Monthly Water Resources and Irrigation Planning: Case Study of Conjunctive Use of Surface and Groundwater Resources

Mohammad Karamouz, F.ASCE[1]; Reza Kerachian[2]; and Banafsheh Zahraie[3]

Abstract: The Tehran metropolitan area is one of the mega cities of the world and has an annual domestic water consumption close to one billion cubic meters. The sewer system mainly consists of traditional absorption wells. Therefore, the return flow from the domestic consumption has been one of the main sources of groundwater recharge. Some part of this sewage is drained into local rivers and drainage channels and partially contaminates the surface runoff and local flows. These polluted surface waters are used in conjunction with groundwater for irrigation purposes in the southern part of the Tehran. In this paper, a systematic approach to surface and groundwater resources modeling in the study area, with its complex system of water supply, groundwater recharge, and discharge, is discussed. A dynamic programming optimization model is developed for conjunctive use planning. The objective function of this model is developed to supply the agricultural water demands, to reduce pumping costs, and to control groundwater table fluctuations. To develop the response function of the aquifers located in the study area, a mathematical model for simulation of the Tehran aquifer water table fluctuations has been developed and calibrated with the available data. Different scenarios are defined to study the long-term impacts of the development projects on conjunctive use policies and water table fluctuations. Comparison of the results showed how significant is the effects of an integrated approach to the surface and groundwater resources allocation in Tehran metropolitan area. The proposed model is a useful tool for irrigation planning in this region.

DOI: 10.1061/(ASCE)0733-9437(2004)130:5(391)

CE Database subject headings: Dynamic programming; Water quality; Water resources management; Irrigation; Case reports; Iran; Urban areas.

Introduction

The integrated use of surface and groundwater resources that is commonly termed conjunctive use is the application of programming techniques for optimum utilization of water resources in a regional scale. Systems approach and mathematical models have long been used in conjunctive surface and groundwater management by many investigators such as Buras (1963); Longebaugh (1970); Maddock (1974); O'Mara and Duloy (1984); Willis et al. (1989); Onta et al. (1991); Yeh (1992); Fredericks et al. (1998); Loaiciga and Leipnik (2001); and Karamouz et al. (2002).

In the early development stages of conjunctive use models, the groundwater was considered as a separate source of water, and actual interaction between the surface and groundwater resources was mostly neglected. In the second stage of the evolution of these models, the partial differential equations of the interaction between surface and groundwater resources, the physical and economic constraints, and pollution transport were considered in descriptive conjunctive use models. In the third stage, the nonlinear differential equations of groundwater flow were considered in optimization models in order to estimate the groundwater table and quality variations. The uncertainties in discharge and recharge parameters have been also considered in stochastic conjunctive use optimization models. In recent years, more complex and user-friendly simulation packages have been used to develop and calibrate the groundwater response equations considering the principle of superposition (Burker and Hitja 1996; Hubell et al. 1997; Johnson et al. 1998).

This paper deals with the development and application of optimization and simulation models for analyzing regional water resources issues in a complex system. The study area is located in the southern part of Tehran, where development of agricultural and industrial activities as well as population growth have resulted in qualitative and quantitative issues in the allocation of water resources. In this paper, major aquifers in the study area, namely, the Tehran and Fashafooyeh aquifers, are simulated using the Graphic Groundwater model (Esling et al. 1993), and the groundwater response equations are explicitly modeled using multiple regression and the principle of superposition.

In order to develop the operating policies for conjunctive use of surface and groundwater resources in agricultural zones, a dynamic programming model is developed. The results of this optimization model and the simulation of water table fluctuations after implementation of different phases of the development

[1]Professor, School of Civil and Environmental Engineering, Amirkabir Univ. (Tehran Polytechnic), Tehran, Iran. E-mail: karamouz@aut.ac.ir

[2]Lecturer, Faculty of Engineering, Univ. of Tehran, Tehran, Iran. E-mail: kerachian@ut.ac.ir

[3]Assistant Professor, Faculty of Engineering, Univ. of Tehran, Iran. E-mail: bzahraie@ut.ac.ir

Note. Discussion open until March 1, 2005. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on September 23, 2002; approved on October 22, 2003. This paper is part of the ***Journal of Irrigation and Drainage Engineering***, Vol. 130, No. 5, October 1, 2004. ©ASCE, ISSN 0733-9437/2004/5-391–402/$18.00.

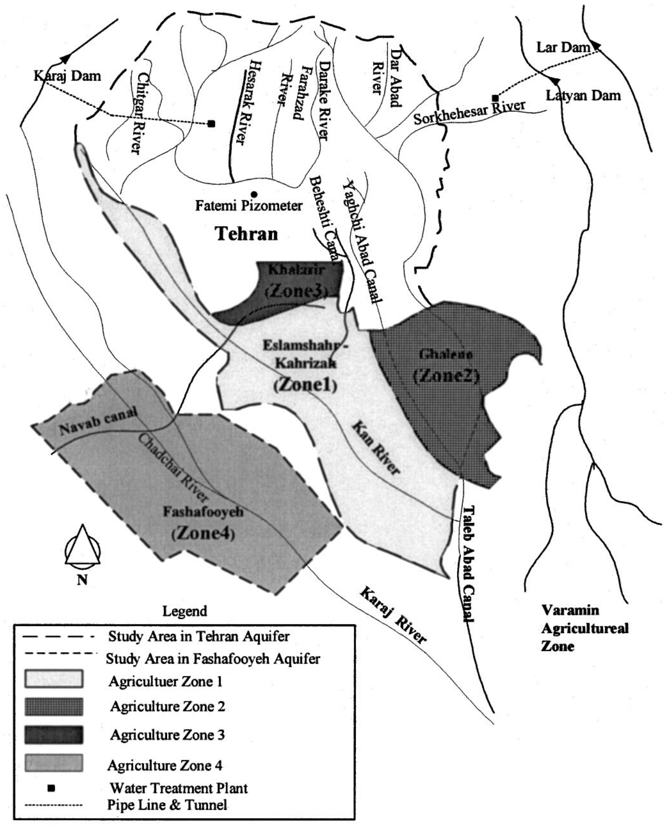

Fig. 1. Tehran and Fashafooyeh agricultural zones in study area

projects in this region are discussed in the following sections of the paper.

Study Area: Water Resources Characteristics

The Tehran plain lies between 35° and 36°35′ Northern latitude and 50°20′ and 51°51′ Eastern longitude, in the south Alborz mountain ranges. It is bounded by the Kan River in the West and the Sorkhehesar River in the East. About one billion cubic meters of water per year are provided for domestic consumption by over eight million inhabitants. Most of the water demand of the Tehran and its suburbs is supplied by three dams, Lar, Latyan, and Karaj, which are located on the Lar, Jajerood, and Karaj Rivers in the adjacent basins, respectively. About 20 to 60% (in the severe drought of the year 2000) of Tehran water demand is supplied from the Tehran and Fashafooyeh aquifers. Fig. 1 is a map of the surface water resources of the Tehran plain. As can be seen in this figure, eight rivers—Kan, Hesarak, Farahzad, Darake, Velendjak, Darband, Darabad, and Sorkhehesar, located from west to east—are considered as local rivers in this study. 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. Shadchai and Karaj Rivers are the surface water resources in the Fashafooyeh region and at the present time only supply the environmental and instream flow requirements.

More than 60% of water consumption in Tehran returns to the Tehran aquifer via traditional absorption wells. Some of the sewage is also drained into local rivers and is used for irrigating agricultural lands in the southern part of Tehran (Daneshvar 1999; Karamouz et al. 2001). Four major agricultural zones, namely, Eslamshahr-Kahrizak (zone 1), Ghaleno (zone 2), Khalazir (zone 3), and Fashafooyeh (zone 4), are the main users of surface and groundwater resources in the southern part of Tehran (Fig. 1). The net monthly water demands of these agricultural zones are presented in Table 1.

Fig. 2 shows the components of the system, including surface and groundwater resources, and the agricultural zones. As shown in this figure, the water demands of zone 1 are supplied from Kan River and two channels carrying urban surface runoff as well as discharge from the Tehran aquifer. In zone 2, the water demands are supplied by Sorkhehesar River and two other channels carrying the urban surface runoffs. The rest of the water demands of this zone is supplied from the Tehran aquifer. There is little sur-

Table 1. Net Monthly Water Demands of Agricultural Zones (million m^3)

Agricultural zone	January	February	March	April	May	June	July	August	September	October	November	December	Annual
1	0.730	0.71	1.35	3.25	10.40	11.00	5.86	7.00	6.40	2.57	2.460	1.03	52.90
2	0.610	0.54	1.00	2.93	9.53	10.57	5.65	7.76	7.00	3.02	2.580	0.83	0.61
3	0.046	0.04	0.11	0.35	1.03	1.21	0.76	0.68	0.51	0.19	0.146	0.06	5.13
4	0.370	0.24	0.40	1.84	6.17	5.74	1.48	1.49	1.28	0.90	1.150	0.42	21.48

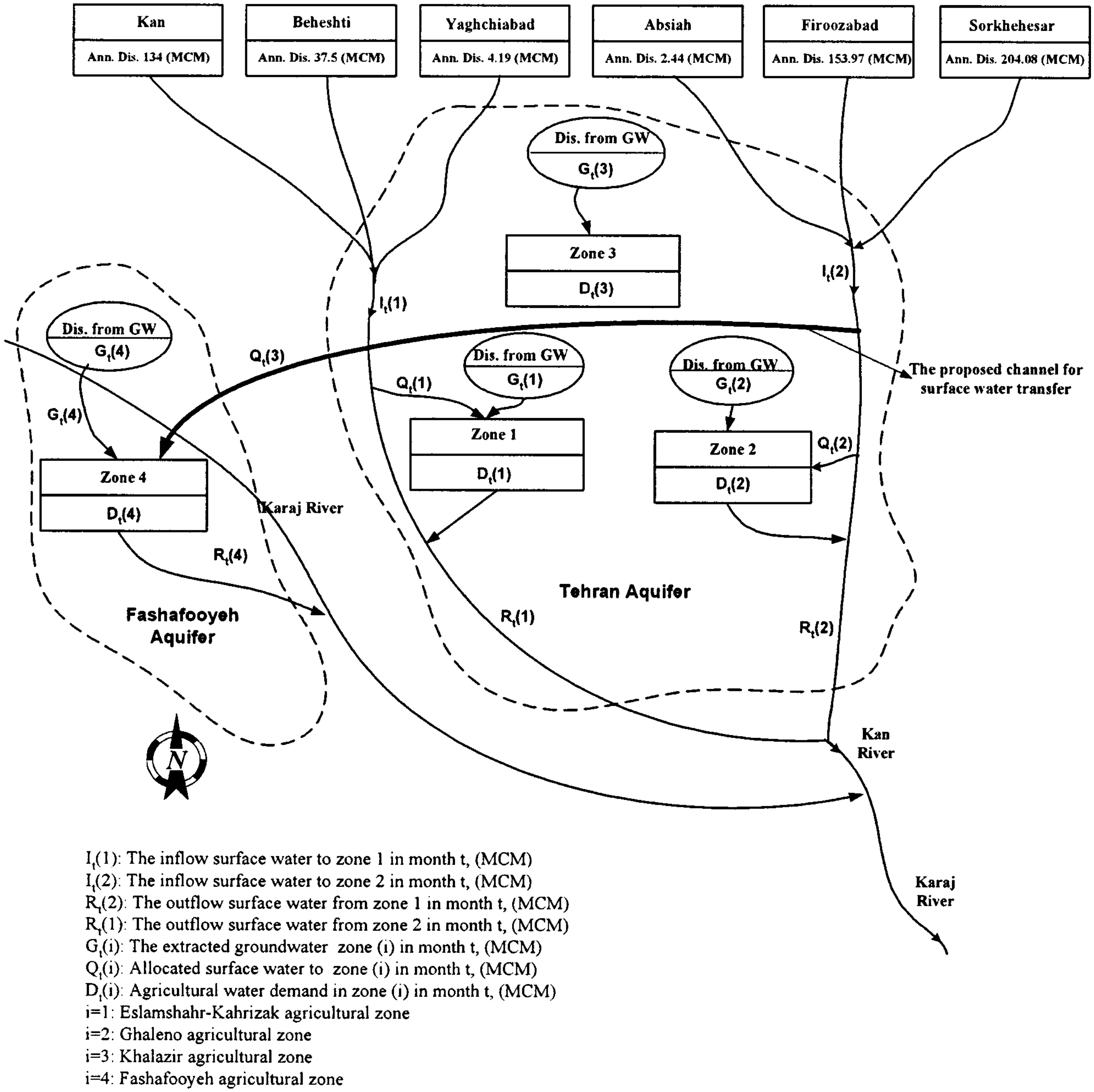

Fig. 2. Components of water resources system supplying agricultural zones in southern part of Tehran

face water in zones 3 and 4 and the water demands of these zones are supplied from the Tehran and Fashafooyeh aquifers, respectively. Table 2 presents the monthly variations of the surface water supply to the agricultural zones.

The current water allocation scheme in these agricultural zones has caused soil and groundwater pollution as well as high groundwater table variation in many parts of the study area. In order to overcome the current problems, several development plans are being investigated and implemented. These projects will change the current balance of recharge and water use in the region (Karamouz 2001; Karamouz et al. 2001).

The Tehran aquifer is divided into two distinct sections: the

Table 2. Monthly Variations of Surface Water Supply to the Agricultural Lands in the Study Area

River/canal	January	February	March	April	May	June	July	August	September	October	November	December	Annual
Kan	12.17	14.55	19.96	22.49	16.41	9.81	6.58	5.47	4.59	7.07	6.21	8.77	134.07
Yaghchi	0.28	0.37	0.38	0.52	0.44	0.42	0.41	0.33	0.27	0.25	0.26	0.26	4.19
Beheshti	2.83	3.29	3.36	4.20	3.75	3.30	3.35	2.90	2.58	2.52	2.68	2.73	37.49
Sorkhehesar	13.73	18.30	22.78	30.65	25.28	21.14	16.27	12.83	10.17	9.25	10.79	12.89	204.08
Absiah	0.18	0.22	0.23	0.29	0.25	0.18	0.24	0.20	0.17	0.16	0.16	0.16	2.44
Firooz Abad	12.19	13.04	13.37	14.68	13.78	13.63	13.35	12.56	11.90	11.68	11.85	11.94	153.97

northern section of Tehran plain, which mainly consists of local aquifers with a low potential for water extraction, and the southern section, which is an unconfined aquifer. The latter is considered the main aquifer of the Tehran plain. While this aquifer is relatively stable with low variations in water table in the north, the southern section has experienced excessive water table fluctuations.

Fashafooyeh aquifer, located in the southwest of Tehran, is an unconfined aquifer that supplies the Fashafooyeh agricultural zone. Most of the agricultural water use in the Fashafooyeh region is supplied from the aquifer, and this has resulted in a severe drawdown in the groundwater table. The general gradient of the groundwater table in this aquifer is from northwest to southeast.

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 discharge from the aquifer is through water extraction from wells, springs, and qanats as well as groundwater outflow and evapotranspiration.

The transmissivity in the Tehran aquifer varies from 1,500 to $3,000\ m^2/day$. The average hydraulic conductivities in the Tehran and Fashafooyeh aquifers are 25 and 18 m/day, respectively. Comparison between the water table levels in April 1985 and April 2001 shows about a nine meters increase in the central and southern parts of the aquifer that is mainly due to sewage discharge.

The inflow to the aquifer boundaries comes from the north, northwest, and eastern parts of the plain. In previous studies of this region, the storage coefficient was estimated to vary from 5.1 to 15% in different parts of the plain (Mahab-Ghods Consulting Engineers 1996). In this study, the storage coefficient is calibrated in different parts of the study area.

In the southern parts of the plain, water quality decreases, and water cannot generally be used for domestic purposes (Mahab-Ghods Consulting Engineers 1996). The most recent and most complete water resources data and information (such as flow rate measurements in the pumping wells, springs, and qanats) are for the 1993–1994 water year, which is used here for estimating different terms of water balance and groundwater simulation of the Tehran and Fashafooyeh aquifers.

Wastewater disposal in Tehran is carried out through more than three million absorption wells. These wells are often 15–20 m deep with a volume of $60\ m^3$. The use of absorption wells has caused a significant rise of the water table in the southern part of Tehran aquifer and has contributed to groundwater pollution.

The Tehran Wastewater Collection Project (TWCP) is the most important ongoing project for solving the current quantity and quality problems of sewage disposal in the study area. The initial study of the TWCP was performed with the aid of the World Health Organization (WHO) and the United Nations (UN). The first phase of this project consists of the establishment of two major wastewater networks in 15,000 hectares; one of them is located in the northern part of the city and will collect wastewater in the areas with impermeable soils, and the other one is located in the southern part, with mostly clay and semi-permeable soils, which is currently under operation. The study of the second stage of the TWCP covers 26,000 ha of the study area. In the third phase (final development stage of the project), the treatment facilities and the wastewater collection network will be implemented for the entire area of 70,000 ha (Mahab-Ghods Consulting Engineers 1996).

Another completed project is a network of drainage wells to lower the groundwater table in the southern part of the city. In this project, more than 100 drainage wells have been constructed. The pumped water is discharged to the local streams and channels and contributes to the surface water in the southern part of the city.

A water transfer channel is under construction to transfer water to a more fertile area in the west (zone 4 in Fig. 1), after treatment by the proposed stabilization ponds (Fig. 2). The optimum capacity of this canal is determined in this study. For more detailed information about surface water resources in the study area, see Karamouz et al. (2002).

In this study, different scenarios have been defined for investigation of the impacts of these projects on the water balance of Tehran aquifer and the optimal allocation of surface and groundwater resources to agricultural zones in the southern part of the study area.

Optimization Model for Conjunctive Use Planning

The main objective of the optimization model for conjunctive use of surface and groundwater resources is the optimal allocation of water to agricultural zones 1–4, which can also be used to determine the optimal capacity of the water transfer channel. The water quality requirement for water supply is also considered as a constraint. The objectives of the model are

- To minimize shortages in supplying the irrigation demands,
- To minimize the pumping costs, and
- To control the average groundwater table fluctuations in the agricultural zones.

The pumping cost is considered as a linear function of pumping power (P_{pump}) as follows:

$$P_{\text{pump}} = \frac{G \,.\, H}{0.102\eta} \tag{1}$$

where P_{pump}=pumping power (kW); G=pumping discharge (m^3/s); H=groundwater table depth (m); and η=pumping efficiency. Because some of the governing equations are nonlinear, the discrete dynamic programming (DP) method has been used in this study. The state variables of the model are the average depth of water table from ground elevation in the agricultural zones $[H_t(i), i=1,\ldots,4]$, and the decision variables that are the courses of action to be taken at each stage t are the allocated water to agricultural zones from surface and groundwater resources $[Q_t(i), i=1,\ldots,3$ and $G_t(j), j=1,\ldots,4]$. The DP model optimizes these decision variables. In this study, the decision variables are discretized to reduce the computational time, because it is difficult and time consuming to find the optimal sets of the decision variables that make the transition from one level of groundwater depth to another. However, the groundwater simulation model can easily provide the groundwater table variation corresponding to different discharge (decision variables) and recharge rates. In this method, the groundwater table depths in agricultural zones are not directly discretized, but they are calculated based on the value of decision variables using the groundwater simulation model. In other words, in time step t, each set of decision variables results in a set of groundwater table depths in agricultural zones $[H_t(i)]$. The values of $H_t(i)$, which correspond to the minimum total operational cost until the end of period t, are assumed to be the state of the system at the end of period t. This method effectively reduces the burden of dimensionality of DP, but may provide local optimal solutions due to the limitations in discretizing the state variables. The values of the state variables are not a set of preassigned positions within the range of their variation, but rather are obtained from implementing the continuity equation and the results of the groundwater simulation model. To assess the accuracy of the DP results, they are compared with the results of a classical genetic algorithms (GAs) based optimization model. The results show that DP model can provide global or near global solutions with a run time near one-tenth of a GA-based optimization model. The recursive function of the DP model is as follows:

$$f_t(\tilde{\boldsymbol{H}}_t) = \text{Min}\{C_t(\tilde{\boldsymbol{G}}_t,\tilde{\boldsymbol{Q}}_t,\tilde{\boldsymbol{H}}_t,\tilde{\boldsymbol{L}}_t) + f^*_{t-1}(\tilde{\boldsymbol{H}}_{t-1})\}$$

$$\tilde{\boldsymbol{G}}_t = \{G_t(i)|i = 1, \ldots ,4\}$$

$$\tilde{\boldsymbol{Q}}_t = \{Q_t(i)|i = 1,2,3\}$$

$$\tilde{\boldsymbol{H}}_t = \{H_t(i)|i = 1, \ldots ,4\}$$

$$\tilde{\boldsymbol{L}}_t = \{L_t(i)|i = 1, \ldots ,4\} \quad (2)$$

where $\tilde{\boldsymbol{G}}_t$=vector of the volume of groundwater extracted from the agricultural zones in month t (million m^3); $\tilde{\boldsymbol{Q}}_t$=vector of surface water allocated to the agricultural zones in month t (million m^3); $\tilde{\boldsymbol{H}}_t$=vector of groundwater table depth at the end of time period t in the agricultural zones (m); $\tilde{\boldsymbol{L}}_t$=vector of cumulative variation of water table level in agricultural zones, until the end of period t (m); $C_t(\tilde{\boldsymbol{G}}_t,\tilde{\boldsymbol{Q}}_t,\tilde{\boldsymbol{H}}_t,\tilde{\boldsymbol{L}}_t)$=operational cost during time period (month) t; $L_t(i)$=cumulative variation of water table level until the end of period t (m); $H_t(i)$=groundwater table depth at the end of time period t, in agricultural zone i (m); $f^*_{t-1}(\tilde{\boldsymbol{H}}_{t-1})$=minimum total operational cost until the end of period $t-1$; $G_t(i)$=volume of groundwater extracted from agricultural zone i, in month t (million m^3); $Q_t(i)$=volume of surface water allocated to agricultural zone i, in month t (million m^3) (i=1,2); $Q_t(3)$=volume of transferred surface water to agricultural zone 4, in month t (million m^3); and i=index of agricultural zones. As shown in Fig. 2, Eslamshahr-Kahrizak (zone 1), Ghaleno (zone 2), Khalazir (zone 3), and Fashafooyeh (zone 4) are the main agricultural zones in the study area.

Eq. (2) shows the recursive function of the model, which consists of two terms. The first of the two components $[C_t(\ldots)]$ shows the operational cost during the time period t and is a function of state and the decision variables. In this equation, $L_t(i)$ shows the cumulative variation of the water table [it is a function of state variable $H_t(i)$]. The second term $[f^*_t(\ldots)]$ shows the minimum total operational cost until the end of period $t-1$.

The water demand of zone 3 is only supplied by groundwater. The streamflow of the Shadchai and Karaj Rivers in zone 4 can only supply the environmental and instream flow demands. Therefore, the agricultural water demands in this zone are supplied from groundwater and transferred surface water through the channel. The operational cost in each period is estimated as

$$C_t(\tilde{\boldsymbol{G}}_t,\tilde{\boldsymbol{Q}}_t,\tilde{\boldsymbol{H}}_t,\tilde{\boldsymbol{L}}_t) = \sum_{i=1}^{4} \text{Loss}_t(i) \quad (3)$$

$$\text{Loss}_t(i) = \alpha[D_t(i) - Q_t(i) - G_t(i)]^2 + \beta[G_t(i) \cdot H_t(i)] + \lambda[|L_t(i)| - L_{\max}(i)]^2$$

$$\alpha = 0 \quad \text{if} \quad D_t(i) \leq [Q_t(i) + G_t(i)]$$

$$\lambda = 0 \quad \text{if} \quad |L_t(i)| \leq L_{\max}(i) \quad (4)$$

where $D_t(i)$=agricultural water demand in zone i in period t (million m^3); $L_{\max}(i)$=maximum allowable cumulative groundwater table fluctuation in agricultural zone i(m); and α,β,λ=relative weights of the three objectives.

The first term in Eq. (4) considers the water supply to agricultural demands; the second term represents the loss associated with the pumping, considering Eq. (1), and the third term represents the loss associated with the groundwater fluctuations. As the different terms of the objective function have different units, the coefficients α, β, and λ are assigned by the decision maker to make them comparable. These coefficients are determined using sensitivity analysis. For this purpose, the domain of the variation of each parameter is determined by trial and error, and then five different values for each parameter (α,β,γ) are selected. This analysis is used in order to investigate the long-term variations of the groundwater table in different agricultural zones, the reliability of water supply, and the pumping cost.

The depths of the average groundwater table in the agricultural zones are calculated as follows:

$$H_t(i) = H_0(i) + L_t(i) = H_{t-1}(i) + \Delta L_t(i) \quad i = 1, \ldots ,4 \quad (5)$$

$$L_t(i) = \sum_{t=1}^{t} \Delta L_t(i) \quad i = 1, \ldots ,4 \quad (6)$$

$$\Delta L_t(i) = f_i(\tilde{\boldsymbol{G}}^*_t, M_t, O_t) \quad (7)$$

where $H_0(i)$=initial depth of groundwater table in agricultural zone i (m); $H_{t-1}(i)$=groundwater table depth at the end of month $t-1$, in agricultural zone i (m); $\Delta L_t(i)$=change of water table level in month t in agricultural zone i (drawdown is considered to be positive) (m); and $f_i(\tilde{\boldsymbol{G}}^*_t, M_t, O_t)$=the groundwater table fluctuation (response function) in the agricultural zone i and month t (m), which is a function of the vector of net groundwater extraction in the agricultural zones ($\tilde{\boldsymbol{G}}^*_t$), recharges by direct precipitation, allocated surface water, and recharges by absorption wells (M_t), outflow at the boundaries, and the groundwater discharge through springs and qanats (O_t). The state transitions, which express the relationship between the input state, the output state, and the decisions, are presented by Eqs. (5) and (7).

The constraints of the model for each month are as follows:

- Estimation of surface water outflow from agricultural zones 1 and 2, $R_t(i)$

$$R_t(i) = \begin{cases} I_t(1) - Q_t(1) - \left(1 - \dfrac{\psi}{100}\right)Q_t(3) & i = 1 \\ I_t(2) - Q_t(2) - \left(\dfrac{\psi}{100}\right)Q_t(3) & i = 2 \end{cases} \quad (8)$$

where ψ=percent of the transferred water to zone 4 from surface water resources of zone 2 (constant); and $I_t(i)$=surface water inflow to zone i in period t in million cubic meters (MCM). It should be noted that, in order to reduce the dimensionality problems, total inflow from different rivers and channels to zones 1 $[I_t(1)]$ and 2 $[I_t(2)]$ are considered in the model (Fig. 2).

- Meeting the minimum instream flow requirements downstream of the agricultural zones

Table 3. Water Balance of Tehran and Fashafooyeh Aquifers (Water Year 1993–1994)

Water balance variable	Tehran aquifer Discharge (MCM)	Tehran aquifer Discharge (MCM)	Fashafooyeh aquifer Discharge (MCM)	Fashafooyeh aquifer Recharge (MCM)
Inflow at boundaries	—	226.70	—	53.61
Precipitation	—	17.80	—	2.56
Infiltration from stream and canals and dry parts of qanats	—	27.30	—	8.28
Infiltration from absorption wells and agricultural return flow	—	334.90	—	1.20
Outflow at boundaries	54.24	—	35.82	—
Discharge from wells and springs	367.20	—	30.51	—
Discharge from qanats	180.80	—	—	—
Change in groundwater volume	4.46	—	—	0.68

$$\sum_{i=1}^{2} R_t(i) \geqslant R_{t,\min} \quad (9)$$

where $R_{t,\min}$=minimum instream flow required in period t; and $R_t(i)$=surface water outflow from zone i in period t (MCM).

- The capacity of the water transfer channel

$$Q_t(3) \leqslant Q_{t,\max} \quad (10)$$

- Water quality constraints

$$\frac{Q_t(i) \cdot C'_t(i) + G_t(i) \cdot C_t(i)}{Q_t(i) + G_t(i)} \leqslant C_{\max} \quad i = 1,2 \quad (11)$$

where $C'_t(i)$=average concentration of surface water quality indicator such as TDS (total dissolved solid) in zone i in period t (mg/L); $C_t(i)$=average concentration of groundwater quality indicator in zone i in period t (mg/L); and $C_{\max}$=maximum concentration of water quality indicator in allocated water (mg/L).

- Availability of surface and groundwater:

$$H_t(i) \leqslant H_{t,\max}(i) \quad (12)$$

where $H_{t,\max}(i)$=maximum allowable depth of groundwater table (m) in zone i in month t. The availability of surface water is implicitly considered in Eqs. (8) and (9).

Development of Groundwater Simulation Model

The groundwater table variation equations are necessary for constructing a conjunctive use model [Eq. (7)]. In this study, the Tehran and Fashafooyeh aquifers are simulated using the Graphic Groundwater model (Esling et al. 1993). The water balances of these aquifers were estimated by Mahab-Ghods Consulting Engineers (1996) based on the data available for discharge from agricultural wells, monthly infiltration rates from channels and rivers, and the agricultural return flows for the water year of 1993–1994. The evapotranspiration is assumed to be negligible because the water table depth has not been less than three meters in the study area. The amount of average monthly inflow or outflow at each boundary cell was determined from the isopotential maps of the Tehran and Fashafooyeh aquifers for that water year. Table 3 shows the water balance of the Tehran and Fashafooyeh aquifers in the water year 1993–1994.

Input data for the model consists of hydraulic conductivity, storage coefficient, bed rock and ground surface elevation, initial water table elevation, recharge, discharge, and evapotranspiration, estimated for each cell in the study area.

There are very limited data for the Fashafooyeh aquifer as compared to the Tehran. Therefore, the cell dimensions in the Tehran aquifer are considered as 0.5 by 0.5 km, whereas in the Fashafooyeh, a cell size of 1 by 1 km is selected. The hydraulic conductivity of each cell was estimated based on the results of pumping tests. The Tehran and Fashafooyeh aquifers are considered as single-layered aquifers; therefore, only the horizontal hydraulic conductivity was estimated. The bedrock elevation for each cell was calculated based on the results of geophysical studies in the region.

Calibration and Verification of the Simulation Model

The initial condition of the groundwater table for each cell was determined based on the piezometric data of 30 and 10 piezometers in the Tehran and Fashafooyeh aquifers, respectively. The boundary conditions of the aquifers are classified as either permeable with specific flow rate, or impermeable. Fig. 3 is a map of the grid layout and boundary conditions of the Tehran aquifer model. The monthly inflow or outflow at the boundaries is estimated for each permeable boundary cell, based on the variation in the piezometric levels and the groundwater characteristics in the cell.

In order to calibrate different parameters of the models, the following steps have been taken:

1. Primary estimation of the hydraulic conductivity for different cells in the steady-state condition; and
2. Estimation of storage coefficient and adjustment of hydraulic conductivity of different cells in the unsteady-state condition.

As the discharge and recharge data are available for the 1993–1994 water year, the water table variations through piezometers in this year were used for validation of the model. For this purpose, the water table elevations computed by the model were compared with the historical data of each piezometer. For example, Fig. 4 shows the comparison between computed and historical water tables for one piezometer in the study area (Palayeshgah piezometer). This figure shows how closely the model can reproduce the monthly water table variations.

Monthly Groundwater Table Variations

The response functions in the optimization model show the monthly groundwater table variations in the Tehran and Fashafooyeh aquifers. They are functions of discharge, recharge, inflow, and outflow at the boundaries as well as the physical characteristics of the aquifers. The linkage of the optimization and

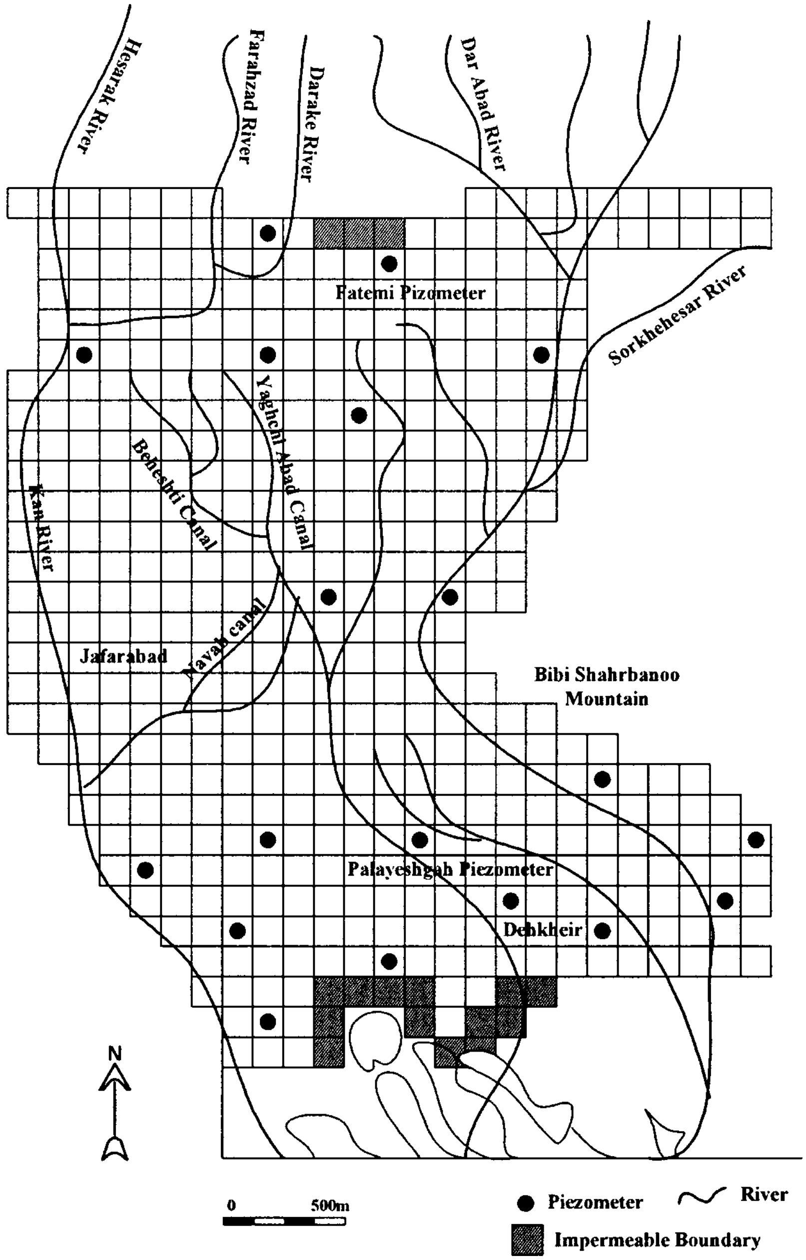

Fig. 3. Generated grid and boundary condition in Tehran aquifer (each cell in figure includes four cells in simulating model)

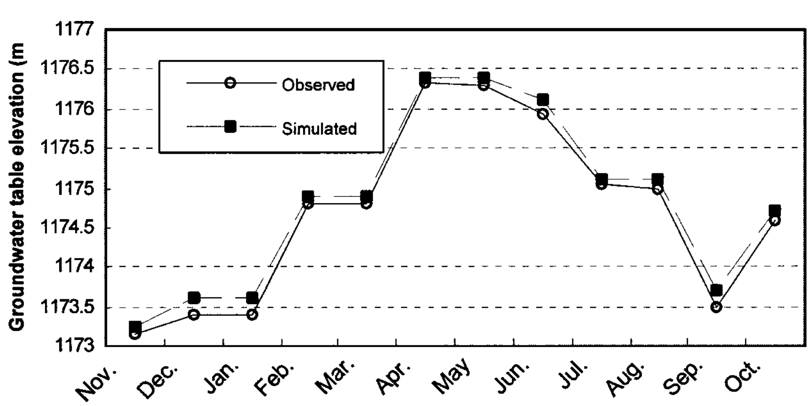

Fig. 4. Comparison between observed and simulated groundwater table in Palayeshgah piezometer (1993–1994)

Table 4. Quantitative Effects of Different Phases of Tehran Wastewater Collection Project (TWCP) on Surface Water Resources in Southern Part of Tehran

Phases of TWCP	Decrease in municipal wastewater recharge (%)	Decrease in groundwater recharge (%)	Total decrease in surface water supply (%)
Implementation of phase 1 of TWCP	21	0	7
Implementation of phase 2 of TWCP	63	100	41

simulation models will significantly increase the problems' dimensionality and the computational time needed to achieve the optimal solution of the model, because for each combination of the state variables, the groundwater table fluctuations should be simulated. Therefore, the response functions of the aquifers are developed and used in the optimization model. In this study, by frequent execution of the groundwater simulation model and by considering the principal of superposition, the equations required for estimating monthly water table variations have been obtained for each agricultural zone, using multiple regression analysis. Precipitation, total monthly groundwater discharge for domestic and irrigation purposes, and total monthly discharge of drainage wells have been considered as variables, and the other factors are assumed to be constant for each month. Based on the results of the calibrated groundwater simulation model, the groundwater table level at the beginning of each month has a negligible effect on the average groundwater table changes in agricultural zones during this month. Therefore, the datum is not considered in response functions. For example, the nonlinear equation for average groundwater variation in zone 2 in May is estimated as follows:

$$\Delta L_{\text{zone 2}} = 0.036G_5(1) + 0.027G_5^2(2) + 0.0064G_5^2(3) + 0.0193G_5(4) + 0.7e^{-5}W - 0.16R - 0.046A - 0.41$$

where ΔL_{zone2}=monthly ground water table variation (m) (positive values refer to water table drawdown); $G_5(i)$=the net groundwater discharge (extracted minus infiltrated) in zone i in the month of May (million m^3); W=total monthly groundwater discharge from drainage wells (million m^3); R=total monthly recharge from precipitation (m/day); and A=total recharge from absorption wells (m/day).

As there is no considerable hydraulic interaction between the Tehran and Fashafooyeh aquifers, the water withdrawal from each of the aquifers does not affect the water table variations in the other one. Similar equations have been developed for other months and agricultural zones. The aquifers' recharge and discharge data in addition to the equations of the monthly groundwater table fluctuations have been used for the simulation of aquifers. The correlation coefficients between computed and observed piezometric data have been more than 90% for all zones.

Results and Discussion

The conjunctive use policies are developed using the proposed optimization model, considering the ongoing and proposed projects such as different phases of the Tehran Wastewater Collection Project (TWCP) and the water transfer project. To consider agricultural water quality requirements, detergent concentration was considered as the representative water quality indicator. Based on the available water quality data, detergent concentration in the study area has the worst deviation from the water quality standards. The detergent concentration should be less than 0.5 mg/L, based on the agricultural water quality standards. The detergent concentration in the surface runoffs of the channels in the southern part of city including Beheshti and Yakhchiabad has been more than 10 mg/L in 70% of the months. The maximum rate of detergent concentration has been about 15 mg/L in Yakhchiabad in April of 1997.

In the last 15 years, groundwater table fluctuations in the study area have been more than ±20 m. In this study, the cumulative average groundwater table variation in each zone is limited over the planning horizon to ±5 m and a high penalty is assigned to the fluctuations outside of this range. Implementation of the TWCP has the following major effects on the surface and groundwater resources of the study area mainly due to wastewater recharge of the aquifer:

1. The groundwater quality will significantly be improved.
2. Recharges by the Kan and Sorkhehesar Rivers and the local channels of the Tehran surface runoff collection system will be reduced. In the current situation, the local channels receive the sewage from some parts of the residential areas in the southern part of the city. After implementation of the TWCP, the sewage will be totally collected by the network; therefore, it will reduce the discharge of the channels and the local streams.
3. Recharge of the rivers and channels from groundwater will be reduced due to a gradual decrease of the average groundwater table in the Tehran aquifer.

Table 4 shows the quantitative effects of different phases of the TWCP on the surface water resources in the southern part of Tehran. Through the network of drainage wells, an annual water

Table 5. Conjunctive Use Rules for Month of July for Scenario 1 (MCM)

Allocated water	Water allocation policy
To zone 1 from surface water	$Q_5(1)=D_5(1)$ if $I_5(1)>D_5(1)$; $Q_5(1)=-4.74+0.98\times I_5(1)$ otherwise
To zone 1 from groundwater	$G_5(1)=12.97$ if $E_4(1)>1{,}045$; $G_5(1)=D_5(1)-Q_5(1)$ otherwise
To zone 2 from surface water	$Q_5(2)=D_5(2)$ if $I_5(2)>D_5(2)$; $Q_5(2)=11.35+0.087\times I_5(2)$ otherwise
To zone 2 from groundwater	$G_5(2)=0$ if $E_4(2)<1{,}000.2$; $G_5(2)=6.3$ if $E_4(2)>1{,}009.2$; $G_5(2)=D_5(2)-Q_5(2)$ otherwise
To zone 3 from groundwater	$G_5(3)=D_5(3)$

Note: $Q_5(i)$=allocated surface water to zone i in July; $D_5(i)$=gross agricultural water demands of zone i in July; $G_5(i)$=allocated groundwater to zone i in July; $I_5(i)$=inflow surface water to zone i in July; $E_4(i)$=average groundwater table elevation at end of June in zone i.

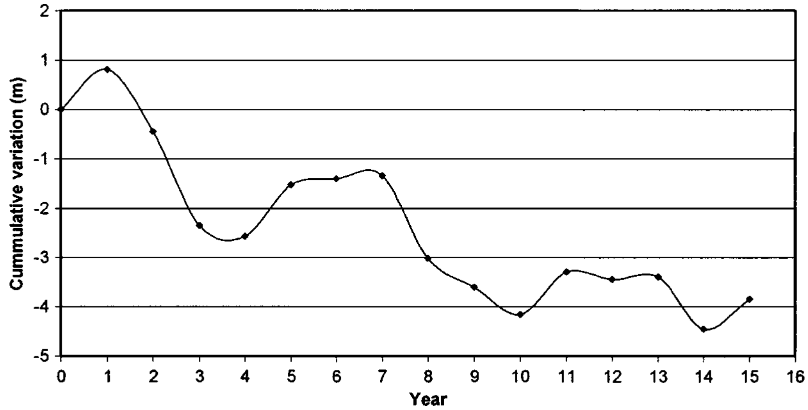

Fig. 5. Cumulative variation of average water table elevation relative to initial condition in zone 1 (scenario 1)

extraction rate of 60 million cubic meters is discharged to the local streams and channels and thus contributes to the surface water in the southern part of the city.

Different scenarios are defined for predicting the fluctuations of the Tehran aquifer water table based on the three phases of the TWCP, operation of drainage wells in the city, and the Tehran population growth until the year 2021. The results of these scenarios can be summarized as follows:

- *First Scenario*: It is assumed that the first phase of the Tehran wastewater collection project and the water transfer to zone 4 are not completed and the water quality limitation is not considered. The operating rules and cumulative groundwater table variation in July (as a critical month) in zone 1 are presented in Table 5 and Fig. 5.
- *Second Scenario*: This scenario is similar to the first scenario, except that the water transfer to zone 4 is considered.
- *Third Scenario*: This scenario is similar to the first one, except that the allocated water quality requirement is considered.
- *Fourth Scenario (Year 2006)*: It is assumed that implementation of the first phase of the TWCP is completed, and drainage wells are not under operation. The first phase of the TWCP covers 150 km^2 of the Tehran metropolitan area. The water transfer to zone 4 and the water allocated quality limitation are not considered in this scenario.
- *Fifth Scenario (Year 2006)*: This scenario is similar to the fourth scenario, but it is assumed that the drainage wells are under operation.
- *Sixth Scenario (Year 2011)*: It is assumed that the drainage wells are out of service. The water transfer to agricultural zone 4 and the water quality constraint are not considered in this scenario. It is also assumed that the implementation of the second phase of the TWCP is completed. In this phase of the TWCP, 260 km^2 of the residential areas within the city will be covered.
- *Seventh Scenario (Year 2021)*: This scenario is similar to the sixth scenario, except that it is assumed that the final phase of the TWCP is completed. In this phase of the TWCP, the wastewater of 700 km^2 of the Tehran metropolitan area is collected.

The results of the model for different scenarios in the month of July, as a dry month, have been presented in Table 6. The gross agricultural water demands in this month in zones 1–4 are 19.5, 18.8, 2.5, and 4.9 million m^3, respectively.

For each scenario, the optimal solution was determined using the recent 15 years of precipitation and stream flow data. The relative weights of the objectives in each scenario have been determined based on sensitivity analyses. The relative weights of different objectives are estimated using sensitivity analyses. In optimal allocation of water, the surface water is given higher priority because of the pumping cost of groundwater discharge.

Comparison between the results of the first and the second scenarios shows that water transfer to zone 4 changes the optimal schemes for allocation of surface and groundwater in the study area. In the second scenario, irrigation demand in zone 2 is supplied mostly by groundwater, and the surface water in this zone is transferred to zone 4 to decrease the shortages in supplying irrigation demands. As presented in Table 6, the increases in groundwater discharge from zone 2 reduce the water withdrawal from zone 3.

The results of the third scenario show the important impacts of water quality constraints on optimal allocation of water resources. The surface water in the southern part of Tehran is so polluted that it cannot be used for irrigation in the current situation, and the agricultural water demands can only be supplied from groundwater resources. Groundwater allocated to agricultural zones in this scenario does not completely supply the water demands because of the limitations on groundwater table fluctuations and pumping costs.

Implementation of different phases of the TWCP improves the

Table 6. Allocated Surface and Groundwater to Different Agricultural Zones in Different Scenarios in the Month of July (MCM)

Allocated water	First scenario	Second scenario	Third scenario	Fourth scenario	Fifth scenario	Sixth scenario	Seventh scenario
To zone 1 from groundwater	16.42	16.42	13.40	17.72	16.42	17.72	17.72
To zone 2 from groundwater	2.51	3.77	0.00	2.51	2.51	2.67	1.67
To zone 3 from groundwater	2.53	2.42	0.17	2.36	2.47	2.25	2.31
To zone 4 from groundwater	0.35	0.35	0.35	0.35	0.35	0.35	0.35
To zone 1 from surface water	3.89	3.89	0.00	3.46	3.89	3.03	3.03
To zone 2 from surface water	16.32	14.65	0.00	9.62	16.32	7.53	7.53

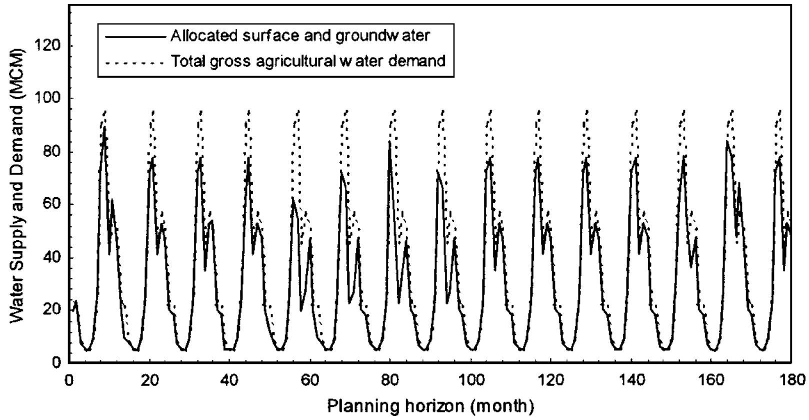

Fig. 6. Monthly water supply and demands in agricultural zones in southern part of Tehran (scenario 4)

quality of surface flows (local flows); therefore, the water quality constraint is not considered in the scenarios that consider different phases of the TWCP. The fourth and fifth scenarios demonstrate the impact of implementation of the first phase of the TWCP on optimal allocation of water resources. After completion of each phase of this project, the discharge of the local streams and channels in the southern part of the Tehran will be decreased, and the optimal allocation of water resources to the agricultural zones will change.

The results of the fourth and the fifth scenarios have shown the impacts of discharge from drainage wells on the conjunctive use of surface and groundwater. In the fifth scenario, the allocated water from surface water is more than in scenario 4, because the drainage wells increase the surface water discharge. The effects of implementation of the second and the final phases of the TWCP are investigated in scenarios 6 and 7. In these scenarios, the surface water resources are decreased significantly and there is not enough water to allocate to the agricultural zones. Therefore, some part of the treated wastewater, in the final phase of the TWCP, should be allocated to this area.

As an example, Fig. 6 shows the time series of the total water supply to agricultural zones as compared with the irrigation demands. As can be seen in this figure, in 5 months of the year the system has not been able to supply all demands, but the shortages in 3 months have been negligible. The shortages have mainly occurred in zone 4, where there is no surface water supply. Similar results are obtained for other scenarios and show the effectiveness of the conjunctive use policies in supplying irrigation demands, while controlling groundwater fluctuations.

Summary and Conclusion

In this study, an optimization model for conjunctive use of surface and groundwater resources and a mathematical model for prediction of water table fluctuations in the Tehran and Fashafooyeh aquifers were developed. Seven scenarios were defined in order to study the impacts of different development projects in the study area. The results have shown the significant impacts of the Tehran Wastewater Collection Project on the water allocation to agricultural zones, and also the important but limited role of drainage wells in controlling groundwater table. The main conclusions based on the results of these scenarios can be summarized as follows:

- The water transfer canal to supply the water demand of zone 4 and to control the groundwater table drawdown in this zone (scenario 2) is highly important.
- The water quality constraint greatly affects the optimal policies for water allocation (scenario 3). Because of the pollution of surface water in the study area, the allocation from surface water is usually limited in dry months (June–October).
- The implementation of the first phase of the TWCP reduces the available surface water resources about 10% as compared with the existing condition (scenario 4). The cumulative groundwater fluctuations have also been reduced to 4 m in this scenario.
- After implementation of the final phase of the TWCP, the treated wastewater should be allocated to the agricultural zone in the southern part of Tehran; otherwise, the cumulative groundwater table fluctuation will be more than 7 m and the water demands will not be completely satisfied.

The developed optimization model provides a compromise solution considering the water supply to different demands, the pumping costs, and the groundwater table variations. The simulation of the optimal policies has showed these policies can control the groundwater table variations. The cumulative groundwater table variation in the piezometers has been more than 20 m in the past 15 years, whereas it is reduced to less than 4 m by applying the optimal operating policies.

The comparisons between the results of different scenarios have shown that the developed policies are able to control groundwater fluctuations in the study area. They also show the importance of an integrated approach for allocating surface and groundwater resources in the Tehran metropolitan area. The mathematical models developed in this study have the flexibility to model different conditions and assumptions and can be used for future planning and operation of water resources in this complex region.

Acknowledgments

This study was partially supported by a grant from the Research Office of Water Resources Management Organization of the Ministry of Energy in Iran. The contribution of Mr. E. Daneshvar, Mr. Behnam Zahraie, and Ms. M. Rahmani is hereby acknowledged. Part of this paper was presented at the 2002 Annual ASCE/EWRI Conference in Roanoke, Virginia.

Notation

The following symbols are used in this paper:

$C_{\max}$ = maximum concentration of water quality indicator in allocated water (mg/L);

$C_t(\tilde{\boldsymbol{G}}_t, \tilde{\boldsymbol{Q}}_t, \tilde{\boldsymbol{H}}_t, \tilde{\boldsymbol{L}}_t)$ = operational cost during time period t;

$C_t(i)$ = average concentration of representative groundwater quality indicator in zone i in time period t (mg/L);

$C'_t(i)$ = average concentration of representative surface water quality indicator in zone i in time period t (mg/L);

$D_t(i)$ = agricultural water demand in zone i and time period t (million m^3);

$f_i(\tilde{\boldsymbol{G}}^*_t, M_t, O_t)$ = groundwater table fluctuation (response function) in agricultural zone i and time period $t(m)$;

$f_t(\tilde{\boldsymbol{H}}_t)$ = minimum total operational cost until end of time period t;

$f^*_{t-1}(\tilde{\boldsymbol{H}}_{t-1})$ = minimum total operational cost until end of period $t-1$;

G = pumping discharge (m^3/s);

$\tilde{\boldsymbol{G}}_t$ = vector of volume of groundwater extracted from agricultural zones in month t (million m^3);

$\tilde{\boldsymbol{G}}^*_t$ = vector of volume of net groundwater extracted from agricultural zones in month t (million m^3);

$G_t(i)$ = volume of groundwater extracted from agricultural zone i in month t (million m^3);

$\tilde{\boldsymbol{H}}_t$ = vector of groundwater table depth at end of time period t in agricultural zones (m);

$H_{t,\max}(i)$ = maximum allowable depth of groundwater table (m) in agricultural zone i in month t;

$H_t(i)$ = depth of groundwater table in agricultural zone i at end of month t(m);

$H_0(i)$ = initial depth of groundwater table in agricultural zone $i(m)$;

$I_t(i)$ = surface water inflow to zone i in the period t (only for zones 1 and 2) (million m^3);

i = index of agricultural zone;

$Loss_t(i)$ = operational cost of zone i in period t;

$L_{\max}(i)$ = maximum allowable cumulative groundwater table fluctuation in agricultural zone $i(m)$;

$\tilde{\boldsymbol{L}}_t$ = vector of cumulative variation of water table level in agricultural zones, until end of period $t(m)$;

$L_t(i)$ = total variation of water table level until end of period t(m);

M_t = recharges by direct precipitation, allocated surface water, and adsorption wells in month t (million m^3) agricultural zone (m);

O_t = outflow at the boundaries and groundwater discharge through springs and qanats in month t (million m^3) agricultural zone (m);

P_{pump} = power of pump (kW);

$\tilde{\boldsymbol{Q}}_t$ = vector of allocated surface water to agricultural zones in month t (million m^3);

$Q_t(i)$ = volume of allocated surface water to agricultural zone i in month t (million m^3);

$Q_{t,\max}$ = maximum capacity of canal (million m^3);

$Q_t(3)$ = volume of transferred surface water to agricultural zone 4 in month t (million m^3);

$R_t(i)$ = outflow surface water from agricultural zones i (only for zones 1 and 2) (million m^3);

$R_{t,\min}$ = minimum instream flow required in period t (million m^3);

t = time (month);

α, β, λ = relative weights of objectives (constants);

$\Delta L_t(i)$ = variation of water table level in period t in zone $i(m)$;

η = pumping efficiency; and

ψ = percent of transferred water to zone 4 from surface water resources of zone 2.

References

Buras, N. (1963). "Conjunctive operation of dams and aquifers." *J. Hydraul. Div., Am. Soc. Civ. Eng.*, 89(6), 111–131.

Burker, S. M. and Hitja, H. M. (1996). "Modeling steady state conjunctive groundwater and surface water flow with analytic elements." *Journal of Water Resources Research*, 30(2).

Daneshvar, E. (1999). "Conjunctive use of surface and groundwater in the South of Tehran." MS thesis, Shahid Beheshtee Univ. Tehran, Iran.

Esling, S. P., Larson, T. A., and Sharpe, D. M. (1993). *User manual: Graphic Groundwater, version 1.1*, Micro-Innovations, Inc., Carbondale, Ill.

Fredericks, J., Labadie, J. W., and Altenhofen, J. (1998). "Decision support system for conjunctive stream-aquifer management." *J. Water Resour. Plan. Manage.*, 124(2), 69–78.

Hubbell, M. J., Bishop, C. W., Johnson, G. S., and Loucks, J. G. (1997). "Numerical groundwater flow modeling of the Snake River plain aquifer using the superposition technique." *Journal of Groundwater*, 35(1), 59–60.

Johnson, G. S., Cosgrov, D. M., and Spinazola, J. (1998). "Use of MODFLOW for development of response function." *Proc., MODFLOW 98 Conf.*, Colorado School of Mines, Golden, Colo.

Karamouz, M. (2001). "Conjunctive use of surface and groundwater resources in the southern part of Tehran." *Final Rep. of Research Project*, Iranian Ministry of Energy, Tehran, Iran.

Karamouz, M., Kerachian, R., Zahraie, B., and Zahraie, B. (2002). "Conjunctive use of surface and groundwater resources." *Proc. ASCE Environmental and Water Resources Institute Conf.* (CD-ROM), Reston, Va.

Karamouz, M., Zahraie, B., Araghi-Nejhad, S., Shahsavarie, M., and Torabi, S. (2001). "An integrated approach to water resources development of the Tehran region in Iran." *Journal of American Water Resources Association*, 37(5), 1301–1311.

Loaiciga, H. A., and Leipnik, R. B. (2001). "Theory of sustainable groundwater management: an urban case study." *Urban Water*, 3, 217–228.

Longebaugh, R. A. (1970). "Determining optimum operational policies for conjunctive use of ground and surface water using linear programming." *Proc., 18th Annual Specialty Conf.* ASCE, New York, 19–21.

Maddock, T. (1974). "The operation of a stream-aquifer system under stochastic demands." *Water Resour. Res.*, 10(1), 1–10.

Mahab-Ghods Consulting Engineers. (1996). *Final Rep. of Groundwater Study in Tehran Plain*, Tehran Water Authority, Tehran, Iran.

O'Mara, G. T. J., and Duloy, J. H. (1984). "Modeling efficient water allocation in a conjunctive use regime: the Indus basin of Pakistan." *Water Resour. Res.*, 20(11), 1489–1498.

Onta, P. R., Gupta, A. D., and Harboe, R. (1991). "Multistep planning model for conjunctive use of surface- and ground-water resources." *J. Water Resour. Plan. Manage.*, 117(6), 662–678.

Willis, R., Finney, B., and Zhang, D. (1989). "Water resources management in North China plain." *J. Water Resour. Plan. Manage.*, 115(5), 598–615.

Yeh, W. W.-G. (1992). "Systems analysis in ground-water planning and management." *J. Water Resour. Plan. Manage.*, 118(3), 224–237.