RESEARCH PAPER

Holistic Approach to Sustainable Groundwater Management in Semi-arid Regions

Ali Moridi[1] · Mohammad Reza Majdzadeh Tabatabaie[1] · Samaneh Esmaeelzade[1]

Abstract

Owing to rational deep understanding of intrinsic nature of groundwater as common pool and decayable resources, together with, lack of withdrawal control by local states, groundwater depletion has been incredibly under consistent withdrawal. Under these circumstances, attempts have been made by users to maximize withdrawal without considering any limitation on account of lack of reliable withdrawal pattern. In this research, sustainable management of groundwater in south western part of Tehran plain has been evaluated by coupling simulation and optimization models of cooperative and non-cooperative approaches. The MODFLOW model and the Artificial Neural Network model are used for simulation of different scenarios after calibration and validation. Then, a non-linear optimization model is used for optimal allocation of groundwater to different water users. Results indicate that users may gain more benefit in early years of withdrawal in non-cooperative approach. However, this may have an adverse effect which implies a decreasing trend in the benefit in such a way that it reaches null in long term period, as this is reflected by dramatic drawdown of groundwater level and its depletion. In cooperative approach, rate of withdrawal from aquifer is determined by considering renewable water volume, together with, groundwater table drawdown constraint. In this approach, water users may gain less benefit than non-cooperative in early years of withdrawal, however, that will offset in 50 years period by means of more benefit.

Keywords Groundwater · Common pool resources (CPRs) · Tehran plain · Conflict resolution

Introduction

After expansion of hydro-machineries, groundwater has been recognized as an extensive source of water supply. However, now-a-days, excessive withdrawals of this natural sources have caused some dramatic consequences, often leading to soil subsidence. Therefore, it is reasonable to consider this as common pool resources. Groundwater resources are the main available source of fresh water in arid and semi-arid environments, upon which, 50% of world population are dependent (Madani and Dinar 2012a; b). With regard to the nature of groundwater, these resources are considered so limited as to cause competition among users for withdrawal. This has led to dramatic water level drawdown in aquifers resulted in land subsidence and aquifer destruction. Kamali and Niksokhan (2017) developed multi-objective optimization for sustainable groundwater management by developing of coupled quantity-quality simulation–optimization model. Jafari et al. (2016a, b), Neshat and Pradhan (2017) and Yousefi et al. (2017) study groundwater quality and quantity risk considering their uncertainty. Behroozi et al. (2015) developed simulation–optimization model for quantitative and qualitative control of urban run-off. Saberi and Niksokhan (2017) used graph model for conflict resolution in optimal waste load allocation.

Decision makers have a lot of problems in common pool resources (such as water, fisheries, …) management related to the nature of their application. It is difficult to restrict public from accessibility of common pool resources; one of the characteristics of CPRs (Common Pool Resources) is their subtractability by which appropriator from that can endanger benefits of other users. On account of these

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characteristics, CPRs users often encounter over consumption and destruction of resources. As a matter of fact, the required background for appropriate and efficient application of CPRs is wise planning for sustainable utilization of CPRs.

Many conducted studies are indicative of instituting CPRs which may play a key role to shape an inter-relationship between CPRs users (Ostrom 1990). Governments may determine permissions, limitations and prohibitions by organizational frame work and definition of laws and policies (Ostrom 1990). Instituting arrangements may include legislation by which individual behavior is formed. In addition, it establishes private and public relations as well as required standards among CPRs users.

In early attempts to differentiate the difficulties resulted from excessive use of CPRS, it has to be associated with the users' notification from the tragic consequences of CPRs (Gordon 1954; Hardin 1968). Madani (2010) described tragedy of CPRs by prisoner's Dilemma game structure in which Nash cooperative solution concept was used. Thus, early researches suggest that rational legislations to be considered to prohibit and regulate excessive use of CPRs so that it could avoid the tragedies (Ostrom 1990, 2010; Castillo and Saysel 2005). Recent studies have stated that future of CPRs with an ad-hoc withdrawal regulation for the users is better than that of prisoners' dilemma structure. This may be justified by group decision making and development of a general rule for CPRs management based on learning from past experiences (Ostrom 1990, 2010; McCarthy et al. 2001; Castillo and Saysel 2005).

Hardin (1968) investigated that when there is no constraint on using resources or no legislation is implemented, water users may make the maximum use of the water which may have benefit in a short time while it appears to have adverse effects in long term periods. Ostorm (2010) suggested that legislation and ownership rights are necessary to prevent from common pool tragedy. In developing countries, where economic conditions are not quite sustainable, unemployment and inflation are commonly two factors causing lack of supervision on groundwater withdrawals.

Madani and Dinar (2011) stated that how to avoid common pool tragedies with variation in decision making and withdrawal strategies even under non-cooperative institution for sustainable common pool resources management. They also investigated cooperative and non-cooperative institutions for sustainable common pool resources withdrawal that could be protected against common pool tragedy by group decision making and appropriate water withdrawal strategies (Madani and Dinar 2011).

Madani and Dinar (2012a, b) determined the rates at which groundwater allocation could be sustainable by applying common pool resources theory and formulation of cooperative and non-cooperative institutions. In their research, an optimization model was developed to divide benefits resulted from common pool resources withdrawal among water users.

In general, there are two main classes to determine governance institution of CPRs:

Non-cooperative management institutions where individual activities may be conducted independent of one another and attempts are made by appropriators to maximize the individual benefits without considering the consequences. However, under some circumstances, it may put appropriators in a situation to make sustainable use of the CPRS when undesirable feedbacks of consequences or external governing conditions are enforced. In this case, there is no cooperation among users and long term benefit may only be achieved by following the regulations.

In cooperative management institutions, CPRs operators essentially, make their decisions to maximize lifetime of CPRs and their group benefits simultaneously. A rational operating approach of CPRs may have advantages or disadvantages for operators in the above institutional categories. For example, in cooperative management, long-term benefits may be gained following high organizational cost. Success of each institutional management depends upon revenue, education level and trust of users as well as size and total use of CPRs. In fact, framework of operating solution for optimum CPRs use depends on each case study. Therefore, it may not be possible to suggest a definite operating solution for CPRs as the institution management may differ from one society of users to another. Hence, it is required to understand type and characteristics of CPRs and social solution of operators to recommend optimum management solution. This begs a comprehensive study to evaluate benefit of each institutional management for sustainable development of CPRs.

As in arid and semi-arid areas, sustainable groundwater management may be more complex than other areas because of limited resources, and excessive withdrawals, its management regime from common pool theoretical viewpoints could introduce a rational solution for group users or individual appropriator under some regulations. This research deals with cooperative and non-cooperative management institutions in groundwater withdrawal, by coupling numerical groundwater and optimization models, have been evaluated. Legal limitations of groundwater withdrawal have been accounted for non-cooperative management institution so as to achieve sustainability by cooperative management institution.

In this paper, sustainable groundwater withdrawal of Tehran aquifer was studied by cooperative and non-

cooperative institutions, this was initially conducted by numerical simulation of the aquifer using MODFLOW to calculate response functions by ANN model. Finally, an optimization model was developed based on cooperative and non-cooperative institutions as well as response functions.

Methodology

Common pool resources are characterized by two features, namely, subtractability and non-excludability. Subtractability is defined as utilization of resources by one user which affects other users. For example, excessive withdrawal of groundwater may cause other users to encounter water shortage. Excludability means that accessibility is allowed on the basis of permission. In groundwater withdrawal, illegal users' excludability may appear rather difficult due to social impacts (Madani and Dinar 2011).

Groundwater is one of the CPRs in which its sustainable management is necessary (Koundouri 2004; Loaiciga 2004; Vrba and van der Gun 2004; Harou and Lund 2008). One of the most important challenges in management of CPRS is complexity of external conditions estimation and water withdrawal monitoring by multiple users.

This study extends previous research works by focusing on groundwater management under cooperative and non-cooperative approaches by coupling up groundwater simulation and ANN models. In this approach, constraints are essentially established by coupling numerical simulation and ANN results. Main components of the groundwater decision making model developed in this study are shown in Fig. 1.

Groundwater Simulation Model

Three-dimensional groundwater movements in porous media may be described as

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right) - W = S_s\frac{\partial h}{\partial t}, \tag{1}$$

where K_{xx}, K_{yy}, and K_{zz} are hydraulic conductivities in x, y, and z directions (LT^{-1}), h: groundwater table (L), W: rate of recharge and discharge per unit area (L^3T^{-1}), S_s: specific storage (L^{-1}), t: time step (T).

The above equation states groundwater motion in non-homogenous media under unsteady state condition along x, y, and z directions. In steady flow condition, the right-hand side of Eq. 1.3 equals zero, and by assuming isotropic and homogenous media, it may be expressed as

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2} - W = 0. \tag{2}$$

Analytical solution of this equation is possible in one-dimensional form. In three-dimensional cases, numerical methods, particularly finite differences may be applied to obtain an approximate solution for the equation.

MODFLOW is a well-known model to simulate groundwater flow in GMS package. It is able to solve steady and unsteady groundwater flow numerically by finite-difference approach. It consists of several modules such as well, river, drainage, recharge and boundary condition.

GMS gives applicants an opportunity to calibrate groundwater table by using piezometric wells and hydrometric station records. To calibrate utilized parameter in groundwater (i.e., hydraulic conductivity, recharge, specific storage), PEST method was used in which the differences between calculated and observed water tables in piezometric wells are minimized.

Artificial Neural Network Model

In optimization of groundwater management, it is required to simulate groundwater flow under different scenarios, which may have difficulties of linking simulation and optimization models and also computation time. To overcome this, meta-models are useful tools for enabling applicants to replace simulation model with ANN model.

In ANN model, relation between dependent and independent variables (i.e., input and output data) is determined by MODEFLOW simulation results with no account of physical conditions of the problem. The ANN model was trained by agricultural well withdrawal as input data and variations of groundwater table as output data whereby these sets were computed by numerical simulation of the aquifer under different withdrawal scenarios. ANN training and test were fulfilled to derive a relationship between withdrawal rate and groundwater table variations.

Optimization Model

In water resources planning and management, problems are traditionally formulated by identifying objective function and constraints. Financial limitations as well as socio-economic issues are the most important constraints by which water resources management optimization modeling can be undertaken. The constraints of the optimization model are:
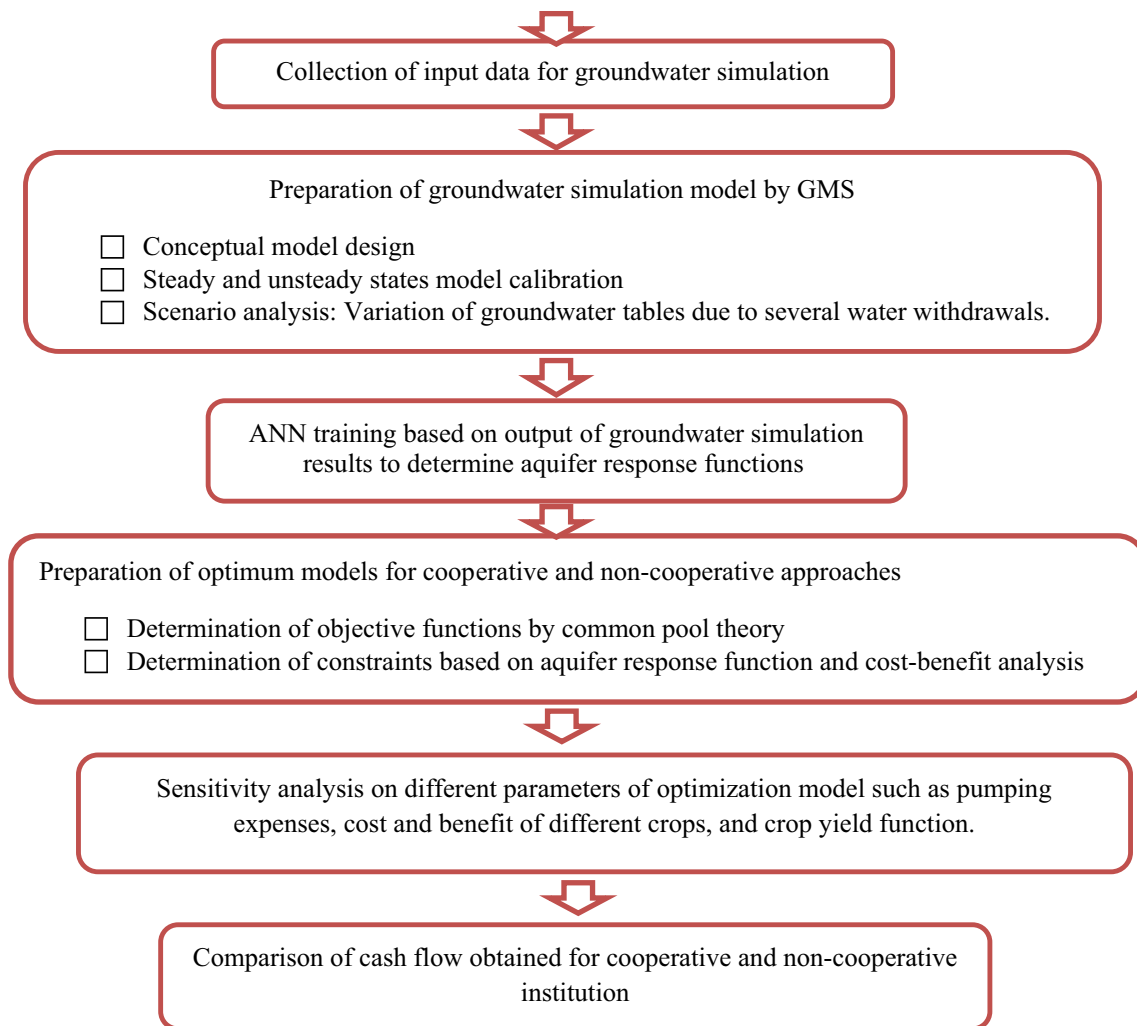
Fig. 1 Schematic flowchart of the methodology

Groundwater Table Variations Function

Groundwater table variations with respect to water withdrawal rates on the basis of trained ANN resulted from simulation of the aquifer, can be expressed as

$$S = \text{purelin}(W_2' \times \text{purelin}(((W_1 \times P) + b_1) + b_2)) \qquad (3)$$

where W_2', W_1, b_1, and b_2: ANN constant to be calibrated, P: water withdrawal rates ($L^3 T^{-1}$), S: groundwater table variations (L).

Cost Function

As there are several costs in agricultural activities, pumping expenses is the only one considered as

$$C_p = \frac{V \times d \times t}{0.102 \times \mu} \times \text{Pr}, \qquad (4)$$

where V: annual withdrawal volume (MCM), d: groundwater abstraction head (m), t: annual pumping time (h), μ: pump efficiency (%), Pr: pumping expense ($ per kwh).

In addition, each farmer has to bear other costs (i.e., fertilizer, seed, irrigation, plants, etc.), which all of them have been considered as a bulk in the optimum model.

Yield Function

Yield function presents crop yield as a function of factors affecting the crop products. One of the important factors affecting the crop yield is amount of allocated water during growth period. Applied yield function by keeping other agricultural inputs constant is

$$\frac{Y_i}{Y_m} = \left[1 - Ky \left(1 - \frac{Q_i}{E} \right) \right], \qquad (5)$$

$$Y_i = Y_m \times \left[1 - K_y \left(1 - \frac{Q_i}{E} \right) \right], \tag{6}$$

where Y_m: maximum crop yield (Kg), Y_i: crop yield for allocated water (Kg), K_y: sensitivity coefficient of crop to water tension, Q_i: allocated water (MCM), and E: crop water demand (MCM).

Revenue Function

The following formulation was used to calculate the gross benefit of the crops:

$$Rt = \gamma \times Y \times L, \tag{7}$$

where γ: price per unit weight (\$/Kg), Y: crop yield (kg/ha), L: area of cultivation (ha).

Benefit Function

Net benefit is the difference between crop sell revenue and purchase of agricultural inputs:

$$A_t = R_n - C_n \tag{8}$$

where, A_t: Annual net benefit of farmers (\$), R_n: Farmers revenue at year n (\$), C_n: Farmers cost at year n (\$).

Economic Evaluation

Figure 2 presents annual cash flow diagram for a period of n years (operation period), in which A is annual net benefit of farmers, P is present value and F is future value.

Future annual net benefit may be converted into present value with $i\%$ rate of interest as

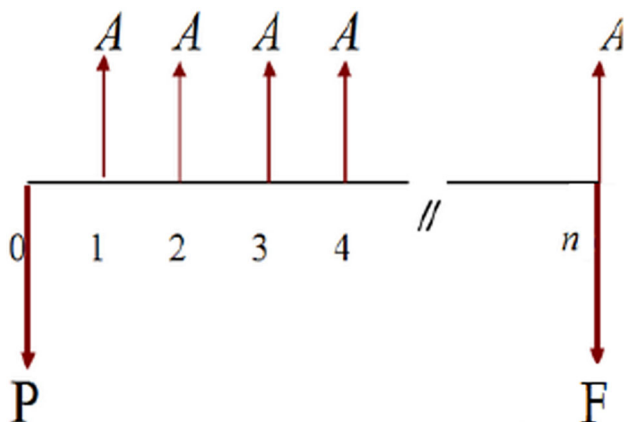$$P = A \left(\frac{P}{A}, i\%, n \right) = A \times \frac{(1+i)^n - 1}{i(1+i)^n}, \tag{9}$$

Fig. 2 Cash flow diagrams

where P: present value (\$), A: annual net benefit of farmers (\$), i: annual rate of interest (%), and n: planning period (year).

Objective Function Based on Cooperative Institution

This essentially deals with group decision making which leads to sustainable utilization, with more life cycle for common pool resources, together with, more benefits for all users.

In this approach, withdrawal permission is established by group agreement considering CPRs constraints in which long-term group benefit is maximized. In cooperative approach, users make their withdrawal planning with regard to groundwater recharge and water table drawdown. Under these circumstances, objective function of optimization model is to maximize sum of farmers' benefits during withdrawal period which is usually in the range of 50–100 years:

$$\text{Max} \sum_{j=1}^{m} P_j \tag{10}$$

subject to Eqs. 3–9.where m: number of farmers and P_j: present value of annual net benefit of farmer j.

Objective Function Based on Non-cooperative Institution

In this approach, there is no group decision making and withdrawal is based upon individual decision making without considering undesirable consequences. Previous studies have shown that lack of legislation and supervision may lead to destruction of CPRs.

In non-cooperative management institution, each user decision is made independently of the others. Hence, each user may have different regulation from others to exploit from CPRS. This may appear as a case where each user proceeds to maximize their own shortterm benefits. This type of decision making may cause to ignore external conditions governed by effect of other user's decision on CPRS status and utility (Gordon 1954). It may formulate as follows:

$$\text{Max} P_j \quad \text{for} \quad j = 1 \text{ to } m \tag{11}$$

subject to Eqs. 3–9, where parameters are defined as before.

Results

Tehran–Karaj plain is located between 35°20′–36°15′ North latitudes and 50°50′–52°15′ East longitudes in Tehran province. The plain area is about 5156 km^2 from

which 43% is mountainous and the rest is flat. There are a number of cities and villages with population of over 12 million people being dependent on the plain aquifer.

The location of the study area is shown in Fig. 3. It is located in southern part of aquifer of Tehran plane. Tehran aquifer is quite large with hydrological and hydrological complexities. However, the model was made for the southern part of the plane, where numbers of agricultural abstraction well are considerable. Western boundary of the study area is connected to the main aquifer hydraulically and has been determined by monitoring wells. It is an unconfined aquifer to be simulated by one layered model. With regard to available records, there are eight monitoring wells in the study area. For which monthly water elevations are available. Annual water depth is also available for each well. The above records were used to work out mean annual water table for each well in 2007.

GMS 6.5 has been applied to simulate south western part of Tehran aquifer as study area. Input data maps are

transmissivity, piezometric surface, ground surface topography, and aquifer bed rocks. In addition, withdrawal wells location and discharge values as well as water table in observation wells were supplied by Tehran Water board. There are eight observation wells in the study area with 10 years of monthly record of water table. There are also 415 operating wells in the area with available depth, withdrawal rates and year of establishment.

These data were used to work out initial water elevation and to calibrate hydrological parameters of the model. Based on available records, there are 415 abstraction wells in the study area. The quantity of abstraction from each well has been taken into account in the model. However, due to large number of the wells, a well was selected as a representative of a group of wells with regard to their locations and assumed that the abstraction was made from each representative well to be equal to the sum of the abstractions from the wells in the group, as this enabled the authors to apply common pool theory. To determine surface recharge parameter distribution in the plane, with regard to land use, several polygons were introduced for surface recharge. With regard to the results obtained from groundwater study and coefficients of return flow resulted from various consumption, quantity of recharged water from each polygon was initially estimated. Further on, these values were adjusted to calibrate the model by finding best agreement between observed and computed values in the monitoring wells. Figure 4 shows the polygons of the conceptual model by which the recharge parameters are defined. Figure 5 displays the mesh size of 100×100 m^2 in computation domain which works out to be 10,000 cells in the domain, cells that are located outside the domain are inactive while those inside the domain are considered
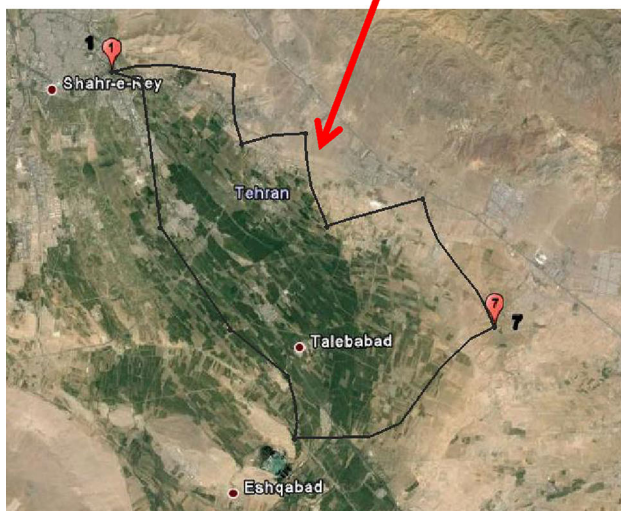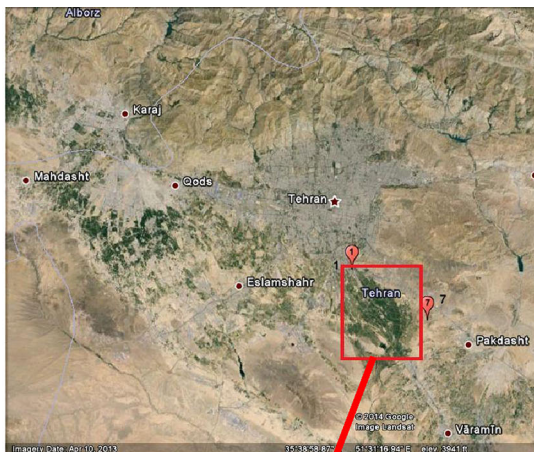

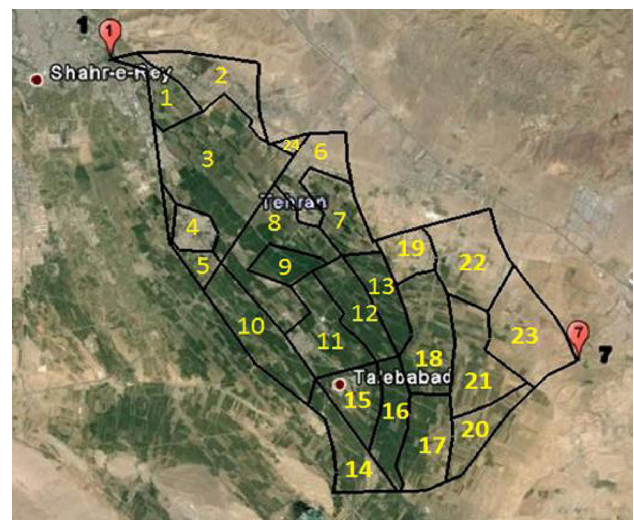Fig. 3 Location of study area compare with Tehran plain and Tehran city

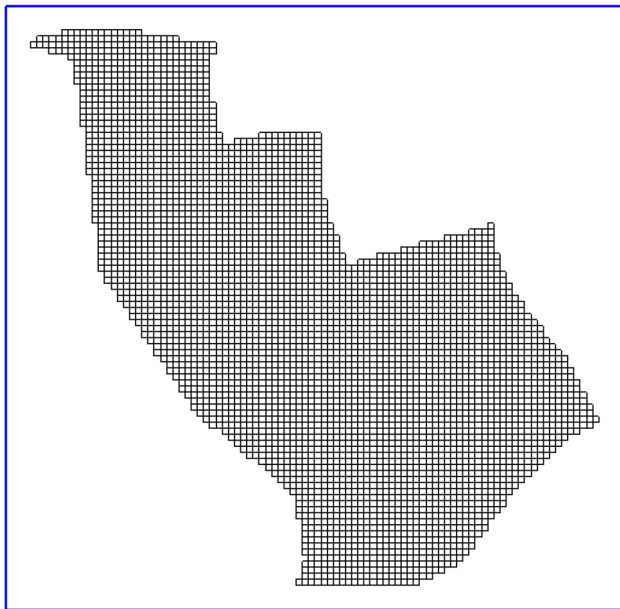Fig. 4 Polygons of the conceptual model by which the recharge parameters are defined

Fig. 5 Mesh size of 100×100 m² in computation domain

active. With regard to available records of monitoring and abstraction wells, the water year 2006–2007 was selected as reference for simulation runs.

The model was calibrated for steady and unsteady conditions by comparing computed and observed water tables in the observation wells (Figs. 6, 7, 8). In the formers, hydraulic conductivity and recharge were computed while in the latter, specific storage was calculated.

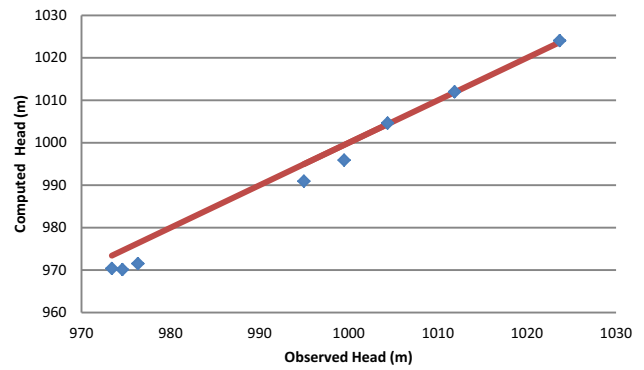**Fig. 7** Calibration and verification results of groundwater simulation in steady state condition
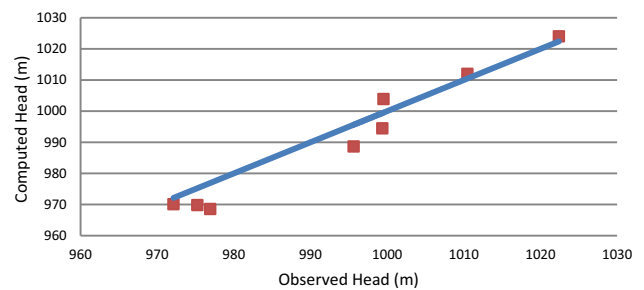

Fig. 8 Calibration and verification results of groundwater simulation in unsteady state condition
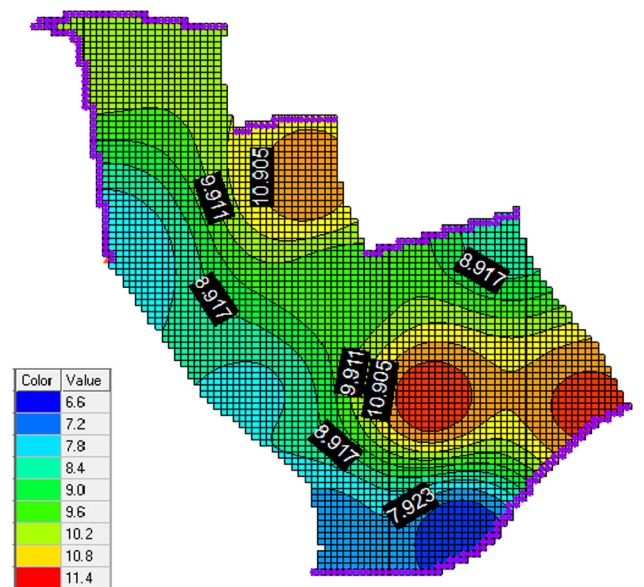

Fig. 9 Variation of hydraulic conductivity in the study area after calibration

Numerical Simulation of Tehran Aquifer

As shown in Fig. 9, the highest value of hydraulic conductivity occurred in alluvial fan at the confluence of Kan and Chitgar rivers equal to 11 m per day, while its lowest

Fig. 6 Comparison of groundwater head at observation wells (Calibration and verification Results of the model)

Table 1 Characteristics of trained ANN model for the study area

RMS (SSE)	Function number of neurons		Number of neurons		Number of layers
	Second layer	First layer	Second layer	First layer	
0.0066	Purelin	Purelin	0	10	2

value is 7 m per day in the South of the plain. Hydraulic conductivity appears to have higher values in the Northern and Central parts of the plain, as this could be reflected by the river confluence and existence of large non-cohesive sediments in these locations. However, further down the plain in the south, finer sediments appear to cause lower hydraulic conductivity.

As mentioned in "Artificial Neural Network Model" section and based on Eq. 3, input and output data of Tehran aquifer to train ANN model are rate of withdrawal from operation wells and variations of water table, respectively. ANN input data consist of a 25×70 matrix, where the first row includes withdrawal rates from 25 operation wells in the first scenario and the rest of the rows include various withdrawal rates for other scenarios. Output data are a row vector with 70 elements by which they are indicators of water table drawdown related to each withdrawal scenario. Table 1 shows results of training and testing of the ANN model, respectively.

Appropriate structure of the ANN has principally been obtained by applying an optimization model where the objective function is to minimize the difference between observed and predicted values. The optimum ANN structure is composed of two layers with ten neurons for the first layer and one neuron for the last layer. After calibration of the ANN model, groundwater table variation equation may be derived as Eq. 3.

For non-cooperative approach, results of the optimization model state that, due to excessive withdrawal, water users may gain short term benefits. However, this may have adverse effects on the aquifer in long term as a result of which could end up with aquifer destruction in long term. Figure 10 reflects water users benefits decrease during withdrawal period which is due to groundwater table drawdown. In addition, this is followed by increasing pumping expense and deepening well. This unsustainable water withdrawal continues to the point where withdrawal expense exceeds the benefits.

Figure 11 shows cash flow (cost–benefit analysis) of water users in cooperative approach. It is noticed that withdrawal has remained unchanged owing to constant groundwater table. Comparison of Figs. 10 and 11 suggest that at the start of water withdrawal period, more benefit is gained by water users in non-cooperative approach than that of the cooperative, however, after 25 years period, the latter overtakes the former.

After running optimization model for cooperative and non-cooperative approaches, withdrawal rates were
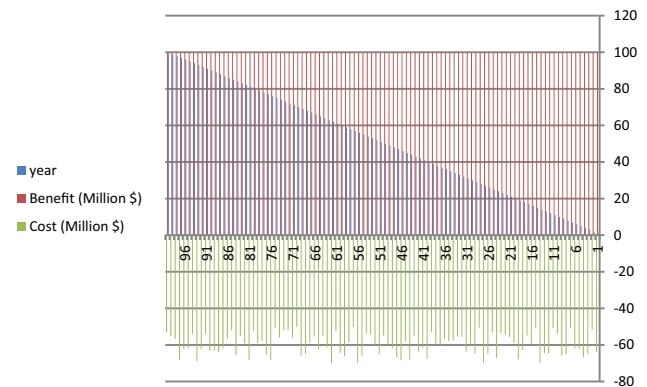
Fig. 10 Cost–benefit diagrams in non-cooperative approach for 100 years period
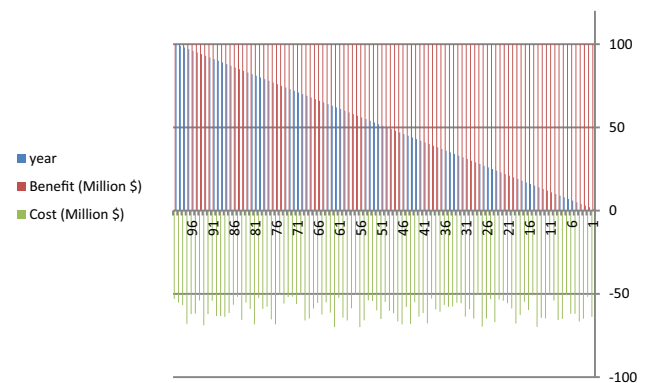
Fig. 11 Cost–benefit diagram in cooperative approach for 100 years period

obtained for operation wells. In non-cooperative approach this is twice cooperative one in early period of operation which may be decreased, with regard to groundwater table drawdown, and tends to zero in 100 years. This variation has been illustrated in cash flow diagram, where expenses of non-cooperative approach are increased, and as a result, its benefit is decreased (Figs. 10, 11).

Conclusion

Natural forest, pastures, fisheries, and groundwater are accounted for common pool resources. One of the significant characteristics of these resources is their subtractability by which it means that their use by an appropriator may have effect on others. Since in economic

models, no expenses is considered for the use of natural resources, this may lead to unlimited use of the resources which may end up with common pool tragedy.

Now-a-days, many common pool resources, particularly, groundwater, may be endangered by unlimited and competitive withdrawals by which they are exposed to destruction. This research has mainly been focused on groundwater conditions in two cooperative and non-cooperative approaches by applying numerical simulation, ANN, economical and optimization models. Southern part of Tehran plain was selected for the case study which was simulated by GMS. Then by applying GMS results, the ANN model was trained and calibrated to generate aquifer response function. Furthermore, optimization models with cooperative and non-cooperative institutions were developed to obtain cash flow diagram for the users.

Results indicate that benefits of the users are more in short term in non-cooperative institution which decreases for a long term planning due to groundwater table drawdown. However, in a 100 year planning period, the users benefit in cooperative institution is much greater than that of the non-cooperative approach. In spite of all advantages of cooperative institution, its implementation may not be as easy. Therefore, it is necessary to impose limitation and regulation on groundwater withdrawals in non-cooperative approach for sustainable management.

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