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Basin water environmental safety assessment based on fuzzy comprehensive evaluation method: a case study

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ABSTRACT

Assessing water environmental safety is important to safeguard sustainable development of social economic and ecological environment in Raohe river basin. In this study, based on the theory of assessing water safety, considering social indicators, economic indicators, resource indicators, environmental pressure indicators, environmental protection indicators and environmental status indicators, we select 20 indicators to establish reasonable indicator system and use fuzzy comprehensive evaluation method to assess water safety situation of Raohe river basin in a long time sequence from the year 2005 to 2016. We divide the security level into five degrees: very safe, safe, basically safe, unsafe and dangerous; get the evaluation results from degree of membership of these five security levels; and then analyze the trends of water environmental safety. The evaluation results show that water environment of Raohe river basin is in basically safe degree.

Keywords: Raohe river basin; Water safety; Index system; Fuzzy comprehensive evaluation

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1. Introduction

Water resource is a restrictive factor to sustainable development of human society. Water environmental safety has been one of main restrictive factors to social economic development in the watershed. The basin water environment is closely related to natural geographical conditions, hydrometeorological conditions, water quality, form of river and lake, and other natural characteristics. It is also directly affected by the social attributes of human activities such as economic development, production and life style in the basin. Therefore, the abovementioned factors are required to be considered to assess the basin water environment safety. Water environment system is a large and complex system. Assessing its safety situation need a practical index system to be established [1–4]. The researchers should get the accurate data of indexes and identify the capacity of them according to the specific conditions of the researching region.

At present, research of water environmental safety mainly focuses on two fields. The first researching field is to study relationship between water environment and society, economics, ecology [5–8]. The second researching field is constructing or applying water environmental evaluation system [9,10]. Khorramshahgol and Moustakis [11] studied Delphic hierarchy process. Jiang and Si [12] applied a new assessment method in Luanhe-Tianjin Water Diversion Project. The information entropy theory was introduced to combine the traditional analytic hierarchy process and fuzzy comprehensive assessment method to establish a fuzzy AHP-IE comprehensive assessment model [12]. Han et al. [13] adopted the entropy method to confirm the weight of environmental index and applied in the water security assessment in several provinces of China. Jin et al. [14] adopted accelerating genetic algorithm based on fuzzy analytic hierarchy process to screen the index and established a Connection Number assessment

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model to assess water security of Chaohu Lake watershed. By combining sensitivity analysis and correlation analysis of the indicators, Yang et al. [15] put forward a new method to determine the weight of assessing index and applied into a case of Baiyangdian Lake. Zhang et al. [16] studied the method of Improved Analytical Hierarchy Process for weight determining to index system of water environment security evaluation. Tang and Zheng [17] adopted fuzzy recognition theory to establish a model to evaluate the water security in Dalian. Wang et al. [18] assessed the water healthy risk in Luojiaying area of Dianchi lake by HRA model.

Because of the different characteristics of each basin, the evaluation content, the index system and the calculation method of water environment safety are different. The traditional evaluation method is more arbitrary when determining the weight of the index. The fuzzy comprehensive evaluation method has good reliability. In order to determine the main influencing factors of water environment safety, and provide a basis for formulating reasonable measures for water pollution prevention and control, it is necessary to establish a simple and practicable water environment safety evaluation system and method. In the evaluation system fields, the fuzzy comprehensive evaluation method is widely applied in water environment safety assessment [12,15,16].

There are five main river basins, including Raohe river basin, in Jiangxi province of China. The research region Raohe river basin is in the north-east Jiangxi province which has the area of 15,300 km^2 and an annual average runoff of 10.76 billion m^3. The climate is mild and annual rainfall is approximately 180–1,900 mm. Most of the rain is received between April and June.

The main pollutants in Raohe river are NH_3-N, TP and dissolved oxygen. Seriously polluted sectors focus around the riverside cities, especially the downstream cities in which an industry is located. There are two main problems of water environment in Raohe river basin. The first problem is that rainfalls distribute temporal uneven, it often leads torrential flood to damage farmland and riverside villages. The second problem is the non-point source pollution that is mainly caused by large quantities of pesticide and fertilizer use, industrial sewage discharged by mining industry and other industries that lead to indexes of water environment far beyond the limit.

2. Methodology

2.1. Construction of assessment index system

2.1.1. Criterion for indexes selection

The fuzzy comprehensive evaluation method is used in the study. The indexes for assessing water environment safety mainly have one or more of the following features. First, the variety of indexes can cause variety of water environment accordingly, such as fertilizer use intensity; second, indexes can reflect regional differentiation, such as urbanization; third, the indexes must be available.

2.1.2. Construction of index array

According to the criterion, 20 indexes are selected in the study. The index system has three classes: class I contains 1 index, class II contains 4 indexes and class III contains 20 indexes, which is shown in Table 1. 20 indexes of class III are relatively independent. The index system can be expressed by array U, $U = \{u_1, u_2, u_3, \ldots, u_{20}\}$. Table 2 lists the values of these 20 indicators in Raohe river basin between the year 2005 and 2016.

Table 1
Construction of assessment index system

Class I	Class II	Class III
Water Environment Safety	Society	Density of population
		Urbanization rate
	Economics	GDP per capita
		Peasant's net income per capita
		Ratio of industrial added value to GDP
		Meat output
		Fruits output
	Resources	Water resource per capita
		Basin annual average runoff
		Arable land per capita
		Ratio of irrigated area to cultivated land area
	Environment	Annual sediment delivery modulus
		Ratio of ecological protection area to territory area
		Ratio of environmental protection investment to GDP
		Fertilizer use intensity
		Sewage discharge per unit industrial added value
		COD discharge per unit industrial added value
		NH_3-N discharge per unit industrial added value
		Fresh water consumption per unit industrial added value
		Irrigation water consumption per unit area

Table 2
Values of the 20 indicator in Raohe river basin during the year 2005–2016

	Year											
	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Density of population (per km^2)	213	217	221	224	226	230	232	235	237	239	240	242
Urbanization rate (%)	30.6	31.1	31.2	31.6	30.4	34.3	34.8	36.0	37.3	38.1	39.4	40.8
GDP per capita (10^3 yuan RMB)	10.8	14.1	15.7	20.0	17.2	18.1	20.7	23.4	25.6	28.9	31.1	34.47
Peasant's net income per capita (yuan RMB)	1920	2,215	2,344	2,681	2,911	3,312	3,367	4,431	5,213	6,194	7,038	8,127
Ratio of industrial added value to GDP (%)	38.0	41.1	43.2	45.7	50.2	53.1	54.9	57.6	56.1	57.3	56.7	57.3
Meat output (10^3 ton)	85.4	80.6	84.4	104.8	116.1	123.7	129.2	127.7	128.5	130.4	129.6	130.9
Fruits output (10^3 ton)	16.66	15.87	17.60	18.63	18.53	18.43	20.52	22.87	21.84	22.17	23.41	22.96
Water resource per capita (10^3 m^3)	4.02	4.16	4.18	4.12	3.70	5.19	3.61	5.35	4.69	4.38	5.10	4.96
Basin annual average runoff (km^3)	6.73	6.96	6.49	11.12	10.10	19.64	10.09	17.66	11.43	13.67	19.80	16.73
Arable land per capita (hm^2)	0.098	0.097	0.097	0.095	0.094	0.092	0.092	0.091	0.090	0.089	0.088	0.088
Ratio of irrigated area to cultivated land area (%)	92.4	93.9	89.5	88.8	90.6	93.4	92.9	94.3	93.6	94.2	94.6	94.3
Annual sediment delivery modulus (ton/km^2)	20.6	26.9	26.8	28.3	29.5	21.8	24.5	23.5	26.1	25.8	24.3	23.6
Ratio of ecological protection area to territory area (%)	13.5	13.5	13.5	15.8	15.8	15.8	16.7	16.7	16.7	17.9	17.9	17.9
Ratio of environmental protection investment to GDP (%)	2.4	2.9	3.2	3.5	2.8	2.6	2.8	2.2	2.7	2.6	2.9	2.7
Fertilizer use intensity (10^3 ton)	48.0	52.0	47.8	50.6	49.1	49.0	54.1	55.3	52.6	57.4	55.9	56.5
Sewage discharge per unit industrial added value (ton/10^3 yuan RMB)	3.90	4.15	4.68	4.34	4.04	4.30	3.86	3.71	3.58	3.67	3.41	3.36
COD discharge per unit industrial added value (ton/10^3 yuan RMB)	8.05	7.49	7.86	7.42	6.14	5.74	4.07	3.67	3.15	2.89	3.06	2.64
NH_3-N discharge per unit industrial added value (ton/10^6 yuan RMB)	248	234	228	213	221	216	215	199	176	168	162	154
Fresh water consumption per unit industrial added value (ton/10^6 yuan RMB)	1.51	1.48	1.39	1.38	1.27	1.31	1.22	1.19	1.11	1.08	1.05	1.02
Irrigation water consumption per unit area (10^3 m^3/ha)	68.47	72.39	88.26	84.53	80.58	81.88	87.01	82.96	79.24	78.13	78.69	77.58

2.2. Construction of fuzzy weight array of assessment index

Calculation of the status value of single index:

$$P_i = \frac{C_i}{S_i} \tag{1}$$

C_i is the measured value of the index and S_i is the extreme value of them.

In this step, the indexes are non-dimensionalized, so they can be compared late.

The weight of each index to upper class II index could be calculated with Eq. (2).

$$a_i = \frac{P_i}{\sum_{i=1}^{20} P_i} \tag{2}$$

The elements in array U have different degrees of importance in the assessment. So different weight of them according to their degrees of importance must be given. In the fuzzy comprehensive evaluation method, a_i essentially represents the importance to evaluation object. In this step, the indexes are normalized to get the weight of each index. The index weights array A is established:

$$A = \{a_1, a_2, \ldots, a_{20}\}, a_i \geq 0 \text{ and } \sum_{i=1}^{20} a_i = 1 \tag{3}$$

In year 2005, as an example, A = {0.0379, 0.0446, 0.1154, 0.0874, 0.0379, 0.0573, 0.0656, 0.0668, 0.1105, 0.0483, 0.0386, 0.0377, 0.0109, 0.0079, 0.0117, 0.0371, 0.0379, 0.0379, 0.0552, 0.0536}.

2.3. Construction of evaluation matrix

2.3.1. Establishment of evaluation array V

For every 21 indexes, we select the extreme value as reference value and trisect the difference of two extreme values. These three parts and two extreme values form five degrees of index. So, the values of array V are I, II, III, IV and V. These five values correspond, respectively, to five water safety degrees: very safe, safe, basically safe, unsafe and dangerous.

$$V = \{v_1, v_2, v_3, v_4, v_5\} \tag{4}$$

Taking the index of per capita water resource (m^3) as an example, the extreme values of the index listed in Table 1 are 0.361 and 0.709. The difference between them is 0.348. Dividing 0.348 by 3 is 0.116. Therefore, the five degrees of this index can be classified according to Table 3.

2.3.2. Construction of single index assessment matrix R

There are several types of membership function in the fuzzy mathematics, such as linear function, trapezoidal function, lower semi-trapezoidal function and so on. According to the indexes we selected, we choose the function below.

$$F(x) = \begin{cases} r_{ij} = \dfrac{x - a_i}{a_{i+1} - a_i} \\ r_{i(j+1)} = \dfrac{a_{i+1} - x}{a_{i+1} - a_i} \end{cases} \qquad a_i \leq x \leq a_{i+1} \tag{5}$$

According the results from Eq. (4), the single index evaluation array R_i is established.

$$R_i = \{r_{i1}, r_{i2}, r_{i3}, r_{i4}, r_{i5}\} \tag{6}$$

There are five factors in R_i correspond, respectively, to five water safety degrees. Value i varies from 1 to 20. From the fuzzy mapping, the fuzzy relationship from array U to array V can be deduced.

$$R \in F(U \times V) \tag{7}$$

It also can be expressed by

$$(u_i, v_i) = f(u_i)(v_j) = r_{ij} \tag{8}$$

So, R_j can be described by the fuzzy array R, $R \in U_{m\times n}$.

$$R = \begin{bmatrix} R_1 \\ R_2 \\ \vdots \\ R_{20} \end{bmatrix} = \begin{bmatrix} r_{11} r_{12} \cdots r_{1m} \\ r_{21} r_{22} \cdots r_{2m} \\ \vdots \\ r_{n1} r_{n2} \cdots r_{nm} \end{bmatrix} \tag{9}$$

In the formula, n = 20 and m = 5.

For example, after calculation, $R_2 = \begin{bmatrix} 0 & 0 & 0.9247 & 0.0753 & 0 \end{bmatrix}$.

2.3.3. Construction of fuzzy comprehensive evaluation matrix B

If the index weights array A and evaluation matrix R has been known, according to the fuzzy matrix synthesis algorithm, the fuzzy comprehensive evaluation matrix B can be deduced.

$$B = A \bullet R \xrightarrow{A \in F(U)} R_f \in F(U \times V) \tag{10}$$

$$B = A \bullet R = \{b_1, b_2, \ldots, b_m\} \tag{11}$$

The fuzzy comprehensive evaluation matrix B represents the membership degree of evaluation object to the V_j after overall consideration about all indexes affecting water environment safety of the case.

3. Results and discussion

3.1. Results

According to methods mentioned above, we can get the fuzzy comprehensive evaluation matrix B as the evaluation result (Fig. 1).

3.1.1. Trend of water environment safety in the basin

The five elements in array correspond to five degrees of water environment safety status and the value means correspondingly membership grade to the very safety degree. Making the curve between the membership grade and the time from the year 2005 to 2016 leads to Fig. 1. It shows that the variation trend of water environment safety from the year 2005 to 2016. The trend indicates that the water environment safety status of Raohe river basin varies little from the year 2005 to 2016.

Table 3
Water safety evaluation and grading criteria of Raohe river basin.

Indexes of Class III	Unit	Reference value	I Very safe	II Safe	III Basically safe	IV Unsafe	V Dangerous
Density of population	Person/km^2	Minimum 213.05	≤213	213–220	220–227	227–235	>235
Urbanization rate	%	Maximum 35.99	≥40.75	35.99–40.75	32.27–35.99	32.27–30.41	<30.41
GDP per capita	10^3 yuan RMB	Maximum 23,394	≥34.37	26.76–34.37	18.52–26.76	10.84–18.52	<10.84
Peasant's net income per capita	yuan RMB	Maximum 4,431	≥8,127	6,006–8,127	3,918–6,006	1,920–3,918	<1,920
Ratio of industrial added value to GDP	%	Minimum 38.00	≤38.00	38.00–44.54	44.54–51.07	51.07–57.61	>57.61
Meat output	10^3 ton	Minimum 80.55	≤80.55	80.55–96.78	96.78–113.02	113.02–129.25	>129.25
Fruits output	10^3 ton	Minimum 15.87	≤15.87	15.87–17.96	17.96–20.73	20.73~23.41	>23.41
Water resource per capita	10^3 m^3	Maximum 5.35	≥5.35	4.73–5.35	4.19–4.73	3.61–4.19	<3.61
Basin annual average runoff	km^3	Maximum 19.64	≥19.64	15.53–19.64	10.87–15.53	6.49–10.87	<6.49
Arable land per capita	hm^2	Maximum 0.098	≥0.098	0.095–0.098	0.92–0.095	0.088–0.092	<0.088
Ratio of irrigated area to cultivated land area	%	Maximum 94.63	≥94.63	92.71–94.63	90.76–92.71	88.81–90.76	<88.81
Annual sediment delivery modulus	ton/km^2	Minimum 20.6	≤20.6	20.6–23.1	23.1–25.7	25.7–28.3	>28.3
Ratio of ecological protection area to territory area	%	Maximum 17.9	≥17.9	16.4–17.9	15.0–16.4	13.5–15.0	<13.5
Ratio of Environmental protection investment to GDP	%	Maximum 3.50	≥3.50	3.14–3.50	2.76–3.14	2.41–2.76	<2.41
Fertilizer use intensity	10^3 ton	Minimum 47.84	≤47.84	47.84–51.08	51.08–54.23	54.23–57.36	>57.36
Sewage discharge per unit industrial added value	ton/10^3 yuan	Minimum 3.36	≤3.36	3.36–3.81	3.81–4.25	4.25–4.68	>4.68
COD discharge per unit industrial added value	ton/10^3yuan	Minimum 2.64	≤2.64	2.64–4.45	4.45–6.25	6.25–8.05	>8.05
NH_3-N discharge per unit industrial added value	ton/10^6yuan	Minimum 154	≤154	154–185	185–217	217–248	>248
Fresh water consumption per unit industrial added value	ton/10^6yuan	Minimum 1.02	≤1.02	1.02–1.18	1.18–1.35	1.35–1.51	>1.51
Irrigation water consumption per unit area	10^3m^3/ha^2	Minimum 68.47	≤68.47	68.47–75.03	75.03–81.65	81.65–88.26	>88.26

Take the year 2012 as example, the second number is the biggest, the third is close to the second, the fourth is more than the first and the fifth is zero. That means the status of Raohe river basin water environment safety is mostly in safe and basically safe and not in very safe and dangerous. A conclusion can be drawn that water environment of Raohe river basin is mostly in basically safe in the year 2016.

3.1.2. Major indexes to influence the basin water environment safety

The results (Fig. 1) of assessing Raohe river basin water environment safety show that the two indexes, which are fertilizer use intensity and annual sediment delivery modulus, weight more in the assessment. It means these two factors have the major influence on the water environment safety of the basin.

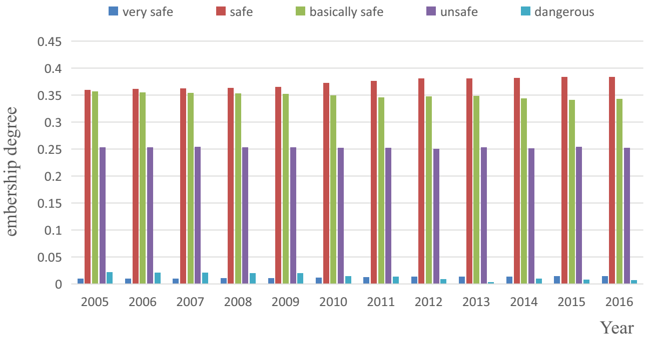

Fig. 1. Trend of water environment safety from the year 2005 to 2016.

3.2. Discussion

3.2.1. Accuracy analysis for the assessment

Though the method used in the case is based on the single index evaluation, it overcomes the shortcoming of either this or that. The fuzzy comprehensive evaluation method overall considers the influence of indexes class III to the upper class II and reflects more accurately the characteristics of water environment system restricted by complex factors. It can fully reflect the fuzzy and indescribable feature of the water environment system in Raohe river basin.

3.2.2. Inadequacy

Because of the limited available index, the index system cannot reflect the true status of water environment safety comprehensively and objectively. It needs more indexes provided by many related fields. The systematicness of assessment must be improved to raise the accuracy of results. The safety of water environment is a dynamic process. It is concerned many factors. This study cannot assess the status of water environment safety timely because of data available from the year 2005 to 2016.

There are several suggestions for assessing the water quality status better. The first is to involve new methods such as combining ground hydrological observation and aerial remote sensing information, using the GIS to calculate the value or simulate the process in order to get the assessment result timely. The second is to construct the research data bank because of study in water environment needing lots of data which involve many related aspects. The third suggestion is to improve the model and to unify evaluation criterion.

Compared with the other evaluation methods, the fuzzy comprehensive evaluation method is used to evaluate the basin water environment safety. The results of assessing basin water environmental safety by the fuzzy comprehensive evaluation method have good reliability and can determine the main influencing factors of water environment safety, and provide the basis for improving the water environment safety level and making reasonable measures for water pollution prevention and control.

4. Conclusion

The fuzzy comprehensive evaluation method, based on fuzzy mathematics, uses the fuzzy variable principle to quantify the factors that are not easy to quantify, and makes a comprehensive evaluation on the status of the subordinate grade of the judged things according to the evaluation index. It is used to evaluate the water environment safety of Raohe basin with improving the method of determining the membership function, the weight coefficient, and the classification method of the water environment safety grade.

By using fuzzy comprehensive evaluation method to evaluate the water environment safety of Raohe basin, the set of factors which was set up includes 20 indexes of 5 evaluation subsets, such as society, economy, resources and environment. The water environment status of Rao River Basin during the year 2005–2016 is evaluated, the dynamic change process of water environment safety in Rao river basin is clearly defined, and the main factors that affect the safety of water environment are identified, and the pertinence is put forward. Safety measures for water environment.

The result shows that fuzzy comprehensive evaluation method is suitable for basin water environmental safety assessment. The evaluation results of Raohe river basin environmental safety during the year 2005–2016 are basically consistent with the actual situation. The water environment status of the Rao river basin is getting better year by year, but some indexes, such as sewage discharge per unit industrial added value, chemical oxygen demand (COD) discharge per unit industrial added value, NH_3-N discharge per unit industrial added value, annual sediment delivery modulus, and the ratio of industrial added value to gross domestic product (GDP), have great influence on the water environment safety, and the prominent contradiction between the sustainable development of economy and society and the water environment safety will exist in a long period.

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