



# Multi-Objective Hydro-Economic Modeling for Sustainable Groundwater Management

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## Abstract

Groundwater sustainability may refer to its exploitation and use for the present needs while maintaining the resource for future generations without unacceptable environmental, economic, and social consequences. For transitioning toward groundwater resource sustainability, specific adaptive management policies should be developed to achieve pre-specified goals. Focusing on demand side measures, this paper develops and applies a hydro-economic based multi-objective optimization model for sustainable groundwater management. Solution to the model develops a tradeoff surface between possible loss to long-term agricultural profit, groundwater level, and required energy for groundwater pumping. Farming practice and cropping pattern, quantity and timing of groundwater pumping, and energy consumption are optimized for transitioning toward long term groundwater sustainability. The simulation model is coupled with a multi-objective particle swarm optimization algorithm for developing a set of non-dominated optimal solutions for sustaining groundwater table in a groundwater basin in Isfahan, Iran. Recovery time of transitioning to groundwater sustainability is dynamically varied to assess the impact of different strategies on agricultural economy, mean annual groundwater level drop, and required energy for pumping. Results show that the optimal strategy for sustaining groundwater level at its present condition would result in 17% reduction in agricultural profit to the region. The same strategy would reduce energy use for groundwater pumping by more than 19%, compared to the business as usual strategy.

**Keywords** Groundwater · Sustainability · Irrigation · Management · Multiobjective · Optimization

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## 1 Introduction

Due to its vital importance for the current and future generations, sustainable utilization of groundwater resources has received growing attention in recent years (Mays 2013; Marsy et al. 2018; Thomas et al. 2018; Ali et al. 2012; Qureshi et al. 2010). Groundwater sustainability may refer to its exploitation and use for the present needs while maintaining the resource for future generations without unacceptable environmental, economic, or social consequences (Gleeson et al. 2012; Pandey et al. 2011; Cao et al. 2013).

From environmental and economic perspectives, sustainable groundwater may be addressed by retrieving groundwater level which can be accomplished through employing a combination of supply side and demand side measures. The supply side measures may consist of surface water substitution, artificial groundwater recharge by means of conjunctive use of surface and groundwater resources (Safavi et al. 2010; Bredehoeft 2011), and cyclic storage strategy (Alimohammadi et al. 2009; Afshar et al. 2010). The demand side measures may call for reduced groundwater extraction through the implementation of appropriate demand management policies in all sectors including, but not limited to, irrigated agriculture (Hu et al. 2010; MacEwan et al. 2017). Demand reduction may either lose productivity or reduce recharge, if water-use efficiency is improved by investing in new irrigation technologies (Harou et al. 2009).

Developing optimal strategy for groundwater sustainability with multiple objectives has a recent origin (Kamali and Niksokhan 2017; McPhee and Yeh 2004; Rothman and Mays 2014). Most of the recent multi-objective approaches have linked a groundwater simulation model with one or another type of optimization algorithms to develop a compromise between groundwater level and environmental objectives. However, none of them has combined a hydro-economic model of groundwater use with an optimization algorithm to develop a set of non-dominated solution strategies for long term groundwater sustainability with the regional loss of profit to the agricultural sector and/or energy required for implementation of the strategy. Although MacEwan et al. (2017) developed a dynamic hydro-economic model for the Kings and Tulare Lake sub-basins of California, their work is a simulation model used to evaluate three groundwater management institutions—open access, perfect foresight, and managed pumping.

In specific, this paper presents a novel approach for groundwater sustainability by developing a hydro-economic based multi-objective optimization approach focusing on demand side measures. While maximizing the long-term benefits to agricultural farming through optimized cropping pattern and minimizing the total energy used for groundwater pumping, the quantity and timing of groundwater withdrawal is optimized for transitioning toward long term groundwater sustainability. Results are presented as a set of non-dominated optimal solutions in two Pareto fronts. A simulation model in system dynamic environment is developed to simulate the hydro-economic impact of any trial solution. The simulation model is coupled with a multi-objective particle swarm optimization algorithm for developing a set of non-dominated optimal solutions for sustaining groundwater table in a groundwater basin in Isfahan, Iran. Recovery time of transitioning to groundwater sustainability is dynamically varied to assess the impact of different strategies on agricultural economy.

## 2 Case Study

The study zone in this research, Isfahan-Borkhar, is a sub-region of the Gavkhoni watershed in Isfahan province, Iran. Based on the existing data, in year 2001, gross groundwater pumping

from this aquifer was approximated as 532 million cubic meters (MCM) which is far away from its safe yield. In fact, the adjacent aquifers (Najaf Abad, Kuhpaye Segazi aquifers) are being depleted with approximately the same rate (Zayandab 2015). The average annual precipitation in the altitudes and plains is 142 and 115 mm respectively (Zayandab 2015). Although Iranian government has installed smart energy water meters to monitor groundwater extraction and associated energy use by individuals, it has not effectively changed the farmers' behavior toward groundwater pumping (Madani et al. 2016). Nonetheless, it is national interest to restore, balance and plan for sustainable groundwater resources throughout the country by employing means of both demand and supply side measures.

### 3 Proposed Methodology and Model Structure

The proposed methodology and model structure is schematically presented in Fig. 1. As illustrated, the general structure integrates four different modules in a dynamic loop which accounts for their interactions. The hydrologic module simulates the groundwater hydrology in a system dynamic platform. For this purpose, a localized lumped approach in *AnyLogic* system dynamic platform is developed to estimate changes in groundwater storage and level, dynamically (Kleijnen and Wan 2007). An optimization module is also included in the heart of the system to address the best cropping pattern and management strategy for hydro-economic consequences and transitioning to groundwater sustainability addressed by the target time. It has no limitation on temporal scale and may efficiently be used in any multi-period problem.

The proposed hydro-economic approach may provide a valuable tool for assessing the tradeoff between agro-economy, energy requirement, and groundwater sustainability. If developed in a system dynamic framework, hydro-economic models would facilitate identification

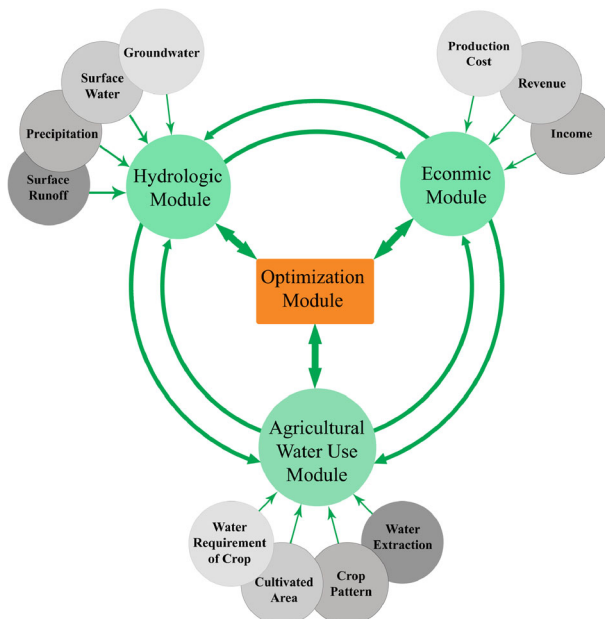


Fig. 1 Schematic representation of the proposed modeling structure

of competing solutions in hydrological and agricultural production systems as well as providing valuable insights into the outcome of any proposed groundwater management policy. Integrated hydro-economic models in groundwater environment are often used to predict and/or compare the evolution of groundwater use, aquifer storage variation, and agricultural productivity under proposed scenarios (Palazzo and Brozović 2014).

### 3.1 Simulation Model

The groundwater simulation model employs water accounting methodology to assess the transitioning toward sustainability of groundwater as management scenarios are implemented. Although the approach is quite simple, it can be difficult to obtain direct measurements or precise estimates of many components of the water balance. Those may include, but not limited to, groundwater inflows and outflows, drainage outflows, and real temporal and spatial distribution of crop evapotranspiration. Despite these limitations, many experiences have shown that even gross estimates of water balances can be quite useful to water managers and researchers (Kijne 1996).

Any simulation model may be thought of a surrogate for the actual system in order to assess its behavior under various scenarios and/or experimentations, which is usually disruptive, not cost-effective, or simply impossible. To minimize the possibility of erroneous results which may lead to very costly and unrealistic management decisions, the simulation model should be a close approximation of the actual system. A simulation model is verified if the conceptual model compares well with the computer representation implementing that conception. On the other hand, validation relates to building the “right model”. Validation is the process of determining whether or not a simulation model is an accurate representation of the system for the predefined objectives of the study (Law and McComas 2001).

In addition to being professionally verified and validated, a simulation model and its results must be credible. A model gains credibility if the decision-makers and other key project personnel (including public users) accept the results as reliable and correct. Credibility can be established if the decision makers agree with the underlying assumptions of the model, if they are involved in its development, and if they share ownership of the model. The reputation of the model’s developer may also help gain credibility (Law and McComas 2001).

The current model borrows part of its legitimacy and verification from the water accounting concept and visualization of the “stock-flow” diagram in the system dynamic template. The model output was closely examined to ensure it was reasonable and sound under a variety of input settings. The simulation model is coded as a lumped parameter in *AnyLogic* system dynamic platform for simulation and optimization of the strategies. *AnyLogic* is a multimethod simulation modelling. It supports three well-known modeling approaches namely: system dynamics, discrete event simulation, Agent-based modeling, and any combination of these approaches within a single model. Although it has been widely used in different disciplines, its application in civil and water resources engineering has a very recent origin (Saed et al. 2019). Unlike most system dynamic simulation modeling tools, *AnyLogic* benefits from a built-in optimization module, called “*OptQuest*”. The *OptQuest* engine uses combination of tabu search, scatter search and neural network for optimization and considers the simulation model as a black box using only the input/output of the model (Kleijnen and Wan 2007).

The most definitive validity test demonstrates how closely the model’s output resembles the actual system’s output, if such data is available. If the data from the simulation model compare “closely” with those from the actual system, then the model of the existing system may be

considered “valid.” Validation is usually achieved through the calibration of the model, either iteratively or automatically. The process uses the insights gained from any discrepancies between the behavior of the actual system and simulation model to improve the model. This process continues until the model’s accuracy is considered acceptable.

To calibrate and validate the simulation model observed data on rainfall distribution, surface runoff, groundwater level and reliable data on groundwater pumping for a 10-year period (2001–2011) are used. The calibration has been performed automatically in *AnyLogic* system dynamic platform employing *OptQuest*.

Groundwater level change between year  $t$  and  $t + 1$  could be defined as a function of agricultural groundwater pumping in time step  $t$  (addressed by OIGW and FCIGW), water year type (addressed by PRL, PRUL), groundwater recharge through deep percolation of surface water (addressed by FCISW, OISW), aquifer’s characteristics (addressed by aquifer storage coefficient which remains constant over the period of simulation), and contribution of other sources which are addressed by IWS and MWS as Eq. 1:

$$\delta \text{DGW}_t = f(\text{PRL}_{t,t-1}, \text{PRUL}_{t,t-1}, \text{IBWT}_{t,t-1}, \text{OIGW}_{t,t-1}, \text{OISW}_{t,t-1}, \text{FCIGW}_{t,t-1}, \text{FCISW}_{t,t-1}, \text{IWS}_{t,t-1}, \text{MWS}_{t,t-1}) \quad (1)$$

Where  $\delta \text{DGW}$  refers to change in groundwater level,  $\text{PRL}$  = low land precipitation,  $\text{PRUL}$  = upland precipitation,  $\text{IBWT}$  = inter-basin water transfer,  $\text{OIGW}$  = land area of orchards irrigated with groundwater,  $\text{OISW}$  = land area of orchard irrigated with surface water,  $\text{FCIGW}$  = land area of field crops irrigated with groundwater,  $\text{FCISW}$  = land area of field crops irrigated with surface water,  $\text{IWS}$  = industrial water supply,  $\text{MWS}$  = municipal water supply. Although disregarded here, interaction terms could have been lagged by 1 year to account for possible intra-year autocorrelation.

Figure 2 compares the results of the model for calibration and validation periods with those of the observed data. Few common criteria (Moriassi et al. 2007), such as Nash-Sutcliffe efficiency (NSE), Root Mean Square Error (RMSE), Ratio of Root Mean Square Error to Standard Deviation of observed data (RSR), and Correlation Coefficient ( $R^2$ ) are used to check the performance of the validation and calibration processes. The performane criteria as  $\text{NSE} = (0.94, 0.92)$ ,  $\text{RMSE} = (0.26, 0.32)$ ,  $\text{RSR} = (0.25, 0.28)$ , and  $R^2 = (0.97, 0.97)$  for calibration and validation periods are respectively observed.

### 3.2 Agricultural Water Use Module

This paper employs the procedure outlined in (FAO 2012) for estimating crops water requirement and yield. To calculate the actual crop evapotranspiration ( $ET_a$ ), the reference evapotranspiration ( $ET_0$ ) is scaled by crop coefficient ( $K_c$ ), and water stress coefficient ( $K_s$ ) as:

$$ET_a = K_s \times K_c \times ET_0 \quad (2)$$

To estimate the yield reduction under water deficit condition, the approach proposed by FAO is used (FAO 2012):

$$\left(1 - \frac{Y_a}{Y_m}\right) = K_y \left(1 - \frac{ET_a}{ET_0}\right) \quad (3)$$

In which  $Y_m$  and  $Y_a$  are the maximum and actual crops’ yields [kg / ha / yr], respectively. Maximum yield,  $Y_m$  of an adapted crop variety, as determined by its genetic makeup and

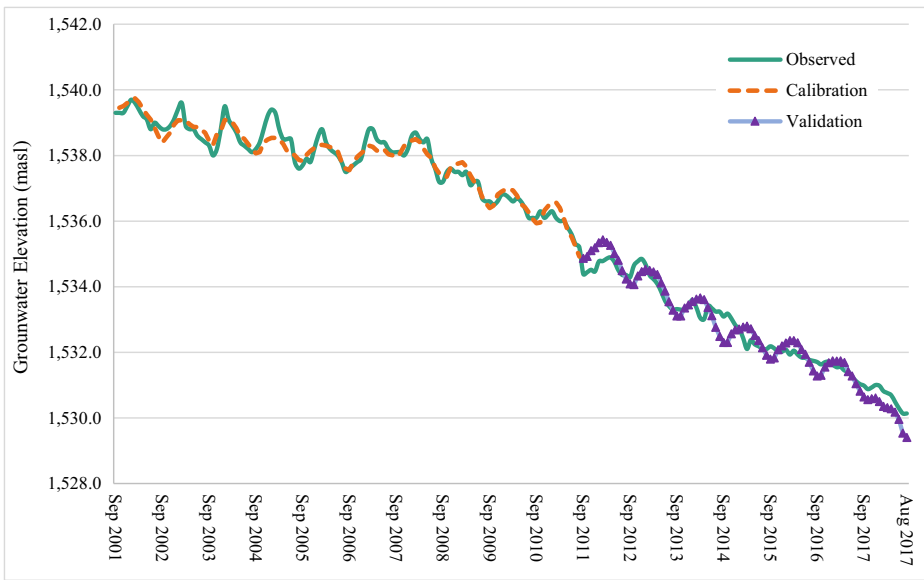


Fig. 2 Simulated and observed groundwater level during calibration and validation period

climate, is determined assuming non-limiting agronomic factors such as water, fertilizers, pest and diseases. In this formulation,  $K_y$  is the crop yield response factor (dimensionless) and accounts for the complex interactions between crop production and water use, where various biological, physical and chemical processes may be involved. The  $K_y$  values vary over the growing season according to growth stages. This study, however, uses average values of  $K_y$  over full growing season (FAO 2012). The relationship has extensively been used and shown a reasonable validity in quantifying the effects of water deficits on yield. In this study, the procedure is fully coded in *AnyLogic* (Kleijnen and Wan 2007) for simultaneous simulation of crop water consumption and optimization of cropping pattern for hydro-economic assessment with groundwater sustainability objective.

The proposed hydro-economic model allows for marginal adjustment due to deficit irrigation common in irrigated agriculture. The built-in optimization algorithm (*OptQuest*) determines whether deficit irrigation, influenced by the characteristics of crop production function, is optimal. The rate of deficit in stress irrigation is bounded with the following constraint:

$$AW_{c,y}/A_{c,y} \geq 0.8 \quad ET_{c,y}/\beta_c \tag{4}$$

In which  $AW_{c,y}$  is the total applied water to irrigate crop  $c$  in year  $y$ ,  $A_{c,y}$  is the total land allocated to crop  $c$  in year  $y$ ,  $c$  is the irrigation efficiency for crop  $c$ , and  $ET_{c,y}$  is the actual evapotranspiration. In fact  $ET_{c,y}/\beta_c$  addresses the applied water per hectare, typical for crop  $c$  in the region. The upper bound of 20% stress in irrigation prevents the mode; from reducing applied water below the range of normal practice.

During the simulation process, depth to groundwater at any period  $t$  ( $h_{gw,t}$ ) is adjusted as:

$$h_{gw,t} = h_{gw,t-1} + \delta DGW_{gw,t} \tag{5}$$

Where  $\delta DGW_{gw,t}$  refers to drop or raise in groundwater level during year number  $t$  and  $h_{gw,t}$  is the average depth to groundwater in the same period.

Excluding the amortized fixed cost of the well construction in the region, pumping cost per cubic meter of water may be addressed as:

$$PC_{gw,t} = CE_{gw} \times \varepsilon \times h_{gw,t} \quad (6)$$

Where  $PC_{gw,t}$  = pumping cost,  $CE_{gw}$  = cost of energy and pumping operation cost per meter of lift, and  $\varepsilon$  accounts for pump's efficiency and translating static head to dynamic head.

### 3.3 Optimization Module

As stated earlier, this study uses *AnyLogic* system dynamic platform for system simulation. Despite most system dynamic simulation models, *AnyLogic* has its own built-in optimization engine, called *OptQuest*. *OptQuest* considers the simulation model as a black box and uses combination of three meta-heuristic search algorithms, namely tabu search, scatter search and neural network (Kleijnen and Wan 2007).

The optimization process in *OptQuest* consists of repetitive simulations of the model with different parameters. It employs very efficient algorithms to vary the controllable parameters from one simulation to another for locating the near optimal values for controllable parameters and/or variables. The optimization process may be terminated either when the maximum number of simulation runs exceeds a predefined number or the value of the objective function stops improving significantly. The *OptQuest* optimization engine receives a sample of the objective function at the end of each simulation run, analyzes the sample, modifies the controllable parameters according to its optimization algorithm, and starts a new simulation. This study uses *OptQuest* for the calibration and verification of the simulation model.

The proposed modeling structure intends to develop a set of non-dominated solutions which simultaneously minimizes (Afshar et al. 2010) the lost profits to irrigated agriculture, (Ali et al. 2012) the total drop in groundwater level, and (Alimohammadi et al. 2009) the total required energy for groundwater pumping during the simulation process. Mathematical representation of the optimization model may be addressed as:

$$\text{Min. (Lost Profit)} \quad (7)$$

$$\text{Min. (Drop in GW level)} = \text{Min} \sum \delta \text{ DGW}_t \quad (8)$$

$$\text{Min. (Pumping Energy)} \quad (9)$$

As presented, the first objective function (Eq. 7), intends to minimize the lost benefit as a result of varying crop-land allocation and irrigation strategy compared to the current condition. The amount of total lost profit accounts for any gain or loss in pumping cost due to positive or negative groundwater level fluctuation as new scenarios are tested. The first objective function may mathematically be presented as:

$$LP = \sum_{y=1}^Y \sum_{c=1}^n PC_c \times (\tilde{A}_c - A_{c,y}) - \sum_{t=1}^T CE_{gw,t} \times (\tilde{\varepsilon} \times \tilde{h}_{gw,t} - \varepsilon \times h_{gw,t}) \quad (10)$$

In which  $LP$  = lost profit during the simulation period,  $PC_c$  = net profit per hectare for crop  $c$ ,  $\tilde{A}_c$  = area allocated to crop  $c$  in the offset year (year 2011),  $A_{c,y}$  = area allocated to crop  $c$  in

year  $y$ ,  $CE_{gw,t}$  = energy unit cost in month  $t$ ,  $\tilde{\varepsilon}$  and  $\varepsilon$  account for pump's efficiency and translating static head to dynamic head under managed and open strategies, and,  $\tilde{h}_{gw,t}$  and  $h_{gw,t}$  are depths to groundwater under managed and open strategy, respectively.

The second objective and third conflicting objectives account for minimum possible groundwater use and minimum pumping energy during the entire planning horizon, respectively.

The total pumping energy under each strategy is calculated as:

$$TPE = \sum_{t=1}^T GW_t \times \varepsilon \times h_{gw,t} \times \gamma \quad (11)$$

Where  $GW_t$  = groundwater withdrawal in month  $t$  and  $\gamma$  is the specific weight of water. The optimization algorithm minimizes three objectives addressed by Eqs. 7, 10, and 11 which intend to develop the tradeoff surface between loss of profit to the farmers, drop in groundwater level, and mean annual energy consumed for groundwater pumping. In addition to constraints for land-crop allocation and groundwater storage balance, the optimization is subject to the set of constraints defined by Eqs. 1–5 for each simulation period. To partially reduce the social consequence of any change in crop reallocation, the model is restricted to keep the reduction in total cultivated area within an acceptable limit to be addressed later. The solution to the multi-objective formulation provides a set of non-dominated solutions with useful information on scenario selection and the economic and hydrologic consequences of any scenario, if implemented.

To solve the proposed multiobjective model for transitioning toward groundwater sustainability, however, a more powerful multiobjective optimizer is required. For this purpose, a multiobjective version of particle swarm optimization algorithm is developed and coupled with the calibrated simulation model to develop a set of nondominated solutions with objective functions defined in Eqs. 7, 10, and 11 (Or equally 7–9).

## 4 Model Application and Results

### 4.1 Model Setup

To setup the model, the baseline condition is simulated and the resulting groundwater level, dominating agricultural cropping pattern and long-term agricultural return was compared with the available observed data. Under the open access strategy (business as usual), the groundwater level is expected to drop continuously (50 cm/year) due to over drafting the aquifer by more than 20% (Fig. 2). As illustrated, under the open-access institution, the aquifer may suffer from overdraft, leading to an unsustainable condition where annual extraction exceeds the overall aquifer recharge. It was shown that under the baseline condition with open access strategy to groundwater pumping and average annual applied water of 399 MCM, the annual agricultural profit would approach to 71.4 billion Iranian tomans in Iranian currency.

It must be pointed out that due to the aquifer characteristics and very low irrigation efficiency in the region, approximately over 45% of the total applied water is assumed to deep percolate into the groundwater aquifer. This study assumes no change of technology and/or methodology in practiced irrigation.

Two different data set was utilized to test the performance of the model. The first setting uses the historical data on groundwater level, hydrology, and climatology, while



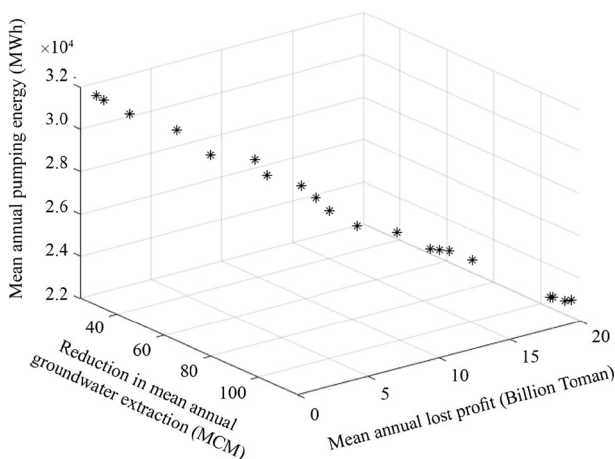
the second set intends to present the possible groundwater level changes on target year of 2030 under different scenarios derived from the optimization model. The data for the second strategy is taken from Tavakoli (2017) which intends to account for impacts from possible climate changes.

## 4.2 Results and Discussion

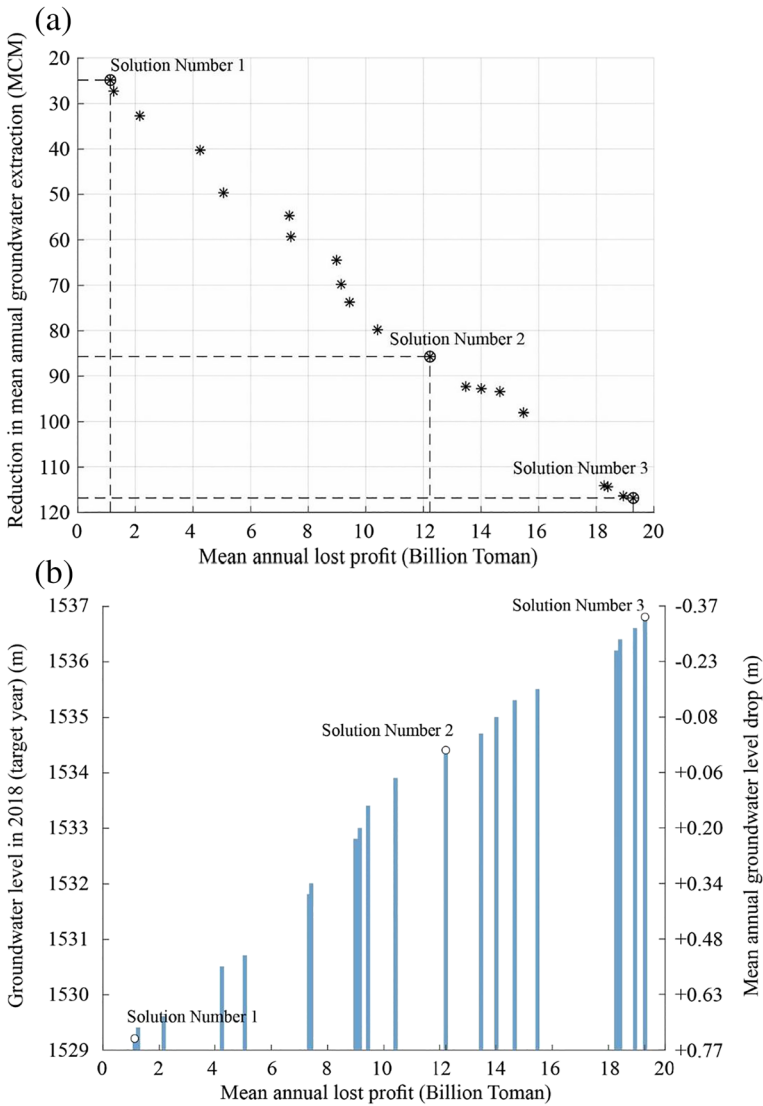
The proposed model was applied to develop a set of non-dominated solutions which compromises between different objectives (Eqs. 8, 10, 11). As stated, the study intends to minimize farmer's lost profit from modified agricultural practices, while minimizing the total energy used for groundwater pumping and promote groundwater sustainability by stabilizing groundwater level with pre-defined retrieval time targets.

Result of the model for the 3-objective case example using the first set of data is presented in Fig. 3 as a Pareto surface. The surface shows the tradeoff between the three identified objectives which compromises between the reduction in mean annual groundwater extraction (or mean annual drop in groundwater level), annual loss of profit, and annual consumed energy. Reduction in mean annual groundwater extraction may help stabilizing groundwater level and transitioning toward groundwater sustainability. Resulted reduction in groundwater extraction would certainly cause some loss of profit to the farmers which may partially be compensated by reduced pumping energy cost. In fact, any raise in groundwater level due to lowering mean annual groundwater extraction would reduce total energy used for groundwater pumping.

To be more specific, results of the model for the first set of data is also represented as two different Pareto fronts in bi-objective structures (Figs. 4 and 5). Figure 4 presents the set of non-dominated optimal solutions which trades off between the mean annual loss of profit and reduction in mean annual groundwater extraction. It also shows the tradeoff between lost profit and the variation in resulted mean annual groundwater level in target year of 2018 as well as the mean annual drop in groundwater level. Implementation of strategies which impose partial restriction on groundwater extraction would stabilize and/or raise groundwater level over the initial condition. For example, implementation of a policy which imposes 20%



**Fig. 3** Pareto surface presenting the set of non-dominated optimal solution for the three objectives

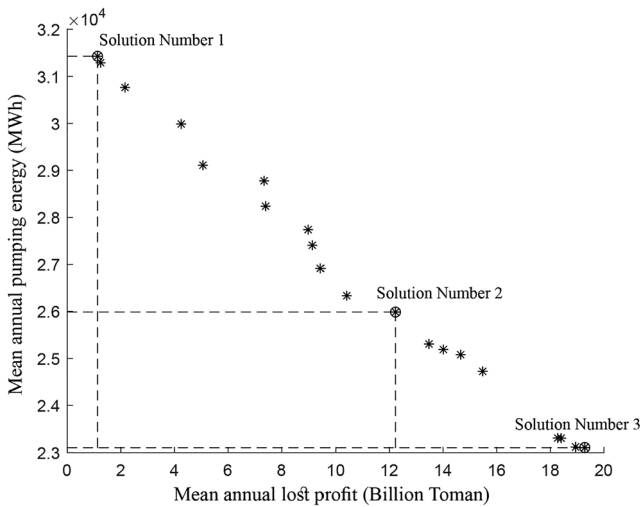


**Fig. 4** a Set of non-dominated optimal solutions (mean annual lost profit vs. reduction in mean annual groundwater extraction) b Set of non-dominated optimal solutions (mean annual lost profit vs. groundwater level in 2018 (mean annual groundwater level drop))

reduction in annual groundwater extraction would approximately stabilize the groundwater level at the initial level of 1534.5 as observed in 2011.

For detail analysis of the results two extreme solutions and a more sustainable one from the set of nondominated optimal solutions are selected. These three scenarios have been intentionally selected from the set of identified non-dominated solution to highlight the consequences of employing open access strategy, safe yield option, and a 10-year groundwater retrieval option.

Solution number 1 (Fig. 4) presents the closest strategy to the business as usual case with open access to groundwater pumping. As a result of this strategy, the groundwater level is



**Fig. 5** Set of non-dominated optimal solutions (mean annual lost profit vs. mean annual pumping energy)

expected to drop to 1529.5 by the end of year 2018 with mean annual drop of 0.70 m. Under this strategy the groundwater extraction will be reduced by 25 MCM annually (reduced by less than 6%) with a slight loss in mean annual profit of one billion Iranian toman. The loss of profit is partially due to additional energy required to lift the groundwater from lower levels because of groundwater level drop.

By applying restrictions on groundwater pumping, the groundwater level would be recovered in the expense of loss of profit. As an extreme solution strategy (solution number 3) the groundwater may annually be recovered by 0.33 m, touching 1537masl by the end of 2018 (Fig. 4). This strategy will reduce the agricultural profit significantly. As presented, the mean annual loss of profit would be as high as 19.28 billion Iranian toman. Under this strategy annual reduction of 116 MCM in groundwater extraction is expected.

Solution number 2 highlights a strategy upon which the groundwater level may be stabilized at its present condition with relatively smaller loss of profit. This solution (Fig. 4) would result in approximately 12.23 billion Iranian toman reduction in mean annual profit with close to 85 MCM reduction in groundwater pumping. Under this strategy, the groundwater level would experience zero drop and stay stable at level of 1534.5. Very small fluctuation from one year to another is expected due to temporal variation of climatological and hydrological inputs. Similar solutions, leading to different strategies and consequences, may be derived from the set of nondominated optimal solutions presented in Fig. 4. It is worth to mention that relying on the past hydro-economic practice, the total annual loss of profit would exceed by an additional 2.5 billion Iranian toman.

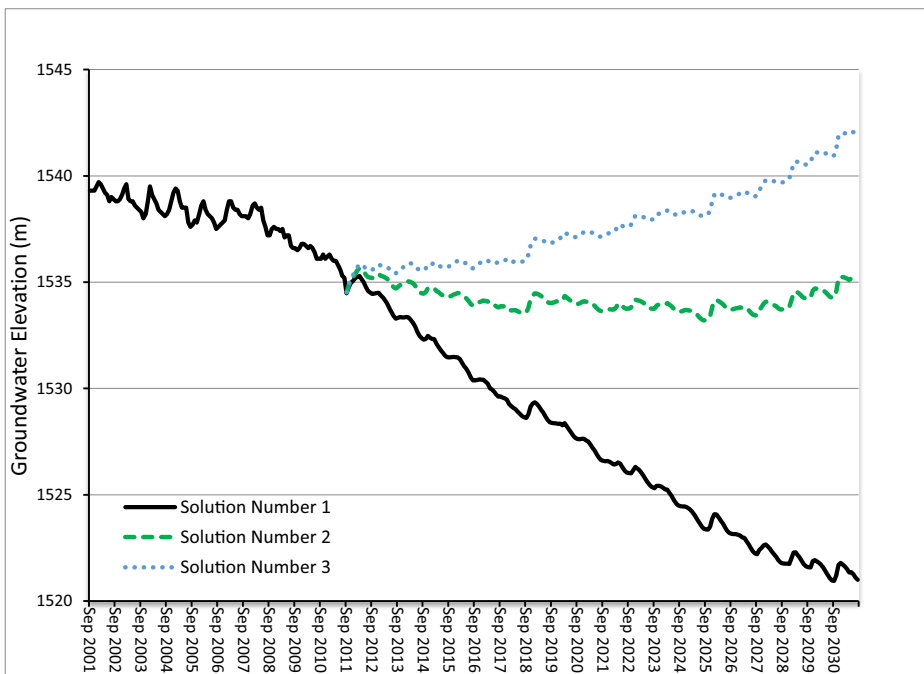
Figure 5 depicts the tradeoff between the mean annual loss of profit and mean annual required pumping energy. It clearly shows how the identified nondominated optimal solutions tradeoff between the mean annual losses of profit and mean annual required pumping energy. In specific, solution number 1, which is the closest solution to the business as usual, requires 31.5 thousand megawatt hours of energy each year. It is 18% more than the energy required under solution number 2 which tries to stabilize the groundwater level at its observed condition of 1534.5masl in 2011. It is therefore important to note how energy requirement varies as the

solution strategies change. For the extreme solution number 3, the required energy would drop by another 9%, compared to solution number 2. Observation of the results presented in Figs. 5 and 6 would help the decision makers to compromise between the loss of profit, groundwater level, and energy in a three- objective environment.

Optimum cropping patterns for the solutions number 1, 2, and 3 are presented in Table.1. As presented, minimization of lost profit under different strategies would call for different cropping pattern. Although some reduction in irrigated land on solution number 2 (for transitioning to groundwater sustainability) is recommended, the proposed optimal cropping pattern has not significantly deviated from the range of dominant cropping pattern in the past practice. The main reduction is observed in irrigated wheat for its relatively low profit per unit of applied water.

Recommended solution, which stabilizes the groundwater level at 1534.4 as observed in year 2011(solution number 2), would reduce the irrigated area by approximately 17% (Table 1). As presented, the reduction is mainly for wheat and barley, which shows smaller return per unit of applied water compared to other major crops. Besides wheat and barley, sugar beet receives some significant cut in hectare, which may be attributed to its high evapotranspiration and relatively smaller return per unit of water. The results show that for all three selected solutions, land area allocated to rice is at its lower bond of 200 ha, whereas those of wheat and barley show significant variations. Lower bound on allocated land for each crop is fixed due to local restrictions and imposed policies.

This article accounts for change in agricultural profit which includes reduction and/or increase in pumping cost. Change in long-term cost of energy and wells' maintenance and rehabilitation is disregarded. Assuming significant increase in energy cost and ever- increasing



**Fig. 6** Groundwater elevation under 3 scenarios: maximum groundwater extraction, sustainable groundwater and minimum groundwater extraction for the period of 2001–2030

**Table 1** Optimum land allocated to different crops (hectares) for the three selected solutions

Crops (hectares)	Wheat	Barley	Alfalfa	Rice	Corn	Sugar beet	Sun flower	Melon	Others	<b>Total (hectares)</b>
Maximum GW Extraction (No.1)	12,800	4900	1600	200	1800	3000	2600	1500	5800	<b>34,200</b>
Sustainable GW Extraction(No. 2)	9500	4100	1300	200	1500	2200	2300	1400	5600	<b>28,100</b>
Minimum GW Extraction (No.3)	9700	3000	1100	200	1300	1900	1600	1200	5300	<b>25,300</b>

groundwater level drop under the current condition (business as usual), the reduced pumping cost and refined land allocation by irrigating high-value and less-intensive crops during the dry years under solution number 2 will further compensate the lost profit. Therefore, one may challenge the previous analysis and claims that reveal little economic benefit to groundwater stabilization.

The second set of data is used to project the consequences of the identified strategies over longer periods into the future. As presented in Fig. 6, solution number 2 would efficiently stabilize the groundwater level in its original level of 1534.5masl for the next 12 years (till 2030). There are small fluctuations around the mean level of 1534.5amsl which are attributed to annual variation of hydrological condition. It is shown that continuing groundwater extraction with the former strategy (business as usual, solution number 1) would cause drastic drawdown in groundwater level (by almost 14 m) in 2030. In addition to significant increase in required energy, it may end up with server environmental damage to the region. Although the next extreme strategy (solution number 3) would retrieve groundwater level to that of 2001 (Fig. 2) by 2028, its economic and social cost to the farmers and government may not justify its implementation.

## 5 Conclusions

Although sustainability of groundwater is often addressed by multigenerational goals, implementation of some adaptive management and policy may help transitioning toward sustainability. From hydro-economic perspective, groundwater sustainability transitioning may be facilitated by groundwater level retrieval through employing combination of supply side and demand side measures. The demand side measures often focus on irrigation demand management where the farmers must be convinced to forego immediate economic benefits for uncertain collective economic benefits from groundwater sustainability.

This paper proposed and tested a methodology for transitioning towards groundwater sustainability through optimized cropping pattern, quantity and timing of groundwater pumping in an irrigated agriculture. It was observed that with the current practice (business as usual), the groundwater depletion rate may cause dramatic drop in groundwater level in near future with significant economic and environmental impacts.

For the case example in this study, resulted reduction in groundwater extraction caused some loss of profit to the farmers which was partially compensated through reduced cost of pumping energy. Implementation of a policy which imposes 20% reduction on annual groundwater extraction would approximately stabilize the groundwater level at the initial level

of 1534.5 as observed in 2011. Assuming no change in cost of energy, this strategy would cause 17% reduction in farmers' profit for which government subsidiary may be needed. The same strategy would reduce energy use for groundwater pumping by more than 19%, compared to the business as usual strategy. It was concluded that some fraction of lost benefit from reduced irrigated area could be compensated by shifting toward less- water incentive agriculture and high value crops as well as reduced cost of energy and well maintenance and rehabilitation. In addition to transitioning toward groundwater sustainability, the proposed strategy would offer another social value by saving more than 19% in use of energy, as a very valuable and restricting development resource, compared to the open access to groundwater strategy (business as usual).

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## Compliance with Ethical Standards

**Conflict of Interest** none.

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