

Developing a Multi-Objective Conflict-Resolution Model for Optimal Groundwater Management Based on Fallback Bargaining Models and Social Choice Rules: a Case Study

Mohammad Reza Alizadeh¹ · Mohammad Reza Nikoo¹ ·
Gholam Reza Rakhshandehroo¹

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Abstract Conflict-resolution models can be used as practical approaches to consider the contradictions and trade-offs between the involved stakeholders in integrated water resource management. These models are utilized to reach an optimal solution considering agents interactions. In this paper, a new methodology is developed based on multi-objective optimization model (NSGA-II), groundwater simulation model, MSP model tree, fallback bargaining procedures and social choice rules to determine the optimal groundwater management policies with an emphasis on resolving conflicts between stakeholders. By incorporating the multi-objective simulation-optimization model and bargaining methods, the optimal groundwater allocation policies are determined and the preferences of the stakeholders as well as social criteria such as justice are also considered. The obtained data set, based on Monte Carlo analysis of calibrated MODFLOW model, is used for training and validating the MSP meta-models. The validated MSP meta-models are linked with NSGA-II to determine the trade-off curve (Pareto front) for the objectives. Social choice rule and fallback bargaining methods, as conflict-resolution models, are applied to determine the best socio-optimal solution among stakeholders, and their results are compared. The effectiveness of the proposed methodology is verified in a case study of Darian aquifer, Fars province, Iran. Results indicated that the solutions obtained by the proposed conflict-resolution approaches have an appropriate applicability. Total groundwater withdrawal, after applying the optimal groundwater allocations,

✉ Mohammad Reza Nikoo
nikoo@shirazu.ac.ir

Mohammad Reza Alizadeh
alizadeh.mohamadreza@yahoo.com

Gholam Reza Rakhshandehroo
rakhshan@shirazu.ac.ir

¹ Department of Civil and Environmental Engineering, Shiraz University, Shiraz, Iran

reduced to 20.85 MCM, resulting in a 4.62 m increase in the mean groundwater level throughout the aquifer.

Keywords Optimal groundwater management · Conflict-resolution · NSGA-II optimization model · M5P meta-models · MODFLOW

1 Introduction

Decision-making for sustainability of groundwater management policies have been always a challenging issue. However, the existing simulation and optimization techniques for groundwater resources allocation do not consider behaviors, gaps and desirabilities of different agents and parties involved in groundwater resource issues. Therefore, it is necessary to manage groundwater resources considering conflicts among stakeholders in which factors such as social justice, economic efficiency and environmental purposes are considered, simultaneously (Walker et al. 2015; Farhadi et al. 2015). The role of game theory in water resource management and conflict-resolution models to solve such conflicts between parties on shared, scarce groundwater resources is undeniable (Madani et al. 2015).

It is possible to use bargaining methods to resolve the conflicts in sustainable water resource management (Bose and Bose 1995; Shirangi et al. 2008). Bargaining may be used easily to describe any condition in which stakeholders are able to gain benefits through cooperation. But if they fail to reach a compromise, no potential benefit will be gained. As a result of bargaining, a sequence of decision making alternatives is composed, which consists distribution of benefits and losses of the conflicting parties (Alfredson and Cungu 2008). In this regard, bargaining models and non-cooperative games have been used for determining optimal water resources and environmental systems management by different researchers (Loáiciga 2004; Salazar et al. 2007; Ganji et al. 2007; Shirangi et al. 2008; Esteban and Dinar 2013; Parsapour-Moghaddam et al. 2015).

Recently, many researchers have been conducted on fallback bargaining (FB) methods and Social Choice Rules (SCR). FB method tries to maximize the minimum satisfaction of all stakeholders. It simulates negotiations in which the confronting parties start negotiations with their most preferred alternatives and retreat step by step until an agreement is made (Brams and Kilgour 2001). In addition, SCR considers principles which establish the appropriate choice for the parties who have different preferences and priorities in choosing possible alternatives (Serrano 2004). In a few studies, FB method is used to resolve water allocation conflicts. These bargaining methods were first proposed by Brams and Kilgour (2001). Later, Brams et al. (2007) proposed an approach to reach a solution for multi-lateral contracts. Agreement in this method is derived based on minimizing the distance of agreement point from the first priority of each conflicting party. Sheikhmohammady et al. (2010) used FB method, SCR and several bankruptcy procedures to find best allocation rules for Caspian Sea resources. Madani et al. (2011) used FB methods to predict the probable results of conflicts in Sacramento Delta in California's San Joaquin River watershed for selection of a strategy for water export. Read et al. (2013) applied some SCR, FB and Multi-Criteria Decision-Making (MCDM) methods to select the optimal energy resource in Firbanks, Alaska. Mahjouri and Bizhani-Manzar (2013) simulated a bargaining process for the stakeholders in a pollutants allocation problem using FB method and determined the best scenario. Martinez and

Esteban (2014) proposed an approach to allocate groundwater resources based on certain types of SCR. They considered uniform rule as a mechanism for optimal water allocation and compared it with proportional and market rules. Recently, Madani et al. (2015) developed a bargaining game in which the stakeholders need to find a solution over a water export problem in California's Sacramento-San Joaquin Delta. Monte-Carlo analysis was combined with FB methods to deal with stochastic bargaining while the efficiency of different water export scenarios was uncertain.

Sustainable groundwater resources management necessitates a balance between conflicting objectives of different involved parties (Nikolic and Simonovic 2015). Accordingly, it would be a challenge to find a compromise in which the conflicting parties withdraw from their most desired preferences in order to reach an impartial decision. To the authors' knowledge, there is no study examining application of FB procedures and SCR to address such conflicts associated with groundwater management problems. So, in this paper, a new multi-objective conflict resolution methodology based on a multi-objective simulation-optimization model, groundwater simulation model (MODFLOW), M5P meta-models, FB methods and SCR is presented. The purpose is to explore and to evaluate efficiency of FB and SCR when such a conflict resolution is sought. As a case study, negotiations among involved conflicting parties in Darian aquifer located in Fars province, Iran, are simulated in the framework of FB and SCR models.

2 Methodology

The flowchart of the proposed multi-objective conflict-resolution methodology for optimal groundwater resource management based on SCR and FB procedures is presented in Fig. 1. The proposed methodology utilizes models including MODFLOW as a groundwater simulation model, M5P meta-models, multi-objective optimization model and bargaining procedures. At the first step of the proposed methodology, the required data for developing groundwater flow simulation model including hydrogeological and hydrological data are collected. Different stakeholders with conflicting objectives which are involved in groundwater resources management problem are also determined. Then, the numerical model of the aquifer is developed using MODFLOW for groundwater flow simulation. Regarding groundwater level fluctuations and aquifer hydraulic conductivity, different management zones are defined for the groundwater allocation management. The MODFLOW simulation model is calibrated for the 3 years of 2010 to 2012 and validated for the year 2013. At the second step, Monte Carlo analysis of validated MODFLOW is performed for different groundwater allocation scenarios. The input-output data obtained based on Monte Carlo analysis of calibrated MODFLOW model is divided into 70 and 30% for training and validating the M5P meta-models, respectively. Moreover, the M5P meta-models are validated using k-fold cross validation method. At step 3, a simulation-optimization model is developed to determine the optimal groundwater allocation policies, considering physical and environmental limitations for the aquifer. In order to serve this purpose, the NSGA-II multi-objective optimization model is linked with the validated M5P meta-models. At step 4, SCR and FB methods, as conflict-resolution models are used for determining the best socio-optimal solution and their results are compared. The main components of the proposed methodology are described in the following sections.

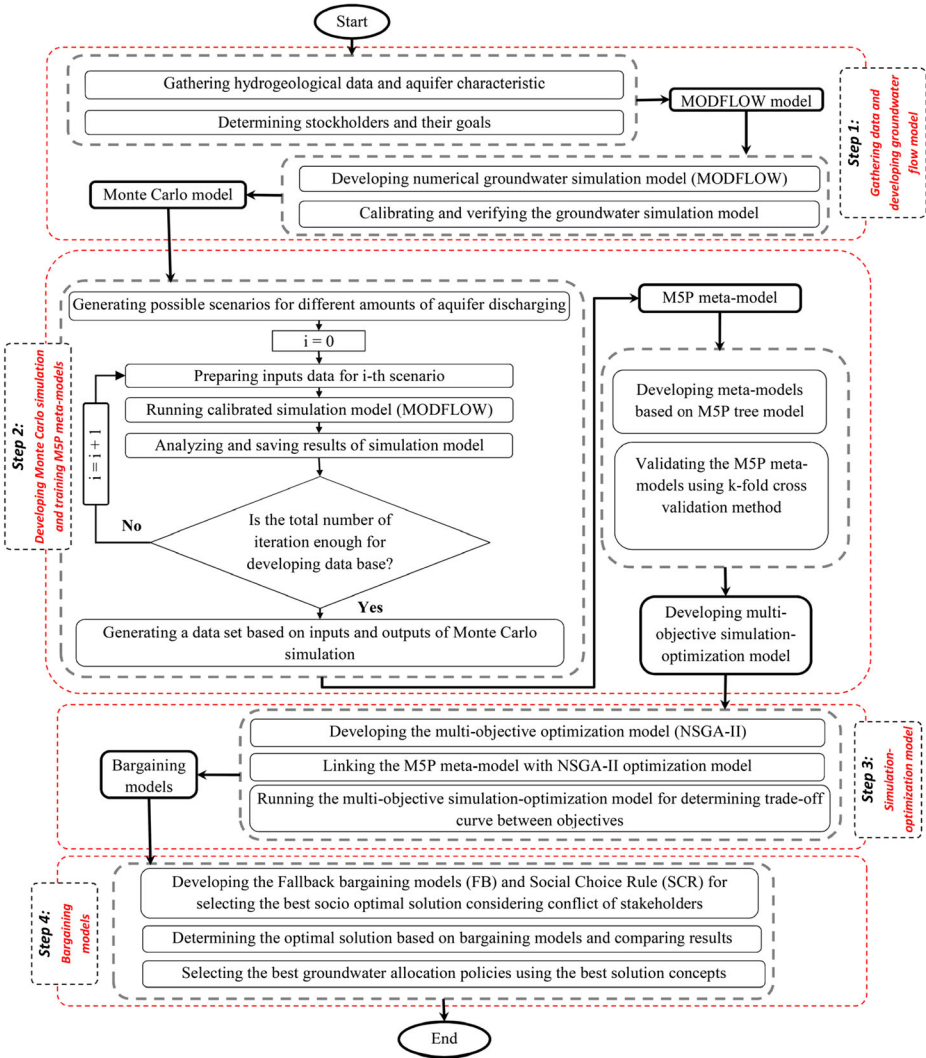


Fig. 1 Flowchart for the proposed methodology

2.1 The M5P Meta-Models for Groundwater Flow Simulation

An M5P model tree is an effective learning method for predicting real values. M5P model outputs are simple, comprehensible and in the form of almost precise regression equations which can be utilized for estimations and predictions.

M5P model trees were first introduced by Quinlan (1992) and later improved by Wang and Witten (1997). Recently, model trees have been used successfully for water and waste load allocations (Nikoo et al. 2013), estimation of spatial transmissivity (Shahriar et al. 2014) and river flow time series modeling (Ajmera and Goyal 2015). In this paper, the M5P meta-models are calibrated using k-fold cross-validation technique. This technique, which is

a popular method to assess database learning algorithm is used in M5P model to evaluate general ability of the M5P model in prediction. This method randomly divides the database into k equal sets, called folds. For training, $k-1$ folds are used as train set and the single remaining fold is used to test the trained model. Training and testing of the model is repeated k times and in each time the training and test data are changed so that all k folds are used as test data. To achieve this purpose in this paper, the meta-models were performed for different number of folds and the appropriate number which resulted in the minimum error was selected.

2.2 Multi-Objective Optimization Model

In the last decade, many researchers have successfully used optimization models in water resource and environmental management problems (Kontos and Katsifarakis 2012; Sidiropoulos et al. 2016). In this paper, the trade-off curve (Pareto front) among conflicting objectives is computed based on NSGA-II. The NSGA-II optimization model was proposed by Deb et al. (2000) to overcome the deficiencies of the previous multi-objective models, such as calculation cost. NSGA-II was later utilized by many researcher (Yandamuri et al. 2006; Nikoo et al. 2014). In NSGA-II, the conflicting objectives of different involved stakeholders result in a set of optimum solutions. In our problem, each solution is a spatial pattern for the optimal amounts of groundwater allocation to different management zones. The main objectives for the stakeholders involved in this paper are:

- Minimizing the water deficit while meeting the users' demands
- Minimizing groundwater level drawdown throughout the aquifer
- Maximizing stakeholders' benefits by considering a justice criteria in optimal groundwater allocation

In the past years, Fars province has been the leading producer of agricultural products in Iran. Therefore, the agricultural sector and farmers have always desired to augment their products and economic benefits within a short time. On the other hand, according to severe and lasting droughts in the province and unplanned withdrawals from illegally drilled wells, Fars Regional Water Company (RWC) has tried to restrict groundwater extractions and has banned agricultural activities in this district. So, farmers and RWC were considered as the conflicting parties in this study. Their objectives and preferences were identified through data analyses. After interviews with experts, the utilities of decision-makers were defined and their preference functions were derived.

Formulation of the proposed multi-objective optimization model to find the optimal groundwater allocation policies are embedded in Eqs. 1 to 10. Pumping rates are considered as decision variables in the proposed optimization model. The multi-objective function for optimization model is defined in a way that 1) minimizes water deficits while meeting the users' demands (Eq. 1), 2) maximizes total net benefit for each agricultural zone in different allocation scenarios, and 3) maximizes equity as a justice criteria in optimal amount and allocations of groundwater. If the computed allocations are close to the users' demands, sustainability of water allocations would be ascertained, shown in Eq. 3. Equity in allocations is a number between 0 and 1 whose maximization is considered as another optimization objective

function. Finally, the three objective functions of groundwater deficit, groundwater drawdown, and equity were computed for the modified allocations.

$$Min Z_1 = \sum_y \sum_r Q_{GWA,r}^y \tag{1}$$

$$Q_{GWA,r}^y = W_1 \cdot \sum_m Q_{Ind,r}^{y,m} + W_2 \cdot \sum_m Q_{Dom,r}^{y,m} + W_3 \cdot \sum_m S_{Ind,r}^{y,m} + W_4 \cdot \sum_m S_{Dom,r}^{y,m} + W_5 \cdot \sum_m S_{Agr,r}^{y,m} \tag{2}$$

$$Min Z_2 = \sum_y \sum_r H_r^y \tag{3}$$

$$Max Z_3 = Min \left(\frac{Q_{Agr,r}^{y,m}}{D_{Agr,r}^{y,m}} \right) \tag{4}$$

Subject to:

$$H = f(Q_{Agr}, Q_{Ind}, Q_{Dom}, H_0, K, Re, \dots) \leq H_{allowable} \tag{5}$$

$$Q_{Agr,r}^{y,m} + Q_{Ind,r}^{y,m} + Q_{Dom,r}^{y,m} = Q_{T,r}^{y,m} \tag{6}$$

$$Q_{Ind,r}^{y,m} + S_{Ind,r}^{y,m} = D_{Ind,r}^{y,m} \tag{7}$$

$$Q_{Dom,r}^{y,m} + S_{Dom,r}^{y,m} = D_{Dom,r}^{y,m} \tag{8}$$

$$Q_{Agr,r}^{y,m} + S_{Agr,r}^{y,m} = D_{Agr,r}^{y,m} \tag{9}$$

$$Q_{Agr,r}^{y,m} + Q_{Ind,r}^{y,m} + Q_{Dom,r}^{y,m} \leq Q_{allowable,r}^{y,m} \tag{10}$$

Where the parameters are defined as:

- Z The objective function for the optimal groundwater allocation model
- $Q_{GWA,r}^y$ The preference function for groundwater supplier and user (dimensionless) for region r , month m , and year y .
- W_1, \dots, W_5 Normalizing coefficients of the preference function for the supplier and the user which incorporate their preferences. These coefficients could represent the importance or the real cost of groundwater exploitation.
- Q_{Agr} Groundwater allocation for agricultural demands (MCM)
- Q_{Ind} Groundwater allocation for industrial purposes (MCM)

Q_{Dom}	Groundwater allocation for domestic purposes (MCM)
S_{Agr}	Volume of groundwater deficit in supplying agricultural demands (MCM)
S_{Ind}	Volume of groundwater deficit in supplying industrial demands (MCM)
S_{Dom}	Volume of groundwater deficit in supplying domestic demands (MCM)
H	Groundwater level drawdown (m)
$H_{allowable}$	The maximum allowable groundwater drawdown (m)
Re	Groundwater recharges (MCM)
K	Average hydraulic conductivity of the aquifer (m/day)
H_0	Initial groundwater level (m)
Q_T	Total allocated groundwater (MCM)
$Q_{allowable}$	Allowable monthly groundwater extraction (MCM)
D_{Dom}	Volume of monthly domestic water demands (MCM)
D_{Ind}	Volume of monthly industrial water demands (MCM)
D_{Agr}	Volume of monthly agricultural water demands (MCM)
f	A function which calculates groundwater level drawdown. (It is derived using the validated MSP meta-models)

Also, indices r , m , and y represent the considered region, month, and year for the parameter, respectively.

Equations 1 to 4 introduce objective functions of the multi-objective simulation-optimization model. Equation 5 represents the constraints for groundwater level drawdowns. Total groundwater allocation for different purposes is calculated through Eq. 6 and supplying water demands from groundwater resources are considered in Eqs. 7 to 9. The volume of monthly allowable water extraction from the aquifer for different purposes is imposed to the model as a constraint (Eq. 10). It should be mentioned that recharge from precipitation, return flow, inflow from the adjacent aquifers, recharge from river, and minimum and maximum groundwater levels are all considered in determining allowable groundwater extractions.

2.3 Social Choice Rules (SCR)

In this paper, SCR and FB methods are applied to the Pareto front solutions to resolve the conflicts between decision-makers and agents. SCR reflects individuals' priorities in a group choice and uses methods to aggregate their preferences. Therefore, SCRs are used to resolve the conflicts in decision-making problems. A subset of the possible options is selected in this method based on the preferences of every individual (Sheikhmohammady et al. 2010). In particular, Condorcet Choice (CC), Borda Scoring (BS), Plurality Rule (PR) and Median Voting Rule (MVR) are used in this study to resolve the conflicts in groundwater allocation management.

2.3.1 Condorcet Choice (CC)

The Condorcet winner is the alternative which is at least as preferable as every other alternative for a majority of bargainers (Young et al. 1982). In this method, the pairwise comparison of the alternatives is performed and in each comparison, the alternative which gains the majority of bargainers' votes is the winner and a positive point is assigned to it. The pairwise comparisons are performed for all possible alternatives and the one which has the highest rank would be preferred over others (Sheikhmohammady and Madani 2008).

2.3.2 Borda Scoring (BS)

In this method, each decision-maker assigns score $m-i$ to the i th alternative which is the most preferred for him/her, where m is the total number of alternatives. In other words, the score assigned to an alternative by decision-makers is the number of times when that alternative is preferred over others. For each alternative, the assigned scores of all decision-makers are computed cumulatively and the alternative with the highest score is considered as the choice set for the conflict.

2.3.3 Plurality Rule (PR)

PR is one of the oldest social choice rule methods. In this method, the alternative with the highest number of votes is considered as the best social choice. Indeed, it concentrates on the first priority of conflicting parties and neglects the alternatives with less votes. The possible alternatives are scored similar to Borda method and the alternatives with the highest scores and highest number of times being chosen are selected as the best choice (Reynolds et al. 2005).

2.3.4 Median Voting Rule (MVR)

In this method, first all possible alternatives are ranked based on the rate of preference by the conflicting parties. Number of times when alternatives are considered as the first to the last priorities are computed. Then, at each level of priority, the first alternative which gains the most voters (more than half of the conflicting parties) is considered as the MVR choice. Factually, it determines the first step when an alternative reaches the most voters. In other words, MVR chooses an alternative which receives the highest support from the conflicting parties (Bassett and Persky 1999).

2.4 Fallback Bargaining Methods (FB)

In FB methods the bargainers start bargaining by introducing their preference rankings among the entire possible alternatives. Then, gradually and step by step the ranking of the preferences reduces (starting with the first alternative and withdrawing toward the second alternative) until all bargainers agree on an alternative. Unanimity fallback bargaining (UFB) and q -approval fallback bargaining (QFB), as two important types of fallback bargaining methods are explained in the following.

2.4.1 Unanimity Fallback Bargaining (UFB)

Suppose that n is the number of bargainers and K is the set of alternatives or suggestions (possible agreements), where $|K| = K < \infty$. In this method, each bargainer composes precisely the priority of his/her own alternatives based on all possible K s. All rankings may be represented by a matrix A whose dimension is $K \times n$. Each ranking is arranged in a descending order. For example, assume that $K = \{a, b, c, d\}$ is a set of suggestions; so, $K = 4$. Assuming only two bargainers, $n = 2$, and their preferences matrix would be (Brams and Kilgour 2001):

$$A = \begin{bmatrix} a & b & c & d \\ b & d & a & c \end{bmatrix}$$

Priority of alternatives for the first bargainer is $(abcd)$, where a is the most and d is the least preferred alternative, and for the second bargainer, the sequence of the preferred alternatives is

(*bdac*), where *b* is the most and *c* is the least preferred alternative. These preferences are illustrated at the first and second rows of matrix *A*, respectively.

The stepped procedure of fallback bargaining would be as:

1. The best alternative for each bargainer is considered. If this choice is the same for all bargainers, it would be the common agreement among bargainers and the process will stop there, and the bargaining is called agreement at the first depth.
2. If no acceptance is achieved at the first depth, then the next most preferred alternative is considered as the agreement at the second depth. If the agreement at this step is not gained either, then the process would continue.
3. If the steps terminate at d^* , $CS = (A)$ is named the compromise set of fallback bargainings for matrix *A* (Brams and Kilgour 2001).

2.4.2 *Q-Approval Fallback Bargaining (QFB)*

If one generalizes UFB method, QFB method is derived in which the decision-making rules for acceptance need *q* bargainers, where $q \in [1, n]$. Up to now an equal number of bargainers and decision-making rules has been assumed; $q = n$. Normally, in UFB method, it is assumed that the agreement should be at least among a simple majority of bargainers, $(q \geq \frac{(n+1)}{2})$, while in QFB method, the results will be applied for each bargainer $1 \leq q \leq n$.

At the end, QFB method results in a compromise set, usually indicated by CS^q , which is a set of alternatives approved by *q* bargainers at different depth increments. For each *q* there is a d_q^* , and if $q = n$, then $d_n^* = d^*$.

An optimality for the trade-off solutions (among all alternatives presented by QFB method) is considerable. However, this is not a good reason to consider all these alternatives as appropriate candidates as the resultants of the two processes of bargaining and voting (Brams and Kilgour 2001).

3 Case Study

The Tashk-Bakhtegan river basin, with a surface area of 31,492 km², is located in Fars province, Iran. Darian aquifer is located at southwest of this river basin. Total area of the study area is 334 km² for which 193.2 km² are composed of plains, and the rest of it (140.8 km²) are elevations. The geographical map of the aquifer in Tashk-Bakhtegan river basin is shown in Fig. 2.

Approximately, 95% of groundwater resources in this plain are alluvial type and the rest are rigid formations. There are 814 operating extraction wells, 11 piezometric wells and 3 qanats in the alluvial aquifer, and 13 operating wells and 2 springs in the rigid formation. In Darian aquifer, 96.94, 2.83 and 0.21% of the entire groundwater resource is allocated to agricultural, domestic and industrial sectors, respectively. In recent years, groundwater overexploitation and drought occurrences have caused a critical reduction in groundwater volume and a severe groundwater level drawdown in the aquifer. Assessment of aquifer hydrographs for 16 years (from 1997 to 2013) indicates a 23-m drawdown equaling a disastrous annual drawdown of 1.44 m (Fars Regional Water Company 2013).

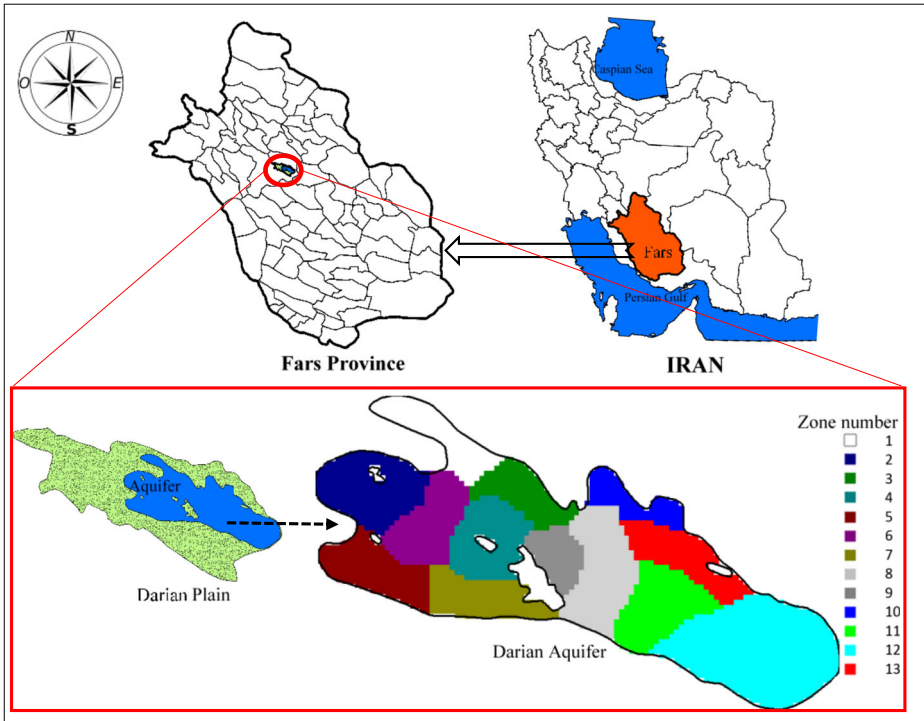


Fig. 2 Geographical map for Darian aquifer as the study area

4 Results and Discussion

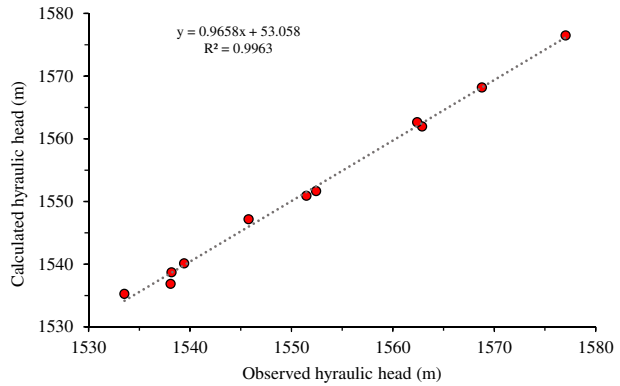
The maximum, average, and mean absolute relative error (MARE) indices for estimation of hydraulic head during calibration (years 2010 to 2012) and validation stages (the year 2013) of MODFLOW model are presented in Table 1.

The average and maximum values of MARE error indices for 3 years of MODFLOW calibration, (2.91 and 4.08%, respectively) are negligible in comparison with the observed hydraulic heads, which suggests that the groundwater simulation model is precisely calibrated (Table 1). As an example, the observed and calculated hydraulic heads during validation period for the 11 piezometric wells at the study area are shown in Fig. 3.

Table 1 Different error indices for estimation of hydraulic head during calibration and validation stages of MODFLOW model

Calibration/Validation	Year	Error indices		
		Average (m)	Maximum (m)	MARE (%)
Calibration period 1	2010	0.377	0.814	2.43
Calibration period 2	2011	0.347	0.799	2.23
Calibration period 3	2012	0.634	1.176	4.08
Entire Calibration stage period	2010–2012	0.452	0.929	2.91
Validation period	2013	0.831	1.718	5.37

Fig. 3 Observed and calculated hydraulic heads during validation period of MODFLOW model



The proposed multi-objective simulation-optimization model based on NSGA-II model resulted in an optimal trade-off between objectives. Since there is no systematic approach to find the best value for the multi-objective optimization parameters, a sensitivity analysis is used for setting the main NSGA-II model parameters to obtain the fastest convergence of better trade-off. Accordingly, the optimized values for NSGA-II model parameters including initial population size, generation, crossover and mutation rate were obtained as 300, 300, 0.8 and 0.2, respectively, based on a try and error analysis.

Using the developed multi-objective groundwater allocation model, 35 points (solutions) on the resulted Pareto front is determined. Then, the best socio-optimal groundwater allocation policy in which the stakeholders agree is selected using different SCR and FB methods. Comparison of the selected solutions using different SCR and FB methods are presented in Table 2.

Proximity of results derived by UFB and QFB methods indicates that the responses of the aquifer based on these two methods are almost the same. Results presented in Table 2 indicate that UFB and QFB methods pay more attention in supplying water for users' demands, and consequently, lead to about 0.29 m increase in the groundwater level. On the other hand, applying CC method causes a maximum reduction in annual groundwater exploitation. Application of this groundwater allocation policy contributes to about 63% reduction in groundwater withdrawal from the aquifer and the groundwater level is averagely lifted 4.62 m. Table 2 also shows that using MVR and CC methods cause increases in the aquifer groundwater level, and consequently, deficits in supplying users' demands. Finally,

Table 2 The socio-optimal solutions using different fallback bargaining methods and social choice rules

Bargaining models/ social choice rules ^a	Groundwater drawdown (m)	Groundwater deficit (m ³ /d)	Equity (Dimensionless)
BS	5.44	2411.73	0.09
UFB, QFB	-0.29 ^b	0.00	0.08
MVR	-4.56	2678.24	0.18
PR	1.09	1881.18	0.18
CC	-4.62	2808.66	0.18

^a BS Borda Scoring, UFB Unanimity Fallback Bargaining, QFB Q-Approval Fallback Bargaining, MVR Median Voting Rule, PR Plurality Rule and CC Condorcet Choice

^b Minus sign indicates an increase in groundwater level.

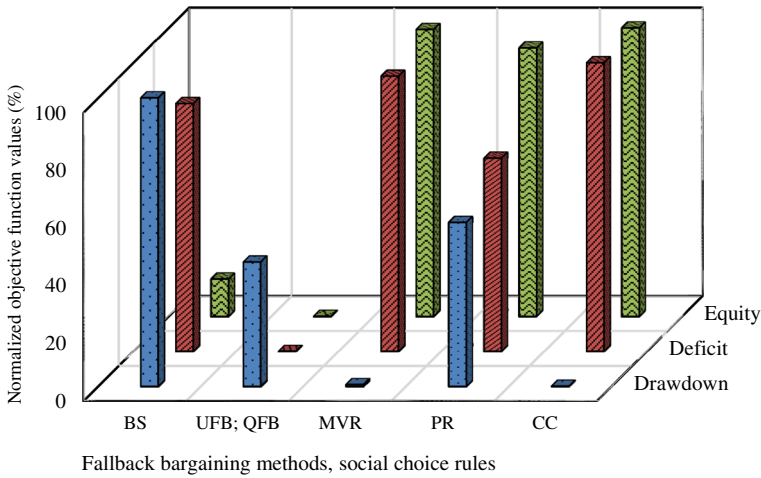


Fig. 4 Objective function values resulted by different fallback bargaining methods and social choice rules

performance of MVR, PR and CC methods are better than other methods in considering the ratio of allocated water to users’ demands and justice criteria (Equity).

To illustrate how changes in the values of three objective functions resulted by different SCR and FB methods affect the groundwater allocation policies, a comparison of final normalized objective-function values by different bargaining methods is shown in Fig. 4.

Figure 5 illustrates groundwater level variations in Darian aquifer based on the results of different SCR and FB methods. As shown, in some groundwater management zones such as 1, 2, 3, 10 and 13, groundwater levels have negligible changes which are smaller than 0.5 m. Apparently, constant head cells (boundary conditions) at the entrance and exit hydrologic boundaries of the aquifer in these zones have caused these small changes. On the other hand, in central areas of the plain (management zones 4, 5, 6 and 7) groundwater level rise is

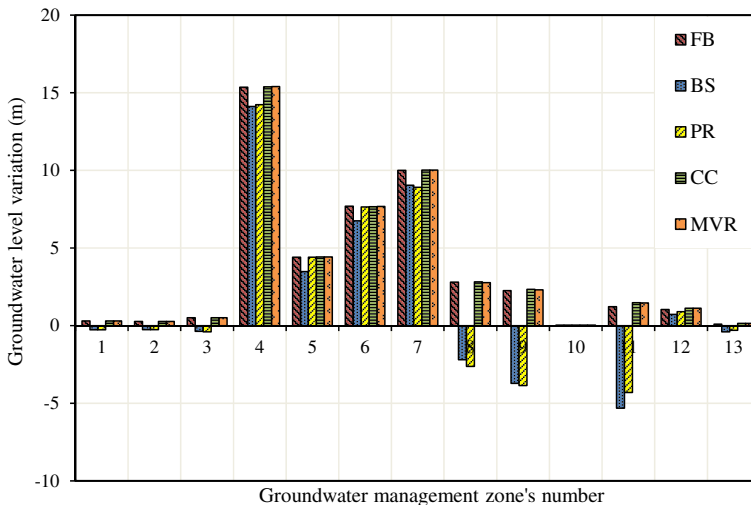


Fig. 5 The variation of groundwater level in different groundwater management zones

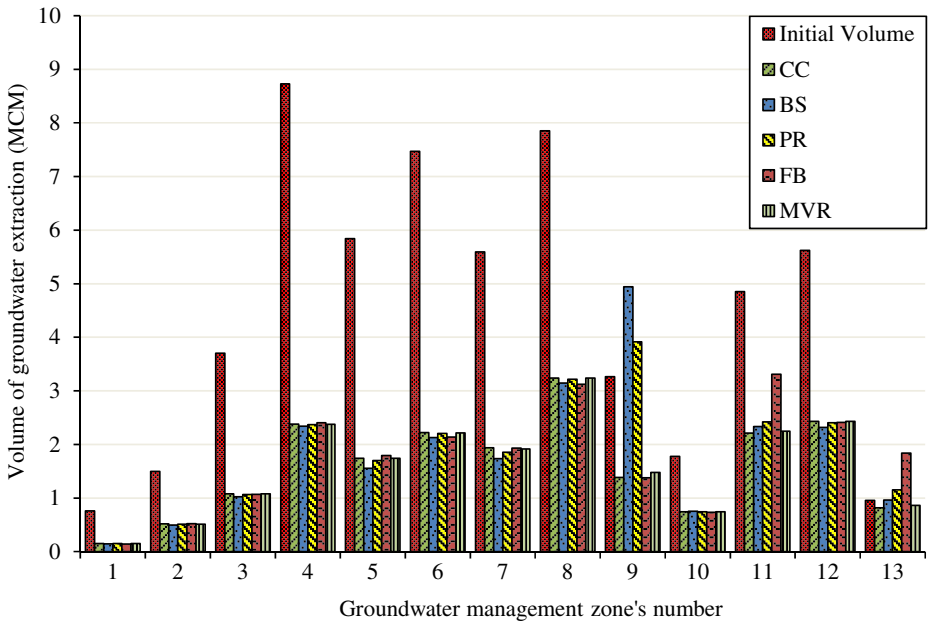


Fig. 6 Volume of groundwater extraction in different management zones

considerable, with increases of up to 15 m. The highest water level lift in management zone 4 reached 15.38 m based on the results of CC method.

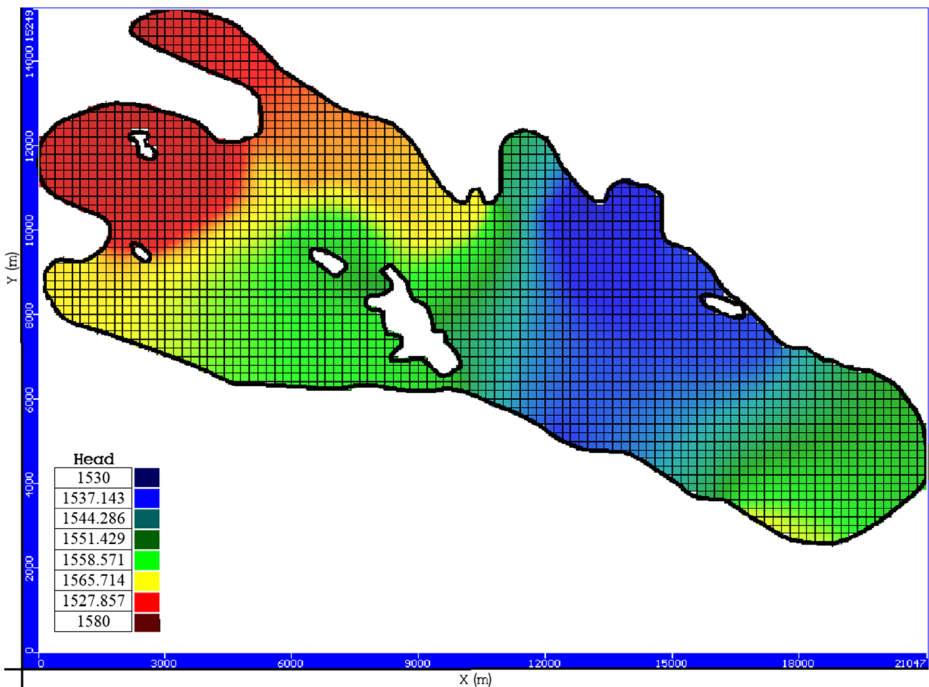


Fig. 7 Groundwater level contour maps based on the results of fallback bargaining methods

Figure 6 shows a comparison between volumes of groundwater extraction in different groundwater management zones derived by different multi-objective simulation-optimization conflict-resolution models. Based on all socio-optimal groundwater allocations computed through bargaining methods, in most zones, variations in average groundwater exploitation are toward a 60% reduction for the entire aquifer. The uppermost negative changes have occurred in southern and south-western parts of the aquifer (zones 4 and 6) which reduce groundwater withdrawal to almost 70%. In central parts of the aquifer, in zones 9 and 13, positive variations of groundwater exploitation is considerable, which may be attributed to a recharge from bottom, and consequently groundwater level lift in these regions.

Accordingly, Groundwater level contour maps over the aquifer for optimal groundwater allocation policy utilizing fallback bargaining methods is shown in Fig. 7.

5 Summary and Conclusion

In this study, a multi-objective simulation-optimization groundwater allocation model is developed and the results of different groundwater allocation policies in Darian aquifer, Fars province, Iran are determined. Based on the preferences of the stakeholders and the social criteria such as justice, the best groundwater allocation policies are determined. Finally, social choice rules and fallback bargaining methods are utilized to select the best socio-optimal solution upon which all stakeholders agree. The results indicated that unanimity fallback bargaining (UFB) and q-approval bargaining (QFB) methods presented almost the same results. As a result, it was concluded that the proposed allocation and exploitation policies have an appropriate efficiency and the consequent groundwater responses of the aquifer would be almost the same. In comparison with other methods, fallback bargaining methods resulted in the least reduction of groundwater withdrawal and an average 0.29 m groundwater level increase throughout the aquifer. When Condorcet choice (CC) method was utilized, the total annual exploitation from the aquifer reduced by 37 MCM, which contributed to about 4.62 m of groundwater level increase. Once median voting rule (MVR) was applied, groundwater level lifted 4.56 m. Additionally, results indicated that social choice rules and fallback bargaining methods may be utilized efficiently to determine groundwater allocation strategies. In future researches, the methodology described in this paper may be utilized in a nondeterministic fashion for setting up quantitative and qualitative models. Fuzzy modelling may also be utilized to incorporate more uncertainty in the utility functions of stakeholders, water demands, hydrogeology parameters, and groundwater quality.

Compliance with Ethical Standards

Conflict of Interest Authors declare that they have had no conflict of interest in conducting this research.

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