



Coupled Simulation-Optimization Model for the Management of Groundwater Resources by Considering Uncertainty and Conflict Resolution

Khadije Norouzi Khatiri, et al. *[full author details at the end of the article]*

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Abstract

Determining the optimized policies in the exploitation of groundwater water resources is a complicated issue, especially when there are several different managers with conflicting goals. The current study presents a new multi-purpose method to reach a compromise among different stakeholders by determining optimal social policies and sustainable hydro-environmental management of underground water resources. This method simultaneously considers qualitative and quantitative simulation and optimization, stakeholders' preferences, and uncertainty analysis. In this study, the recharge was determined and incorporated in MODFLOW groundwater current model and MT3DMS pollution transfer model by using the hydrological model SWAT. In addition, DREAM (zs) algorithm (derived from algorithms based on Markov chain Monte Carlo) was used to examine the uncertainty of MODFLOW model parameters. The optimal head and TDS rate were determined in the studied aquifer by linking the model with MOPSO. Then, the Pareto frontier derived from the previous step, was utilized to determine the allocation rate of groundwater resources among a set of non-dominated solutions using Social Choice Rules (SCR) including Condorcet, Median Voting Rule (MVR), and Fallback Bargaining (FB) including unanimity fallback bargaining and fallback bargaining with impasse. The results showed that almost all the selected methods of conflict resolution in this research behaved similarly, and their results were not significantly different from each other. However, the comparison of these methods indicated that the MVR with the minimum reduction in withdrawal discharge and the maximum elevation in response to optimal allocation policies had the best performance. The amount of water extracted from the study area is about 540 million m³/year, which reaches 395 million m³/year.

Keywords Simulation-optimization · Groundwater · MOPSO · Uncertainty · Social choice · Conflict resolution

1 Introduction

Increased demand for water as well as reduced rainfalls and surface flows can negatively affect the groundwater resources, which are sometimes the only available resources in arid and semi-arid regions. In addition, groundwater resources might be overused if they are shared between

several stakeholders (Ostrom 1990; Esteban and Dinar 2013; Mahmoodzadeh et al. 2014; Huang et al. 2016).

The hydro-environmental management of water resources is a multi-criteria decision-making issue, requiring various social, economic, and environmental considerations as well as issues related to the quality and quantity of the water (Gleick 2000; Peña-Haro et al. 2009; Madani et al. 2014; Roozbahani et al. 2015).

Over the past few years, instead of taking into account only the economic considerations in multi-criteria decision-making issues, various complicated aspects such as the stakeholders' preferences and environmental issues have been examined (van den Brink et al. 2008; Andik and Niksokhan 2020).

Several researchers have recently used Fallback Bargaining (FB) and Social Choice Rules (SCR) to solve the conflicts. The FB method aims to maximize all stakeholders' minimum satisfaction by simulating negotiations among the stakeholders so that they prefer to gradually withdraw for reaching an agreement irrespective of their superior choices (Brams and Kilgour 2001). On the other hand, the SCR method considers some principles which determine a suitable choice for the stakeholders with different preferences and priorities in choosing the possible choices (Serrano 2004). Table 1 shows a summary of the studies on groundwater management.

SCR has been widely used water trade and its related economic aspects (Howe et al. 1986; Easter and Hearne 1995; Barberà et al. 1997; Lee and Jouravlev 1998). Raquel et al. (2007) determined the optimal scenario for groundwater withdrawal in Guanajuato state in Mexico using four different conflict resolution methods. They used game theory for determining the optimal allocation among 12 different scenarios of groundwater withdrawal. In another study, Sheikhmohammady and Madani (2008) used SCR and FB for conflict resolution of the common resources in the Caspian Sea by proposing five choices during the negotiations. Read et al. (2013) considered a wide range of social choice models, FB, and MCDM for choosing a suitable energy resource for Fairbanks in Alaska, as a multicriteria-multi-decision-maker problem. It included a large number of stockholders requiring consideration of economic, political, social, and environmental criteria in reaching the decision for presenting the best solution. Madani et al. (2015) presented a method to analyze bargaining problems of Sacramento Delta in California in which the stakeholders were not aware of the outcome of the different results of the bargaining. They combined Mont-Carlo method with FB to map uncertainty in random bargaining problems. The problem was modeled as a bargaining game in which the environment and water exporters strived to reach an agreement through bargaining while the outcomes resulting from implementation of different water export options were unknown. Degefu et al. (2016) used a combination of the bankruptcy theory and unsymmetrical Nash theories for water allocation in border rivers on the Nile. The results suggested that this method could be efficiently used for the conflict resolution of border rivers.

A serious concern in dealing with multi-objective models is the choice of an answer from among a set of non-dominated solutions forming the Pareto frontier curve. Alizadeh et al. (2017a, b) and Nafarzadegan et al. (2018) used SCR and FB methods to resolve the conflicts among various stockholders' objective functions and determine the desirable compromise solution. Martinez and Esteban (2014) proposed a system for groundwater allocation based on a type of Social Choice (SC) simulations. The uniformity rule was considered as a mechanism for the optimal allocation of water resources and compared with the ratio rule and the trade rule. Additionally, the optimization problem was solved with GAMS simulation, and the proposed structure was evaluated in the Western La Mancha aquifer in Spain.

Table 1 Summary of the previous studies on groundwater management

Author (year)	Simulation	Quality		Uncertainty	Optimization	Game theory or Conflict resolution	Surface water models	Case study
	Quantity	Quantity	Quality					
Raquel et al. (2007)	Groundwater loading effects of agricultural management systems (No grids: three large aquifers)				Linear programming	Cooperation of all beneficiaries (grand coalition)		ARLID irrigation District, Guanajuato, Mexico
Bazargan-Lari et al. (2009)	MODFLOW	MT3D			NSGA-II	YCRT		Tehran aquifer, Iran
Kerachian et al. (2010)	MODFLOW	MT3D			NSGA-II	RSBT		Tehran aquifer, Iran
Martinez and Esteban (2014)						SCR social choice		Western La Mancha aquifer, Spain
Zekri et al. (2014)	Qualitative linear simulation (No grids: a single hypothetical aquifer)					Cooperation of all beneficiaries		Example (A coastal region in Oman)
Parsapour-Moghaddam et al. (2015)	MODFLOW				NSGA-II	MCSGA and NGA		Rafsanjan plain, Iran
Alizadeh et al. (2017a)	MODFLOW			Monte Carlo	NSGA-II	SCR-Fallback Bargaining		Tashk-Bakhtegan river basin, Iran
Alizadeh et al. (2017b)	MODFLOW			Monte Carlo	NSGA-II	SCR-Fallback Bargaining		Kavar-Mahanloo aquifer, Iran
Kamali and Niksookhan (2017)	MODFLOW				MOPSO		SWAT	Isfahan-Barkhoar, Iran
Moridi et al. (2018)	MODFLOW				Non-linear programming			A part of Tehran plain, Tehran province, Iran
Nazari and Ahmadi (2019)	MODFLOW				Multi-objectives optimization	Non-cooperative game theory		Bad-Khaledabad, Iran

During the past few decades, a large number of simulation-optimization models have developed which employed CACO, PSO, and GA optimizations for solving the problems related to groundwater resources (Ketabchi and Ataie-Ashtiani 2015; Kamali and Niksokhan 2017; Norouzi et al. 2020).

On the other hand, a number of contesting and incommensurable goals should be examined to identify optimal water allocation strategies (Nafarzadegan et al. 2018). Making decisions about the sustainability of the management of groundwater resources has always been a complicated problem. However, current simulation and optimization techniques for groundwater allocation do not consider various stakeholders' behaviors, gaps, and preferences. Therefore, it is absolutely crucial to manage groundwater resources in view of the conflicts related to social justice, economic efficiency, and environmental goals (Walker et al. 2015; Farhadi et al. 2016).

Game theory has an undeniably important role in the water resources management and conflict-resolution models for solving conflicts on shared, scarce groundwater resources among different stakeholders (Madani et al. 2015).

These studies used the results of resolution-optimization in different conflict resolution models to reach an optimal allocation. In addition, uncertainty in simulation models could significantly affect the determination of the best solution for different water management stakeholders.

A few studies on the management of groundwater resources have used uncertainty algorithms (Norouzi et al. 2020; Alizadeh et al. 2017a, b). Given the fact that the implementation of the simulation-optimization model is very time-consuming, several researchers prefer to use the meta-model. In the present study, simulation and optimization were directly linked using MATLAB.

After determining the best answer on the Pareto frontier curve and allocating the initial costs of the treatment, common methods of cooperative games such as Nucleolus were used. Niksokhan et al. (2009) considered the reallocation of the treatment costs. Bazargan-Lari et al. (2009) codified a conflict resolution simulation for combined exploitation of surface and groundwater resources while taking into account water quality problems. They used multi-objective simulation-optimization, NSGA-II, Young conflict resolution, and qualitative-quantitative simulations of groundwater of MODFLOW and MT3D to codify the conflict resolution simulation. In another study, Kerachian et al. (2010) applied the fuzzy game theory to manage groundwater resources by applying Rubenstein bargaining theory. NSGA-II was used to develop the trade-off curve between the objectives. In addition, Rubenstein Sequential Bargaining Theory (RSBT) was employed to reach a solution in the trade-off curve. Parsapour-Moghaddam et al. (2015) developed a method based on a new evolutionary game to determine the evolutionary stable equilibrium strategies in the combined exploitation of surface and groundwater for users with conflicting goals. Their proposed method did not provide a logical and realistic framework for describing water users' uncooperative behaviors in using joint surface and groundwater resources. For optimal allocation, the multi-objective NSGA-II model was linked to MODFLOW model. Further, a loss/damage function was used to control the decline in the groundwater level. The findings indicated that this method could be utilized for developing allocating surface and groundwater.

A review of the previous studies indicated that collaborative actions in cooperative approaches have more advantages compared with individual actions in non-cooperative

approaches. For example, Nakas et al. (2002), Esteban and Albiac (2012), and Esteban and Dinar (2013) maintained that the total net profits increased by 2.3%, 17%, and .6%, respectively.

In addition, given the environmental damages, the total net profits in Esteban and Albiac (2012) and Esteban and Dinar (2013) increased by 4% and 4.8%, respectively. To sum up, previous studies focused on implementing the cooperative management approach for groundwater resources by using different optimization tools, groundwater simulation models, and cooperative solution methods such as game theory, SCR, and FB (Nakas et al. 2002; Loáiciga 2002, 2004; Raquel et al. 2007; Esteban and Albiac 2012; Esteban and Dinar 2013; Zekri et al. 2014; Alizadeh et al. 2017a, b; Nafarzadegan et al. 2018; Moridi et al. 2018).

Stakeholders might have disagreements over a wide range of issues (e.g., water volume) in the optimal exploitation of groundwater resources. Therefore, it is highly important to find a solution through which reaching a compromise is facilitated and bargainers can retreat from their top priority positions to reach a fair outcome. The present study aimed to evaluate the efficiency of conflict resolution models to achieve such a solution. To this end, the feasibility of obtaining optimal solutions was examined in a multi-objective optimization problem through combining groundwater simulation models with optimization and conflict resolution models such that the different scenarios generated by the optimization model could be implementable via a simulation model in a purposeful interaction. The simulation results would be practical for optimization and conflict resolution models.

In this study, the given aquifer was first simulated using MODFLOW and MT3DMS quantitatively and qualitatively, whose recharge parameter was determined through SWAT simulation. The simulation was concurrently linked to the DREAM (zs) uncertainty algorithm, which minimized the errors of input parameters. Then, these parameters were used as the input for the simulation-optimization. Finally, the pareto frontier curve from the previous stage was used to obtain the extent of the groundwater resource allocation from among the nondominant set of solutions using Social Choice Rules (SCR) such as Condorcet, Median Voting Rule (MVR), and fallback bargaining including unanimity fallback bargaining and fallback bargaining with impasse. To the best of our knowledge, no study has examined groundwater management using the direct link between SWAT, MODFLOW, MT3DMS, DREAMzs, MOPSO, and the conflict resolution model. In the materials and methods section, the numerical models of groundwater, uncertainty, stakeholders, and their utility functions in optimization are described. Then, the procedures for simulation-optimization as well as the social rules are explained.

2 Study Area

The study area of Isfahan-Borkhar, covered with Isfahan Regional Water, is considered one of the prohibited and critical areas of Iran. With approximately 1500 km² aquifer area, it is one of the largest areas covered with Isfahan Regional Water (Kamali and Niksokhan 2017). Figure 1 shows the location of this area in Gavkhuni Basin and Isfahan Province.

There has been considerable pressure on water resources due to the high growth of population, industry, and agriculture in this region. Furthermore, considering the annual extraction of 438 to 604 m³/year from groundwater resources, the region is facing a continuous decline in water table level with an average of 97 cm/year and aquifer reservoir deficit of 84 m³.

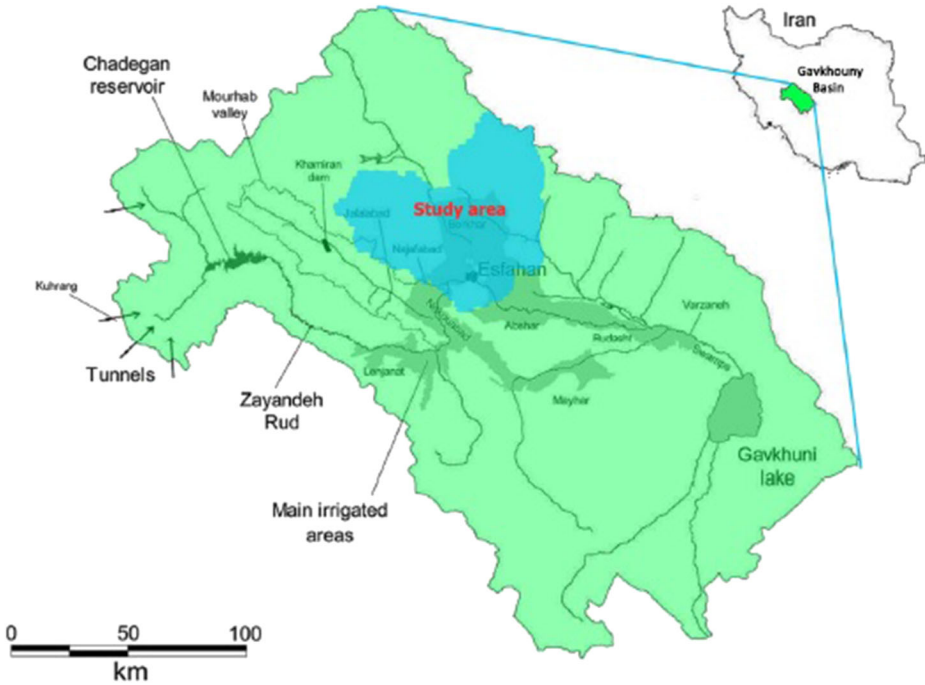


Fig. 1 Isfahan-Borkhar studied area

3 Methodology

The temporal and local distributions of the recharging parameter from the surface were first determined by a hydrological model (SWAT) (Arnold et al. 2012, 1998; Gassman et al. 2007). Subsequently, a quantitative and qualitative groundwater simulation model was developed based on the statistics and data available from the region as well as the recharge input of the SWAT model. To this end, GMS v10.1 was used thanks to its several special features such as the potential for the development of a conceptual model and automatic conversion to a numerical model as well as the compatibility with GIS-Based systems. In GMS, MODFLOW (McDonald and Harbaugh 1988) and MT3DMS (Zheng and Wang 1999) models were also used as the quantitative and qualitative simulators, respectively. Calibration of these models is very important prior to application in the prediction and evaluation of system responses against what is not observed. DREAM (zs) algorithm was used to analyze the uncertainty (Vrugt et al. 2009). This method, highly capable of investigating the parametric space with minimum replication, was linked to the simulator by a link coded in MATLAB. Then, the developed simulating models capable of calculating processes and necessities of planning for the aquifer exploitation were linked to a multi-objective metaheuristic optimizer model to optimize the exploitation of the studied aquifer and water resource system. To this end, Multiple Objective Particle Swarm Optimization (MOPSO) was used (Kennedy and Eberhart 1995). The decision variable in this optimizer model was the pump discharge values in the exploited wells. The objectives included minimization of annual groundwater table and groundwater quality changes as well as limitations such as supplying water requirement, pumping rate, and maximization of daily pumping hours. MODFLOW and MT3DMS simulating models were recalled for each

variable. Next, the general heuristic rules and updating of variables along with guidance of the evolutionary search process and the basic population continued in the metaheuristic optimization model for optimizing the exploitation and design variables to reach convergence. Coding was performed in MATLAB to link the simulation to the optimization. Next, the Pareto curve obtained in the previous stage was used to retrieve the amount of groundwater allocation among a set of non-dominated solutions using SCR and FB methods (Sheikhmohammady et al. 2010). Figure 2 outlines the research methodology.

4 Combining SWAT and MODFLOW Models

In this study, the consecutive or one-way combination method was used for combining SWAT and MODFLOW models. In SWAT, a basin is divided into several sub-basins which are further divided into subsets called Hydrological Response Units (HRUs). To develop the SWAT simulator model of Isfahan-Borkhar aquifer, the inputs including Digital Elevation Model (DEM), weather data, soil data, and land use data were divided into four categories. It should be noted that HRUs are a combination of land use, soil and, land slope.

The development and calibration of SWAT and MODFLOW models were carried out separately. The results of the SWAT model such as recharge were used as the input for the MODFLOW model. After developing the SAWT model, the groundwater recharge values and their temporal plus local changes were converted to the format of the data input in the MODFLOW model in GMS. The output of the SWAT model for recharge values included a text file in which the time series of recharge values for each HRU were presented in mm/month. The data related to each sub-basin were extracted from HRULandUseSoilsReport.txt (Kamali and Niksokhan 2017). These data included the HRUs number and the area of each HRU in every sub-basin as well as other data including the vegetation type, land slope, and soil type in each HRU. Based on the above issues, the recharge value in each sub-basin was calculated by considering the area of HRUs available in each and their recharge values using recharge formulas (Alemayehu et al. 2017). The abovementioned steps were taken via a computer program coded in MATLAB, creating recharge values in MODFLOW for each

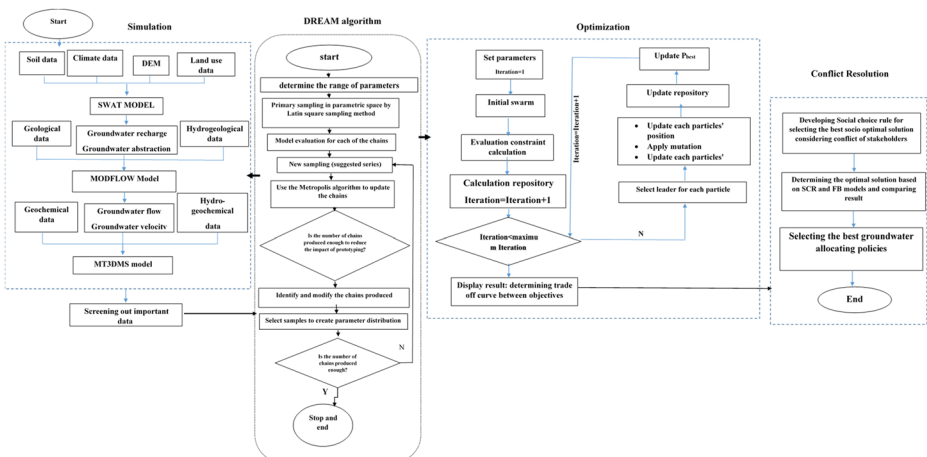


Fig. 2 A flowchart for research method Implementation Flowchart

sub-basin in the form of a text file from SWAT output files. The temporal pattern of the recharge values in the modeling scope was monthly from the beginning of a water year during 2002–2003 with 125-time steps.

5 Groundwater Numerical Model

After collecting and preparing the available data for developing the model, the aquifer recharge estimation was carried out by SWAT hydrological model. Subsequently, the conceptual aquifer quantitative model was developed in GMS and converted to MODFLOW quantitative numerical model (Kamali and Niksokhan 2017; Norouzi et al. 2020). Then, the quantitative numerical model was calibrated using a two-step calibration process. Isfahan-Borkhar aquifer is an unconfined aquifer, where gridding with equal sized cells (500×500) was used for the modeling. The initial head was interpolated through the head of observational wells and kriging algorithm in GIS. Hydraulic conductivity values were between 0.0001 and 100 m per day; horizontal anisotropy was between 10^{-10} and 100; storage coefficient ranged between 0.006 and 0.6, and the recharge was also calculated considering the SWAT model output, most of which were modified in the calibration process and ultimately, its value lied between 10^{-10} and 0.008 m per day (Kamali and Niksokhan 2017; Norouzi et al. 2020). MT3DMS is a powerful 3D numerical model for the simulation of the dissolved materials transfer in complex conditions and hydrological environments. This model is capable of simulating transfer processes either independently or collectively. MT3DMS is capable of simulating multiple pollutants and their reactions. Several researchers have linked this model to the MODFLOW model and facilitated solving the problems related to transfer with no need to develop a new model (Zheng and Wang 1999).

TDS in Isfahan-Borkhar aquifer was calculated using the values of observation wells. The aquifer qualitative conceptual model was developed in GMS and converted to MT3DMS qualitative numerical models. Then, the numerical qualitative model was calibrated through a one-step calibration process. Finally, this optimized model was used as the basis for the aquifer qualitative model development. The calibration operation of the qualitative modeling lasted for 96 months from 7 October (2002) to 7 October (2010). Furthermore, the validation was carried out for 29 monthly time steps from 7 October (2010) to 7 March (2013).

Figure 3 (a) demonstrates the calibrated steady-state result for 7 November (2002). Green, yellow, and red represent the errors under 0.5 unit, within the range of 0.5 and 1 unit, and larger than 1 unit, respectively. The results of the monitoring indicated that the major share of the computed groundwater elevation lies within a 0.5 m interval from the observed value. Figure 3(b) displays the validated outcome for the end of the simulation model, i.e. 7 March (2013). Table 2 shows the calibration and validation results of all the piezometers. The errors for heads indicated that MODFLOW is adequately calibrated

6 Uncertainty Module

The most recent MCMC method proposed by Vrugt et al. (2009) was used in this study, which improved the revised version of Global Optimization Algorithm of Shuffle Complex Evolution Metropolis (SCEM-UA). It is self-adaptive and can update the initial population within the framework of the initial population evolution (Vrugt et al. 2003). Using multiple chains

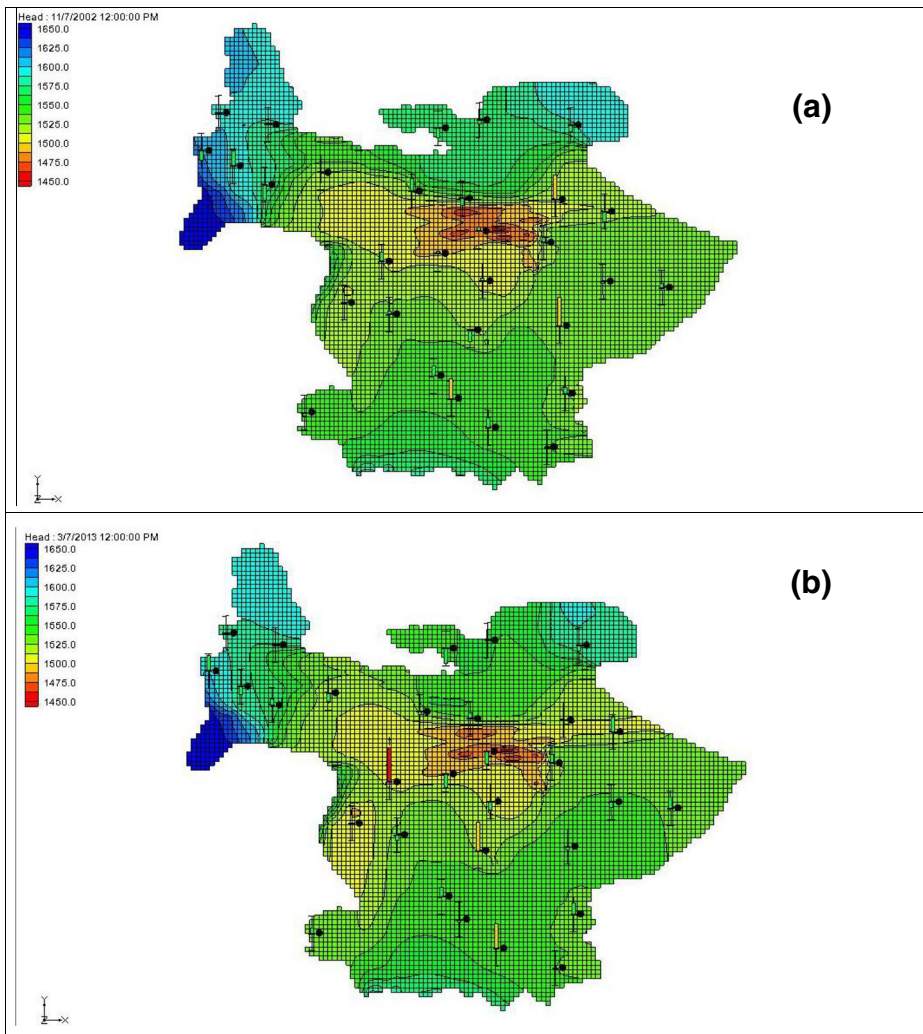


Fig. 3 Head of water: **a** 7 November 2002, and **b** 7 March 2013) at 125-time step)

simultaneously combined as well as Latin Hypercube Sampling (LHS) method as the posterior distribution, DREAM (zs) algorithm studies the feasible parameter space and automatically regulates the proposed distribution of the sampler towards the stationary target distribution.

1. Creating an initial population of parameters vector θ^i ($i = 1, \dots, N$) using posterior distribution.

Table 2 The result of quantitative model calibration

Errors	Mean error (m)	Mean absolute error (m)	Root mean squared error (m)
Transient calibration	-0.059	0.315	0.510
Validation	-0.012	0.121	0.337

- Evaluating the model using a set of selected parameters and calculating density $\pi(\theta^i)$ for each chain of i .

In the present study, the model was evaluated by Standard Least Squares (SLS). In calibration, the objective function of the square error sum is conventionally used to find the certain values of the parameters minimizing the objective function (Vrugt et al. 2008).

$$F_{SLS} = \sum_{i=1}^n e_i(\theta)^2 \quad (1)$$

where e is the difference between the observed head data and the simulated model data, and θ represents the parameters of the model.

- Calculation of mutation (dx^i) in the i^{th} chain using differential evolution (Storn and Price 1997; Price et al. 2005)

$$dx^i = (1 + e)\gamma(\delta \cdot d') \sum_{j=1}^{\delta} (\theta^{r_1(j)} - \theta^{r_2(j)}) + \varepsilon \quad (2)$$

$\theta^{r_1(j)}$ and $\theta^{r_2(j)}$ denote the parameters related to the two selected series of r_1 and r_2 in the previous chains which were randomly selected, e and ε are considered as random phrases, and γ indicates the coefficient depending on δ and d' , whose best estimation is expressed by $\gamma = \frac{2.38}{\sqrt{2\delta d'}}$ equation (Ter Braak 2006). δ is the number of paired chains applied to create the proposed series, and d' represents the number of parameters for the i^{th} chain whose value has changed in the proposed series.

- Creating the proposed parameter series (v^i) in each chain (i) using eq. 3 where θ^i is the parameter series in the previous step (the initial population).

$$v^i = \theta^i + dx^i \quad (3)$$

- Creating U vector with the size of $d \times 1$ is random and with uniform standard distribution (d is the number of parameters and $U \in [0,1]$), and subsequently substitution of each member of $V_j^i (j = 1, 2, \dots, d)$ with θ_j^i using the following design and via the confluence likelihood of CR:

$$v_j^i = \begin{cases} \theta_j^i & \text{if } U \leq 1 - CR. \quad d' = d' - 1 \\ v_j^i & \text{otherwise} \end{cases} \quad (4)$$

6. Calculating density $\pi(v^j)$ by using the objective function and Metropolis probability acceptance formula $\alpha(\theta^i, v^j)$ (Metropolis et al. 1953)

$$A(\theta^i, v^j) = \begin{cases} \min\left(\frac{\pi(v^j)}{\pi(\theta^i)}, 1\right) & \text{if } \pi(\theta^i) > 0 \\ 1 & \text{if } \pi(\theta^i) = 0 \end{cases} \quad (5)$$

7. Creating the random number of u with standard uniform distribution of ($u \in [0, 1]$) (If $\alpha > u$ or $\alpha = 1$, the series is acceptable, i.e. $\theta^i = v^i$. Otherwise, the last series of θ^i enters the chain)
8. Calculating Gelman and Rubin convergence diagnostic of R (only the parameter series reaching convergence is used ($R \leq 1.2$) for each posterior distribution parameter) (Gelman and Rubin 1992)

In this study, Hydraulic Conductivity (HC), Horizontal Anisotropy (HA), Storage Coefficient (SC), and Recharge (RCH) are considered as the input parameters with errors.

7 Stockholders

The present study aimed to implement the optimal policies of groundwater allocation. Hence, identifying decision-makers and stockholders as well as determining the objectives and their utilities are highly important. There are usually stockholders with different and often conflicting utilities in the exploitation of groundwater resources. In the studied region, there are two main stockholders, namely, farmers and the Department of Environment.

The major part of the studied region includes farmlands. In this region, the groundwater plays a significant role in supplying the water requirements. The groundwater table in this region had a great fall due to the latest droughts as well as unplanned exploitation of groundwater. Meanwhile, farmers prefer to increase their benefits by increasing the withdrawal of groundwater. Therefore, this sudden increase leads to augmented benefits for farmers, which results in groundwater drawdown. However, the decrease in the groundwater table is considered undesirable by the Department of Environment since it increases water salinity as well as land subsidence.

8 Optimization

MOPSO optimization method was used in the present study. Further details about this method were reported in Eberhart and Kennedy (1995). The decision variables in the optimization model are the pump discharge values in the well. The objective functions minimize both the quantitative and qualitative instability.

$$\begin{aligned}
 \text{Min } F_1 &= \sum_{t=1}^{N_{tp}} \sum_{j=1}^{N_j} |H_{tj} - H_{1j}| \text{ for } t = 1.2 \dots N_{tp} \text{ and } j \\
 &= 1.2 \dots N_j \tag{6} \\
 \text{Min } F_2 &= \sum_{t=1}^{N_{tp}} \sum_{j=1}^{N_j} |C_{tj} - C_{1j}| \text{ for } t = 1.2 \dots N_{tp} \text{ and } j \\
 &= 1.2 \dots N_j
 \end{aligned}$$

F_1 and F_2 represent the objective functions, N_{tp} is the total number of planning months which is equal to 125 months, N_j denotes the total number of model cells which is equal to 15,912, and H_{tj} shows the head of water at the t^{th} time step in the j^{th} cell. In addition, H_{1j} refers to the head of water in the first time step in the j^{th} cell, C_{tj} is the TDS of water in the t^{th} time step in the j^{th} cell, and C_{1j} represents the water TDS in the first time step in the j^{th} cell.

The constraints of the optimization in this study were quantitative and qualitative types. Qualitative constraints include limiting the TDS in wells while the quantitative constraints include limitations in accessible surface water, pump discharge in exploited wells, and water supply-demand.

$$GW_{tp} = t_d \sum_{k=1}^{NW} Q_{k,tp} \quad \forall t_p = 1 \dots N_{tp} \tag{7}$$

$$C_{k,tp} = f(\widetilde{C}, \widetilde{H}, \Omega, C_{Re,tp-1}) \quad \forall t_p = 1 \dots N_{tp} \tag{8}$$

$$SW_{tp} = D_{tp} - GW_{tp} \quad \forall t_p = 1 \dots N_{tp} \tag{9}$$

$$SW_{tp}^{min} \leq SW_{tp} \leq SW_{tp}^{max} \quad \forall t_p = 1 \dots N_{tp} \tag{10}$$

$$Q^{min} \leq Q_{k,tp} \leq Q^{max} \quad \forall t_p = 1 \dots N_{tp} \tag{11}$$

$$C^{min} \leq C_{k,tp} \leq C^{max} \quad \forall t_p = 1 \dots N_{tp} \tag{12}$$

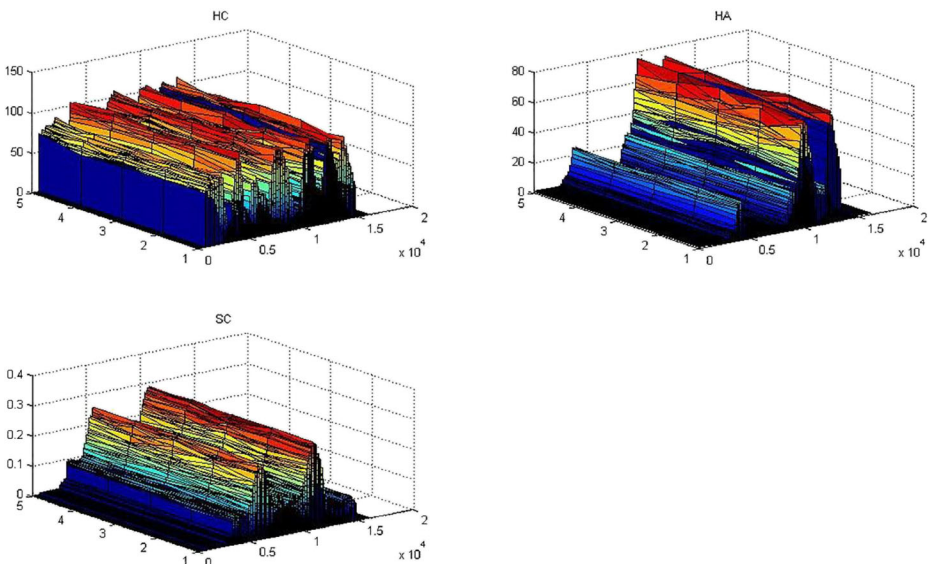
GW_{tp} is the total water pumped from the farming wells in the month of t_p , t_p represents the month counter, t_d denotes the number of days in the month of t_p , and $Q_{k,tp}$ shows the discharge of the k well in the month of t_p (m/day). Additionally, k is the well counter, NW refers to the total number of pumped wells available in the region, N_{tp} is the total number of planned

Table 3 Summary of approaches used for social decision-making and their procedure

Method	Description
Condorcet	The selected option is an option chosen by all the stockholders during paired comparison, compared with other options.
Median Voting Rule	The selected option is the option chosen by most of the stockholders at the maximum possible level of ranking.
Unanimity Fallback Bargaining	Unless there is no agreement between the bargainers, the bargainers decline in their utility (one rank each time) and lead to later and lower ranks until they reach an agreement on one option for the first time, while that agreement is not empty.
Fallback Bargaining with Impasse	Instead of reaching an agreement and reaching a lower utility, the bargainers prefer to put themselves in an impasse and do not lower their expectations below a certain level. They put an impasse in their utility row and do not accept below that at all.

months, C_{kt,t_p} represents the concentration of TDS in the k well in the month of t_p (mg/lit), SW_{t_p} is the amount of surfaced water consumed in the month of t_p (m^3), and D_{t_p} denotes the water demanded by farmers in the month of t_p based on squared meter. Further, $SW^{\min}_{t_p}$ shows the minimum consumed surface water in the month of t_p based on squared meter which is equal to zero (m^3), and $SW^{\max}_{t_p}$ indicates the maximum surfaced water consumed in the month of t_p based on squared meter which is equal to the total agricultural demands in the region (m^3). Furthermore, C^{\min} is the minimum TDS of the consumed water which is equal to zero, and C^{\max} denotes the maximum TDS of the consumed water which is equal to 2000 mg/lit. The demanded consumed water amount in the studied region, supplied from surface and groundwater, was 600 MCM.

In order to read the input set to be introduced into DREAM (zs) algorithm, it was necessary to prepare the input file format. Then, after inserting them in DREAM (zs) algorithm and correcting the current errors (uncertainty), another file was coded in MATLAB again so that MODFLOW model could read them and calculate the output. To this end, a code was

**Fig. 4** Inputs predicted by DREAM (zs) (HC, HA, SC)

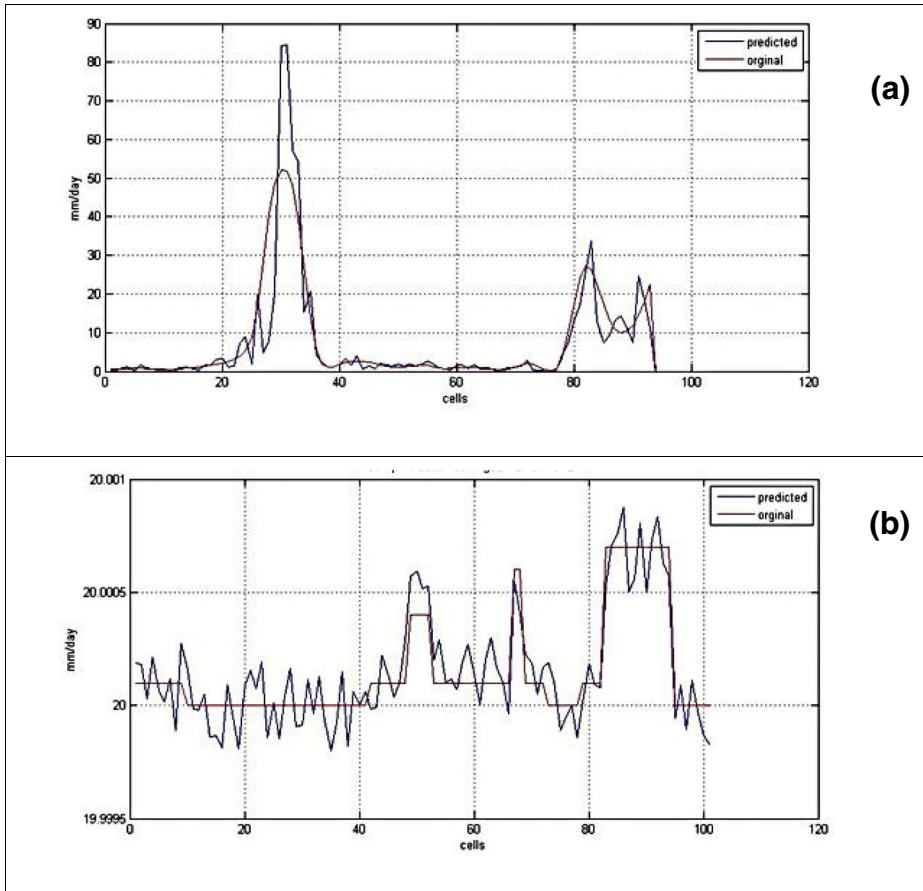


Fig. 5 Diagram of predicting hydraulic conductivity by **a.** Recharge, **b.** DREAM (zs) Algorithm, and comparison with observational values

developed so that the parameters would be separated from the model inputs and code them into the format necessary for the DREAM (zs) algorithm.

When the inputs (hydraulic conductivity HC, horizontal anisotropy HA, storage coefficient SC, & recharge RCH) were prepared with the format proper for DREAM (zs) algorithm, they were recalled by MODFLOW and inserted in DREAM (zs) algorithm whose output was the inputs estimated by the model based on the least head conflict. Subsequently, the MODFLOW model received the inputs from the previous stage and produced the outputs, which occurred as long as they converged. Then, the output from the previous stage was recalled by MOPSO. As to the objective functions, the most optimized head and TDS were calculated for each aquifer cell grid. The obtained results were entered into the conflict resolution model.

9 Conflict Resolution Model

Social decision-making methods are processes for extracting social preferences through considering all personal preferences (Madani et al. 2014). In this research, SCR and FB

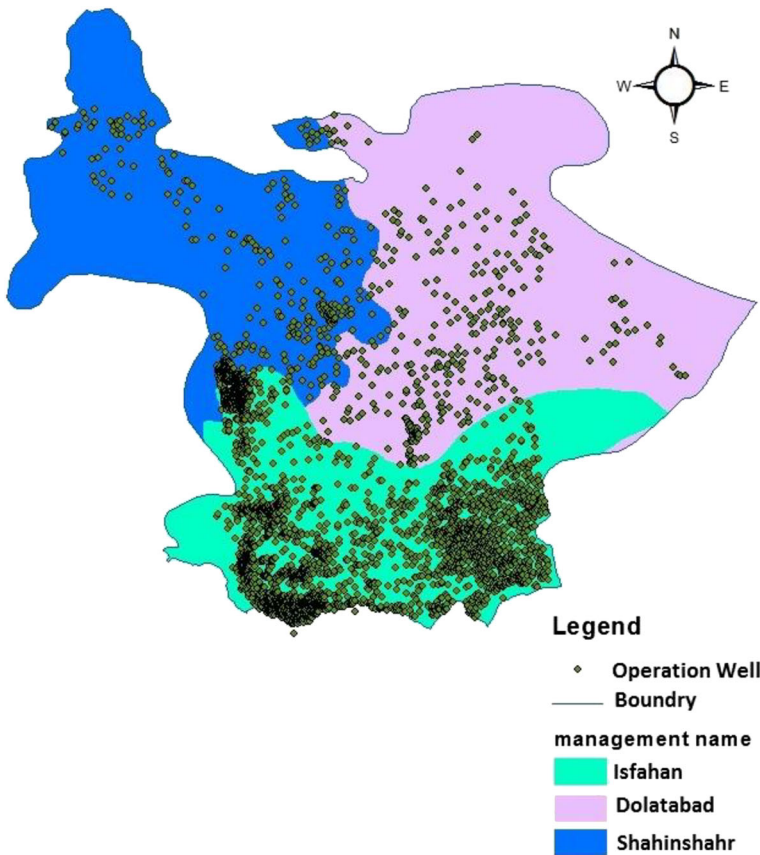


Fig. 6 Isfahan-Borkhar aquifer management districts

methods were used. Table 3 shows the approach used for decision-making of SCR including Condorcet and median voting rule as well as the FB method such as unanimity fallback bargaining and fallback bargaining with impasse.

10 Results and Discussion

As explained in the methodology section, Fig. 4 presents the HC, SC, and HA inputs, which were predicted by DREAM (zs). Figure 5 shows the optimal value of hydraulic conductivity parameters and recharge predicted by DREAM (zs) and MOPSO against their observational

Table 4 Optimized points obtained from the conflict resolution models

Conflict Resolution Model	Coordinates of Optimization Point in Pareto frontier
Condorcet Choice Rule	26
Median Voting Rule (MVR)	27
Unanimity Fallback Bargaining	20
Fallback Bargaining with Impasse	22

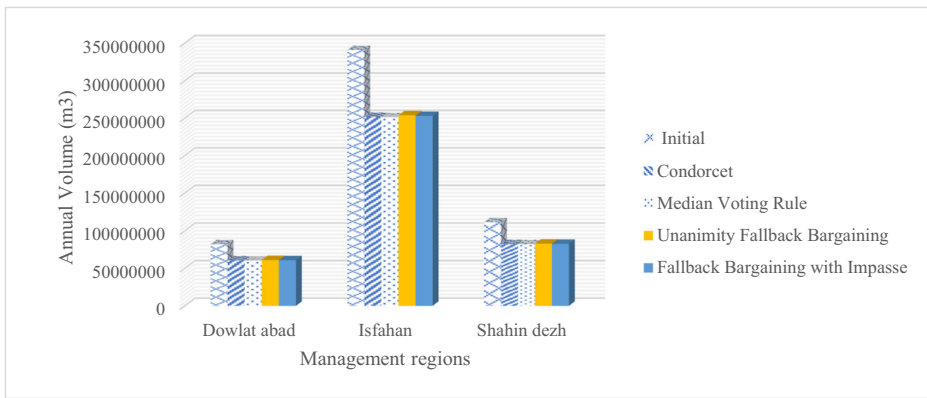


Fig. 7 Withdrawn water volume using SCR and FB methods

values. The tendency of DREAM (zs) uncertainty algorithm is towards the largest predicted optimal value which is close to the real value without losing the main nature of the parameter. It is noteworthy that only 100 cells were compared in this diagram due to the high number of the aquifer grid cells.

The outputs of the simulation-optimization model as well as the uncertainty algorithm in the studied region (Norouzi et al. 2020) are explained in details. The studied region was divided into management districts matching the districts in country divisions (Fig. 6).

MOPSO multi-objective optimization was used to retrieve Pareto frontier curve between the conflicting objectives of the drawdown and TDS values. Finally, SCR and FB were used for finding the most optimal non-dominated solution on the Pareto frontier curve among the objectives for meeting all constraints and objectives of the problem.

Table 4 presents the optimal points obtained from the multi-objective optimizer model using conflict resolution methods of SCR and FB.

Figure 7 shows the volume of withdrawn annual water in management regions using the optimal points obtained from various conflict resolution methods. As can be observed, since the selected optimal points are close to each other, the output results including water discharge and volume are close to each other in different methods. Accordingly, the percentage of the

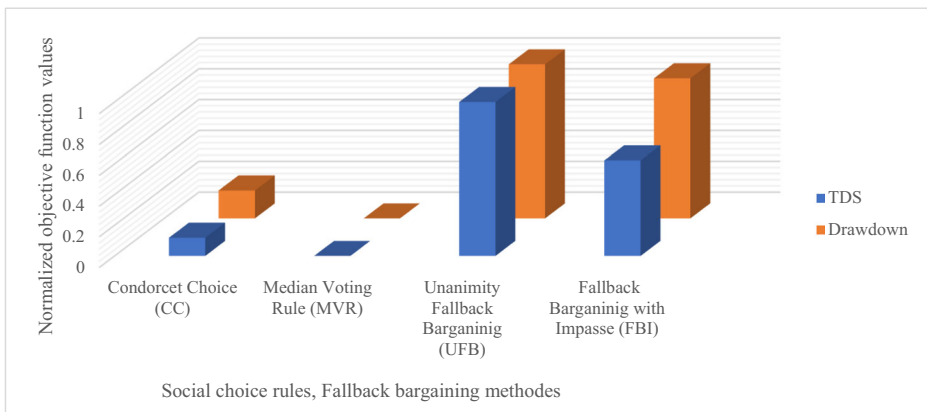


Fig. 8 Groundwater drawdown and TDS reduction in SCR and FB methods

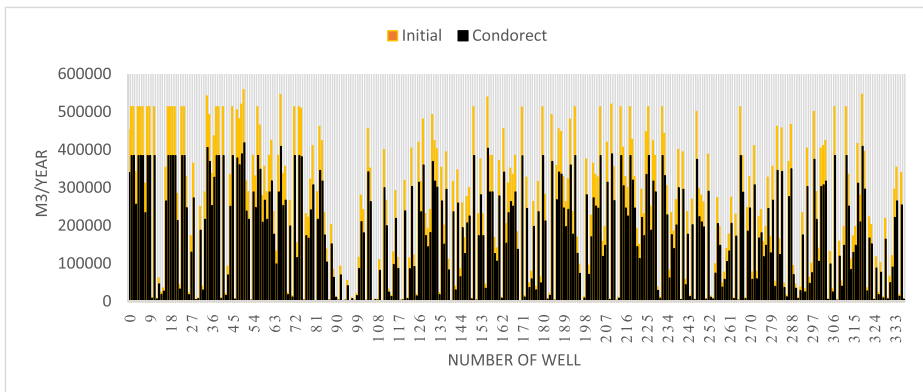


Fig. 9 A comparison between optimal discharge and initial discharge values for each well using Condorcet method in Dolat abad

water withdrawal volume decline in all methods is equal to 25% on average. Figure 8 demonstrates the amount of drawdown and TDS reduction from the abovementioned methods.

The annual discharge of the aquifer by the operation wells is generally equal to 534 million m³. When the optimized allocation policies were applied, this amount reached an average of 395 million m³ in all methods. Figure 9 presents the graph related to the optimal discharge values and the initial discharge related to each well in the management region via the Condorcet method as an example. Table 5 shows the optimal discharge after applying conflict resolution methods in management regions.

Based on the results, almost all the selected methods of conflict resolution in this research behaved similarly and their results were not significantly different from each other. Nevertheless, the MVR model had the best performance due to its minimum decline in withdrawal discharge compared to the other methods and the maximum increase in response to optimal allocation policies. Figure 10 displays the groundwater head and TDS change maps before and after the application of allocation policies.

Based on the results and zoning maps, the saline waters have expanded in both the eastern and western parts. In the study area, the number of groundwater level curves decreases from high mountains to the center of the plain, which varies from a maximum of 1670 m in the northwestern part of the aquifer to a minimum of 1530 m in the south and southwest and up to 1480 m in the center of the plain.

Towards the center of the aquifer, the Groundwater level curve are seen as closed curves and form a drop cone, which may be related to the large number of exploitation and discharge wells. In the middle of the plain, there is more power to lower the water level in exchange for

Table 5 Optimal discharge values using SCR and FB methods

Discharge	Dolat Abad	Isfahan	
Initial	224,611.0	934,144.02	305,133.70
Condorcet Choice Rule	168,039.65	698,866.99	228,281.58
Median Voting Rule (MVR)	167,811.27	697,917.18	227,971.33
Unanimity Fallback Bargaining	169,563.72	705,205.50	230,352.02
Fallback Bargaining with Impasse	168,930.57	702,572.29	229,491.89

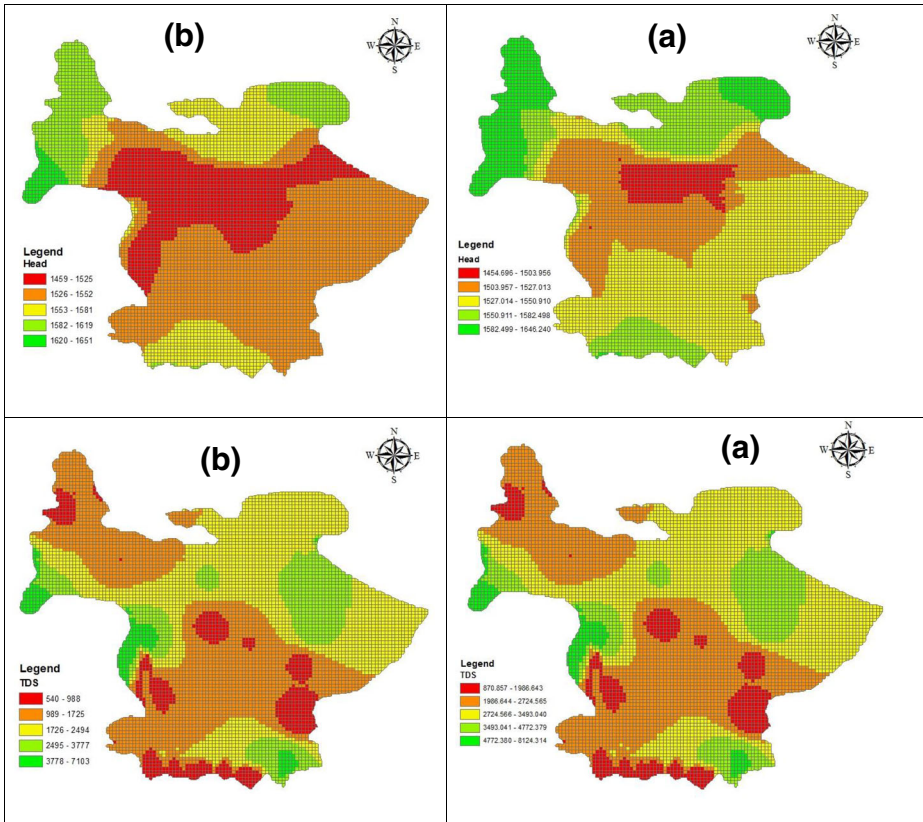


Fig. 10 Groundwater head and TDS change maps before (a) and after (b) the application of allocation policies

exploiting from the aquifer. Thus, more limited exploitation policies should be considered in this regard.

In the study area in the northwestern, eastern and southwestern regions of the aquifer, the drop in water level reached about -25 to -47 m during 15 years. Increasing the discharges from the operating wells and lack of delivering water have put pressure on the aquifer and severely depleted groundwater levels. The results indicated that acceptable relative conditions can be obtained in the process of lowering the groundwater level if we reduce the amount of exploiting aquifer in the current situation by an average of 25%.

11 Conclusion

Considering the nonlinearity and multi-objectivity of the studied problem, the output obtained from the problem solution was in the form of a series of non-dominated solutions forming the Pareto frontier curve between the utility (objective functions). In addition, the present study aimed to find the compromise point based on the produced non-dominated points using SCR and FB approaches. The results indicated that different SCR and FB approaches could help water stockholders and managers achieve a better understanding of the available management options and the interaction method of the utilities of the stockholders involved in the problem

while applying these choices. The present study compared the best available options for compromise and conflict resolution among different stockholders with different options identified by SCR and FB. This comparison provides the decision-making authorities with valuable information on optimal strategies for water governance as well as some methods for reaching multi-purpose agricultural and environmental stability in Isfahan-Borkhar aquifer.

The comprehensive model proposed in this study includes different factors such as the effects of withdrawal from aquifer on decreasing the groundwater level, salinity level, and effective uncertainties. In this model, water is allocated to create a balance between water supply and demands by observing the amount of permissible drop of groundwater level and TDS reduction. The results of using optimizations, different Pareto scenarios, and the conflict resolution model indicated the efficiency of this model for developing appropriate regulations in groundwater allocation and management.

Considering the obtained results, it seems that the methodology proposed in this study had a good performance in reallocation of groundwater resources. In addition to preserving the groundwater quality and decreasing the consequences of its excessive withdrawal, the proposed model increased stockholders' satisfaction through applying the methods based on SCR and FB.

The proposed methodology in this study could be used and extended for other complex surface and ground water systems in future studies. In addition, it is necessary to examine the inter-organizational interactions and legal issues of aquifer. In this research, only the executive implementation of comprehensive water resources management was considered. Thus, further research can be conducted in organizational fields.

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Compliance with Ethical Standards

Conflict of Interest None.

Nomenclature

<i>MOPSO</i> ,	Multi-objective particle swarm optimization;
<i>MODFLOW</i> ,	Finite difference groundwater flow modeling software;
<i>TDS</i> ,	Total dissolved solids;
<i>MCDM</i> ,	Multiple-criteria decision analysis;
<i>FB</i> ,	Fallback bargaining;
<i>NSGA-II</i> ,	Nondominated sorting genetic algorithm II;
<i>MT3DMS</i> ,	Modular Three-Dimensional Multispecies Transport Model Dimensional Multispecies Transport Model;
<i>RSBT</i> ,	Rubenstein sequential bargaining theory;

<i>GAMS</i> ,	General Algebraic Modeling System;
<i>SWAT</i> ,	Soil & Water Assessment Tool;
<i>DREAM (zs)</i> ,	Differential Evolution Adaptive Metropolis;
<i>MVR</i> ,	Median Voting Rule ;
<i>GMS</i> ,	Groundwater Modeling System;
<i>DEM</i> ,	Digital elevation model;
<i>SLS</i> ,	Standard least squares;
<i>HRU</i> ,	Hydrological response unit;
<i>SCEM-UA</i> ,	Shuffle Complex Evolution Metropolis;
<i>CACO</i> ,	Continuous ant colony optimization;
<i>GA</i> ,	Genetic Algorithm;
<i>GAMS</i> ,	General Algebraic Modeling System;
θ^i ,	initial population of parameters vector;
$\pi(\theta^i)$,	Density;
e ,	Difference between the observed data and the simulated model data;
<i>ith</i> ,	Chain using differential evolution ;
e and ε ,	Random phrases;
δ ,	Number of paired chains;
ν^i ,	Parameter series;
u ,	Random number;
R ,	Gelman and Rubin convergence;
<i>HC</i> ,	Hydraulic Conductivity;
<i>HA</i> ,	Horizontal Anisotropy;

SC ,	Storage Coefficient;
RCH ,	Recharge;
$MCMC$,	Markov chain Monte Carlo;
N_{tp} ,	Total number of planning months;
N_j ,	Total number of model cells;
H_{tj} ,	Head of water at the t th time step in the j th cell;
H_{1j} ,	Head of water at the first time step in the j th cell;
C_{tj} ,	TDS of water at the t th time step in the j th cell;
C_{1j} ,	TDS of water at the first time step in the j th cell;
GW_{tp} ,	Total water pumped from the farming wells in the month of tp ;
t_p ,	Month counter;
t_d ,	Number of days in the month of tp ;
$Q_{k,tp}$,	Discharge of well of k in the month of tp ;
k ,	Well counter;
NW ,	Total number of pumped wells available;
N_{tp} ,	Total number of planned months;
$C_{kt,tp}$,	Concentration of TDS in the well of k in the month of tp (mg/lit);
SW_{tp} ,	Amount of surfaced water consumed in the month of tp (m ³);
D_{tp} ,	Water demanded by farmers in the month of tp ;
SW_{tp}^{min} ,	Minimum consumed surface water in the month of tp ;
SW_{tp}^{max} ,	Maximum surfaced water consumed in the month of tp ;
C^{min} ,	Minimum TDS;
C^{max} ,	Maximum TDS

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Affiliations

Khadije Norouzi Khatiri¹ · Mohammad Hossein Niksokhan¹ · Amin Sarang¹ · Asghar Kamali¹

✉ Mohammad Hossein Niksokhan
niksokhan@ut.ac.ir

¹ School of Environment, College of Engineering, University of Tehran, Tehran, Iran