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Hydro-environmental management of groundwater resources: A fuzzy-based multi-objective compromise approach

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A B S T R A C T

Sustainable management of water resources necessitates close attention to social, economic and environmental aspects such as water quality and quantity concerns and potential conflicts. This study presents a new fuzzy-based multi-objective compromise methodology to determine the socio-optimal and sustainable policies for hydro-environmental management of groundwater resources, which simultaneously considers the conflicts and negotiation of involved stakeholders, uncertainties in decision makers' preferences, existing uncertainties in the groundwater parameters and groundwater quality and quantity issues. The fuzzy multi-objective simulation-optimization model is developed based on qualitative and quantitative groundwater simulation model (MODFLOW and MT3D), multi-objective optimization model (NSGA-II), Monte Carlo analysis and Fuzzy Transformation Method (FTM). Best compromise solutions (best management policies) on trade-off curves are determined using four different Fuzzy Social Choice (FSC) methods. Finally, a unanimity fallback bargaining method is utilized to suggest the most preferred FSC method. Kavar-Maharloo aquifer system in Fars, Iran, as a typical multi-stakeholder multi-objective real-world problem is considered to verify the proposed methodology. Results showed an effective performance of the framework for determining the most sustainable allocation policy in groundwater resource management.

1. Introduction

It is undeniable that significant damages and intense changes, including increasing air temperature, changes in precipitation, and therefore water crisis phenomenon have all been imposed by unsustainable human activities on environment (Dietz et al., 2003). Climate change, in particular, has caused consecutive droughts in arid and semi-arid areas like Iran, which in turn has led to accelerating water crisis and environmental problems in this area. Apart from droughts, other key factors such as mismanagement of water resources and lack of public awareness with respect to correct consumption of water resources in all agricultural, municipal and industrial sectors have intensified this phenomenon (Foltz, 2002).

Today, due to consecutive droughts, groundwater resources have become the major reliable source for water supply in most parts of the world (Gholami et al., 2015; Farhadi et al., 2016). In addition, industrial, agricultural and human activities have led to pollution of this limited water resource, and caused serious hydro-environmental problems (Re et al., 2014; Kazakis and Voudouris, 2015).

Hydro-environmental management of water resources is a multi-criteria decision making issue, which always necessitates socio-economical, environmental, and water quality and quantity considerations (Gleick, 2000; Peña-Haro et al., 2009; Madani et al., 2014; Roozbahani et al., 2015). Over the past years, instead of only considering economic aspects in multi-criteria decision making problems, more complicated aspects such as stakeholders' preferences and environmental issues have been examined (Van den Brink et al., 2008; Mirchi et al., 2010; Nikoo et al., 2016). In this regard, decision makers have implemented Social Choice (SC) methods in water resources and environmental problems to find the best solution among all optimal alternatives. Laukkanen et al. (2002) considered approval voting approach in a natural resource management, and compared it with some other methods. Multi-criteria approval method was introduced as a potential approach for forest planning. Srdjevic (2007) applied SC methods together with an analytic hierarchy process (AHP). Effectiveness of the proposed methodology was verified in a case study of San Francisco river basin, Brazil. The results showed this methodology could be more effective in a real decision making problem. Goetz et al. (2008) utilized two different sequential allocation rules for a share

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allocating problem of irrigation water among different agricultural stakeholders in Ebro Basin, Spain. Sheikhmohammady and Madani (2008) introduced different solutions based on SC rules and Fallback Bargaining (FB) method for negotiations over the legal status of Caspian Sea. Sheikhmohammady et al. (2010) applied SC rules, FB concept, and bankruptcy procedures to determine socio-optimal resolution for dispute among the five Caspian states. Results of the models were compared to ensure the best and most fair allocation of shares. Morais and de Almeida (2012) used a group decision-making based on all stakeholder's preferences to find the possible solution generally agreed by all different involved agents in a water resources problem. In addition, Mahjouri and Bizhani-Manzar (2013) applied Condorcet winner as a SC theory and two kinds of FB methods to find a compromise set of different alternatives for dischargers' treatment scenarios in a waste load allocation problem.

Uncertainties in behavior and preferences of involved stakeholders and influential physical parameters of the system can have very significant impacts on determining the most agreeable solution for decision makers in water resource management. To deal with uncertainties in social desirability and preferences of decision makers, fuzzy-based approaches for SC methods have been proposed (Nurmi, 1981; Zahariev, 1987; Kacprzyk et al., 1992, 2008; García-Lapresta and Martínez-Panero, 2002; Zarghami, 2011). Due to simplicity and good performance, application of Fuzzy Social Choice (FSC) methods have recently increased in hydro-environmental management problems. Madani et al. (2014) combined voting methods with a Monte-Carlo selection to consider uncertainties in Sacramento-San Joaquin Delta's water export conflict. In order to make decisions under uncertainty, SC methods were applied to determine the most preferred alternative. This methodology, also examined the risk of each alternative selected by different decision makers. Mahjouri and Abbasi (2015) developed a waste load allocation model considering uncertainties related to randomness and imprecision of input parameters of their model. Fuzzy parameters with probability distribution functions were considered to cope with uncertainty. SC methods were employed to select the final alternative among optimal solutions.

Although there have been very limited efforts in application of fuzzy group decision making and fuzzy SC in water resources management in the last decade, there is no study to examine application of FSC methods to consider uncertainty in decision making in hydro-environmental management of groundwater resources. This study discusses the significance of incorporating conflicting objectives of stakeholders and uncertainties in their preferences in integrated groundwater quality and quantity management. The main purpose of this study is to provide a new fuzzy multi-objective groundwater allocation model based on multi-objective qualitative and quantitative simulation-optimization model, FSC methods and FTM, which simultaneously considers the conflicts and negotiation of main stakeholders, uncertainties in decision makers' preferences, existing uncertainties in the groundwater parameters (input data) and groundwater quality and quantity issues. This paper examines application of four FSC methods including Fuzzy Borda Count (FBC), Fuzzy Approval Voting (FAV), Fuzzy Min-Max (FMM) and Fuzzy Linguistic Quantifier (FLQ) to determine socio-optimal and sustainable policies for a hydro-environmental management of groundwater resources. Optimal allocation policies are determined to meet agricultural, industrial and domestic demands considering water quality issues, main uncertainties and multi-stakeholder interactions. The proposed framework is used for a real-world case study, Kavar-Maharloo aquifer in Fars, Iran, which is developed utilizing qualitative and quantitative groundwater simulation models (MODFLOW and MT3D), multi-objective optimization model (NSGA-II), Monte Carlo analysis, general FTM and FSC methods.

In the following section, Kavar-Maharloo aquifer in Fars, Iran, is presented as a case study. In the "methodology" section, the main steps in the proposed methodology for developing fuzzy multi-objective groundwater allocation model is described. Uncertainty analysis and general FTM are discussed. Then, different involved stakeholders in the problem and their objective function are presented. Four different FSC methods are briefly described. Lastly, results of applying the developed methodology on a real-world groundwater system are presented and compared.

2. Study area

Due to consecutive droughts in most plains of Iran, particularly in Fars province, groundwater resources have become the major reliable source of water supply in different industrial, agricultural and domestic sectors. Excessive groundwater withdrawals, regardless of the extraction capacity of this resource, not only has led to sharp drops in groundwater levels, but also contributed to saltwater intrusion into freshwater aquifers, and disturbed the hydrostatic equilibrium between salt and fresh waters in some areas. As a result, numerous environmental problems including groundwater quality deterioration, water-table decline, increase in soil salinity, and land subsidence have emerged. One of these plains is Kavar-Maharloo aquifer system, located in central parts of Fars province, Iran (Fig. 1). This plain has a total area of 323 km^2 with about 147.10 km^2 of flat and 175.90 km^2 of elevated areas. In addition, Kavar-Maharloo plain covers 131.5 km^2. Maharloo Lake, the largest saline lake (saltier than seawater) in Fars province, located in north-eastern parts of the plain. There are 882 water withdrawal sources including wells, springs, and qanats in the Kavar-Maharloo area. Water level observations show a sharp decline of 11.8 meters over an 11-year period (2004–2014), indicating an average annual drop of 1.08 meters (Fars Regional Water Organization, 2014). In order to apply the proposed methodology on the study area, Kavar-Maharloo aquifer was divided into six groundwater management subregions (Fig. 1) and it was modeled in MODFLOW. Then, different groundwater allocation policies for hydro-environmental management of the aquifer with multi-stakeholders' interactions and groundwater contaminations were analyzed using multi-stakeholder multi-objective optimization models and FSC methods.

Required data for developing groundwater simulation model including hydrogeological and hydrological data are collected from Fars Regional Water Organization as a branch of Iran's Ministry of Energy. The range and statistical properties of the collected input data for groundwater simulation model are presented in Table 1.

3. Methodology

A flowchart for the overall structure of the proposed fuzzy multi-objective groundwater allocation methodology for hydro-environmental management of groundwater resource using FSC is presented in Fig. 2. The main parts of the proposed structure are discussed in detail below.

In the first step, MODFLOW and MT3D were used to develop a qualitative-quantitative groundwater simulation model. The changes of groundwater drawdown and Total Dissolved Solid (TDS) concentration are considered as quantitative and qualitative behavior of Kavar-Maharloo aquifer system, which are simulated via calibrated MODFLOW and MT3D models after applying different allocation scenarios. MODFLOW is a three-dimensional model based on finite difference solution to solve equations of a groundwater flow system (Harbaugh and McDonald, 1996). In addition, MT3D is a three-dimensional transport simulator, which solves the partial differential equation for solute transport based on a finite difference solution and simulates advection, dispersion and