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A Novel Water Quality Evaluation Method Based on Efficacy Coefficient Method

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In order to evaluate quality of the water environment, a novel water quality evaluation method is proposed. Water quality evaluation problem includes several influencing indices, which lead it become a multi-attribute decision making (MADM) problem. Then the new evaluation method is developed from the concept of a well-known MADM method named efficacy coefficient method. In the evaluation process, coefficient of variation (CV) method is used to determine the weights of indices. Finally, a practical case study proved that the proposed water quality evaluation method is efficient and feasible.

1. Introduction

The rapid developments of social economy and human activities have a great impact on water resources. Water quality is an important factor for water resources. In order to improve water quality and protect the environment, it is necessary to carry out effective water quality monitoring and evaluation of water resources. Pollution coming from chemical, physical and biological contaminants by anthropogenic activities received great environmental attention all over the world (May et al., 2006; Noori et al., 2010; Li et al., 2014). There are various solutes in natural water, such as dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD) and so on, which influence water quality (Liu and Zou, 2012). Then a water quality evaluation problem can be regarded as a multi-attribute decision making (MADM) problem. In recent years, various MADM methods are developed and applied in many fields, such as supplier selection, material selection, information fusion (Liu and Meng, 2009; Jahan and Edwards, 2013; Ren and Yang, 2013).There are also many MADM methods are developed for solving water quality evaluation problems. These methods are fuzzy comprehensive evaluation method (Icaga, 2007), the matter element method (Kou, 2013; Wong and Hu, 2014), comprehensive index method (Chen et al., 2010), attribute recognition method (Yu et al, 2013), set pair analysis (Du et al.,2014), Variable Weight Method (Ren and Zhou, 2015) and grey relation analysis (GRA) method (Liu, 2015).
Efficacy coefficient method is a well known MADM method, and it defined the mathematical formula for the efficacy coefficient to express the contribution of variables to a system in progress process (Yang and Gao, 2006). Efficacy coefficient method has been applied in many fields, such as sustainable development capacity of logistics industry (Yu, 2013), evaluation of gas explosion disaster risk (Li et al., 2013).
For the water quality evaluation problem, this paper will develop a new evaluation method based on efficacy coefficient method combining with the coefficient of variation (CV) method, which is an objective method for determining the weights of evaluation indices.

2. Efficacy Coefficient Method for Water quality evaluation

This section will develop a new water quality evaluation method based on the concept of efficacy coefficient method. In the following discussion, we first establish a water quality evaluation model, and then propose the new evaluation method. Suppose that there are *m* water samples $A_1, A_2, ..., A_m$ waited to be evaluated for their water quality grades, and each object belongs to one grade of water quality standards, which are denoted by $C_1, C_2, ..., C_K$. There are *n* indicators (indices) $o_1, o_2, ..., o_n$. x_{ij} is the measurement value of A_i on the indicator o_j. Thus the water sample A_i can be written as $A_i = (x_{i1}, x_{i2}, ..., x_{in})$, $i = 1, 2, ..., m$. Then the sample space matrix can be expressed by the following matrix:

$$X = (x_{ij})_{m\times n} = \begin{matrix} \\ A_1 \\ A_2 \\ \vdots \\ A_m \end{matrix} \begin{matrix} \begin{matrix} o_1 & o_2 & \cdots & o_n \end{matrix} \\ \begin{pmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{pmatrix} \end{matrix}.$$

Suppose F is some attribute space, and $C_1, C_2, ..., C_K$ is an ordered series of grades in the attribute space F. The series satisfies the condition $C_1 > C_2 > \cdots > C_K$. Such a space can be established for the standard grades of every evaluation indicator. The standard grade matrix can then be expressed with

$$A = (a_{ij})_{n\times K} = \begin{matrix} \\ o_1 \\ o_2 \\ \vdots \\ o_n \end{matrix} \begin{matrix} \begin{matrix} C_1 & C_2 & \cdots & C_K \end{matrix} \\ \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1K} \\ a_{21} & a_{22} & \cdots & a_{2K} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nK} \end{pmatrix} \end{matrix}$$

where a_{ij} satisfies $a_{i1} < a_{i2} < \cdots < a_{iK}$ or $a_{i1} > a_{i2} > \cdots > a_{iK}$.

Then for establishing the water quality evaluation model, the attribute measures are firstly to be transformed as follows (Liu, 2015):

Let $\mu_{ijk} = \mu(x_{ij} \in C_k)$ be the attribute measure of indicator value x_{ij}, which takes the attribute levels from the set C_k. The calculation formulas of μ_{ijk} are given as follows:

Suppose that a_{ij} ($i = 1, 2, ..., m$) satisfies $a_{i1} < a_{i2} < \cdots < a_{iK}$, then

i) If $x_{ij} \le a_{i1}$,

then $\mu_{ij1} = 1, \mu_{ij2} = \cdots = \mu_{ijK} = 0$;

ii) If $x_{ij} \ge a_{iK}$,

then

$\mu_{ijK} = 1, \mu_{ij1} = \cdots = \mu_{ijK-1} = 0$,

iii) If $a_{il} \le x_{ij} \le a_{i(l+1)}$,

then

$$\mu_{ijl} = \frac{|x_{ij} - a_{i(l+1)}|}{|a_{il} - a_{i(l+1)}|}, \mu_{ij(l+1)} = \frac{|x_{ij} - a_{il}|}{|a_{il} - a_{i(l+1)}|}$$

and

$\mu_{ijk} = 0, k < l$ or $k > l + 1$.

Then the water quality evaluation problem can be modeled as a MADM model with the following attribute recognition matrix

$$H_i = (\mu_{ijk})_{n\times K} = \begin{matrix} & C_1 & C_2 & \cdots & C_K \\ o_1 & \mu_{i11} & \mu_{i12} & \cdots & \mu_{i1K} \\ o_2 & \mu_{i21} & \mu_{i22} & \cdots & \mu_{i2K} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ o_n & \mu_{in1} & \mu_{in2} & \cdots & \mu_{inK} \end{matrix} .$$

In water quality evaluation, there are many factors, such as oxygen dissolved (DO), oxygen demand biochemical (BOD), chemical oxygen demand (COD). The relative importance of between these factors are different because of the nature of the indices (factors), such as physical properties, chemical properties, biological properties, etc. And the corresponding pollution characteristics leads to different nature of pollution to some water demand of the target water body damage. Coefficient of variation (CV) method is an objective method for determining index weights. The steps of the CV method is given as follows:

(i) Normalize the water sample measurement matrix $X = (x_{ij})_{m\times n}$ into $R = (r_{ij})_{m\times n}$.

In general, indexes can be classified into two types: the-larger-the-better type and the-smaller-the-better type. The normalization method is to preserve the property that the range of a normalized number r_{ij} belongs to the closed interval [0,1]. Hence, the water sample measurement matrix $X = (x_{ij})_{m\times n}$ is transformed into the normalized fuzzy decision matrix $R = (r_{ij})_{m\times n}$, where r_{ij} obtained by the following rule (Xu, 2004):

If the *j*th-indicator is the-larger-the-better type, , such as dissolved oxygen (DO), then

$$r_{ij} = \frac{x_{ij} - x_j^-}{x_j^+ - x_j^-};$$

If the *j*th attribute is the-smaller-the-better type, such as NH3-N, then

$$r_{ij} = \frac{x_j^+ - x_{ij}}{x_j^+ - x_j^-}$$

Where $x_j^+ = \max_{1\le i\le m}\{x_{ij}\}$ and $x_j^- = \max_{1\le i\le m}\{x_{ij}\}$.

Obviously, $r_{ij} \in [0,1]$ is the data of the *i*th evaluating object on the indicator o_j.

(ii) Let $\bar{x}_j = \frac{1}{m}\sum_{i=1}^{m} x_{ij}$, $s_j = \sqrt{\frac{1}{m}\sum_{i=1}^{m}(x_{ij} - \bar{x}_j)^2}$, and $CV_j = s_j / \bar{x}_j$, then the indicators' weights can be calculated as follows:

$$w_j = \frac{CV_j}{\sum_{j=1}^{n} CV_j},\ j = 1, 2, ..., n.$$

We can easily to show that the weights satisfy $w_j \ge 0,\ \sum_{j=1}^{n} w_j = 1,\ j = 1, 2, ..., n$.

Further the evaluation steps of the new proposed water quality evaluation method based on efficacy coefficient method are given as follows (Yang and Gao, 2006):

Step 1. Establish the MADM decision matrix of water quality evaluation problem as above-mentioned.

Step 2. Determine weights of indicators using CV method.

Step 3. Compute efficacy coefficient of each index as follows:

$$d_{ijk} = \mu_{ijk} \times 40 + 60$$

Where μ_{ijk} is the attribute measure of indicator value x_{ij}, $i = 1, 2..., m$ and $j = 1, 2, ..., n$ belong to the class C_k.

Step 4. Compute comprehensive efficacy coefficient $D_i \quad (i = 1, 2, ..., m)$ of each water sample:

$$D_{ik} = \prod_{j=1}^{n} d_{ijk}^{w_j}, i = 1, 2, ..., m$$

Step 5. Evaluate the water samples according to the following water quality recognition rule:
If

$$k_0 = \arg\max_{1 \le k \le K} \{D_{ik}\},$$

Then the sample A_i belonging to the grade k_0.

3. Application Example

To illustrate the practicability and feasibility of the new water quality evaluation method, an example discussed in Xu et al. (2014) is adopted.

Tongli Town, one of the six ancient towns, located in the east of the ancient canal in Suzhou City, China. It was built in the Song Dynasty, which has been 1000 years of history, and it is 18 kilometers away from Suzhou City, 80 kilometers away from Shanghai. Tongli area of 33 hectares, surrounded by five lakes, from net rivers will be divided into seven island townships. The ancient town is beautiful town surrounded by water. In 1982, Tongli Town has become the first and only to the town as a town of cultural relics protection units of Jiangsu province. In 1995, it was listed as the first batch of historical and cultural towns in Jiangsu province. In 1998, the town was inscribed as the world heritage list on preparedness. With the increase in the number of tourists and the development of business, the local water environment has caused some pollution. This paper intends to evaluate the water quality. According to Chinese Surface Water Environment Quality Standards (GB3838-2002), this article selects the following evaluation indicators (indices): DO (o_1), COD (o_2), COD_{Mn} (o_3), BOD_5 (o_4),TN (o_5), NH_3N (o_6) and TP (o_7). Five water quality grades I (Good), II (Fine), III (Ordinary), IV (Poor) and V (Poor) and the corresponding to standards of water quality are reported in Table 1. Indicator measure values of water samples are reported in Table 2.

Table 1: National quality standards of suface waters (GB3838-2002) of China (units of mg/L)

Grade	o_1	o_2	o_3	o_4	o_5	o_6	o_7
I	7.5	15	2	3	0.2	0.15	0.02
II	6	15	4	3	0.5	0.5	0.1
III	5	20	6	4	1	1	0.2
IV	3	30	10	6	1.5	1.5	0.3
V	2	40	15	10	2	2	0.4

Table 2: Water monitoring data of Tongli Town

	o_1	o_2	o_3	o_4	o_5	o_6	o_7
A_1	3.60	28.17	7.30	5.33	6.09	3.83	0.36
A_2	1.65	31.00	8.07	5.45	6.35	3.35	0.34
A_3	2.28	26.67	7.40	5.55	5.79	2.77	0.30
A_4	4.12	25.00	6.97	4.90	5.73	2.32	0.29
A_5	2.52	28.00	6.50	4.22	5.30	2.34	0.21

The steps of the proposed method are given as follows:

Step 1. According to Table 2, the sample space matrix $X = (x_{ij})_{8 \times 7}$ is obtained as follows:

$$X = \begin{pmatrix} 3.60 & 28.17 & 7.30 & 5.33 & 6.09 & 3.83 & 0.36 \\ 1.65 & 31.00 & 8.07 & 5.45 & 6.35 & 3.35 & 0.34 \\ 2.28 & 26.67 & 7.40 & 5.55 & 5.79 & 2.77 & 0.30 \\ 4.12 & 25.00 & 6.97 & 4.90 & 5.73 & 2.32 & 0.29 \\ 2.52 & 28.00 & 6.50 & 4.22 & 5.30 & 2.34 & 0.21 \\ 2.52 & 25.00 & 7.47 & 5.85 & 5.28 & 2.31 & 0.23 \\ 1.52 & 34.17 & 9.20 & 6.65 & 7.11 & 3.72 & 0.51 \\ 2.67 & 22.83 & 6.43 & 4.75 & 5.19 & 2.09 & 0.22 \end{pmatrix}$$

Take monitoring point (sample) A_1 as the example, the steps of the proposed method are given as follows.

Step 2. The attribute recognition decision matrix $H_1 = (\mu_{1jk})_{7\times5}$ are obtained as follows:

$$H_1 = \begin{matrix} \\ o_1 \\ o_2 \\ o_3 \\ o_4 \\ o_5 \\ o_6 \\ o_7 \end{matrix} \begin{matrix} I & II & III & IV & V \\ \end{matrix} \begin{pmatrix} 0 & 0 & 0.3000 & 0.7 & 0 \\ 0 & 0 & 0.1830 & 0.8170 & 0 \\ 0 & 0 & 0.6750 & 0.3250 & 0 \\ 0 & 0 & 0.3350 & 0.6650 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0.4 & 0.6 \end{pmatrix}$$

Step 3. By CV method, the weights can be calculated as follows:

$w_1 = 0.1439, w_2 = 0.1469, w_3 = 0.1423, w_4 = 0.1154,$

$w_5 = 0.1321, w_6 = 0.2011, w_7 = 0.1183$

Step 4. The comprehensive efficacy coefficient D_{i1} of each alternative are calculated as

$D_{11} = 60$, $D_{21} = 60$, $D_{31} = 69.5820$, $D_{41} = 72.4340$, $D_{51} = 74.0213$.

Step 5. Due to the maximum $D_{51} = 74.0213$., so according to the water quality recognition rule, monitoring point (sample) A_1 belongs to the grade V standard, and briefly denote $A_1 \to \mathrm{V}$.

Similarly, other monitoring points' water quality results can be obtained as $A_2 \to \mathrm{V}, A_3 \to \mathrm{V}, A_4 \to \mathrm{IV}, A_5 \to \mathrm{V}$. This result is in agreement with Xu et al. (2014). From the analyzed result, the water quality of Tongli Town is poor, which requires the local government to develop policies and provide financial support to improve the local water environment.

4. Conclusion

For the water quality evaluation problem, we develop a new water quality evaluation method based on efficacy coefficient method combining with coefficient of variation method. Coefficient of variation method is an objective weighting method which can overcome subjective randomness. This new evaluation method is easy to perform by using computer softwares and can be easily accepted by engineers. A case study is used to validate the application of the proposed method, and the example shows that the proposed method is effective and feasible. The proposed method can also be applied to other fields, such as multi-sensor target recognition, air quality evaluation, etc.

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