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Maximizing Water Productivity and Minimizing Virtual Water for Determining an Agronomic-Economic Program and Optimizing the Crop Production Strategy in the Sistan Region, Iran

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ABSTRACT

Aims: Indiscriminate water use has caused irreparable damage to limited water resources, and the agricultural sector consumes the most significant amount of water. The reduction of water resources and the continuation of drought and its continuation in recent years have necessitated revision and change in the agricultural industry more than ever. Global warming and the loss of freshwater resources have turned attention to promoting crop water productivity by focusing on the role of crops' embedded virtual water. Indeed, production programming is based on maximizing water productivity, and minimizing virtual water gradually replaces traditional patterns based on maximizing production and yields.

Materials & Methods: The present research aimed to present a cropping pattern and water allocation to crops and regions based on the virtual water scenario and water productivity. The research used a bi-level programming model (leader-follower) to optimize irrigation water allocation among irrigated regions and crops and determine the optimal cropping pattern in regions Zabol, Zahak, Nimruz, Hamun, and Hirmand for 2022-2023. The leader in the model is The Sistan and Baluchestan Regional Water Authority, which controls the total water allocations, and the followers are the agricultural sectors, competing over the allocated water. The objective for the leader is to minimize the Gini coefficient. The followers' objectives are maximizing economic profit, water productivity, and virtual water. The model used in the study is solved by a metaheuristic process, a combination of the dynamic genetic algorithm, a non-dominated sorting genetic algorithm (NSGA), and a fuzzy programming method.

Findings: The result showed that in the current conditions of the Sistan Region, the wheat crop is the most cultivated area. Considering the water productivity, the highest cultivation area with 6567.2 ha belongs to melon, and if we consider virtual water, the highest cultivated area belongs to melon with 6495 ha, and the lowest cultivated area belongs to alfalfa with 542 ha. When virtual water and water productivity were considered, the system's economic profit was estimated at 3.02×10^{13} IRR and 3.04×10^{13} IRR, respectively. Also, the highest water and cultivation area were assigned to melon and onion.

Conclusion: Considering the Virtual water content (VWC), less water was assigned to crops with higher Virtual water content, i.e., wheat and barley. When the water productivity index was considered, the results revealed that more water was allocated to crops such as melon and onion with higher water productivity. The proposed model can be used to determine a cropping pattern that considers minimizing virtual water and maximizing water productivity as its objectives. Using the concept of virtual water and water productivity in the proposed model can prevent the wastage of water resources in the agricultural sector and protect the environment. Therefore, using the concepts of virtual water and water productivity to guide planning and investment in agricultural development projects in the Sistan Region is recommended.

Keywords: Economic Profit; Leader-Follower; Sistan; Virtual Water; Water Allocation; Land Allocation..

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Introduction

Water is unquestionably one of the gravest challenges of humanity and the most controversial field of thinking for leading theorists in the world [1]. Water shortage has provoked disputes and conflicts among water users in different sectors. These conflicts can be mitigated to a great extent by fair allocation of water. The key to the basic allocation of water is to adhere to the goals of social justice, economic benefits, environmental conservation, and risk control [2,3,4]. Researchers have employed a wide range of methods for the allocation of water resources, e.g., optimization models[5], optimization-simulation methods[6], stochastic programming[7], multilevel method[8], multi-objective method[9], non-cooperative method[8], game theory, artificial networks[9] and goal programming [10,11], Simulation of the dynamics of water resources[12], WEAP simulation[13,14], multiple attribute decision making (MADM) method with a water governance approach[15]. The Virtual water trade presents a new method for exploiting hidden water flows and the water used for commodity, food, and energy production [16]. Virtual water is the total water consumed in a service and commodity production process [17,18, 19]. Virtual water trade (VWT) showed the amount of embedded water in crops for trading purposes [20].

International trade indirectly displaces a great deal of water among countries. Traded crops, which may contain high volumes of embodied water, conduct global water redistribution [21, 22]. Virtual water flow is a method to balance water distribution between high-water and low-water areas [23, 24].

Some studies on providing a cropping pattern for the sake of optimizing virtual water consumption include Jahanbeen's [25] research on managing blue water consumption and increasing green water consumption in efforts to propose a suitable cropping pattern, Shahidi and Morovatneshan's [26] research on the use of a genetic algorithm to minimize virtual water in an optimal cropping pattern for the Birjand plain, Sedghamiz et al.'s [27] research on the use of the concept of virtual water and multi-objective optimization model for the proper allocation of agricultural and environmental water in Golestan Province, and finally, Xu et al.'s [28] research on the allocation of the water resources of transboundary rivers based on the virtual water index. The following is also a review of research on the concept of virtual water for the optimal allocation of water resources. Delpasand et al. [29] proposed a multi-objective optimization model for Iran to maximize income and minimize direct and indirect water use in producing strategic agricultural and industrial commodities. The results showed wheat had the highest share in the agricultural sector's water consumption. In contrast, potatoes and tomatoes were more profitable due to their relatively higher prices and lower water consumption, amounting to about 400 $m^3.t^{-1}$ of the crop. Ye et al. [30] developed a multi-objective model for the water allocation procedure between Agriculture and urban, which were the two primary water users of total water consumption in Beijing. Water resources included virtual and physical water. Considering the goals of maximizing economic profit and minimizing the environmental effects of water consumption, The results showed that the physical water resources mainly satisfied urban and environmental demand and that the imbalance between water demand and supply could be redressed by importing virtual water to water-scarce regions. Su et al. [31] used a multi-objective optimal allocation model to allocate agricultural water resources to maximize the agricultural sector's net profit, improve agricultural water use efficiency, and maximize the ratio of green water use in the Xiang River basin. The results showed that water allocation using the proposed model is optimal compared to 2007. At the same time,

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the planting ratio of corn reduces, and the ratio of cash crops increases. Hekmatnia et al. [32] proposed a cropping pattern based on the virtual water and irrigation requirements after calculating the water demand of the crops and their virtual water content. The results revealed that the mean irrigation requirement of crops in the Hirmand basin was about 7800 $m^3.ha^{-1}$, and their virtual water content was 2.3 $m^3.kg^{-1}$.

In addition to the contents of virtual water, water productivity is an essential index in macro-level planning of water supply, allocation, and consumption [33]. The concept of water productivity, first proposed by Molden, means the ratio of net yield or income of farming, forestry, aquaculture, animal husbandry, or a combined agricultural system to the water used to achieve the net profit [34]. Iran's rank in water productivity is 102 among 123 countries, reflecting its failure to define proper indices for monitoring and evaluating the goals of regulations and programs, especially the water productivity index [35]. Since the agricultural sector mainly consumes the water resources in Iran and the water resources have a descending fluctuating trend, the crop production policy is recommended for the sake of preserving and reserving water resources to focus on crops that could both enhance water productivity and match the virtual water content of the crops [36]. Pouran and Raghfar [37] used the TOPSIS algorithm to compare the cropping pattern derived from optimization to maximize the water productivity of determinate crops with the conventional cropping pattern derived from the objective of maximizing profit in Ilam and Semnan, Iran. The result showed that cultivation patterns with the goal of maximum water productivity in the investigated Provinces are in better condition than the cultivation pattern resulting from profit evaluation.

Karimzadeh et al. [38] determined an optimal cropping pattern for small-scale farms in the Chenaran region in Mashhad, Iran, using linear and multi-objective models to maximize three indices: gross profit, water productivity, and energy efficiency. The results showed that the cropping pattern resulting from linear planning to maximize water productivity has higher and more profit. However, it needs to meet the necessary variety of crops of the cropping pattern. The result of the weighted multi-objective method has the relative advantage of water efficiency, energy efficiency, and net profit compared to the existing model in the region, and it can be implemented in the short term. In their study of virtual water, Khoramivafa et al. [39] evaluated the productivity and ecological footprint of water in corn and wheat farms in the Kuzran Region. The results showed that the amount of virtual water in corn was more than that of wheat, and water productivity for wheat was more than that of corn. Also, there is a severe water shortage in the region, cultivation of crops such as corn must be stopped, and plants like saffron must be replaced in the Kouzaran farmers' agricultural planning.

The literature review reveals that managing water resources and consumption in the agricultural sector needs to look into crops' virtual water and water productivity. Therefore, this study addresses this research gap by investigating the allocation of water resources in the region, along with the virtual water trade, to water users. The main question in this study is whether the allocation of water and land is optimal when considering the concept of virtual water and water productivity in the Sistan Region between different regions and crops. Assuming that the cultivation pattern in the Sistan Region could be more optimal, the primary purpose of this study is to examine the cultivation pattern in the Sistan Region with emphasis on the concept of virtual water

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and water productivity. This research uses a bi-level (leader-follower) programming model with an emphasis on the concepts of virtual water and water productivity and their integration with the proposed model to optimize irrigation water allocation among irrigation regions and crops and determine an optimal cropping pattern for crops in five areas, including Zabol, Zahak, Nimruz, Hamun, and Hirmand, from 2021 to 2022. The research simultaneously considers conflicting objectives, including fairness in water allocation, economic profit, virtual water, and water productivity.

The model developed in this research can optimally allocate limited water and land resources sustainably. The results can help local decision-makers develop more profitable crop cultivation strategies and contribute to sustainable agricultural development and the management of regional water resources, which would provide more scientific instructions.

Materials & Methods

Study site

The study site is the transboundary basin of Hirman, an important basin in the southeast of Iran (61°50'E., 30°-31° N.), which plays a leading role in the subsistence of the Sistan Region. The Sistan Region has an arid and hyper-arid climate. The region has five counties (Hirmand, Hamun, Nimruz, Zabol, and Zahak). Figure 1 displays the geographical location of the region. On the one hand, the climatic conditions and the complete dependence on the Hirman River have created an extreme water crisis with adverse impacts on the regional economy, agriculture, and environment, so water management has been complicated [40]. The amount of water entering the Sistan Region in 18 years (out of the last 40 years) has been less than the water rights. In recent years, based on the new constructions in Afghanistan and the water policies of this country, the amount of water entering has decreased. It has been very noticeable. Since the region is suffering from an unbalanced spatial and temporal distribution of water and is simultaneously struggling with population growth, urbanization, and the development of the industrial and agricultural sectors, the increased demand for water is unavoidable for which water resources management has become imperative for hindering the encounter with water crisis and the likely stresses [41], given that the agricultural sector in the Sistan Region is the most water consumer, which is struggling with water shortage and reduction of Hirmand river water supply and lack of formal plan for water allocation, adopting a proper method and developing a model for determining an optimal cropping pattern and optimally allocating water to the irrigation regions and crops are a leap toward the management of water resources.

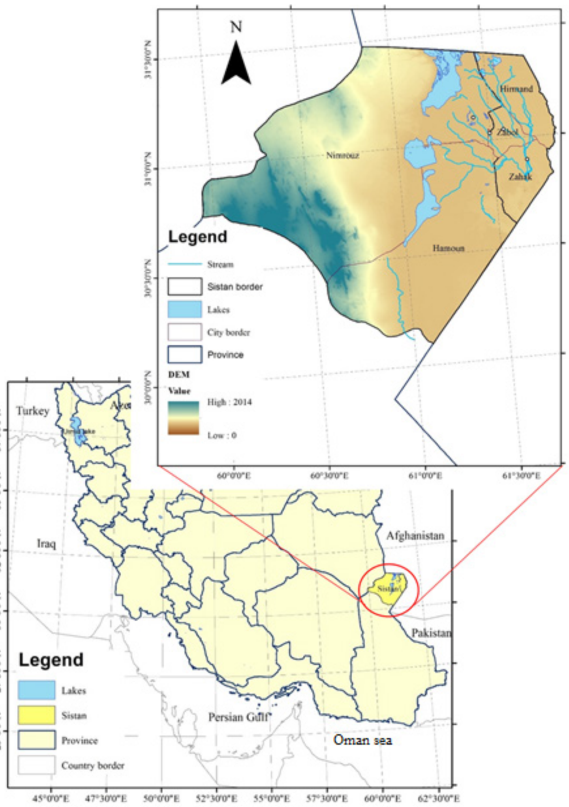

Figure 1) The geographical location of the Sistan Region.

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A bi-level multi-objective programming (BMOP) model[42] is an optimization model with a bi-level hierarchical structure that can manage the problem of bi-level decision-makers in the water management system and offset the potential benefits of different decision-making levels simultaneously. In such problems, two decision-makers try to optimize their desired goals, which sometimes conflict with each other. The second-level decision-maker optimizes its objectives under the parameters taken from the first-level decision-maker. [42]. The leader-follower model is the bi-level programming model used in the present work[43].

Von Stackelberg, in 1934, introduced this method as a non-cooperative game. The hierarchical nature of decision-making in this game requires an equilibrium solution. The leader's optimal move depends on the Nash equilibrium among the followers. A leader is fully aware of the follower's payoff functions before deciding and can determine the equilibrium of the follower's game. Similarly, for each leader's decision, the followers to maximize their payoff function can calculate their equilibrium reaction. The framework of a bi-level model can be formulated as follows[42]:

Upper-level:

$$Min\,F_0\left(x\right)=Min\,\left(f_{01}\left(x\right),f_{02}\left(x\right),\ldots,f_{0n_1}\left(x\right)\right.$$ Eq. (1)

Lower-level

$$Min\,F_1\left(x\right)=Min(f_{11}\left(x\right),f_{12}\left(x\right),\ldots,f_{1n_2}\left(x\right)$$ Eq. (2)

$$Min\,F_q\left(x\right)=Min(f_{q1}\left(x\right),f_{q2}\left(x\right),\ldots,f_{qn_q}\left(x\right)$$ Eq. (3)

$$s.t$$
$$\sum_{j=1}^{n}a_{ij}x_j\le b_i,x_j\ge 0,j=0,1,\ldots,q,i=0,1,\ldots,n$$ Eq. (4)

where $F_0\left(x\right)$ and $F_1\left(x\right)\sim F_q\left(x\right)$ represent the lower-level and upper-level objective functions, x_j and b_i are column vectors with the components of *j* and *i*, and a_{ij} is a matrix of left-hand side coefficients of decision x_j. The upper-level objective function is the leader, and the lower level is the follower objective function [42]. This research uses an optimal strategy for allocating irrigation water and determining an optimal cropping pattern in the agricultural sector by following a bi-level multi-objective model and integrating thev contents of water productivity and water virtual. Based on this model, two decision-making institutions are being considered. The first is the upper-level decision-makers, the local managers, who allocate water between the irrigation areas. The decision Xi represent $_{s\,i}$ t. The second is the lower-level decision-makers, farmers (followers), who distribute water among crops represented by Y_{ij} and determine the cultivation area of the crops in the cropping pattern represented by A_{ij}. i and j represented the irrigation regions and crops in the irrigation region, respectively.

Estimation of virtual water

The virtual water (VWC) of a crop is expressed as follows [19]:

$$VWC_{ij}=\frac{CWR_{ij}}{yield_{ij}}$$ Eq. (5)

where *CWR* represents the crop water requirement of crop j in region i, and $yield_{ij}$ represents the mean yield (kg). If a crop's VWC is estimated at >1 $m^3.kg^{-1}$, it is considered a water-intensive crop; otherwise, it is considered a low-water crop. This holds for agricultural and horticultural crops [21].

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Conceptualization of water productivity

Various methods have been proposed in the theoretical literature for measuring productivity. In Molden et al.'s [43] study, the physical productivity index of resources from the quantitative and physical aspect of crops is defined as production per unit of water, which is obtained by dividing mean crop yield (kg) by the rate of water consumption (m^3) [43]:

$$WPC_{ij} = \frac{yield_{ij}}{CWR_{ij}} \quad \text{Eq. (6)}$$

- Upper-level objectives

To ensure a balanced water allocation among the basin's stakeholders, justice in water allocation must be maximized. The Gini coefficient measures the justice distribution. In general, the Gini coefficient measures income inequality. However, it also measures land and water use inequality [44]. Therefore, a water distribution inequality criterion can be defined at the basin level, the value of which is expressed as the following objective function in water allocation [44].

$$minGini = \sum_{i=1}^{m}\sum_{i'=2}^{m}\left|\frac{X_i}{R_i} - \frac{X_i}{}\right| \quad \text{Eq. (7)}$$

$$/\,\text{'Ri'}2m\sum_{i=1}^{m}\frac{X_i}{R_i} - water\ penalty\ up$$

The Gini coefficient has a value from 0 to 1 in this equation. As the value approaches 0, different regions are assigned equal water per economic unit, so water allocation is more just. On the contrary, as the value approaches 1, a region should be assigned more water to supply economic profits. m represents the number of regions, and R_i is the function of economic profit, calculated by Eq. (8) [43]:

$$R_i = \sum_{j=1}^{n}((b_{ij}.F_{ij}) - C_{ij}).A_{ij} - \gamma X_i,\ i = 1, 2, \ldots, m \quad \text{Eq. (8)}$$

F_{ij} is the water-crop production function, b_{ij} is the crop's price in region i, C_{ij} is the cast of crop j in region i, and γ is the water price determined by the leader.

The constraint corresponding to the upper-level decision-makers' objective function is that the total water allocated to the irrigation region cannot exceed the total water available to the agricultural sector, as shown by S. It is represented by Eq. (9) [42]:

$$\sum_{i=1}^{m} X_i \leq \text{S} \quad \text{Eq. (9)}$$

- Lower-level objectives

The objective function for the follower is defined as follows [42]:

$$max\sum_{i=1}^{m} R_i = \sum_{j=1}^{n}((b_{ij}.F_{ij}) - C_{ij}).A_{ij} - \gamma X_i - water\ penalty\ low - Area\ penalty \quad \text{Eq. (10)}$$

Considering the VWC and water productivity of the studied crops, the second objective function for the lower level in the proposed model is defined as

$$\min VWC_j = \sum_{j=1}^{n} VWC_{ij}.A_{ij} \quad \text{Eq. (11)}$$

$$\max WPC_j = \sum_{j=1}^{n} WPC_{ij}.A_{ij} \quad \text{Eq. (12)}$$

The constraints of the lower-level decision-makers' objective function are as follows[42]:

$$\sum_{j=1}^{n} Y_{ij} A_{ij} \leq X_i \quad i = 1, 2, \ldots, m \quad \text{Eq. (13)}$$

$$\sum_{j=1}^{n} A_{ij} \leq A_i \quad i = 1, 2, \ldots, m \quad \text{Eq. (14)}$$

$$F_{ij} = a.\left(\eta\sum_{j=1}^{n} Y_{ij}\right)^2 + b.\left(\eta\sum_{j=1}^{n} Y_{ij}\right) + c,$$

$$i = 1, 2, \ldots, m, \quad j = 1, 2, \ldots, n \quad \text{Eq. (15)}$$

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a, b, and c are parameters of the water–crop production function, η is irrigation efficiency, and A_i is the arable land in region i.

Calculation of penalty function

The constraint satisfaction problems are defined in the objective function as a penalty function. Regarding the upper-level objective function, if the water allocated to each region exceeds the total available water, Eq. (16) is used. Regarding the lower-level objective function, Eq. (17) is used as the penalty function of the maximum available water if the water consumed for crops exceeds the total allocated water, and Eq. (18) is used as the penalty function of the maximum arable land if the cultivation area exceeds the maximum available area [45]. Here, α is the coefficient of the penalty function for the upper-level objective function, β is the coefficient of the penalty function for the lower-level objective function, and μ is the coefficient of the penalty function for the arable land. The values of these parameters were set at 100 by trial and test[45].

$$water\ penalty\ up = \alpha((\sum_{j=1}^{n} X_i / S) - 1) \quad \text{Eq. (16)}$$

$$water\ penalty\ low = \beta((\sum_{j=1}^{n} A_{ij}.Y_{ij} / X_i) - 1) \quad \text{Eq. (17)}$$

$$Area\ penalty = \mu((\sum_{j=1}^{n} A_{ij} / A_i) - 1) \quad \text{Eq. (18)}$$

The model used in the study is solved by a metaheuristic process, which combines the dynamic genetic algorithm, non-dominated sorting genetic algorithm (NSGA), and fuzzy programming method [42,45]. To this end, the membership functions of the upper-level and lower-level objective functions are calculated by Eq. (19).

$$M^U = \begin{cases} 0, F \geq F_{max} \\ \dfrac{F_{max} - F}{F_{max} - F_{min}}, F_{min} \leq F \leq F_{max} \\ 1, F \leq F_{min} \end{cases}$$

$$M^{L1} = \begin{cases} 0, f_1 \leq f_{1min} \\ \dfrac{f_1 - f_{1min}}{f_{1max} - f_{1min}}, f_{1min} \leq f_1 \leq f_{1max} \\ 1, f_1 \geq f_{1max} \end{cases} \quad \text{Eq. (19)}$$

$$M^{L2} = \begin{cases} 0, f_2 \leq f_{min} \\ \dfrac{f_2 - f_{2min}}{f_{2max} - f_{2min}}, f_{2min} \leq f_2 \leq f_{2max} \\ 1, f_2 \geq f_{2max} \end{cases}$$

Figure 2 displays the general framework of the model.

Since the research is at the regional level, the data required were of the document type registered by the state-run agencies and relevant organizations. The data required to be related to crop area, price and cost of crops, yield, Water requirements, and water availability were collected in 2022-2023 from the Agriculture Jahad Organization of Sistan and Baluchistan Province and the Regional Water Company of Sistan and Baluchestan Province. The statistical summary of the data is presented in table1 .

A combination of the genetic algorithm solved the proposed model and NSGA encoded in Visual Studio code 1.3 using the Python programming language 3. Figure 3 displays the flowchart of the algorithm used.

Findings

Selection of agricultural products done based on various considerations such as regional conditions, quantity and quality of water and soil resources, ecological conditions and water requirements of agricultural products, production of typical and low-water agricultural products, management

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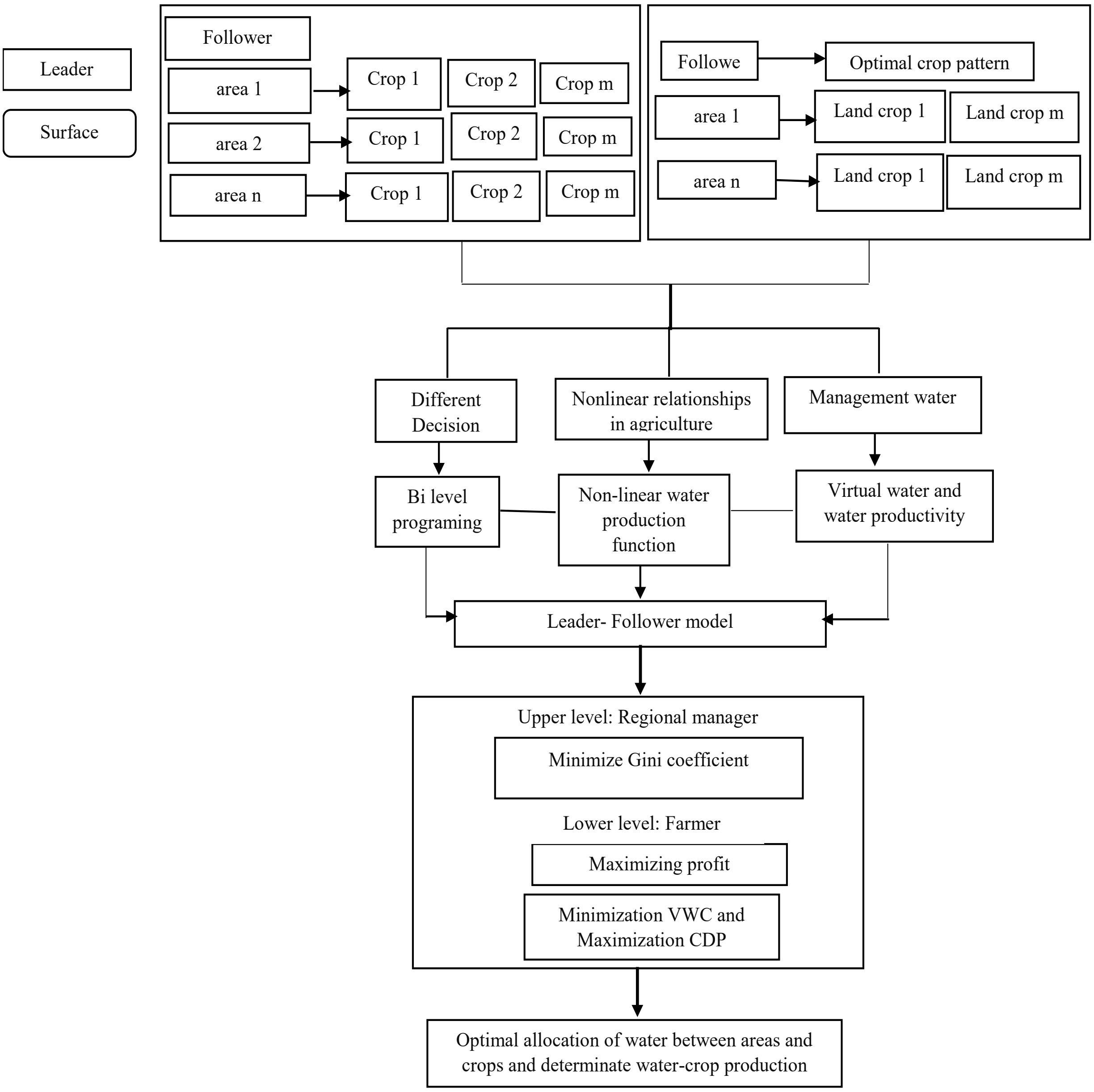

Figure 2) The general flowchart of the model in the present research.

Table 1) price and cost of the different crops (IRR.ha^{-1}).

Crop	Wheat		Barley		Onion		Alfalfa		Melon		Watermelon		Crop Area
Region	Price	Cost	Price	Cost	Price	Cost	Price	Cost	Price	Cost	Price	Cost	
Hirmand	55000	40×10^6	65000	40×10^6	80000	150×10^6	25000	10×10^6	200000	15×10^6	100000	15×10^6	47736
Hamun	55000	40×10^6	65000	40×10^6	80000	150×10^6	25000	10×10^6	200000	15×10^6	100000	15×10^6	32787
Nimruz	55000	40×10^6	65000	40×10^6	80000	150×10^6	25000	10×10^6	200000	15×10^6	100000	15×10^6	28562
Zabol	55000	40×10^6	65000	40×10^6	80000	150×10^6	25000	10×10^6	200000	15×10^6	100000	15×10^6	16925
Zahak	55000	40×10^6	65000	40×10^6	80000	150×10^6	25000	10×10^6	200000	15×10^6	100000	15×10^6	23487

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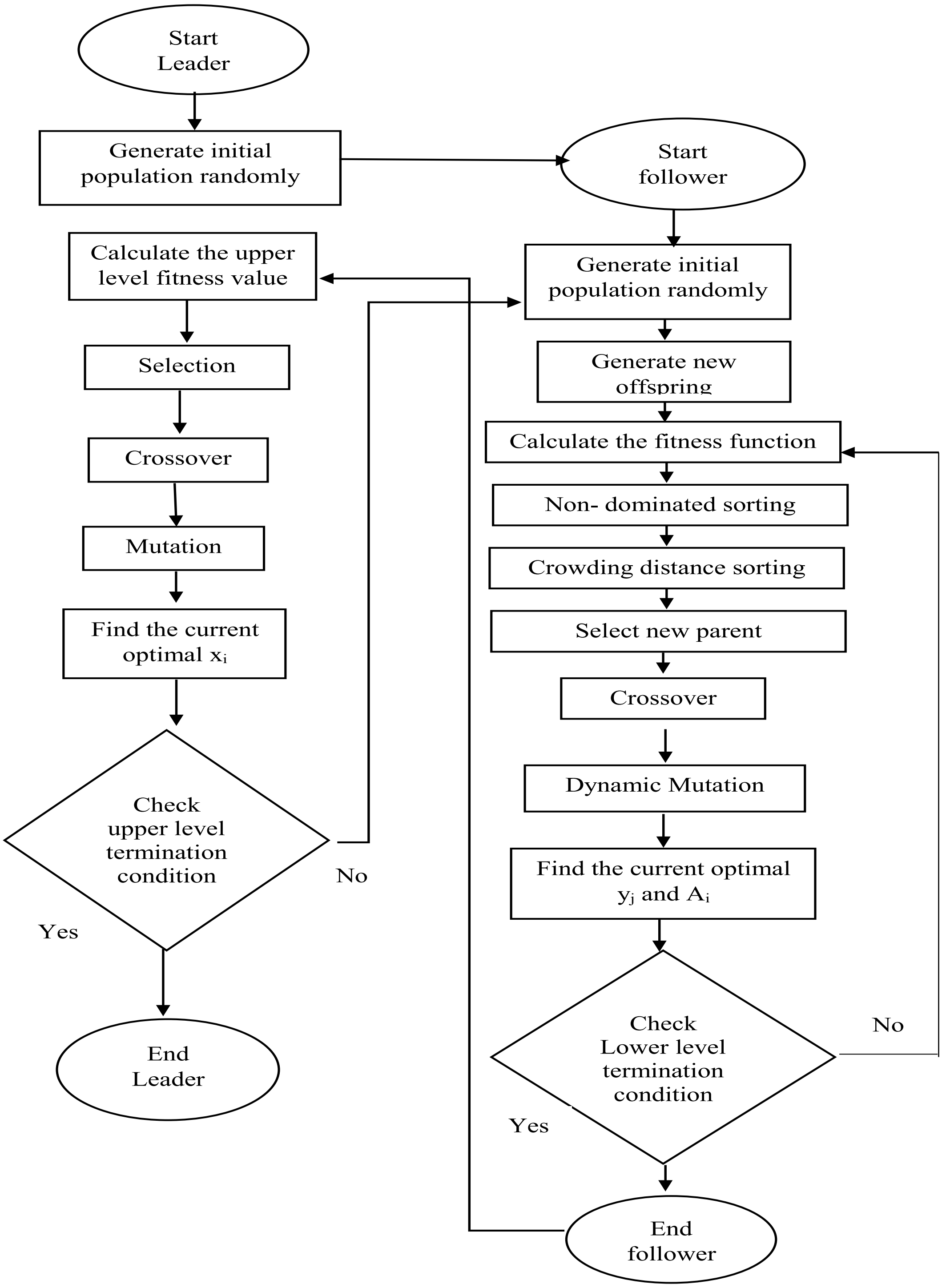

Figure 3) The flowchart of the non-dominated sorting genetic algorithm used in the research.

structure in farms, and the effect of factors such as existing cultivation experiences and the tendencies of the users in the region. To estimate the water-crop production function for each studied crop in five counties of the Sistan Region, we used the coefficients of quadratic water-crop production functions calculated by Ghaffari Moghadam et al. [8]. They are shown in Table 2.

An optimal solution for the genetic algorithm requires adjusting parameters like population size, replication number,

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Table 2) The water-crop production functions coefficients for different crops [8].

Crops	Zabol, Nimruz and Hamun			Zahak			Hirmand		
	a	b	c	a	b	C	a	b	c
Wheat	-83×10^{-5}	0.87	-270	-83×10^{-5}	0.87	-270	-44×10^{-6}	0.5	-163
Barley	-51×10^{-6}	0.53	-132	-51×10^{-6}	0.53	-132	-51×10^{-6}	0.53	-132
Onion	-32×10^{-5}	5.25	-2274	-32×10^{-5}	0.87	-2274	-37×10^{-5}	5.25	-2274
Melon	-82×10^{-5}	8.4	-1834	-82×10^{-5}	0.53	-1834	-46×10^{-5}	5.1	-240
Watermelon	-41×10^{-5}	5	-1664.6	-41×10^{-5}	3.81	-1266	-16×10^{-5}	3.8	-1260
Alfalfa	-48×10^{-6}	2.14	-1266	-48×10^{-6}	2.14	-1266	-48×10^{-6}	2.1	-1266

Table 3) The best values of the genetic algorithm's regulatory parameters.

Factors	Tested	Selected
Population size	20 25 30	20
Number of iterations at the upper level	700 800 1000	700
Number of iterations at the lower level	30 50 100	30
Upper-level mutation rate	1000000 2000000 5000000	1000000
Lower-level mutation rate	200000 500000 1000000	200000
Upper-level mutation probability	0.8 1 1.2	1.2
Lower-level mutation probability	0.4 0.6 0.8	0.8

mutation, and crossover. The optimal values of the initial parameters of this algorithm were obtained by experience from repeatedly running the algorithm and trial and error. The best values were estimated for these parameters by changing them and comparing the objective functions' optimal response results in each case (Table 2).

Table 4 presents the VWC and water productivity of the crops, including water requirements and crop yields in region i. The mean water requirement of selected crops in the study for the Sistan Region is 8686 $m^3.ha^{-1}$. The highest water requirement is related to alfalfa, which needs 22440 $m^3.ha^{-1}$; the lowest is related to melon, which needs 4500 $m^3.ha^{-1}$. Each crop's VWC and water productivity were calculated based on their water requirements and yields. Table 5 presents the mean VWC of the crops in Sistan Region in 2022-2023.

The results of Table 5 show that watermelon, melon, and onion products are in the category of a low-water crop, and wheat, aarley, and

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Table 4) Crop yields (yield) and water requirements (WR) in different regions (kg.m^{-3}) [40].

	Wheat		Barley		Onion		Alfalfa		Melon		Watermelon	
	Yield	WR	Yield	WR	Yield	WR	Yield	WR	Yield	WR	Yield	WR
Hirmand	1800	5360	1240	5000	34190	7490	18000	22440	17470	4500	18800	7330
Hamun	1540	5360	1350	5000	26890	7490	17360	22440	13590	4500	18110	7330
Nimruz	1480	5360	1300	5000	28020	7490	20650	22440	17730	4500	21500	7330
Zabol	1540	5360	1350	5000	26890	7490	17360	22440	13590	4500	18110	7330
Zahak	1720	5360	1490	5000	28060	7490	17660	22440	17840	4500	22890	7330

Table 5) The VWC of the crops in different regions (m^3.kg^{-1}).

	Wheat	Barley	Onion	Alfalfa	Melon	Watermelon
Hirmand	2.98	4.03	0.22	1.25	0.26	0.39
Hamun	3.48	3.70	0.28	1.29	0.33	0.40
Nimruz	3.62	3.85	0.27	1.09	0.25	0.34
Zabol	3.48	3.70	0.28	1.29	0.33	0.40
Zahak	3.12	3.36	0.27	1.27	0.25	0.32

alfalfa products are in the category of water-intensive crop since their virtual water is less than one, and barley has the highest content of virtual water in these products.

Water productivity and crop yield are directly related; crops with lower yields are less water-productive. According to Table 6, onions and Melons have the highest water productivity: 3.5 for the melon crop and 3.8 for the onion crop per m^3 of water. Wheat and barley had the lowest water productivity.

Optimal water and land allocation

Based on the indices calculated for each crop, water allocation and cropping patterns were planned for each county in the Sistan Region using leader-follower modeling.

Conditions were assumed for the region to solve the model. It was supposed that the region was struggling with drought, the total water allocated to the agricultural sector was 260 ×10^6 m^3, and the irrigation efficiency was 35%. According to the results, the system's total profit is 3.02 × 10^{13} IRR, and the Gini coefficient is 0.00215, close to zero. It means the fair allocation of water among the regions. The index $\frac{X_i}{R_i}$ is similar among all counties, reflecting the fair water distribution among the regions. The highest economic profit was related to Hamun and the lowest to Hirmand. The total cultivation area estimated by the model is 14475 ha. Hamun has the highest cultivation area. Thus, 14475 ha of the arable lands can be cultivated with the available water. Figure 4 displays the results of the crops' allocated water and cultivation area in different regions. Therefore, the economic efficiency of products and the amount of virtual water imported products with high virtual water consumption can help water resources management in the Sistan Region.

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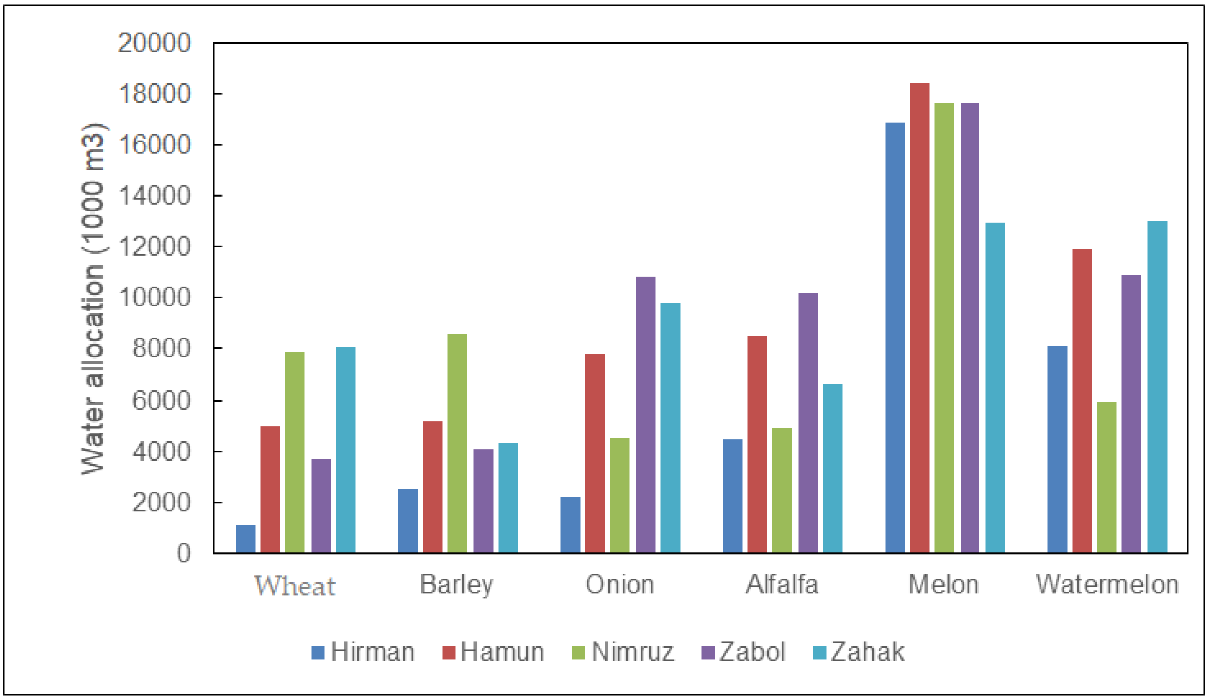
Figure 4 shows that melon has received the highest amount of water in all regions because it has a high yield, low water requirement, low VWC, and high economic productivity. The lowest amount of water has been allocated to wheat and barley due to their high VWC and low yields. The proposed model determined crop cultivation areas based on the water allocated to them and their water requirements. Melon has the highest crop cultivation area, and alfalfa has the lowest due to its high water requirement. If maximizing water productivity is considered the second objective at the



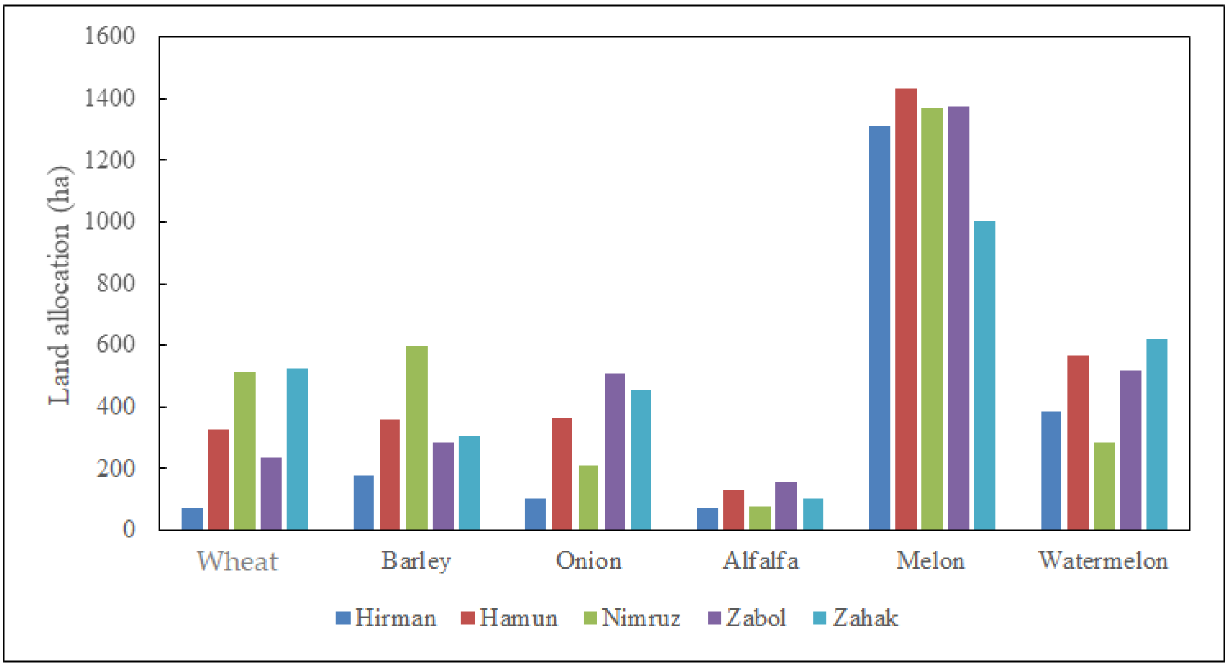


Figure 4) The amount of allocated water and cultivation area of the crops in different regions considering virtual water.

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Table 6) Water productivity of the crops in different regions (kg.m^{-3}).

	Wheat	Barley	Onion	Alfalfa	Melon	Watermelon
Hirmand	0.34	0.25	4.56	0.80	3.88	2.56
Hamun	0.29	0.27	3.59	0.77	3.02	2.47
Nimruz	0.28	0.26	3.74	0.92	3.94	2.93
Zabol	0.29	0.27	3.59	0.77	3.02	2.47
Zahak	0.32	0.30	3.75	0.79	3.96	3.12

Table 7) The results of optimizing the cropping pattern and water allocation considering virtual water among the studied regions.

Decision variables	Hirmand	Hamun	Nimruz	Zabol	Zahak
Water allocation per unit of economic benefit	0.0000087	0.0000085	0.0000085	0.0000085	0.0000088
Economic profit (IRR)	4.34×10^{12}	6.91×10^{12}	6.08×10^{12}	6.82×10^{12}	6.08×10^{12}
Cultivated area (ha)	2125.5	3186.6	3061	3081.9	3019.6
Water allocated to area (1000m^3)	35370	56808	49540	57278	54791
The system's total profit (IRR)	3.02×10^{13}				
Gini coefficient	0.00215				
Total cultivation area (ha)	14475				

follower level in the proposed model, the model's results will be as follows: Table 8. The results reveal that the system's total profit estimated by the model is 3.04×10^{13} IRR, considering water productivity. The Gini coefficient was calculated to be 0.0035. Since it is close to zero, the regions have received some water. Also, the equal value of $\frac{X_i}{R_i}$ among the counties shows the just water allocation among them. The highest profit is related to Zahak, and the lowest is Zabol. The total cultivation area in this scenario is 14368.6 ha. Zahak was assigned the highest and Zabol with the lowest cultivation area. Figure 5 displays the results of the crops' allocated water and cultivation area in different regions.

Considering water productivity, the highest amount of water was allocated to melon in all regions due to its high water productivity. In most regions, the lowest amount of water was allocated to alfalfa due to its high water requirement and barley due to its low yield. The cultivation areas of the crops were determined based on the amount of allocated water. Melon has the highest cultivation area, and alfalfa has the lowest one.

Table 9 compares the cultivation area of the crops in three states: (i) the proposed cropping pattern considering the water productivity index, (ii) the proposed cropping pattern considering the virtual water, and (iii) the current cropping pattern region over the last ten years.

According to Table 8, Considering the water productivity, the highest cultivation area,

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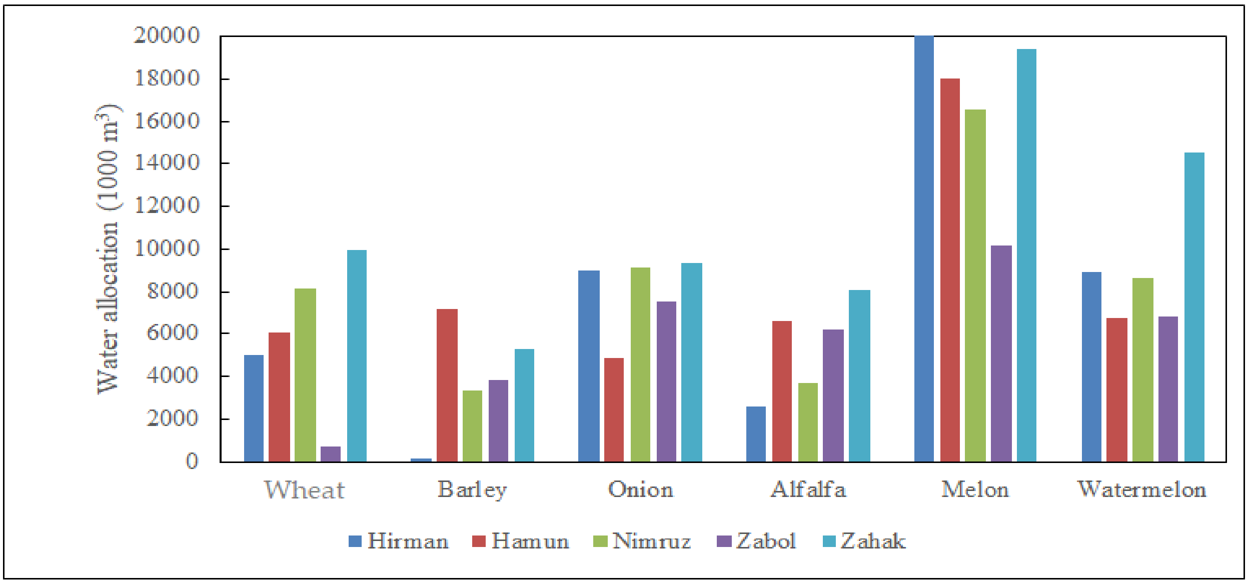

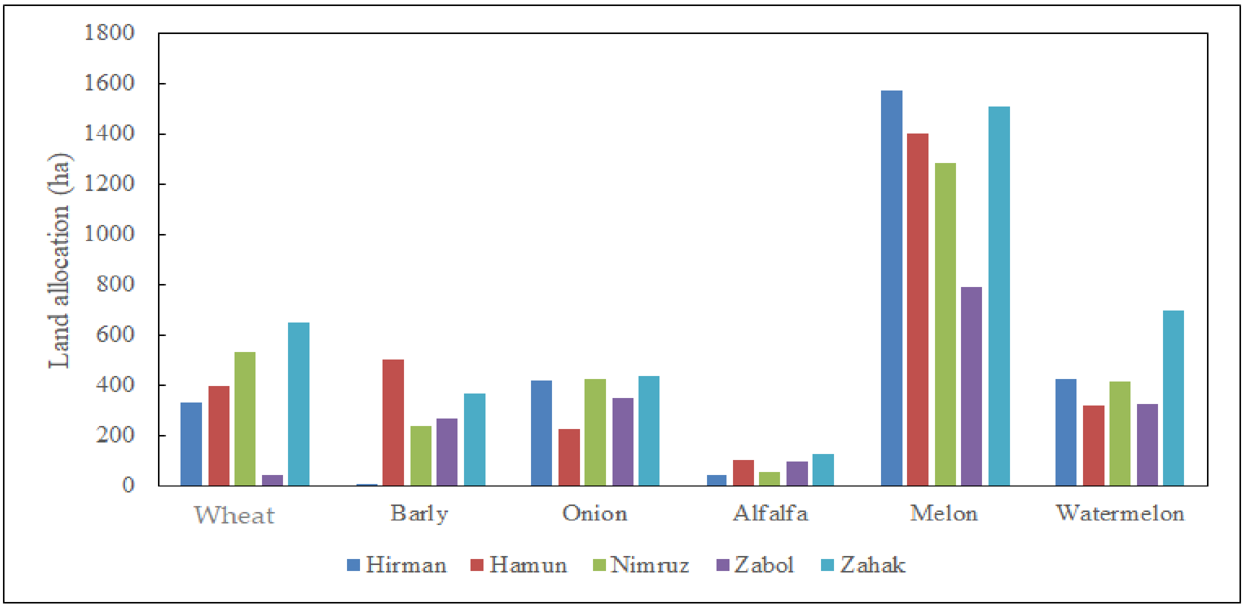

Figure 5) The crops' allocated water and cultivation area in different regions considering water productivity.

Table 8) shows the results of optimizing the cropping pattern and water allocation, considering water productivity among the studied regions.

Decision variables	**Hirmand**	**Hamun**	**Nimruz**	**Zabol**	**Zahak**
Water allocation per unit of economic benefit $\frac{X_i}{R_i}$	0.0000085	0.0000084	0.0000085	0.0000086	0.0000088
Economic benefit (IRR)	5.53×10^{12}	6.27×10^{12}	6.2×10^{12}	4.05×10^{12}	8.21×10^{12}
Cultivated area (ha)	2796.6	2953.3	2951	1879	3788
Water allocated to area ($1000m^3$)	45885	49487	49518	35234	66666
The system's total profit (IRR)	3.04×10^{13}				
Gini coefficient	0.0035				
Total cultivation area (ha)	14368.6				

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Table 9) The cultivation area of the crops in the proposed cropping patterns (ha).

	Wheat	Barley	Onion	Alfalfa	Melon	Watermelon
Water productivity	1948	1386.6	1863.5	424.2	6567.2	2179.1
Virtual water	1681.4	1730	1646	542	6495	2380.6
Recent 10-year average	45215	4468	156	4347	4810	1601

with 6567.2 ha, belongs to melon, and the lowest cultivated area, with 424.2 ha, belongs to alfalfa. Also, if we consider virtual water, the highest cultivated area belongs to melon, with 6495 ha, and the lowest cultivated area belongs to alfalfa, with 542 ha.

Discussion

The differences in the VWC of the crops in different regions are rooted in their differing yields because the VWC of a crop depends on its yield per unit area. The higher the crop yield is, the lower its VWC will be. The lowest yield is related to barley, and the second lowest is wheat. Since these crops have low yields, they have high VWC. Wheat has the highest VWC in Hamun and Zabol. Onion has the lowest VWC among the studied crops. Hekmatnia et al. [31] calculated the mean VWC of crops in Sistan and Baluchistan Province, whose results agreed with ours. Delpasnd et al. [29] showed that wheat, among the strategic agricultural products, has the highest share of virtual water use.

Wheat has the highest cultivation area in the region in the current conditions. Suppose income maximization or water use optimization is the goal. In that case, the cropping pattern shifts toward high-yielding crops that have higher economic income, and the cultivation area of crops like wheat and barley, whose economic profits are low, and alfalfa, whose VWC is high and water productivity is low, is reduced in favor of crops like melon, watermelon, and onion. These findings are consistent with Ghaffari Moghadam et al. [8], who concluded that low-yielding crops like wheat and barley must replace high-yielding crops like melon and onion in the cropping pattern. In addition, Su et al. [31] concluded in their study that using the water resources allocation model considering the concept of VW has led to the optimal allocation of water resources. According to the results obtained from this research, virtual water can be one of the appropriate factors for selecting alternative crops in agricultural areas facing water crisis. The comparison of the optimal cultivation pattern to the farmers' indicates that to reduce virtual water consumption, increase water productivity, and achieve profit; one should cultivate crops such as melons and onions and refuse to cultivate other crops.

Conclusion

The literature review reveals that managing water resources and consumption in the agricultural sector needs to look into crops' virtual water and water productivity. Therefore, This research uses a bi-level (leader-follower) programming model with an emphasis on the concepts of virtual water and water productivity and their integration with the proposed model to optimize irrigation water allocation among irrigation regions and crops and determine an optimal cropping pattern for crops in five areas, including Zabol, Zahak, Nimruz, Hamun, and Hirmand, from 2021 to 2022. The research gap between this study and other studies done in this field was that this study simultaneously considers conflicting objectives, including justice in water allocation, economic profit, virtual water, and water productivity.

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With this model, an optimal strategy can be proposed for crop cultivation in different regions under different conditions. Considering the VWCs, less water was assigned to crops with higher VWC, i.e., wheat and barley. In addition, lower cultivation areas were assigned to them in the cropping pattern. Crops like melon and onion, whose VWC is lower, received more water in the proposed model and had more cultivation area than other crops. Thus, the cropping pattern is improved in different regions. It includes crops that have a relative advantage and need less virtual water consumption, which would result in the optimal allocation of cultivation area based on water constraints in each region. Also, since the crop yield effectively reduces specific water consumption by agricultural and horticultural crops, thereby reducing the export of virtual water, it is crucial to focus on enhancing yields per unit area to maintain their export level and simultaneously reduce pressure on water. Applying modern farming technologies and improved seeds can be effective in this regard.

When the water productivity index was considered, the results revealed that more water was allocated to crops with higher water productivity, such as melon and onion. Then, they gained higher cultivation areas, too. On the contrary, crops like wheat and barley, whose water productivity is low, received less water, and less cultivation area was assigned to them. Thus, a solution to improve the regional production system is to replace crops with higher water requirements with crops with lower water requirements, especially for improving the agricultural system in low-water regions. It is better to substitute crops with lower water productivity with those with higher water productivity in certain regions to increase water use efficiency. As such, water can be saved for crops with higher economic value or other domestic consumption. A virtual water and water productivity strategy solves regional water shortages and effectively uses water resources.

Ethical Permission

The authors of this study approve of sending it to the ECOPERSIA journal and declare that this study is not under revision in any other scholarly journals. The authors chose Dr. Zahra Ghaffari Moghadam (the first author) as the corresponding author and delegated all the responsibility of the article to her regarding the relationship with ECOPERSIA.

Conflicts of Interest

The authors declare no conflict of interest.

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Authors' Contributions

Zahra Ghaffarti Moghadam: Investigation, Methodology, Formal Analysis, Writing - Original Draft.Ali Sardarshahraki: Supervision, Data curation, Writing - Review & Editing.

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