



Assessment of water productivity improvement strategies using system dynamics approach

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Abstract

This study utilizes a system dynamics approach (SD) to assess the effects of water productivity improvement strategies on the Qazvin plain, Iran, and the uncertainty of the individual and interactive effects. The key indicators included in the important strategies are cropping pattern scenarios (CPS), deficit irrigation (DI), and modern irrigation systems development (MISD). Plain-scale results show that CPS 7, CPS 4, and CPS 8 had the highest physical water productivity (WP_p) at 2.11, 1.99, and 1.95 kg/m³, respectively, representing a 21, 14, and 12 percent increase over CPS 1. Compared with CPS 1, CPS 4, CPS 6, and CPS 8 showed the highest values of WP_e (5678, 5568, and 5503 Rials/m³, respectively). At the field scale, under DI, WP_p increased for all crops (except corn, which was the most sensitive), but WP_e is only increased for tomato, canola, pea, and barley and reduced for corn, potato, beans, lentils, and sugar beet. The WP_e was affected by the DI, the irrigation system type, and the CPS. CPS 7 and CPS 6 had the highest and lowest water requirements, respectively, with 11,699 and 8207 m³/ha. Volume decline in aquifers is significantly affected by both CPS and DI. The CPS6, CPS8, and CPS2 were better than other scenarios. By modifying the cropping pattern, it is possible to prevent aquifer decline, thus improving the aquifer status (CPS5). MISD increased both field and plain WP_p for all crops. The MISD improved groundwater resources and reduced demand by increasing efficiency to improve aquifer condition.

Keywords Irrigation scheduling · Virtual water · Modern irrigation system · System dynamics · Water productivity

Introduction

Drought and water shortages are climatic realities. As the population grows and the demand for water increases, this problem will become even more acute (Okello et al. 2015; United Nations 2015; Pirmoradian 2020). Approximately 92% of Iran's water budget is consumed by the agriculture sector, which is the largest consumer of the nation's water. Yet, it accounts for only 18% of the nation's Gross Domestic Product (GDP) and is considered one of the most sensitive resources for human societies (Saatsaz 2019). Due to the scarcity of water resources in the world, it is vital to pay

attention to agriculture and water productivity (FAO 2016). For sustainable agriculture and food security, increasing water productivity (WP) is one of the best strategies for coping with water scarcity and improving water management (Descheemaeker et al. 2013). It is possible to easily meet the water consumption requirements of other sectors, such as drinking and industry, by increasing WP in agriculture and allocating water savings in this sector (Richter et al. 2017). The development of modern irrigation systems, the switch to modern irrigation systems, optimize cropping patterns, the use of deficit irrigation (Shammout et al. 2018; Ahmadpour 2022), and the improvement of irrigation transmission efficiency have all been adopted as methods of improving WP in agriculture. It has been proposed to optimize cropping patterns (Elnmer et al. 2015; Ramezani Etedali et al. 2019) and improve the efficiency of irrigation networks. By improving WP in irrigation and drainage networks, there can be a significant reduction in the pressure on the government's limited water resources, as well as an increase in the incomes of farmers, the assurance of food security, and the welfare of the community. In order to improve WP, field

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experiments and studies have been used to study and analyze different water management techniques (Fghire et al. 2015). However, although these experiments are highly valuable, they have significant limitations. The main limitations of these experiments may be the high cost and time requirements, the regional validity of the study, and the limited number of scenarios that can be examined through field trials. Furthermore, field studies are subject to errors due to the inherent complexity of the water, soil, and plant systems. Consequently, computer models have been developed in this field in a number of ways. A powerful method for analyzing the status of systems is system dynamics (SD), one of the most effective methods for researching social and economic issues. SD is a modeling and simulation technique that is particularly suitable for long-term, chronic, and dynamic management issues. As a result of this approach, it is important to understand how physical processes, information flows, and management policies interact and how these factors influence the dynamics of the variables (Vlachos et al. 2007). The SD approach has been applied to a variety of agriculture and natural resource problems, including agriculture, land and soil resources, hydrology and water resources, and food systems (Turner et al. 2016). Hydrology and water resource management problems associated with local weather features are inherently complex, which makes them suitable for the SD approach (Paqualino et al. 2015). The following are some previous studies that have been presented at different locations. Asmorowati and Sarasanty (2021) designed an SD model for predicting the availability of water in future as a basis for planning water resources. As a result of this study, it was found that land-use change affects water availability in the sub-basin and that water conservation scenarios are capable of maintaining water availability in future. According to Layani et al. (2021), the highest sustainability index was achieved by controlling water demand under optimistic weather conditions. For this reason, the government should provide a context in which people can learn how to control their daily water consumption. A SD approach was employed in Qazvin province, Iran, by Nasariaamdarloo et al. (2020) to manage water resources. Based on the results of the study, the developed systematic model is applicable to a wide range of situations and may provide useful information to water resource managers in cities that are experiencing water shortages. By using the SD approach, Barati et al. (2019) developed a smart groundwater governance (SGG) model to help policy makers and decision makers better understand the short- and long-term impacts of their actions, plans, and policies. In Tabriz plain, Iran, SD modeling was used to determine safe groundwater level fluctuations and exploitation. Based on the results of the study, this model provides a better understanding of the challenge of balancing supply and demand in arid or semi-arid regions when water resources undergo drastic changes

(Nassery et al. 2017). An SD approach to adaptation strategies has been presented by Madani et al. (2017) regarding the interaction between water resource development and biophysical and socio-economic subsystems. An integrated SD simulation model was developed by Kotir et al. (2016) to study feedback processes and interactions between the population, water resources, and agricultural production subsectors of the Volta River Basin in West Africa. The results of their study indicated that the simulated outputs matched the observed reality of the water resources system. A SD approach was also used to simulate proposed changes to water governance by integrating supply, demand, and asset management (Sahin et al. 2016). A sustainable water management approach for a coastal area in Shandong province, China, has been presented by Huanhuan et al. (2016). A sustainable water resources management and agricultural development approach was used by Koti et al. (2016) in the Volta River Basin, Ghana. Li et al. (2014) evaluated water strategies using the SD approach. Using the SD approach, Zhuang (2014) integrated the management of water and energy resources. Karamouz et al. (2011) used the SD approach to assess the economic effectiveness of water supply and demand strategies. Kwakkel and Slinger (2012) have presented a comprehensive dynamic system model for developing policies and managing coastal aquifers. An SD approach has been presented by Giordano et al. (2012) for conflict analysis in groundwater management. Due to the growing population and renewable water resources, it is necessary to increase water productivity to satisfy food demand. However, the need to increase water productivity will vary across countries based on factors such as population, consumption pattern, and per capita water availability. Furthermore, despite the fact that virtual water trade has the potential to reduce pressure on the country's vital water resources, its role and potential should not be neglected. Moreover, virtual water exporters' unions may provide special conditions for the future import and export of virtual water, and it can also serve as an economic and political tool to exert pressure on countries with limited water resources. Due to this, even though there are significant opportunities to alleviate water crises through the importation of virtual water, an increase in water productivity should still be considered in order to help achieve food and water security in the country. Iran is one of the countries that has been recommended increasing the productivity of water and land in order to prevent the increase of food dependence. The development of modern irrigation systems, the switch to modern irrigation systems, the use of deficit irrigation (Shammout et al. 2018; Ahmadpour 2022), and the improvement of irrigation transmission efficiency have all been adopted as methods of improving WP in agriculture. A system dynamics approach is a suitable method to study water, and it permits us to study an important indicator such as water productivity, which is

affected by a variety of irrigation factors, which in turn have mutual effects. According to the reviewed studies, no SD approach has not been used to examine the effects of cropping patterns and pressurized irrigation systems on physical water productivity (W_{Pp}) and economic water productivity (W_{Pe}). Therefore, in this study in light of the existing complexities in the relationships between factors affecting water productivity in irrigation networks. Accordingly, the SD approach is used to model the Qazvin irrigation network, which is one of the most important irrigation networks in Iran. By using this SD approach, different technical and management options were evaluated on water efficiency, and solutions prioritized at the level of irrigation networks to improve water productivity. Consequently, prioritizing solutions based on the stability of the aquifer has been considered.

Materials and methods

Experimental site

An area of 15,820 km² was studied in the province of Qazvin, Iran (longitude 48°45' to 50°51' and latitude 35°24' to 36°48'; Fig. 1). The climate of the Qazvin province is cold and semiarid, with an average annual precipitation of

approximately 330 mm. A large portion of the province is located in the Salt Lake basin, while a smaller portion is located in the Sefidrood basin in the northern part of the province. As one of Iran's most important agricultural hubs, Qazvin province is home to 480,000 hectares of agricultural lands, 80,000 farmers, and more than 30 percent of arable land. Wheat, barley, and maize are the most important crops in the Qazvin province (Fig. 1).

This study evaluated water productivity improvement strategies in the Qazvin plain using a dynamic productivity model. The next section briefly describes the principles of this method and the framework for the productivity model.

Methodology and description of the model

Methodology of system dynamics (SD)

An example of system dynamics (SD) modeling is a simulation technique that is used to determine how a system will change based on a specific course of action (Simonovic 2009). The SD modeling process involves five general steps: (1) defining the problem; (2) describing the system; (3) developing the model; (4) validating the model; and (5) analyzing policies using the model. VENSIM programming is used to model SD, which is an object-oriented simulation

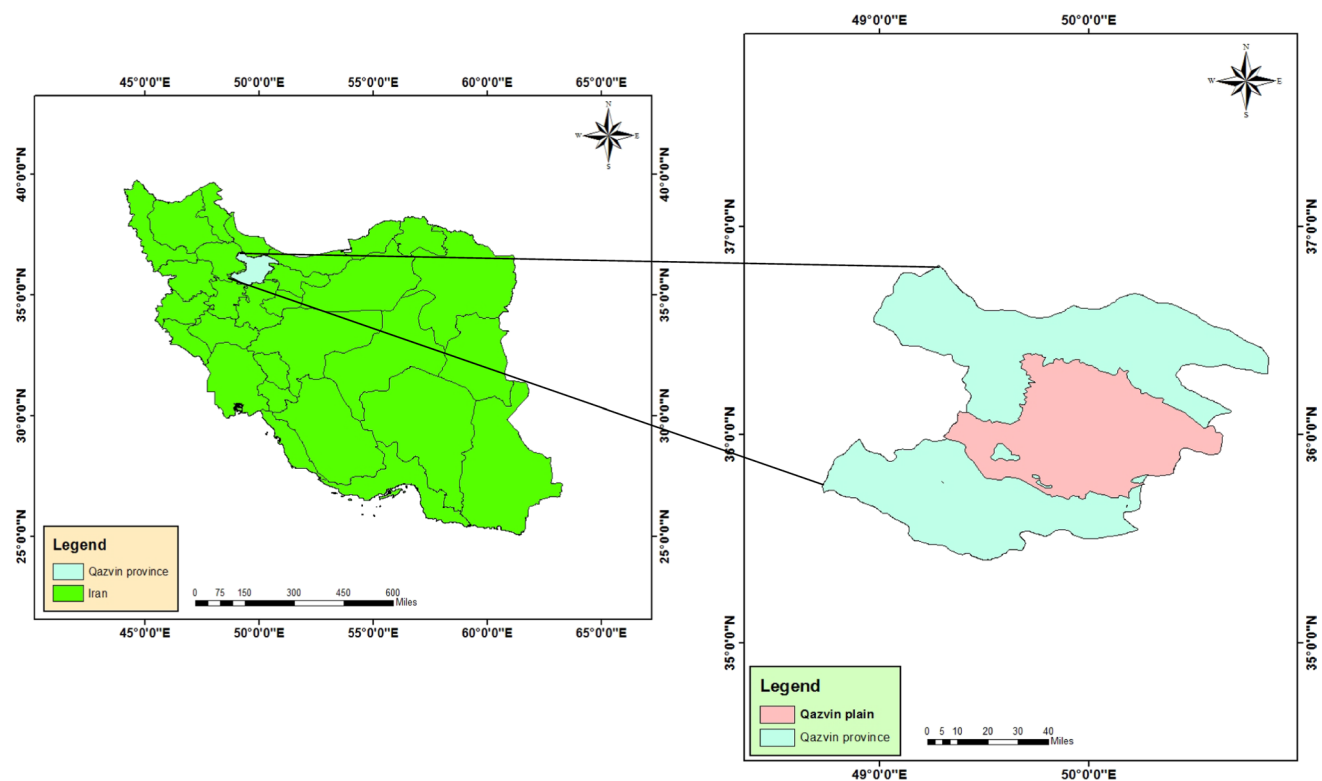


Fig. 1 Location of Qazvin province

environment based on feedback (Ventana Systems 2010; Madani et al. 2017).

Defining the problem

The problem definition step involves identifying the problem in the system that the existing entity is seeking to resolve (Goodman 2006). The low water productivity of agriculture and the uncertainty of the individual and interactive effects of water productivity improvement strategies on the plain are some of the problems to which this study was designed to provide solutions.

Description of the system

In this phase, the first step is to determine the boundary of the system. This step involves focusing on the boundary of the system within which the complex structure is formed. Alternatively, one can determine the actual behavior of the system by explaining the subvariables (variables affecting the reference variable). The present study examined the problems of water productivity at different levels, categorized variables affecting water productivity at different levels on the basis of previous studies, and then evaluated variables affecting water productivity.

Causal-effect loops diagram

This is one of the most important steps in SD modeling. A causal-effect loop diagram represents a comprehensive understanding of the system structure, including positive and negative relationships between variables, and is a useful tool for drawing feedback structures. Figure 2 illustrates the cause-effect loop diagrams of the WP_p model at the field scale.

Stock and flow diagram

The two basic concepts of SD analysis are stock and flow, as well as feedback. Stocks and flows are used to indicate accumulations and depletions as a result of flows within a system. Figure 3 shows the stock and flow of the Qazvin plain WP_p model.

Model subsystems

Water and production subsystem (field scale)

As part of this subsystem, the factors affecting evapotranspiration and crop yield are considered, such as deficit irrigation, changes in irrigation systems, and improving irrigation

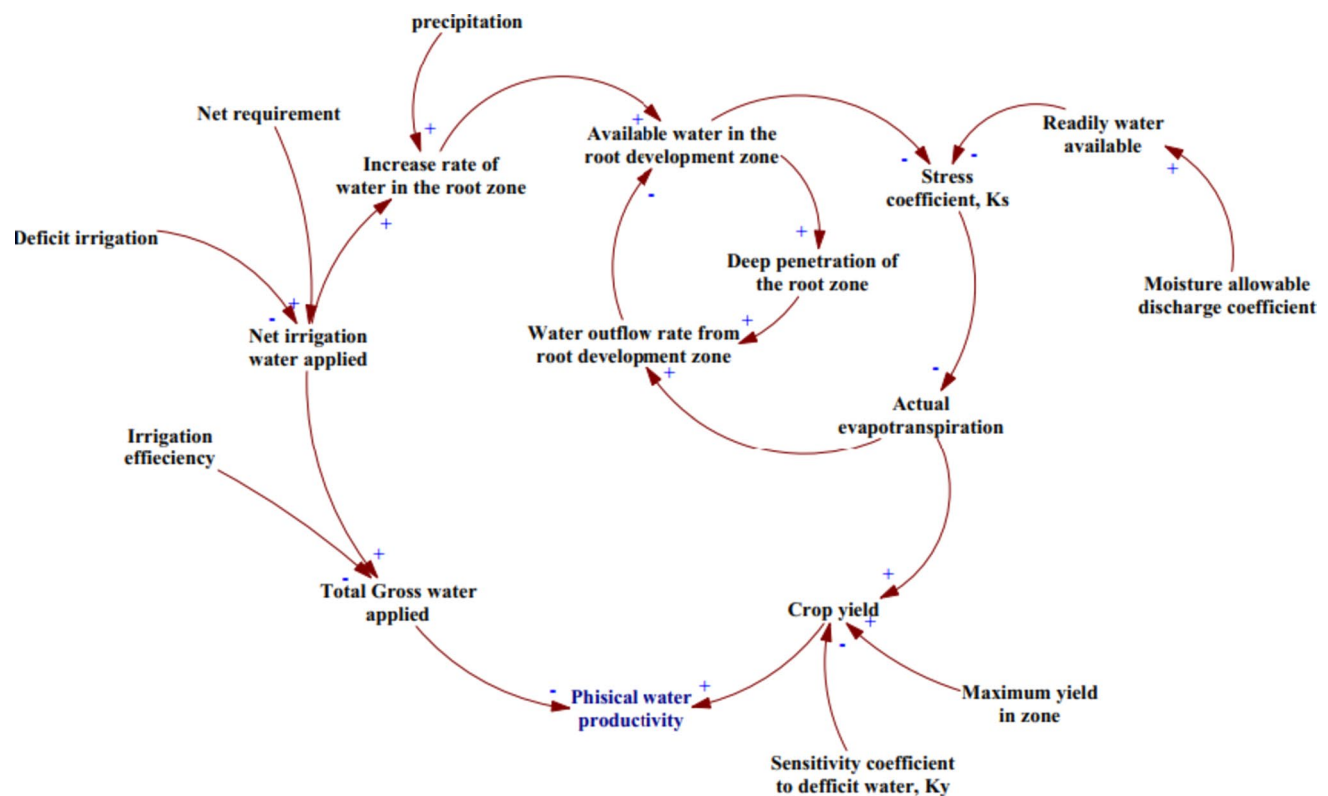


Fig. 2 Causal-effect loops diagram of the physical water productivity (WP_p) model at field scale

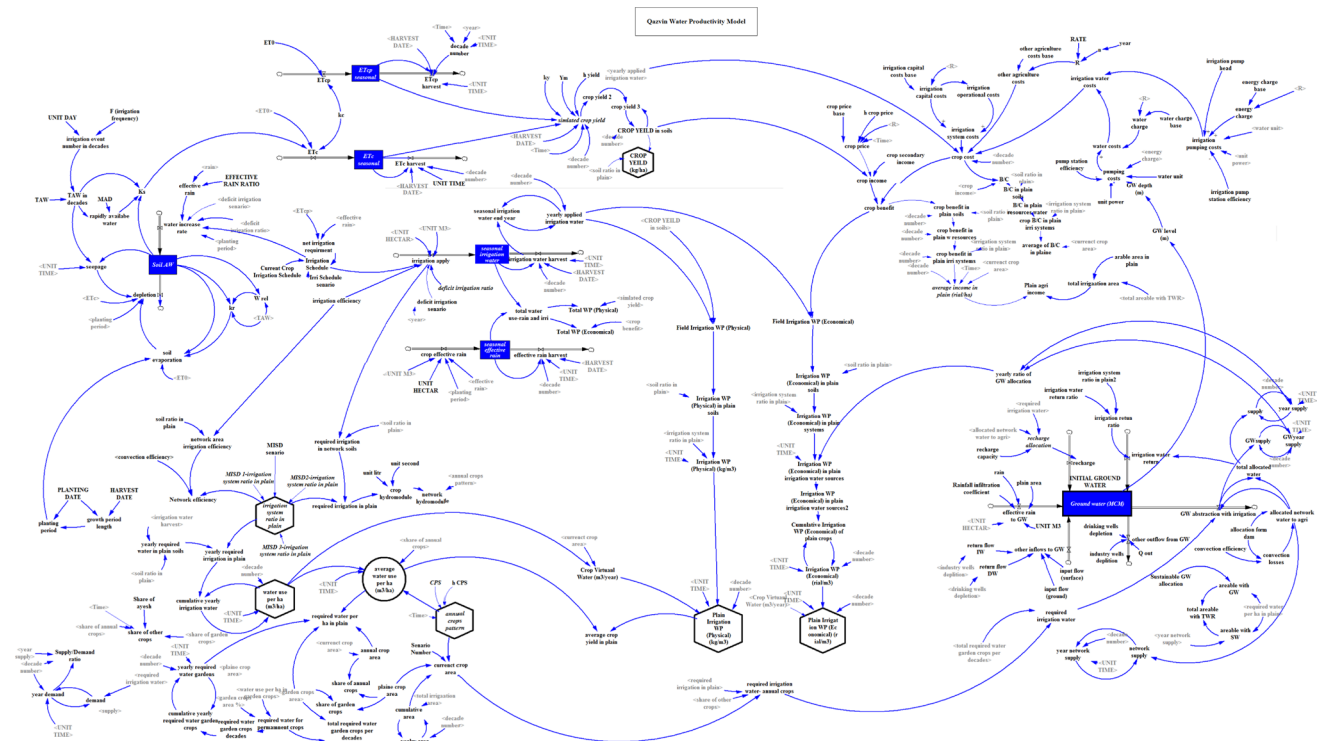


Fig. 3 Stock and flow diagram of the water productivity (WP) model of Qazvin plain

efficiency. It is important to consider the potential evapotranspiration of the crop, the actual evapotranspiration of the crop, effective rainfall, net irrigation requirement, deficit irrigation coefficient, irrigation efficiency, irrigation depth in each period, irrigation water applied during the growing season, soil water availability, drought stress coefficient, soil surface evaporation, and crop yield as variables of the field subsystem.

Economic factors subsystem

Among the components of this subsystem are planting crops costs, water costs (by type of surface and underground source), irrigation systems and secondary pumping costs, and the value of the crops. Economic variables include the cost of water, the cost of pumping irrigation, the cost of irrigation water, the cost of irrigation systems, other agricultural costs, crop costs, crop prices, income, and benefit of cultivation per hectare.

Water resources subsystem

Variables related to surface and groundwater resources are included in this subsystem. An important variable in this subsystem is the aquifer inventory, effective precipitation to groundwater, groundwater discharge by agriculture, irrigation return flow, and other aquifer inflows, outflows, and

water allocations from reservoir dams to agriculture (Qazvin irrigation network), among others.

Cultivation pattern-plain surface subsystem

In this subsystem, information on cropping patterns, plant growth periods, the area of the crop cultivation, the amount of crop water required based on irrigation efficiency in the plain, and the percentage of the different irrigation systems in the plain is all included.

Model validation

SD models are always evaluated on the basis of their particular structural characteristics (Winz et al. 2009). It is essential to validate the model structure and behavior before using the model in scenario analysis (Barlas 1996; Forrester and Senge 1980). A dimensional accuracy test and a model behavior test were used to validate the model in this study.

Dimensional accuracy test

This is one of the basic tests that should be considered at the beginning of the modeling process. The measurement units for each variable produced by the model should be examined in this test. During the development of the model, it was examined whether the units were compatible with one

another. Figure 4 shows an investigation of the dimensional accuracy of the final model.

Behavior tests

In this test, the model outputs are examined. Data generated by the model should be compared with data from field studies or historical data from the system. The conventional relative error (RE) and root mean square error (RMSE) indices (Zacharias et al. 1996) are used to assess the behavior of the system. The RMSE and RE are defined as follows:

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (P_i - O_i)^2}{n}} \tag{1}$$

$$RE = \frac{(P_i - O_i)}{O_i} \times 100\% \tag{2}$$

where P_i and O_i are the predicted and observed values, respectively, and n is the total number of data.

RE and RMSE have zero minimum values. Plant growth and yield are important parameters in determining water productivity. Consequently, this parameter is used as a reference parameter when evaluating the performance of the model. By using the above model, crop yields were simulated under different irrigation scenarios and compared with the results

of field studies and the Aqua Crop model. In Fig. 5a, b, and c, examples of model performance evaluation are shown.

For example, Fig. 5a illustrates that the simulated and observed yields are in good agreement. Between the simulated and observed yields, root mean square error (RMSE) and relative error percentage (RE) were within 400 kg/ha and 0.07, respectively. In Fig. 5b and c, the model's performance is also shown in simulating the level of the aquifer. Model evaluation was conducted using observational data from 2006 to 2014. Data related to the Qazvin aquifer were obtained from the Regional Water Company of Qazvin (Regional Water Company of Qazvin, 2014a). In this period, the aquifer's water level has decreased by an average of 1.25 m per year. According to the model, the annual drop over this period is estimated at 1.43 m per year, with an average error of 17 cm per year. As the developed dynamic model requires little input information, it is capable of being linked to larger-scale dynamic models (such as plain and grid).

Studied strategies

It should be noted that the scenarios that have been applied in the current research on the studied area include deficit irrigation scenarios, development of pressurized irrigation systems (including drip and sprinkler irrigation systems), and changing cropping patterns. In order to select these three scenarios, a SWOT analysis was conducted in order to examine the strengths, weaknesses, opportunities, and threats in

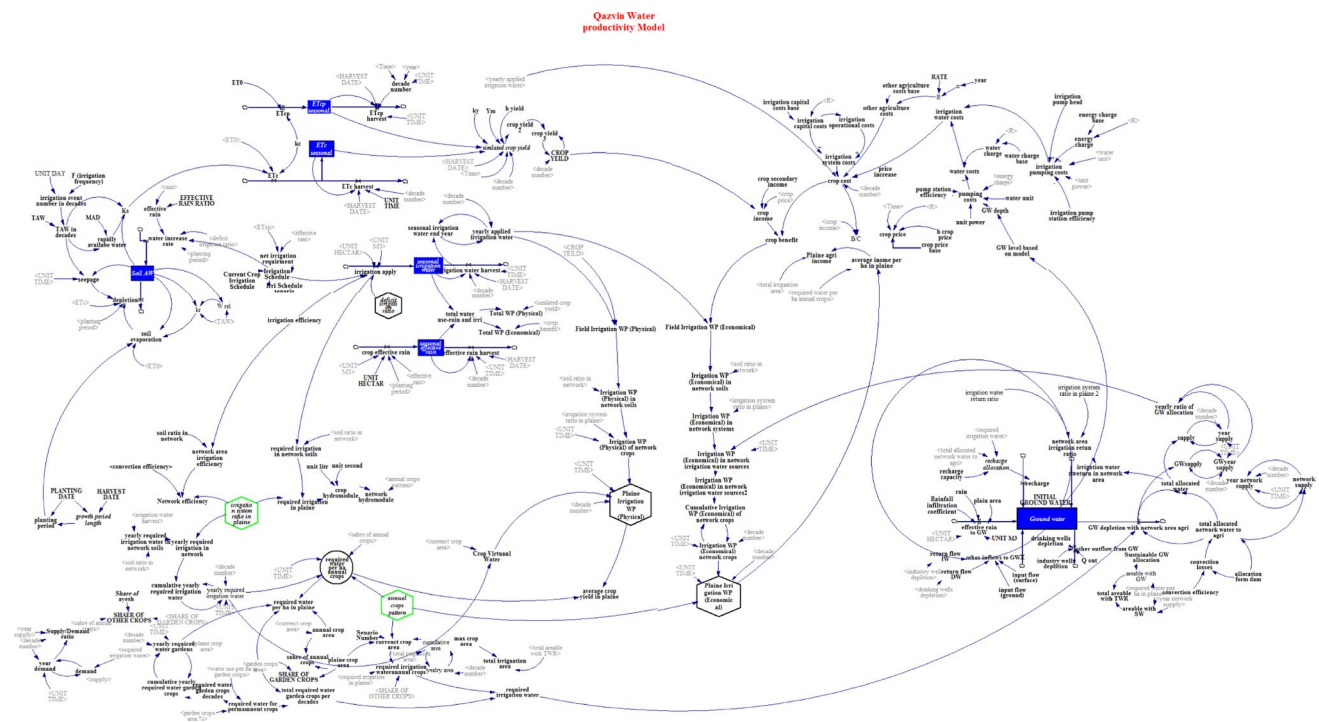
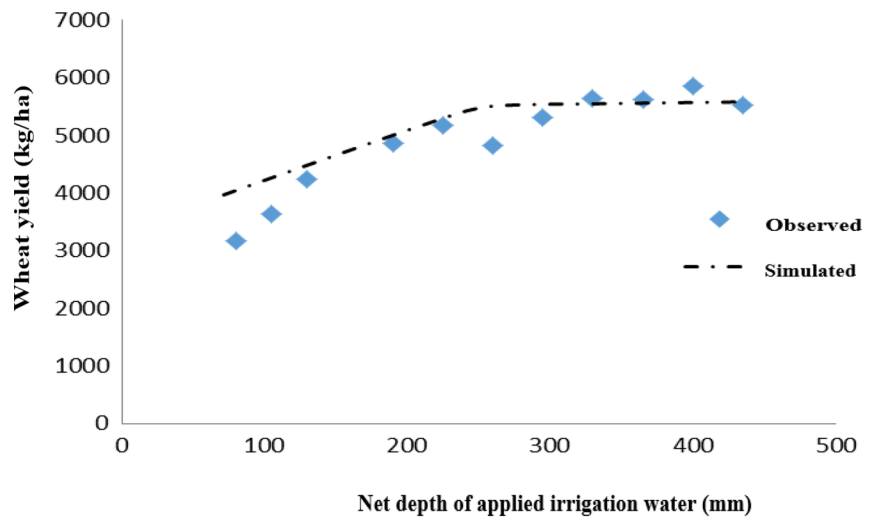
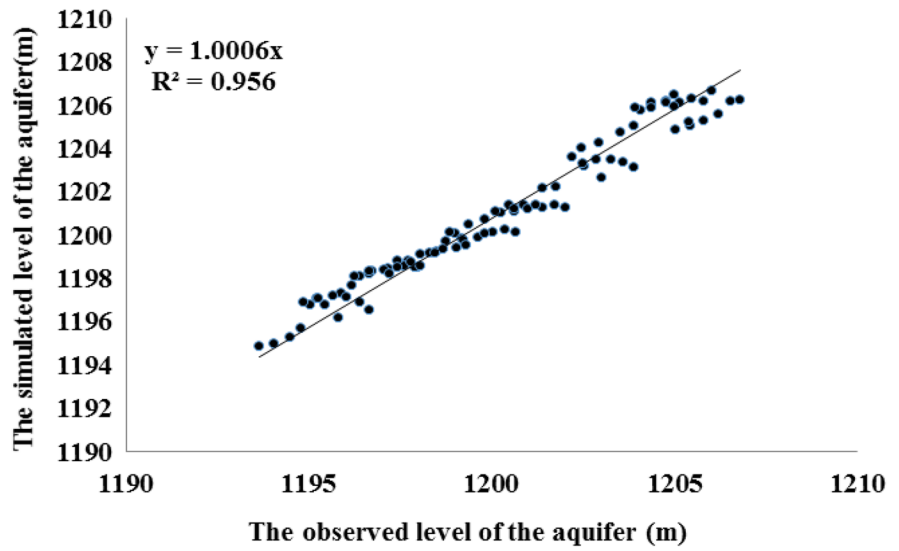


Fig. 4 Investigation of the dimensional accuracy of the final model

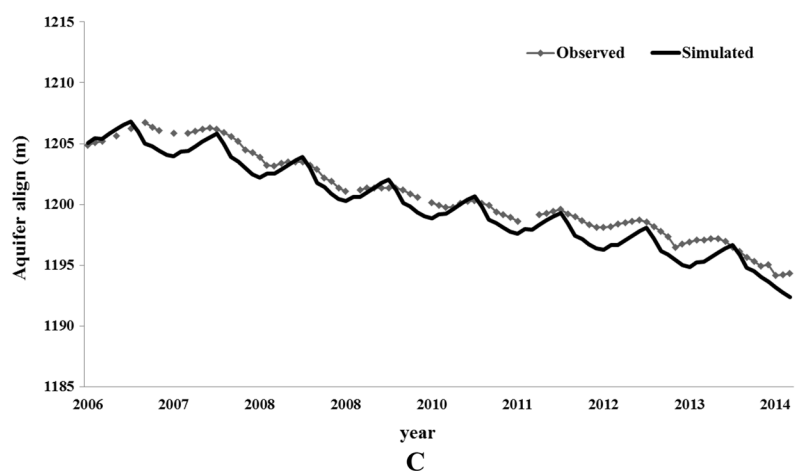
Fig. 5 Model evaluation— comparison of a simulated and observed yield values of the wheat crop, b the relationship between simulated and observed aquifer level values, and c simulated and observed aquifer level process



a



b



c

Qazvin plain. By reviewing previous studies and consulting with experts, we determined the plain's strengths, weaknesses, opportunities, and threats. After the questionnaire had been prepared and its content validity determined, it was filled out by experts and 16 questionnaires were reviewed in total. Several of the categories raised in the Qazvin plain are influenced by the economic, social, political, cultural, and environmental conditions at the national and basin levels. During the analysis of the results, 17 opportunities were identified for improving and upgrading the level of water productivity in the plain. These opportunities were ranked according to their importance (Table 1).

Based on the results obtained, the most important opportunities in the plain include the existence of expert, scientific and technical potential, reforming irrigation and low irrigation planning, implementing new irrigation methods, promoting agricultural and garden species with greater productivity, and implementing new irrigation methods. Water productivity can be improved by deficit irrigation and supplementary irrigation. In areas with deficit irrigation, higher productivity can be achieved by giving less water. To achieve greater water efficiency, these two areas are very important in irrigation planning. Also, it is possible to promote agricultural and garden species with higher productivity on irrigation plains, which shows their potential. Qazvin's favorable climate has enabled various crops to be grown there, and this variety of cultivation illustrates how different crops can be adapted to the

climatic and natural conditions of the region. Due to these conditions, agricultural and garden species with higher productivity can be developed and promoted. The implementation of new irrigation methods at the network level is also considered an opportunity to improve water efficiency. The use of technology can be an effective tool for transforming water resource management. By implementing modern irrigation techniques on the level of the plain, it is possible to improve the efficiency of the use of water resources. Finally, it is important to note that water management strategies such as deficit irrigation, the implementation of new irrigation methods, and changing cropping patterns can contribute to the optimal management of agricultural water consumption in the Qazvin plain irrigation network by facilitating the development and promotion of agricultural and garden species with greater productivity. It should also be effective in terms of the amount of water extracted from surface and underground sources, as well as have a significant effect on aquifer conditions. According to the research conducted, the inability to change irrigation management methods and the common cultivation pattern will reduce the volume of the plain's aquifer and reduce its underground water supply.

For the purpose of evaluating water productivity improvement strategies, the following strategies and scenarios were utilized:

- Practices of deficit irrigation (DI).

Table 1 Identification and prioritization of opportunities in the plain

| Row | The subject of opportunities in the plain | Average | standard deviation | Ranking of importance | The ranking of disagreement |
|-----|--|---------|--------------------|-----------------------|-----------------------------|
| 1 | Enhancing the efficiency of water use by the companies using the network | 3.75 | 0.66 | 5 | 13 |
| 2 | Treatment and re-use of wastewater | 3.78 | 0.86 | 4 | 8 |
| 3 | Possibility of promoting high-productivity agricultural and gardening species | 4.00 | 0.87 | 3 | 7 |
| 4 | Deficit irrigation | 4.00 | 0.79 | 3 | 9 |
| 5 | The implementation of new irrigation techniques | 4.19 | 0.53 | 2 | 14 |
| 6 | Providing opportunities for people to participate in improving the condition of the network | 3.33 | 1.01 | 11 | 4 |
| 7 | Possible formation of marketing unions for agricultural products | 2.80 | 0.98 | 14 | 5 |
| 8 | A possibility of forming irrigation service companies | 3.53 | 0.88 | 9 | 6 |
| 9 | Correcting the irrigation plan and updating the plant water requirement document | 4.19 | 0.88 | 2 | 6 |
| 10 | Potential for setting up ancillary industries | 3.40 | 0.71 | 10 | 12 |
| 11 | A possibility of developing rainfed agriculture for some agricultural crops | 3.19 | 0.73 | 12 | 11 |
| 12 | The possibility of modifying crop rotation with an approach appropriate to the climate of the region | 3.69 | 0.77 | 6 | 10 |
| 13 | The possibility of improving and automating irrigation systems | 3.56 | 1.06 | 8 | 2 |
| 14 | The existence of a budget line for the Qazvin plain | 3.40 | 1.02 | 10 | 3 |
| 15 | The proximity of Qazvin plain to the Tehran consumer markets | 3.67 | 1.07 | 7 | 1 |
| 16 | The presence of numerous documents (articles, reports, theses, etc.) in the Qazvin plain | 2.88 | 0.86 | 13 | 8 |
| 17 | Existence of expert, scientific, and technical resources | 4.33 | 0.47 | 1 | 15 |

- Development of modern irrigation systems (MISD): A field-scale calculation of water productivity is performed for all three types of irrigation systems: surface, sprinkler, and drip irrigation systems.
- The cropping pattern scenario (CPS).
- Combinations of scenarios (resulting from the combination of different scenario models).

In this study area, sprinkler irrigation (mainly height-fixed sprinklers), drip irrigation, and surface irrigation are the most common irrigation systems (mainly furrow irrigation). The area devoted to sprinkler, drip, and surface irrigation is about 9, 16, and 75%, respectively (Ministry of Jihad Agriculture, 2015). The tariff for Water Withdrawn for agricultural use is about 1050 (Rials/m³) for water rate and about 2100 (Rials/m³) for pumping costs (Ministry of Energy 2015). To evaluate the effects of irrigation systems on depth infiltration and evapotranspiration fractions, in addition to field evaluations, data analysis of irrigation system evaluation reports in Qazvin plain was conducted and each of the beneficial and non-beneficial components was determined (Ghahroodi et al. 2015).

The model incorporates strategies and policies that use extrinsic parameters associated with them. In order to determine the impact of existing system conditions and different scenarios in future, a model was developed for the period 2006–2025. In Table 2, external variable parameters and levels are presented for the relevant variable for policymaking.

Evaluation of strategies

For the evaluation of the strategies, various indices were used including physical water productivity (WP_p), economic water productivity (WP_e), crops virtual water, water requirements per hectare of cropping pattern, and aquifer volume change indices.

The WP_p (kg/m³) and WP_e (Rial/m³) was defined as follows:

$$WP_p = \frac{Y}{I + P} \tag{3}$$

$$WP_e = \frac{I_n}{I + P} \tag{4}$$

WP_p indicates the physical water productivity (kg/m³), Y indicates the crop yield (kg/ha), I and P indicate irrigation water depth and precipitation, respectively, (m³/ha), WP_e indicates the economic water productivity (Rial/m³), and I_n indicates net income (Rial). The net income (I_n) was calculated as follows:

$$\text{Net income} = \text{Total revenue} - \text{total expenses} \tag{5}$$

In order to simulate changes in the surface and volume of the aquatic environment, the mass survival principle was applied as follows:

$$Q_{in} + Q_p + Q_l + Q_{SW} + Q_R + Q_A - (Q_W + Q_{Eg} + Q_d + Q_{out}) = \Delta V \tag{6}$$

Table 2 Studied strategies

| Strategies | Scenarios | Abbreviations |
|--------------------------------------|--|---------------|
| Deficit irrigation | Full irrigation | FI |
| | Deficit irrigation 15% | DI 15% |
| | Deficit irrigation 20% | DI 20% |
| | Deficit irrigation 25% | DI 25% |
| Modern irrigation system development | Development of modern irrigation systems at a current rate of 2% annually | MISD 2% |
| | Development of modern irrigation systems at twice the current rate, 4% annually | MISD 4% |
| | Development of modern irrigation systems with half the current rate, 1% annually | MISD 1% |
| Cropping pattern scenario | Current cropping pattern without considering fallow condition | CPS 1 |
| | Current cropping pattern with considering fallow condition | CPS 2 |
| | Allocation of fallow lands to the cultivation of strategic crops (Wheat, grain (corn) and forage (maize)) | CPS 3 |
| | Allocation of fallow lands to the cultivation of low water-demand industrial crops (canola) and crops with high WP _e (tomatoes) | CPS 4 |
| | Allocation of fallow lands to the cultivation of low water-demand crops (wheat, barley, peas, lentils, and canola) | CPS 5 |
| | Allocating 50% of the current cultivated area of high water-demand crops to other crops | CPS 6 |
| | Allocating cultivated areas associated with crops with low WP _p to products with high WP _p (sugar beet, beans, potatoes, tomatoes, forage (maize), and alfalfa) | CPS 7 |
| | Reducing the cultivated area associated with crops with low WP _e and allocating it to low water-demand industrial crops (canola) and crops with high WP _e (tomatoes) | CPS 8 |

where Q_{in} is the side entrance underground stream from the heights or upstream plain, Q_p is the aquifer feeding on the influence of precipitation on the plain, Q_I is the aquifer feeding on agricultural intrusive waters, Q_{SW} is the aquifer feeding on drinking water and industrial wastewater, Q_R is the aquifer feeding surface streams or rivers, Q_A is the rate of artificial feeding, Q_W is the groundwater consumption, Q_{Eg} is the evaporation from groundwater, Q_d is the drainage from the aquifer, Q_{out} is the output groundwater flow from the aquifer, and ΔV is the aquifer fixed storage changes. The data related to the equation above were derived from the water resource balance report for the study area (Regional Water Company of Qazvin, 2014b).

As a result of applying the strategies, their effects on these parameters and model behavior were extracted and evaluated.

Results and discussion

Field-scale physical crop water productivity (WP_p)

At the field scale, irrigation management and the type of irrigation system will have an effect on physical water productivity by affecting the amount of water consumed and the yield of the crop. Table 3 illustrates the average WP_p on a plain scale. Among the crops, tomato, watermelon, and forage maize ranked highest in terms of WP_p . WP_p values obtained in this part relate to the Qazvin plain and differ

from those in the province. Crop yields are higher in the Qazvin plain than in the province as a whole.

In a study, the positive planning model was used to determine how farmers adapt to water scarcity in a grain-producing area of France that relies on underground water sources. The results showed that about 20% of the farmers tended to reduce the water intensity for irrigated crops by making water scarcity an option, 50% shifted their cultivation patterns to rainfed agriculture, and approximately 25% shifted to crops which did not require as much water (Gravelin and Merel, 2012). Dastvar sand Shirdeli (2014) examined the optimal pattern of cultivation of agricultural lands downstream of the Bouin dam using a single-objective mathematical model and presented the analysis of the results of their study for five-year planning horizons. According to the results, the physical productivity of water will increase from 50% in the first period to 70% at the end of the study period.

Field-scale economic crop water productivity (WP_e)

Besides the amount of water consumed and the yield of the crop, this indicator also includes production costs and other economic factors. Table 3 illustrates the WP_e for the crops plain. Melon and tomato had the highest economic water productivity on the field scale among the crops. These results are based on a combination of benefits and crop cultivation costs with current irrigation systems for each crop, as well as water costs by type of water source. According to the model, the WP_e of Qazvin plain crops under different irrigation systems has increased in almost all crops since

Table 3 Physical crops water productivity (WP_p) and economic water productivity (WP_e) in Qazvin plain

| Crop | Scenario | Indicator | |
|------------|------------------|--|--|
| | | Physical crops water productivity (kg/m ³) | Economic water productivity (Rial/m ³) |
| Wheat | MISD 2% & DI 15% | 0.70 | 3781 |
| Barely | | 0.75 | 2524 |
| Sugar beet | | 3.30 | 3738 |
| Chickpea | | 0.30 | 6887 |
| Lentil | | 0.18 | 2544 |
| Bean | | 0.19 | 5464 |
| Potato | | 2.60 | 4887 |
| Rapeseed | | 0.44 | 4917 |
| Tomato | | 4.56 | 13,389 |
| Corn | | 0.75 | 5645 |
| Maize | | 3.99 | 2922 |
| Alfalfa | | 0.71 | 3065 |
| Cucumber | | 2.67 | 9941 |
| Melon | | 3.34 | 24,915 |
| Watermelon | | 4.34 | 11,654 |
| Vegetables | | 1.64 | 8992 |

the implementation of modern irrigation systems. However, MISD in low water-intensive crops (such as wheat and barley), despite increasing WP_e (Rial/m³), has decreased the usefulness of cultivation per hectare (Benefit/Cost). As a result, it should be noted that the increase in benefit per unit of water is not always synonymous with the increase in benefit per unit of area.

Plain-scale physical crop water productivity

In addition to DI and irrigation system type, the CPS also influences WP_p on a plain scale. CPS 7, CPS 4, and CPS 8 had the highest WP_p with 2.11, 1.99, and 1.95 kg/m³, respectively, with an increase of 21, 14, and 12 percent over CPS (Table 4).

Under CPS 4, fallow lands were allocated to the cultivation of low water-demand crops (canola) and crops with high WP_e (tomatoes). As part of CPS 7, the cultivation areas of crops with low WP_p (wheat, barley, lentils, chickpeas, and canola) were reduced to the minimum allowable, and these areas have been added to those crops with high WP_p (sugar beet, beans, potato, tomato, maize, and alfalfa). The cultivated areas associated with crops with low WP_e were reduced to the minimum allowable level in CPS 8, and these areas have been added to the cultivation areas of low water-demand industrial crops (canola) and crops with high WP_e (tomatoes). As shown in CPS 1, the plain current status has a WP_p of 1.74 kg/m³. In a study carried out in Tunisia, Hailu (2017) examined the relationship between yield, water productivity, and the slope of increasing water productivity of wheat as a result of changes in irrigation levels under five different scenarios, including faro, drip, and sprinkler irrigation under mulch and non-mulch conditions. Among the used scenarios, drip irrigation is the most yield, while sprinkler irrigation without mulch has the least yield. In

comparison with other irrigation systems, drip irrigation provides the highest level of productivity. In drip irrigation, in deficit irrigation conditions, the changes in water productivity for increasing water consumption are greater than those for the rest of the scenarios.

Plain-scale economic water productivity

As a result, in addition to DI and irrigation system type, CPS scenarios also affected WP_e . Compared to CPS 1, the highest values of WP_e were found in CPS 4, CPS 6, and CPS 8 (5678, 5568, and 5503 Rial/m³, respectively), which had an increase of 21, 18, and 17.5%, respectively, when compared to CPS 1 (Table 4). CPS 8 reduced the cultivation area. As a result of applying the strategies, their effects on these parameters and model behavior were extracted and evaluated of crops with low WP_e to the minimum level allowable, and these areas were added to the cultivation area of low water-demand industrial crops (canola) and crops with high WP_e (tomatoes). Considering that CPS 4 allocates fallow lands to cultivate valuable crops (canola and tomatoes), its high WP_e is fully justified. There is a difference between CPS 4 and CPS 8 in that the areas cultivated for crops with low WP_e are not reduced; only fallow areas are assigned to crops with high WP_e . According to CPS 6, cultivated areas of high water-demand crops have been reduced by up to 50% and are allocated to cultivation of other crops. Due to the fact that this scenario is ranked in second place in terms of WP_e (Table 4), it demonstrates that high water-demand crops do not have a greater WP_e than low water-demand crops. As well, despite CPS 7's high WP_p , it did not rank among the top scenarios for achieving high WP_e , suggesting that high WP_p at plain scale may not be the most relevant factor when choosing the best cropping pattern.

Variability of virtual water in crops

As shown in Fig. 6, crop virtual water has varied from 2006 to 2017 (the statistics for 2006 were derived from the water comprehensive plan and the statistics for 2017 were derived from the results of this study). The volume of virtual water refers to the volume of water used in the production of each crop. There is a direct correlation between the volume of virtual water and the productivity and cultivation area of each crop. According to Fig. 6, the virtual water of maize, tomato, and alfalfa increased by 68, 64, and 36%, respectively. It is evident from Table 4 that these crops have high WP_p , and one of the reasons for the high WP_p in the Qazvin plain can be attributed to the change in cropping patterns.

Moreover, these crops are also highly water-intensive and are referred to as water-intensive crops. Consequently, increasing the WP_p in the plain scale cannot be considered

Table 4 Physical water productivity (WP_p) of plain in different cropping pattern scenarios (CPS)

| Scenario | Indicator | |
|----------|--|--|
| | Physical crops water productivity (kg/m ³) | Economic water productivity (Rial/m ³) |
| CPS 1 | 1.74 | 4685 |
| CPS 2 | 1.74 | 4686 |
| CPS 3 | 1.78 | 4600 |
| CPS 4 | 1.99 | 5678 |
| CPS 5 | 1.61 | 4644 |
| CPS 6 | 1.56 | 5568 |
| CPS 7 | 2.11 | 5235 |
| CPS 8 | 1.95 | 5503 |

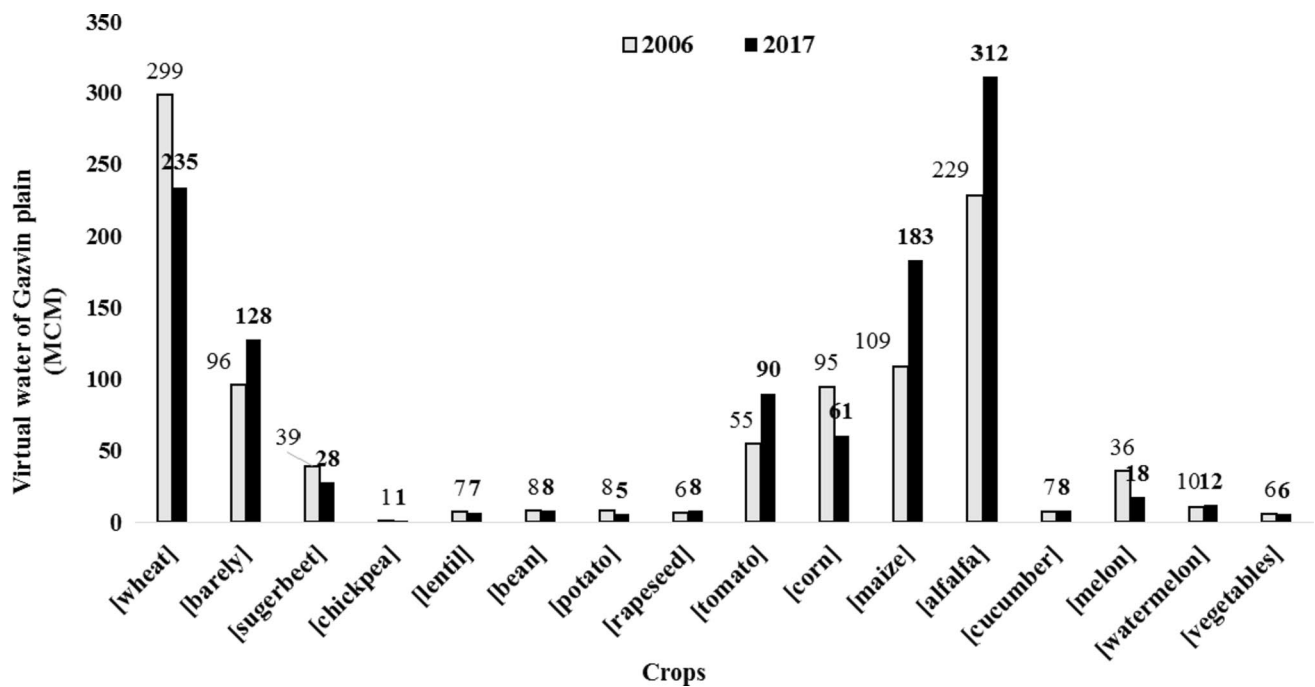


Fig. 6 Variation of plain crops virtual water volume over 11 years

an indicator of success in water management and should be considered in conjunction with the changes in the CPS and virtual water management.

Amount of water required per hectare of cropping pattern

Water resources can be analyzed using this index. It is important to be aware of the effectiveness rate of cropping patterns, deficit irrigation management, and the development of modern irrigation systems on agricultural water demand. As shown in Fig. 7, the maximum and minimum water requirements were 11,699 and 8207 m³/ha, respectively, for CPS 7 and CPS 6.

Figure 7 shows that crops with high WP_p tend to increase water demand and are not recommended. Both CPS1 and CPS2 had the same water requirements since their cropping compositions were the same, while in CPS2, only the cultivation area was lower (due to the control fallow). Figure 8 depicts the interaction of MISD and DI scenarios on the water requirement per hectare of cropping pattern in the 2025 horizon. The figure shows the water requirement per hectare for the three cropping patterns CPS1 (current pattern), CPS6 (which had the least water requirement), and CPS8 (one of the high WP_e scenarios with a lower water requirement per hectare than current pattern).

The DI is presented in order to illustrate the prospects for the future and strategies for adapting to water shortages. Optimal DI degree in different years based on economic,

irrigational, and environmental factors will differ for different agricultural components. Even though increasing DI decreases the water requirement per hectare of cropping patterns, it should be noted that DI results in reduced crop yield, agricultural income, and WP_e . The developed model calculates crop loss, income loss, and decrease or increase in WP_e for each crop and the whole cropping pattern, and this report primarily presents results at the plain scale. By applying DI at rates of 20 and 25 percent, the WP_e is reduced to 21 and 30 percent, respectively. Therefore, a DI version must be based on economic analysis. Geerts and Raes (2009) studied the water productivity of crops under deficit irrigation conditions. According to the research results, deficit irrigation is effective in increasing water productivity if a minimum amount of seasonal moisture is provided for farming various crops. According to Ferrers and Soranio (2007), regular deficit irrigation in fruit trees and grapes increases not only water productivity but also farmers' profits. Using the model, the farmer's income is calculated for each hectare of cropping pattern, which allows for the estimation of the amount of DI that farmers are willing to accept.

Aquifer volume (groundwater status)

Considering that cropping patterns and irrigation management have an undeniable impact on groundwater resources, the impact of different scenarios on these resources has been examined in this section. Figure 9 illustrates how the aquifer volume varies under MISD. MISD has been observed to

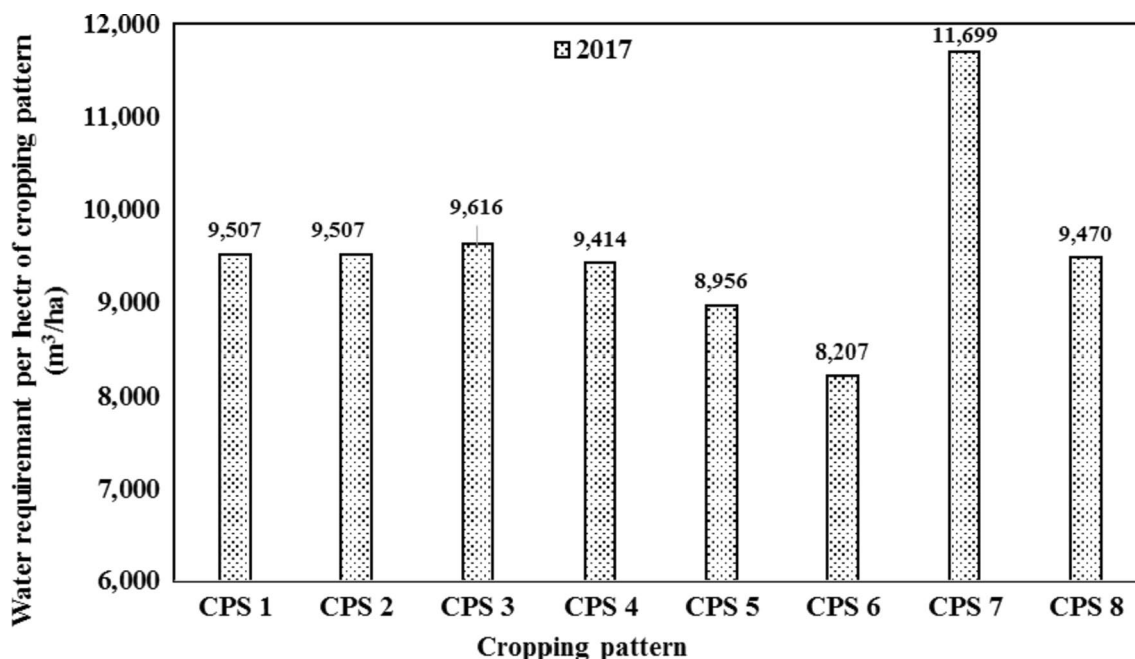


Fig. 7 Comparison of water requirement per hectare of cropping pattern scenarios in current status (2017)

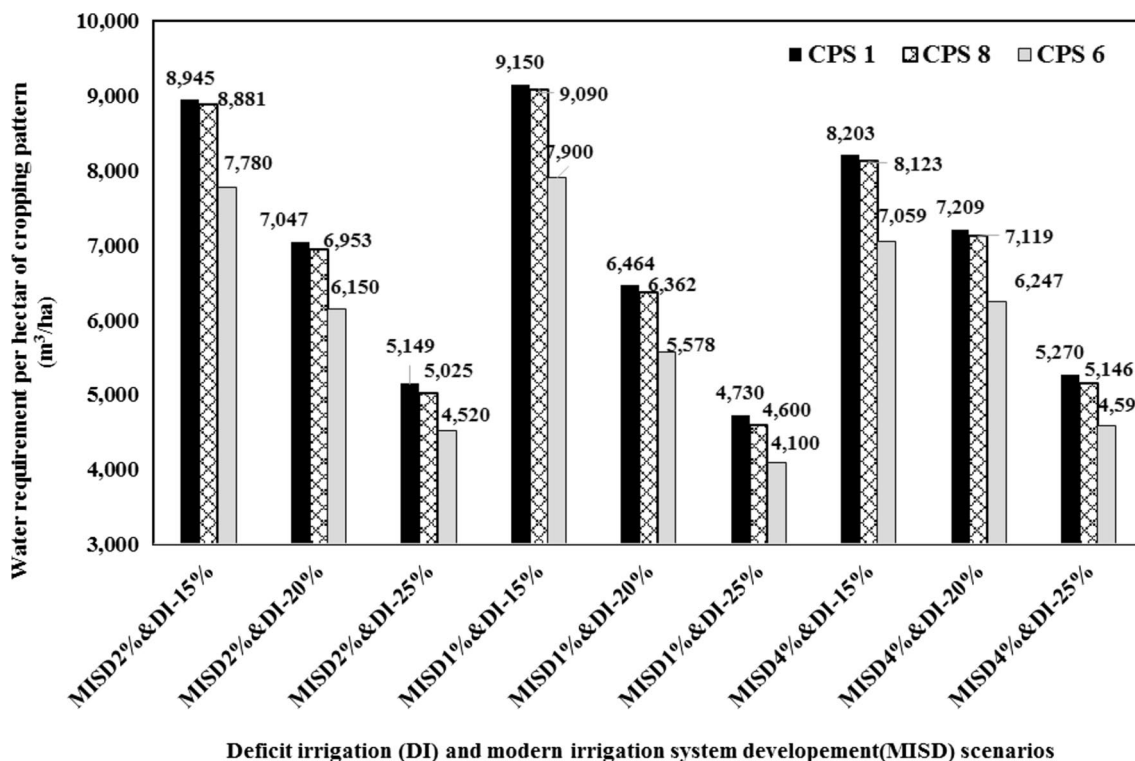


Fig. 8 Water requirement per hectare from cropping pattern in hybrid scenarios (CPS and MISD) in 2025 horizon

have a positive effect on groundwater resources, however, this effect is not as significant as the effect of modifying cropping patterns. The MISD, as it became more efficient,

reduced demand and consequently improved the condition of the aquifer; however, by reducing the return flow, it caused the aquifer to decline. Thus, its overall effect depends on a

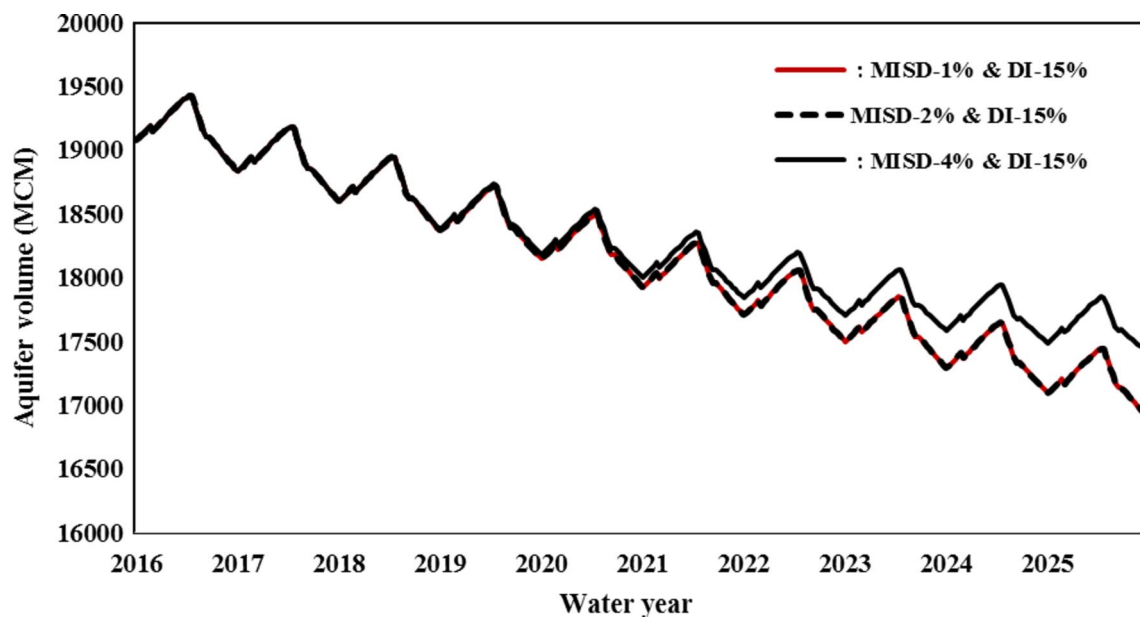


Fig. 9 Prediction of aquifer drop behavior in modern irrigation system development (MISD) scenarios (unable to control cultivation or water withdrawals) Analyzing the behavior of aquifer drop as a func-

tion of the modern irrigation systems development (MISD) scenarios (unable to control cultivation or water withdrawals)

variety of factors, such as control and non-control factors that have been investigated in MISD and CPS.

As a result of uncertainty and ambiguity regarding the interruption of return flow in pressurized irrigation systems, the return flow in these irrigation systems has been presented in the model in the most pessimistic manner possible (the return flow rate for modern irrigation systems in the model is assumed to be zero). In terms of deep percolation to aquifer, the most pessimistic scenario is the case in which there is no return flow to the groundwater resources. The government was not expected to be able to control the fallow level in MISD when predicting aquifer drop behavior. In the past, it has not been possible for the government to do so. The aquifer process will be improved if the cultivation level is monitored using facilities and rules, and the farmers do the fallow. Figure 10 illustrates the comparison of the effect of irrigation system development on the aquifer at control and non-control fallow levels. Aquifers can be protected from further degradation if it is possible to control the fallow level with the irrigation system development with current trends (2% of crop cultivation area annually). Otherwise, the destruction of the aquifer will continue at a rapid pace.

For the purpose of determining the effect of CPS on the aquifer, DI level and MISD have been considered to be the same for all CPS (MISD with current trend and average DI of 15%). As can be seen, the CPS significantly impacted the aquifer. As compared to other scenarios, CPS6, CPS8, and CPS2 performed better. Various other scenarios, including continuing the current cropping pattern, increasing the area

cultivated with high WP_p , and increasing the area cultivated with high WP_e , can seriously compromise aquifer stability (Fig. 11).

In a field study, Alizadeh et al. (2012) optimized cropping patterns for balancing groundwater resources. Based on their study, using the specified model over the ten-year planning period will not only enable them to achieve several goals, but will also reduce the deficit of the underground water reservoir in the study region. As well, Khashei-siuki et al. (2010) determined the pattern and optimal crop density in Neyshabur plain based on the groundwater balance model and PSO meta-exploration. Based on the results of this study, it has been demonstrated that the maximum income can be obtained from the water extracted from the Neyshabur plain aquifer by reduction of the cultivated area of most spring crops by 33% and increase of the cultivated area of wheat, barley, and canola by 33%.

Figure 12 illustrates the variation of aquifer volume in the CPS1, CPS6, and CPS8. Each CPS simulates the MISD based on the current trend. By modifying the cropping pattern, it is possible to prevent the aquifer decline, thus improving the aquifer status (CPS5). Since CPS6 is difficult and resistant to execution, CPS8 is recommended.

This study examined various scenarios, including CPS8, which had high WPE, low water usage per hectare, and greater conformity with aquifer sustainability, as well as analyzing the current situation and planning for a possible and desirable future for Qazvin plain. It is possible to define and explore many other scenarios. As a result of the

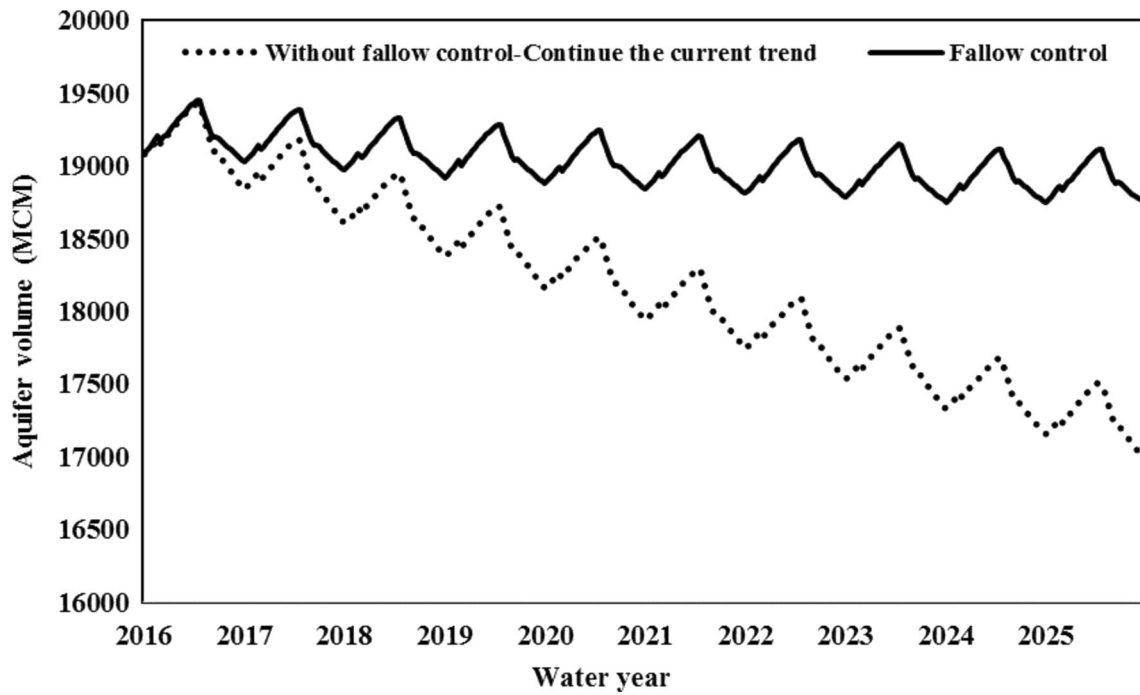


Fig. 10 Prediction of aquifer drop behavior at 2% annually of modern irrigation systems development (MISD) (in both control and non-control fallow levels)

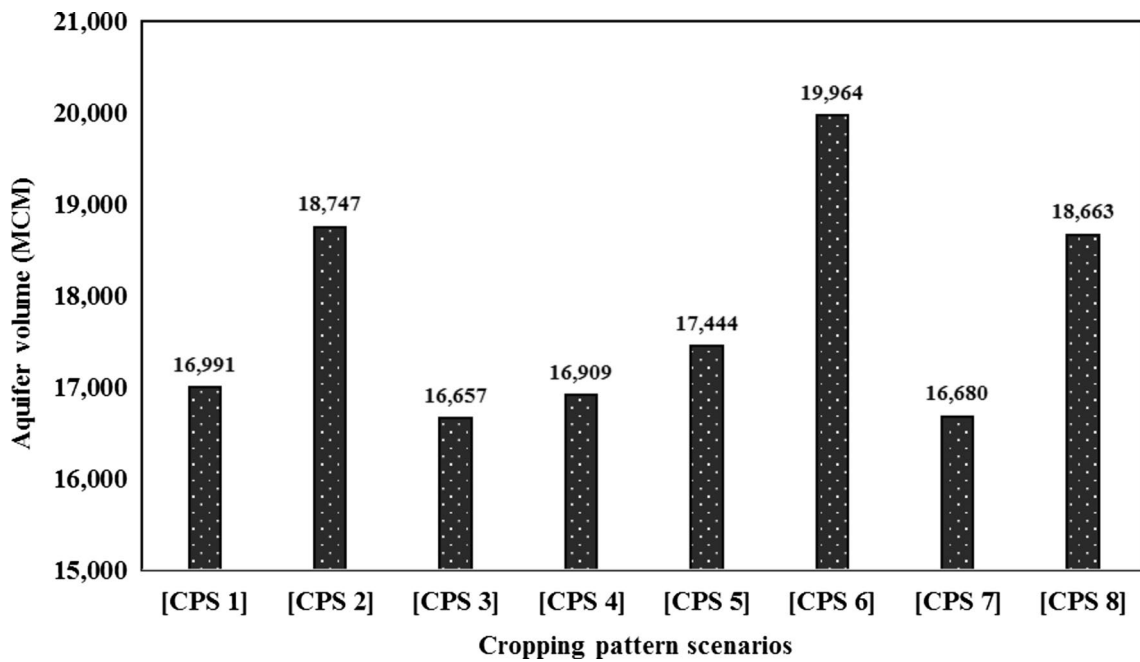


Fig. 11 Aquifer volume prediction in 2025 under cropping pattern scenarios (CPS)

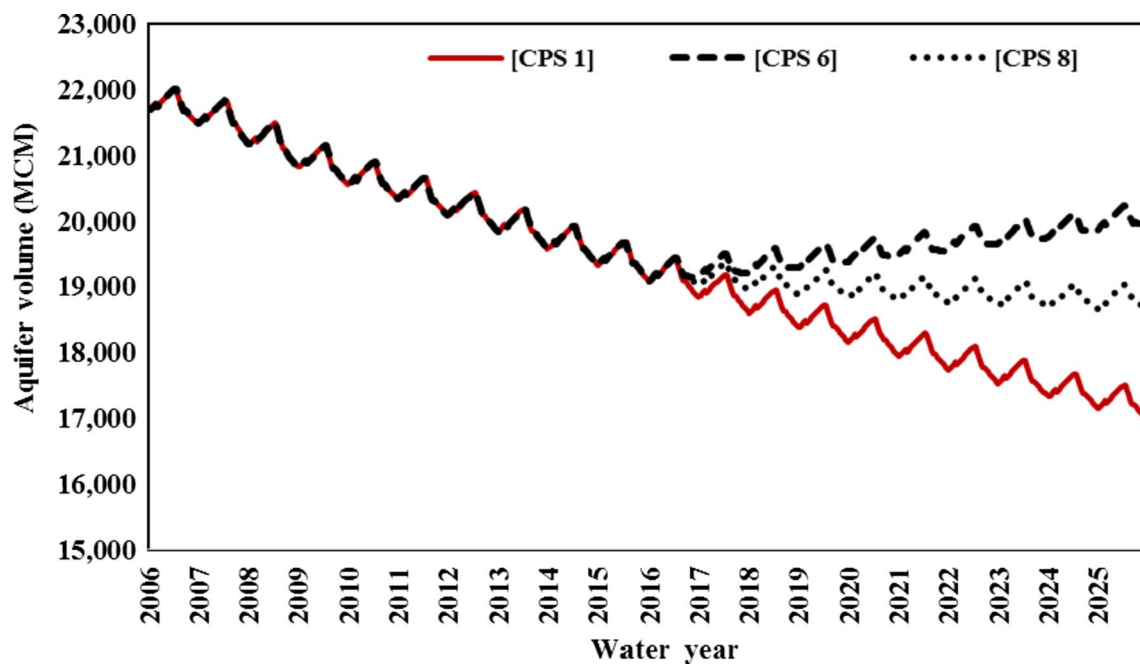


Fig. 12 Aquifer drop behavior in cropping pattern scenarios (CPS)

model's capabilities, it is possible to analyze and utilize different patterns for the purpose of decision making by executives and policymakers.

Conclusion

The present study examined the application of the system dynamics (SD) approach to assess water productivity improvement strategies. In order to formulate the strategies, four key indicators were considered: cropping pattern scenarios (CPS, 8 scenarios), deficit irrigation scenarios (DI, 4 scenarios), modern irrigation systems development (MISD, 4 scenarios), and hybrid scenarios. According to the results, the system dynamics can be used to evaluate the impact of different agricultural water management improvement strategies on yield, water productivity, and the status of water resources. As a result of applying deficit irrigation (DI) scenarios at the field scale, physical water productivity (WP_p) increased for almost all studied crops (except grain corn, which was most sensitive to DI), but economic water productivity (WP_e) increased only for tomato, canola, pea, and barley and decreased for corn (grain (corn) and forage (maize)), potato, beans, lentils, and sugar beet (grain and forage). In addition to the plant's sensitivity to drought stress, DI's effect on WP_e is also affected by the crop economy (crop prices and crop costs) and the amount of water consumed by the plant. Therefore, the effect of a specific DI treatment on the crop WP_e can be various in different years. The DI has increased WP_p on the plain scale, but depending

on the type of cropping pattern and irrigation system development can lead to an increase or decrease in WP_e . Additionally, the modern irrigation system (MISD) has increased the WP_p on the plain scale, and depending on the type of cropping pattern and the deficit irrigation level can lead to an increase or decrease in WP_e . On the plain scale, the cropping pattern scenarios (CPS) had a significant effect on the WP_p and WP_e . The highest economic water productivity (WP_e) was obtained in CPS 4, CPS 6, and CPS 8 by a 21, 18, and 17.5% increase as compared to CPS 1, respectively. The CPS and DI have a significant effect on future aquifer volume and its decline over time. If MISD is not accompanied by increased cultivation area, it can help improve aquifer status. But if MISD results in non-control fallow or increased cultivation area, it will have a negative effect on the aquifer. Overall, the results showed that the effects of water productivity improvement strategies at field and network scales were not the same. Also, non-control fallow levels will have dangerous consequences for the Qazvin aquifer.

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Declarations

Conflict of interest The authors declare no conflicts of interest.

Consent to participate All authors gave explicit consent to participate in this study.

Consent to publish All authors gave explicit consent to publish this manuscript.

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