A Conflict-Resolution Model for the Conjunctive Use of Surface and Groundwater Resources that Considers Water-Quality Issues: A Case Study

Mohammad Reza Bazargan-Lari · Reza Kerachian · Abbas Mansoori

Abstract The conjunctive use of surface and groundwater resources is one alternative for optimal use of available water resources in arid and semiarid regions. The optimization models proposed for conjunctive water allocation are often complicated, nonlinear, and computationally intensive, especially when different stakeholders are involved that have conflicting interests. In this article, a new conflict-resolution methodology developed for the conjunctive use of surface and groundwater resources using Nondominated Sorting Genetic Algorithm II (NSGA-II) and Young Conflict-Resolution Theory (YCRT) is presented. The proposed model is applied to the Tehran aquifer in the Tehran metropolitan area of Iran. Stakeholders in the study area have conflicting interests related to water supply with acceptable quality, pumping costs, groundwater quality, and groundwater table fluctuations. In the proposed methodology, MODFLOW and MT3D groundwater quantity and quality simulation models are linked with the NSGA-II optimization model to develop Pareto fronts among the objectives. The best solutions on the Pareto fronts are then selected using YCRT. The results of the proposed model show the significance of applying an integrated conflict-resolution approach to conjunctive use of surface and groundwater resources in the study area.

Introduction

Most decision-support systems developed for the conjunctive use of surface and groundwater resources use conventional multiobjective optimization models to provide water-allocation policies. However, in complex surface and groundwater systems, multiple conflicting objectives related to different stakeholders should be taken into account. For example, improvement of groundwater quality in an urban area is in conflict with decreasing the construction cost of wastewater collection networks. In such a region, controlling groundwater table level fluctuations and decreasing pumping costs are also two conflicting objectives. Under such circumstances, multiobjective decision-making techniques are useful to develop optimal operating polices for the conjunctive use of surface and groundwater resources.

Different optimization models have been developed for groundwater quality and quantity management. Yeh (1992) and Das and Datta (2001) reviewed state-of-the-art of systems analysis and optimization techniques developed in this field. In most previous works, linear programming, dynamic programming, and metaheuristic optimization techniques were used to analyze conjunctive-use problems.

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Karamouz and others (2004) developed a dynamic programming optimization model for the conjunctive use of surface and groundwater resources in agricultural zones in southern Tehran. Karamouz and others (2007) combined genetic algorithms and artificial neural networks to propose a methodology for the conjunctive use of surface and groundwater resources. In the present case study, the models proposed by Karamouz and others (2004, 2007) are improved to explicitly consider the conflicting objectives of different stakeholders. Therefore, a new game theoretic approach, instead of a single objective optimization model, is used.

Because different stakeholders are involved in the conjunctive use of surface and groundwater resources, a conflict-resolution technique should be employed to resolve conflicting interests. Conflict is defined by Brown (1995) as "a form of interaction among parties that differ in interests, perceptions, and preferences" (p. 317). When a conflict exists among more than two individuals, the preferred action is to reach an agreement. Many advances in water-resources management have been cited in literature; however, studies focusing on conflict resolution in water-resources management, especially regarding the conjunctive use of surface and groundwater resources, have been limited.

Lejano and Davos (1995) applied n-person cooperative game theory to a water-reclamation and -reuse project in Southern California. Richards and Singh (1996) used the Nash bargaining theory for water allocation. Supalla and others (2002) applied game theory in the allocation of water between Colorado, Nebraska, and Wyoming, all of which receive insufficient water from the Platte system to meet all competing demands.

Loaiciga (2004) developed a game-theoretic approach to calculate sustainable groundwater-extraction rates. He compared the results of cooperative and noncooperative conflict-resolution approaches. Coppola and Szidarovszky (2004) applied game theory to identify the optimal trade-off between water supply volume and the risk of contamination for a municipal well field in accordance with the priorities and preferences of a water-supply sector, a community, and a company whose wastewater was contaminating the aquifer. Carraro and others (2005) presented noncooperative bargaining models to water-allocation problems. Gopalakrishnan and others (2005) presented a decision support system that includes a graph model for conflict resolution to analyze the strategic aspects of a multiparty water dispute.

Kerachian and Karamouz (2006, 2007) developed two stochastic models for water-quality management in reservoir and river–reservoir systems. In their works, the expected value of the Nash product, which incorporates the inherent uncertainty of reservoir inflow, is considered as the objective function of the stochastic models. Salazar and others (2007) compared 12 alternative groundwater extraction scenarios using 4 different conflict-resolution methods, namely, nonsymmetric Nash, nonsymmetric Kalai–Smorodinsky, nonsymmetric area monotonic, and nonsymmetric equal loss.

Complexity of groundwater-management problems, especially in the conjunctive use of surface and groundwater resources, usually leads researchers to use evolutionary algorithms (EAs), which are search methods that take their inspiration from natural selection and survival of the fittest in the biologic world. An EA is a subset of evolutionary computation, a generic population-based metaheuristic optimization algorithm. An EA uses some mechanisms inspired by biologic evolution: reproduction, mutation, recombination, and selection. Candidate solutions to the optimization problem play the role of individuals in a population, and the cost function determines the environment within which the solutions "live". Evolution of the population then takes place after repeated application of the previously mentioned operators. EAs also facilitate linkage between nonlinear optimization and groundwater quantity and quality simulation models. One of the efficient multiobjective evolutionary algorithms (MOEAs), which is described here, is the Nondominated Sorting Genetic Algorithm II (NSGA-II). The NSGA-II was originally proposed by Deb and others (2000). In recent years, this method has been applied to watershed management (Dorn and Ranjithan 2003), groundwater remediation (Reed and Minsker 2004), and waste-load allocation in rivers (Yandamuri and others 2006).

In this article, a conflict-resolution methodology for the conjunctive use of surface and groundwater resources that considers water-quality issues is presented. This methodology combines several models, namely, the NSGA-II, Young Conflict-Resolution Theory (YCRT), and MODFLOW and MT3D (modular three-dimensional transport) groundwater quantity and quality simulation models. MODFLOW and MT3D have been developed by Harbaugh and McDonald (1996) and Zheng and Wang (1999), respectively. In the proposed methodology, trade-off curves among objectives are developed using the NSGA-II, and the best nondominated solution is selected using YCRT. In this article, it is shown that this selected solution would provide a compromise solution that can be used for developing optimal operating policies for the conjunctive use of surface and groundwater resources.

To show the applicability and efficiency of the proposed methodology, it was used for conflict resolution in the conjunctive use of surface and groundwater resources in the Tehran metropolitan area in Iran. The methodology provides optimal values for decision variables, which are the area covered by the Tehran Wastewater Collection Project (TWCP) and the groundwater resources allocated to some agricultural zones in the southern part of Tehran.

Study Area

The study area was the Tehran metropolitan area, which has an annual domestic water consumption of approximately 1 billion cubic meters. Tehran plain lies between 35° and 36°35′ Northern latitude and 50°20′ and 51°51′ Eastern longitude, where it is bounded by the Kan River in the west and the Sorkhehesar River in the east. The local rivers and agricultural zones in this region are shown in Fig. 1. These rivers do not play a significant role in supplying water demands of the city, but they partially supply water to the agricultural lands in the southern part of Tehran. More than 8 million people live in Tehran City, and approximately 60% of domestic water consumption in this region returns to the Tehran aquifer by way of traditional absorption wells (Karamouz and others 2004). Three major agricultural zones, namely, Eslamshahr-Kahrizak (zone 1), Ghaleno (zone 2), and Khalazir (zone 3), are considered to be the main users of surface and groundwater resources in the southern part of Tehran (Fig. 1). The net monthly water demand of the agricultural zones and average monthly discharge of the local rivers are listed in Table 1.

The Tehran aquifer is mainly recharged by inflows at the boundaries, by precipitation, by local rivers, and by return flows from domestic, industrial, and agricultural water users. The discharge from the aquifer is through water extraction from wells, springs, and qanats as well as groundwater outflow and evapotranspiration.

Wastewater disposal in Tehran is carried out through >3 million absorption wells, which are often 15 to 20 m deep. The use of absorption wells has caused groundwater pollution and a significant rise of the water table in the southern part of Tehran.

Some part of disposed wastewater in Tehran City is drained into local rivers and urban runoff drainage system and partially contaminates the surface-water resources in southern Tehran. These polluted surface waters are used in conjunction with groundwater for irrigation purposes in the agricultural zones. As an example, Fig. 2 shows the mean detergent concentration in surface water allocated to the agricultural zones.

The TWCP is the most important ongoing project for solving the current problems related to wastewater disposal in the study area. The initial study of the TWCP was performed with the aid of the World Health Organization and the United Nations. This project has different phases as illustrated in Fig. 3. Currently the first phase of this project is being implemented with the financial aid of the World Bank.

Stakeholders and Their Conflicting Objectives

The multiobjective problem described in this article consists of four objective functions: (1) minimizing the
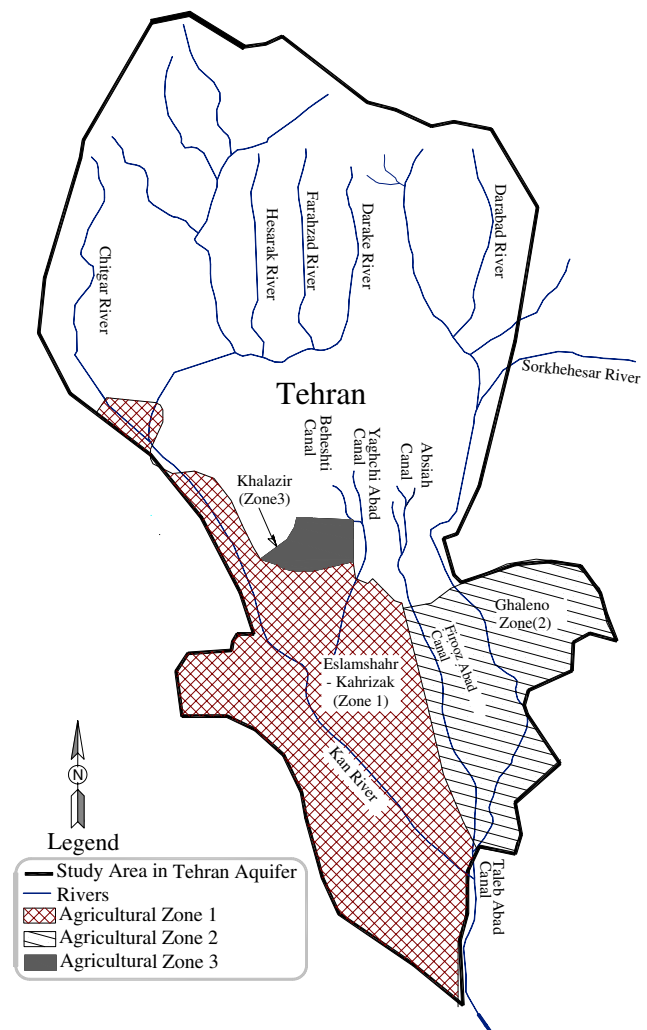
Fig. 1 Surface water resources and agricultural zones in the study area

construction cost of the TWCP, (2) minimizing the Mean Nitrate Concentration (MNC) in the regions in which the nitrate concentration in groundwater violates the standards, (3) minimizing the Maximum Annual Groundwater Table Rise (MAGTR), and (4) reducing the Total Pumping Power (TPP) used for allocating groundwater to demands. These objectives are described and formulated as the objective functions of involved stakeholders in the study area as follows.

Stakeholder 1: Iran Department of Environment

The Iran Department of Environment (IDOE) prefers to protect the quality of groundwater resources in the study area by increasing the coverage of the TWCP, which leads to reducing wastewater discharge to the aquifer. Previous studies show that nitrate can be considered as a suitable water-quality indicator in the Tehran aquifer. Therefore,

Table 1 The average discharge of local rivers and net monthly waters demands in agricultural zones (million m^3)

Month	Zone								
	Eslamshahr-Kahrizak (zone 1)				Ghaleno (zone 2)				Khalazir[a] (zone 3)
	Discharge of local rivers			Net demand	Discharge of local rivers			Net demand	Net demand
	Kan	Yaghchi	Beheshti		Sorkhehesar	Absiah	Firooz Abad		
Jan	12.17	0.28	2.83	0.73	13.73	0.18	12.19	0.61	0.05
Feb	14.55	0.37	3.29	0.71	18.30	0.22	13.04	0.54	0.04
Mar	19.96	0.38	3.36	1.35	22.78	0.23	13.37	1.00	0.11
Apr	22.49	0.52	4.20	3.25	30.65	0.29	14.68	2.93	0.35
May	16.41	0.44	3.75	10.40	25.28	0.25	13.78	9.53	1.03
Jun	9.81	0.42	3.30	11.00	21.14	0.18	13.63	10.57	1.21
Jul	6.58	0.41	3.35	5.86	16.27	0.24	13.35	5.65	0.76
Aug	5.47	0.33	2.90	7.00	12.83	0.20	12.56	7.76	0.68
Sep	4.59	0.27	2.58	6.40	10.17	0.17	11.90	7.00	0.51
Oct	7.07	0.25	2.52	2.57	9.25	0.16	11.68	3.02	0.19
Nov	6.21	0.26	2.68	2.46	10.79	0.16	11.85	2.58	0.15
Dec	8.77	0.26	2.73	1.03	12.89	0.16	11.94	0.83	0.06
Sum	134.1	4.19	37.49	52.76	204.1	2.44	154	52.02	5.13

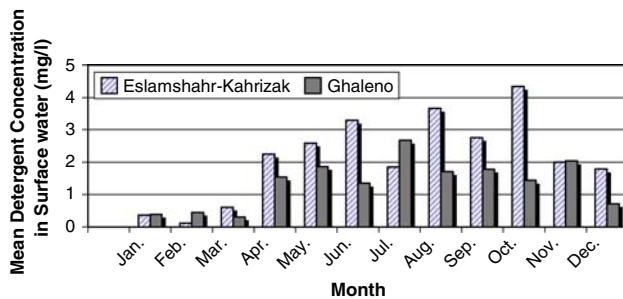[a] Zone 3 has no surface flow

Fig. 2 Mean detergent concentration in the allocated surface water to the agricultural zones in Tehran region

the objective function of IDOE is characterized by minimizing the MNC in the regions in which the nitrate concentration violates the IDOE standard and is defined in Equation 1 as follows:

$$Minimize: MNC = \frac{\sum_{m=1}^{12} \frac{\sum_{i=1}^{n} NC_{im}}{n}}{12}, \tag{1}$$

where MNC represents the regions where the nitrate concentration violates the IDOE standard (mg/L), NC_{im} is the average nitrate concentration in cell i in month m of cells that violate the standards, and n is the total number of cells in which one of the monthly nitrate concentrations violates the IDOE standard (10 mg/L).

Stakeholder 2: Iran Management and Planning Organization

The Iran Management and Planning Organization (IMPO), which sponsors the TWCP, would like to decrease the construction costs of the TWCP. Therefore, the IMPO is looking for minimum coverage of the TWCP. The objective of the IMPO is in conflict with the interests of the IDOE. In this study, the area covered by the TWCP is considered to be a decision variable in the multiobjective optimization model. The objective function of IMPO is defined as follows (Eq. 2):

$$Minimize: C, \tag{2}$$

where C is the construction cost of the TWCP (in USD).

Stakeholder 3: Tehran Regional Water Company

Supplying the domestic and agricultural water demands is the main concern of the Tehran Regional Water Company (TRWC). The domestic water demand of Tehran City and its suburbs is supplied from the Lar, Latyan, Karaj, and Taleghan dams. Therefore, minimizing the irrigation water deficit in the southern part of Tehran is considered to be one of the objectives of the TRWC. In this regard, the following index is defined (Equations 3 and 4):
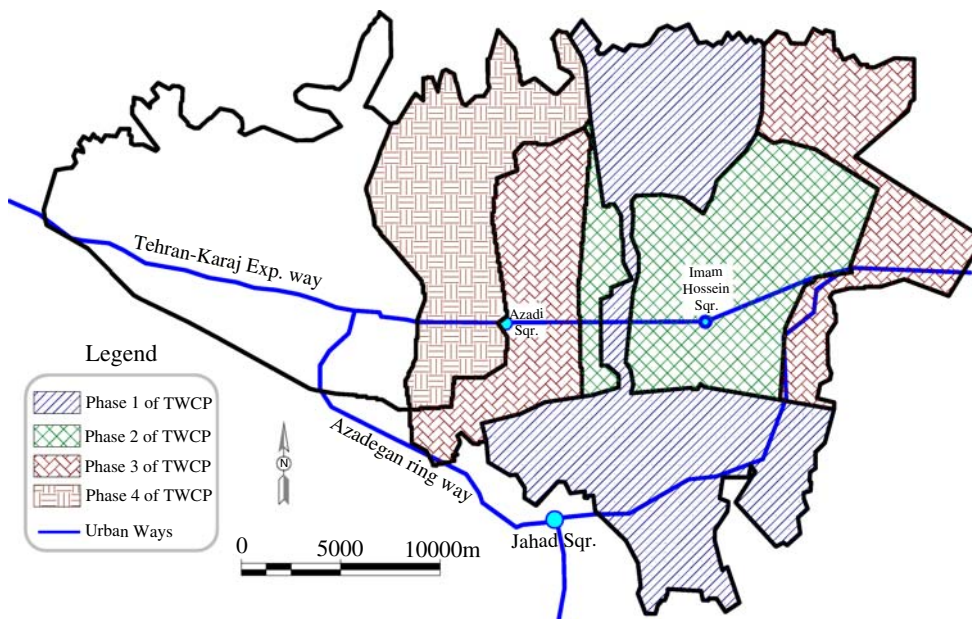
Fig. 3 Different phases of the TWCP

$$DI = \sum_{z=1}^{3} \sum_{m=1}^{12} DI_{zm} \qquad (3)$$

$$DI_{zm} = \begin{cases} \sum_{z=1}^{3} \sum_{m=1}^{12} (Q_{zm} + G_{zm} - D_{zm})^2 & if \quad Q_{zm} + G_{zm} > D_{zm} \\ 0 & if \quad Q_{zm} + G_{zm} \leq D_{zm} \end{cases} \qquad (4)$$

where DI is the water deficit index, DI_{zm} is the water-deficit index in agricultural zone z in month m, Q_{zm} is the average volume of surface water allocated to agricultural zone z in month m (million m^3), G_{zm} is the average volume of groundwater extracted in agricultural zone z in month m (million m^3), and D_{zm} is the agricultural water demand in zone z in month m (million m^3).

Another objective of the TRWC is controlling the average groundwater table level fluctuation. As mentioned previously, the study area included a residential and an agricultural region. The groundwater table in the residential region is rising because of considerable recharge through the absorption well. To control the rise of the groundwater table, decreasing MAGTR in the residential region is considered as the second objective of the TRWC and is defined as follows (Eq. 5):

Minimize: MAGTR, $\qquad (5)$

where MAGTR is the maximum annual groundwater table rise in the residential region (m).

Stakeholder 4: Agricultural Sector (Farmers)

As mentioned previously, agricultural zones are located in the southern part of Tehran. The groundwater table

level in this region is rising because of aquifer recharge through domestic adsorption wells. In addition to available surface waters, the contribution of groundwater resources in supplying the water demands of agricultural lands is considerable, and farmers prefer to increase their benefits by decreasing pumping costs. Because the increase in the groundwater table level decreases pumping cost, there is a conflict of interest between the Agricultural Sector (AS) and the TRWC. The general path of Tehran's groundwater flow is from north to south. Therefore, agricultural return flows do not have a considerable effect on the nitrate concentration of the Tehran aquifer.

To quantify the objective function of the AS, pumping cost is assumed to be a linear function of pumping power (Karamouz and others 2004), and the farmers' objective function is defined based on TPP (Eqs. 6 and 7):

$$Minimize: TPP = \sum_{m=1}^{12} \sum_{z=1}^{3} P_{zm} \qquad (6)$$

$$P_{zm} = \frac{G_{zm} \cdot H_{zm}}{0.102\eta}, \qquad (7)$$

where TPP is total pumping power (kW), P_{zm} is pumping power in zone z in month m (kW), G_{zm} is total pumping discharge in zone z in month m (m^3/s), H_{zm} is the average groundwater table depth in zone z in month m (m), and η is pumping efficiency. It should be noted that the first objective of TRWC can be considered as the second objective of the AS.

Stakeholder 5: Iran Ministry of Health

The quality of water allocated for irrigation purposes is the main concern of the Iran Ministry of Health (IMH) in the southern part of Tehran. Based on available data obtained from existing surface-water and groundwater monitoring systems in the study area, the detergent concentration is the worst, and it can be considered as a water-quality indicator for evaluating the quality of water allocated to the agricultural zones. The maximum allowable detergent concentration in irrigation water is approximately 0.5 mg/L. Therefore, as a constraint in the optimization model, the monthly mean detergent concentration, which is calculated using the following equation (Eq. 8), must be <0.5 mg/L:

$$DC_{zm} = \frac{G_{zm} \times GDC_{zm} + Q_{zm} \times SDC_{zm}}{G_{zm} + Q_{zm}}, \qquad (8)$$

where DC_{zm} is the mean detergent concentration in surface water allocated to agricultural zone z in month m (mg/L), SDC_{zm} is the mean detergent concentration in surface water allocated to agricultural zone z in month m (mg/L), and GDC_{zm} is the mean detergent concentration in the groundwater allocated to agricultural zone z in month m (mg/L).

Existing water quality data show that the average detergent concentration in the Tehran aquifer is approximately 0.1 mg/L; however, as shown in Fig. 2, the detergent concentration in the local rivers in southern Tehran is much greater than the standard level. Therefore, increasing the groundwater contribution in supplying irrigation water demands improves the quality of the allocated water but increases total pumping cost. It clearly shows that the IMH and the AS have conflicting interests.

The study area included a residential and an agricultural region, which are located in the northern and southern parts of Tehran metropolitan area, respectively. Discharging domestic wastewater in this region has increased the nitrate concentration in groundwater in the residential region. To improve groundwater quality in the residential region, the TWCP is under construction. The area covered by the TWCP in the residential region can significantly affect groundwater quality in the northern part of Tehran.

The groundwater table is rising in the residential region because of considerable recharge through absorption wells. The groundwater table rise in the residential region can be controlled by increasing water discharge from agricultural wells located in the central and southern parts of Tehran.

To obtain the trade-off among conflicting objectives of the stakeholders, two optimization models were developed. The first optimization model considers the objectives of the IDOE and the IMPO in the residential region and provides a trade-off between the MNC and the construction costs of the TWCP. Therefore, Equations 1 and 2 are considered to be objective functions of the first optimization model. The

decision variable of this optimization model (x'_1) is the percent of residential region covered by the TWCP $(0 \leq x'_1 \leq 100)$.

By selecting an optimal solution on this trade-off curve, optimal coverage of the TWCP is defined. Therefore, the area covered by the TWCP (decision variable of the first optimization model) is known in the second optimization model. Minimizing MAGTR and TPP (Equations 5 and 6) are conflicting objectives in the second optimization model. Decision variables in the second optimization model are annual water discharge from wells. Each monthly discharge has a feasible range of 0 to 84 million m^3 due to the capacity of available pumps. As the monthly agricultural water demands are completely satisfied, the rest of each monthly water demand is supplied using surface-water resources. Based on the constraints of the second optimization model, agricultural demands are completely supplied, and the detergent concentration in the water allocated to meet agricultural demands must be <0.5 mg/L (see Equations 3 and 8 for more details). A simple penalty approach is used for constraint handling in the multiobjective optimization model. More details about the optimization model will be presented in the next sections.

Methodology

Figure 4 presents a flowchart of the proposed methodology. As shown in this figure, the methodology includes three models: a numeric groundwater quantity and quality simulation model, a multiobjective optimization model, and a conflict-resolution model.

### Groundwater Quantity and Quality Simulation

MODFLOW (Harbaugh and McDonald 1996), which is a three-dimensional finite difference groundwater flow model, was selected for groundwater flow simulation in the study area. The following basic equation is solved by MODFLOW (Eq. 9):

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right) - w = S_s\frac{\partial h}{\partial t}, \qquad (9)$$

where, K_{xx}, K_{yy} and K_{zz} are the hydraulic conductivities along the X, Y, and Z directions, respectively, volumetric flux w represents a source or sink of water, h is the head of groundwater, S_s is the specific storage of the aquifer material, and t is time.

MT3D, which was developed by Zheng and Wang (1999), is used to solve the governing partial differential equations describing three-dimensional transport of

Fig. 4 The flowchart of the proposed conflict-resolution methodology for the conjunctive use of surface and groundwater resources in Tehran region
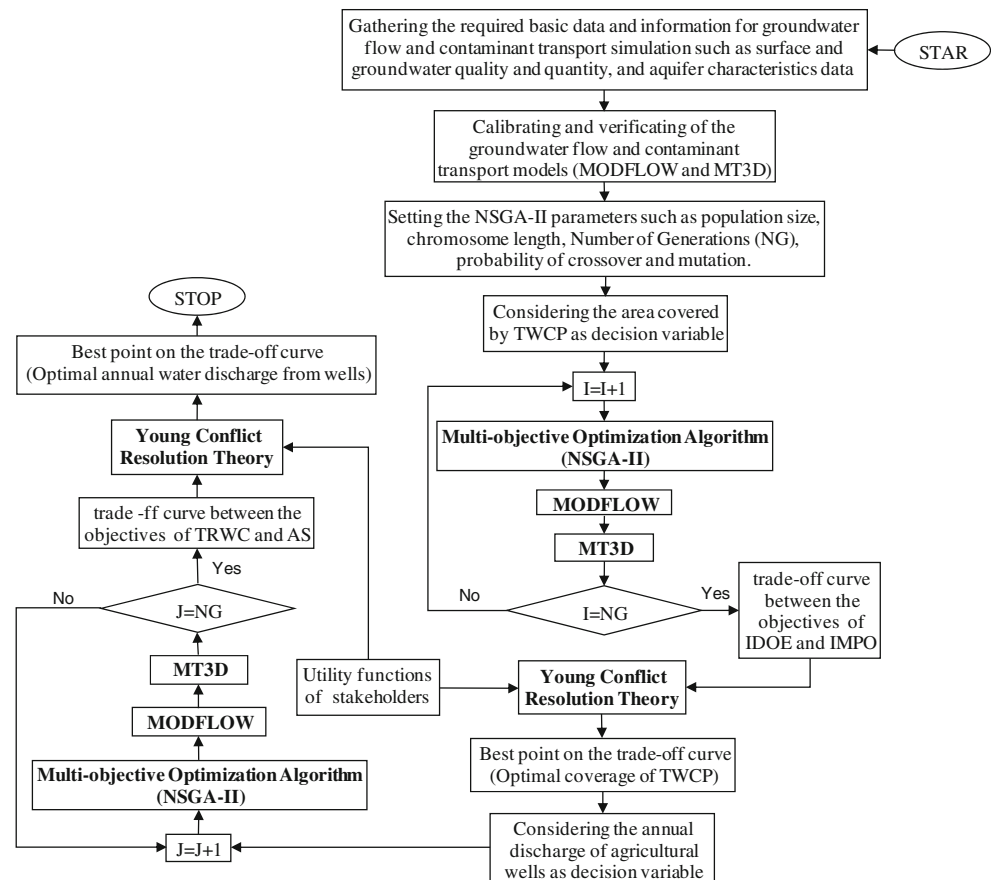
contaminants in groundwater. In this study, MT3D simulates the temporal and spatial variations of the nitrate concentration in the Tehran Aquifer. The results of calibration and verification of both the MODFLOW and MT3D models show that they can be effectively used for simulating groundwater quantity and quality in the study area based on different scenarios defined by the optimization model. More details about the groundwater simulation models are presented in the Results section.

Multiobjective Optimization Model

In practical applications, searching for all Pareto-optimal solutions is a difficult and time-consuming process. To calculate the trade-off curve (Pareto front) among the objectives of stakeholders, a fast and elitist MOEA is required. MOEAs that use nondominated sorting and sharing have been criticized mainly for their computational complexity, their nonelitism approach, and the need to specify a sharing parameter (Deb and others 2002). In this study, the NSGA-II, which has been proposed as a nondominated sorting-based MOEA by Deb and others (2000, 2002), is used. In the NSGA-II, the sharing function approach is replaced with a crowded-comparison approach, which eliminates the previously mentioned difficulties. The

new approach does not require any user-defined parameter for maintaining diversity among population members. Deb and others (2002) showed that the NSGA-II, in most test problems, is able to find much a better spread of solutions and better convergence near the true Pareto-optimal front compared with the Pareto-archived front determined by some elitist MOEAs.

In the NSGA-II, the entire population is sorted according to their nondominance over the other solutions. Based on the number of dominated solutions, a rank is assigned to a particular member of the population. A front is comprised of members having the same rank. The front consisting of rank 1 member is the current best estimate of the Pareto front. To preserve diversity among the population of same generation, the crowding-distance approach is used. The crowding distance is the largest cuboid that encloses the current member but uses members on the same front. The selection operator used is tournament selection, where both children and parents in the same generation compete with each other. The members having a better rank are selected automatically. If any two members have the same rank, the one having the greater crowding distance is selected. The process selection, recombination and mutation process is iterated until a sufficient number of generations. Note that there is no convergence criterion

except the number of generations. Therefore, it is important to set an appropriate population size and maximum number of generations in this algorithm. A more in-depth introduction to structure of the NSGA-II is provided in Deb and others (2000, 2002).

Figure 4 illustrates the flowchart of the proposed multiobjective optimization framework. As shown in this figure, the groundwater flow and contaminant transport simulation models are linked with the NSGA-II. Each solution generated by the NSGA-II module is sent to the MODFLOW and MT3D simulators, and the predicted aquifer responses are sent to the NSGA-II module for fitness function evaluation. Then the evaluated solutions are sorted according to the fast nondominated approach proposed by Deb (2001). Subsequently, a new population is generated using the Tournament selection operator. This process is repeated until the total number of generations as a stopping criterion is achieved. Then the final set of nondominated solutions is saved in an output file. In this study, the process is stopped when the maximum number of generations is met. The maximum number of generations is selected that best provides a robust Pareto front. As shown in Fig. 4, the best point on the trade-off curve is calculated using YCRT, which incorporates the objective functions of stakeholders in the study area.

Conflict-Resolution Methodology

In most water resources and environmental systems, decision makers are concerned with finding a compromise solution that balances conflicting objectives in a socially acceptable manner. These problems are more complicated when different stakeholders are involved, each of whom may has a different set of priorities and preferences. To deal with this class of multiobjective conflict-resolution problems, conflict-resolution techniques are usually used as a special field of game theory. Young (1993) introduced a theory for bilateral bargaining, through which evolutionary conflict resolution maximizes payoffs of stakeholders as much as possible. In this theory, stakeholders are assumed to have only a partial understanding of the game they are playing. Stakeholders of each side locally optimize their payoffs by heuristic exploitation of available information. This theory assumes two finite, possibly overlapping classes or populations of agents, I_1 and I_2. During each period, two randomly drawn agents, $j \in I_1$ and $k \in I_2$, play a two-stakeholder finite game in the role of stakeholders 1 and 2, respectively. Periods need not be of identical length. Agents have von Neumann-Morgenstern utility functions u, which are their private knowledge. Therefore, beliefs about the opponent stakeholder must be based on past observations (Napel 2002), must assume that (1) each population is perfectly homogeneous, (2) the utility function of each agent is

weakly concave and strictly increasing. Napel (2002) proved that this evolutionary game converges to the unique division $(x, 1 - x)$ such that x maximizes the strictly quasi concave function (Eq. 10):

$$R(x) = \min \left\{ \min_{j \in I_1} \frac{\frac{\partial u_j(x)}{\partial x}}{u_j(x)}, \ \min_{k \in I_2} \frac{\frac{\partial v_k(1-x)}{\partial x}}{v_k(1-x)} \right\}. \tag{10}$$

In this bargaining theory, the share of each stakeholder (x_1 and x_2) have the same units ($x_1 + x_2 = 1$), whereas in the present study, as previously described, the utility functions of the stakeholders are based on some values having different units. Moreover, the constraint $x_1 + x_2 = 1$ is not satisfied. To overcome this inconsistency in units, new variables, L_1 and L_2, are defined and shown in Fig. 5

After this substitution, YCRT is applied to the problem with the following variables (Eq. 11):

$$x_1 = \frac{L_2}{L_1 + L_2} \quad \text{and} \quad x_2 = \frac{L_1}{L_1 + L_2}. \tag{11}$$

By defining the utility functions of the stakeholders based on x_1 and x_2, the assumptions of YCRT are satisfied [see Shirangi and others (2008) for more details]. This modification removes the limitations of YCRT so that it can be applied to many real-world conflict-resolution problems. In this study, YCRT is used for conflict resolution in the conjunctive use of surface and groundwater resources in Tehran metropolitan area.

Experimental Design

Figure 6 shows the grids, active and inactive cells, and boundary conditions in the simulation model. As shown in this figure, the continuous domain is replaced by a discretized domain with 500 m × 500 m cells. In this regard,
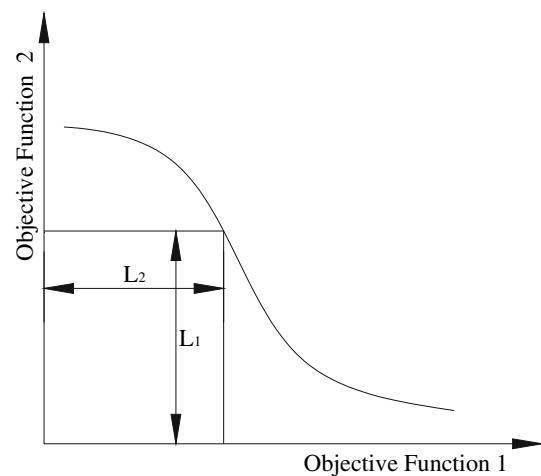

Fig. 5 A typical Pareto front and the definition of L_1 and L_2

the model grid consists of 50 rows and 60 columns. The Tehran aquifer is mainly recharged by inflow at the boundaries, precipitation, local rivers, and return flows from domestic, industrial, and agricultural water use. The developed model is calibrated and verified using available data from the existing 40 monitoring wells in the study area. In the calibrated model, transmissivity varies from 1500 to 3000 m²/d. The average hydraulic conductivity and storage coefficient are also 25 m/d and 6%, respectively. The aquifer in the study area is unconfined and almost single layer. The boundary conditions of the aquifer are classified as either permeable with specific flow rate or impermeable (Fig. 6).

The United States Geological Survey's MODFLOW and MT3D codes are used for estimating monthly groundwater table and quality variations. Because the most precise aquifer water budget has already been estimated for 1993 to 1994, this water budget is used for calibrating and validating the simulation models. The hydraulic conductivities and storage coefficients are calibrated using the monthly piezometric data obtained from existing monitoring wells. Because the
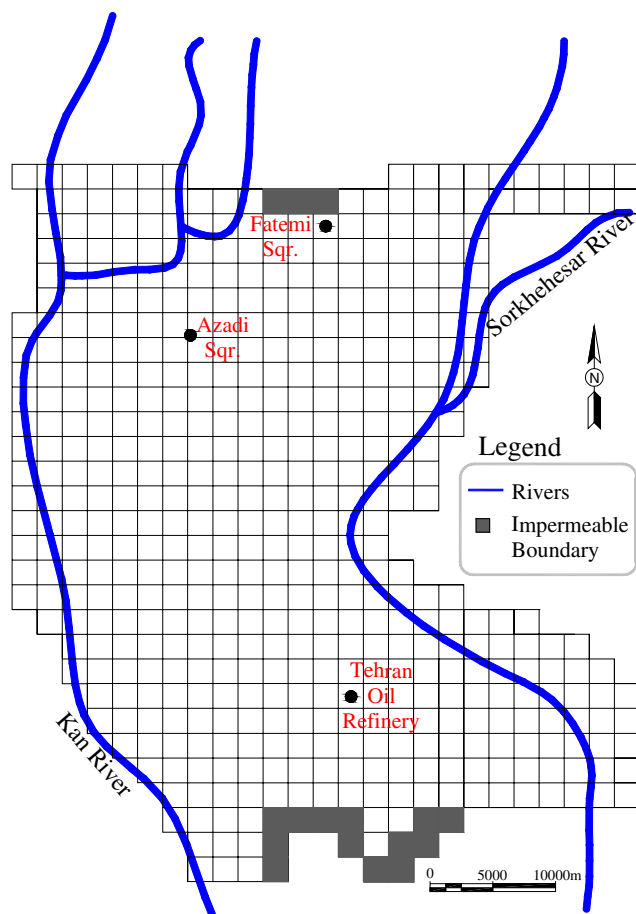
aquifer is considered to be single layer, only the horizontal hydraulic conductivities are estimated. The bedrock elevation for each cell was calculated based on the results of some previous geophysical studies in Tehran region.

Because the groundwater-simulation models should simulate the monthly policies provided by the optimization models, monthly stress periods are considered in the simulation models. To calibrate different parameters of the models, the following steps were taken: (1) primary estimation of the hydraulic conductivity for different cells in the steady-state condition (hydraulic conductivity of each cell estimated based on the results of pumping tests) and (2) estimation of storage coefficient and adjustment of hydraulic conductivity of different cells in the unsteady-state condition.

As mentioned previously, the available data from 1993 to 1994 are used for model calibration and verification. For this purpose, the water table elevations computed by the model were compared with the historic monthly data of each piezometer. The correlation coefficients between computed and observed piezometric data have been >90% in all months, and there is no clear bias or tendency in the simulation model predictions (Fig. 7). For more detailed information about simulation model calibration and versification, the reader is referred to Karamouz and others (2007).
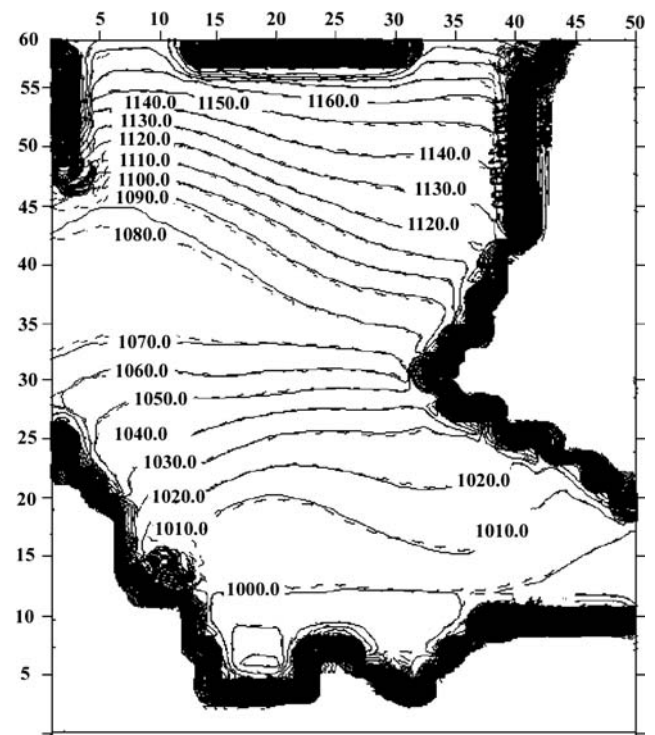

Fig. 6 Generated grid and boundary conditions in the groundwater simulation model developed for the Tehran aquifer (each cell in figure includes four cells in the simulation model)

Fig. 7 Comparison between observed and simulated groundwater table levels in December 1993

In the residential region, which is located in the northern part of the study area, the main pollution source is domestic wastewater discharged to the aquifer. Therefore, nitrate concentration is considered a groundwater-quality indicator in the residential region. The average concentrations of nitrate and total nitrogen in raw domestic wastewater in the study area are 5 and 90 mg/L, respectively. Approximately 86% of total nitrogen can be converted to nitrate through the nitrification process (Hammer and Hammer 1996). Therefore, it is assumed that the ultimate nitrate concentration in wastewater discharged to the Tehran aquifer is 77 mg/L, and the nitrate load in each cell is calculated considering the volume of domestic wastewater discharged. The initial nitrate concentration in the residential region is obtained using the existing groundwater-quality monitoring system. MT3D provides four solution schemes for the advection term, including the method of characteristics, modified method of characteristics, hybrid method of characteristics, and upstream finite difference method. In this study, the upstream finite difference method is used to decrease the simulation runtime. The main input data and parameters used in the simulation models are listed in Table 2.

Because both the MODFLOW and the MT3D models were primarily written using FORTRAN 77; therefore, to provide an acceptable compatibility between optimization and simulation models, the NSGA-II code is also developed using FORTRAN.

Table 2 Values of the main parameters used in groundwater quantity and quality simulation models

Parameter	Value
Grid spacing along row (m)	500
Grid spacing along column (m)	500
Transmissivity (m²/d)	Approximately 1500–3000
Effective porosity	0.25
Average longitudinal dispersivity (m)	25,000
Average storage coefficient (%)	6
Average coefficient of hydraulic conductivity (m/d)	25
Average initial nitrate concentration (kg/m³)	36.6
Solution scheme	Upstream FDM
Courant number (%)	90
Simulation flow type	Transient
Total period number	12
Total simulation time (d)	365
TRPT	100
TRPV	1
Effective molecular diffusion coefficient	0

FDM = finite difference method; TRPT = ratio of horizontal transverse dispersivity to longitudinal dispersivity; TRPV = ratio of vertical transverse dispersivity to longitudinal dispersivity

The parameters of the NSGA-II optimization model were set taking into account suggestions in the literature for specifying these parameters. The population size is considered to be 100. Although determination is a trial-and-error process, the total number of generations is considered to be equal to 200. As suggested by Deb and others (2002), the total number of generations should be at least twice the population size. Mutation probability is set as the inverse of population size. The best value of the probability of cross-over is considered to be equal to 0.7, which is also obtained through a trial-and-error process.

Results and Discussion

The trade-off curve between the objectives of stakeholders 1 (IDOE) and 2 (IMPO) is determined using the NSGA-II model considering their objective functions (Fig. 8). Results clearly indicate that there is a conflict between the objectives of stakeholders 1 and 2. Figure 8 clearly shows that implementing TWCP decreases MNC and partially improves the utility of IDOE.

Before applying YCRT, objectives of stakeholders 1 and 2 are normalized (scaled) between zero and one. Because the trade-off curve shown in Fig. 8 has an almost horizontal section, this section, which contains some nearly dominated solutions, is not considered in normalizing the trade-off curve.

Figure 8 contains valuable information pertaining to the existing conflicts between the objectives of the IDOE (stakeholder 1) and the IMPO (stakeholder 2). To find the best solution on the trade-off curve, YCRT is used. Figures 9 and 10 show the details of applying YCRT to the normalized trade-off curve. Figure 9 shows the utility functions of the IDOE and the IMPO based on different values of x_1 and x_2, respectively. The utility functions were obtained through a brainstorming session with decision makers and experts of the IDOE and the IMPO. Therefore,
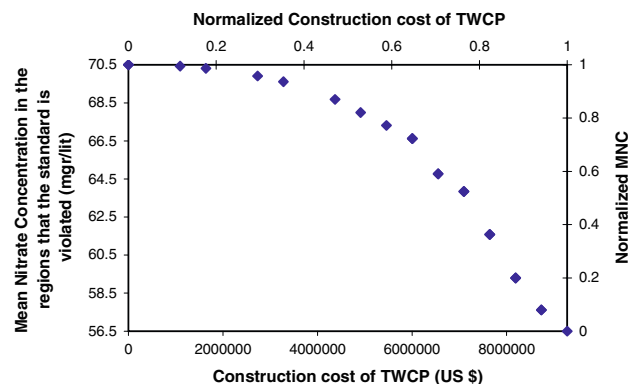

Fig. 8 Trade-off curve between the objectives of the IDOE (stakeholder 1) and the IMPO (stakeholder 2)
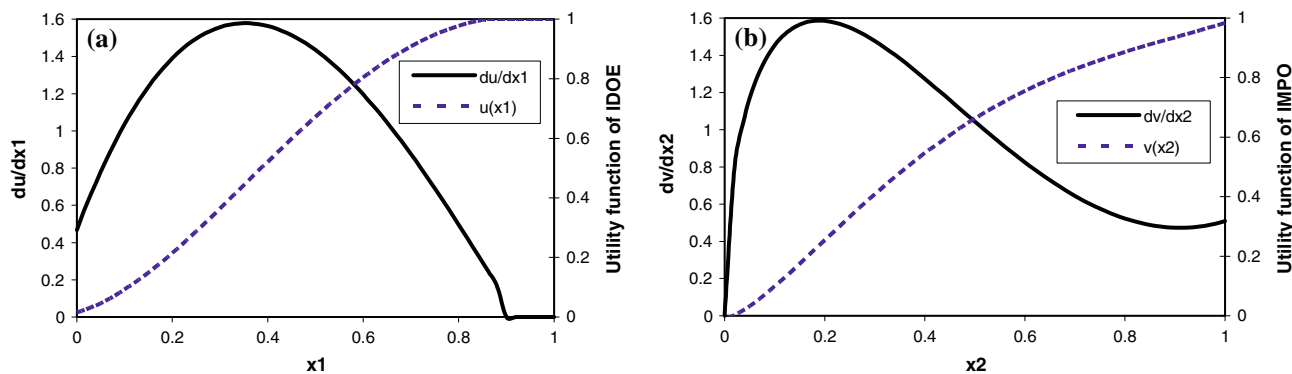
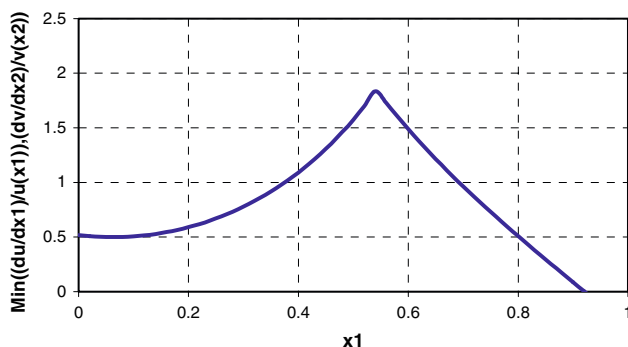**Fig. 9** Utility functions of (**a**) the IDOE and (**b**) the IMPO and their derivatives

Fig. 10 The variations of R vs. x_1 in conflict resolution between the IDOE and the IMPO

Fig. 11 The trade-off curve between the objectives of the TRWC (stakeholder 3) and the AS (stakeholder 4)

no weighting method is used. The derivatives of these utility functions are also shown in Fig. 9 (see Eq. 10 for more details). Variation of R vs. x_1 is shown in Fig. 10. The maximum value of R in Fig. 10 represents the solution of YCRT, which corresponds to MNC = 67.03 mg/L. Based on this solution, the optimal coverage of the TWCP and its construction costs are obtained as 10.75%. and USD 5.9 million, respectively.

The optimal value of the coverage of the TWCP is used as a constraint in the NSGA-II to find a trade-off curve between the objectives of stakeholders 3 and 4, which are related to MAGTR and TPP (Fig. 11). The objectives of stakeholder 3 (water supply to meet demands) and 5 (detergent concentration in allocated water) are also considered as two constraints in the NSGA-II.

As illustrated in Fig. 11, a conflict exists between MAGTR and TPP, and a compromise solution should be found. To resolve this conflict, after normalizing (scaling) the trade-off, YCRT is again used. More details regarding to the application of YCRT are presented in Figs. 12 and 13.

The variations of R vs. x_1 in conflict resolution between the AS and the TRWC is shown in Fig. 13. The maximum value of R in this figure represents the YCRT solution, which corresponds to MAGTR = 1.54 m and TPP =
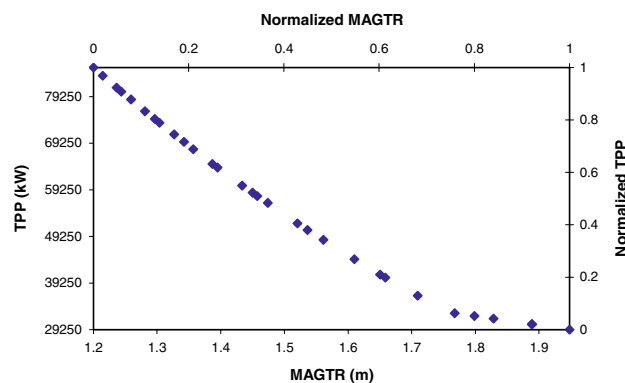
52055 kW. This condition happens if the annual water discharge from agricultural wells is 820 million m^3.

To check the acceptability of the proposed solution, some decision makers and experts from the sectors involved were interviewed. Based on the optimal solution, agricultural water demand is completely supplied and the quality of water allocated to agricultural demand satisfies the standards. Therefore, the main objective of the IMH, the first objective of the TWRC, and the second objective of the AS are completely satisfied. Because MAGTR is reduced from 1.9 to 1.5 m, optimal policies improve the second objective of the TWRC. Decision makers of the AS also accepted the optimal solution because it improves the quality of the water allocated to agricultural zones. However, it partially increases the pumping cost. Decision makers of the IMPO as a governmental organization also accepted the area, which should be covered by the TWCP. They claimed that this area is not far from their previous plan for construction of a Tehran wastewater collection system. They also explained that they pay attention to the sustainable development of the study area. TWCP, as the most important infrastructure in Tehran, is supported financially by the World Bank. The results of interviews clearly show that the proposed methodology has provided a
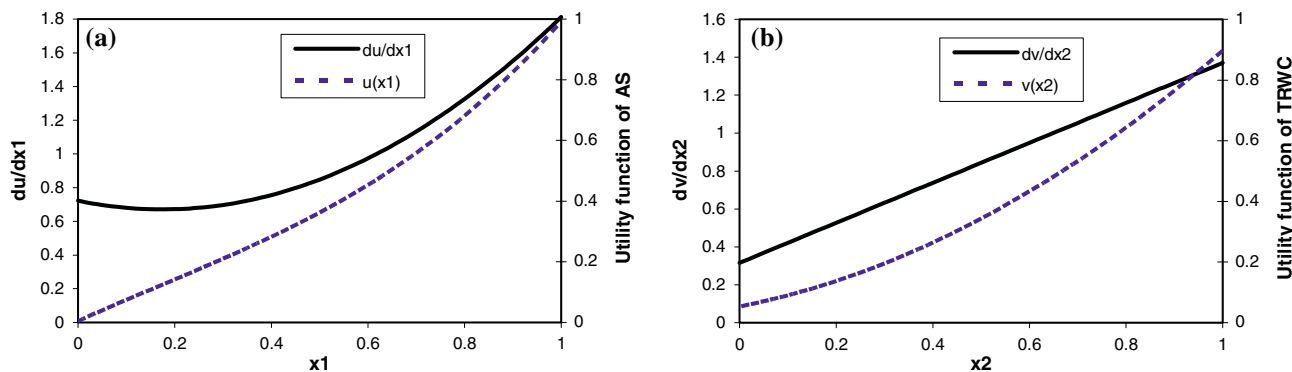
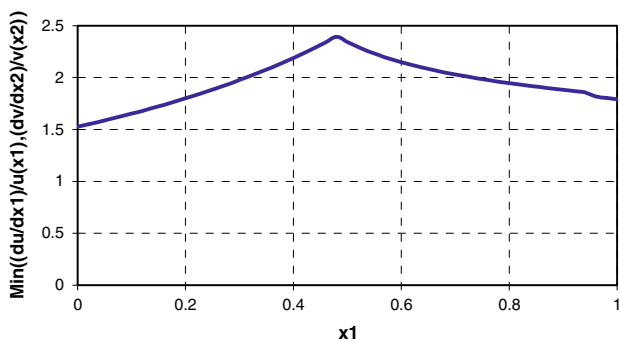**Fig. 12** Utility functions of (**a**) the AS and (**b**) the TRWC and their derivatives

Fig. 13 The variations of R vs. x_1 in conflict resolution between the AS and the TRWC

compromise solution that the stakeholders are willing to accept.

Summary and Conclusions

This article presents a new methodology for optimizing the conjunctive use of surface and groundwater resources in a multistakeholder environment with conflicting interests. This multiobjective problem is solved by combining NSGA-II optimization, MODFLOW and MT3D simulation, and YCRT. The proposed model was applied to the Tehran aquifer in the Tehran metropolitan area in Iran. Stakeholders in the study area have some conflicting interests related to supplying water demands, including increasing acceptable water quality, decreasing pumping costs, improving groundwater quality, and controlling groundwater table level fluctuations. The NSGA-II optimization model can provide some Pareto fronts among the objectives. The best nondominated solutions on the Pareto fronts are then defined using YCRT. Selecting disagreement points for stakeholders, which is required in Nash bargaining theory, is not necessary in YCRT. This conflict-resolution method also considers several utility functions defined by each stakeholder (sector). Therefore, existing

uncertainty in the utility functions of stakeholders can be also incorporated. It may also be a valuable tool for a mediator in a negotiation by bringing stakeholders to an attainable win–win solution.

The results of this case study show the significance of applying an integrated approach to surface and groundwater resources management in the Tehran region. As a compromise solution for the stakeholders, the proposed methodology provided optimal coverage of the TWCP as well as the optimal monthly policies for surface and groundwater allocation to agricultural demands. These operating policies can improve groundwater quality and control groundwater table level fluctuations in the study area.

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