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Research article

A fuzzy-logic based decision-making approach for identification of groundwater quality based on groundwater quality indices

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ABSTRACT

Due to inherent uncertainties in measurement and analysis, groundwater quality assessment is a difficult task. Artificial intelligence techniques, specifically fuzzy inference systems, have proven useful in evaluating groundwater quality in uncertain and complex hydrogeological systems. In the present study, a Mamdani fuzzy-logic-based decision-making approach was developed to assess groundwater quality based on relevant indices. In an effort to develop a set of new hybrid fuzzy indices for groundwater quality assessment, a Mamdani fuzzy inference model was developed with widely-accepted groundwater quality indices: the Groundwater Quality Index (GQI), the Water Quality Index (WQI), and the Ground Water Quality Index (GWQI). In an effort to present generalized hybrid fuzzy indices a significant effort was made to employ well-known groundwater quality index acceptability ranges as fuzzy model output ranges rather than employing expert knowledge in the fuzzification of output parameters. The proposed approach was evaluated for its ability to assess the drinking water quality of 49 samples collected seasonally from groundwater resources in Iran's Sarab Plain during 2013–2014. Input membership functions were defined as “desirable”, “acceptable” and “unacceptable” based on expert knowledge and the standard and permissible limits prescribed by the World Health Organization. Output data were categorized into multiple categories based on the GQI (5 categories), WQI (5 categories), and GWQI (3 categories). Given the potential of fuzzy models to minimize uncertainties, hybrid fuzzy-based indices produce significantly more accurate assessments of groundwater quality than traditional indices. The developed models' accuracy was assessed and a comparison of the performance indices demonstrated the Fuzzy Groundwater Quality Index model to be more accurate than both the Fuzzy Water Quality Index and Fuzzy Ground Water Quality Index models. This suggests that the new hybrid fuzzy indices developed in this research are reliable and flexible when used in groundwater quality assessment for drinking purposes.

1. Introduction

Groundwater is a major water resource in semiarid areas; its quality and availability are key issues for environmental managers and hydrogeologists (Jiang et al., 2009; Bain et al., 2014). Groundwater is often one of the few reliable resources of water available to rural communities in semiarid areas such as Iran (Girman et al., 2007) where population growth and the resulting intensification of water demand is causing increased scarcity of drinking water resources. Temporal changes in the origin of the recharged water, hydrologic events, and anthropogenic activities may cause periodic changes in groundwater quality (Vasanthavigar et al., 2010). Generally, water quality declines during passage downstream and through movement from a recharge zone to a discharge. Numerous methods to evaluate drinking water quality criteria are available in the published literature (Lumb et al., 2011).

A pioneer in the field, Horton (1965) defined the Water Quality Index (WQI), ranging from 0 (poor) to 100 (ideal), based on eight

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Nomenclature

AI	Artificial Intelligence
AMSL	Above Mean Sea Level
BOD_5	Biological Oxygen Demand (over 5 days of incubation at 20 °C)
CAM	Cosine Amplitude Method
CCME-WQI	Canadian Council of Ministers of the Environment Water Quality Index
DO	Dissolved Oxygen
FGQI	Fuzzy Groundwater Quality Index
FGWQI	Fuzzy Ground Water Quality Index
FIS	Fuzzy Inference Systems
FWQI	Fuzzy Water Quality Index
GIS	Geographic Information System
GQI	Groundwater Quality Index
GWQI	Ground Water Quality Index
TDS	Total Dissolved Solids
WHO	World Health Organization
WQI	Water Quality Index

water quality parameters weighted according to their relative importance. Horton's efforts were followed by research that strived to develop less subjective and more sensitive WQIs (e.g. Bolton et al., 1978; Liou et al., 2004; Said et al., 2004; Nasiri et al., 2007; Dos Santos Simoes et al., 2008; Cordoba et al., 2010; Vicente et al., 2011; Zhao et al., 2013; Nazeer et al., 2014; Al-Mutairi et al., 2014; Aminu et al., 2014). An improved version of the WQI (Brown et al., 1970), in which relevant parameter selection followed the Delphi method, was adopted in the United States by the National Sanitation Foundation (NSF-WQI). The Canadian Council of Ministers of the Environment Water Quality Index (CCME-WQI) developed an updated approach (CCME, 2001). The main changes in recently developed WQIs are found in the interpretation and calculation procedures (Lumb et al., 2011). The WQI methods are not perfect and weaknesses include assigning input parameter weights, their interpretation, index calculation methods, and appropriate WQI ranges denoting acceptable water quality (Lumb et al., 2011; Abbasi and Abbasi, 2012; Mohebbi et al., 2013).

Most WQI studies have used surface water quality indices for groundwater quality assessment even though the important parameters in surface and groundwater quality are different. Biological and physicochemical parameters are important for surface water, whereas hydrochemical parameters like major anions and cations are important in groundwater quality assessment. In a first attempt to develop a WQI for groundwater, Tiwari and Mishra (1985) employed the surface WQI to rank groundwater for drinking purposes. While many groundwater quality assessment studies mimicked this procedure over the years (Ramachandramoorthy et al., 2010; Chaturvedi and Bassin, 2010; Ketata-Rokbani et al., 2011; Sadat-Noori et al., 2014), others used different approaches and modes of interpretation to develop groundwater specific WQIs (Banoeng-Yakubo et al., 2009; Giri et al., 2010; Banerjee and Srivastava, 2011; Shi et al., 2013; Mohebbi et al., 2013; El-Fadel et al., 2014; Abtahi et al., 2015).

A simple WQI based on nine hydrochemical parameters including heavy metals was proposed by Soltan (1999) to assess the water quality of 10 artesian wells located near the Dakhla oasis in Egypt. On the basis of drinking water guidelines, Stigter et al. (2006) developed a groundwater quality index and a composition index using a correspondence factor analysis on several important groundwater hydrochemical parameters. Vasanthavigar et al. (2010), working in Tamilnadu, India, used 12 hydrochemical parameters to evaluate groundwater quality for drinking purposes.

In some cases, researchers have attempted to develop groundwater quality indices that specifically considered important physicochemical parameters. Based on the NSF-WQI and using normalized parameter values rather than sub index values, Saeedi et al. (2010) developed a robust indexing methodology for groundwater - the Ground Water Quality Index (GWQI). When faced with the difficulty of water quality studies in inaccessible regions, hydrogeologists began to use Geographic Information Systems (GIS) in an effort to better understand the spatial distribution of water quality parameters (Selvam et al., 2014). Babiker et al. (2007) proposed a GIS-based Groundwater Quality Index (GQI) that used a statistical methodology to translate water quality parameters into a new index consistent with WHO standards.

Notwithstanding the wide scope of these studies, the deterministic indices that have been proposed, and the WQI approaches that have been implemented in water quality assessment have not considered environmental and experimental uncertainties which occur throughout their assessment. Therefore, an advanced decision-making approach is required. Introducing a threshold of safety instead of a single value to WQI standards is one approach to overcome the difficulties in handling uncertainty in water quality evaluation (Dahiya et al., 2007).

To address problems in the WQI approach such as its failure to incorporate significant parameters of water quality and their inherent uncertainty, some new water quality assessment approaches based on Artificial Intelligence (AI) have been proposed (Nikoo et al., 2011; Gazzaz et al., 2012; Maiti et al., 2013; Patki et al., 2015). Fuzzy logic is one of the AI methods which has been extensively applied in the development of WQIs. Fuzzy logic is a promising tool for the development of environmental indices since it has the ability to reflect human understanding and expert knowledge. Also, it can deal with non-linear, uncertain and ambiguous datasets. The linguistic format of the model makes it more understandable for the public, managers, and non-experts (Gharibi et al., 2012a).

Introduced by Zadeh (1965), fuzzy logic is a mathematical discipline based on fuzzy set theory instead of classical mathematics. A recent increase in fuzzy model applications in the field of water quality assessment indicates that fuzzy-rule-based models are useful in solving water resources problems (Liou et al., 2003; Lermontov et al., 2009; Ocampo-Duque et al., 2013; Wang et al., 2014). Employing fuzzy sets instead of crisp values, Sii et al. (1993) addressed the uncertainties associated with water quality to create an applicable fuzzy set rather than the conventional scale of 0–100 generally used in WQI methodology. Based on fuzzy inference systems (FIS), Ocampo-Duque et al. (2006) proposed a fuzzy WQI wherein dissolved oxygen (DO) and organic matter (BOD_5) were represented by trapezoidal membership functions, and input levels were assumed to be adequate to evaluate water quality. Lermontov et al. (2009) developed a fuzzy WQI and compared its applicability to three conventional WQIs in Brazilian river watersheds, specifically testing the Fuzzy Water Quality Index on the Ribeira do Iguape River.

The novel fuzzy-logic-based surface water WQI for drinking water purposes devised by Gharibi et al. (2012a) provided more precise results than traditional methods. Another fuzzy-logic-based surface water WQI used by Ocampo-Duque et al. (2013) showed that the flexible boundaries among the linguistic terms in the fuzzy-logic-based WQI allowed for more accurate classification of

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