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Simulation-Optimization Modeling of Conjunctive Use of Surface Water and Groundwater

Hamid R. Safavi · Fatemeh Darzi · Miguel A. Mariño

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Abstract Water resources management in semiarid regions with low precipitation and high potential of evapotranspiration is a great challenge for managers and decision makers. In those regions, both sources of water should be managed conjunctively so as to minimize shortages of water in dry seasons. In conjunctive use, the difficulty increases as one must represent the response of both systems interactions, and develop management strategies that simultaneously address surface water and aquifer regulation. This paper focuses on the simulation-optimization for conjunctive use of surface water and groundwater on a basin-wide scale, the Najafabad plain in west-central Iran. A trained artificial neural network model is developed as a simulator of surface water and groundwater interaction while a genetic algorithm is developed as the optimization model. The main goal of the simulation-optimization model is to minimize shortages in meeting irrigation demands for three irrigation systems subject to constraints on the control of cumulative drawdown of the underlying water table and maximum capacity of surface irrigation systems. To achieve the main goal, three scenarios are presented. Results of the proposed model demonstrate the importance of the conjunctive use approach for planning the management of water resources in semiarid regions.

Keywords Surface water · Groundwater · Conjunctive use · Semiarid regions · Optimization · Simulation, Genetic algorithm · Artificial neural network

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H. R. Safavi (✉) · F. Darzi
Department of Civil Engineering, Isfahan University of Technology, Isfahan, Iran
e-mail: hasafavi@cc.iut.ac.ir

F. Darzi
e-mail: fdarzidarya@yahoo.com

M. A. Mariño
Department of Civil and Environmental Engineering, University of California,
Davis, CA 95616, USA
e-mail: MAMarino@ucdavis.edu

1 Introduction

In central Iran, semiarid regions with low precipitation and high potential of evapotranspiration are abundant. Rapid population growth, increased irrigation, and industrial development during the past decades have caused an increasing pressure on water resources in semiarid regions (Safavi et al. 2002). In those regions, both sources of water should be managed conjunctively so as to minimize fluctuations in total water demands caused by variations in rainfall patterns. Conjunctive use has been defined in more ways than one, but in general it is defined as the allocation of surface water and groundwater in terms of quantity and/or quality so as to achieve one or more objectives while satisfying certain constraints (Mariño 2001; Afshar et al. 2008). Conjunctive management compounds the challenges of managing either surface water and groundwater separately. The difficulty increases as one must represent the response of both systems' interactions, and develop management strategies that simultaneously address surface water and aquifer regulation. Traditionally, conjunctive use models have been formulated as optimization models (Chavez-Morales et al. 1985; Hantush and Mariño 1989). Conjunctive use models based on the particular problem under consideration and the assumptions may be classified as linear programming models, dynamic programming models, hierarchical optimization models, nonlinear programming models, evolutionary algorithms, and simulation-optimization models (Vedula et al. 2005). Linear programming has been applied successfully in conjunctive modeling (Rogers and Smith 1970; Nieswand and Granstorm 1971; Louie et al. 1984; O'Mara and Duloy 1984; Hantush and Mariño 1989; Elmangnouni and Treichel 1994; Sethi et al. 2002; Vedula et al. 2005). Dynamic programming has been used because its advantages in sequential decision making processes and applicability to nonlinear systems (Buras 1963; Aron 1969; Coskunoglu and Shetty 1981; Onta et al. 1991; Provencher and Burt 1994; Barlow 1997). Hierarchical or multilevel optimization models have been applied successfully (Maddock 1972, 1973; Haimes and Dreizin 1977; Morel-Seytoux 1975; Yu and Haimes 1974; Dreizin and Haimes 1977; Paudyal and Gupta 1990). Because of the most conjunctive use problems are nonlinear, nonlinear programming has been used (Willis et al. 1989; Matsukawa et al. 1992). The main disadvantage of classical optimization techniques is that most of those methods are based on gradient search techniques. Most of the time, those gradients are calculated numerically. The numerical estimation of gradients is the most expensive part of optimization-based management models. Moreover, numerical calculation of gradients may sometimes lead to large errors. Evolutionary techniques such as genetic algorithm (GA), simulated annealing (SA), etc. have been used as tool for solving the optimum conjunctive management models, because of their relative efficiency in identifying global optimal solutions especially for nonlinear non-convex problems (Wang and Zheng 1998; Karamouz et al. 2002). The development of simulation-optimization models for conjunctive use expanded rapidly in the recent years (Basagaoglu et al. 1999; Mariño 2001; Bhattacharjya and Datta 2005). Simulation models account for the physical behavior of surface water–groundwater systems, whereas optimization models account for the conjunctive management aspects of the systems (Basagaoglu and Mariño 1999). One of the primary advantages of the simulation-optimization model is that it provides a structured means to evaluate trade-offs between sustained rate of groundwater withdrawals and surface water depletion (Barlow et al. 2003), but incorporation of the simulation model within an optimization-based management model is complex and difficult. Embedding technique and response matrix approach are the two methods generally used to incorporate the simulation model within the management model (Gorelick 1983). Incorporation of a highly nonlinear simulation model within the management model would take considerably large computational time to achieve any optimal solution. The computational time requirement to achieve an optimal solution can be reduced by some approximation of the simulation model or use of a trained artificial neural network (ANN) model as an approximate simulator of the physical processes (Bhattacharjya and Datta 2005). A GA-based optimization technique is especially suitable for externally linking the simulation model within the optimization model.

The work presented here focuses on the simulation-optimization for conjunctive use of surface water and groundwater on a basin-wide scale, with a trained ANN model developed as a simulator of surface water and groundwater interaction. The ANN model is externally linked with a GA-based optimization model of the conjunctive water system. The proposed methodology is illustrated by applying it to the semiarid Najafabad plain, a part of the Zayanderood River Basin, located in west-central Iran.

2 Study Area

The study area is Najafabad plain a part of the Zayandehrood River Basin located in west-central Iran (Fig. 1). In recent years, water has become increasingly scarce

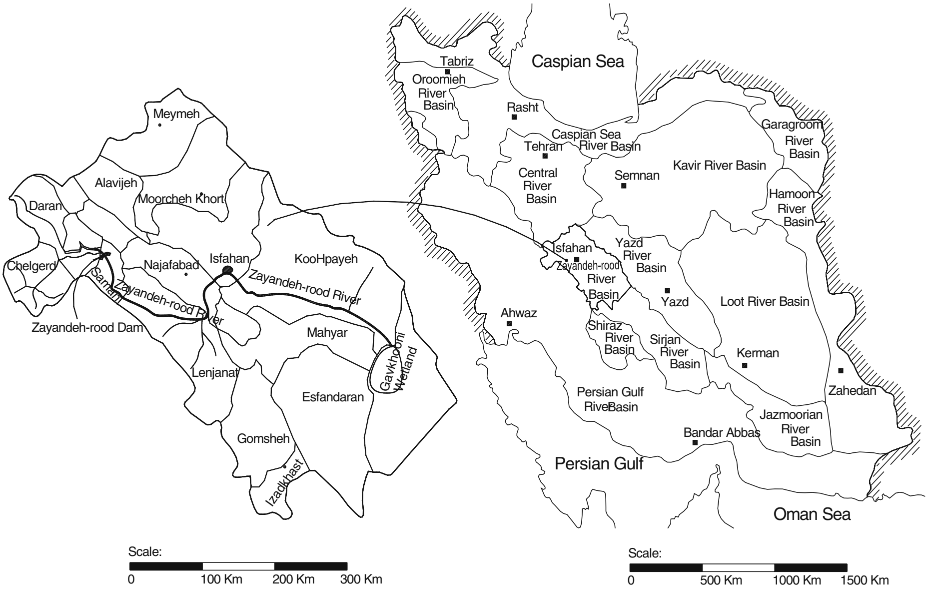


Fig. 1 Najafabad plain in the Zayandehrood River Basin

Table 1 Annual precipitation, pumping, and drawdown in Najafabad plain

Year	2001	2002	2003	2004	2005	2006
Precipitation (mm)	123.2	155.5	145.5	166.8	186.3	163.1
Pumping (MCM)	616.0	880.0	705.9	736.0	717.0	783.0
Drawdown (m)	5.35	3.82	2.50	1.25	2.30	2.84

and the Zayandehrood Basin has shown signs of salinization of agricultural land and increased pollution in the lower reaches of the river. The Najafabad plain has an area of approximately 1,720 km^2 while the Najafabad aquifer has an area of about 1,142 km^2, with geographical coordinates between 500 57′ to 510 44′ north longitudes and 320 20′ to 320 49′ east latitudes. Elevation of the Najafabad plain varies from 2,900 m above sea level in the northwest to 1,580 m in the southeast. The Najafabad plain aquifer is recharged by irrigation percolation; canals and river seepage and precipitation directly on the plain. Aquifer recharge incidental to irrigation is a significant component of the water budget and has varied as irrigation practices have evolved.

Total annual precipitation in the Najafabad plain during 2001–2006 is shown in Table 1. The effective coefficient of recharge to groundwater is about 30% of total precipitation. Groundwater withdrawals from the Najafabad aquifer during 2001–2006 were increased as shown in Table 1. The total number of pumping wells in the Najafabad aquifer is about 10,160 wells with various depths between 17 to 120 m and discharge rate ranging from 2 to 110 l/s (Isfahan Regional Water Authority 2005).

The Najafabad subbasin has a predominately semi-arid climate. Average rainfall is only 150 mm per year and most of the rainfall occurring in the winter months

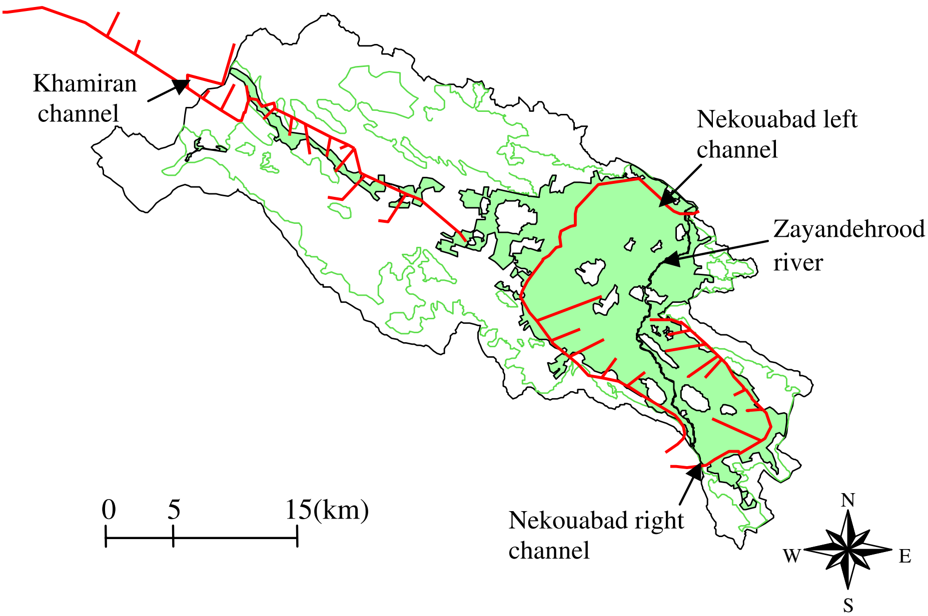


Fig. 2 Nekouabad and Khamiran irrigation channels

Table 2 Basic information of Nekouabad and Khamiran irrigation systems

Name of channel	Designed command area (km^2)	Design discharge (m^3/s)	Length of main channel (km)	Length of secondary channels (km)
Nekouabad right bank	140.0	15.0	35.3	45.0
Nekouabad left bank	480.0	50.0	60.0	77.0
Khamiran	25.0	4.5	40.0	46.0

from December to April. During the summer there is no effective rainfall. Annual potential evapotranspiration is about 1950 mm (Jamab Consulting Engineers 2002).

As shown in Fig. 1, a part of the Zayandehrood River with length of 36 km passes the west side of subbasin. The average width of this reach of the river is 45 m. This reach of the river recharges the aquifer.

Modern surface irrigation started with the construction of Nekouabad diversion weir in the past 38 years. This diversion weir controls both a left bank and right bank main channels. Khamiran surface irrigation also started with the construction of Khamiran Dam in 1992 (Fig. 2). Table 2 shows the basic information of these irrigation systems.

In the past 7 years, a historical low rainfall in the head of the Zayandehrood Basin, combined with a growing demand for water, has triggered in water management at basin and irrigation system level. In view of these changes, farmers have been forced to find strategies to cope with water scarcity at field level. The used strategies are mainly increasing groundwater use, adapting the production strategies, or shifting their livelihood to other activities. If the present increasing trend of groundwater abstraction continues, it may further lead to a decline in the water table. In these situations, both sources of water should be managed conjunctively so as to minimize fluctuations in total water supply caused by variations in rainfall patterns. Thus, ideally in a controlled and well managed conjunctive water use system, an increase in groundwater withdrawals occurs in times of drought and permits temporary mining of the aquifer to reduce surface supplies. In times of abundant surface water supplies, a greater than normal application of surface water would enable aquifer to replenish their supplies. In this paper, the conjunctive use polices for surface water and groundwater resources are developed for minimizing water shortage for irrigation areas in the Najafabad plain subject to constraints on groundwater withdrawals and irrigation-system capacities.

3 Methodology

3.1 Simulation Model

Safavi and Bahreini (2009) developed a simulation model of the Najafabad aquifer to characterize the interactions of surface water and groundwater under uncertainty, using a finite difference discretization and MODFLOW-2000 (Harbaugh et al. 2000) to simulate steady and transient conditions. The model was calibrated to steady state (2001) and transient (2002–2004) observations. The model consists of 106 rows, 138 columns, and one layer. The total active cells are 4,587. The horizontal extent of the

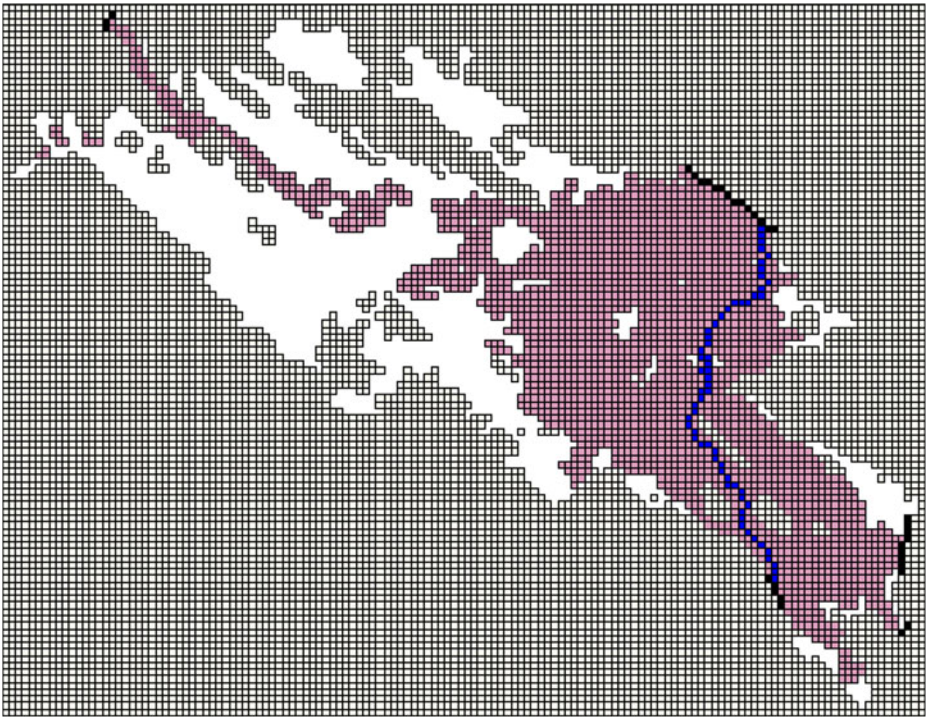


Fig. 3 Grid and boundary conditions of the simulation model of Najafabad aquifer

active area of the simulation model is shown in Fig. 3. Grid cells are in uniform length of 500 m each side. The model extends from the water table to the intersection of the aquifer with underlying bedrock. The minimum saturated thickness of the simulated aquifer is about 25 m on the westside while the maximum saturated thickness is about 90 m on the eastside of the aquifer.

Boundary conditions for the model consisted of no-flow on the northern, southern and western boundaries and specified head (lateral boundary condition) on the interfaces with Isfahan-Borkhar aquifer on the northeast, Lenjanat aquifer on the southeast, and Mahyar aquifer on the eastern boundaries.

The initial conditions are given by interpolating hydraulic head data measured in 49 observation wells located in the Najafabad aquifer during the summer of 2001.

Calibration of the steady-state model for the Najafabad aquifer was performed by comparing the average simulated and observed heads in 49 observation wells in 2001. Figure 4 shows the five different zones used to represent variations in hydraulic conductivity. Table 3 shows hydraulic conductivities of these five zones based on calibration.

Transient model calibration determined specific yields of the aquifer. Hydraulic conductivities determined from the calibrated steady-state model calibrations were used in the transient model. The simulation period encompasses three water years (2002–2004) with monthly stress periods. Hence the simulation period was divided into three stress periods. Assigned to each stress period were recharge rates, return

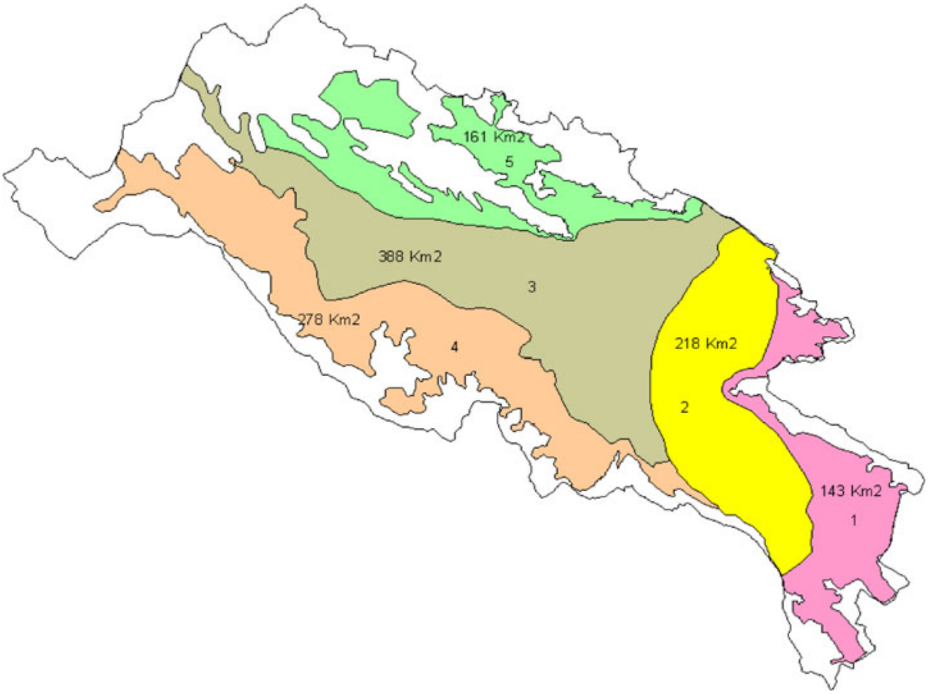


Fig. 4 Five different zones of hydraulic conductivity in Najafabad aquifer

flow from irrigation farms, net precipitation rates, and beginning and ending heads of observation wells. Specific yields were adjusted to simulate the slope of the hydrographs. Table 4 shows the calibrated specific yields for five different zones in the Najafabad aquifer.

3.2 Simulation Using Artificial Neural Networks

The conjunctive use process involves calling the simulation model several thousands of times to verify the constraints. This linkage of the optimization and simulation models will significantly increase the computational problems and also the time needed to achieve the optimal solution of the model. In this study, the simulation model is replaced by a trained ANN. The predictive efficiency of an ANN model is largely dependent on the architecture of the ANN model. After frequent execution of the simulation model MODFLOW-2000 (Harbaugh et al. 2000) for different sets of recharge-discharge values, the selected ANN needed is trained for estimating seasonal groundwater levels for each irrigation zone. On the basis of trial and

Table 3 Values of hydraulic conductivity after calibration

Zone number	1	2	3	4	5
K (m/day)	0.88	0.73	0.61	1.0	1.0

Table 4 Values of specific yields after calibration

Zone number	1	2	3	4	5
S_y	0.04	0.07	0.078	0.05	0.05

error, the total seasonal groundwater pumping, the total seasonal recharge and the average groundwater level in each irrigation zone at the beginning of the season are considered as input variables and the groundwater level variation for each irrigation zone at the end of season is considered as output variable. In this study, we adopt a single hidden layer standard back-propagation feed-forward ANN model. This model has three neuron layers. These are the input, output, and hidden layers. The number of neurons in the input layer is equal to the number of input variables and the number of neurons in the output layer is equal to the number of output variables. The number of neurons in the hidden layer is dependent on the complexity and nonlinearity of the problem (Bhattacharjya and Datta 2005). In this study, the input layer has ten neurons with a tansigmoidal transfer function and the output layer has three neurons with a pure linear transfer function. The general form of the average groundwater level variation for each season in each irrigation zone is estimated as:

$$\Delta H = \ purelin \ \left(w_2^T \ \tan sig\left(\left(w_1 \ Q_1\right) + b_1\right) + b_2\right) \tag{1}$$

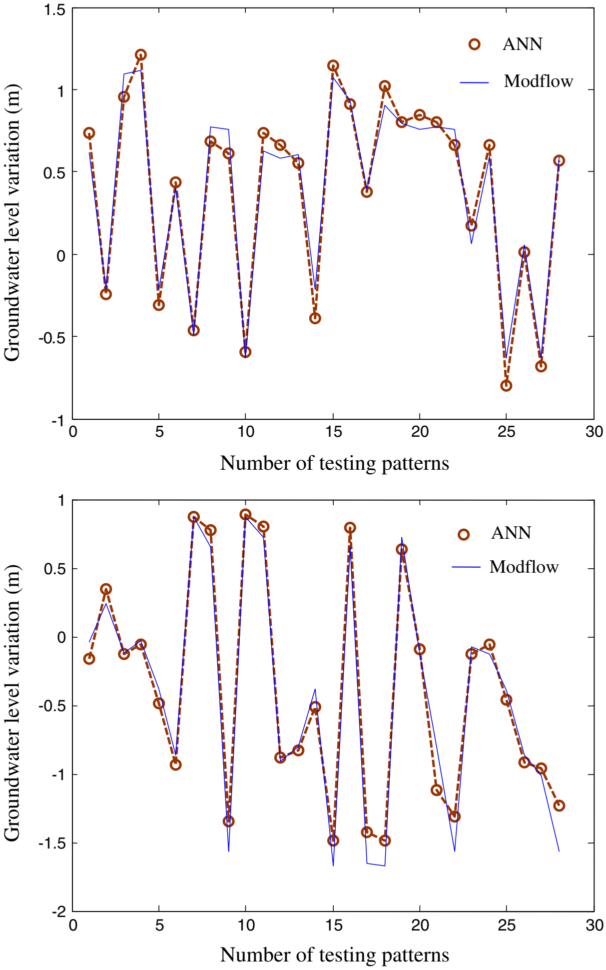
in which: ΔH = vector of the average groundwater level variation (m); w_2^T = matrix of weight parameter in the second layer of the ANN model; w_1 = matrix of weight parameter in the first layer of the ANN model; Q_1 = input matrix which consists of the average discharge from each irrigation zone (MCM), mean precipitation for each season (MCM), and average groundwater level at the beginning of each season for each irrigation zone (m); b_1 = vector of bias parameter in the first layer of the ANN model; and b_2 = vector of bias parameter in the second layer of the ANN model.

Because the variation of groundwater level at the end of each season depends on the average groundwater level at the beginning of the season, the output of ANN for the last season will be used as input for the next season. For training and testing, 512 input/output sets (patterns) are randomly generated using the calibrated MODFLOW-2000 code. The total set of generated patterns is divided into three subsets. About 100 patterns are kept aside for validation, 130 patterns for prediction, and 280 are used for training the neural network. The patterns are normalized and trained with a back-propagation algorithm. To determine the accuracy of the ANN model, the average coefficient of correlation (R^2) is used. Table 5 shows the goodness of fit (R^2) in calibration of the ANN model for each irrigation zone. Figure 5 shows some results of the validated ANN model for simulation of the groundwater level variation for each three irrigation zones. In view of the above, the developed ANN

Table 5 Average coefficient of correlation (R^2) using ANN model

Season	Fall	Winter	Spring	Summer
Nekouabad left irrigation zone	0.981	0.994	0.987	0.997
Nekouabad right irrigation zone	0.961	0.993	0.991	0.977
Khamiran irrigation zone	0.990	0.999	0.992	0.996

Fig. 5 Goodness of fit for typical data sets using MODFLOW-2000 and ANN model



model mimics the MODFLOW-2000 model very well and can be used in the GA-based optimization model.

3.3 Water Demands for Irrigation

Typically there is a two-season cropping pattern in Najafabad irrigation systems. Summer crops include potato, rice, onion, and vegetables while winter crops are dominated by wheat, barley and vegetables. In addition, there are some annual and perennial crops, including alfalfa, orchards and sugarcane. Table 6 shows cropping patterns in Najafabad irrigation systems. Annual cropping intensity is about 170% with slightly higher values for winter rather than summer crops (Sally et al. 2001).

Figure 6 illustrates a typical cropping calendar, considering the main crop types in the Najafabad plain.

Based on cropping area for each irrigation system (Nekouabad right bank, Nekouabad left bank, and Khamiran) and the potential evapotranspriation of the crops

Table 6 Cropping patterns in Najafabad irrigation systems

Crop	Planting Date	Harvest Date	Area (ha)	Percent
(a) Winter				
Wheat	Nov	Jun	21,832	35.5
Barley	Nov	May	4,982	8.1
Onion	Oct	Jun	8,118	13.2
Fodder	Oct	Jun	4,920	8.0
(b) Summer				
Rice	Jun	Oct	15,006	24.4
Potatoes	Feb	Jun	5,744	9.3
Vegetables	Mar	Oct	12,054	19.6
(c) All year				
Sugar beet	All year	All year	1,599	2.6
Orchards	All year	All year	6,863	11.2
Alfalfa	All year	All year	7,380	12.0
Actually cropped area (ha)			88,498	
Channel command area (ha)			61,500	
Summer cropping intensity				79.1
Winter cropping intensity				90.6
Annual cropping intensity				169.7

estimated by using the FAO-CROPWAT program (FAO 1992), the net monthly water demands of these irrigation systems are presented in Table 7. The seasonal water demands are shown in Fig. 7.

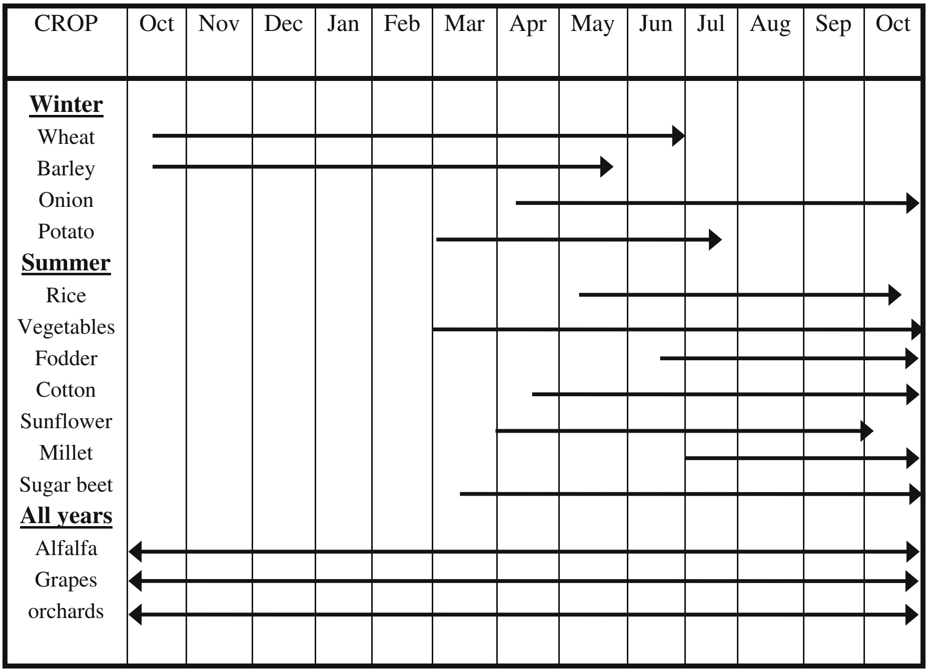


Fig. 6 Typical crop calendar, Najafabad plain

Table 7 Net monthly water demands of irrigation systems (MCM)

Irrigation system	January	February	March	April	May	June	July	August	September	October	November	December	Annual
Nekouabad right	0.226	1.58	3.755	12.491	21.045	36.454	32.324	32.466	24.389	11.926	2.933	0.839	180.428
Nekouabad left	0.446	3.995	8.376	27.959	45.719	85.923	69.375	64.707	48.524	26.714	7.811	1.984	391.533
Khamiran	0.035	0.246	0.625	2.861	5.006	7.597	6.34	5.407	3.955	3.067	0.628	0.13	35.897
Total	0.707	5.821	12.756	43.311	71.77	129.974	108.038	102.58	76.868	41.707	11.372	2.953	607.858

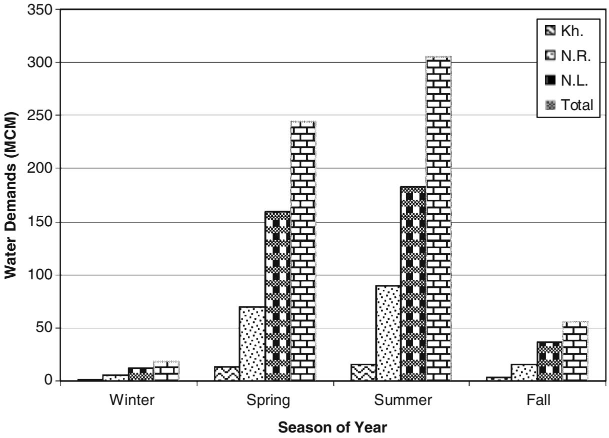


Fig. 7 Seasonal water demands of irrigation systems

3.4 Management Model

The objective of the optimization model for the conjunctive use of surface water and groundwater is to minimize shortages in meeting irrigation demands for 3 irrigation systems in the Najafabad plain subject to constraints on the control of cumulative drawdown of the water table and maximum capacity of surface irrigation systems:

$$Minimize\ Z = \left\{ \begin{array}{ccc} \left(\sum_{k=1}^{3} \sum_{i=1}^{m} \sum_{j=1}^{4} \left(D_{kij} - Sup_{kij} \right)^2 \right), & if & D_{kij} \geq Sup_{kij} \\ 0 & if & D_{kij} \leq Sup_{kij} \end{array} \right\} \tag{2}$$
$$k = 1, \ldots, 3, \quad i = 1, \ldots., m, \quad j = 1, \ldots, 4$$

$$Sup_{kij} = a_k.\, GW_{kji} + a_k.\, b_k.\, c_k.\, SW_{kij} \tag{3}$$

$$Z = Z + Z_l \tag{4}$$

$$Z_l = R.(\Delta L_{ik} - \Delta L_{\max})^2 \tag{5}$$

subject to:

1. Cumulative water-table drawdown:

$$\sum_{i=1}^{m} \sum_{j=1}^{4} \Delta L_{ijk} \leq \Delta L_{\max k} \tag{6}$$

$$\Delta L_{ik} \leq \Delta L_{\max} \quad i = 1, \ldots, m \tag{7}$$

2. Capacity of irrigation systems:

$$\frac{SW_{ijk}}{N.b_k} \leq \alpha.CC_{\max k} \qquad \forall k \tag{8}$$

in which, Z = objective function; k = number of irrigation zones (for Khamiran zone, k = 1, Nekouabad right, k = 2, and for Nekouabad left, k = 3); i = number of years; m = number of years in the planning horizon; j = number of seasons (j = 1 for fall, j = 2 for winter, j = 3 for spring, and j = 4 for summer); R = penalty coefficient; Z_1 = penalty function; GW_{kij} = volume of groundwater extracted in agricultural zone k in season j of year i (MCM); SW_{kij} = volume of water supplied from surface water to agricultural zone k in season j of year i (MCM); D_{kij} = agricultural water demand in zone k in season j of year i (MCM); ΔL_{kij} = groundwater-level variation in agricultural zone k in season j of year i (m); $\Delta L_{\max k}$ = maximum allowable cumulative groundwater variation in zone k; $CC_{\max}$ = maximum surface water supply capacity for each irrigation system (MCM/day); N = number of operation days for each irrigation system in each season; a_k = efficiency of water use in the farm in agricultural zone k; b_k = efficiency of water use in the main channels in agricultural zone k; c_k = efficiency of water use in the secondary channels in agricultural zone k; and α = coefficient between 0 and 1 for limiting of channel conveyances.

Constraint 1 limits the cumulative drawdown of the water table within an acceptable range during the planning horizon. Based on constraint 2, the volume of water supplied from surface water is limited by the capacity of each irrigation system. The objective function 2 along with constraint 6, 7, and 8 constitutes a nonlinear optimization problem. Groundwater-level variation (ΔL) in each zone is a function of the volume of groundwater extracted in agricultural zone GW_{kij}, the inflow/outflow at the boundaries, recharge by direct precipitation, return flow from surface irrigation and leakage from the bed of the Zayandehrood River. Variations of groundwater level are simulated using the developed ANN model which is externally linked with the optimization model.

3.5 Linkage Between ANN-Simulation Model and GA-Based Optimization Model

Genetic algorithms (GA) are considered to be powerful and robust tools for nonlinear function optimization. These algorithms are computationally simple, but powerful in their search for improvement after each generation (Goldberg 2000).The basic techniques of GA are designed to simulate the mechanism of population genetics and natural rules of survival in pursuit of the ideas of adaptation. One of the great advantages of GA is that it dose not require differentiability of either the objective function or the constraint function (Bhattacharjya and Datta 2005). GA does not assume unimodality of the objective function. The constraints handling capacity of GA are also better than that of classical optimization techniques, because of the population-based approach in GA (Deb 2001). Generation of the initial population, representation and encoding, selection, crossover, and mutation are the main steps in the GA-based optimization models. In this study, the gene values are the seasonally-allocated groundwater and surface water to the agricultural zones. A chromosome consists of the combination of these genes as decision variables as

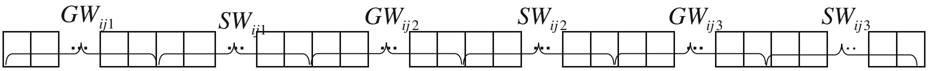


Fig. 8 Typical chromosome for GA model

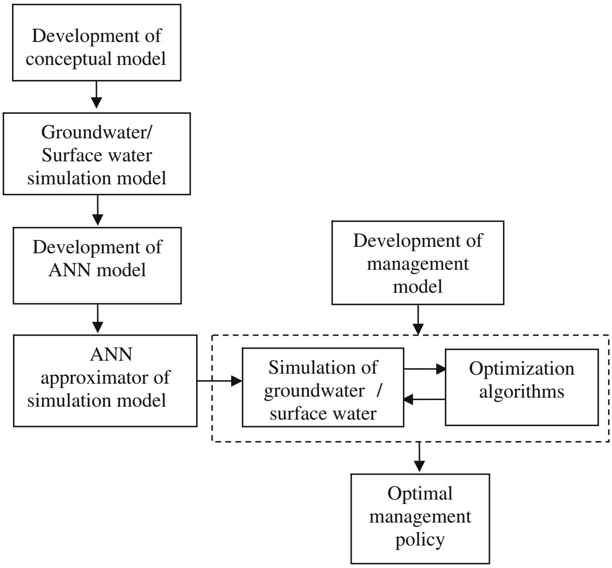


Fig. 9 Schematic representation of the linked simulation-optimization model

shown in Fig. 8. The number of genes in a chromosome is equal to K.N.Y.S, where K = number of agricultural zones, N = number of water sources (surface water and groundwater), Y = number of planning years, and S = number of seasons in each year. For example, when there are three agricultural zones and two water sources (SW and GW), the number of genes in a chromosome for a 4-year planning horizon based on four seasons in the year is equal to 96.

Real-coded GA is used in this study. There are three operators namely, selection, crossover, and mutation to generate new population of points from the old population. In the selection operator, a set of chromosomes is selected as initial parents at the reproduction stage on the basis of their fitness. The fittest are given a greater chance of survival as well as a greater probability of reproducing more off-springs. The process of mating is implemented through the crossover operator. Mutation, an arbitrary change of the genes, is implemented to preserve the genetic diversity in the population. Mutation probability of occurrence can be kept low as it can potentially disrupt a good solution (Vasan and Raju 2009). For the selection of the new set of population for the next generation, a tournament selection operator with size two is used in this study. The process is continued until a termination criterion of a pre-set maximum number of generation is met.

Figure 9 shows a schematic representation of the developed methodology using a linked ANN-simulation and GA-optimization model.

4 Simulation-Optimization Results

The aforementioned simulation-optimization model is applied to the Najafabad Plain. The main goal is the conjunctive use of surface water and groundwater resources to minimize shortages in meeting irrigation demands. To achieve the main goal, three scenarios are considered:

4.1 Scenario I

The aim of this scenario is to formulate an operation model for irrigation systems assuming the reliability of surface waters flowing into the basin (which is also a function of the operation model of the Zayandehrood Dam reservoir in the upstream of the basin) with maximum use of the available groundwater so as to meet the total water demand. The latter is determined by the cultivated area and the cultivation model employed in the region. Along these lines, priority is given to groundwater use with surface water only serving as a complementary supply. It is assumed that the maximum capacity of the main irrigation channels comprises the only constraint on surface water utilization for allocation of water to irrigation systems. Results from the model indicate that the achievement of the mentioned objectives becomes possible only when groundwater-level variations are controlled according to the model presented in Fig. 10 for groundwater extraction and surface water allocation to different irrigation zones. The complementary impact of groundwater on providing for the water demand and the compliance of the peaks of water use from both resources with that of agricultural demands during the growing season is clearly observed in Fig. 10.

Results in Fig. 10a show that surface water is the predominant supply source in the Khamiran irrigation zone. This is because inadequate groundwater recharge and the resulting low aquifer storage have put limitations on groundwater extraction in this zone. The trend of changes in water extraction from the aquifer is seen to be a function of recharge in preceding periods so that better recharge events in preceding periods make higher quantities of extraction possible. This trend is clearly witnessed in the 11th period (i.e., spring of the third year).

A greater portion of the water demand can be supplied from groundwater resources to the Nekouabad left and right irrigation systems due to the better condition of the aquifer and the better recharge from the Zayandehrood River in these zones. It is observed in Fig. 10b for the Nekouabad right irrigation system that the maximum supply reaches 92% of the demand during the 12th period, which coincides with the summer time in the third year. The reasons for this include both the control on groundwater-level drawdown, which prohibits great water extraction, and the limitation of channel capacity, that limits surface water supply. The exploitation of these two resources throughout the years of system operation exhibits an almost constant trend, which has given rise to relatively sustainable conditions in the zone. Similar conditions are observed in Fig. 10c which depicts the situation of the Nekouabad left irrigation system.

The adoption of this conjunctive use policy has limited water table drawdown in the Khamiran zone, the Nekouabad right and left irrigation zones, respectively, to 1.5, 1.44, and 2.66 m. Figure 11 shows the groundwater-level distribution at the end of the operation period.

Based on the results obtained from this scenario, the average annual volume of surface water that must be supplied to the three zones of Khamiran, Nekouabad left, and Nekouabad right irrigation systems are 58, 219, and 444 million cubic

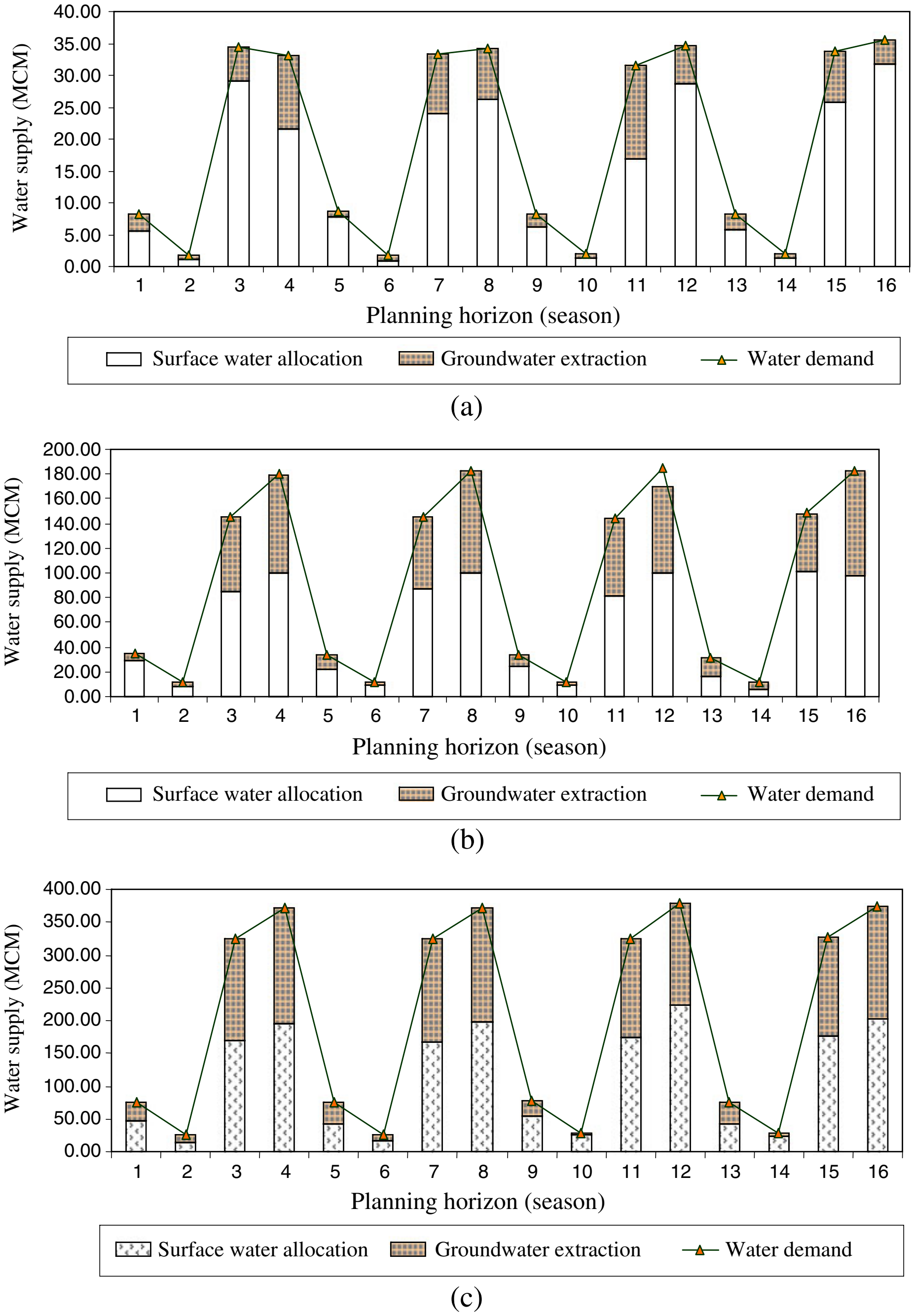


Fig. 10 The water demand and seasonal allocated surface water and groundwater to **a** Khamiran, **b** Nekouabad right, **c** Nekouabad left irrigation zones

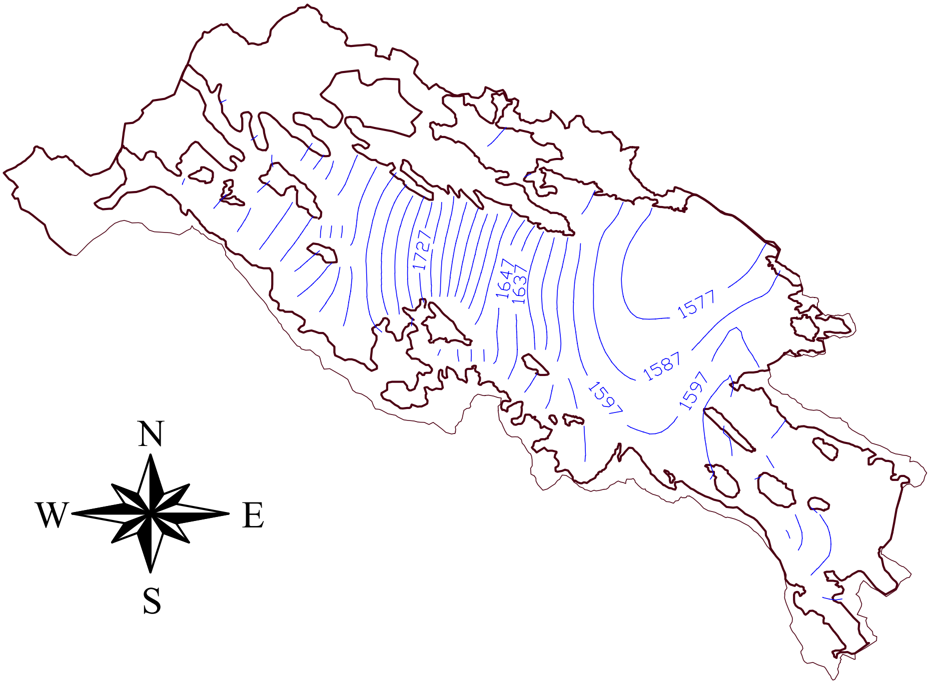


Fig. 11 Groundwater table level at the end of planning horizon

meters (MCM), respectively. The important question, however, is whether or not such volumes of water are ever available. The answer to this question is provided by a glance at the existing long-term statistics. Over the years of the irrigation system operation, this policy was practical to exercise during wet years prior to 1997 when adequate water was available. However, present conditions of water scarcity and modern irrigation systems in operation do not allow for such a policy to be exercised. For instance, the volumes of water available in the three irrigation systems during the water year 2004 were 27.5, 70.8, and 152.9 MCM, respectively, for Khamiran, Nekouabad right, and Nekouabad left zones, which clearly shows considerable differences with those proposed in the present scenario.

The present scenario is only meant to expose the potentials existing in the Najafabad Plain and to investigate the possibility for full development or exploitation of the arable land in the region if and when a proper and appropriately formulated water exploitation policy is adopted for the whole Zayandehrood river basin.

4.2 Scenario II

The Nekouabad operation model depends on the total annual inflow by both the river and the inter-basin water transmission tunnels as well as on the operation model of the Zayandehrood Dam in the Zayandehrood River Basin. Considering the fact that the present simulation-optimization model only involves one of the sub-basins and based on the policy for operating the irrigation systems, the maximum volume of surface water available in each period is computed based on the average volume of water available in each irrigation system. The ratio of the volume allocated to each system to the channel capacity is then computed. The average values of these volumes are finally calculated to be used as conditions on the surface water available in the optimization model. The objective function was expressed as Eq. 2 and the related constraints for groundwater use were obtained from Eqs. 6, 7, and 8. The results from the model are presented in Fig. 12, expressed as volume of water use from surface and groundwater resources in each zone.

Groundwater extraction over the operation years takes a constant trend but with different volumes for different years. The reason for this behavior might be found in the policy adopted to maintain the constraints imposed on groundwater-level variations and the effect of groundwater level at the beginning of each period on the aquifer response to the stresses in that period. Consequently, and as a result of these constraints on groundwater level, exploitation of the two resources will be such that the above conditions are satisfied while the value of the objective function is simultaneously improved. With these conjunctive uses of surface and groundwater resources, the supply for agricultural water demand will be as in Fig. 13, showing that the total water demand is not fully satisfied under this scenario.

The water supply potential in the Najafabad plain does not meet the total agricultural water demand in the region. Average percentages of water supplied by the irrigation systems over the 4-year period are presented in Table 8. During the summer when agricultural water use is in its peak, for instance, the average percentages of water supplied in Khamiran, Nekouabad right, and Nekouabad left irrigation systems are 53%, 67%, and 66%, respectively. Conjunctive use of groundwater and surface water resources according to the optimized model obtained from the execution of the present scenario will lead to a groundwater-level drawdown of 1.82, 2.1, and 3.13 m, respectively, in the three agricultural zones at the end of the 4-year operation period.

4.3 Scenario III

Assuming that the present policy for irrigation system operation will be continued by 2011 and constraints similar to those in the above scenarios will be imposed on groundwater use, the water demand was corrected for the third scenario and the optimization model was executed for a 12-year period (2000–2011). Based on the above assumptions, the volumes of surface and groundwater use in the Plain to supply for the agricultural water demand were obtained from executing the simulation-optimization model, which are presented in Fig. 14.

The cumulative groundwater drawdown over the 12-year period for Khamiran, Nekouabad right, and Nekouabad left zones were calculated at 1.4, 2.04, and 3.08 m, respectively. Comparison of these values and the corresponding values observed in the Najafabad plain under actual operation conditions over the period 2000–2004 indicates a better preservation of groundwater-level drawdown the longer period of operation. In fact, such conditions can only be achieved by reducing pressure on groundwater resources and the resulting reduced demand, which will, in turn, entail a more sustained and sustainable exploitation of the resources by the users. The above method of water exploitation from the two existing resources will not be capable of supplying for the total water demand in the Plain and not all the arable land will, therefore, be cultivated. However, Fig. 15 for the total volume of water harvested

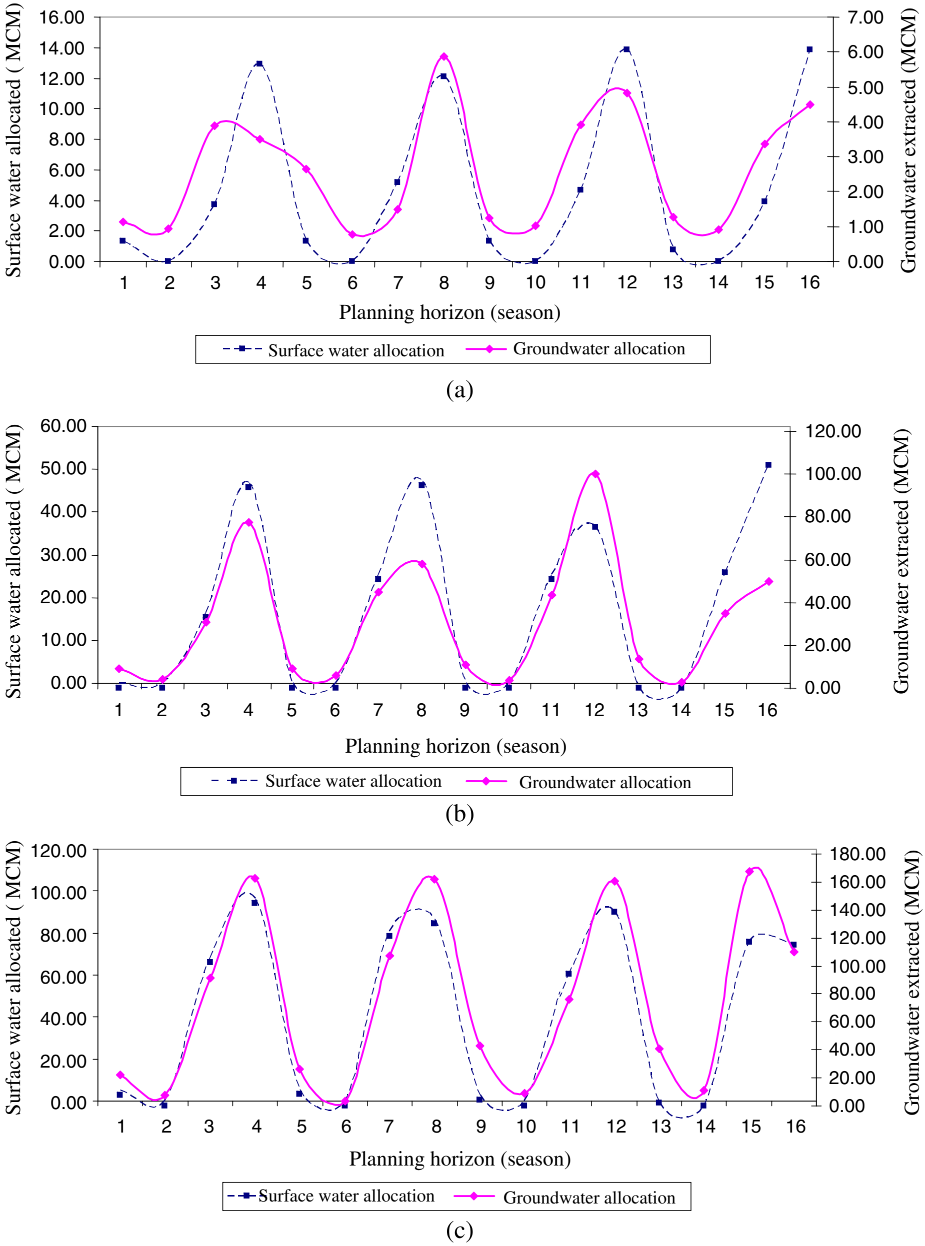


Fig. 12 The seasonal allocated surface water and groundwater to **a** Khamiran, **b** Nekouabad right, and **c** Nekouabad left irrigation zones

versus the agricultural water demand shows that a relatively sustainable farming can be expected with a higher reliability if the water demand is corrected as in scenario II. It should be mentioned, however, that if greater groundwater level drawdowns are

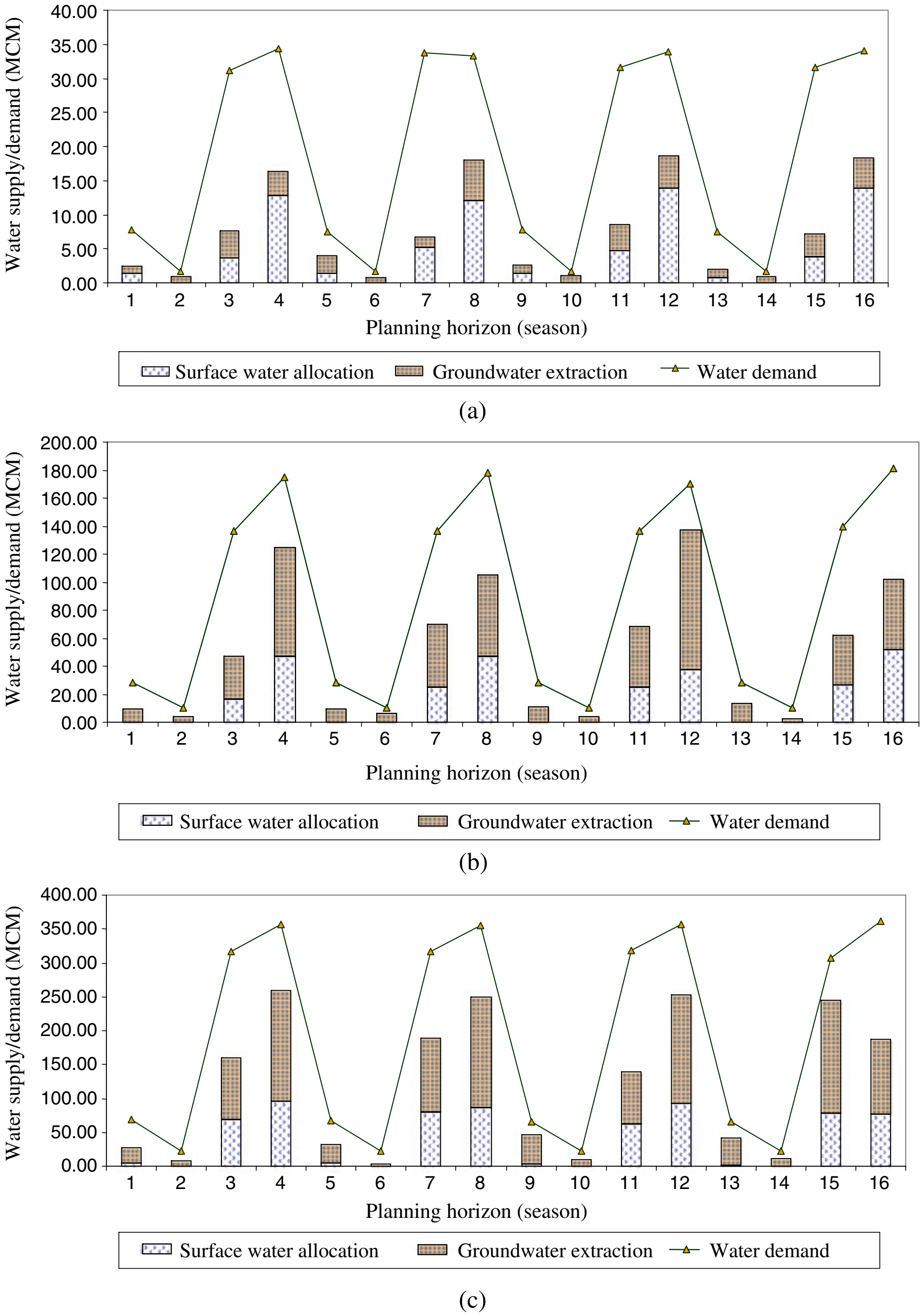


Fig. 13 The water demand and seasonal allocated surface water and groundwater to **a** Khamiran, **b** Nekouabad right, and **c** Nekouabad left irrigation zones

Table 8 The average percentages of water supply in each irrigation zones

Irrigation zone	Fall	Winter	Spring	Summer
Khamiran	40	56	24	53
Nekouabad right	38	42	45	67
Nekouabad left	55	34	58	66

allowed, then more of the groundwater can be extracted to yield a higher cultivated area, but the objective behind our present scenarios is only to estimate the optimized level of water extraction according to the criteria defined in each scenario.

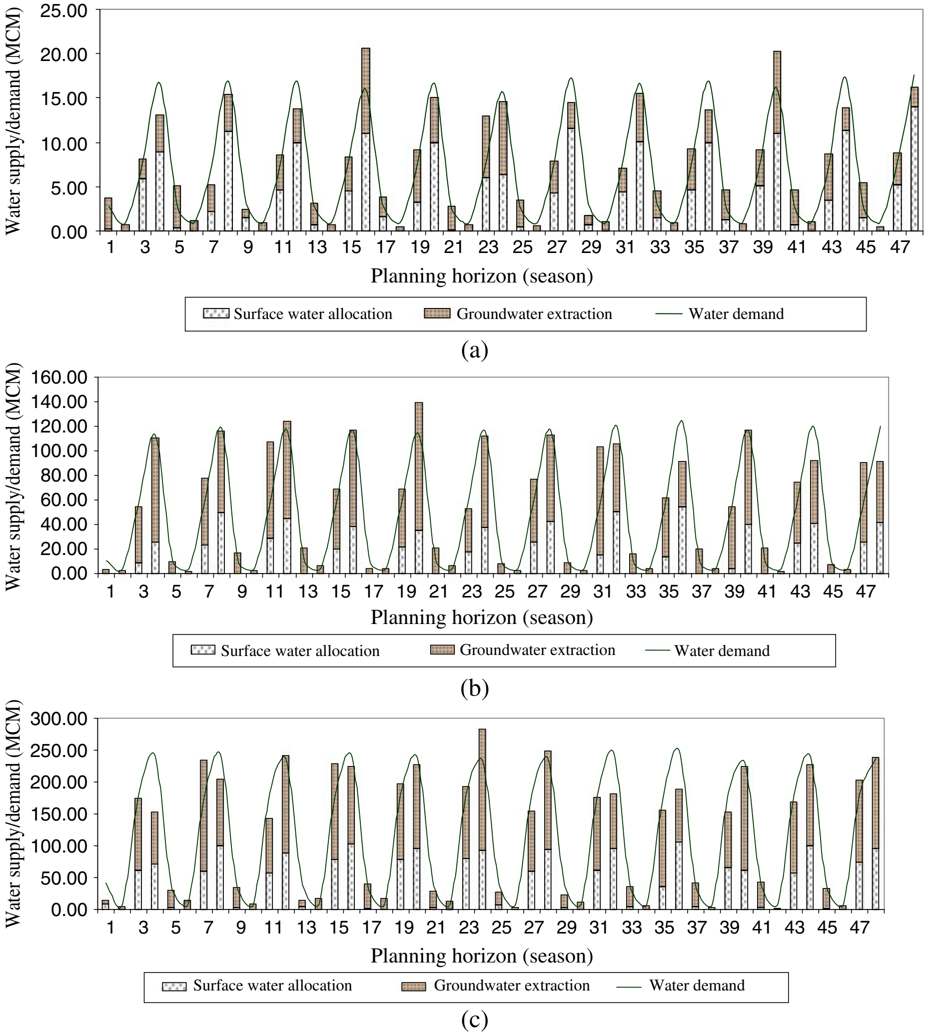


Fig. 14 The water demand and seasonal allocated surface water and groundwater to **a** Khamiran, **b** Nekouabad right, and **c** Nekouabad left irrigation zones

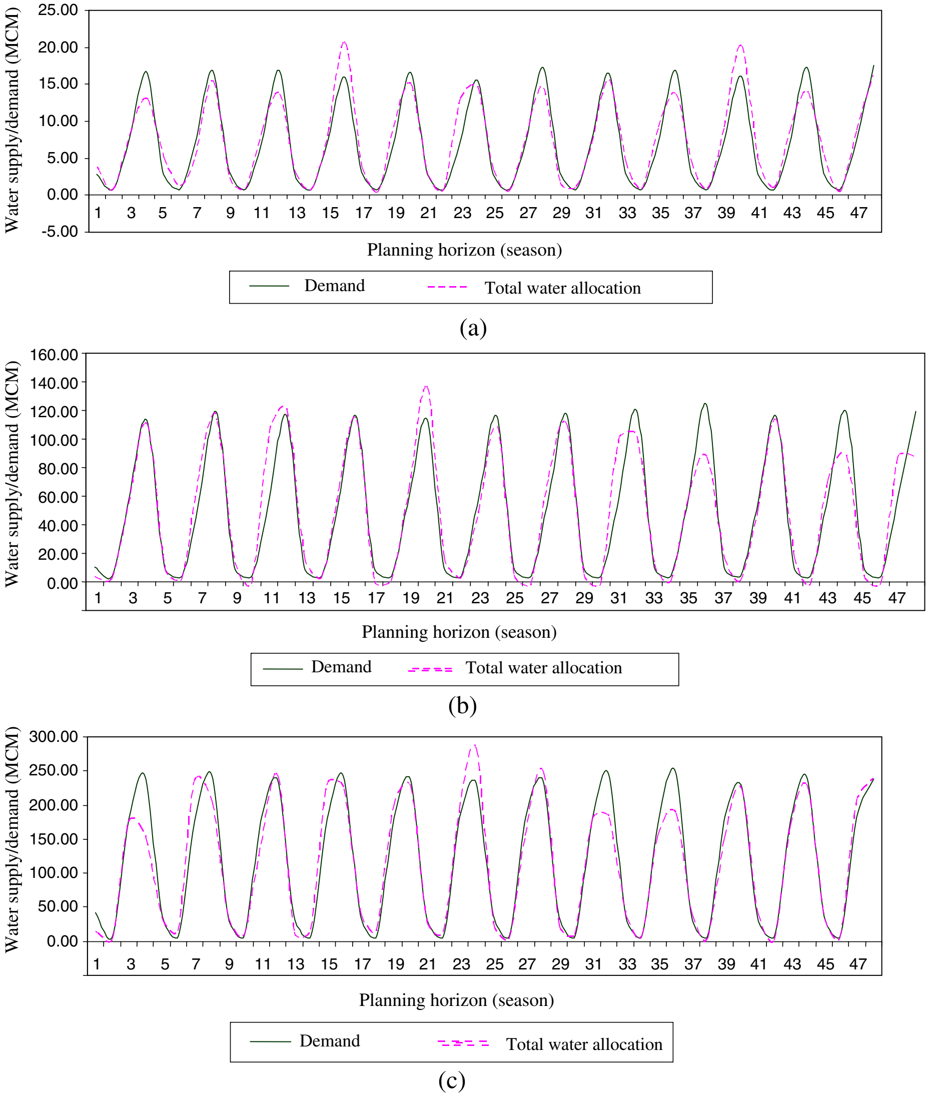


Fig. 15 The water demand and total water allocated from surface water and groundwater to **a** Khamiran, **b** Nekouabad right, and **c** Nekouabad left irrigation zones

5 Conclusions

A linked simulation-optimization methodology was developed for conjunctive use of surface water and groundwater in semiarid regions. The model was intended for large-scale planning of semiarid regions using seasonal time steps. The trained ANN model as a simulator of surface water and groundwater interaction was linked with a GA-based optimization model. The ANN model calculated groundwater-level variations at different time steps. The objective of the conjunctive model was to minimize shortages in meeting irrigation demands. The formulated optimization model was solved using a real coded GA. The performance of the developed methodology was demonstrated in the Najafabad Plain in west-central Iran. The performance of the ANN-GA-based conjunctive model largely depended on the accuracy and adequacy of the ANN model used as an approximate simulator of the interaction of surface water and groundwater processes. The simulation-optimization model developed in this study has the flexibility to model different conditions and assumptions and can be used for planning the management of irrigation systems.

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