series. The favourable stability of the combined evaluation model is largely attributed to the combined effect of decreasing evaluation risks and the integration of the Genetic Algorithm characterized by its excellent self-adaptation, fault-tolerance and robustness. This feature can be significant for water security evaluation in ungauged basins: indicator values through analogy from neighbouring regions can still work on this model with the inaccuracy to some tolerable degree, and the evaluation could still be applicable and constructive for further analysis and study.

CONCLUSIONS

At a global level, water security is emerging as one of the highest priorities on the development agenda. In this study, a Combined Evaluation Model for regional water security evaluation was set up to use both subjective requirements of decision-maker and objective evaluation information. The results of the case study of the North River basin in South China suggest that CEM-GA combines information on both subjective and objective weights, hence objective evaluation information and the requirements of the decision-maker can be well balanced. Besides, the favourable stability of the combined evaluation model presents great significance for water security evaluation in ungauged basins. Therefore this model can be extensively applied into water security evaluation of various regions.

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