Official Journal of the World Water Council
Water Policy

Water Policy Vol 25 No 9, 851 doi: 10.2166/wp.2023.122

Evaluating water policies under the changing conditions of climatic variables in North Khorasan Province, Iran

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ABSTRACT

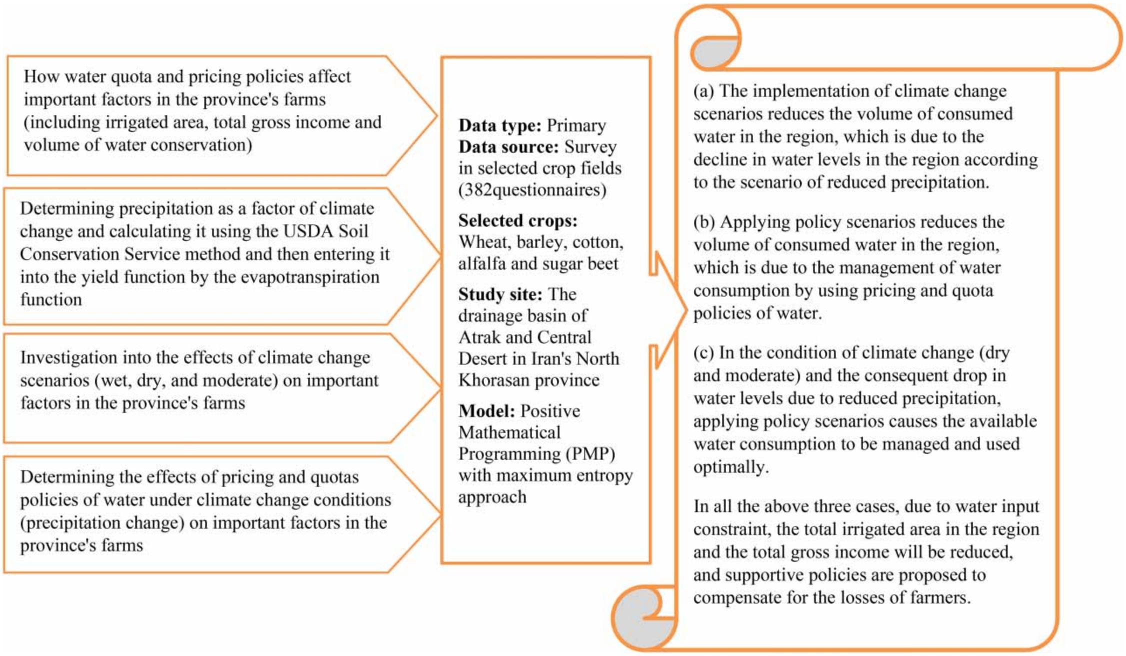
The paper aimed to evaluate the impacts of water pricing and quota policies under changing climatic conditions on the major production factors using economic-biophysical modeling. The data were collected by 382 questionnaires focusing on wheat, barley, cotton, alfalfa, and sugar beet crops in the 2017–2018 cropping year in North Khorasan Province, Iran. Climate change scenarios were defined as wet, moderate, and dry scenarios resulting from precipitation changes. The results showed that climate change scenarios reduce the total irrigated area of crops and total water used. Due to the effect of precipitation on crop yield, dry and moderate climate changes reduce the total gross income, while wet climate changes increase it. The scenarios of quota and pricing policies were then applied under climate change scenarios. The amount of water conserved by applying the quota policy was equal to the quota rate, while the impact of the pricing policy varied depending on the type of climate change. The highest amount of water conserved belonged to the conditions of dry climate change in Atrak and Central Desert catchments, which was about 6.8–8.6 and 3.83–14.48%, respectively. As the climate moves toward drought conditions in this province, the implementation of such policies can partially protect water resources.

Key words: Climate change, Economic-biophysical modeling, North Khorasan Province, Policy-making, Water

HIGHLIGHTS

- The effects of climate change and water policies scenarios were evaluated by an economic-biophysical modeling for the major crops in the 2017–2018 cropping year in North Khorasan province.
- The climate change will reduce the irrigated area and the total gross income of farmers.
- By the quota and pricing policies of water under climate change conditions, the available water for optimal consumption can be managed.

GRAPHICAL ABSTRACT



How water quota and pricing policies affect important factors in the province's farms (including irrigated area, total gross income and volume of water conservation)

Determining precipitation as a factor of climate change and calculating it using the USDA Soil Conservation Service method and then entering it into the yield function by the evapotranspiration function

Investigation into the effects of climate change scenarios (wet, dry, and moderate) on important factors in the province's farms

Determining the effects of pricing and quotas policies of water under climate change conditions (precipitation change) on important factors in the province's farms

Data type: Primary
Data source: Survey in selected crop fields (382questionnaires)

Selected crops: Wheat, barley, cotton, alfalfa and sugar beet

Study site: The drainage basin of Atrak and Central Desert in Iran's North Khorasan province

Model: Positive Mathematical Programming (PMP) with maximum entropy approach

(a) The implementation of climate change scenarios reduces the volume of consumed water in the region, which is due to the decline in water levels in the region according to the scenario of reduced precipitation.

(b) Applying policy scenarios reduces the volume of consumed water in the region, which is due to the management of water consumption by using pricing and quota policies of water.

(c) In the condition of climate change (dry and moderate) and the consequent drop in water levels due to reduced precipitation, applying policy scenarios causes the available water consumption to be managed and used optimally.

In all the above three cases, due to water input constraint, the total irrigated area in the region and the total gross income will be reduced, and supportive policies are proposed to compensate for the losses of farmers.

1. INTRODUCTION

Agriculture is a vital economic sector worldwide, providing food, energy, and livelihood to a growing human population (Wreford & Topp, 2020). Climate change is increasingly recognized as a serious threat to agriculture (IPCC, 2014), one of whose possible consequences is the aggravation of water scarcity. Temperature rise results in a higher rate of evapotranspiration, which subsequently increases the water demand of crops. Furthermore, the projected increase in the variability of precipitation will lead to a more uncertain and scarce water supply in the future (Feike & Henseler, 2017). The occurrence of erratic extreme events has increased as well.

Water scarcity could be addressed by using different policy intervention mechanisms directed both at demand- and supply-side management. Demand-side management policies include various types of water quotas, different water pricing schemes, and incentives (subsidies) for the adoption of water-efficient technologies (Zuo *et al.*, 2015). For supply-side management, policies include public investment in water supply, such as wastewater treatment for agricultural use or aquifer recharge, and water extraction from the ocean (Purvis & Dinar, 2020). Numerous studies have evaluated the efficiency of policy interventions in specific regions (Aidam, 2015; Feike & Henseler, 2017; Chu & Grafton, 2020). In these studies, planning methods have been adopted to evaluate the effectiveness of policies such as pricing, taxation, and quota. The results show that these policies negatively impact water demand, crop yield, production, and profit. As such, Feike & Henseler (2017) suggest that subsidies can be used alongside these policies.

Adaptation to climate change has become a major objective of the agricultural sector and is of particular interest to policy-makers and stakeholders. The substantial reduction in the available renewable water resources over time and the increase in water-consuming economic activities have widened the gap between the water quantities supplied and demanded (Purvis & Dinar, 2020). Some researchers have examined the effects of climate change on agricultural factors such as yield, production, and income (Elouadi *et al.*, 2017; Lu *et al.*, 2019; Ureta *et al.*, 2020). These studies have estimated the effects of temperature and precipitation on farm factors using regression and mathematical programming methods. The findings reveal that climate change has a significant impact on the examined factors. Accordingly, factors such as agricultural technology innovation, policy intervention mechanisms, increasing investment, changes in cropping patterns, and education of farmers can effectively alleviate the negative effects of climate change. Forni *et al.* (2016) provided a more complete representation of a water system and water consumers by integrating climate-driven hydrologic simulation models and economic optimization models. They showed that climate change can affect a region's environment and economy by altering water resource flows and allocations. Wickramasinghe *et al.* (2021) also assessed and mapped the vulnerability of the agricultural sector in Sri Lanka to climate change and showed that there is considerable spatial variability in agricultural vulnerability. They also found that the characteristics of neighbors are a vital factor in determining the vulnerability status of an area, so the influence of neighbors should be considered in these assessments.

A serious challenge for economists is to understand farmers' decisions and behaviors concerning crop allocation, water use, and future expectations that might be implemented by farmers in response to policies and changing climatic conditions (Zuo *et al.*, 2015; Forni *et al.*, 2016; Graveline, 2016). Future policies for water conservation should be commensurate with the effects of climate change. This requires scientific evidence on the combined effects of land-use selection, water conservation policies, and global change (Schönhart *et al.*, 2018). Few studies have analyzed climate scenarios and alternative water policies for developing and implementing appropriate policies (Qureshi *et al.*, 2013; Escribano Francés *et al.*, 2017; Schönhart *et al.*, 2018). These studies have discussed tools for managing and adopting appropriate policies to tackle climate change. Qureshi *et al.* (2013) and Schönhart *et al.* (2018), for instance, have studied climate scenarios with similar temperature trends and different precipitation patterns reflecting the uncertainty of climate change.

Despite the multitude of studies on the impact of climate change and policy-making in the agricultural sector, to the best of our knowledge, no study has examined the impact of these two factors simultaneously. Most studies have only investigated the effects of climate change and have suggested appropriate policies, while it is important to provide an appropriate solution to manage the situation given the global climate change and its implications for agriculture. No study has so far focused on the implications of water pricing and quota policies in conditions where the region's climate is changing and differs from baseline conditions. Comparing the consequences of the two policies in the conditions of climate change and examining their effectiveness in reducing agricultural water is another innovation of this research. Water resources are limited inputs in the agricultural sector and are strongly influenced by precipitation patterns and climate change. Therefore, policy-making for the optimal allocation of this input in the conditions of climate change is significant.

Our case study was conducted at the level of growers of major crops in North Khorasan Province, Iran. This province, with an altitude of 1,326 m above sea level and average annual precipitation of 230 mm, has an arid and semi-arid climate. The climate of the province has changed in recent years following a 32% decrease in precipitation and an increase in air temperature. Reforming consumption patterns in different sectors is the only way to overcome the crisis of water scarcity and depletion of water resources (Agricultural Jihad Organization of North Khorasan province, 2017).

In North Khorasan, the frequency of droughts has increased in recent decades compared to its long-term trend, and the agricultural sector has greatly been impacted by these droughts. The droughts have depleted groundwater levels, increased the number of authorized and unauthorized wells, and decreased the surface water volume. Especially in the Central Desert catchment, the status of water reserves has been aggravated in most parts. Due to the reduction of surface water supply and uncontrolled extraction of groundwater from the plains of this province, appropriate policy programs must be adopted to manage irrigation water use.

This research sought to examine what kind of policy can be proposed for water consumption management in North Khorasan Province considering the phenomenon of climate change. To this end, the impact of water quotas and pricing policies under climate change conditions was evaluated. Based on the maximum area under cultivation, five major crops of the province, including cotton, barley, wheat, sugar beet, and alfalfa were selected. Then, using biophysical-economic modeling and questionnaire data of the 2017–2018 cropping year, the effects of scenarios were investigated on the irrigated area of crops, total gross margins, and conserved water.

The study site in North Khorasan included the drainage basins of Atrak, Central Desert, Gharesoo and Gorgan, and Gharehghom. Figure 1 displays the catchment area in North Khorasan. About 92% of the area of this province is located in the catchments of Atrak and the Central Desert. The research was conducted in the two main drainage basins of Atrak and the Central Desert.

The remainder of this paper is organized as follows: Section 2 discusses materials and methods, including a positive mathematical programming (PMP) model, yield function modeling, and the data collection and sampling technique. The evaluation results of water policy instruments, climate change scenarios, and water policy instruments under climate change conditions are presented and discussed in Section 3. Section 4 presents the conclusions. Finally, some policy recommendations are given in Section 5.

2. MATERIALS AND METHODS

Mathematical programming models have been adopted to link biophysical and economic information in a biophysical and economic modeling framework (Qureshi *et al.*, 2013). A biophysical-economic modeling system is used to analyze the impact of climate change and water resources management policies and scenarios (Adamson *et al.*, 2009; Qureshi *et al.*, 2013). In this study, the biophysical-economic modeling system has two separate processes. The first process involves the PMP, which is the economic component of the model, and the second process includes the yield function based on water requirements and precipitation, which is the biophysical component of the model.

2.1. Positive mathematical programming model

PMP was first proposed by Howitt (1995). It is a method to calibrate mathematical programming models against an observed behavior during a reference period by using the information provided by the dual variables of calibration constraints (Howitt, 1995; Paris & Howitt, 1998). PMP is a three-step procedure in which a non-linear cost function is calibrated against observed values of inputs consumed for agricultural production. In the basic formulation, the first step is a linear program providing marginal values that are used in the second step to estimate the parameters for a non-linear cost function and a production function. In the third step, the calibrated production and cost functions are employed in a non-linear optimization program. The solution to this non-linear program is calibrated against the observed values of production inputs and output. The linear program in Step 1 is:

$$\text{Max } Z = p'x - c'x \tag{1}$$

$$\text{Subject to: } Ax \leq b \quad [\lambda] \tag{2}$$

$$x \leq x_0 + \varepsilon[\rho] \tag{3}$$

$$x \leq 0 \tag{4}$$

where z is the scalar of the objective function value, p is an $(n \times 1)$ vector of product prices, x is an $(n \times 1)$ non-negative vector of production activity levels, c is an $(n \times 1)$ vector of accounting costs per unit of activity

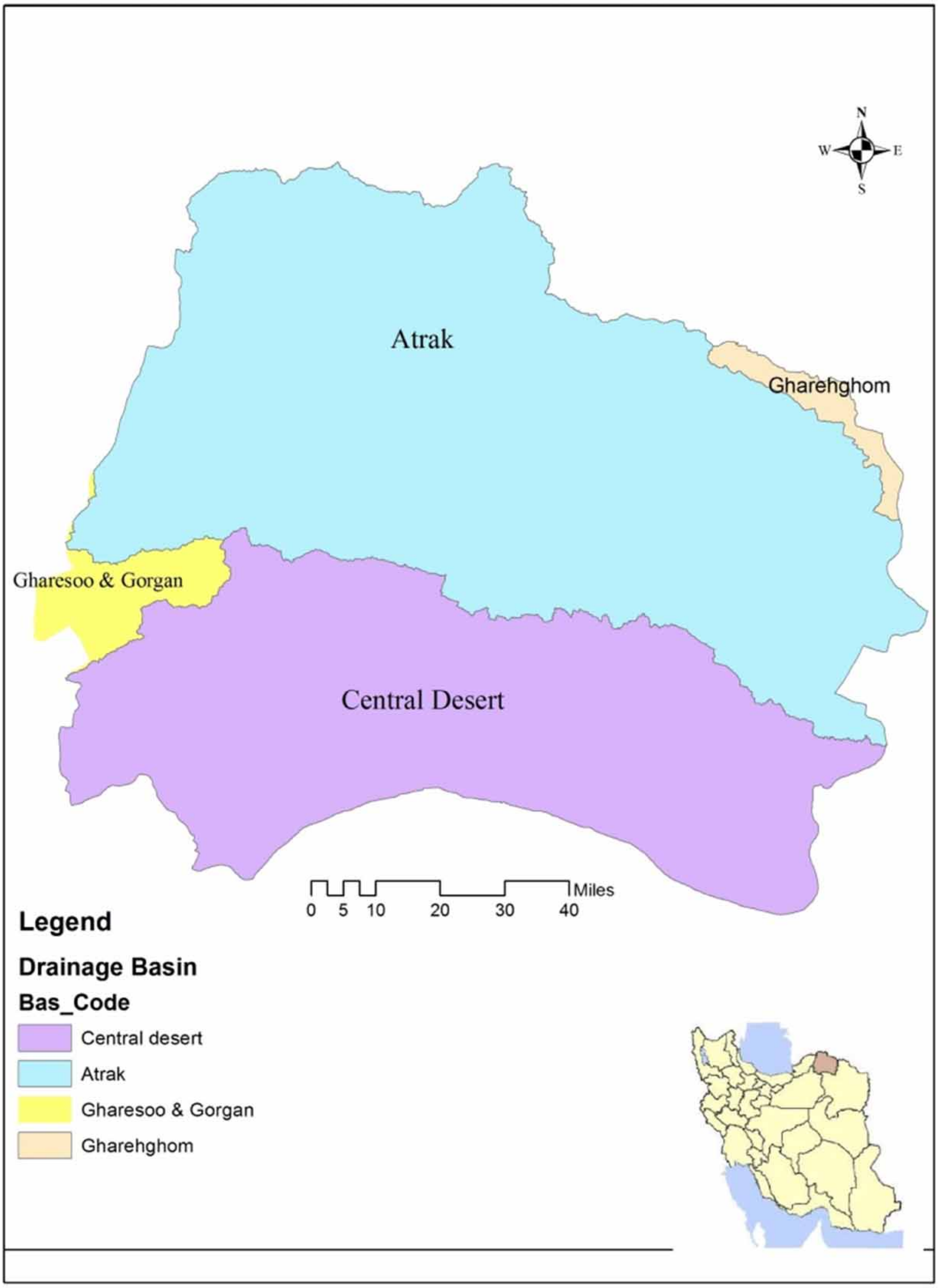


Fig. 1 | Map of drainage basins in the North Khorasan Province.

(including the cost of land, labor, fertilizer, pesticide, machinery, and water inputs), A is an $(m \times n)$ matrix of technical coefficients in resource constraints, b is an $(m \times 1)$ vector of available resource levels, x_0 is an $(n \times 1)$ non-negative vector of observed activity levels, ε is an $(n \times 1)$ vector of small positive numbers for preventing linear dependency between the structural constraints (1a) and the calibration constraints (1b), λ is an $(m \times 1)$ vector of duals associated with the allocable resource constraints, and ρ is an $(n \times 1)$ vector of duals associated with the calibration constraints.

Assuming that all activity levels are strictly positive and all allocable resource constraints are binding at the optimal solution, the first-order conditions of model (1) provide the following dual values as in Heckelei & Wolff (2003):

$$\rho^p = p^p - A^{p'}\lambda \tag{5}$$

$$\rho^m = 0 \tag{6}$$

$$\lambda = (A^{m'})^{-1}(p^m - c^m) \tag{7}$$

The vector x is partitioned into an $[(n-m) \times 1]$ vector of preferable activities x^p constrained by the calibration constraints (1b) and an $(m \times 1)$ vector of marginal activities x^m constrained by the allocable resource constraints (1a). The other vectors ρ, p, and c and the matrix A are partitioned accordingly. Howitt (1995) and Paris & Howitt (1998) interpret the dual variable vector ρ associated with the calibration constraints as capturing any type of model miss-specification, data errors, aggregate bias, risk behavior, price expectations, technological knowledge, and personal preferences. In the second step of PMP, these duals are used to calibrate the parameters of the non-linear objective function. An ordinary case considers calibrating the parameters of a variable cost function C^v, which has the typical multi-output quadratic functional form while holding the variable input prices constant at the observed market level as follows:

$$C^v(x) = \frac{d'x + x'Qx}{2} \tag{8}$$

where d is an $(n \times 1)$ vector of parameters of the cost function and Q is an $(n \times n)$ symmetric, positive (semi-) definite matrix with typical element q_{ij} for activities i and j. The variable marginal cost vector MC^v of this typical cost function is set equal to the sum of the accounting cost vector c and the differential marginal cost vector ρ as follows:

$$\mathrm{MC}^v = \frac{\partial \mathrm{Cv}\,(x_0)}{\partial x} = d + Qx_0 = c + \rho \tag{9}$$

where $\nabla C^v(x)_{x0}$ is a $(1 \times n)$ gradient vector of first derivatives of $\mathrm{Cv}(x)$ for $x = x_0$. Note, however, that the derivatives (9) of this *variable* cost function do not incorporate the opportunity cost of fixed resources (Ap'λ) which remain captured in the ultimate model by the dual values of the resource constraints.

The relationship gives a system of n equivalents that has $[n + n(n+1)/2]$ parameters. This specific problem is 'ill-posed' because the number of parameters to be specified is greater than the number of observations. The simulation behavior of the resulting model will differ drastically depending on the matrix of second derivatives. Therefore, the parameters of the cost function, i.e., the vector d and the matrix Q, must be correctly estimated. Howitt (1995) described the maximum entropy method as the best way to estimate the parameters of matrix Q. To calibrate the marginal cost function, Paris & Howitt (1998) exploited the maximum entropy estimator to determine all elements of the vector d and the matrix Q using the Cholesky factorization of this matrix Q to guarantee that the calibrated matrix Q is actually symmetric positive semi-definite. This estimator in combination with PMP allows calibrating a quadratic variable cost function accommodating complementarity and competitiveness among activities still based on a single observation but using a priori information on support bounds.

The last step combines the calibrated functions into a non-linear optimization program. This base program does not include a policy shock and is used to ensure that the calibrated model reproduces the observed base year conditions:

$$\text{Max } Z = \frac{p'x - \hat{d}'x' - x'\hat{Q}x}{2} \tag{10}$$

$$\text{Subject to:} Ax \leq b \qquad [\lambda] \tag{11}$$

$$x \geq 0 \tag{12}$$

This non-linear model yields a new calibration for the observed production level (x) and farmland shadow price without the calibration constraints of step1. Once the new calibration is complete, the model is fit to implement different policy scenarios while taking into account price interventions, public payments, quota systems, and environmental interventions.

2.2. Modeling yield function: Response to irrigation and effective rainfall

In addition to environmental characteristics and soil conditions, crop yield is a function of climate change behavior patterns. Climate variables include precipitation, temperature, solar radiation, and wind speed. Of course, rainfall variations can greatly affect crop yields. In this regard, climate change can be studied through variable crop water requirements. The yield function is represented by a non-linear crop water production function as follows:

$$\text{Yield}_i = f(\text{ET}_i) = a_i + b_i * \text{ET}_i + c_i(\text{ET}_i)^2 \tag{13}$$

where ET_i denotes crop water requirement or evapotranspiration; a_i is the intercept of the yield response function; b_i is the slope coefficient of the yield response function; and c_i is the quadratic coefficient of the yield response function (Qureshi *et al.*, 2013). The amount of irrigation water IW_i required to meet a crop's ET depends on the effective rainfall (ERain) and on-farm irrigation efficiency (IEff) as follows:

$$\text{IW}_i = \frac{(\text{ET}_i - \text{ERain})}{\text{IEff}_i} \tag{14}$$

Effective rainfall is a part of the rainfall that is effectively used by the crop, not considering water losses through surface runoffs, percolation, and evapotranspiration. We used the effective rainfall calculated by the method of the United States Department of Agriculture (USDA). Equation (14) can be written as follows:

$$\text{ET}_i = (\text{IW}_i * \text{IEff}_i) + \text{ERain} \tag{15}$$

By incorporating Equation (15) into the crops yield function, changes in crop yields due to precipitation change can be calculated. Then, the yield function equation is defined instead of yield in the third step of the PMP model. In this way, the effects of climate change scenarios were investigated on the agricultural outputs and economic indicators of farmers. Parameters a, b, and c used in crop water production functions were derived by combining field-level data on yield and crop water requirements. The crop water requirements were taken from the Netwat software, calculated using the Penman-Monteith method and climate data of the study area. Based on the behavioral pattern of precipitation climatic variable, climate change scenarios are defined as dry, wet, and moderate. The average of the percentage change in maximum, minimum, and medium precipitation during the period of 2006–2018 from the base year in each catchment is considered as climate change scenarios. The amount of percentage change in maximum, medium, and minimum precipitation from the base year is defined as the wet, moderate, and dry climate change, respectively.

2.3. Data and sampling technique

We selected wheat, barley, cotton, sugar beet, and alfalfa growers in North Khorasan Province as the statistical population. The data were collected using a questionnaire. The required data are cross-sectional for the 2017–2018 cropping year. According to the population size (i.e., 38,450), 380 questionnaires were filled out by stratified sampling technique in two drainage basins of Atrak and Central Desert through interviews with farmers. To improve the precision of the sampling and to incorporate statistical population features into the sample, the stratified sampling method was adopted in which the entire population was divided into subgroups of the drainage basins. The climate data were supplied by North Khorasan Meteorological Administration. Additional information was collected by referring to the Agriculture Jihad Organization and the Regional Water Company of North Khorasan.

3. RESULTS AND DISCUSSION

This section presents the results of the PMP for drainage basins of Atrak and the Central Desert and the effects of the policy scenarios of pricing and quota and the climate change scenario on the cropping pattern. The scenarios of this study are defined and implemented in three stages.

3.1. Evaluation of water policy instruments

In this study, two instruments of quota and pricing of water were selected as the policy instruments. Table 1 presents the results of solving the planning model of changes in the cropping pattern after applying the scenarios of a 10, 20, or 30% increase in water price and the scenario of decreasing the water available to farmers for irrigation compared to the base year.

Evidently, in the Atrak catchment, the irrigated area of all the crops is reduced after applying different scenarios of increasing the water price. Cotton and wheat have the lowest and highest declines in the irrigated area at 2.24 and 3.23%, respectively. One explanation for this result is that crop area is reduced according to the crop income per unit of irrigation water. Although cotton has a high water requirement, its irrigated area is reduced less than the other crops due to its higher income per unit of water per unit area. This result is also true in scenarios of increasing water quotas. According to the results, by applying the scenarios of quota and pricing policies, the irrigated area and total gross income are reduced. However, due to farmers' limited access to water resources in the quota policy, it is more likely to witness a decline in the irrigated area and total gross income. By applying a 30% reduction in the water quota, the total irrigated area and total gross margin are reduced by 30.7 and 27.5%, respectively, while a 30% increase in water prices decreases the total irrigated area and total gross margin by 3.08 and 11.3%, respectively. Furthermore, in both policies, water use is reduced with a rise in scenarios. In the quota policy, the amount of water use reduction is equal to the amount of limitation in water availability, while in the pricing policy, the reduction in water use is much lower.

Based on the results, the implementation of the water price increase and quota policies in the Central Desert catchment yield results are similar to those in the Atrak catchment. Under the scenario of increasing water prices

Table 1 | Impacts of the water policy instruments on the irrigated area of crops (hectare) and total gross margins (million rials) compared to the reference scenario.

Policy instruments scenarios		**Reference scenario**	**Water pricing**			**Water quota**		
			10%	**20%**	**30%**	**10%**	**20%**	**30%**
Atrak	Irrigated area of crops							
	Alfalfa	3,716.2	3,677.9 (−1.03)	3,640.4 (−2.04)	3,603.7 (−3.03)	3,397.6 (−11.3)	2,879 (−22.5)	2,460.4 (−33.8)
	Cotton	4,165.1	4,133.6 (−0.76)	4,102.5 (−1.5)	4,071.9 (−2.24)	3,866.4 (−7.17)	3,567.6 (−14.3)	3,268.9 (−21.5)
	Barley	10,127	10,025 (−1.01)	9,924.6 (−2)	9,826.5 (−2.96)	9,074.2 (−10.4)	8,021.6 (−20.8)	6,969.1 (−31.2)
	Sugar beet	963.8	954.32 (−0.98)	945.03 (−1.95)	935.92 (−2.89)	880.13 (−8.68)	796.46 (−17.4)	712.79 (−26)
	Wheat	33,341	32,974 (−1.1)	32,614 (−2.18)	32,263 (−3.23)	29,848 (−10.5)	26,356 (−21)	22,863 (−31.4)
	Total irrigated area	52,313	51,764 (−1.05)	51,227 (−2.08)	50,701 (−3.08)	46,967 (−10.2)	41,620 (−20.4)	36,274 (−30.7)
	Total gross margin	1,106.3	1,063.7 (−3.85)	1,021.9 (−7.62)	981.02 (−11.3)	1,005 (−9.15)	903.75 (−18.3)	802.5 **(−27.5)**
Central Desert	Irrigated area of crops							
	Alfalfa	2,075.4	2,053.3 (−1.06)	2,031.7 (−2.1)	2,007.1 (−3.29)	1,920.2 (−6.56)	1,765.1 (−15)	1,609.9 (−22.4)
	Cotton	1,815.5	1,799.1 (−0.9)	1,783 (−1.79)	0.00 (−100)	1,696.3 (−7.48)	1,577.1 (−13.1)	1,457.9 (−19.7)
	Barley	12,188	12,009 (−1.47)	11,835 (−2.89)	19,235 (57.8)	10,902 (−10.6)	9,615.6 (−21.1)	8,329.5 (−31.7)
	Sugar beet	1,204.1	1,191.6 (−1.04)	1,179.4 (−2.05)	1,799.5 (49.4)	1,111.8 (−7.67)	1,019.5 (−15.3)	927.2 (−23)
	Wheat	14,159	13,932 (−1.6)	13,713 (−3.15)	6,730 (−52.5)	12,526 (−11.5)	10,893 (−23.1)	9,260.8 (−34.6)
	Total irrigated area	31,442	30,985 (−1.45)	30,542 (−2.86)	29,772 (−5.3)	28,156 (−10.4)	24,871 (−20.9)	21,585 (−31.3)
	Total gross margin	574.73	543.04 (−5.51)	512.2 (−10.9)	359.23 (−37.5)	526.19 (−8.4)	477.65 (−16.9)	429.11 (−25.3)

Note: The numbers in parentheses are percentage changes compared to the reference scenario.

and quotas in the Central Desert catchment, the irrigated area of all the crops is decreased. Due to the higher gross income per unit of water, the cultivated area of cotton declines to a lesser extent than the other crops. Conversely, the cultivated area of wheat is decreased to a greater extent than the other crops. Applying the scenario of a 30% rise in the water price will significantly increase the cultivated area of barley and sugar beet, and these two crops will replace the cultivation of cotton and wheat to the extent that the irrigated area of cotton will be zero and the irrigated area of wheat will be reduced by 52.5%.

The results reveal that by applying the scenarios of quota and pricing policies, the total irrigated area, total gross income, and the amount of water used by farmers are reduced. Nevertheless, the rate of reduction in these parameters is higher in the quota than the pricing policy. Moreover, with the increase in water prices, the decrease in the total gross margin of farmers is much greater than the reduction in the total irrigated area of crops, and with a 30% increase in the water price, the total gross margin decreases to about 37.5%. Therefore, the optimal policy will be different if the policy-maker seeks to control the amount of water used and damage farmers less concurrently. In the pricing policy scenarios of water, the rate of decrease in the gross income is greater in the Central Desert catchment than in the Atrak catchment, which is due to the critical water shortage conditions in this catchment.

3.2. Evaluation of climate change scenario

In this study, the effects of climate change were defined as the change in precipitation and its effect on crop evaporation and, thus, crop yields. The results of dry, moderate, and wet climate change scenarios are presented in Table 2.

The results show that in both basin drainages, the implementation of the dry climate change scenario reduces the total irrigated area, total gross margin, and the irrigated area of all the crops. The results suggest that the irrigated area of alfalfa and sugar beet is reduced more than that of the other crops due to their high water requirements. In fact, with a decline in precipitation and a corresponding decrease in available water resources, the irrigated area of crops that use more water per unit area will experience a further reduction. Besides, barley, which has lower income returns than water consumed, will experience a further decrease in its irrigated area. The moderate climate change scenario yields results similar to the dry climate change scenario because the

Table 2 | Impacts of the 'climate change' on the irrigated area of crops (hectare) and total gross margins (million rials) compared to the reference scenario.

Drainage basin scenarios of climate change	**Atrak**				**Central Desert**			
	Reference scenario	**Dry**	**Moderate**	**Wet**	**Reference scenario**	**Dry**	**Moderate**	**Wet**
Irrigated area of crops								
Alfalfa	3,716.2	3,145.5 (−15.4)	3,659.6 (−1.52)	3,687 (−0.79)	2,075.4	1,922.2 (−7.38)	2,051.4 (−1.16)	2,076.3 (0.04)
Cotton	4,165.1	4,015.1 (−3.6)	4,135.5 (−0.71)	4,174.5 (0.23)	1,815.5	1,781.9 (−1.85)	1,805.4 (−0.56)	1,824.3 (0.48)
Barley	10,127	9,317.7 (−7.99)	9,995.2 (−1.3)	10,208 (0.8)	12,188	11,833 (−2.91)	12,105 (−0.68)	12,190 (0.02)
Sugar beet	963.8	661.14 (−31.4)	917.48 (−4.81)	1,022.2 (6.05)	1,204.1	1,174.1 (−2.49)	1,210.5 (0.53)	1,184.8 (−1.6)
Wheat	33,341	32,872 (−1.41)	33,252 (−0.27)	33,125 (−0.65)	14,159	14,026 (−0.94)	14,120 (−0.27)	14,153 (−0.04)
Total irrigated area	52,313	50,011 (−4.4)	51,960 (−0.68)	52,217 (−0.18)	31,442	30,707 (−2.24)	31,293 (−0.47)	31,428 (−0.04)
Total gross margin	1,106.3	1,028.5 (−7.03)	1,094.9 (−1.03)	1,108.9 (0.24)	574.73	556.37 (−3.2)	571.45 (−0.57)	574.88 (0.03)

Note: The numbers in parentheses are percentage changes compared to the reference scenario.

precipitation decreases compared to the base year. Only the irrigated area of sugar beet in the Central Desert catchment increases to about 0.53%. Based on the results, applying a wet climate change scenario in both catchments reduces the total irrigated area and increases the total gross margin. In fact, increasing precipitation compared to the base year raises the evapotranspiration rate and, consequently, the yield of the crops, so farmer incomes increase. The results suggest that the wet climate change scenario in the Atrak catchment raises the irrigated area of cotton, sugar beet, and barley, and reduces the irrigated area of alfalfa and wheat. Furthermore, in the Central Desert basin drainage, the irrigated area of alfalfa, cotton, and barley is increased, and the irrigated area of sugar beet and wheat is decreased.

Evidently, by applying climate change scenarios compared to the base year, the amount of water use is decreased by about 0.08–5.84% in the Atrak catchment and by about 0.07–2.47% in the Central Desert catchment. Profitability is the most important factor in farmers' decision to cultivate a crop. Precipitation change as a result of climate change affects crop yields and farm profitability. According to the results, the decrease in crop profitability will reduce farmers' willingness to cultivate irrigated crops, and the total irrigated area of crops compared to the base year will decrease in both catchments. With climate change, the total gross margin also varies by about −7.04 to 0.24% in the Atrak catchment and by about −3.19 to 0.03% in the Central Desert catchment. Given that the volume of precipitation in the Atrak catchment is higher than that in the Central Desert catchment, precipitation provides a larger share of crop water requirements. Moreover, due to the direct effect of precipitation on surface runoff and the greater use of surface water resources for farm irrigation in the Atrak catchment compared to the Central Desert catchment, changes in precipitation will have a greater impact on the amount of water used, total irrigated area, and total gross margin. Since farmers resort to groundwater in response to reduced precipitation in order to meet their crop water requirements in the Central Desert catchment, more groundwater sources are abstracted. Therefore, the irrigated area is reduced to a lesser extent. This is observed in reality, too. In the Central Desert catchment, we have witnessed a drop in groundwater resources and the critical status of the plains due to the drought in recent years and the irregular abstraction of groundwater resources.

3.3. Evaluation of water policy instruments under climate change conditions

The main purpose of this study was to investigate the impact of pricing and quota policies on water use under climate change conditions. To this end, scenarios of 10, 20, or 30% increase in water prices under the scenarios of dry, moderate, and wet climate change were applied separately. The results of water pricing and climate change are presented in Table 3.

The results of the pricing policy under dry and moderate climate change in the Atrak catchment, as well as climate change scenarios in the base year conditions, show a decrease in the irrigated areas of all crops. Alfalfa and sugar beet with the highest water requirements will have the largest reduction in the irrigated area. Thus, with a 30% increase in water prices, the irrigated area of alfalfa and sugar beet crops will decrease by 17.9 and 33.4% in dry climate change, respectively. As the amount of precipitation decreases, the water requirement of the crops should be met by increasing irrigation, in which case, the demand for water rises. Moreover, due to increasing water prices and water supply at higher price levels, the cost of farm irrigation increases. Farm yield is also reduced by reducing effective rainfall. As a result, farmers will be reluctant to grow crops, and the intensity of the decrease in the irrigated area of crops and the total gross margin of farmers will increase more sharply than in the base year. Consequently, with a 30% rise in the water price in the conditions of dry climate change, the total irrigated area and total gross margin will drop by about 7.35 and 17.7%, respectively. The application of the water pricing scenario under wet climate change conditions in the Atrak catchment indicates that the irrigated areas of wheat and alfalfa decrease and the irrigated areas of the other crops increase. Still, as the

Table 3 | Impact of the policy instrument 'Water Pricing' under scenario of climate change on the irrigated area of crops (hectare) and total gross margins (million rials) compared to the reference scenario.

Scenarios of climate change water pricing	Dry climate change			Moderate climate change			Wet climate change		
	10%	20%	30%	10%	20%	30%	10%	20%	30%
Atrak									
Irrigated area of crops									
Alfalfa	3,113.2	3,081.6	3,050.6	3,622	3,585	3,548.9	3,684	3,655.4	3,618.5
	(−16.2)	(−17.1)	(−17.9)	(−2.54)	(−3.53)	(−4.5)	(−0.87)	(−1.64)	(−2.63)
Cotton	3,984.7	3,954.8	3,925.3	4,104.2	4,073.4	4,043	4,185.9	4,165.3	4,134.2
	(−4.33)	(−5.05)	(−5.76)	(−1.46)	(−2.2)	(−2.93)	(0.5)	(0.004)	(−0.74)
Barley	9,223.7	9,131.7	9,041.4	9,894.5	9,795.7	9,698.9	10,214	10,136	10,035
	(−8.92)	(−9.83)	(−10.7)	(−2.29)	(−3.27)	(−4.23)	(0.87)	(0.09)	(−0.9)
Sugar beet	654.62	648.22	641.95	908.45	899.6	890.92	1,020.6	1,012.6	1,002.9
	(−32.1)	(−32.7)	(−33.4)	(−5.74)	(−6.66)	(−7.56)	(5.9)	(5.07)	(4.05)
Wheat	32,509	32,155	31,809	32,885	32,527	32,177	33,081	32,790	32,437
	(−2.5)	(−3.56)	(−4.6)	(−1.37)	(−2.44)	(−3.5)	(−0.78)	(−1.65)	(−2.71)
Total irrigated area	49,486	48,971	48,468	51,414	50,881	50,358	52,186	51,759	51,228
	(−5.41)	(−6.39)	(−7.35)	(−1.72)	(−2.74)	(−3.74)	(−0.24)	(−1.06)	(−2.07)
Total gross margin	988.53	949.32	910.9	1,052.7	1,011.3	970.75	1,076.9	1,037.2	995.81
	(−10.6)	(−14.2)	(−17.7)	(−4.84)	(−8.58)	(−12.3)	(−2.65)	(−6.24)	(−9.98)
Central Desert									
Irrigated area of crops									
Alfalfa	1,901.8	1,881.8	1,856	2,029.6	2,008.3	1,984.1	2,059.6	2,037.9	2,012
	(−8.36)	(−9.33)	(−10.6)	(−2.21)	(−3.24)	(−4.4)	(−0.76)	(−1.81)	(−3.05)
Cotton	1,765.8	1,750	0.00	1,789.1	1,773.1	0.00	1,808.6	1,792.5	0.00
	(−2.74)	(−3.61)	(−100)	(−1.45)	(−2.34)	(−100)	(−0.38)	(−1.27)	(−100)
Barley	11,659	11,490	18,780	11,928	11,755	19,156	12,043	11,869	19,238
	(−4.34)	(−5.72)	(54.1)	(−2.13)	(−3.55)	(57.2)	(−1.19)	(−2.62)	(57.8)
Sugar beet	1,162	1,150.1	1,751	1,198	1,185.7	1,803.6	1,172.9	1,160.9	1,779.1
	(−3.05)	(−4.49)	(45.4)	(−0.51)	(−1.53)	(49.8)	(−2.59)	(−3.59)	(47.7)
Wheat	13,801	13,584	6,729.9	13,894	13,675	6,701.3	13,964	13,744	6,782.1
	(−2.52)	(−4.06)	(−52.5)	(−1.87)	(−3.41)	(−52.7)	(−1.38)	(−2.93)	(−52.1)
Total irrigated area	30,290	29,856	29,117	30,838	30,398	29,645	31,048	30,604	29,811
	(−3.66)	(−5.04)	(−7.39)	(−1.92)	(−3.32)	(−5.71)	(−1.25)	(−2.66)	(−5.18)
Total gross margin	525.51	495.47	345.31	539.92	509.22	357.36	544.12	513.23	358.97
	(−8.56)	(−13.8)	(−39.9)	(−6.06)	(−11.4)	(−37.8)	(−5.33)	(−10.7)	(−37.5)

Note: The numbers in parentheses are percentage changes compared to the reference scenario.

price of water increases, the rate of increase in the irrigated area of sugar beet decreases, and the irrigated areas of the other crops decline. Also, the total irrigated area and the total gross margin decrease, and with a 30% increase in water prices, they will drop by 2.09 and 9.98%, respectively.

In the Central Desert catchment, increasing the water prices under climate change conditions yields similar results to the water pricing scenario in the base year, and the irrigated areas of alfalfa, cotton, and wheat decrease. Under the scenarios of 10 and 20% elevation in the water price, the irrigated area of barley and sugar beet will decrease, but with a 30% elevation in the water price, the irrigated area of these two crops will increase. Implementing the policy of increasing the water price under the dry and moderate climate change exacerbates the intensity of the drop in the total irrigated area of crops. With a 30% rise in the water price, the rate of increase in the irrigated area of sugar beet and barley will decrease. In this catchment, the total irrigated area and total gross margin will decrease more intensely than water pricing in the base year conditions. For example, with a 30% increase in water prices under dry climate change, the total irrigated area of crops and total gross margin will decline by about 7.39 and 39.9%, respectively. Applying the policy of increasing water prices under the conditions of wet climate change will reduce the intensity of the decrease and will increase the intensity of the increase in the crops' irrigated areas. Under these conditions, due to increased precipitation and improved crop cultivation conditions, with raising the water prices, the total gross margin and total irrigated area of crops will decrease with less intensity compared to the base year conditions.

According to the results, by applying the water pricing policy under the climate change scenarios compared to the base year, the total irrigated area of the crops in the Atrak and Central Desert catchments decreases by about 0.24–7.35% and 1.25–7.39%, respectively. Besides, the amount of water use will decrease by about 0.12–8.67% in the Atrak catchment and by about 1.24–14.5% in the Central Desert catchment.

The results of the scenarios of quota policy under climate change conditions are reported in Table 4.

Based on the results, by applying the quota scenarios under the climate change conditions, the irrigated areas of all the crops will be reduced in the Atrak and Central desert catchments. Due to the higher income returns of cotton per unit of water used, it will have the lowest decrease in its irrigated area. As climate change progresses from drought to humidity, the irrigated areas of the crops will decline less. This result indicates that the crops are sensitive to changes in precipitation.

The total irrigated area of the crops will decline in the Atrak catchment by about 8.65–30.79% and in the Central Desert catchment by about 10.1–31.3% under the scenarios of the quota policy and precipitation change. Also, the total gross income in the catchments of Atrak and the Central Desert is reduced by about 8.72–29.1 and 8.38–26.5%, respectively. Although the application of quota scenarios under climate change conditions will reduce the total irrigated area more in the Central Desert than in the Atrak catchment, the rate of decrease in total gross margin in this catchment is less. In fact, precipitation meets a higher share of crop water requirements in the Atrak compared to the Central Desert catchment. As a result, any change in precipitation has a greater impact on crop yield in this catchment. The volume of water saved in the two catchments after the implementation of the scenarios is presented in Figure 2.

When quota and pricing policies for water are applied under climate change conditions, the amount of water use is decreased in both Atrak and Central Desert catchments. In both catchments, the percentage of water-saving is much higher under the water quota policy than the water pricing policy. In the quota policy, the water used to irrigate the farms has been reduced compared to the quota rate. Moreover, by applying the pricing policy under the dry climate change scenario compared to the wet climate change scenario, the water used for farm irrigation is further reduced. With the decrease in precipitation in the region, the reduction of crop yield, and the rise in water cost, the income and profit per unit area decline. Farm profitability is the most important goal of the farmer. Therefore, reducing the farm profit diminishes the tendency to cultivate the field, thereby decreasing the total irrigated area and, thus, the volume of water used. With the implementation of the pricing policy in the base year conditions in the Atrak and Central Desert catchments, the volume of conserved water is about 1.02–3 and 1.24–12.25%, respectively. Nevertheless, in the conditions of climate change, the amount of conserved

Table 4 | Impact of the policy instrument 'Water Quota' under scenarios of climate change on the irrigated area of crops (hectare) and total gross margins (million rials) compared to the reference scenario.

Scenarios of Climate change quota policy	Dry climate change			Moderate climate change			Wet climate change		
	10%	20%	30%	10%	20%	30%	10%	20%	30%
Atrak									
Irrigated area of crops									
Alfalfa	2,971.4	2,552.8	2,134.2	3,275.9	2,857.3	2,438.7	3,265.1	2,846.5	2,427.9
	(−20)	(−31.3)	(−42.6)	(−11.8)	(−23.1)	(−34.4)	(−12.1)	(−23.4)	(−34.7)
Cotton	3,890.9	3,592.1	3,293.4	3,861.7	3,563	3,264.2	3,896	3,597.3	3,298.6
	(−6.58)	(−13.8)	(−20.9)	(−7.29)	(−14.5)	(−21.6)	(−6.46)	(−13.6)	(−20.8)
Barley	8,879.8	7,827.3	6,774.8	9,030.4	7,977.9	6,925.3	9,169.6	8,117	7,064.5
	(−12.3)	(−22.7)	(−33.1)	(−10.8)	(−21.2)	(−31.6)	(−9.45)	(−19.8)	(−30.2)
Sugar beet	626.33	542.66	458.99	840.78	757.11	673.44	939.53	855.86	772.19
	(−35)	(−43.7)	(−52.4)	(−12.8)	(−21.4)	(−30.1)	(−2.52)	(−11.2)	(−19.9)
Wheat	31,419	27,926	24,433	30,050	26,558	23,065	29,630	26,137	22,644
	(−5.77)	(−16.2)	(−26.7)	(−9.87)	(−20.3)	(−30.8)	(−11.1)	(−21.6)	(−32.1)
Total irrigated area	47,787	42,441	37,095	47,059	41,713	36,367	46,900	41,554	36,207
	(−8.65)	(−18.9)	(−29.1)	(−10)	(−20.3)	(−30.5)	(−10.3)	(−20.6)	(−30.8)
Total gross margin	986.41	885.16	783.9	1,002.1	900.83	799.57	1,009.8	908.55	807.29
	(−10.8)	(−20)	(−29.1)	(−9.42)	(−18.6)	(−27.7)	(−8.72)	−17.9)	(−27)
Central Desert									
Irrigated area of crops									
Alfalfa	1,805.4	1,650.2	1,495.1	1,903.4	1,748.3	1,593.1	1,924.2	1,769	1,613.9
	(−13)	(−20.5)	(−28)	(−8.29)	(−15.8)	(−23.2)	(−7.29)	(−14.8)	(−22.2)
Cotton	1,692.1	1,572.9	1,453.7	1,691.7	1,572.6	1,453.4	1,704.1	1,584.9	1,465.7
	(−6.8)	(−13.4)	(−19.9)	(−6.82)	(−13.4)	(−19.9)	(−6.14)	(−12.7)	(−19.3)
Barley	10,864	9,578	8,292	10,879	9,592.7	8,306.7	10,917	9,630.8	8,344.7
	(−10.9)	(−21.4)	(−32)	(−10.7)	(−21.3)	(−31.8)	(−10.4)	(−21)	(−31.5)
Sugar beet	1,104.6	1,012.3	919.96	1,122.5	1,030.2	937.84	1,091.4	999.1	906.78
	(−8.3)	(−15.9)	(−23.6)	(−6.78)	(−14.5)	(−22.1)	(−9.36)	(−17)	(−24.7)
Wheat	12,796	11,164	9,531.1	12,563	10,930	9,279.8	12,533	10,900	9,267.8
	(−9.62)	(−21.2)	(−32.7)	(−11.3)	(−22.8)	(−34.3)	(−11.5)	(−23)	(−34.5)
Total irrigated area	28,262	24,977	21,692	28,159	24,874	21,589	28,170	24,884	21,599
	(−10.1)	(−20.6)	(−31)	(−10.5)	(−20.9)	(−31.4)	(−10.4)	(−20.9)	(−31.3)
Total gross margin	519.81	471.28	422.74	525.16	476.62	428.08	526.58	478.04	429.5
	(−9.56)	(−18)	(−26.4)	(−8.62)	(−17.1)	(−25.5)	(−11.9)	(−16.8)	(−25.3)

Note: The numbers in parentheses are percentage changes compared to the reference scenario.

water varies depending on the type of climate change. In the conditions of dry and moderate climate change, with decreasing the volume of precipitation compared to the base year and increasing the need for irrigation of the farm, changing the price of water will have a greater impact on farmers' profits. By applying pricing policies

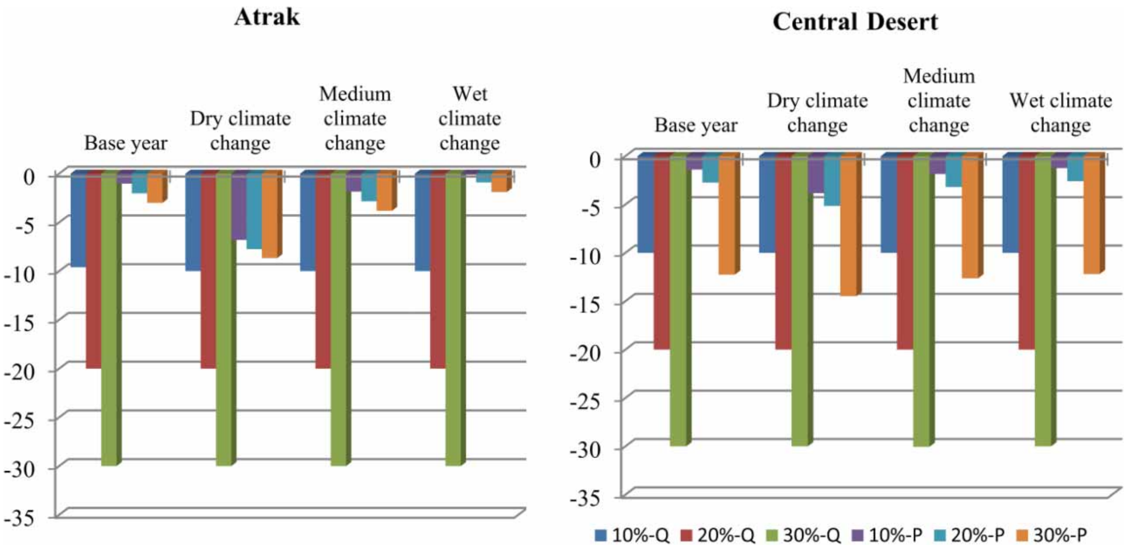


Fig. 2 | Percentage of conserved water after implementation of water policies under climate change scenarios.

under conditions of dry climate change, the amount of conserved water in the Atrak and the Central Desert catchments will be about 6.8–8.6 and 3.83–14.48%, respectively. Conversely, by applying the pricing policy under conditions of wet climate change, due to the increase in precipitation compared to the base year, the amount of conserved water in the Atrak and the Central Desert catchments will be about 0.12–1.82 and 1.24–12.18%, respectively, which is less than the amount of conserved water in the base year conditions. As such, if the policy-makers' goal is to control water volume to a certain extent, the quota policy is more appropriate than the pricing policy.

4. CONCLUSION

This study sought to examine policies that could manage water use in the face of climate change. To this end, the effects of pricing and quotas policy scenarios under climate change scenarios were analyzed on the two catchments of Atrak and the Central Desert. The impact of these scenarios was evaluated using the economic-biophysical modeling, including the PMP model, the maximum entropy, and the questionnaire data for the 2017–2018 crop base year. Based on the results, the scenarios of irrigation water pricing and quota policies reduce the total irrigated area of the crops, the total gross income, and the amount of water use. The rate of reduction in water use is much lower under the pricing than the quota policy, so the quota policy is superior for controlling a certain volume of water use. These findings are consistent with those of Shi *et al.* (2014) and Oulmane *et al.* (2019). Besides, due to the larger volume of irrigation water per unit area in the Central Desert than in the Atrak catchment, the water pricing policy will result in greater saving on water use and a further decrease in the total gross margin.

In this study, the dry, moderate, and wet climate changes were defined as climate change scenarios. After applying climate change scenarios in the Atrak and Central Desert catchments, the total irrigated areas of the crops decrease and the optimal cultivation pattern changes. Wineman & Crawford (2017) and Lei *et al.* (2016) reached the same conclusion in their studies. The total gross margin decreases as a result of dry and moderate climate change, and increases with a wet climate change. Elouadi *et al.* (2017), Schönhart *et al.* (2018), and Ponce *et al.* (2014) also showed that climate change affects farm yield and income. Due to the higher share of effective precipitation in meeting the water needs of plants and supplying a higher percentage of irrigation water from surface water sources in the Atrak catchment than in the Central Desert catchment, precipitation changes will have a greater impact on the studied factors. The consequences of water pricing and quota policy scenarios under precipitation change scenarios are similar to those of policy scenarios under base year conditions in both catchments, except that the irrigated area of the crops, water use volume, and total gross income decrease to a different extent. Dry and moderate climate changes increase, whereas wet climate changes reduce the severity of the decline. Increasing precipitation reduces the need for irrigation, and a higher percentage of the crop water requirement is met through effective precipitation. It also increases income by increasing crop yield. Therefore, raising the water price under wet compared to dry climate change has a lesser effect on decreasing the irrigated areas of the crops. As the climate shifts from dry to wet, the percentage decline in the irrigated area of high-income crops decreases, and in the cropping pattern, more crops are grown with higher incomes.

5. POLICY RECOMMENDATIONS

In general, the results reveal that the implementation of water quota and water pricing policies in North Khorasan Province would steer local farmers toward consuming less water by affecting water demand, although it would decrease the total gross income of the cropping pattern. This can partially mitigate the depletion of groundwater reserves and contribute to the optimal consumption of the available water. It is recommended that officials apply these policies and prioritize them in their policy-making decisions and programs in the province as an appropriate and practical strategy to alleviate the demand for irrigation water and preserve and ensure the sustainability of water resources. An assessment of the effects of climate change (declining precipitation) indicates that the available water resources, and consequently the irrigated area of crops, will be reduced. It is recommended that the deficit irrigation methods be used to have a more sustainable effect on the conservation of water resources while keeping lower-income crops (e.g., wheat, which is a strategic crop for the entire country) in the cropping pattern. Implementing subsidy policies, providing facilities and loans with low-interest rates to farmers to purchase basic equipment, equipping farms with modern irrigation systems, and other incentives and supporting policies can increase farmers' gross profit. These policies can partially alleviate farmers' losses due to climate change.

The model proposed herein has appropriate features for comparing the results of the outputs, and using this method, one can easily examine the effects of climate scenarios and policy-making simultaneously. Researchers can also focus more on biophysical modeling, including the introduction of other climatic and weather parameters such as changes in air temperature and increasing periods of drought. The proposed model is relatively definite and there is no direct accounting for uncertainty and risk associated with economic parameters. The inclusion of these factors can make it possible to analyze the sensitivity of crops.

DATA AVAILABILITY STATEMENT

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

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Adamson, D., Mallawaarachchi, T. & Quiggin, J. (2009). Declining inflows and more frequent droughts in the Murray-Darling Basin: Climate change, impacts and adaptation. *Australian Journal of Agricultural and Resource Economics 53*, 345–366.

Agriculture Jihad Organization of North Khorasan Province (2017). *Report of Water and Soil Management and Engineering Landscape of Water and Soil.*

Aidam, P. W. (2015). The impact of water-pricing policy on the demand for water resources by farmers in Ghana. *Agricultural Water Management 158*, 10–16.

Chu, L. & Grafton, R. Q. (2020). Water pricing and the value-add of irrigation water in Vietnam: Insights from a crop choice model fitted to a national household survey. *Agricultural Water Management 228*, 105881.

Elouadi, H., Ouazar, D., Doukkali, M. R. & Elyoussfi, L. (2017). A mathematical model for assessment of socio-Economic impact of climate change on agriculture activities: Cases of the East of Morocco (Africa). *Indian Journal of Science and Technology 10*(17), 108921.

Escribano Francés, G., Quevauviller, P., González, E. S. M. & Amelin, E. V. (2017). Climate change policy and water resources in the EU and Spain, A closer look into the water framework directive. *Environmental Science & Policy 69*, 1–12.

Feike, T. & Henseler, M. (2017). Multiple policy instruments for sustainable water management in crop production – a modeling study for the Chinese Aksu-Tarim Region. *Ecological Economics 135*, 42–54.

Forni, L. G., Medellín-Azuara, J., Tansey, M., Young, C., Purkey, D. & Howitt, R. (2016). Integrating complex economic and hydrologic planning models: An application for drought under climate change analysis. *Water Resources and Economics 16*, 15–27.

Graveline, N. (2016). Economic calibrated models for water allocation in agricultural production: A review. *Environmental Modelling Software 81*, 12–25.

Heckelei, T. & Wolff, H. (2003). Estimation of constrained optimisation models for agricultural supply analysis based on generalised maxi mum entropy. *European Review of Agricultural Economics 30*(1), 27–50.

Howitt, R. E. (1995). Positive mathematical programming. *American Journal of Agricultural Economics 77*(2), 329–342.

IPCC (2014). Summary for policymakers, climate change 2014: Impacts, adaptation, and vulnerability. In: *Part A: Global and Sectoral Aspects, Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Field, C. B., Barros, V. R., Dokken, D. J., Mach, K. J., Mastrandrea, M. D., Bilir, T. E., Chatterjee, M., Ebi, K. L., Edtrada, Y. O., Genova, R. C., Girma, B., Kissel, E. S., Levy, A. N., MacCracken, S., Mastrandrea, P. R. & White, L. L., eds.). Cambridge University Press, Cambridge, United Kingdom; New York, NY, USA, pp. 1–32.

Lei, Y., Zhang, H., Chen, F. & Zhang, L. (2016). How rural land use management facilitates drought risk adaptation in a changing climate -A case study in arid northern China. *Science of the Total Environment 550*, 192–199.

Lu, S., Bai, X., Li, W. & Wang, N. (2019). Impacts of climate change on water resources and grain production. *Technological Forecasting & Social Change 143*, 76–84.

Oulmane, A., Frija, A. & Brabez, F. (2019). Modelling farmers' responses to irrigation water policies in Algeria: An economic assessment of volumetric irrigation prices and quotas in the Jijel-Taher irrigated perimeter. *Irrigation and Drainage 68*(3), 507–519.

Paris, Q. & Howitt, R. E. (1998). An analysis of Ill-Posed production problems using maximum entropy. *American Journal of Agricultural Economics 80*, 124–138.

Ponce, R., Blanco, M. & Giupponi, C. (2014). The economic impacts of climate change on the Chilean agricultural sector. A non-linear agricultural supply model. *Chilean Journal of Agricultural Research 74*(4), 404–412.

Purvis, L. & Dinar, A. (2020). Are intra- and inter-basin water transfers a sustainable policy intervention for addressing water scarcity. *Water Security 9*, 100058.

Qureshi, M. E., Whitten, S. M., Mainuddin, M., Marvanek, S. & Elmahdi, A. (2013). A biophysical and economic model of agriculture and water in the Murray-Darling basin. Australia. *Environmental Modelling & Software 41*, 98–106.

Schönhart, M., Trautvetter, H., Parajka, J., Blaschke, A. P., Hepp, G., Kirchner, M., Mitter, H., Schmid, E., Strenn, B. & Zessner, M. (2018). Modelled impacts of policies and climate change on land use and water quality in Austria. *Land Use Policy 76*, 500–514.

Shi, M., Wang, X., Yang, H. & Wang, T. (2014). Pricing or quota? A solution to water scarcity in Oasis regions in China: A case study in the heihe river basin. *Sustainability 6*, 7601–7620.

Ureta, C., González, E. J., Espinosa, A., Trueba, A., Piñeyro-Nelson, A. & Álvarez-Buylla, E. R. (2020). Maize yield in Mexico under climate change. *Agricultural System 177*, 102697.

Wickramasinghe, M. R. C. P., De Silva, R. P. & Dayawansa, N. D. K. (2021). Climate change vulnerability in agriculture sector: An assessment and mapping at divisional secretariat level in Sri Lanka. *Earth Systems and Environment 5*, 725–738.

Wineman, A. & Crawford, E. W. (2017). Climate change and crop choice in Zambia: A mathematical programming approach. *NJAS-Wageningen Journal of Life Sciences 81*, 19–31.

Wreford, A. & Topp, C. F. E. (2020). Impacts of climate change on livestock and possible adaptations: A case study of the United Kingdom. *Agricultural Systems 178*, 102737.

Zuo, A., Wheeler, S. A., Adamowicz, W. L., Boxall, P. C. & Hatton-Macdonald, D. (2015). Measuring price elasticities of demand and supply of water entitlements based on stated and revealed preference data. *American Journal Agricultural Economics 98*(1), 314–332.

First received 23 January 2022; accepted in revised form 3 August 2023. Available online 22 August 2023