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Research article

A universal calibrated model for the evaluation of surface water and groundwater quality: Model development and a case study in China

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ABSTRACT

Water quality evaluation is an important issue in environmental management. Various methods have been used to evaluate the quality of surface water and groundwater. However, all previous studies have used different evaluation models for surface water and groundwater, and the models must be recalibrated due to changes in monitoring indicators in each evaluation. Water quality managers would benefit from a universal and effective model based on a simple expression that would be suitable for all cases of surface water and groundwater, and which could therefore serve as a standard method for a region or country. To meet this requirement, we attempted to develop a universal calibrated model based on the radial basis function neural network. In the new model, the units and values of the evaluation indicators for surface water and groundwater are normalized simultaneously to make the data directly comparable. The model's training inputs comprise the normalized value in each of a water quality indicator's grades (e.g., the nitrate contents defined in a regulatory standard for grades I to V) for all evaluation indicators. The central vector of the Gaussian function is used as the average of the evaluation indicators' normalized standard values for the five grades. The final calibrated model is expressed as an equation rather than in a programming language, and is therefore easier to use. We used the model in a Chinese case study, and found that the model was feasible (it compared well with the results of other models) and simple to use for the evaluation of surface water and groundwater quality.

1. Introduction

Surface water and groundwater are important natural resources that are facing serious pollution and shortages around the world (Goss and Richards, 2008; Bowmer, 2011; Hurley et al., 2012). A lot of attention has therefore been paid to the safety of both water resources. Evaluation of water quality is a key method that planners use to ensure water security (Liou and Lo, 2005; Icaga, 2007). Therefore, effective evaluation methods should be developed for both surface water and groundwater resources to secure water safety and support sustainable development and human health.

During the last 60 years, many methods have been introduced for water quality evaluation (e.g., Karmakar and Mujumdar, 2006; Razmkhah et al., 2010; Dietzel and Reichert, 2012; Dotto et al., 2012). The most commonly used evaluation methods can be divided into three categories according to their complexity in implementation. The first category is based on a simple comparison of monitoring values with local standards (Debels et al., 2005). This method can judge the quality level for each monitored indicator, but can't calculate the cumulative effects of multiple indicators to provide an overall water quality level. The second category is based on linear methods, including the development of a water quality index or the use of an uncertainty method such as fuzzy set theory or grey relational methods. The models in these methods are linear, and are established according to the interactions among the different evaluation indicators. These methods provide a more holistic evaluation of the water quality and overcome the limitation of methods in the first category (Ip et al., 2009; Ramakrishnaiah et al., 2009; Gharibi et al., 2012; Ocampo-Duque et al., 2006). However, in practice, the interactions among the evaluation indicators are usually non-linear, so linear models may be not be sufficiently accurate for water quality evaluation. To overcome this shortcoming, artificial intelligence methods (the third category), such as backward-propagating neural networks and support vector

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machines (Kuo et al., 2004; Karamouz et al., 2009), are adopted to reflect the non-linear relationships among the evaluation indicators. Artificial intelligence methods appear to provide a more scientifically realistic description of evaluation indicators in nonlinear form than the other two categories of methods (Singh et al., 2009; Gazzaz et al., 2012).

However, in the development of artificial intelligence methods (as is also the case in linear methods), the emphasis has conventionally been placed on the evaluation of one particular water resource at a time (Chang et al., 2001; Chau, 2006; Dahiya et al., 2007). Due to the separate evaluation indicators and standards (caused by heterogeneity in substances), different evaluation models must be established for surface water and groundwater, respectively. Gazzaz et al. (2012) used the artificial neural network model to evaluate the surface water quality, while Khaki et al. (2015) used it to evaluate the groundwater quality. Even for different cases of surface water (groundwater), different evaluation models are established (Singh et al., 2009; Gazzaz et al., 2012) because of diverse involved evaluation indicators (caused by spatial heterogeneity). In addition, existing artificial intelligence methods for surface water or groundwater quality evaluation are insufficiently user-friendly, as they are usually expressed in the form of a programming language. The optimized method developed in one study can rarely be used by other water quality evaluators. In general, it is so unpractical and uneconomic for water managers to repeatedly establish similar evaluation models for different water quality evaluation cases of both surface water and groundwater.

To overcome that, we intend to build a universal model with a simple mathematical expression that is suitable for different water quality evaluation cases of both surface water and groundwater. It is so convenient for the water quality managers use one simple equation to evaluate the water quality of multiple cases, and which can then act as a standard method for a region or country. The developed universal calibrated model is based on artificial intelligence methods, which we hope will provide a strong starting point for developing more sophisticated models in the future. The main steps in this research are as follows: First, to account for units and values variations among evaluation indicators for surface water and groundwater, we simultaneously normalized the indicators to make the data directly comparable. Second, we took advantage of the refined radial basis function (RBF) neural network to develop a universal model. In the RBF, the normalized classification grades of all evaluation indicators are treated as the training inputs, and the average of normalized grades is used as the central vector of the Gaussian function. The final calibrated model is then expressed as a formula rather than in a programming language, making it easier to understand and evaluate. In the final step, we performed a case study in China to demonstrate the use of the proposed method and confirm its validity.

2. Methods

A universal model for the evaluation of both surface water and groundwater quality is intended to be established. It is worth mentioning that the actual physical/chemical processes and the heterogeneity that characterizes the surface water and groundwater systems could influence the water quality (Bobba, 2012). Herein, the actual physical/chemical processes, which is usually include in water quality simulation model (Chau, 2006; Dietzel and Reichert, 2012), will not be considered in the established model for three reasons: 1) the processes are assumed to be completed before the water sampling stage; 2) the general water quality did not significantly change over time in the sampling stations without external force (e.g., waste discharge) (Gharibi et al., 2012), and 3) the responsiveness of the physical/chemical processes cannot be directly evaluated and have been shifted to the water quality indicators. Only the heterogeneity of surface water and groundwater system will be studied.

The heterogeneity of surface water and groundwater can be addressed in the following two aspects. One is the heterogeneity in substances of surface water and groundwater systems. Heterogeneity in substances is represented as different types and concentrations of physical, chemical and biological indicators in surface water and groundwater systems. Two series of evaluation indicators and standards are used for the evaluation of surface water and groundwater quality, respectively. The other is the spatial heterogeneity of surface and groundwater systems. Spatial heterogeneity can be generally defined as the variability of evaluation indicators involved in different surface water and groundwater evaluation cases. For water quality evaluation, spatial heterogeneity involves complexity in two aspects: (1) number of evaluation indicators involved, (2) types of evaluation indicators involved. To deal with the heterogeneity, a new model is proposed suitable for different cases of both surface water and groundwater quality evaluation. The framework of the proposed model is shown in Fig. 1 and detailed information about the proposed model is described as following.

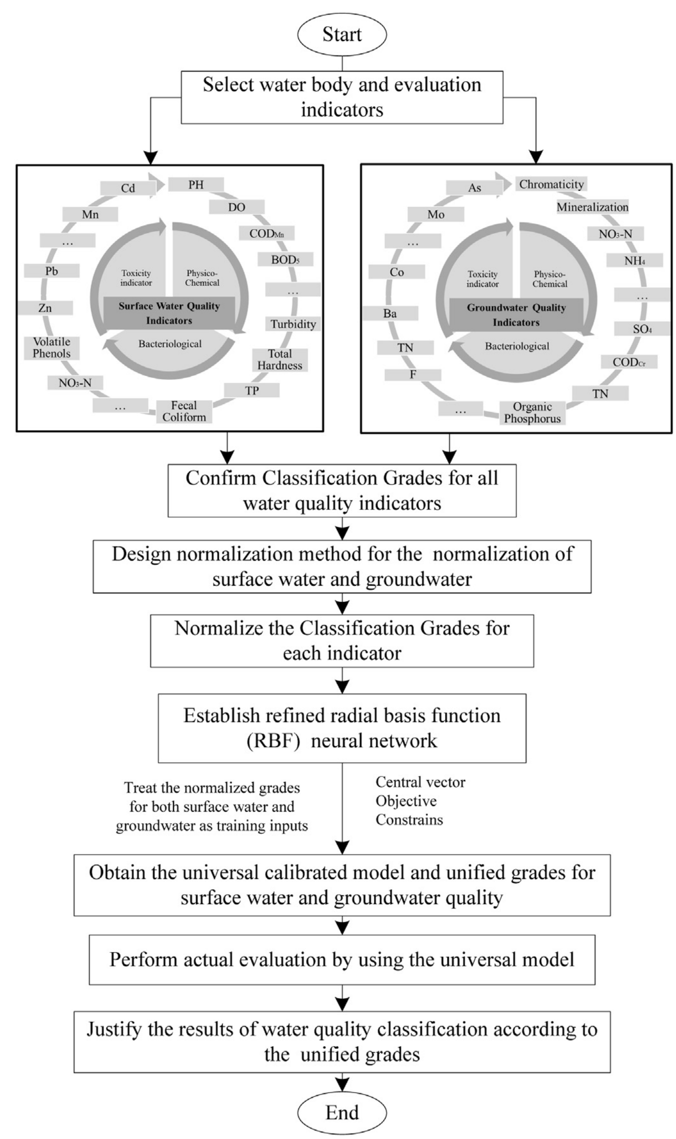

Fig. 1. The framework of the proposed model.