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Application of improved extension evaluation method to water quality evaluation

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SUMMARY

The extension evaluation method (EEM) has been developed and applied to evaluate water quality. There are, however, negative values in the correlative degree (water quality grades from EEM) after the calculation. This is not natural as the correlative degree is essentially an index based on grades (rankings) of water quality by different methods, which are positive. To overcome this negativity issue, the interval clustering approach (ICA) was introduced, which is based on the grey clustering approach (GCA) and interval-valued fuzzy sets. However, the computing process and formulas of ICA are rather complex. This paper provides a novel method, i.e., improved extension evaluation method, so as to avoid negative values in the correlative degree. To demonstrate our proposed approach, the improved EEM is applied to evaluate the water quality of three different cross-sections of the Fen River, the second major branch river of the Yellow River in China and the Han Jiang River, one of the major branch rivers of the Yangtse River in China. The results of the improved evaluation method are basically the same as the official water quality. The proposed method possesses also the same merit as the EEM and ICA method, which can be applied to assess water quality when the levels of attributes are defined in terms of intervals in the water quality criteria. Existing methods are mostly applicable to data in the form of single numeric values.

1. Introduction

The safety of water resources is of pressing importance worldwide (Xia and Hu, 1997a,b; Xia and Chen, 2001; Huang and Xia, 2001; Kumar et al., 2006; Murray et al., 2012; Ravikumar et al., 2013; Chan et al., 2013). Owing to population growth, rapid economic development and urbanization, the imbalance between the supply and demand of water resources has become a serious problem (Huang and Xia, 2001). Pollution is destined to affect the biological integrity of aquatic systems, degrade the quality of water and affect human health directly and indirectly. Evaluation of water quality is one of the main tasks of ensuring water security. Therefore, effective evaluation methods and concrete evaluation criteria for assessing the risk of water resources must be developed in order to secure water safety for sustainable development and public health. Thus research on water quality evaluation has been of increasing interest (e.g. Nives, 1999; Stambuk-Giljanovic, 1999; Alberto et al., 2001; Wunderlin et al., 2001; Kyozuka et al., 2001; Wang, 2002; Grace et al., 2002; Simenonov et al., 2003; El-Baroudy and Simonovic, 2004; Ouyang, 2005; Ouyang et al., 2006; Zhang et al., 2008; Lermontov et al., 2009; Gharibi et al., 2012; Scannapieco et al., 2012; Ma et al., 2013; Sharma et al., 2013; Voyslavov et al., 2013; Mohebbi et al., 2013; Wang et al., 2013; Ocampo-Duque et al., 2013). In the process of evaluation, however, there exist two main problems: complexity and uncertainty (Ip et al., 2009; Wong and Hu, 2013).

To overcome the complexity problem, Rough Set theory, interrelated with fuzzy set theory, has been applied to environmental quality evaluation in China (Ip et al., 2007). The number of water quality indexes is reasonably reduced so as to simplify the evaluation process. In the application to the Hang Jiang River water quality, the thirteen water quality attributes have been reduced to 4 or 5 important ones, which determine the overall water quality for the segments and periods under consideration.

Uncertainty is an intrinsic problem in water resource assessment (Beck, 1987). There are two assessment methods dealing with this uncertainty problem—fuzzy synthetic evaluation and grey correlative assessment.

The fuzzy synthetic evaluation (FSE) is applied to water quality evaluation (WQE) by many authors such as Lu et al. (1999) for the evaluation of water quality in the Fei-Tsui Reservoir in Taiwan, Lu and Lo (2002) for the diagnosis of reservoir water quality, Dahiya et al. (2007) and Singh et al. (2008) for the analysis of groundwater quality and Icaga (2007) for the classification of water quality in the Eber Lake water in Turkey. In the work of Lu et al. (1999), the investigation results showed that the long-term change of

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water quality and the overturn phenomena could not be observed by using the Carlson index, but was detected by fuzzy synthetic evaluation. According to the results of Lu and Lo (2002), fuzzy synthetic evaluation does a better job of detecting short-term changes of water quality and exploring the overturning phenomena than the Carlson Index. Better interpretation of the results can provide valuable information to decision makers and aid reservoir management. In the research of Lu and Lo (2002), one complementary evaluation method, self-organizing map (SOM), for diagnosing water quality has been used to develop a trophic state classifier and is illustrated with a case study of trophic status assessment for Fei-Tsui Reservoir in Taiwan. The results of SOM are compared with those of the Carlson index and fuzzy synthetic evaluation, showing that the inconsistent records can be mapped to the conflicting data zone of the SOM output map. The papers of Dahiya et al. (2007) and Singh et al. (2008) reported the application of fuzzy set theory for decision-making in the assessment of physico-chemical quality of groundwater. Fuzzy synthetic evaluation models give the levels of certainty for the quality of the water based on the prescribed limits of various regulatory bodies and opinion of the experts from the field of drinking water quality. In the method of Icaga (2007), traditional quality classes are transformed into continuous form and then the concentration values of the different quality parameters are summed using fuzzy rules. Finally, defuzzification of these summed values develops an index. An application of this proposed index for physical and inorganic chemical parameters in the Eber Lake water (in Turkey) are studied to demonstrate the practical application and feasibility of the index.

In addition, more literatures used fuzzy methods for the evaluation of water quality. For examples, Chang et al. (2001) discussed the identification of river water quality using three fuzzy synthetic evaluation approaches and compared the results with the conventional Water Quality Index (WQI) for rivers. Liou et al. (2003) applied two-stage fuzzy set theory to river quality evaluation. A new indexing method of water quality using FSE was proposed by Sadiq and Rodriguez (2004). Uricchio et al. (2004) developed a decision support system that provides information on the environmental impact of human activities by examining their effects on groundwater quality. Zou et al. (2006) gave an entropy method for the determination of weights for evaluating indicators in fuzzy synthetic evaluation for water quality assessment. To consider both randomness and fuzziness, Wang et al. (2007) built a hybrid fuzzy model for water quality evaluation by integrating Shannon entropy and introducing generalized weighted distance. To consider both randomness and fuzziness, Wang et al. (2007) built a hybrid fuzzy model for water quality evaluation by integrating Shannon entropy and introducing generalized weighted distance.

Furthermore, fuzzy clustering analysis was also used to evaluate environmental water quality (Kung et al., 1992; Chen, 1993; Liou and Lo, 2005).

Deng (1989) formally introduced the grey system theory (cf. Xia et al., 1997a). Xia (1995) proposed the grey correlative assessment method for regional water quality assessment with an application to the Fen River in China. Recently the grey relational method has been applied to the analysis of hydrological time series (Wong et al., 2006) and evaluation of river environment quality in China (Ip et al., 2009). These applications were demonstrated that the grey relational method is a useful tool for analysis of inexact data, short sample and incomplete hydrological data.

In fuzzy and grey evaluation methods, the value of water quality standard is regarded as a single value (Zou et al., 2006). However, in many applications, alternative methods are used. For example, in China, water qualities are classified into five grades with regard to the values of seven physical and chemical constituents, namely, C_1 = DO = Dissolved Oxygen, C_2 = BOD = Biochemical Oxygen Demand, C_3 = HOB = Hydroxybenzene, C_4 = CN^- = Cetane Number, C_5 = Hg = Mercury, C_6 = As = Arsenic and C_7 = Cr^{+6} = Chromium (see Appendix A). It is clear that in many applications, a single water quality grade is not adequate to describe and classify water resources. A classification in terms of an interval is more suitable. To analyze data in the form of intervals, new methods should be developed.

In 1983 Cai developed the concept of matter-element (see Xia and Hu, 2004). Since then, the basic theory has gradually been established and applied in many areas (David et al., 1997; He and Chen, 1997; Huang 2006; Liu 1996; Qian et al., 2009; Liu and Zou, 2012). Evaluation method based on extension set was developed into the extension evaluation method (EEM) (Xia and Hu, 2004). But there are negative values in the correlative degrees so that this is out of accord with the basic thought of "belong to a certain grade" in the evaluation of water quality (see Appendix B). The general practice is that grades of water quality are positive.

Even though the interval clustering approach (ICA) was proposed to avoid negative values, the computing process and formula of ICA are rather complex. Could we solve the negative values problem itself by improving the method of EEM? In this paper we attempt to provide a modification, namely improved extension evaluation method, by modifying the computing method of correlative degrees, and present an application of this new theory to WQE by the improved EEM to classify the water quality grade with reference to the water quality criteria for individual chemicals. Our proposed method makes up the insufficiency of fuzzy and grey evaluation methods discussed above. While existing evaluation methods only give a coarse grading of the water quality, our proposed method will give a finer water quality grading. The computing process and formula of improved EEM are also simpler than those of ICA. There are many contemporary models for uncertainty identification such as WASP5 (Ambrose et al. 1991) and CE-QUAL-W2 (Cole and Wells 2004). But new model proposed in this paper cannot be compared with these models for non-incorporation.

This paper is organized as follows. In Section 2, we introduce the basic concepts of matter-element, extension distance, simple correlative function and primary correlative function. We put forward new formulas for correlative degree and extension weight, and show an algorithm on EEM. This section provides two modifications in correlative degree, and the corresponding evaluation method, the improved EEM. Section 3 demonstrates applications to river environmental quality evaluation of the Fen River and the Han Jiang, the major branch rivers of the Yellow River and the Yangtse River in China respectively. Finally a brief conclusion is given in Section 4.

2. Materials and methods

2.1. Matter-elements

For the sake of simplicity and self-completeness, only simplified and relevant notations are provided below (cf. Xia and Hu, 2004).

Let N be a site name and C a character name associated with a quantity V. Then $R = \begin{bmatrix} & N \\ C & V \end{bmatrix}$ is called a matter-element. If the site has n characters $C_1, C_2, \ldots, C_n$ with corresponding quantities $V_1, V_2, \ldots, V_n$ respectively, then

$$R = \begin{bmatrix} & N \\ C_1 & V_1 \\ C_2 & V_2 \\ \vdots & \vdots \\ C_n & V_n \end{bmatrix}$$