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Economic impacts of water market simulation in agriculture

Leyla Nourani [a], Seyed Nematolla Moosavi [b,*] and Abdoulrasool Shirvanian [c]

[a] Ph.D. student of Agricultural Economics, Department of Agricultural Economics, Marvdasht Branch, Islamic Azad University, Marvdasht 71787-34748, Iran
[b] Department of Agricultural Economics, Marvdasht Branch, Islamic Azad University, Marvdasht 71787-34748, Iran
[c] Department of Economic, Social and Extension Research Department Fars Agricultural and Natural Resources Research and Education Center Agricultural Research, Education and Extension Organization (AREEO), Shiraz, Iran
*Corresponding author. E-mail: snmousavi@miau.ac.ir

LN, 0000-0002-9547-1504; AS, 0000-0003-0158-5453

ABSTRACT

Water market is one of the modern issues in demand management in face of water scarcity, which is increasingly used in different parts of the world as a tool for optimal allocation of water consumption and transfer of water to consumers with higher final efficiency. Despite the benefits of forming a water market, such markets are not yet developed in developing countries, such as Iran. Accordingly, this study examines the economic impact of water market design on farmers' livelihood in Iran. The data of this study were collected using a multistage random sampling method from 100 users with water rights in the irrigation network of Ramjerd plain in Fars province. The data were analyzed using positive mathematical programming and scenario making. The results showed that with the formation of the water market, the gross margin of the total lands with irrigation network of Ramjerd plain increased from 2,013.080 billion Rials to 2,194.2200 billion Rials. As a result, the agricultural economic situation of the region experienced an increase of 9%. therefore an appropriate legal and regulatory structure is recommended to create a water market on the lands located within the irrigation networks.

Key words: demand management, gross margin, positive mathematical programming, water market

HIGHLIGHTS

- Comprehensive assessment of the effects of water market design on farmers' gross margin and crop pattern by region.
- Application of positive mathematical programming to simulate the effects of water market formation on economic situation of farmers.
- In terms of water transfer costs in order to make the effects of water market policy more realistic.

INTRODUCTION

Rapid population growth in recent decades has led to a sharp increase in water demand for agriculture and industry (IWRM 2010). Moreover, episodic climate change and droughts have been major causes of water shortage in arid and semi-arid regions (Marchiori *et al.* 2012; Ngondjeb 2013; Pakmehr *et al.* 2020; Mirzaei *et al.* 2021). Thus, there is an imbalance between water supply and demand leading to the recognition of future water crises as the greatest global social threat in terms of effect (OECD 2015; WEF 2017; Mirzaei & Zibaei, 2021).

Various views have been offered to resolve this imbalance. Some views focus on improving supply-side policies, while others concentrate on managing demand-side (Grafton & Wheeler 2018). For example, Zetland (2014) believes that due to the continued increase in water demand, solving water shortage problems will not be possible through the application of technical approach related to supply-side measures (such as the construction of dams, irrigation networks, etc.), however, demand-side management strategies are a higher priority (Maqsood *et al.* 2005). Thus, demand management is considered the most fundamental solution to control water consumption and water supply management (Aljanabi *et al.* 2018). There is also another new view in balancing water supply and demand in face of a shortage. According to this view, the water market is one of the effective and ideal tools for reallocating water resources, which can increase the efficiency of water consumption and mitigate the economic impact of water shortage (Randall 1981; Easter & Huang 2014).

The water market is a market with trading sellers and buyers (Xu *et al.* 2018). Agricultural economists explain that by having a system of private property rights capable of transferring water resources, the local and regional water market can strengthen the reliability of the access to water and reduce farmers risk'. It can also lead to an optimal allocation of water (Johansson 2000). In other words, the water market is a mechanism for allocating water based on the exchange of water consumption rights resulting in an optimal allocation of water (Pujol *et al.* 2006). This market consists of agreements by which water rights owners exchange the rights with each other or with new applicants according to certain and pre-determined rules (Kemper 2001). Thus, the water market reallocates water between various consumers based on primary allocation and the transfer of the right to use water resources to other consumers. Hence, the formation of a water market paves the way to transfer water to more value-added consumption (Du *et al.* 2017; Pérez-Blanco *et al.* 2020). In practice, this view has been accompanied by public support as a tool for water management (Rissman *et al.* 2017). Thus, after the successful formation of water markets in the United States and Australia, water markets have been widely implemented by private sectors and governments in various countries, such as Chile (Bauer 2004), South Africa (Nieuwoudt & Armitage 2004), China (Zheng *et al.* 2013) and England (Lumbroso *et al.* 2014).

The agricultural sector is the largest consumer of water resources (Brinegar & Ward 2009; Gao *et al.* 2017). Therefore, water scarcity affects the agricultural sector more than other sectors in society. These effects threaten farmers' livelihoods and access to food security (Pascual *et al.* 2017). Therefore, it seems that the water market view in the agricultural sector is very important to create a balance between water supply and demand.

Agriculture is the largest consumer of water in Iran, consuming about 90% of available water (Boazar *et al.* 2019). Due to the arid geographical position of Iran, rainfall less than one-third of the global average, evaporation of more than three times the global average, inadequate distribution of rainfall, and a share of less than 0.115% of freshwater to feed the growing population and increasing water demand, it is a strategic issue to plan the optimal allocation water for agriculture (Nazemosadat *et al.* 2006; Hadizadeh *et al.* 2018). According to researchers, mismanagement and lack of comprehensive planning have exacerbated the water crisis in Iran (Fani *et al.* 2016; Zargan & Waez-Mousavi 2016). Thus, agricultural policy reform, management approaches and the implementation of water conservation measures to improve farmers' livelihoods can increase the economic efficiency of water use (Hadiyan *et al.* 2020). In this regard, consolidating exchangeable water rights and strengthen water markets are among reforming measures, which can mitigate the impact of these challenges and lead to optimal management of water resources in Iran.

Water market formation and the above-mentioned global experiences have advantages in various countries as a result of the effective role of this market in the optimal allocation of water consumption and transferring water to consumers with higher economic efficiency. However, such a market has not yet been developed in Iran. Therefore, it is important to study the impact of the formation of this market on farmers' livelihood and the cultivation pattern of the region to increase the awareness among stakeholders and policymakers about the function of this market.

In this context, Positive Mathematical Programming (PMP) is one of the main models in the field of mathematical programming. It provides decision-makers with different decision options by creating a diverse decision-making space (Buysse *et al.* 2007; Mardani *et al.* 2016). This model is an empirical method of analysis using all available information to explain producers' responses to external changes (Heckelei 2002; Arfini *et al.* 2008). Unlike Normative Mathematical Programming (NMP), the PMP model adjusts some parameters to accurately reproduce[1] the initial state. Considering the advantages of the PMP model, this model has been consistently used worldwide to evaluate agricultural policies such as the water market (Graveline 2016; Sapino *et al.* 2020). Accordingly, in this study, the impact of water market design on farmers' gross profit (gross margin) was evaluated using the PMP model.

To evaluate the function of the proposed water market approach in this study, the irrigation network of Ramjerd plain in Fars province, Iran, was used as the study area. Ramjerd plain, as one of the most important agricultural areas, has always faced water resource constraints. In the second section, the study area will be explained. Section 3 deals the methodology of the study. The results of the study will be analyzed in the fourth section. Finally, the conclusion and suggestions will be presented in section 5.

STUDY AREA

Ramjerd is one of the important plains located downstream of the Dorodzan dam. It is a part of the Dorodzan Irrigation and Drainage Network in the Northwest of Fars province. Dorodzan irrigation and drainage network is one of the largest irrigation and drainage networks in Iran, located 100 km Northwest of Shiraz on Kor River. The map of the Ramjerd Irrigation network downstream of Dorodzan dam is shown in Figure 1.

[1] Reproduction means that the optimal activity level obtained from the calibrated model exactly matches the values observed in the initial state.

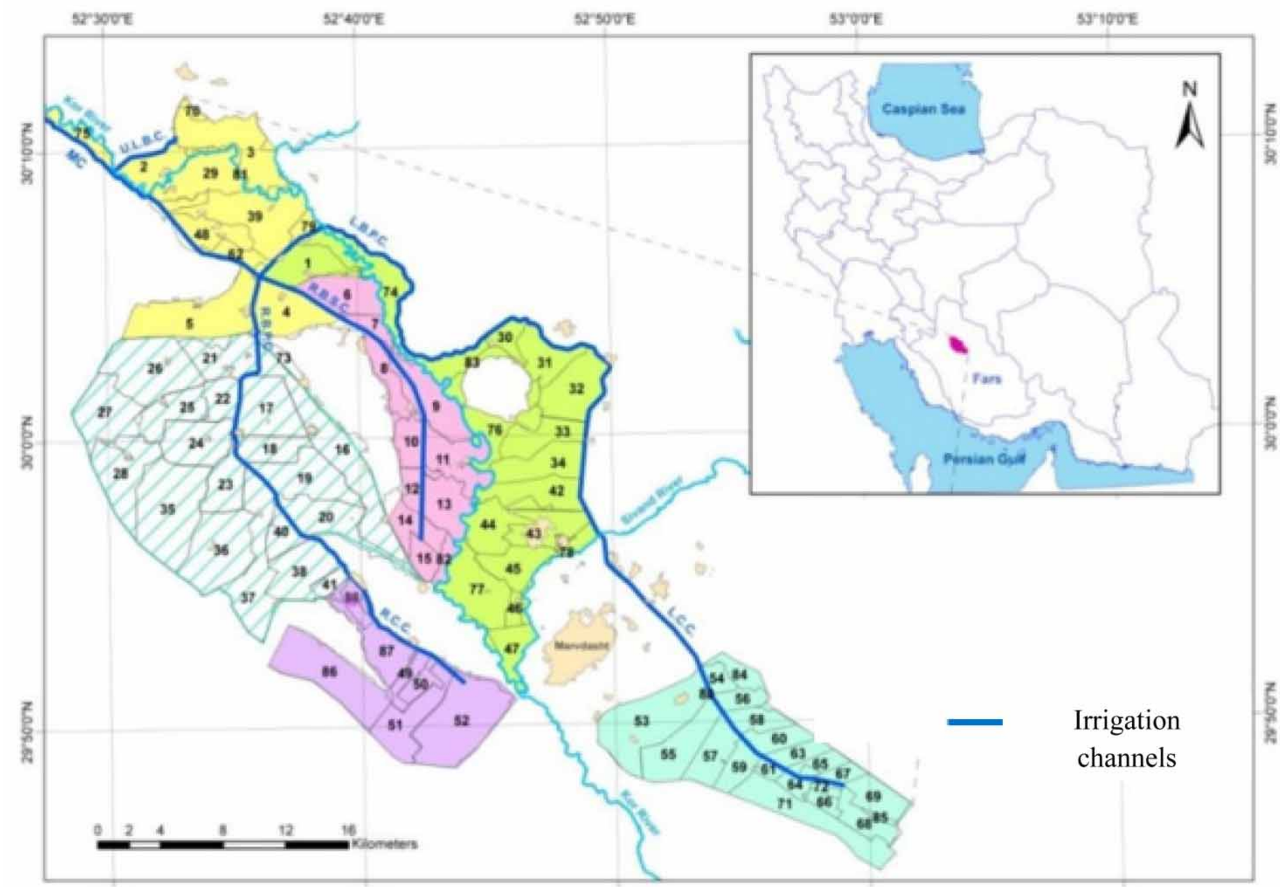

Figure 1 | Ramjerd irrigation network map (in) downstream of Dorodzan dam, Fars province.

The main income of the inhabitants of Ramjerd plain comes from agriculture. Farmers are mainly engaged in agriculture, and the water needed for 42,000 hectares of land in Ramjerd is supplied by the irrigation and drainage network (Fars Regional Water Company 2012). This irrigation network consists of the main channels and sub-channels including Ordibehesht, Hamoon, Abraj, and Left channels (Figure 2). In April and May, the entry of water into the channels is high, in November there is little water, and in February there is no water in the channels. Compared to other channels, Hamoon receives less water, which is higher in the Abraj channels with the lowest cultivation level in most years. This is a sign of injustice in water distribution resulting in discontent among farmers. Other problems of this region are the lack of investment in modern irrigation systems owing to the high cost and lack of profitability due to small cultivated areas and traditional irrigation channels and irrigation methods (Fars Regional Water Company 2012). According to the conditions mentioned in this area, the continuation of this process will lead to instability of the water resources, while creating serious challenges in agriculture and lowering the standard of farmers' livelihood.

MATERIALS AND METHODS

The present study uses the PMP model to investigate the impact of water market simulation on the economic situation of farmers in Ramjerd plain, Fars province. The general framework of materials, methods, and evaluation process to achieve the goal is presented in Figure 3. The general framework and methods show that it is necessary to know the study area and collect data first. Then, the process of specifying the PMP model was carried out to solve the linear programming model in the base year and determine the dual values. The parameters of the nonlinear objective function were estimated by calibrating the cost function. Finally, the final programming model was prepared and the water market formation scenario was implemented. Its impact on gross profit (gross margin) was evaluated as a measure of farmers' economic status. The sensitivity analysis of the model was conducted by changing the price of water to check the validity of the model and determine the equilibrium price of water in the market. Then, the obtained equilibrium price was used in the final model.

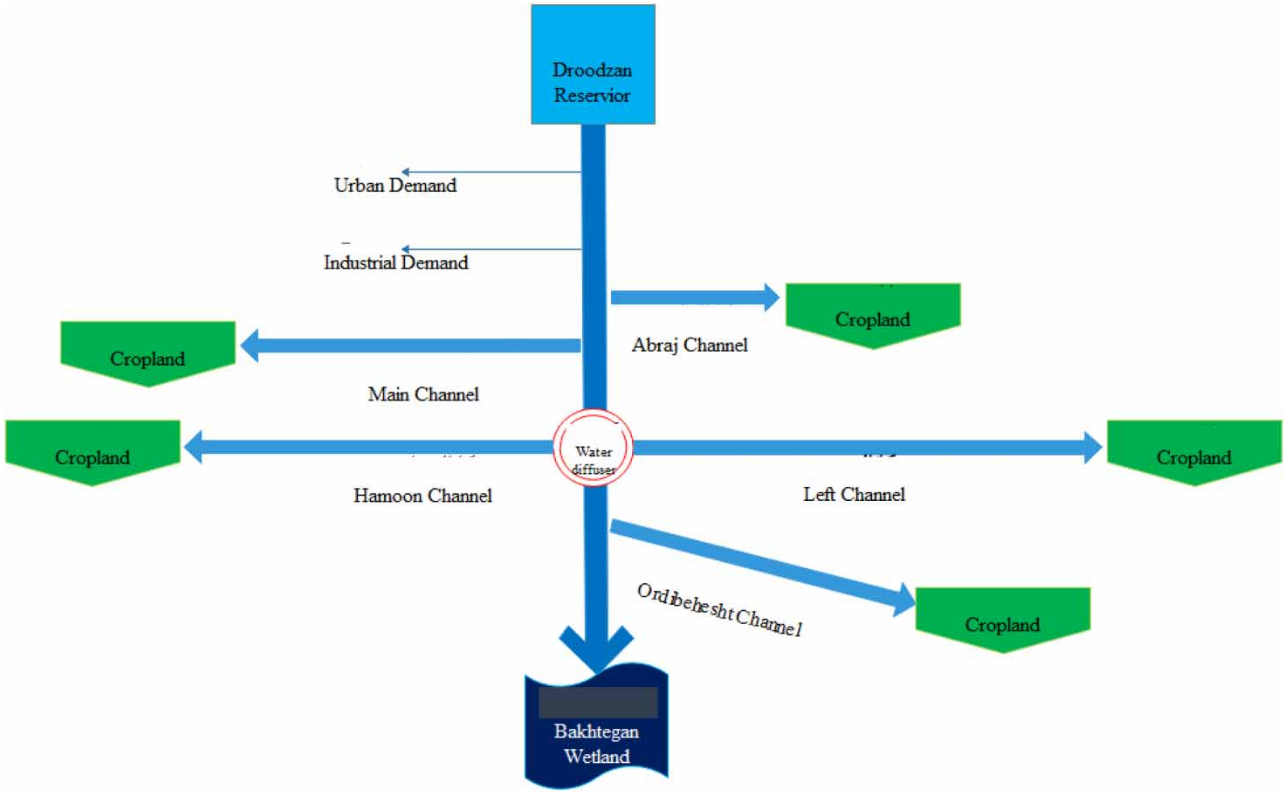

Figure 2 | The schematic diagram of the location of the irrigation and drainage channels of the Ramjerd plain downstream of the Dorodzan dam.

The PMP model assumes an equilibrium on the base year and from the level of activities observed in the base year. Additional information is extracted to define a nonlinear objective function in a way that the results of this nonlinear model are closed to the observed values (Sapino *et al.* 2020).

Positive Mathematical Programming (PMP) includes three general steps (Howitt 1995):

1. Specifying the linear programming model while considering calibration constraints.
2. Application of dual values of the first step model to determine the parameters of the nonlinear objective function.
3. Application of calibrated objective function as a nonlinear programming model to analyze policies and scenarios.

Before explaining the PMP algebraic model, all variables, parameters, and sets used in this model are summarized in Tables 1 and 2.

Step 1: solving the linear programming model and determining dual values

In the first step, calibration constraints are added to all resource constraints of a linear programming model, which limit the level of activity to the observed levels of the base period. Assuming that the total regional profit is maximized, the initial model is as follows in Equations (1)–(6) (Howitt 1995; Howitt *et al.* 2012):

$$Maximize\ \ Z = \sum_g \sum_i \left(v_i\, yld_{gi} - \sum_j c_{gij} \right) x_{gi,land} - \sum_g \sum_i (TEW_{ig}.Pw) x_{gi,land} \tag{1}$$

$$Subject\ to: \sum_i a_{gij}\, x_{gi,land} \leq b_{gj} \quad \forall g, j \quad [\lambda^1] \tag{2}$$

$$\sum_i TEW_{ig}\, x_{gi,land} \leq TWU_g \quad \forall g \quad [\lambda^1] \tag{3}$$

$$x_{gi,land} \leq \tilde{x}_{gi,land} + \varepsilon \quad \forall g, i \qquad [\lambda^2] \tag{4}$$

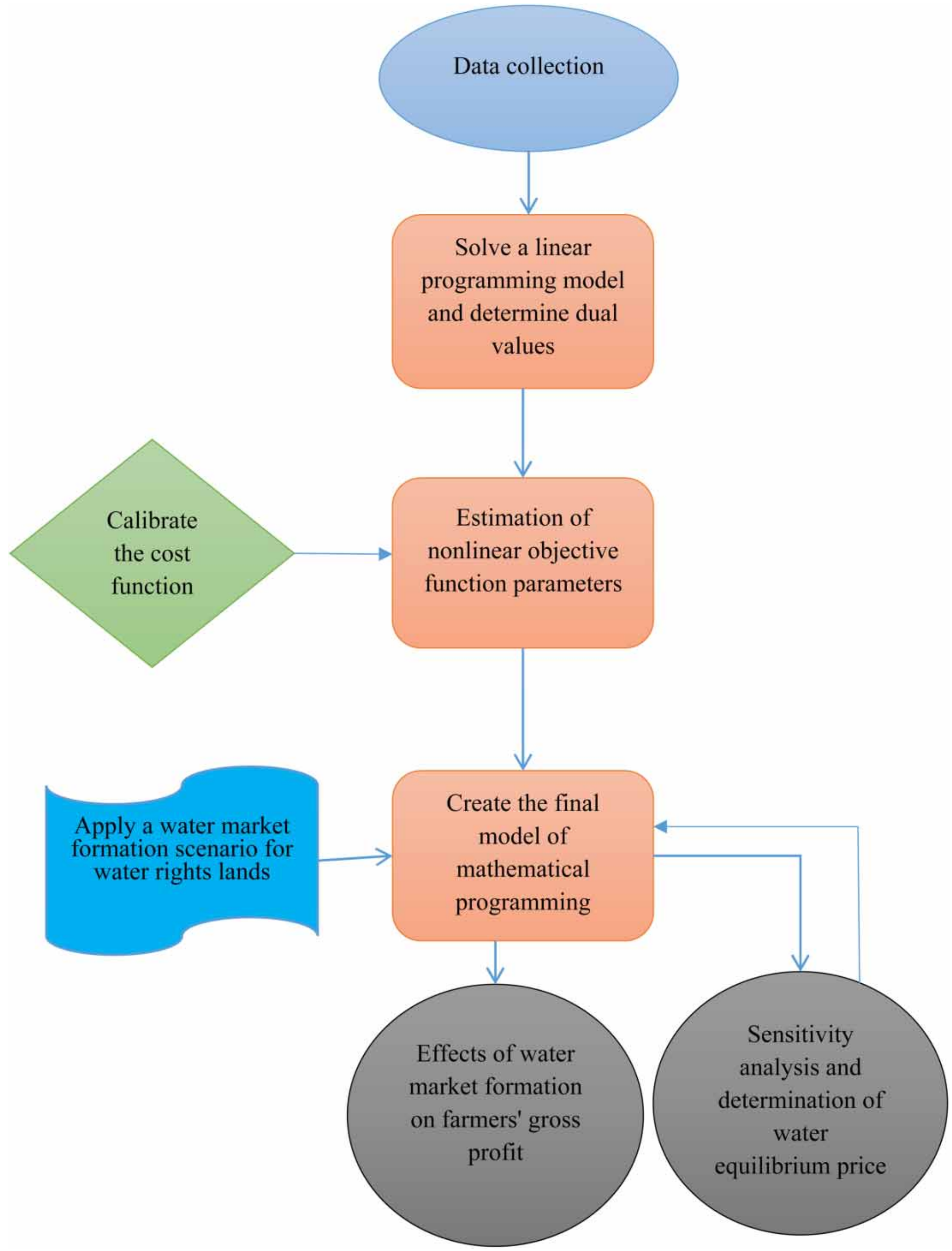

Figure 3 | The framework of materials, methods, and process of the study.

Table 1 | Explanation of variables and study sets

Type	Sign	Explanation	Type	Sign	Explanation
Set	i	Crop type	Variable	λ^1	Dual variables related to resource constraints
Set	j	Type of crop inputs	Variable	λ^2	Dual variables related to calibration constraints
Set	g	Agricultural areas	Variable	Z	Objective function value (gross profit)
Variable	$x_{gi,land}$	Area under cultivation			

Table 2 | Explanation of study parameters

Sign	Explanation	Sign	Explanation
v_i	Price crop	Pw	Water price
a_{gij}	The amount of use of the production inputs	d	Linear component parameters of the cost function
$\tilde{x}_{gi,land}$	Area under crop cultivation i in the base year	Q	Quadratic component parameters of the cost function
c_{gij}	Cost of inputs except water	TEW_i	Water requirements
b_{gj}	Amount of input available except water input	$b^{+}_{gi,land}$	Maximum area under cultivation
ε	Small positive numbers	$b^{-}_{gi,land}$	The minimum amount of cultivated area
TWU_g	Available water rights	yld_{gi}	Crop yield
TEW_{ig}	Water requirements	C_i^v	Variable costs
a_{gij}	Technical coefficients of inputs except water input	Wtc	The cost of transferring each cubic meter of water

$$b^{-}_{gi,land} \le x_{gi,land} \le b^{+}_{gi,land} \quad \forall g, i \tag{5}$$

$$x_{gi,land} \ge 0 \quad \forall g, i \tag{6}$$

Equation (1) shows the objective function of maximizing gross margin (gross profit) and Equations (2) and (3) present systemic constraints. More specifically, Equation (2) presents a constraint related to crop input other than water, and Equation (3) presents a constraint related to water input where the consumption should be less than the amount of available input. Equations (4) and (5) present the constraints of the calibration model. Equation (6) provides the constraint of the non-negative level of activities.

Howitt (1995) and Heckelei (2002) interpreted the vector of λ^2 dual values associated with calibration constraint to represent any type of model specification error, data error, aggregation error, risk behavior, and price expectations. In the calibration of an ascending nonlinear cost function, the dual vector of λ^2 is interpreted as the differential marginal cost vector. Together with cost vector (C), it determines the marginal and the actual cost of producing the observed *i* activity, which is discussed in the next section.

Step 2: estimation of nonlinear objective function parameters

In the second step, the dual values obtained in the first step are used to estimate the parameters for the nonlinear objective function. In other words, in this step dual values are used to calibrate the parameters of the nonlinear objective function. In this case, the activity levels observed during the base period are replicated by the objective nonlinear function without calibration constraints (Howitt 1995). To calibrate the model, the quadratic cost function was used as in Equation (7):

$$\mathrm{C}_{\mathrm{i}}^{\mathrm{v}} = \sum_{\mathrm{g}} (\mathrm{TEW}_{\mathrm{ig}}.\mathrm{Pw}) + \sum_{\mathrm{g}} \sum_{\mathrm{j}} \mathrm{c}_{\mathrm{gij}} = \mathrm{d}'\mathrm{x} + \frac{1}{2}\mathrm{x}'\,\mathrm{Qx} \tag{7}$$

where vector $d\ (n\times 1)$ is one of the component parameters of the linear cost function and Q is the semi-definite positive matrix and symmetric with $(n\times n)$ dimensions of the component parameters of the quadratic cost function.

Howitt (1995) showed that the marginal cost (MC) vector for the aforementioned cost function, is equal to the sum of the accounting cost vector (c) and the differential final cost vector(λ^2) according to Equation (8):

$$MC_i = \frac{\partial C_i^v(x)}{\partial x} = d + Qx = c + \lambda^2 \tag{8}$$

The Heckelei & Britz (2000) proposed approach was used to estimate the parameters of the cost function. This method assumes that the observed vector of the accounting cost for each activity (c) is equal to the average cost of the quadratic cost function for each crop. Consequently, the values of the vector *d* parameters and the diagonal elements of the matrix

Q are obtained using the following Equations (9) and (10):

$$q_{ii} = \frac{2\lambda_i^2}{\tilde{x}_i} \tag{9}$$

$$d_i = c_i - \lambda_i^2 \tag{10}$$

where d is the linear component of the cost function and q is the diagonal elements of the cost function (Hardaker *et al.* 2004).

Step 3: creating a final nonlinear programming model

In the third step of the PMP method, the functions estimated in the previous step were examined in the objective function of the problem. A nonlinear programming model similar to the original problem was used except for calibration constraints but considering other systemic constraints. The nonlinear objective function in this step is in the form of Equation (11):

$$Maximize\ \ Z = \sum_g \sum_i (v_i\ yld_{gi})\, x_{gi,\,land} - \sum_g \sum_i \left(d_i + \left(\sum_g \sum_{ii} (q_{i,ii} * x_{gi,\,land}) \right) * x_{gi,land} \right) \tag{11}$$

Water market formation model

Designing a water market requires first to describe the exchange mechanism in the market (Figure 4). According to Figure 3, two groups of farmers A and farmers B are assumed in the water market and their share of water in the water market is ATW and BTW, respectively. In the absence of water markets, each group of farmers attempts to maximize their benefits with the amount of water available. The level less than the water input demand curve for each group of farmers is the total value of the farmer's production from water consumption. Therefore, the amount of water (TW) for Group B farmers is the total value of production (income) equal to the SRBTW area, and for Group A farmers equal to the LHATW area. In other words, the value of the marginal production for water input for Group A and B farmers is equal to HTW and RTW, respectively. Because the input demand curve is the same as the value marginal product (VMP) curve.

Now, we assume that a water market is created and the possibility to exchange water between different groups of farmers is established. In this case, Group B farmers would be buyers of the water due to the higher marginal production value. Group A farmers would be sellers of the water in the market owing to the lower marginal production value of water input. Group A and Group B farmers can maximize their profit respectively by buying and selling water. The question now is at what point both groups of farmers reach the maximum profits? The answer would be the maximum profit, which is provided at the point where the demands of the two groups of farmers are met. In this way, Group B farmers buy water equivalent from TW to OW, and Group A farmers sell the same amount of water. Hence, the value of the production of Group B farmers will increase by the area of ORTWOW and the cost of buying water is OMTWOW. The results indicate that increasing the value of the products of Group B farmers is more than the cost of buying water. Thus, the formation of the water market and the exchange of water between farmers result in a profit equivalent to ORM for Group B farmers. Due to the formation of the water market and the sale of water by Group A farmers, the value of their products will decrease by the size of the area

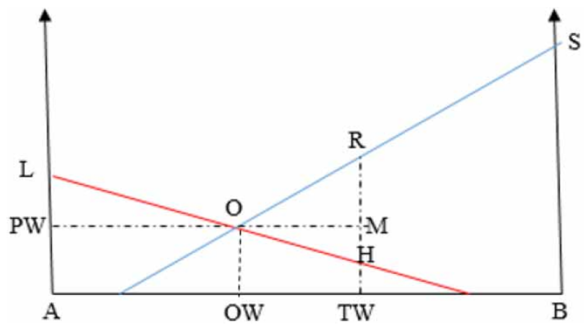

Figure 4 | A water market mechanism model.

OHTWOW. The income of Group A farmers from the sale of water is OMTWOW area. The results indicate that the income from the sale of water is more than the decrease in the value of the products of Group A farmers. Thus, the formation of a water market and the sale of water by Group A farmers results in a profit equivalent to OMH for Group B farmers. The total increase in profit of the two groups of farmers is the ORH area indicating the improvement in the economic status of farmers.

Finally, to examine the scenario of water market formation, the objective function will be in the form of Equation (12) and the constraints of the model would be the same as constraints of the model without water market, except for the amount of water consumed as Equation (13):

$$\begin{aligned} Maximize\ \ Z = & \sum_g \sum_i (v_i\, yld_{gi}) x_{gi,land} + PW * \sum_g \left(TWU_g - \sum_i TEW_{ig}\, x_{gi,land} \right) \\ & - \sum_g \sum_i \left(d_i + \left(\sum_g \sum_{ii} (q_{i,ii} * x_{gi,land}) \right) * x_{gi,\,land} \right) \end{aligned} \tag{12}$$

$$Subject\ to\!:\ TWU_g - \sum_i TEW_{ig}\, x_{gi,land} = sb \tag{13}$$

TMU is the specific amount of water rights for each region, and $\sum_i TEW_{ig}\, x_{gi,land}$ specifies water consumption in each region. PW specifies the cost of water. If the amount of water rights is more than the amount of water consumption in each area that area will sell and benefit the water. If the amount of water consumption is more than the water rights, that area will buy the water and the cost of purchasing water will be deduced from the gross margin**.** *sb* in Equation (13) indicates the difference between water rights and water consumption.

The cost of the water market was included in the model to study the effect of water market formation on the conditions of farmers. Considering the cost of water transfer, Equation (1) will be replaced by Equation (14):

$$Maximize\ \ Z = \sum_g \sum_i \left(v_i\, yld_{gi} - \sum_j c_{gij} \right) x_{gi,land} - \sum_g \sum_i (TEW_{ig}.(Pw + Wtc)) x_{gi,land} \tag{14}$$

Given the cost of water transfer, Equation (7) will be changed to Equation (15):

$$C_i^v = \sum_g (TEW_{ig}.(Pw + Wtc)) + \sum_g \sum_j c_{gij} = d'x + \frac{1}{2} x'Qx \tag{15}$$

Considering the cost of water transfer, Equation (12) will turned to Equation (16):

$$\begin{aligned} Maximize\ \ Z = & \sum_g \sum_i (v_i\, yld_{gi})\, x_{gi,\,land} + (PW + Wtc) * \sum_g \left(TWU_g - \sum_i TEW_{ig}\, x_{gi,land} \right) \\ & - \sum_g \sum_i \left(d_i + \left(\sum_g \sum_{ii} (q_{i,ii} * x_{gi,land}) \right) * x_{gi,land} \right) \end{aligned} \tag{16}$$

Required data and data collection method

To investigate the effects of water market formation on the irrigation network of Ramjerd plain, 13,733 hectares of lands covered by this basin with water rights were included in the analysis. In this study, the required data included the information about functions, technical coefficients of production input, and production cost extracted through a questionnaire and interviews with the farmers in the study area. For this purpose, a sample of farmers covered by the irrigation network of Ramjerd plain was selected using a multistage random sampling model. Based on this, the current water consumption was calculated first. Then, according to the area under cultivation in the census by Fars Regional Water Authority in the year 2016, the amount of water withdrawn in each village was divided by the area under cultivation in that village to obtain the amount of water consumed per hectare of cultivated land. Then, to determine the number of sample villages in each group, a simple random sampling model was used as Equation (17):

$$n = \frac{NS^2}{(N-1)D + S^2} \tag{17}$$

where n is the number of samples for each group, N represents the number of community members (number of villages in each group), s^2 is the variance of water consumption in each group and D shows the estimation error, which is calculated from the Equation $D = b^2/4$. Also, b is the amplitude of the estimation error, the amount of which is for groups 1–3. It was considered as 3,000, 900, 15,000 m^3 of water according to water consumption data, respectively. Accordingly, a total of 100 farmers was randomly chosen for interviews. The clustering was done based on the values obtained by the SPSS software and the villages were divided into three groups based on water consumption. The calculated sample volume is presented in Table 3.

Other information regarding the status of water resources, water requirement of crops, specific water rights of channels, the area under cultivation of crops, and area of lands with water rights were obtained from Fars Regional Water Authority.

RESULTS

Given the role of price in market formation, Figure 5 provides information on the water market price and its sensitivity analysis.

According to the information in Figure 5, a change in the price of water causes a difference in the quantity of water supply by sellers and the quantity of water demand by buyers. The positive values of the difference between supply and demand indicate a surplus of water supply and the negative values represent an excess of water demand. This matches theory and market expectations. Hence, when the prices are low, excess demand will be created in the market. Moreover, as prices rise, excess demand gradually decreases. When the price continues to rise, the excess demand will be replaced by surplus supply, which

Table 3 | Statistical sample in each of the exploitation groups in the irrigation network of Ramjard plain

Group number	Water consumption	Population size (person)	Sample size (person)
1	Low	660	38
2	Medium	218	30
3	High	230	32

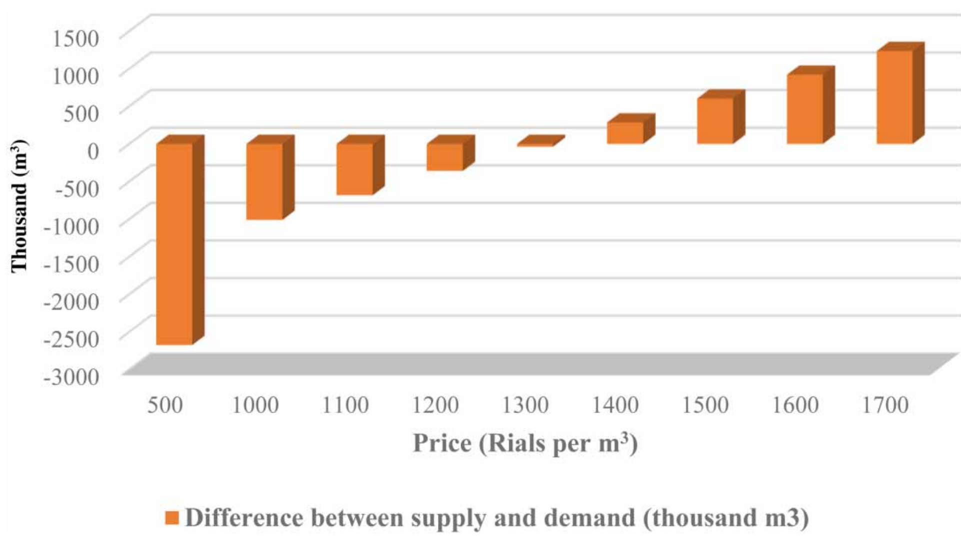

Figure 5 | Water price sensitivity analysis to form an assumptive water market.

Table 4 | Equilibrium price and total water exchanges in the equilibrium price of water market

Item	Values
Equilibrium price (Rials per m^3 of water consumed)	1,311
Total water exchanges (million m^3)	25.291

dominates the market. As seen in Figure 5, for the prices less than 1,400 Rials per m^3 of water consumption, there is an excess of water demand. For the prices of 1,400 and above there is a surplus of water supply in the market. Therefore, it is concluded that the equilibrium price in the water market of Ramjerd plain irrigation and Dorodzan dam downstream drainage network is in the range of 1,300–1,400 Rials per m^3 of water consumption. Table 4 represents the exact price of water, which is the equilibrium price of the market and the volume of the water exchanged at this price in the water market.

The results of Table 4 indicate that, for 1,311 Rials per m^3, equilibrium is achieved on the water market. At this price, the total supply or market demand is about 25.291 million m^3, which can be exchanged between lands with water rights.

Considering the possibility of this volume of water exchange in case of water market formation, Table 5 shows the combination of crop pattern and the total land area of the Ramjerd plain irrigation network in two situations with and without a water market. According to the information in this Table 5, the combination of crop patterns with the presence of a water market shows that the composition of cultivation has not changed much compared to the conditions without a water market and only barley production is removed from the crop pattern. In addition, with the presence of the water market, the total area under cultivation increases from 12.259 hectares to 13.733 hectares representing an increase of 12%.

Among the crop pattern, in the presence of a water market, three crops of rice, wheat, and sugar beet showed 10.45%, 23.17%, and 40.67% increase in area under cultivation respectively compared to conditions without a water market. Thus, improvement of farmers' living conditions can be expected due to changes in the crop pattern. As rice and sugar beet are two high-yield crops increasing the gross margin of farmers. Figure 6 provides a clearer understanding of this problem.

Figure 6 shows that the water market improves the gross margin of lands with water rights in Ramjerd plain from about 2,194.200 billion Rials to 2,013.080 billion Rials, which is equivalent to 9%. As a result, the formation of the water market in this region can improve the economic status of the farmers.

Considering the separation of cultivated lands by irrigation channels and the possibility of exchanging water among the lands covered by channels, Table 6 indicates information on the impact of the water market on cultivated lands covered by each channels. According to Table 6, with the formation of the water market, the gross margin of the lands with water rights covered with main channels, Abraj, Left, Hamoon, and Ordibehesht show an increase of 13.906, 3.63, 19.900, 135.224, and 8.440 billion Rials respectively compared to the lack of water markets. Thus, water market formation has the most positive effect (+18.83%) on the lands covered by the Hamoon channels and the least positive effects on the lands covered by the Ordibehesht channels (+2.35%).

Next, the details of excess water demand and surplus supply in each irrigation channels will be examined. Figure 7 shows the status of water exchange in different areas at the level of irrigation and drainage network of Ramjerd plain downstream of the Dorodzan dam with and without a water market.

Table 5 | Pattern of cultivation of agricultural lands of Ramjerd plain irrigation network with and without a water market

Crops	Without water market (hectares)	With water market (hectares)	Changes (hectares)
Wheat	5,322	6,555	+1,233 (+23.17%)
Rice	1,040	1,463	+423 (+40.67%)
Maize	2,547	2,614	+67 (+2.67%)
Barley	400	0	−400 (−100%)
Sugar beet	354	391	+37 (+10.45%)
Tomatoes	2,596	2,710	+114 (4.39%)
Total	12,259	13,733	+1,474 (12%)

Values in parentheses indicate the percentage change.

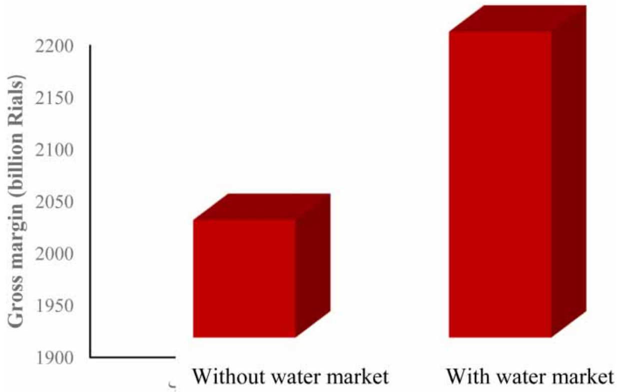

Figure 6 | The gross margin of Ramjerd irrigation channels with and without the water market.

Table 6 | Comparing the gross margin of irrigated lands covered by different irrigation channels without/with the water market

Channels	Gross margin without water market (billion Rials)	Gross margin with water market (billion Rials)	Changes
Main channels	335.952	349.858	+13.906 (+4.14%)
Abraj channels	60.208	63.838	+3.630 (+6.03%)
Left channels	539.804	559.704	+19.900 (+3.69%)
Hamoon channels	718.291	853.515	+135.224 (+18.83%)
Ordibehesht channels	358.829	367.269	+8.440 (+2.35%)

Values in parentheses indicate the percentage change.

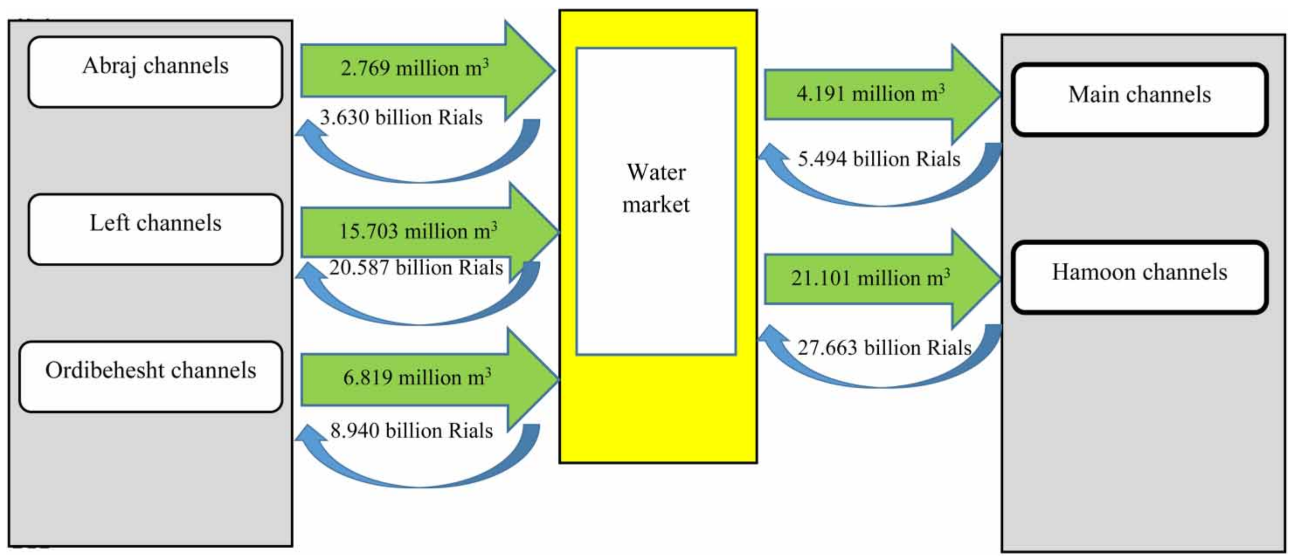

Figure 7 | Water market status of the lands covered by irrigation and drainage network of the Ramjerd plain.

Based on the information in Figure 7, three areas covered by Abraj, Left, and Ordibehesht channels supply water to the market while two areas covered by main and Hamoon channels demand water from the market. Also, the value of water supply and demand on the market is equal to each other as 33.157 billion Rials. According to Figure 7, the highest and the lowest water supply is provided by the farmers in the lands covered by Left channels and Abraj channels, respectively. The farmers of the Hamoon channels are mostly demanding to buy water.

One of the issues in water market formation is the costs related to water transportation. Tables 7 and 8 analyze the sensitivity of the impact of water transfer costs between users of the lands covered by different irrigation channels of Ramjerd plain in different scenarios of water transfer costs equal to 10, 20, and 30% of water price on the crop pattern gross and margin of the region.

The results indicate that the increase in the water transfer cost slightly increases the area under cultivation of wheat, fodder corn and slightly decreases the area under cultivation of rice, sugar beet, and tomato. Therefore, the cost of water transfer will not have a great impact on the share of different crops in the crop pattern. To understand the economic impact of water transfer cost, the rate of gross margin in different scenarios of water transfer costs by land covered by irrigation channels of Ramjerd plain is presented in Table 8.

The results of Table 8 indicate that, in the aforementioned scenarios, the gross margin of water-demanding areas including lands covered by the main channels and Hamoon decreases slightly. However, the gross margin of water-supplying areas including lands covered by Abraj, Left, and Ordibehesht increased slightly. In general, the cost of water transfer under the market scenario affects the crop pattern and gross margin of Ramjerd plain, but to an insignificant extent.

To illustrate the effect of water transfer costs on the total hypothetical water market, Figure 8 shows the status of water exchanges among lands covered by different channels in the fourth scenario, which involves the highest water transfer costs.

According to Figure 8, the three areas covered by Abraj, Left, and Ordibehesht channels are still supplying water to the market and the two regions covered by the main channels and Hamoon are still demanding water from the market. However, the amount of water exchange in the Ramjerd plain irrigation network increases from 25.229 to 25.697.3 million m^3. Also, the value of exchanges rises by about 10.645 billion Rials as a result of the cost of water transfer. Therefore, it can be inferred that there is no change in water supply and demand regions in terms of water transfer cost. However, the quantity and value of water exchanges increase at the irrigation network level.

Table 7 | Arable area of Ramjard plain irrigation network with the water market in different scenarios of water transfer costs (unit: hectare)

Crops	Scenario 1 (no transfer cost)	Scenario 2 (10% water price)	Scenario 3 (20% water price)	Scenario 4 (30% water price)
Wheat	6,555	6,577	6,598	6,618
Rice	1,463	1,444	1,426	1,409
Maize	2,614	2,618	2,622	2,626
Barley	0	0	0	0
Sugar beet	391	390	388	387
Tomatoes	2,710	2,704	2,699	2,693
Total	1,373	13,733	13,733	13,733

Table 8 | Comparing the gross margin of water rights lands and with the water market and under different water transfer costs (unit: billion Rials)

Channels	Scenario 1 (no transfer cost)	Scenario 2 (10% water price)	Scenario 3 (20% water price)	Scenario 4 (30% water price)
Main channels	349.858	348.810	347.774	346.750
Abraj channels	63.838	64.187	64.535	64.883
Left channels	559.704	560.957	562.235	563.536
Hamoon channels	853.515	848.241	842.986	837.749
Ordibehesht channels	367.269	367.651	368.046	368.452

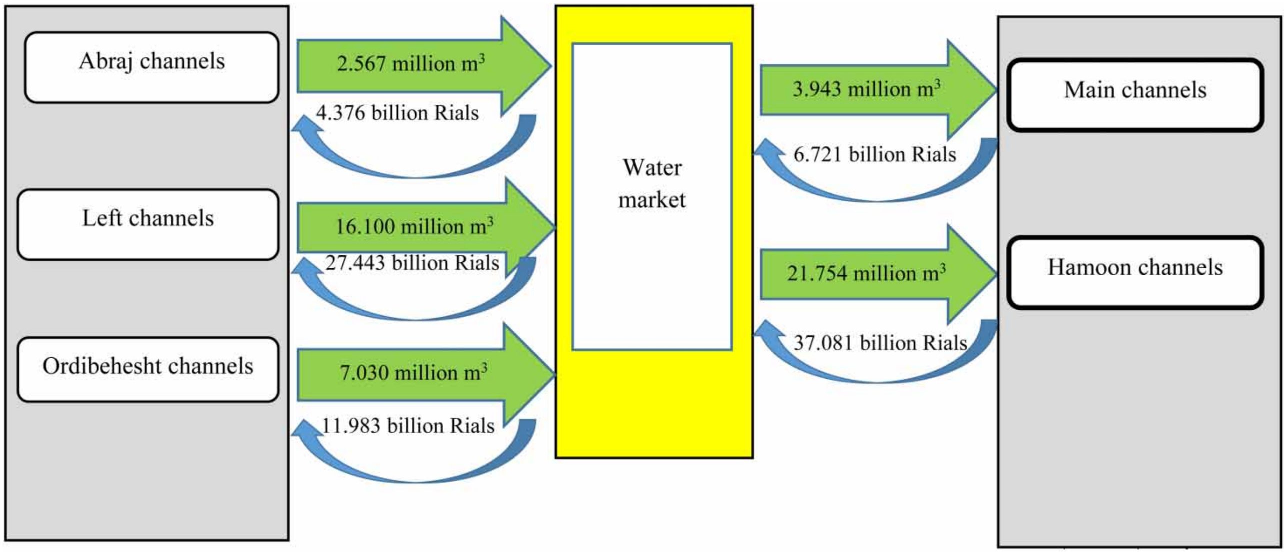

Figure 8 | The state of the water market of the land covered by the Ramjerd plain irrigation network, considering the cost of water transfer between different regions.

CONCLUSION AND RECOMMENDATIONS

Water price is one of the key parameters of the water market model. In this study, the value of 1,311 Rials per m^3 of water was obtained as the price of water for consumption and exchange on the market. The results of the sensitivity analysis indicated that at prices below the equilibrium price, there is an excess of demand. Moreover, at prices above the equilibrium price, there is a surplus of supply in the water market. Hence, the results of the sensitivity analysis prove the validity of the designed model. According to theoretical issues, prices above the equilibrium price of surplus supply and at prices below the equilibrium price of excess demand prevail in different markets. Then, the designed water market was solved by considering the price of 1,311 Rials per m^3 of water in the form of PMP. The results of the PMP model indicated that the formation of a water market increases the area under cultivation of crops except for the barley. As a result, increasing the area under cultivation can lead to an increase in agricultural production. Among the products, there is an increase in the cultivated area of high-yield crops with high water consumption, such as rice, tomatoes, and sugar beets. Thus, with the formation of the water market and with a certain amount of water rights, the increase in the cultivation of high-yield water products will be achieved. Therefore, given the existing agricultural potential and water rights, the water market provides a good opportunity to exchange water to improve the economic status of farmers in the region covered by the water market. Hence, the composition of their crop pattern is particularly improved to improve the region's economy. Thus, it is vital to pay attention to create the necessary platform for marketing the products added to the pattern, which requires facilitating the marketing of these products through the necessary policies in this area.

In a more detailed look at the effects of the water market formation, it is indicated that water demanders (farmers covered by main channels and Hamoon) on average have higher gross margin than water suppliers (farmers covered by Abarj, Left and Ordibehesht channels). This suggests that in the areas demanding water (water demander), there is the potential to improve the gross margin by changing the cropping pattern. However, in the areas known as water suppliers, it is not possible to improve gross margin by changing crop patterns.

Considering water transfer costs between users covered by different irrigation channels of Ramjerd plain, it was found that these costs do not have a significant impact on the composition of the water supply and demand group. However, they affect the volume and value of exchangeable water to some extent. Another noteworthy point about the agricultural water market is that the infrastructure should be provided to encourage farmers to invest in the water sector and the use of irrigation technologies to save water. Thus, they enter the water market and earn revenue from its sale and optimal use. Therefore, the adoption of the necessary rules and regulations and the establishment of an appropriate mechanism for close monitoring of this market should be on the agenda.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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