Journal of Hydrology 541 (2016) 1303–1315

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

Effectiveness evaluation of objective and subjective weighting methods for aquifer vulnerability assessment in urban context

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ARTICLE INFO

Article history:
Received 21 May 2016
Received in revised form 12 August 2016
Accepted 18 August 2016
Available online 20 August 2016
This manuscript was handled by Corrado Corradini, Editor-in-Chief, with the assistance of Philip Brunner, Associate Editor

Keywords:
Groundwater vulnerability
GIS
Entropy information method
Fuzzy pattern recognition
Single-parameter sensitivity analysis
Grey incidence analysis

ABSTRACT

Groundwater vulnerability assessment has been an accepted practice to identify the zones with relatively increased potential for groundwater contamination. DRASTIC is the most popular secondary information-based vulnerability assessment approach. Original DRASTIC approach considers relative importance of features/sub-features based on subjective weighting/rating values. However variability of features at a smaller scale is not reflected in this subjective vulnerability assessment process. In contrast to the subjective approach, the objective weighting-based methods provide flexibility in weight assignment depending on the variation of the local system. However experts' opinion is not directly considered in the objective weighting-based methods. Thus effectiveness of both subjective and objective weighting-based approaches needs to be evaluated. In the present study, three methods – Entropy information method (E-DRASTIC), Fuzzy pattern recognition method (F-DRASTIC) and Single parameter sensitivity analysis (SA-DRASTIC), were used to modify the weights of the original DRASTIC features to include local variability. Moreover, a grey incidence analysis was used to evaluate the relative performance of subjective (DRASTIC and SA-DRASTIC) and objective (E-DRASTIC and F-DRASTIC) weighting-based methods. The performance of the developed methodology was tested in an urban area of Kanpur City, India. Relative performance of the subjective and objective methods varies with the choice of water quality parameters. This methodology can be applied without/with suitable modification. These evaluations establish the potential applicability of the methodology for general vulnerability assessment in urban context.

1. Introduction

Groundwater vulnerability for an area is defined as the relative chance of groundwater getting contaminated due to geological and hydrogeological characteristics of aquifer (Neshat and Pradhan, 2015a). Generally, secondary information is used to infer the possibility of future contamination for a particular area. Index-based vulnerability heavily depends on the scale of data availability, analysis, spatial map resolution and final visualization. Among the various vulnerability assessment methods in use, DRASTIC (Aller et al., 1985) is the most popular. However, it is rigid in assigning ratings and weights to the sub-features and features, (Thirumalaivasan et al., 2003) respectively. Proper representation of the regional problems cannot be achieved with this inflexible approach of weight assignment. The present study proposes three methods - Entropy information method, Fuzzy pattern recognition method and Single parameter sensitivity analysis, for modifying the weights of the DRASTIC parameters to consider local variations. Moreover, effectiveness of these methods was evaluated based on grey incidence analysis.

DRASTIC uses a numerical ranking system to assess groundwater pollution potential in the hydrogeologic settings (Sahoo et al., 2016a). This system contains three significant parts: weights, ranges and ratings (Aller et al., 1985). The weights are assigned to the features (i.e. Depth to the water table, Recharge rate, Aquifer media, Soil media, Topography, Impact of vadose zone and hydraulic Conductivity). The features are again classified into different ranges or sub-features. The sub-features are assigned ratings. The rigidity in assigning weights in DRASTIC may put the reliability of assessing vulnerability of the study area into a questionable position. To ensure a proper assessment of vulnerability and representation of regional complexities, direct mathematical computa-

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http://dx.doi.org/10.1016/j.jhydrol.2016.08.035
0022-1694/

tion of the observations is required. There are two approaches used for weight calculation– subjective methods and objective methods (Wang and Lee, 2009). The subjective weighting methods decide weights solely according to the preference or judgments of decision makers. The decision makers' preferences are then followed by application of some mathematical models e.g., weighted least squares method, mathematical programming models to calculate the overall evaluation of each decision maker (Wang and Lee, 2009). The objective weighting method, on the other hand, calculates weights by solving mathematical models automatically without any consideration of the decision makers' preferences (e.g. entropy method) (Wang and Lee, 2009). The actual observations are put to use for calculation purpose in objective weighting methods.

The single-parameter sensitivity analysis (Napolitano and Fabbri, 1996) is a method for comparing effective weight that each feature has on each subarea (a cluster of pixels with unique combination of the D, R, A, S, T, I and C). Subjectivity is associated with the selection of ratings and weights that have to be assigned to the DRASTIC sub-features and features, respectively (Napolitano and Fabbri, 1996). A very recent study by Pacheco et al. (2015) showed that the weights calculated by this method can be used as modified DRASTIC weights. Pacheco et al. (2015) used this method along with three other methods – Spearman correlation, logistic regression and correspondence analysis. The weight modifications by these techniques were based on statistical methods. Their study tried to draw a correlation between the nitrate concentrations and ratings assigned to the sub-features. These weight modification techniques were indirect in nature. The single-parameter sensitivity analysis, however, was GIS-based and a direct method for calculating weights. Single-parameter sensitivity analysis has been used by many researchers for effective weight calculation of DRASTIC parameters (Babiker et al., 2005; Al-Hanbali and Kondoh, 2008; Rahman, 2008; Yu et al., 2012; Sener et al., 2013; Pathak et al., 2009; Neshat and Pradhan, 2015a,b).

Several methods related to fuzzy-based approaches have been used in vulnerability assessment problems. Fuzzy pattern recognition method (Zhou et al., 1999; Shouyu and Guangtao, 2003; Pathak et al., 2008), GIS-based fuzzy-rule based tool (Dixon et al., 2002; Dixon, 2005), fuzzy inference method (Afshar et al., 2007) and fuzzy hierarchical clustering method (Nobre et al., 2007) had been used with DRASTIC for vulnerability assessment. The GIS-based fuzzy-rule based tool uses GIS coupled with fuzzy inference engine. Fuzzy inference method employs a set of rules upon which the decisions are made. These rules involve experts' knowledge. Fuzzy hierarchical model includes fuzzy logic system and allows human reasoning to be incorporated in its algorithm. These methods are dependent on experts' judgment and hence, are purely of subjective nature. Fuzzy pattern recognition method, on the other hand, is an objective weighting method which is based on fuzzy pattern recognition model and takes into account the uncertainty associated with vulnerability assessment efficiently (Shouyu and Guangtao, 2003).

The entropy information method considers the variability in the information. The effects of decision-makers in calculation of weights are eliminated. Entropy-based weight modification had been integrated with fuzzy logic to modify weights of DRASTIC features (Yu et al., 2012). Entropy concept of weight modification has been used in water quality assessment (Zou et al., 2006; Jianhua et al., 2011) and in other water resources studies (Singh, 1997). The application of entropy weight modification has never been used independently for the DRASTIC weight modification. A brief review on the various subjective and objective weight modification methods is presented in Table 1.

The efficacy of the subjective and objective weight modification methods in the present study was determined from the correlation between water quality parameters and vulnerability indices. Grey incidence analysis (Deng, 1989) proves to be an efficient method when the data does not satisfy any typical type of probability distribution (Liu and Lin, 2010). This analysis proves to be a good method in extracting important statistical characteristics irrespective of the sample size. It can analyze systems where statistical methods do not give appropriate results (Liu and Lin, 2006). This method determines correlation between variables based on the similarity between geometric curves of the data sequences. In the field of water resources studies, grey incidence analysis had been used in very few studies (Wong et al. (2006): hydrological time-series analysis; Ip et al. (2009): river water quality evaluation).

The literature on DRASTIC suggests that most of the works have focused on the vulnerability assessment of a specific study area. The present study emphasized on the effectiveness evaluation of the vulnerability assessment methods instead. The aim of the present work is to evaluate the effectiveness of the subjective and objective weight modification methods using grey incidence analysis. The DRASTIC method and Single-parameter sensitivity analysis are the subjective weighting methods; and entropy information method and fuzzy pattern recognition method are the objective weighting methods. This study included techniques which directly calculate or modify weights and do not depend upon indirect methods of weight modification through correlation with water quality parameters. Grey incidence analysis-based validation of modified DRASTIC methods is a new attempt made. In general, vulnerability assessment studies are carried out on a watershed scale or aquifer scale. The present study has made an attempt to carry out the vulnerability assessment on a city scale. This study also attempted to assess the groundwater vulnerability for an urban setup, unlike the usual agricultural land use scenarios.

2. Methodology

Subjective weighting methods depend on the expert-opinion while the objective methods stress on the mathematical evaluation of data. Potential uncertainty in expert judgment is the main disadvantage of the subjective methods, while the objective methods do not benefit from the knowledge and experience of the decision-makers (Alemi-Ardakani et al., 2016). DRASTIC method uses weights decided by a team of experts (Aller et al., 1985). The DRASTIC method is classified as a subjective method. The single-parameter sensitivity analysis uses the same weights of DRASTIC to analyze the effect of single input data on the final resultant map. The single-parameter sensitivity analysis is, thus, categorized under subjective weighting method. The entropy information method and fuzzy pattern recognition method involve mathematical calculations to derive weights of the parameters. These methods are, therefore, grouped under objective approaches of weight modification. The weight assigning and further evaluation procedures in subjective and objective methods are discussed in the following subsections (details of methodologies are described in Appendix A). The overall methodology for DRASTIC weight modification is presented in a schematic diagram in Fig. 1.

2.1. DRASTIC method

DRASTIC uses a numerical ranking system to assess groundwater pollution potential in the hydrogeologic settings. DRASTIC vulnerability index is calculated using Eq. (1).

$$DRASTIC = D_w D_r + R_w R_r + A_w A_r + S_w S_r + T_w T_r + I_w I_r + C_w C_r \qquad (1)$$

where subscript w and r denote weight and rating respectively. The DRASTIC features are Depth to the water table (D), Recharge rate