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Systemic insights into agricultural groundwater management: case of Firuzabad Plain, Iran

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Abstract

Groundwater decline poses a significant sustainability challenge in arid and semi-arid areas where groundwater plays a major life sustaining role. Recent years have marked a drastic decrease in the groundwater table (about 1.1 m/yr equivalent to 19.3 million cubic metres) in the Firuzabad Plain, Iran, where policies to restore groundwater have mostly failed. A holistic view is required to manage the basin's water resources, taking into account key biophysical, socio-economic, and political aspects. This paper applies system dynamics simulation as an integrative approach for modeling the causal relationships that drive the long-term system trajectory. Results suggest that increasing groundwater withdrawal is creating limits to growth archetypal behavior. Groundwater stress affects the livelihood of agricultural communities by reducing profitability and resource depletion. Re-establishing regional groundwater balance within the next 30 years requires that irrigation efficiency be improved to reduce net consumptive water use while maintaining the current level of agricultural production.

Keywords: Groundwater resource management; Policy making; Sustainability; System dynamics modeling

1. Introduction

Water security is a critical concern around the world, threatening the livelihood of human communities and sustainability of ecosystems (Vörösmarty *et al.*, 2010). While water demand continues to grow due to rapid population growth and agricultural development in vast areas of the Middle Eastern countries, water supply is dwindling as a result of reduced snowpack and altered rainfall patterns and streamflow regimes coupled with increased evapotranspiration, making surface water resources systems less reliable (Dolatyar & Gray, 2016). On the other hand, reliance of agrarian communities on groundwater for irrigation can cause resource depletion due to negative balance in areas where groundwater withdrawal exceeds recharge. If this situation lasts for an extended period of time,

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emergence of severe water stress is inevitable. Characterizing the dynamic groundwater balance based on hydrologic fluxes and withdrawals is essential for sustainable water resources management, and effective policies.

System dynamics modeling (SDM) is an approach for simulation of complex systems in a flexible and transparent manner in order to facilitate understanding of the system's trajectory through time by capturing non-linear causality and information feedbacks among interlinked variables (Forrester, 1997; Sterman, 2000). Founded on control theory, the approach is widely used to test the outcome of alternative policy options, accounting for counterintuitive system behavior to uncover potential unintended consequences. Recent years have witnessed a proliferation of studies that apply SDM as a methodology to address dynamically complex water resources management problems, including watershed-scale lake water quality management in the Dianchi Lake basin in China (Liu *et al.*, 2015) and the Kalamazoo Watershed in the USA, and water utility management and financial planning in Ontario, Canada. Simonovic and Rajasekaram developed an integrated water resources management dynamic model for Canada. They simulated the model for 12 scenarios to investigate their impacts on fresh water availability, wastewater treatment, economic growth, population growth, energy generation and food production. The results showed a very strong dependence of Canada's future development on preserving acceptable quality of the water resources and controlling the level of water use in different sectors (Simonovic & Rajasekaram, 2004).

In his thesis in 2013, Mirchi presented a dynamics simulation to distinguish a number of proposed total maximum daily load (TMDL) reduction policies (Mirchi, 2013). It was proved that, for an effective TMDL plan, it should be considered a component of a continuous sustainability process, which considers the functionality of dynamic feedback relationships between socio-economic growth, land use change, and environmental conditions (Mirchi & Watkins, 2012; Rehan *et al.*, 2015), sustainable water resources management in Nevada (Stave, 2003) and Singapore (Xi & Poh, 2013), groundwater management conflicts in southern Italy (Giordano *et al.*, 2012), and policy analysis (Tidwell *et al.*, 2004; Beall *et al.*, 2011; Wei *et al.*, 2012). In Iran, SDM has been applied to investigate water resources development policies in the Zayandeh-Rud River basin and Lake Urmia basin by Gohari and his colleagues. They tried to estimate the reliability of inter-basin water transfer to meet the increasing water demand in the above-mentioned basin (Hassanzadeh *et al.*, 2012; Gohari *et al.*, 2013; Zarghami & Rahmani, 2015). Conjunctive use of groundwater and surface water resources has also been studied by Niazi *et al.* (2014).

In this study, SDM is applied to simulate groundwater management in the Firuzabad Plain, Iran. The model is developed to aid in better understanding the system structure (i.e., variables and their interrelationships) and processes governing the groundwater drawdown problem. Reviewing the literature implies the usefulness of the system dynamics tool in the field of water resource management. However, an agricultural plain like Firuzabad has its own characteristics that distinguish it from similar works. The government has tried various efforts to remediate the groundwater level for many years. The irrigation efficiency is low and the farmers need to know their role in managing water resources. Similar to many other regions in the developing world, the agricultural sector is the main source of household income in Fars Province, the third largest Iranian province. Inefficient use of valuable water resources is widespread in the Iranian agricultural sector due to lack of investment in modern irrigation systems, poor planning and management, and lack of appropriate education programs through agricultural extension services. Consequently, traditional methods of water distribution and irrigation coupled with production of water-intensive crops and dwindling water supplies due to climate change have triggered significant water stress in agricultural areas of Iran during recent decades. Production decisions are typically made based on short-term profit outlook and market conditions, whereas long-term benefits and costs based on water availability and its economic value are often overlooked. This paper contributes to water resources SDM literature by explicitly incorporating benefits and costs of agricultural production in the simulation of policy interventions for reducing groundwater overdraft, which threatens the sustainability of agricultural production.

2. Method

The following general steps have been recommended for the SDM process: (1) problem articulation (boundary selection); (2) formulation of a dynamic hypothesis which is a working theory of how the problem arose; (3) development of a simulation model; (4) model verification and sensitivity analysis; and (5) policy design and evaluation (Sterman, 2000). These steps are explained below after a brief description of the study site.

2.1. Study area

Located in a semi-arid region of the Middle East, Iran is surrounded by the Caspian Sea from the north and the Persian Gulf from the south. The country is characterized by hydroclimatic heterogeneity and a small average annual precipitation of about 250 mm/yr, which is lower than one-third of the global average. Spatial distribution of precipitation is very uneven, i.e., 70% of the country receives less than 30% of the total precipitation. With more than 60% arid lands and 20% semi-arid regions, Iran falls into the category of water scarce countries where fresh water per capita is less than 25% of the world's average (Rockström *et al.*, 1999). The country has been suffering from prolonged droughts, inefficient agriculture, mismanagement of water resources, and a thirst for population growth and development (Madani, 2014). Droughts have particularly harmed the agriculture sector, water accessibility in urban areas, and natural ecosystems.

The Firuzabad Plain (Figure 1) is one of 180 active agricultural plains, recommended by the Fars Regional Water Authority as a suitable case study for integrated water resources modeling (Definition of Business Studies, 2015). Furthermore, availability of input data and technical studies by the government made this agricultural plain a suitable candidate for modeling. Situated between 28°40′ N, 28°58′ N latitude and 52°17′, 52°46′ E longitude, the plain is underlain by an 88 km^2 aquifer in southwestern Fars Province (Majid, 2014). Average humidity in this semi-arid region with mild winters (average temperature 9 °C) and hot summers (average temperature 30 °C) ranges from 27% in spring to a maximum of 64% in winter. Mean annual precipitation is 400 mm, with most rainfall occurring between December and February. In 2010, the region had a population of approximately 65,000 people, 90% of whom were engaged in agricultural business. The total amount of agricultural land is about 12,500 ha, most of which is a mix of wheat fields and citrus plantations, accounting for almost 97% of agricultural water use. Crop production mainly relies on groundwater resources for irrigation (e.g., approximately 83%), making agriculture a major driver of groundwater stress in the province (Rasouli *et al.*, 2012). The remaining irrigation demand is met by withdrawing water from the Firuzabad River.

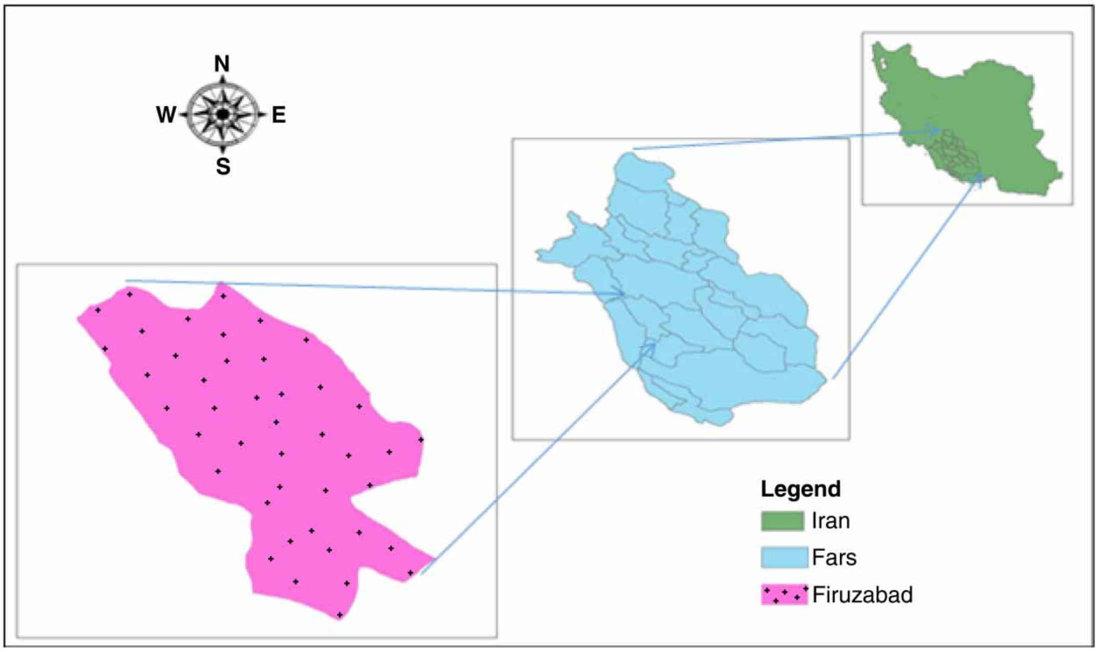

Fig. 1. The Firuzabad Plain.

2.2. Problem articulation and dynamic hypothesis

Within the last two decades, a significant fall in the groundwater level of the Firuzabad aquifer has been recorded, alerting the community of farmers and regional managers. Operating costs are increasing because of drying wells, springs and qanats (an ancient groundwater withdrawal method using a series of vertical shafts taping into a mildly sloping gallery), and declining water quality and groundwater level in wells. The groundwater decline problem was investigated as the main regional challenge (Figure 2).

Due to government policies for agricultural self-sufficiency in the late 1990s, farmers were allowed to increase the number of wells to boost agricultural production (Figure 3). Thus, groundwater withdrawal for irrigation gradually exceeded natural aquifer recharge, causing a significant groundwater table decline. Severe groundwater table drawdown, changed the river-aquifer interaction, whereby the Firuzabad River turned into a losing stream that recharged the aquifer instead of being fed by influx of groundwater. Subsequently, the regional water management authority started imposing drastic policies to restrict groundwater withdrawal. However, restrictive policies were not received well by agricultural producers due to adverse impacts on production, in turn, hurting the economic condition of the agrarian communities. Consequently, conservation-oriented water management policies were not pursued rigorously to avoid further backlash from farmers.

Input data to investigate the dynamic hypothesis were gathered from a variety of sources such as available literature and published government reports, as well as expert interviews. The main types of data include information on groundwater recharge from adjacent karst aquifers, groundwater recharge from precipitation, groundwater withdrawal, groundwater recharge from riverbed, groundwater discharge to the river, groundwater recharge return flows, and groundwater level, all available for the period 1992–2008 (displayed in Table 1) from the Fars Regional Water Organization Database

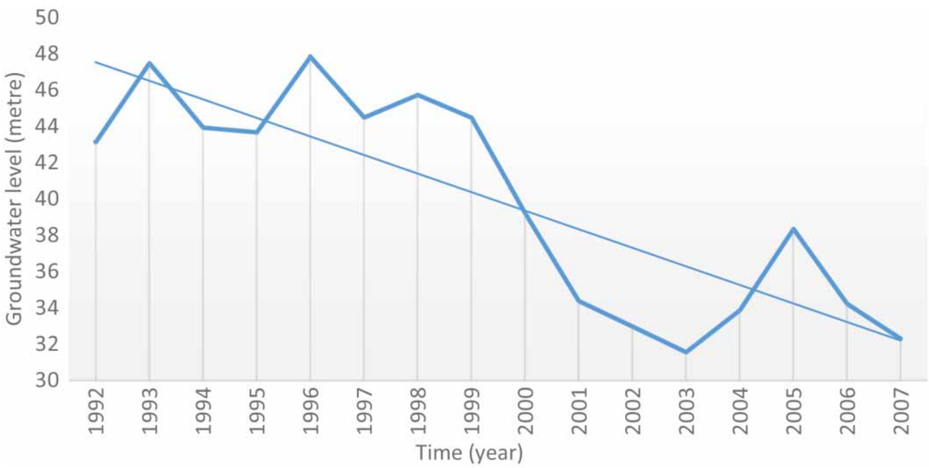

Fig. 2. Groundwater table decline over time.

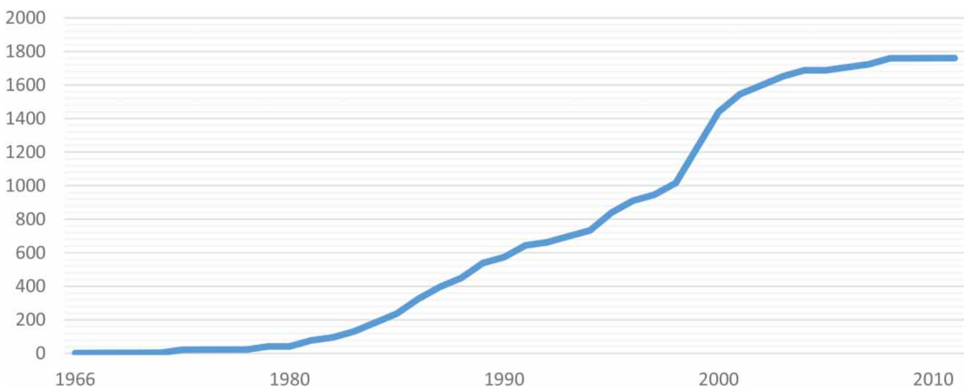

Fig. 3. Number of wells in the Firuzabad Plain.

(Definition of Business Studies, 2015). Other data, such as area of land under cultivation, population and annual population growth rate, price of crops, drinking water use in agriculture and industry, and production cost, were all acquired mainly from previous studies (Majid, 2014; Keshavarz, 2015).

2.3. Simulation model

The simulation model was developed based on the causal loop diagram (CLD) and stock-and-flow diagrams (SFD) of the system components.

2.3.1. Causal loop diagram. A conceptual model (McClain *et al*., 2005) and CLD of the problem are shown in Figures 4 and 5, respectively. The aquifer can be conceptualized as a three-dimensional box in which the water volume varies over time (Figure 4). It receives water from precipitation, inflow from adjacent aquifers, recharge from riverbed, and recharge from return flow, which is the non-consumptive portion of the withdrawn groundwater. It loses water to consumptive uses, evapotranspiration, outflow to the adjacent aquifers, withdrawal by pumpage and discharge to riverbed.

Table 1. Groundwater balance components for water years (1992–2008) (Definition of Business Studies, 2015).

Water year	Precipitation (mm)	Groundwater recharge (MCM[a])				Groundwater discharge (MCM)	
		Precipitation	Adjacent karst aquifer	Riverbed	Return flow[b]	River	Withdrawal
1992–1993	855	85.9	83.7	0	53.4	44.6	110.3
1993–1994	243	0.0	31.4	0	44.2	37.7	96.3
1994–1995	651	26.0	46.5	0	49.4	20.6	121.1
1995–1996	889	85.3	93.9	0	59.0	44.6	130.0
1996–1997	363	8.6	41.1	0	48.3	47.1	114.4
1997–1998	763	64.4	79.8	0	55.7	46.5	140.3
1998–1999	452	25.0	49.9	0	50.4	36.8	116.1
1999–2000	276	3.6	26.9	5.2[c]	59.4	13.1	174.8
2000–2001	303	0.6	19.0	2.6	55.5	0	179.4
2001–2002	509	27.0	26.8	3.8	54.6	0	160.3
2002–2003	420	14.4	24.6	2.9	49.8	0	147.6
2003–2004	601	30.6	47.7	10.5	62.2	0	147.6
2004–2005	849	80.1	88.0	50.4	62.6	0	188.6
2005–2006	403	8.1	49.3	10.3	55.6	0	188.6
2006–2007	444	26.3	31.9	7.4	45.9	0	166.8
2007–2008	253	5.8	20.4	4.4	37.7	0	130.0

[a]MCM: million cubic metres.
[b]Total return flow from irrigation, and domestic and industrial uses.
[c]In year 2000, Firuzabad River turned into a losing stream due to significant groundwater table decline.

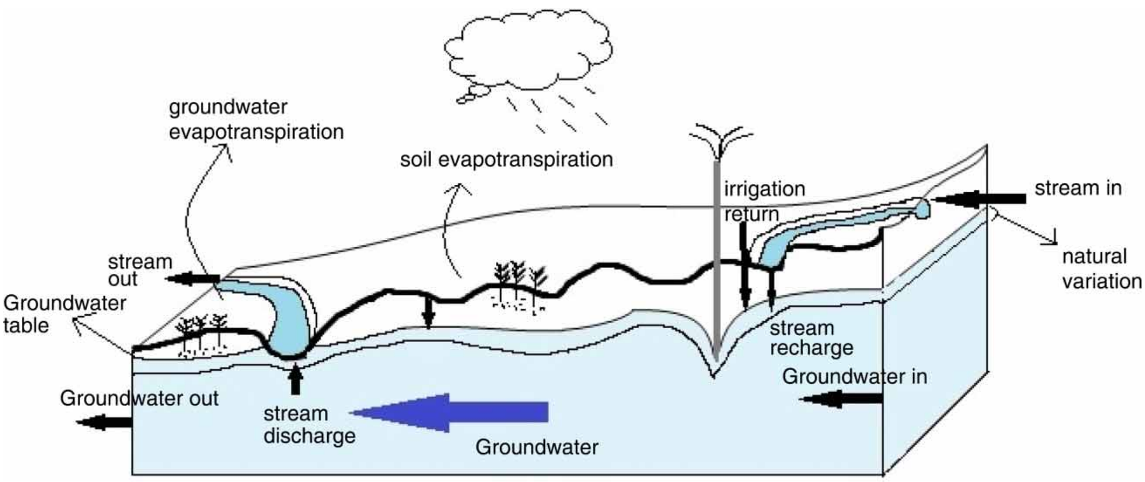

Fig. 4. The conceptual model.

The CLD of the groundwater decline problem in the Firuzabad Plain includes hydrogeological and socio-economic subsystems (Figure 5). It illustrates the relations between key components and feedback mechanisms of the system including six balancing and four reinforcing loops. Two balancing feedback loops (B1 and B2) represent the interactions between groundwater volume (storage) and outflows: the

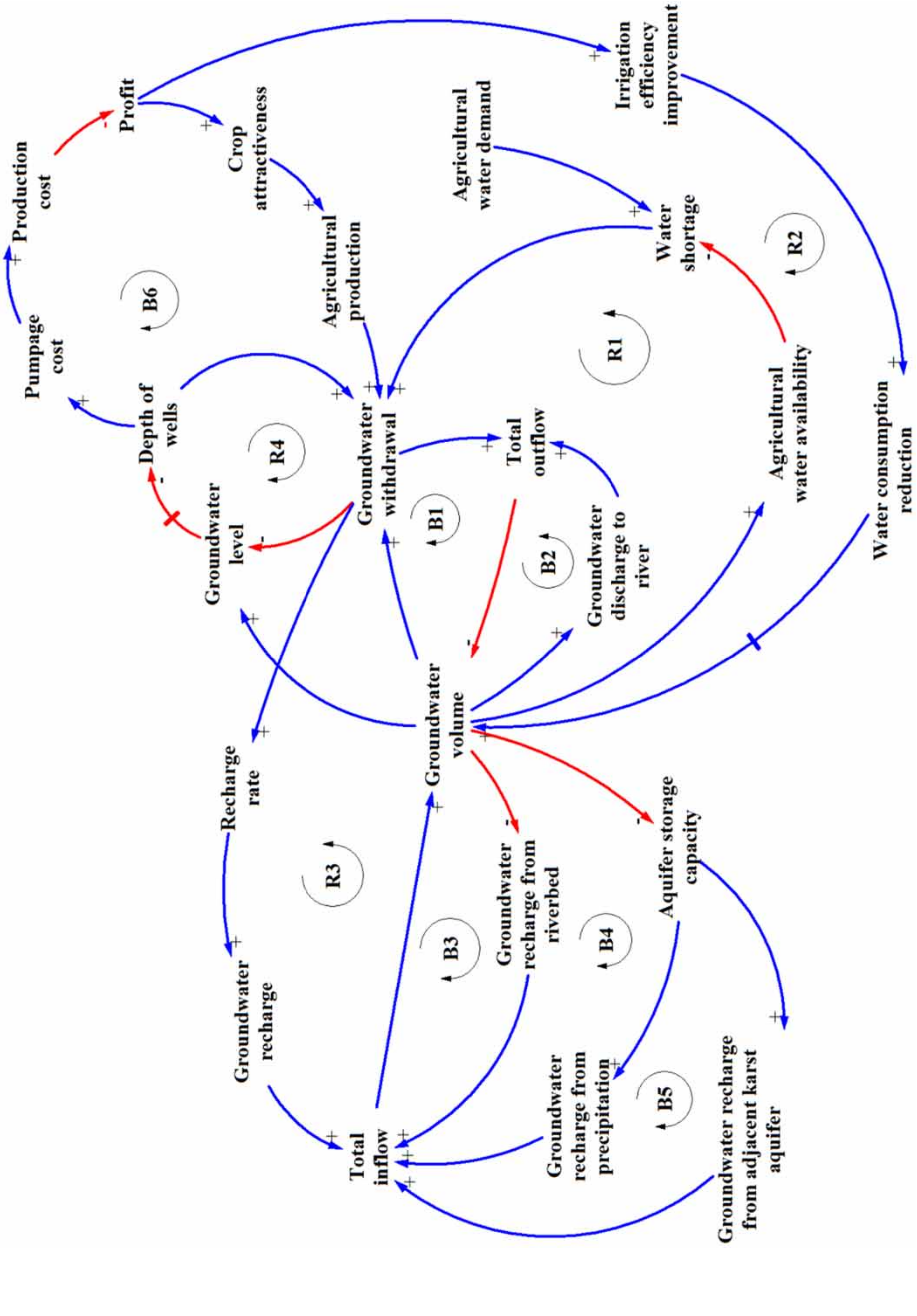

Fig. 5. The CLD, causal loop diagram.

larger the groundwater volume, the larger total outflows, which in turn decreases groundwater volume (balancing effect). Three additional balancing feedback loops (B3, B4 and B5) capture the biophysical interaction between groundwater and inflows: the larger the groundwater volume, the smaller total inflows, reducing groundwater volume. The final balancing feedback loop (B6) represents the relationship between groundwater volume and farmers' profit: the larger the groundwater volume, the smaller the pumping cost, increasing the farmers' profit, which, in turn, encourages agricultural development, and ultimately reduces the groundwater volume (balancing feedback).

The first reinforcing feedback loop (R1) illustrates the causal relationship between groundwater volume and water shortage: small groundwater volume means small water availability for agriculture (larger shortage), which increases groundwater withdrawal and causes groundwater storage to shrink because of the larger total outflow. The second reinforcing loop (R2) shows the relation of groundwater volume to investment in increasing agricultural efficiency, a process that involves delay: the larger the groundwater volume, the more profitable the agricultural production, which can enable farmers to improve agricultural water use efficiency and increase water saving, which, over time, helps increase groundwater volume. The third reinforcing loop (R3) captures the interactions between groundwater volume and groundwater recharge. The fourth reinforcing feedback loop (R4) visualizes relations between groundwater table drawdown and the need for deeper wells that mine groundwater and cause overdraft.

2.3.2. Stock-and-flow model. A quantitative stock-and-flow model based on the conceptual model and CLD of the system, facilitates the investigation of system behavior over time, which is essential for policy evaluation. The model consists of four key segments, the groundwater model, the water supply model, the population model, and the economic model. The simulation horizon is 55 years (starting from 1992), and contains the critical period (i.e., 2007) when groundwater began to decline. The model is run at an annual time step.

The groundwater model (Figure 6) includes a single stock to simulate the volume of water in the aquifer at each time step using the mass balance equation (Equation (1)). It uses time series data sets for multiple input variables (e.g., *GRAK*, *GRP*, *GRR*, and *GRF*) to output *groundwater discharge to the river (GDR)* and *groundwater withdrawal (GDP)*. Referring to Figure 7, the inflows and outflows, are calculated based on historical hydrologic data imported through the 'get Excel' data function in VENSIM.

$$GV(t) = GV(t-1) + GRAK(t) + GRP(t) + GRR(t) + GRF(t) - GDR(t) - GDP(t) \tag{1}$$

where GV: groundwater volume; GRAK: groundwater recharge from adjacent karst aquifer; GRP: groundwater recharge from precipitation, function of annual precipitation rate; GRR: groundwater recharge from riverbed; GRF: groundwater recharge by return flows; GDR: groundwater discharge to river; GDP: groundwater discharge due to pumping; and t: time index.

The water supply model is developed based on demand and supply theory. On the demand side, agriculture, industry and drinking water use sectors determine the total demand for water. Supply is the amount of water needed to be withdrawn from the aquifer (Figure 8).

$$WS(t) = WS(t-1) + GDP(t) - AWU(t) - DWU(t) - IWU(t) \tag{2}$$

where WS: water supply; AWU: agricultural water use; DWU: drinking water use; and IWU: industrial water use.

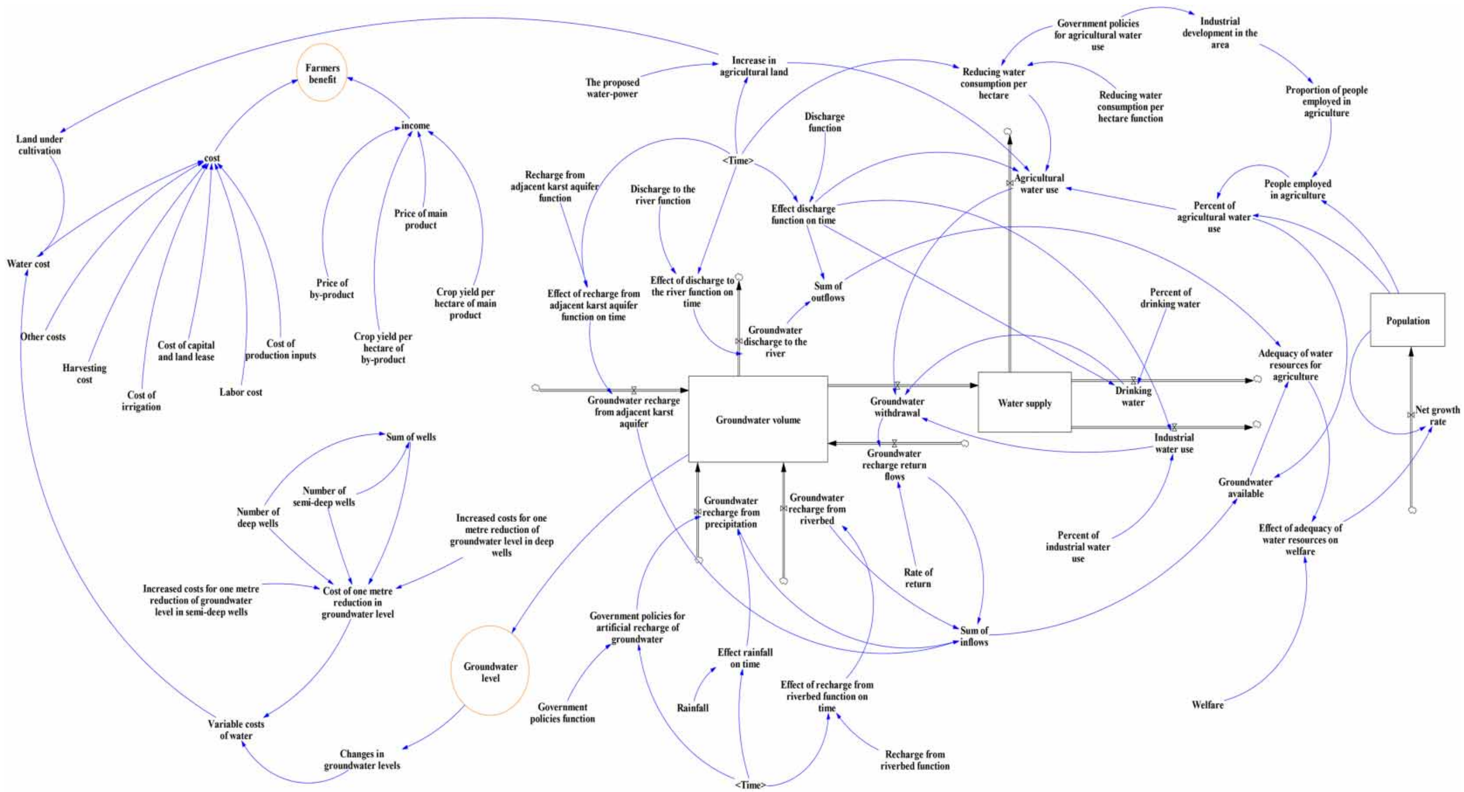

Fig. 6. The SFD, stock-and-flow diagram.

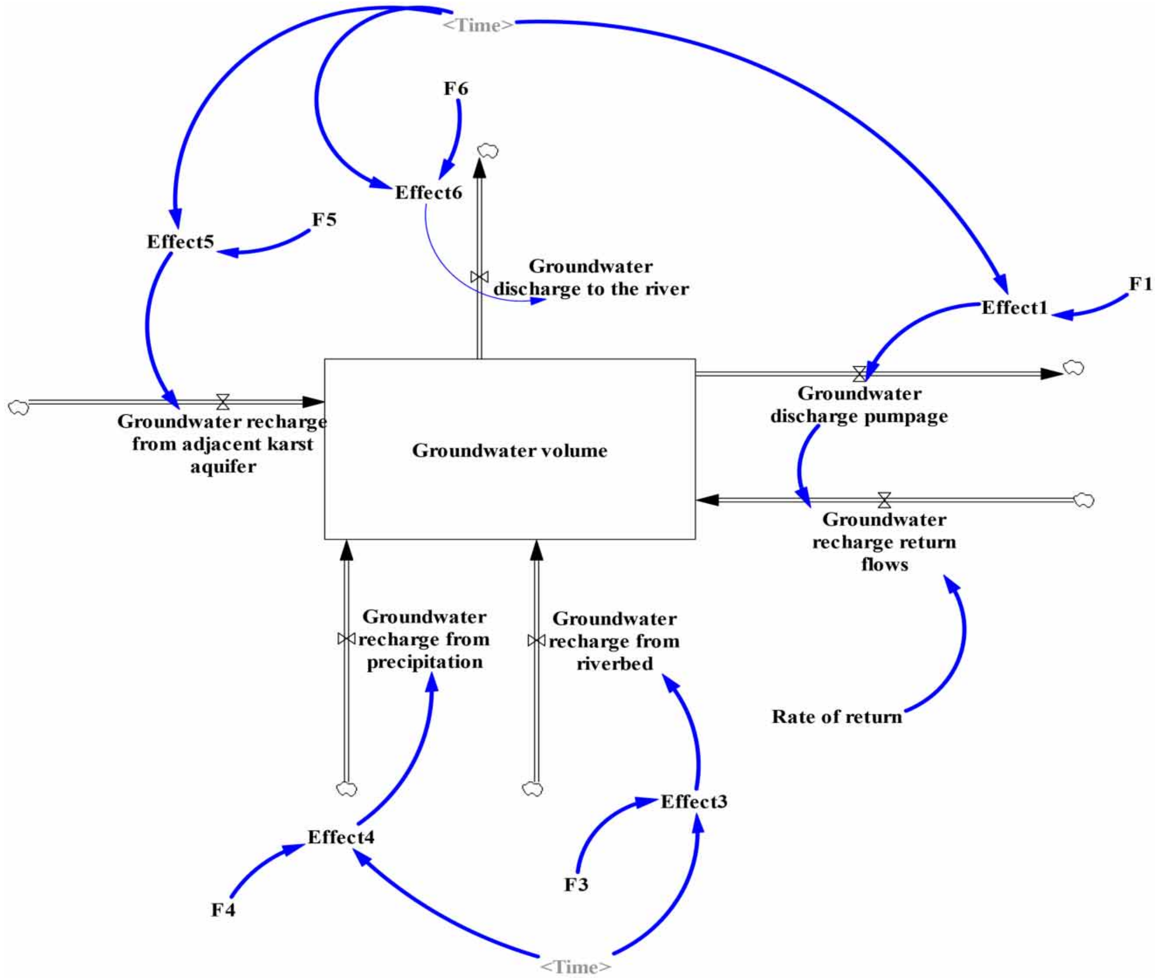

Fig. 7. Groundwater volume, inflow and outflow.

The population model is based on a primary population structure (Figure 9). Furthermore, the economic model is developed based on the basic profit function, i.e., the difference between income and production costs (Figure 10).

2.4. Verification and sensitivity analysis

A series of qualitative and quantitative tests were conducted to verify the model. Qualitative tests include system unit consistency test and system structure test. The unit consistency test is automatically completed by Vensim PLE. For the system structure test, the model structure was qualitatively evaluated to ensure it represents the real system reasonably well and model equations do not violate the laws of physics. The quantitative verification tests were conducted by analyzing the model's ability to reproduce observed system behavior (e.g., groundwater level). Simulated groundwater levels for the baseline period (1992–2007) closely track observational data, capturing inter-annual variability and overall pattern of groundwater

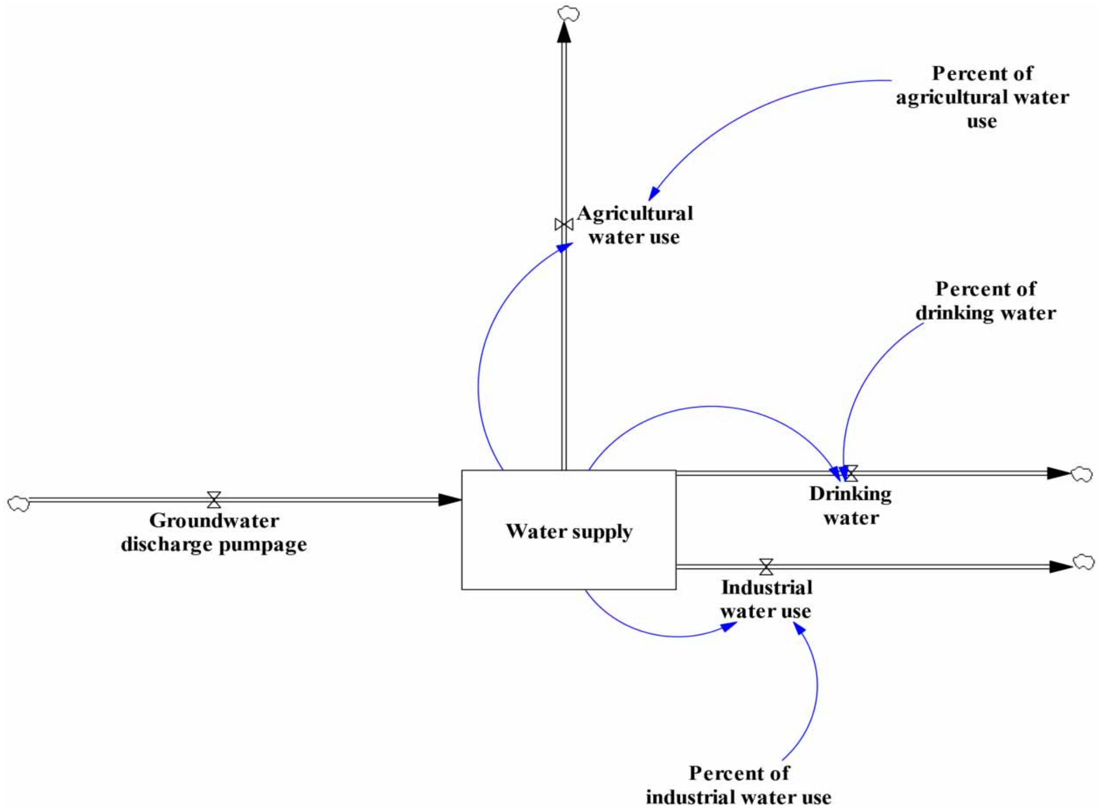

Fig. 8. Water supply subsystem.

table decline (Figure 11). Small values of absolute relative error and mean absolute relative error, two widely-used evaluation indices, further confirm reasonable model performance (Figure 12).

Model sensitivity analysis was conducted to identify key drivers of system changes. Long-term behavior of groundwater level was tested as the target variable by running the model under extreme and average values of each model variable. It is observed that groundwater withdrawal has the highest influence on groundwater level, 5.91 metres in this case. The results imply that the greatest impact on groundwater level is caused by groundwater withdrawal (Figure 13), which is the main policy lever for mitigating drastic groundwater table drawdown. Likewise, the model is highly sensitive to groundwater recharge from precipitation in terms of extreme and average value. While, this variable is primarily governed by natural biophysical parameters, it can be used as an important component of a mitigation policy using rainwater capture.

3. Policy evaluation

The model is run under four groundwater decline mitigation policy scenarios for the Firuzabad Plain. Table 2 provides a brief description and the main variables of each policy scenario. Essentially, the basic variables of each scenario are adjusted in the model to simulate the long-term effect of the

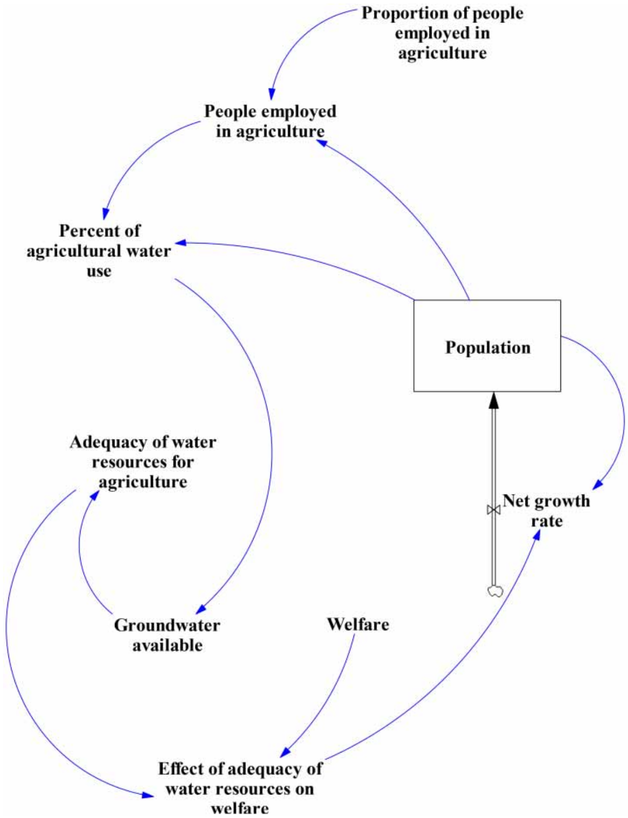

Fig. 9. Population subsystem.

corresponding policy. The business as usual scenario (scenario 1) presumes that national and regional water authorities do not intervene to mitigate the problem. The second scenario focuses on irrigation efficiency improvement, which can be realized by supporting farmers to modernize the agricultural practices, using efficient irrigation systems and advanced farming equipment to reduce net consumptive use of water.

Irrigation cost may increase the total cost of production leading to a reduction in benefit to the farmer. This is shown in Figure 10, the economic subsystem. The policy of improvement in irrigation has been recently introduced by the central government. Referring to this supportive package, the farmers will only pay 15% of the total investment required for an efficiency project and the rest will be supplied by funds from the local government. Some local studies have shown an increase in efficiency of 1 percent as mentioned in this paper, 25 USD is required per hectare of cultivated land while based on this policy, the farmer needs to contribute less than 4 USD in this plan. Considering his 625 USD of profit in each hectare, this cost cannot have a significant impact. Needless to say, in the current modeling, the farmers are not the decision makers who need to invest for the recommended policies. However, the improvement (1 percent annually) is also considered smooth and doable within 30 years to reach the maximum level of efficiency, estimated as 70%. If the current policy incurs 100% of the cost of improvement to the farmers, the behavior of farmers' economic benefit has been regenerated under the specified scenarios which indicate that the only way to reduce it is under the no-action scenario

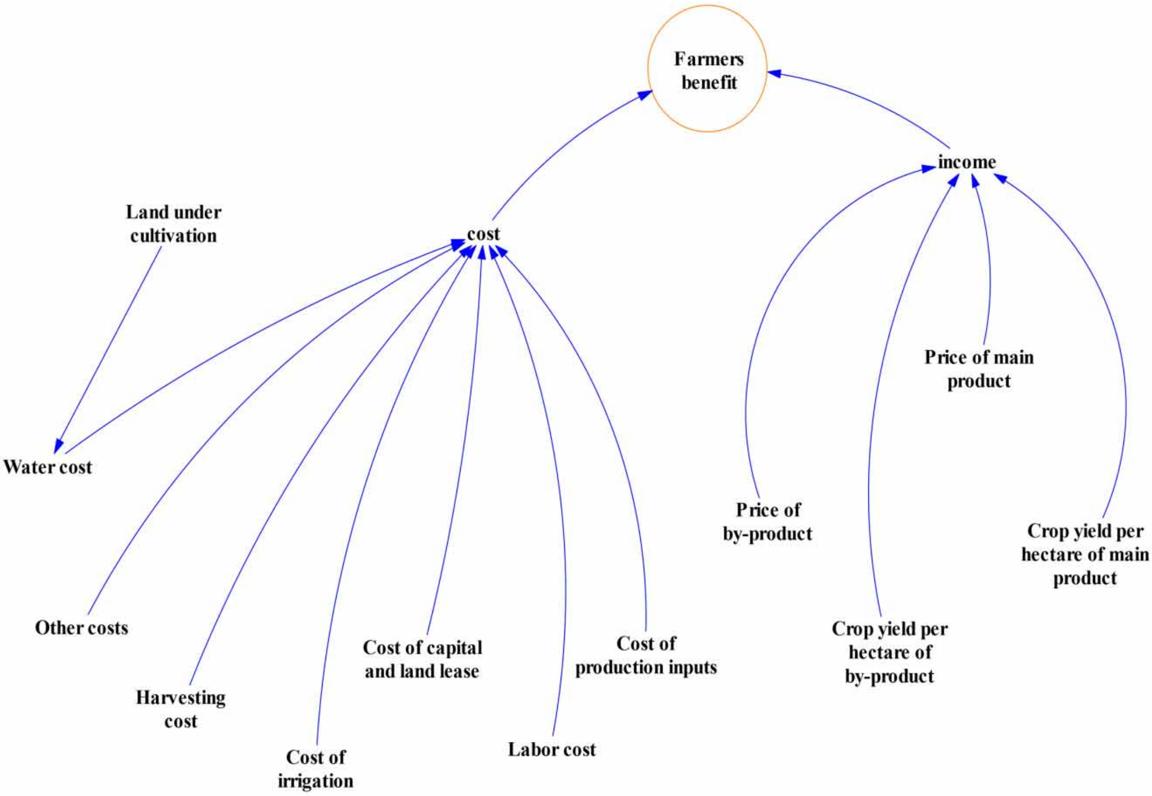

Fig. 10. Economic subsystem.

and the profit will be sustained in almost any condition. This is mainly due to the low cost of irrigation improvement.

Furthermore, financial incentives for cultivation of less water-intensive crops and providing agricultural extension services to train the farmers in order to raise their awareness of water scarcity are suitable measures for scenario 2. The third policy scenario was recently proposed by a consulting firm (Majid, 2014) to expand the agricultural lands by 0.5% per year while increasing the agricultural water use efficiency. The fourth mitigation scenario is the result of discussions with water experts in the region, which includes a combination of scenarios 2 and 3 along with an aquifer recharge and storage recovery policy, primarily through increased rainwater capture.

The results indicate that groundwater table recovery would require reducing water consumption per hectare of cultivated land by 1% (scenario 2) (Figure 14).

The groundwater management problem in the Firuzabad Plain is essentially governed by the limits to the growth system archetype (Meadows *et al.*, 1972) which states the continuous growth of any system that thrives on finite resource supplies will eventually be curbed because of facing resource constraints. As shown in Figure 14, continuation of the BAU scenario will cause excessive decline (on average about a metre per year) in the groundwater level which also significantly decreases the farmers' profit. In the long run, this trend can create a regional economic crisis in the agricultural sector, potentially triggering out-migration due to adverse impacts on the livelihood of the agricultural community.

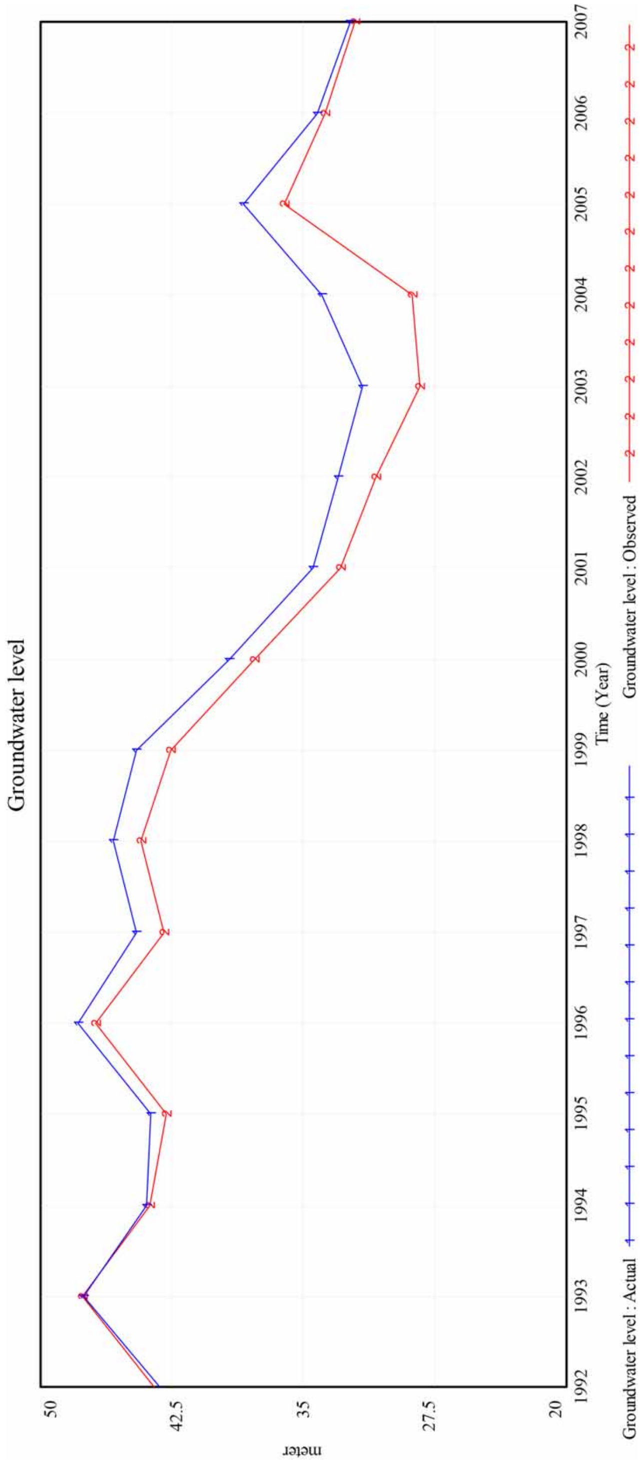

Fig. 11. Simulated and observed groundwater levels.

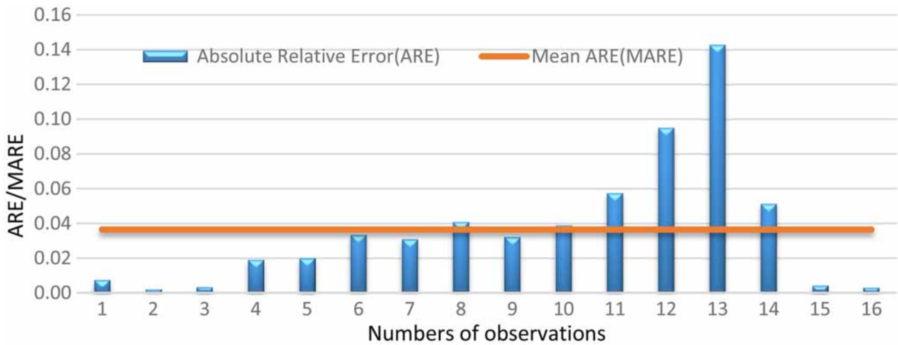

Fig. 12. Absolute relative error (ARE) and mean absolute relative error (MARE).

Tackling the problem is critically important to sustain agriculture as a way of life, which has been practiced for generations. Mid-century projection of groundwater level under the BAU scenario illustrates the effect of hydrologic variability. Overall, this policy will result in unsustainable agricultural production made possible by mining of fossil groundwater, which will not be replenished at the rate that can support the current level of irrigation. The second scenario outperforms the other scenarios in terms of groundwater table recovery and sustaining the profitability for land owners. In effect, reducing net consumptive water use by increasing irrigation efficiency can significantly decrease the groundwater table drawdown, helping to adjust withdrawal with natural supply capacity while maintaining profitability of agricultural production in the long run. However, this policy should be complemented by appropriate land management policies to ensure water savings are not used to increase crop production by expanding cultivated lands. The impact of the absence of supplemental land management policies is captured by running the model under policy scenario 3. While this policy (EILI) can delay the acute resource depletion problem, its effectiveness is limited as compared with policy scenario 2 (EI).

The fourth scenario (EILIGR), which includes groundwater recharge by increasing infiltration, is found to be superior to BAU and EILI scenarios. Although the effect of agricultural expansion can cause the system to underperform as compared with scenario 2, EILIGR holds promise to mitigate the groundwater problem while maintaining a steady profit for the farmers, which is significantly larger than that of the BAU scenario (Figure 15).

4. Conclusions

A system dynamics model is developed to investigate the hydrologic and socio-economic aspects of groundwater balance in an Iranian agricultural plain. The presented CLD, SFD, and the simulation results provide insight into Firuzabad groundwater management problem, where increasing groundwater withdrawal from a growing number of wells is pushing the system toward its limit in terms of water resources availability. Consequently, significant groundwater table drawdown poses a serious threat to sustainability of agricultural production, a major source of income for agrarian communities in the region. The results of the business as usual policy scenario illustrate that the past and current government policies have not been effective to maintain the regional balance of groundwater. The model

Fig. 13. Sensitivity analysis results.

Table 2. Policy scenarios.

Scenario	Description	Main model variable(s)
Scenario 1 (BAU)	Business as usual	Current trends continue
Scenario 2 (EI)	Efficiency increase: reduction in water consumption per square metre of land under cultivation by 1% per year for 30 years	Reducing water consumption per hectare – Agricultural water use – Groundwater volume – Groundwater level
Scenario 3 (EILI)	Efficiency increase and agricultural land increase: policy scenario 2 and 0.5% annual increase in areas under cultivation (from 12.5 to 18.5 thousand hectares)	Reducing water consumption per hectare – Agricultural water use – Groundwater volume – Groundwater level – Increase in agricultural land
Scenario 4 (EILIGR)	Efficiency increase, agricultural land increase, and rainwater capture: policy scenario 3 along with increased groundwater recharge by increasing the infiltration of precipitation by 10%	Reducing water consumption per hectare – Agricultural water use – Groundwater volume – Groundwater level – Increase in agricultural land – Government policies for artificial groundwater recharge – Groundwater recharge from precipitation

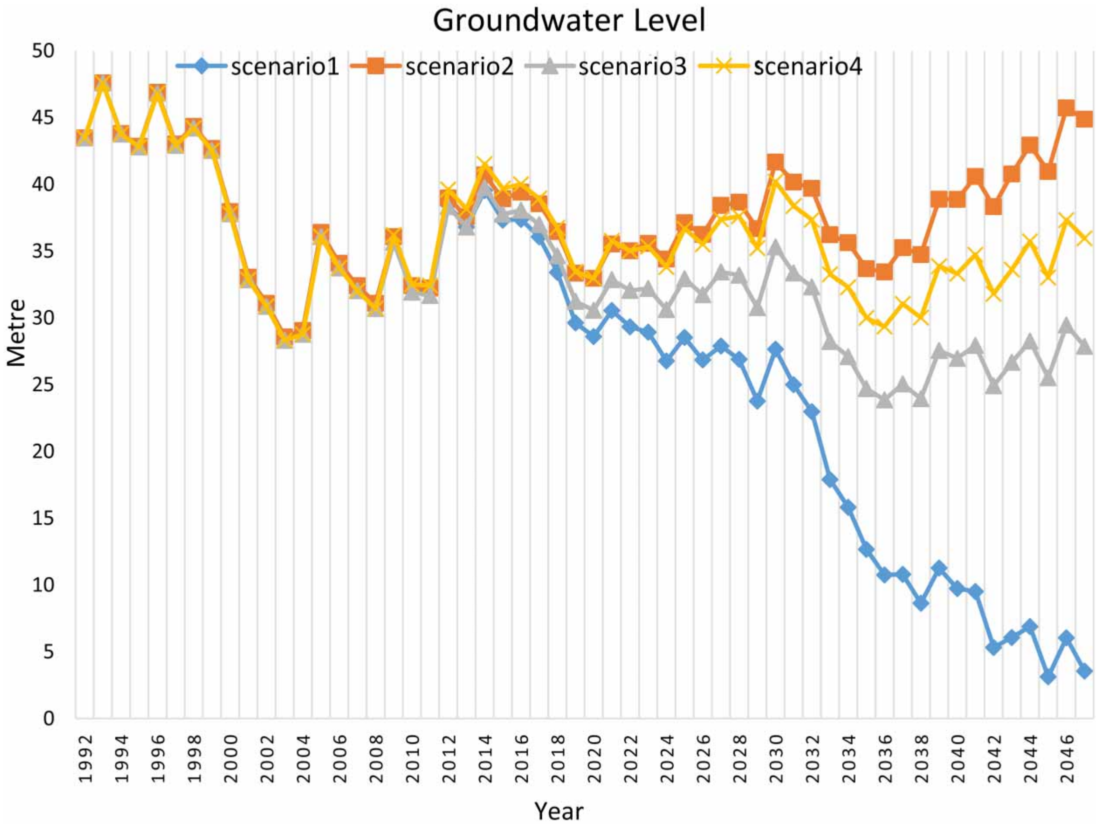

Fig. 14. Groundwater level, different scenarios.

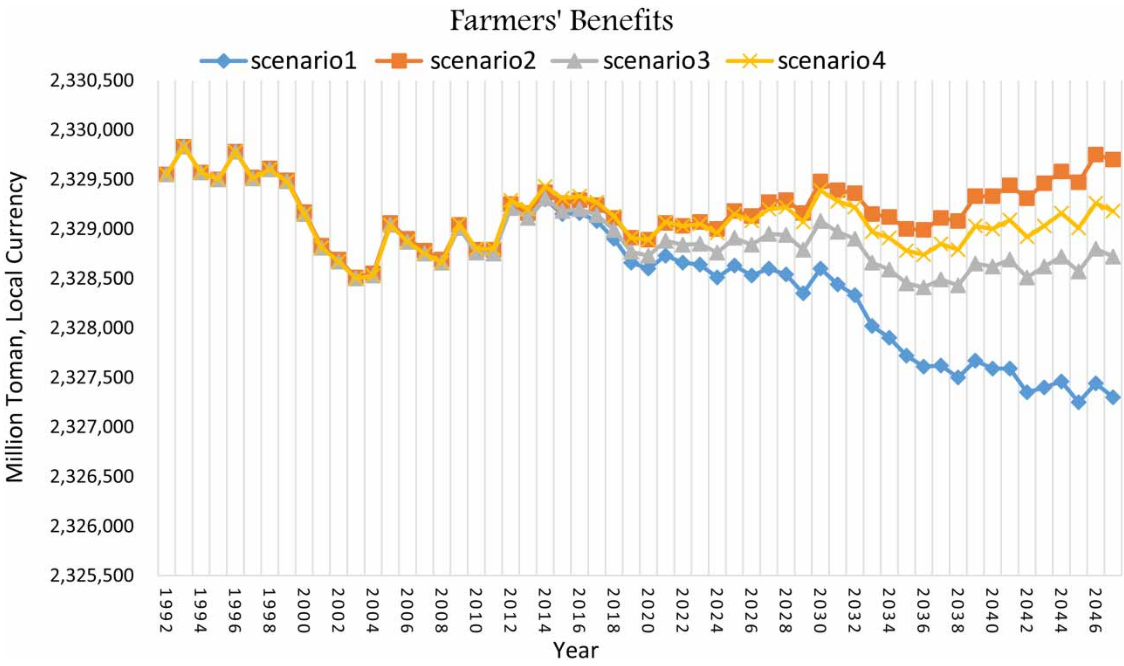

Fig. 15. Behavior of farmers' benefits under different scenarios and under the policy of full payment by farmers.

was also run under other groundwater decline mitigation policies, including irrigation efficiency improvement, and a combination of agricultural expansion and groundwater recharge. If the current level of agricultural production holds into the future, increasing the irrigation efficiency to reduce net consumptive water use by 1% per hectare per year can help re-establish the groundwater balance within the next 30 years. However, this mitigation policy requires government intervention to modernize irrigation and farming practices, and raise awareness in farming communities about the importance of groundwater table restoration to sustain agricultural production as a sustainable way of life. Recently, the government has started to encourage the agricultural sector to install drip irrigation which has higher efficiency than the traditional methods. Based on this plan, 15% of the investment needs to be financed by the farmers which is absolutely not remarkable when compared to the calculated benefit from the products. Even if it is fully financed by the farmers, the benefit will remain feasible though there is a decrease due to irrigation cost that is connected to production cost in the model. It is important to devise incentive-based programs and punitive actions to facilitate aquifer storage recovery. Furthermore, agricultural extension services and non-governmental organizations can play a significant role by training the farming communities.

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