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Optimized cropping patterns under climate-change conditions

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Abstract A mathematical model is developed in this study with the goal of maximizing agricultural benefits in the Aidoghmarsh river basin, Iran. The results show that the cultivated area of various crops and their agricultural benefits would be increased over the planning horizon with proper management and modification of cropping patterns despite the decline in streamflow and increasing water demand under climate-change conditions. Therefore, considering the optimal cropping pattern increases agricultural benefits by 14 and 17% under baseline climatic and climate-change conditions, respectively, compared to present conditions. This paper's results indicate that areas cultivated with various crops would increase under climate-change conditions compared to baseline climatic conditions, except for alfalfa.

1 Introduction

Low rainfall and increased food production to meet consumption are exacerbated by climate-change in arid regions of the world, Iran being a case in point (Alizadeh and Kamali 2002; Fahimzadeh 2013). The current annual production of irrigated agriculture in Iran is over 57 million t. The water use productivity is approximately 0.7 kg of product per cubic meter of water which is very low compared to those of developed countries. Socioeconomic studies have estimated that the annual Iranian food production must rise to 186 million t, which would require about 266 billion m³ of water if the current water use productivity remains at 0.7 kg of

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product per cubic meter of water. This amount of water is not available. Rather, the water use productivity in Iran's agriculture sector would have to be between 1.8 and 2 kg of product per cubic meter to achieve the desired increase in food production (Keshavarz and Sadeghzadeh 2000). Geologic evidence shows that the Earth's climate has been altered by changing CO₂ concentrations in the post-Industrial Revolution era. The anthropogenic emission of CO₂ and other greenhouse gases is changing the modern climate and causing multiple adverse effects in water resources (Ashofteh et al. 2014). This study addresses the management of cropping patterns to adapt to a changing climate. Several studies have researched the nexus between water scarcity and agricultural production and the means to improve food security through innovation and efficient use of available resources. A few such studies are summarized next.

Singh et al. (2001) applied linear programming (LP) to determine the optimal cropping pattern in an irrigation district in India. The objective function was the maximization of agricultural revenue at different water availability levels. Benli and Kodal (2005) developed a non-linear optimization model for the determination of optimal cropping patterns under limited water supply conditions in the Gap project in the southeastern Anatolian Region of Turkey. The model yields the optimal distribution of crop areas, irrigation water needs, and the total farm profit. Eslami and Zahraei (2005) maximized revenue from agricultural production in the Varamin plain, Iran, applying the genetic algorithm (GA). They found that the production of cucumber and tomatoes must be raised and the area of cultivation devoted to wheat reduced to achieve stated goals. Nagesh-Kumar et al. (2006) presented a GA model for calculating the optimal operating policy and the optimal crop water allocations from a single-purpose irrigation reservoir in India, and the results were compared with those from the LP method. Sethi et al. (2006) examined rice crop pattern in Orissa province, eastern India, which is hindered by seawater intrusion into the coastal aquifer. They implemented deterministic linear programming (DLP) and chance-constrained linear programming (CCLP) models to allocate available land and water resources optimally on a seasonal basis so as to maximize the net annual revenue in the study area. Moradi-Jalal et al. (2007) developed a mathematical model for optimal multi-crop irrigation associated with reservoir operation policies in a reservoir–irrigation system. The objective function was to maximize the annual benefit of the system by supplying irrigation water for a proposed multi-crop pattern over the planning period. They solved the model with the LP method, which was applied to a reservoir–irrigation system in Iran. Sarker and Ray (2009) formulated a crop-planning problem as a multi-objective optimization model. Then, they solved two different versions of the problem employing three different optimization approaches including, constrained method, NSGAI algorithm, and a proposed multi-objective constrained algorithm (MCA). The results showed that the proposed algorithm delivered solutions superior to those of the non-linear version of the crop-planning model. Barikani et al. (2011) determined the optimized crop pattern over a 10-year planning horizon in the Qazvin plain, Iran, with using inter-temporal programming method relying on groundwater for irrigation. Musavi and Ghorghani (2011) tested the effect of increasing the price of water and reducing water consumption on the net income of farmers in the Boker plain, Iran. Noory et al. (2012) reported application of mixed-integer linear (MIL) programming, continuous particle swarm optimization (CPSO), and discrete particle swarm optimization (DPSO) for optimizing irrigation water allocation and a multi-crop planning problem. Galán-Martín et al. (2015) applied a decision-support tool based on a multi-stage LP model that identifies optimal cropping plan decisions under the new Common Agricultural Policy. They applied this method in a Spanish agricultural region to maximize farmers' net return.

The agricultural sector accounts for the largest share of water use in Iran, which is vulnerable to reduction of natural water sources in a changing climate. This work's objective is to determine modifications of the cropping pattern in the Aidoghmoush basin, Iran, considering climate-change impacts to meet food production goals. The modified cropping pattern under climate-change conditions is compared to the optimal cropping pattern under baseline climatic conditions. This work develops a mathematical model for the maximization of agricultural revenue over 14-year horizon in the Aidoghmoush basin. The model's optimization is carried out with the genetic algorithm (GA). This paper's methodology is novel in its approach to optimizing cropping pattern under changing climatic conditions, which is demonstrated with a specific arid region condition.

2 Mathematical model development

This study's objective is the determination of the optimal cropping patterns in the Aidoghmoush basin under baseline climatic and climate-change conditions so that the total benefit from crop production is maximized during the planning horizon. Only irrigation water demands were considered. Three constraints on water availability are considered in this work: (1) the mass balance of a water-supply reservoir considering evaporative loss, (2) limited available areas for seasonal crops and orchards, and (3) limited reservoir capacity. In this paper the simulation interval is monthly.

The evaporation from the reservoir depends on its average free surface area, which in turn depends on storage. The area–storage function of the reservoir system is applied to obtain the free surface area of the reservoir in all operation months based on Eq. (1).

$$A_{i,m} = \alpha \times S_{i,m} + \beta \quad \text{for} \quad i = 1, 2, \dots, I \quad \text{and} \quad m = 1, 2, \dots, 12 \quad (1)$$

where $A_{i,m}$ is the average free surface area of the reservoir in the m th month of the i th year; $S_{i,m}$ denotes the average storage in the m th month of the i th year; I is the number of years during the planning horizon; and α and β are constants. The volume of monthly evaporation equals the monthly evaporative depth multiplied by the average free surface area of the reservoir. If there is precipitation falling on the reservoir area during the month, then that precipitation is subtracted from the monthly evaporative depth.

The main difference between seasonal crops and orchards is that areas allocated to orchards cannot be changed as readily as those for seasonal crops during the planning horizon. In other words, the area of orchards remains constant during the planning horizon while the area of seasonal crops may change during the planning horizon.

The objective function [Eq. (2)] of this paper's optimization scheme consists of maximizing the agricultural average annual benefit over a planning horizon of I years under baseline climatic and climate-change conditions (Moradi-Jalal et al. 2007).

$$Z = \text{Max} \left[\sum_{i=1}^I \sum_{p=1}^P C_{i,p} X_{i,p} + \sum_{i=1}^I \sum_{u=1}^U C_{i,u} X_{i,u} \right] \quad (2)$$

where X denotes the area allocated to seasonal crops or orchards; C equals the unit benefit of seasonal crops and orchards; p and u denote the indices for seasonal crops and orchards, respectively; and P and U denote the number of seasonal crops and orchards, respectively.

Maximizing agricultural benefit is subject to physical and operational reservoir–irrigation constraints (Moradi-Jalal et al. 2007). The monthly storage equation is as follows

$$\sum_{p=1}^P V_{i,m,p} X_{i,p} + \sum_{u=1}^U V_{i,m,u} X_{i,u} + EV_{i,m} + S_{i,m} = S_{i,m-1} + Q_{i,m} \quad (3)$$

for $i = 1, 2, \dots, I$ and $m = 1, 2, \dots, 12$

where $V_{i,m,p}$ is the unit rate of irrigation water demand for the p th seasonal crop in the m th month of the i th year; $V_{i,m,u}$ is the unit rate of irrigation water demand for the u orchard in the m th month of the i th year; $Q_{i,m}$ is the reservoir inflow in the m th month of the i th year; and $EV_{i,m}$ is the reservoir evaporation in the m th month of the i th year. Equation (3) represents the monthly mass balance equation of the reservoir–irrigation system, which involves the volumes of irrigation water and reservoir inflow.

During each year of the planning horizon, the total area allocated to seasonal crops and orchards may not exceed the maximum amount available areas (Moradi-Jalal et al. 2007).

$$\sum_{p=1}^P X_{i,p} \leq A_{agr} \quad \text{for } i = 1, 2, \dots, I \quad (4)$$

$$\sum_{u=1}^U X_{i,u} \leq A_{frt} \quad \text{for } i = 1, 2, \dots, I \quad (5)$$

where A_{agr} and A_{frt} denote the maximum areas available to cultivate seasonal crops and orchards, respectively.

The reservoir–irrigation system is also constrained by the total volume of water stored in the reservoir according to Eq. (6).

$$S_{\min} \leq S_{i,m} \leq S_{dam} \quad \text{for } i = 1, 2, \dots, I \quad \text{and} \quad m = 1, 2, \dots, 12 \quad (6)$$

where S_{dam} is the maximum reservoir storage. Equation (6) states that reservoir storage in the m th month of the i th year is less than the total volume of the reservoir.

There is a constraint on areas cultivated with orchards. Thus, Eq. (7) implies that the area allocated to orchards does not increase during the planning horizon.

$$X_{i,u} \leq X_{i+1,u} \quad \text{for } i = 1, 2, \dots, I-1 \quad \text{and} \quad m = 1, 2, \dots, 12 \quad (7)$$

It is assumed that the initial reservoir storage in the first month of the planning horizon is equal to the reservoir storage at the end of the planning horizon, the so-called carryover constraint

$$S_{1,1} \leq S_{I,12} \quad (8)$$

Penalty functions are added (under maximization) to the objective function to ensure that constraints in Eqs. (4)–(8) are satisfied. Penalty values are deducted from the objective function to account for violations of constraints as follows

Penalty on violation of constraint (4):

$$PF1_i = 10^{a_1} \cdot \left(b_1 + \left(\sum_{p=1}^P X_{i,p} - A_{agr} \right) \right)^2 \quad \text{for } i = 1, 2, \dots, I \quad (9)$$

Penalty on violation of constraint (5)

$$PF2_i = 10^{a_2} \cdot \left(b_2 + \left(\sum_{u=1}^U X_{i,u} - A_{frt} \right) \right)^2 \quad \text{for } i = 1, 2, \dots, I \quad (10)$$

Penalty on violation of constraint (6):

$$PF3_{i,m} = 10^{a_3} \cdot (b_3 + (S_{i,m} - S_{\min}))^2 \quad \text{for } i = 1, 2, \dots, I \quad \text{and } m = 1, 2, \dots, 12 \quad (11)$$

Penalty on violation of constraint (8):

$$PF4 = 10^{a_4} \cdot (S_{1,1} - S_{I,12})^2 \quad (12)$$

where $PF1_i$, $PF2_i$, $PF3_i$, and $PF4$ denote penalty functions resulting from the violation of constraint Eqs. (4)–(8); and $a_1, a_2, a_3, a_4, b_1, b_2$, and b_3 are positive constants in penalty functions.

3 The genetic algorithm

The GA is an evolutionary algorithm which is used in many fields, particularly in engineering, as a search and optimization tool (Bozorg-Haddad 2014). This algorithm is based on random search and attempts to replicate the natural process of natural evolution. The GA provides a close estimate of the optimal solution based on a search algorithm that progressively improves the populations of iterative solutions.

The GA's optimization flowchart is depicted in Fig. 1. In this algorithm, the basic data and decision variables are inputs to the simulation model. The state variables and the objective function corresponding to each iterative stage are calculated. The fitness function is obtained for each of the iterative answers considering the problem constraints. The decision variables are modified according to the fitness function in the optimization algorithm and re-enter the simulation model. The GA selects a number of potential answers in the present iteration to become the potential answers in the next iteration. The selected answers are superior in terms of their fitness function in comparison to other answers. The next step of the GA is to produce new answers after the selection process employing crossover and mutation processes that constitute a new generation of answers that make up the population of the next iteration. This process continues until the algorithm ends (Bozorg-Haddad 2014). The fitness function improves from the current generation to the next and the algorithm search converges towards the global solution.

4 The study region

The study area is the Aidoghmouth river, in East Azerbaijan, northwestern Iran, located between $46^\circ 52'$ to $47^\circ 45'$ east longitude and $36^\circ 43'$ to $37^\circ 26'$ north latitude (Fig. 2). The catchment area covers

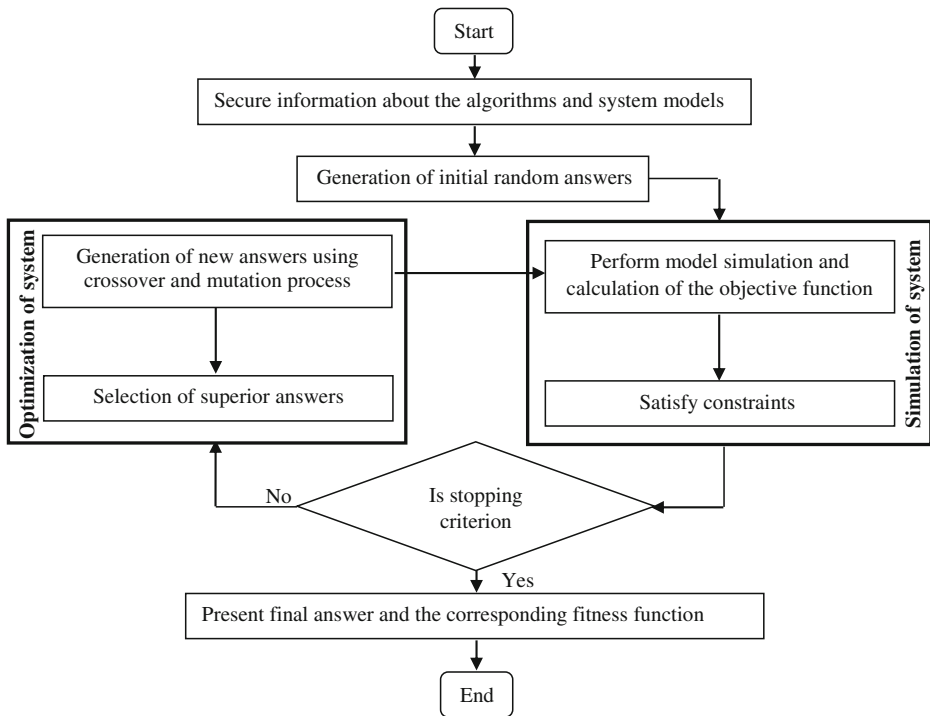


Fig. 1 Flowchart of the GA (after Bozorg-Haddad 2014)

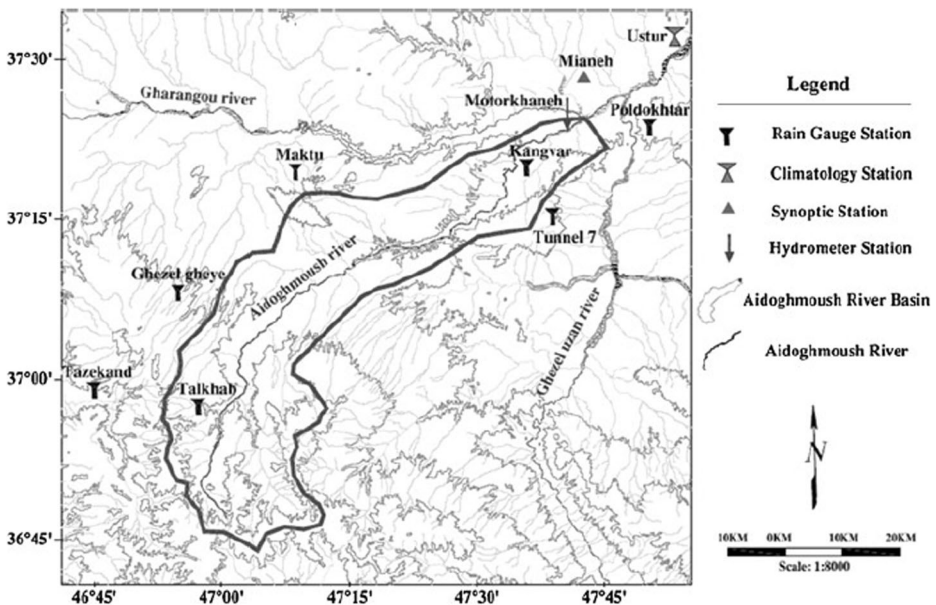


Fig. 2 Layout of the river basin and monitoring stations

1802 km². The elevation of the catchment varies from 1060 to 2500 m above sea level. The Aidoghmarsh river's length equals 80 km and originates within the Ghur-Ghur heights and discharges to the Ghezel-Uzan river. The Aidoghmarsh river's average annual discharge equals 190×10^6 m³. Annual rainfall average in the basin equals 336.2 mm; the rainiest months are April and May. Average annual temperature in the catchment equals 11.6 °C. The maximum and minimum temperatures are 31.9 and −16.8 °C, respectively, the former occurring in July and the latter in February. The baseline climatic and climate-change 14-year periods employed in this study are 1987–2000 and 2026–2039 based on recommendations by Ashofteh et al. (2014).

The data for this study include meteorological variables (precipitation and evaporation), reservoir inflow, monthly irrigation demand of seasonal crops and orchards, and the characteristics of reservoir (maximum and minimum storage and coefficients of the storage-area function).

Meteorological data from the Miyane synoptic station located downstream of the Aidoghmarsh dam was used for the baseline climatic conditions (1987–2000). Having evapotranspiration and effective rainfall, net irrigation demand is determined based on Eqs. (13)–(16) (Ashofteh et al. 2014).

$$IR_m = ET_{cm} - Ra_{effm} \quad \text{for} \quad m = 1, 2, \dots, 12 \quad \text{and} \quad c = 1, 2, \dots, U + P \quad (13)$$

$$ET_{cm} = K_{cm} \times ET_{om} \quad \text{for} \quad m = 1, 2, \dots, 12 \quad \text{and} \quad c = 1, 2, \dots, U + P \quad (14)$$

$$\begin{aligned} Ra_{effm} &= Ra_m / 125 \times (125 - 0.2 \times Ra_m) & \text{if } Ra_m \leq 250 \text{ mm} \\ Ra_{effm} &= 125 + 0.1 \times Ra_m & \text{if } Ra_m \geq 250 \text{ mm} \end{aligned} \quad \text{for } m = 1, 2, \dots, 12 \quad (15)$$

$$V_m = IR_m \times A_c \quad \text{for} \quad m = 1, 2, \dots, 12 \quad \text{and} \quad c = 1, 2, \dots, U + P \quad (16)$$

where IR_m denotes the net irrigation demand in the m th month; ET_{cm} denotes evapotranspiration of the c th crop or orchard in the m th month; Ra_{effm} is the effective rainfall in the m th month; K_{cm} is the plant coefficient of the c th crop or orchard in the m th month; ET_{om} represents the reference evapotranspiration or potential evapotranspiration in the m th month; Ra_m denotes the rainfall in the m th month; V_m equals the volume of water demand in the m th month; and A_c denotes the cultivated area of the c th crop.

The FAO Penman–Monteith method was used for ET_{om} calculation with the CROPWAT software. Net rainfall was calculated from climatological conditions in the study region using monthly rainfall statistics and the soil conservation service method for runoff generation (Smith 1992).

Forecasting of weather variables, temperature, and precipitation under climate-change conditions (2026–2039) was performed employing the HADCM3 model (IPCC 2007). The hydrological model IHACRES was employed to simulate reservoir inflow. Inputs to the IHACRES model are regional-scale temperature and precipitation from the HADCM3 model. It is necessary to determine ET_{om} to calculate the irrigation demand under climate-change conditions, which requires relative humidity, wind speed, and other data which were not available. Therefore, ET_{om} was estimated from a function relating temperature and ET_{om} under baseline conditions. This function is a polynomial regression equation (Ashofteh et al. 2014).

Calculation of the plant coefficient requires having ET_{om} , wind speed at 2 m aboveground, and relative humidity. The calculated ET_{om} as stated above was employed for this purpose. The wind speed under climate-change conditions was considered similar to that of the baseline conditions.

Table 1 Irrigation schedule of crops in the Aidoghmouth irrigation network

Crop	Month											
	Oct	Nov.	Des.	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.
Wheat	a	a	a	a	a	a	a	a	a			a
Wheat	a	a	a	a	a	a	a	a	a			
Alfalfa	a							a	a			
Soybean								a	a	a	a	a
Corn								a	a	a	a	a
Maize	a							a	a	a	a	a
Potatoes	a							a	a	a	a	a
Walnut	a						a	a	a	a	a	a

^a The month that each of the seasonal crops and orchards under goes irrigation

The relative humidity under climate-change conditions was calculated with regression equation between relative humidity and ET_{om} under baseline conditions (Ashofteh et al. 2014).

Seasonal crops in the study region include wheat, barley, alfalfa, soybean, corn, maize, and potatoes. The orchard crop is walnut. Table 1 lists the crops produced in the Aidoghmouth irrigation network. The area of walnuts remains constant during the planning horizon. Alfalfa has an inter-annual cultivation period in the study region. The areas of seasonal crops change annually. Table 2 lists the values of the parameters appearing in Eqs. (1)–(8).

5 Results and discussion

The average annual reservoir inflow under baseline and climate-change conditions are depicted in Fig. 3, where it is seen that the amount of reservoir inflow under climate-change conditions sometimes exceeds and sometimes is less than the inflow under baseline climatic conditions. Overall, the average annual reservoir inflow under baseline climatic conditions and climate-change conditions equals 402.65×10^6 and $399.08 \times 10^6 \text{ m}^3$, respectively, pointing to a slight reduction of reservoir inflow under climate-change conditions.

The average annual rainfall under baseline climatic conditions and climate-change conditions are shown in Fig. 4, where it is seen that average annual rainfall equals 328.41 mm and 361.26 mm under baseline climatic and climate-change conditions, respectively.

Figure 5 illustrates the irrigation demand by crops under baseline climatic and climate-change conditions. It shows that the irrigation demand would increase during climate-change

Table 2 The value of parameters employed in the mathematical model

Parameter	Amount/number	Units
$S_{\min}$	0.03	—
β	0.8	—
I	14	—
P	7	—
U	1	—
$S_{\min}$	8.9	(10^6 m^3)
S_{dam}	145.7	(10^6 m^3)
A_{agr}	8775	(ha)
A_{frt}	4725	(ha)

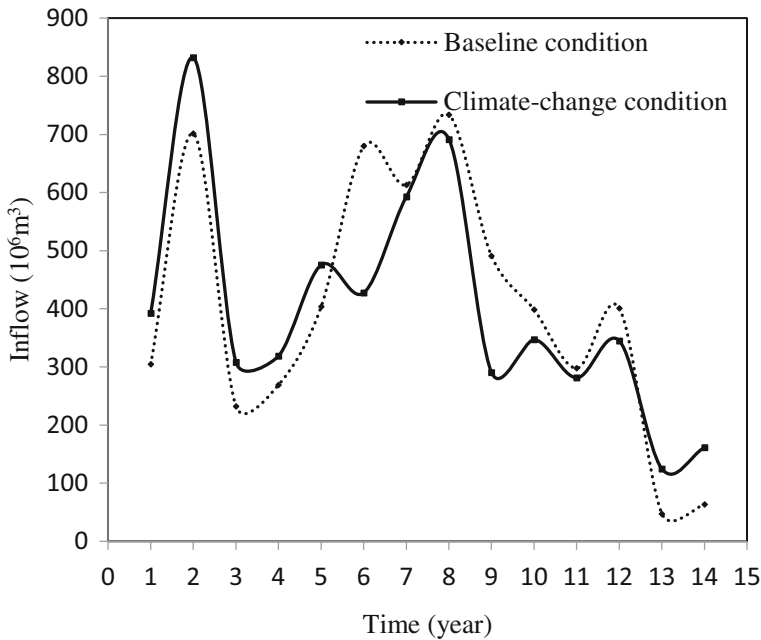


Fig. 3 Average annual inflow under baseline climatic and climate-change conditions

conditions. The average annual irrigation demand by different crops under baseline climatic and climate-change conditions is listed in Table 3.

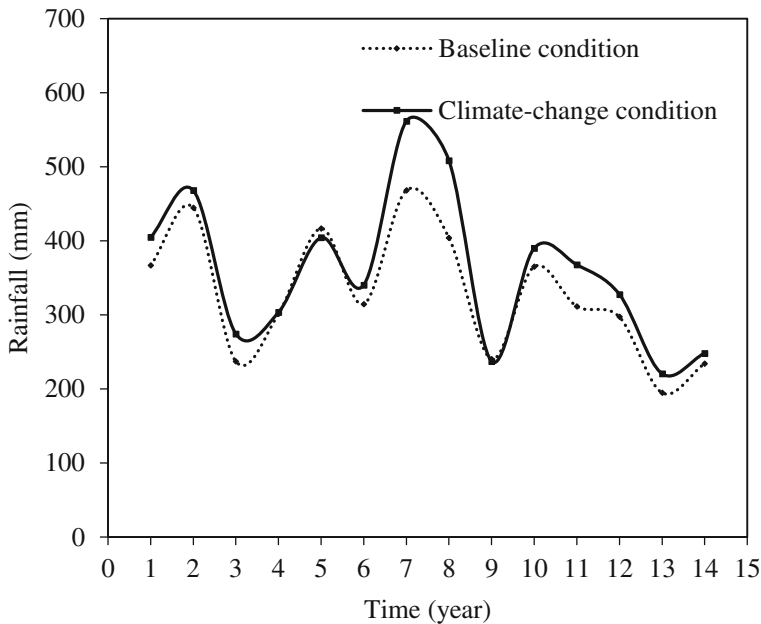


Fig. 4 Average annual rainfall under baseline climatic and climate-change conditions

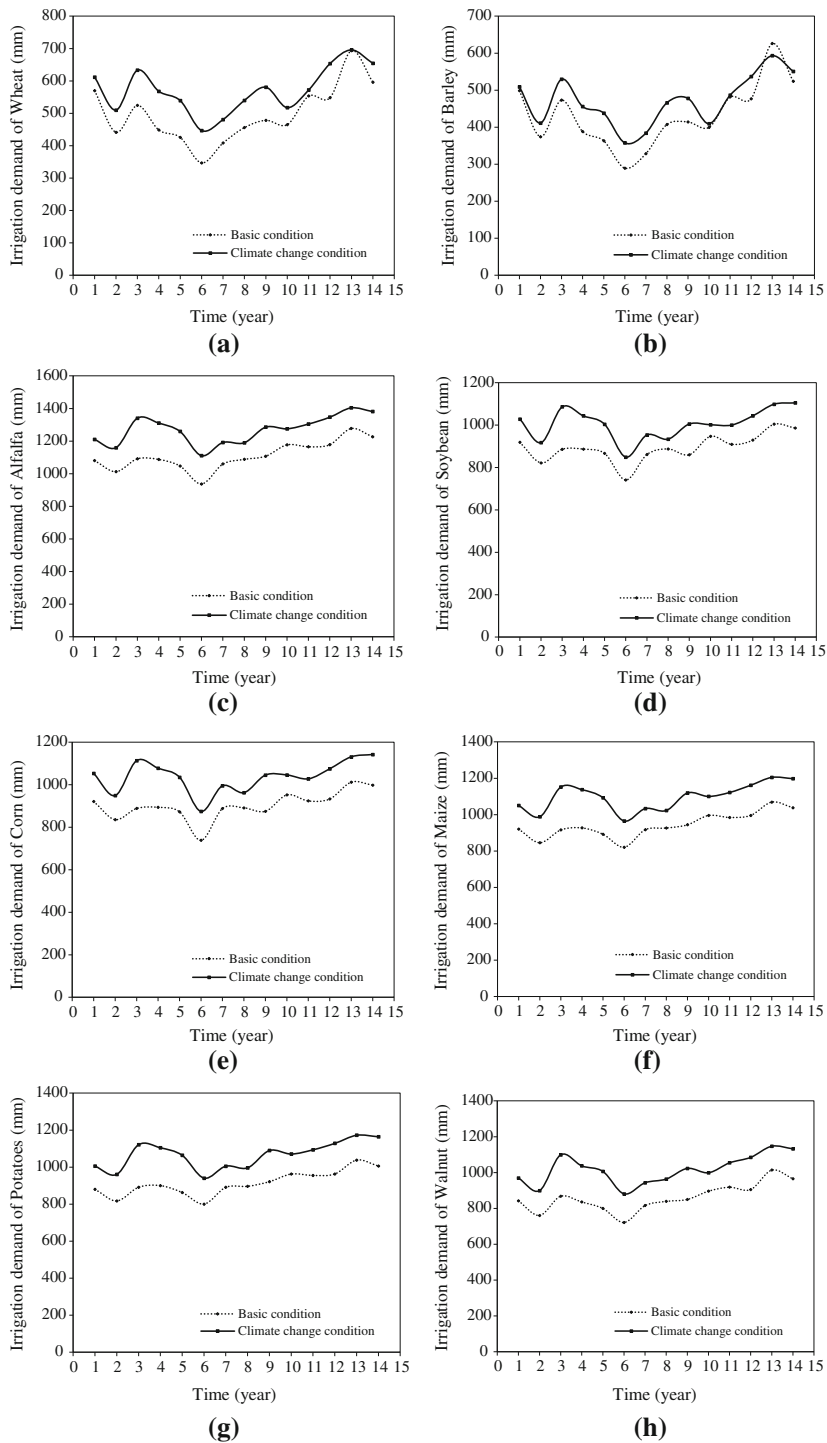


Fig. 5 Average irrigation demand of different crops under baseline climatic and climate change conditions. **a** Wheat. **b** Barley. **c** Alfalfa. **d** Soybean. **e** Corn. **f** Maize. **g** Potatoes. **h** Walnut

Table 3 Average annual irrigation water demand of different crops during the planning horizon

Cinditions	Irrigation demand (mm)							
	Wheat	Barley	Alfalfa	Soybean	Corn	Maize	Potatoes	Walnut
Baseline climatic	496.76	431.80	1109.70	893.26	901.67	942.39	912.97	859.41
Climate-change	571.70	471.85	1269.53	1005.10	1037.63	1096.42	1065.64	1017.14

This study's key objective is the determination of the optimal areas to be allocated to various crops (that is, the optimal cropping pattern) within the Aidoghmoush catchment over 14-year planning horizons under baseline climatic and climate-change conditions employing the GA. The GA in MATLAB toolbox was implemented for this purpose. The GA parameters (Table 5) were determined by sensitivity analysis (Table 4).

The GA was run ten times for the cases associated with baseline climatic and climate-change conditions, and the best run was determined based on the maximum objective function (maximum crop benefit) (Table 5). Figure 6 shows graphs of monthly reservoir storage and the volume of reservoir overflow during the planning horizon. Figure 7 depicts the optimal cultivated areas for seasonal crops and orchards under baseline climatic and climate-change conditions.

Five scenarios were defined and analyzed to assess the water shortage for irrigation, including (1) simulation of the reservoir–irrigation system with the irrigation demand under baseline climatic conditions and present cultivated area, (2) simulation of the system with the irrigation demand under baseline climatic conditions and optimal cultivated area associated with the baseline climatic conditions, (3) simulation of the system with the irrigation demand under climate-change conditions and cultivated area associated with climate-change conditions, (4) simulation of the system with the irrigation demand under climate-change conditions and with present cultivated area, and (5) simulation of the system with the irrigation demand under climate-change conditions and the cultivated

Table 4 Results of the sensitivity analysis

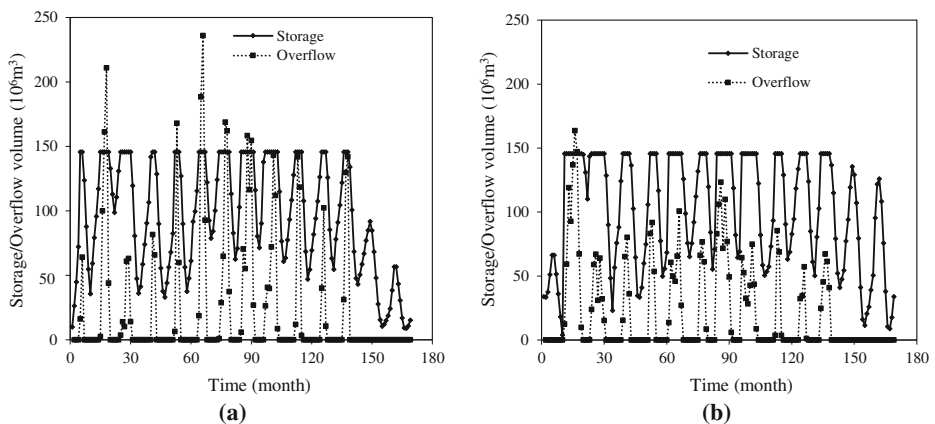
Crossover rate	Mutation rate	Benefit (10^8 \$)		
		The number of chromosomes in each population		
		100	300	500
0.5	0.01	1.1	1.11	1.17
	0.05	1	1.14	1.14
	0.1	1	1.13	1.17
0.6	0.01	1	1.08	1.09
	0.05	1	1.14	1.16
	0.1	0.97	1.08	1.14
0.7	0.01	1	1.14	1.18
	0.05	1.1	1.12	1.16
	0.1	0.98	1.1	1.11
0.8	0.01	1	1.07	1.15
	0.05	1	1.13	1.15
	0.1	1	1.13	1.15

Table 5 Parameters employed with the GA

Parameter	Number/type
The number of chromosomes in each population	500
Type of selection	Roulette wheel
Crossover rate	70%
Type of crossover	Two-point
Mutation rate	1%
Number of iterations	5000

area associated with optimal baseline climatic conditions. Each of these scenarios corresponds to present baseline climatic conditions, optimal baseline climatic conditions, optimal climate-change conditions, combination of climate-change and present baseline climatic conditions, and combination of climate-change and optimal baseline climatic conditions, respectively. The reservoir–irrigation system was simulated under each of the scenarios using a standard reservoir operation policy (SOP) rule, and the amount of water shortage was calculated. The results are listed in Table 6. Table 6 also lists the average area cultivated with each crop and the total benefit from crop production that occurs during the planning horizon corresponding to the five scenarios. The results corresponding to the scenarios establish that the largest water shortage is associated with scenario 1 which represents the baseline climatic conditions. The water shortage equals zero in scenarios 2 and 3. This implies that proper management and selection of the optimal cropping pattern avoids water shortage while crop production yields net revenue. The results in Table 6 indicate that there is a water shortage in scenario 4. In other words, the simulations predict a water shortage if the cultivated area under climate-change conditions remains equal to the present one under baseline climatic conditions. Also, the amount of water shortage equals zero for scenario 5. Therefore, if the cultivated area under climate-change conditions equals the optimal area under baseline climatic conditions, there would not be water shortage but the benefit from crop production would be reduced relative to optimal climate-change conditions.

The calculated total benefits during the planning horizons corresponding to the five scenarios shown in Table 6 indicate that by choosing optimal crop patterns associated

**Fig. 6** Charts of monthly storage and reservoir overflow volume during the planning horizons for **a** baseline climatic conditions and **b** climate-change conditions

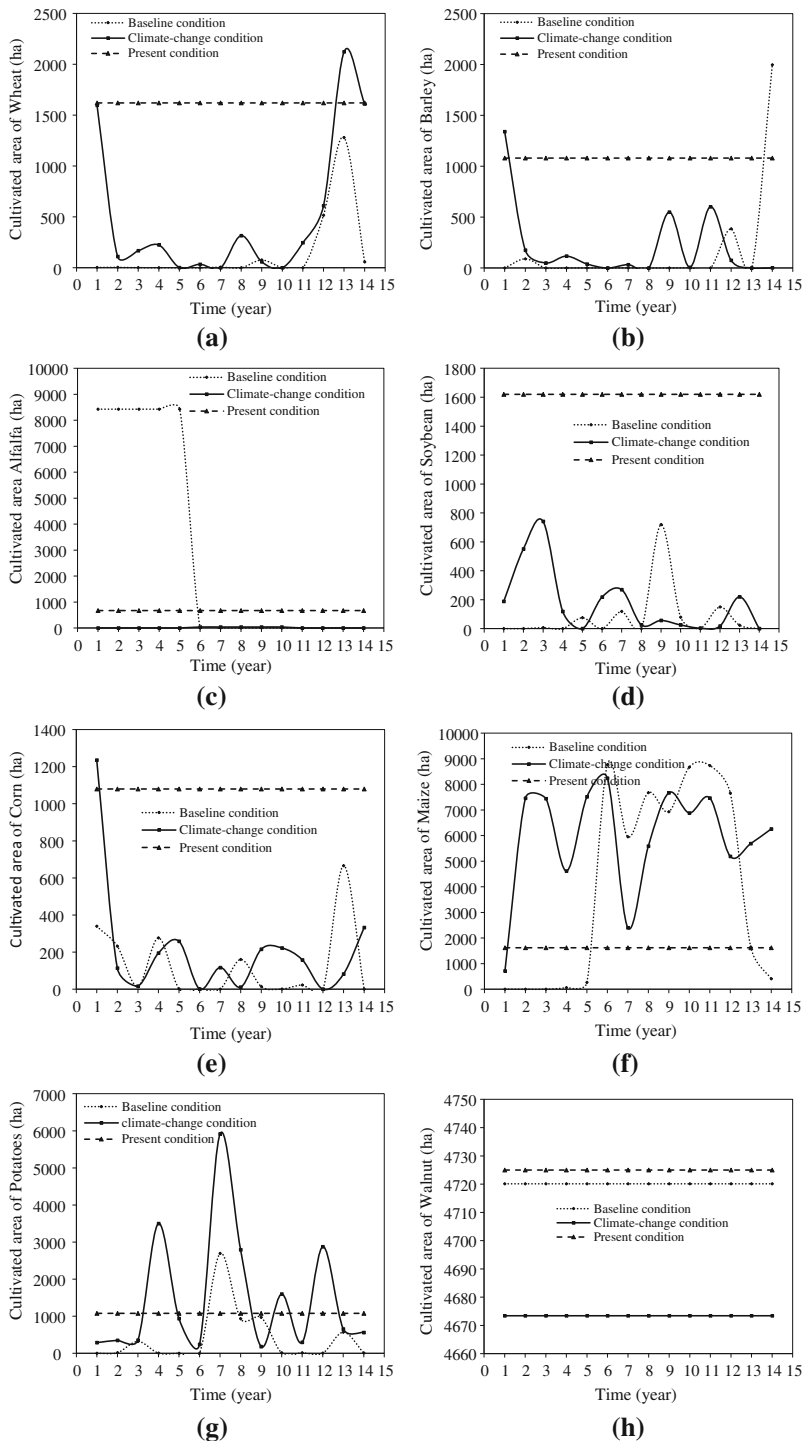


Fig. 7 The optimal cultivated areas of several crops under baseline climatic climate change conditions. **a** Wheat. **b** Barley. **c** Alfalfa. **d** Soybean. **e** Corn. **f** Maize. **g** Potatoes. **h** Walnut

Table 6 Comparison of the average optimal area under cultivation of various crops, total benefit, and the water shortage calculate within the planning horizon for five scenarios

Crop	Area under cultivation (ha)				
	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Wheat	1620	139.34	507.42	1620	139.34
Barley	1080	177.52	213.77	1080	177.52
Alfalfa	675	3011.75	13.62	675	3011.75
Soybean	1620	84.03	174.33	1620	84.03
Corn	1080	123.50	211.40	1080	123.50
Maize	1620	4055.47	5939.33	1620	4055.47
Potatoes	1080	396.98	1468.52	1080	396.98
Walnut	4725	4720.10	4673.45	4725	4720.10
Total benefit (10^8 \$)	1.1	1.2	1.3	1.1	1.2
Water shortage (10^6 m ³)	91.64	0	0	18.67	0

with scenarios 2 and 3, the amount of crop benefit increases 14 and 17%, respectively. The unit benefits from cultivation of the various crops were considered equal under baseline climatic and climate-change conditions. This explains why the total benefits corresponding to scenarios 4 and 5 are similar to those of scenarios 1 and 2, respectively. Also, the results listed in Table 6 establish that the average area cultivated with alfalfa under climate-change conditions would decrease significantly compared to baseline climatic conditions during the planning horizons. This is caused by the alfalfa irrigation demand which is the largest under climate-change conditions, and, therefore, its cultivated area is reduced by optimization.

6 Concluding remarks

This paper's results have shown that under climate-change conditions, the average reservoir inflow would decrease slightly compared to the reservoir inflow under baseline climatic conditions, and the average rainfall and the average irrigation water demand of various crops would increase. Yet, it appears possible to increase the cultivated areas under climate-change conditions by proper management and modification of the cropping pattern and to achieve maximized benefits in the planning horizons. Moreover, this work's findings indicate that optimization of the cultivated areas with various crops would increase under climate-change conditions compared to baseline climatic conditions, except for alfalfa.

$A_{i,m}$, average free surface area of the reservoir in the m th month of the i th year; $S_{i,m}$, average storage in the m th month of the i th year; α , constant in area–storage function of the reservoir; β , constant in area–storage function of the reservoir; Z , objective function; X , area allocated to seasonal crops and orchards; C , unit benefit of seasonal crops and orchards; p , indices for seasonal crops; u , indices for orchards; P , number of seasonal crops; U , number of orchards; $V_{i,m,p}$, unit rate of irrigation water demand for seasonal crop p in the m th month of the i th year; $V_{i,m,u}$, unit rate of irrigation water demand for orchard u in the m th month of the i th year; $Q_{i,m}$, reservoir inflow in the m th month of the i th year; $EV_{i,m}$, reservoir evaporation in the m th month of the i th year; A_{agr} , maximum area available to cultivated seasonal crops; A_{frt} , maximum area available to cultivated orchards; S_{dam} , maximum reservoir storage; $a_1, \dots, a_4$, positive constants in the penalty functions; b_1, b_2, b_3 , positive constants in the penalty

functions; PF , penalty function; IR_m , net irrigation demand in the m th month; ET_{cm} , evapotranspiration of the c th crop or orchard in the m th month; Ra_{effm} , effective rainfall in the m th month; K_{cm} , plant coefficient of the c th crop or orchard in the m th month; ET_{om} , reference evapotranspiration or potential evapotranspiration in the m th month; Ra_m , rainfall in the m th month; V_m , volume of water demand in the m th month; A_c , cultivated area of the c th crop

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