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Using Fuzzy Theory and Principal Component Analysis for Water Shortage Risk Assessment in Beijing, China

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***Abstract*—Considering that the water shortage risk assessment is a fuzzy concept with multiple indicators and classes, and there is the limit for the weight value of fuzzy comprehensive evaluation method, the fuzzy mathematics method and the principal component analysis (PCA) are combined to evaluate the water shortage risk from 2001 to 2008 in Beijng. The weight problem has been modified by adopting the PCA, which make the weight value more objective. From quantitative assessment, the water shortage risk of Beijing stays high level from 2001 to 2008 and the unique channel for risk reduction is to improve the water saving technologies and increasing the sewage treatment rate.**

Keywords-water shortage risk assessment; fuzzy mathematics method; principal component analysis; Beijing.

I. Introduction

In recent years, the water shortage is becoming more and more serious with the socioeconomic development and the climatic change in the world [1,2]. As the Chinese capital, Beijing has the limited water resources, in where the water resources per capita are far below 500 m^3 (the international serious short-water line suggested by the United Nations). The water shortage would bring high risk with the expanding economy, increasing population and improving living condition in this city. Quantitative assessment on the water shortage risk for Beijing is necessary to provide the basis for appropriate allocation and effective use of the water resources and to avoid serious damage brought by the water shortage to the city.

The water shortage has aroused a great attention to the risk assessment. Some researchers have evaluated the water shortage risk brought by river quality [3,4], reservoir irrigation [5], and the drought [6]. The risk assessment for the water shortage is a fuzzy concept with multiple indicators and classes. The fuzzy comprehensive evaluation method has been proved effective in solving problems of fuzzy boundaries and controlling the effect of multiple indicators on assessment results [7,8]. However, the scientific character of weight value is not clear when applying fuzzy comprehensive evaluation method in risk assessment. Especially, the weight value which usually contains the information of the individual indicator only but has nothing to do with the relationship between assessment objects.

The principle component analysis (PCA) is able to solve this problem. PCA is a way of identifying patterns in data, and expressing the data in such a way so as to highlight their similarities and differences. It describes the data set in terms of its variance. Each principal component describes a percentage of the total variance of a data set and elaborates loadings or weights that each variate contributes to this variance. That is to say, the first principal component of a data set describes the greatest amount of variance in the data set. The coefficients of the principal components quantify the loading or weight of each variate to that amount of variance. The other main advantage of PCA is that once you have found these patterns in the data, you can compress the data by reducing the number of dimensions, without much loss of information [9,10].

Based on the concept mentioned earlier, this paper combines the PCA method with the fuzzy mathematics method to evaluate the water shortage risk in Beijing from 2001 to 2008. The organization of this paper is as follows: Section 2 describes the general fuzzy comprehensive evaluation and the PCA methods; Section 3 evaluates the water shortage risk by using the combination of these methods; and Section 4 presents the conclusions and discusses future research.

II. Methodologies

A. *Fuzzy comprehensive evaluations*

Fuzzy comprehensive evaluation is the process of evaluating an objective utilizing the fuzzy set theory, which comprehensively considers the contributions of multiple related indicators according to weights and decreases the fuzziness by using membership functions [11,12]. The procedure of fuzzy comprehensive evaluation is described as follows:

1) Select assessment parameters: It is crucial to select assessment parameters that are representative and rational to form an assessment indictor matrix U, which is based on the actual local situation. The balance between the demand and the supply of the water resources were considered to be critical for the water resource shortage risk [13]. In this paper, there are two main indicators affecting the assessment results: the demand and the supply of the water resources. Therefore, the assessment U can be expressed as:

U = {demand of the water resources, supply of the water resources}

The demand of the water resources is related to agriculture, industry, domestic and the sewage treatment, and so the demand of the water resources is represented by agricultural water, industrial water, domestic water and the sewage treatment rate. Correspondingly, let the subset U_1 be:

U_1 = {agricultural water, industrial water, domestic water, sewage treatment rate}

So, the assessment U can be also expressed as:

U = {agricultural water, industrial water, domestic water, sewage treatment rate, supply of the water resources}

Let $U = (u_i)$ $(i = 1, 2, \cdots, 5)$.

2) Establish assessment criteria: The assessment criteria can be classified into five categories. Let the evaluation set be:

V = {bad, poor, ordinary, fine, good}

3) Establish membership functions: The membership functions represent the degree to which the specified concentration belongs to the fuzzy set. We select the homogeneous distribution as membership functions. Let bad class value be k_1, poor class value be k_2, by parity of reasoning, there are five values, i.e., k_1, k_2, k_3, k_4, k_5. Let $k_3 = (k_1+k_5)/2$, $k_2 = (k_1+k_3)/2$, $k_4 = (k_3+k_5)/2$. Therefore, the membership degrees of assessment parameters at each class can be described quantitatively by a set of formulae comprised of membership functions as follows:

$$\mu_{v1}(u_i) = \begin{cases} 0 & u_i > k_2 \\ \dfrac{k_2 - u_i}{k_2 - k_1} & k_1 \le u_i < k_2 \\ 1 & u_i < k_1 \end{cases} \tag{1}$$

$$\mu_{v2}(u_i) = \begin{cases} \dfrac{u_i - k_1}{k_2 - k_1} & k_1 \le u_i < k_2 \\ \dfrac{k_3 - u_i}{k_3 - k_2} & k_2 \le u_i < k_3 \\ 0 & u_i < k_1 \ or\ u_i \ge k_3 \end{cases} \tag{2}$$

$$\mu_{v3}(u_i) = \begin{cases} \dfrac{u_i - k_2}{k_3 - k_2} & k_2 \le u_i < k_3 \\ \dfrac{k_4 - u_i}{k_4 - k_3} & k_3 \le u_i < k_4 \\ 0 & u_i < k_2 \ or\ u_i \ge k_4 \end{cases} \tag{3}$$

$$\mu_{v4}(u_i) = \begin{cases} \dfrac{u_i - k_3}{k_4 - k_3} & k_3 \le u_i < k_4 \\ \dfrac{k_5 - u_i}{k_5 - k_4} & k_4 \le u_i < k_5 \\ 0 & u_i < k_3 \ or\ u_i \ge k_5 \end{cases} \tag{4}$$

$$\mu_{v5}(u_i) = \begin{cases} 0 & u_i < k_4 \\ \dfrac{u_i - k_4}{k_5 - k_4} & k_4 \le u_i < k_5 \\ 1 & u_i > k_5 \end{cases} \tag{5}$$

where $\mu_{v_j}(u_i)$ is the membership function from i th indicator for j th class, and $j = 1, 2, \cdots, 5$.

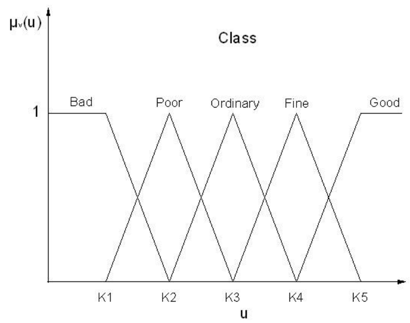

Figure 1. Membership function for class

4) Calculate assessment coefficient set: As a comprehensive evaluation mathematic model of major indicator dominating, the Zadeh operator $M(V,\bullet)$ takes "$\bullet$" and "V" to denotes intersection and union operators, respectively, and is commonly used in the fuzzy comprehensive evaluation [14]. However, this operator might neglect some useful information, especially the information of those nonmain indicators, when there are many qualitative indicators and each weight is small.

So, the weight average operator $M(+,\bullet)$ has been introduced, which takes "+" and "$\bullet$" to replace "V" and "Λ", respectively:

$$B = W \bullet R \tag{6}$$

where B is the assessment coefficient [15].

The assessment coefficient considers and maintains all the indicators through each indicator's weight. This offers a basis for the synthetic evaluation with multiple indicators.

5) Judge object class: The maximum membership principle is an analysis method which is widely used in decision and evaluation. However, this principle has an obvious defect of information loss, which may cause failure of judgment and deflection of result. In order to avoid it, the weighted average principle has been put forward to replace the maximum membership principle.

B. PCA for the weight factor

SPSS software (SPSS, Chicago, IL) was used to perform principal component for U_1. Mathematically, PCA normally involves the following six major steps for weigh value: (1) start by standardizing variable data (each indicator value), i.e., standardization of the measurements to ensure that they all have equal weights in the analysis; (2) calculate the covariance matrix; (3) find the eigenvalues and the corresponding eigenvectors; (4) discard any components that only account for a small proportion of the variation in data sets [16]. For this study, a factor correlation coefficient that is greater than 0.85 (or 85%) was considered significant. Stations that do not have any factors with correlation coefficients greater than this value were considered as non-principle stations; (5) calculate related coefficient of each indicator according to selected principal components; and (6) the weight value of each indicator would be obtained by the related coefficient normalization.

C. Weighted average principle for object class judgment

The weighted average principle has been put forward to judge the object class [17]. With the weighted average principle, the classes z = (z_1, z_2, . . . , z_5), such as z = (1, 2, . . . , 5) have been take to variables, the assessment coefficients B have been taken to calculate weights, and the formula is as follows:

$$A_i = \frac{\sum_{i=1}^{5} b_i z_i}{\sum_{i=1}^{5} b_i} \tag{7}$$

where, the result A_i is the class eigenvalue of i th object.

The risk grades of water resource are classed as extremely low risk, low risk, moderate risk, high risk and extremely high risk. Extremely low risk is negligible, low risk is acceptable, moderate risk is marginal, high risk is serious and extremely high risk is unbearable. In 0-1 interval, let extremely low risk be 0-0.2, low risk be 0.2-0.4, moderate risk be 0.4-0.6, high risk be 0.6-0.8 and extremely high risk 0.8-1. We assign z_1 = 0.05, z_2 = 0.25, z_3 = 0.5, z_4 = 0.75 and z_5 = 0.95 according to the risk grades, correspondingly.

III. RESULTS

According to Beijing Statistical Yearbook [18], the related data of the factors in the set U from 2001 to 2008 can be obtained (Table I). The assessment criteria of the factors are selected by the factor characteristics (Table II). For the supply factor of the water resources, the water resources per capita are difficult to rise along with city expansion and population increase in Beijing. Therefore, we select the international serious short-water line suggested by the United Nations as the good class value of the supply factor (Table II). Since the supply factor of the water resources is difficult to increase, improving water use efficiency is necessary. We select Israeli related factors of supply and demand water resources as references [19] because this nation has the high efficient water saving technologies for water resource shortage. As the capital of China, Beijing should have better water saving technologies than that of the national average; therefore we select Chinese average as reference factors of the water resource demand [20]. For the bad value of the supply factor, Israeli water resource per capita is selected as the reference (Table II). For the factors of the agricultural water, industrial water and domestic water, we select the Israeli average as the good class value and select Chinese average as the bad class value (Table II). For the sewage treatment rate, the rate is less than 70% which was not sustainable utilization for water resources and the rate has reached 99% in many cities of developed countries [21]; thus we select 99% as the good class value and select 70% as the bad class value (Table II).

According to the fuzzy comprehensive evaluation method, it is necessary to determine every main affecting indicator together with setting the evaluating indicators (Table I), the evaluating set (Table II), and the membership function (from equation (1) to (5)). Thus, the fuzzy sets (from R_{2001} to R_{2008}) of the water shortage in Beijing from 2001 to 2008 are:

$$R_{2001} = \begin{bmatrix} 0.42 & 0.58 & 0 & 0 & 0 \\ 0 & 0 & 0.44 & 0.56 & 0 \\ 0 & 0 & 0.44 & 0.56 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0.73 & 0.27 & 0 & 0 & 0 \end{bmatrix} \quad R_{2002} = \begin{bmatrix} 0.02 & 0.98 & 0 & 0 & 0 \\ 0 & 0 & 0.15 & 0.85 & 0 \\ 0 & 0.01 & 0.99 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0.99 & 0.01 & 0 & 0 & 0 \end{bmatrix}$$

$$R_{2003} = \begin{bmatrix} 0 & 0.76 & 0.24 & 0 & 0 \\ 0 & 0 & 0.19 & 0.81 & 0 \\ 0 & 0 & 0.45 & 0.55 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0.86 & 0.14 & 0 & 0 & 0 \end{bmatrix} \quad R_{2004} = \begin{bmatrix} 0.06 & 0.94 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.96 & 0.04 \\ 0 & 0 & 0.23 & 0.77 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0.68 & 0.32 & 0 & 0 & 0 \end{bmatrix}$$

$$R_{2005} = \begin{bmatrix} 0 & 0.99 & 0.01 & 0 & 0 \\ 0 & 0 & 0 & 0.83 & 0.17 \\ 0 & 0 & 0 & 0.37 & 0.63 \\ 1 & 0 & 0 & 0 & 0 \\ 0.61 & 0.39 & 0 & 0 & 0 \end{bmatrix} \quad R_{2006} = \begin{bmatrix} 0.64 & 0.36 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.79 & 0.21 \\ 0 & 0 & 0 & 0.45 & 0.55 \\ 0.48 & 0.52 & 0 & 0 & 0 \\ 0.57 & 0.43 & 0 & 0 & 0 \end{bmatrix}$$

$$R_{2007} = \begin{bmatrix} 0.85 & 0.15 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.75 & 0.25 \\ 0 & 0 & 0.02 & 0.98 & 0 \\ 0.14 & 0.86 & 0 & 0 & 0 \\ 0.55 & 0.45 & 0 & 0 & 0 \end{bmatrix} \quad R_{2008} = \begin{bmatrix} 0.92 & 0.08 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.75 & 0.25 \\ 0 & 0 & 0 & 0.80 & 0.20 \\ 0 & 0.77 & 0.23 & 0 & 0 \\ 0 & 0.97 & 0.03 & 0 & 0 \end{bmatrix}$$

Following major steps, SPSS software is used to calculate the relative principal components for the water resource demand factors according to the data in Table I. In the Table III, the accumulative variance percentage of the second correlation coefficient is greater than 85%; therefore, most of information quantities of original observed variable could be compressed in the first two principal components. The initial factor loadings of the first two principal components are in the Table IV. From the eigenvectors obtained in the PCA (Table III), the first two principle components, F1 and F2, could be given as:

F_1=0.5586u_1 + 0.5644u_2 - 0.2491u_3 - 0.5539u_4 (8)

F_2=0.0864u_1 + 0.2251u_2 + 0.9631u_3 - 0.1163u_4 (9)

where the coefficients are calculated by initial factor loadings in the Table IV divided by the extraction of the corresponding eigenvalues in the Table III (e.g. 0.5586=0.962/sqrt(2.966)). According to the first two principle components, the synthesis model could be calculated as

$$F=0.4507u_1 + 0.4868u_2 + 0.0197u_3 - 0.3198u_4$$

where the coefficients are calculated following two steps: (1) the first two component coefficients (equation (8) and (9)) multiplication by corresponding variance percentage (Table 3), respectively, and then divided by the addition of the first two component variance percentage (Table 3); (2) to addition of the corresponding results (e.g. 0.4507=(0.5586*74.159+0.0864*21.970)/(74.159+21.970)).

In the synthesis model, the related coefficient of each indicator is the weight of each factor and the weight values of the indicators in U_1 set would be obtained after normalization (e.g. 0.32=0.4507/(0.4507+0.4868+0.0197 + 0.3198)):

$$W_1 = \{0.32, 0.34, 0.02, 0.32\}$$

For obtaining the weight values of the factors in U, the each numerical value in W_1 need to multiplication by the weight value of the water resource demand (0.16=0.32*0.5). Therefore, the weight values of the factors in U could be given as:

$$W = \{0.16, 0.17, 0.01, 0.16, 0.5\}$$

According to the equation (6), the fuzzy membership function from 2001 to 2008 in Beijing could be given as:

TABLE I. THE WATER RESOURCE DATA IN BEIJING FROM 2001 TO 2008.

	2001	2002	2003	2004	2005	2006	2007	2008
Agricultural water ($m^3/10^4$ RMB GDP)	2153.5	1845.2	1536.7	1413.6	1349	1439.2	1228	1063.8
Industrial water ($m^3/10^4$ RMB GDP)	98	73.4	68.6	49.3	39.8	34	27.6	23.7
Domestic water (m^3/ capita)	88	76.9	90.3	87	88.4	87.8	86.4	88.3
Sewage treatment rate (%)	42	45	50.1	53.9	62.4	73.8	76.2	78.9
Water resources (m^3/ capita)	139.7	114.7	127.8	145.1	153.1	157.1	148.1	205.5

TABLE II. THE ASSESSMENT CRITERIA FOR THE ASSESSMENT PARAMETERS.

		2001	2002	2003	2004	2005	2006	2007	2008
Agricultural water	k_1	2424.2	2259.3	1975	1674.6	1596.8	1524.3	1257.4	1077.5
($m^3/10^4$ RMB GDP)	k_5	544.4	577	564.5	568.2	611.1	588.5	467.5	426.3
Industrial water	k_1	262	240.9	214.2	188.5	166.4	147.2	126.9	108.2
($m^3/10^4$ RMB GDP)	k_5	5.5	5.9	7.0	5.6	6.6	6.3	4.6	4.2
Domestic water	k_1	47	48.2	48.8	50.1	51.6	52.8	53.8	54.9
(m^3/ capita)	k_5	111	105.9	114	103.3	92.2	92.2	97.5	96.6
Sewage treatment	k_1	70	70	70	70	70	70	70	70
rate (%)	k_5	99	99	99	99	99	99	99	99
Water resources	k_1	114	114	114	114	116	116	104	103
(m^3/ capita)	k_5	500	500	500	500	500	500	500	500

$B_{2001}=W \cdot R_{2001}$=(0.5922, 0.2278, 0.0792, 0.1008, 0)

$B_{2002}=W \cdot R_{2002}$=(0.6582, 0.1619, 0.0354, 0.1445, 0)

$B_{2003}=W \cdot R_{2003}$=(0.5900, 0.1961, 0.0762, 0.1377, 0)

$B_{2004}=W \cdot R_{2004}$=(0.5096, 0.3104, 0.0023, 0.1709, 0.0068)

$B_{2005}=W \cdot R_{2005}$=(0.4650, 0.3534, 0.0016, 0.1448, 0.0352)

$B_{2006}=W \cdot R_{2006}$=(0.5096, 0.3104, 0.0023, 0.1709, 0.0068)

$B_{2007}=W \cdot R_{2007}$=(0.4334, 0.3866, 0.0002, 0.1373, 0.0425)

$B_{2008}=W \cdot R_{2008}$=(0.1472, 0.6210, 0.0518, 0.1355, 0.0445)

and then, the comprehensive evaluation values for water resource risk would be obtain by equation (7) from 2001 to 2008 in Beijing (Fig. 2). The bigger value indicates higher risk.

TABLE III. TOTAL VARIANCE EXPLAINED FOR THE WATER RESOURCE DEMAND FACTORS

Component	Initial eigenvalues	Variance percentage (%)	Accumulative (%)
1	2.966	74.159	74.159
2	0.879	21.970	96.128
3	0.140	3.459	99.624
4	0.015	0.376	100.00

Extraction Method: Principal Component Analysis.

From the Fig. 2, although the risk curve is on a declining trend from 2001 to 2008, the risk values of the water shortage are high in Beijing. Beijing has paid much attention to the water shortage through water conservation, waste water control and water saving (Table I), which have reduced the water shortage risk year after year. In 2008, the risk value was 84% of that in 2001. However, the water shortage risk would increase with the city expansion and population growth if the water saving technologies does not be improved in this city. By comparison, the water saving technologies on agriculture and industry in Beijing is far below that in Israel (Table I and Table II). If the supply of the water resource maintains in 2008 and the demand of the water reaches the good class value, the water shortage risk value would be 0.39 by using the same method. This result shows the water shortage risk would be decreased low level by improving the water saving technologies and increasing the sewage treatment rate.

TABLE IV. COMPONENT MATRIX OF THE INITIAL FACTOR LOADINGS

Component	Agricultural water (u_1)	Industrial water (u_2)	Domestic water (u_3)	Sewage treatment rate (u_4)
1	0.962	0.972	-0.429	-0.954
2	0.081	0.211	0.903	-0.109

Extraction Method: Principal Component Analysis.

IV. CONCLUSION

In this paper, the fuzzy mathematics method and PCA are combined to assessment the water shortage risk from 2001 to 2008 in Beijng. The weight problem has been modified by adopting the PCA, which make the weight value more objective. From quantitative assessment, the water shortage risk of Beijing stays high level from 2001 to 2008 though the government has taken measures to improve water resource use. By comparison, the water use efficiency on agriculture and industry in Beijing is far below that in Israel. Through the city expansion and development, the unique channel for risk reduction is to improve the water saving technologies and increasing the sewage treatment rate in Beijing.

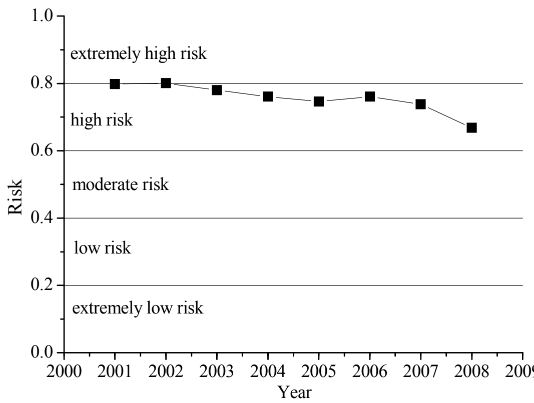

Figure 2. The risk of water shortage from 2001 to 2008 in Beijing

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