Conjunctive effect of water productivity and cultivation pattern on agricultural water management

Hamid Mahsafar, Mohsen Najarchi, Mohammad Mahdi Najafizadeh and Mohammad Mirhoseini Hezaveh

ABSTRACT

Agricultural water resources are scarce in Iran, and agricultural water management is essential to overcome this limitation. Determination of the water productivity index (WP) using the methods of optimization of cropping patterns and optimal water allocation is the most effective tool in water management in the agricultural sector. In this study, a non-linear optimization model was used to calculate the maximum WP in the Qazvin plain irrigation network. The proposed model was applied to six different water supply scenarios including 100% and 90%, 80%, 70%, 60%, and 50% of full irrigation volume. The results showed that the scenario of 60% of full irrigation could increase the WP index by 8.5%, while with the implementation of this scenario, the net benefit from the sale of agricultural products was reduced to the amount of 247×10^9 Iranian Rials (IRR), which was 28% less than the existing conditions in the region. Therefore, the 60% water supply was selected as the economical and efficient scenario in the irrigation of Qazvin plain. It can be claimed that the most important index in agricultural water management is the WP index.

Key words | cultivation pattern, net benefit, Qazvin plain, water management, WP

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INTRODUCTION

Water is one of the main natural resources that can be used in multiple sectors. It is the main ingredient used in the agricultural sector and plays a fundamental role in sustainable development and agriculture (Dinar *et al.* 1997). Agricultural water management includes different aspects of irrigation such as irrigation efficiency, water-saving, water productivity index (WP), and crop yield (Valipour 2014). An optimal strategy is necessary for the allocation of irrigation water to increase WP and develop permanent crop production (Li *et al.* 2015). Evaluation of water efficiency is an important component of water resource management and improving water efficiency is the key to achieving the sustainable utilization of water resources (Wu *et al.* 2017). A limited irrigation scheme could be the best scenario for increasing WP, and is an important instrument for decreasing irrigation water demands (Fernandes-Silva *et al.* 2010). An optimal cropping pattern and deficit irrigation can improve the WP of an irrigation network (Montazar & Rahimikob 2008). Tafteh *et al.* (2014) offered a schedule for distributing irrigation water and also an optimal cropping pattern to maximize net benefit and WP. Results revealed that a 30–35% water deficit would result in an increase in WP by 54%. The cropping pattern could be designed for each region based on local considerations and with regard to the main agricultural sector policies to increase the efficiency of water. Recently, the management and planning of water resources have become an important topic in most countries. For this purpose, linear and non-linear optimization methods have been used (Akbari 2016). The linear programming model is a technique for optimization with a linear function subjected to linear equality and inequality constraints that are not always satisfied. However, the non-linear programming model does

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not have linear constraints (Hillier & Lieberman 1980). Carvallo *et al.* (1998) developed a non-linear optimization model for determining the optimal allocation of agricultural water for various cropping patterns. Kuo *et al.* (2000) suggested an optimization model with a genetic algorithm for the optimization of agricultural water in an irrigation scheme. McGuckin *et al.* (1992) suggested a stochastic production frontier model of irrigation for evaluating the sources of economic inefficiency in irrigation crops. The results have demonstrated that farm irrigation practices have a usual technical efficiency of 81%. Field information from moisture sensors can increase technical productivity by 3.9%. Benli & Kodal (2003) used linear and non-linear optimization methods for distributing irrigation water for farms under the limits of water resources in the southeast of Antalya in Turkey. Comparing the results of linear and non-linear models shows that the non-linear model has more profit than the linear model under the condition of limited irrigation water resources. Kipkorir *et al.* (2002), Ghahraman & Sepaskhah (2004), and Li *et al.* (2015) have conducted studies with the aim of increasing the net income of agricultural products by applying linear and non-linear optimization models to the optimal allocation of water resources to the agricultural sector in terms of the limits of water resources. The results showed that non-linear models offer more benefits than linear ones. Marques *et al.* (2005) developed an economic production model to survey the influence of water prices on cropping patterns, agricultural production, and water and irrigation technology use. Results demonstrated that variations in water price and convenience affect the desirability of different irrigation technologies. Haouari & Azaiez (2001) used a linear programming model to determine optimum cultivation patterns under deficit irrigation conditions. The results of the research showed that mathematical models are well able to manage the volume of water needed for agriculture by providing a proper cultivation pattern of water deficit conditions. Garg & Dadhich (2014) developed an optimization model to reach the highest net benefit of agricultural products with a choice of deficit irrigation scenarios. They found that optimal cropping patterns and amount of irrigation water could be effective factors in increasing the net benefit of agriculture in the studied area. Wang *et al.* (2015) evaluated the effects of water use efficiency on agricultural irrigation using a variable fuzzy evaluation model. The model was applied to the Beitun irrigation region and the results show that water use efficiency and profits in the Beitun irrigation region were both at the level of medium efficiency from 2006 to 2008. Alarcón & Juana (2016) evaluated the efficiency of water markets in management of agricultural water. The results show that water markets are useful tools for managing limited water resource by giving users the flexibility to purchase further water from those with surplus. Water markets can help to save water and reallocate water to more valued uses while improving both water use and increase productivity. The aim of this study is the management of agricultural water consumption under the terms of the highest benefit from the sale of agricultural products and maximum water saving in the region using the WP index. In order to solve the non-linear model, Lingo standard software was utilized.

MATERIALS AND METHODS

Study areas

The Qazvin irrigation network is located in the northwest of Iran as shown in Figure 1. The study area was selected owing to being located in Asia, with climatic conditions similar to Central Asia, and because of the importance of agriculture as a primary economic activity. This area is one of the most important agricultural production regions in Iran (Ababaei *et al.* 2014). Mean annual precipitation, temperature, and evaporation in the region are 269 mm, 11.6 °C, and 1,063 mm, respectively. The Qazvin irrigation network covers 60,000 hectares and its water is provided from Taleghan dam as well as 102 integrated wells that are spread along the network area. Wheat, alfalfa, barley, tomato, and corn are the existing cropping pattern in the region with coverage areas of 71%, 12%, 11%, 4%, and 2%, respectively. The water operators union is responsible for distributing the irrigation water to the farmers that they have taken from the Regional Water Organization (RWO) of Qazvin in the irrigation network. RWO also controls this union in order to improve the efficiency of irrigation management (Mahsafar 2017).

In the agricultural sector, WP is defined as the crop yield or the benefit and the crop value per cubic metre of water (Cai & Sharma 2010). In this study, the WP index was

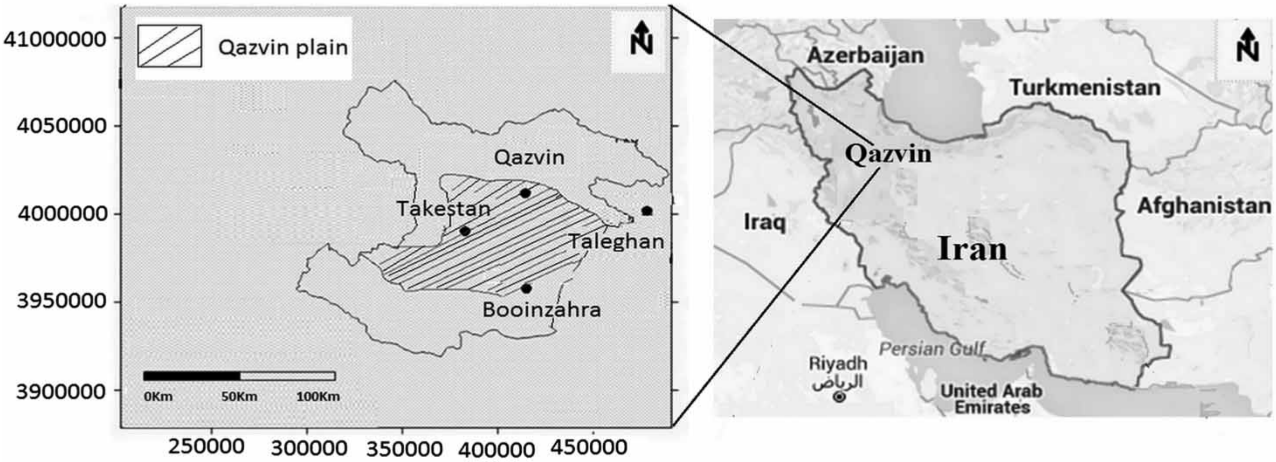

Figure 1 | Location of the Qazvin plain.

defined as the ratio of total net benefit to the total volume of the crops' water requirement. The method intended to maximize the WP index under the water supply scenario was based on the following steps: (1) specifying the input data (crop yield, irrigation water, cultivation area, and production cost); (2) finding the actual crop yield function (Y_a) based on the highest potential crop yield (Y_p) in the water–yield function based on Equation (1); (3) forming the objective function; (4) applying water supply scenarios; (5) finding the optimal WP index; and (6) calculating the optimal cultivation area under maximum net benefit from the sale of agricultural products and volume of water saving.

Input data

The characteristics of the major crops in the existing cropping pattern were obtained from Najarchi *et al.* (2011) and Ministry of Jihad-e-Agriculture of Iran (2015). Table 1 shows the characteristics of the major crops, including the cultivated area (A_i), potential crop yield (Y_p), yield response factor (K_y), annual water requirement for crop i (W_i), and production cost (P_c).

Surface and ground water resources

The water supply requirements for the Qazvin plain irrigation network were provided from Taleghan dam and 102 integrated wells spread along the command area. Taleghan River is one of the most important rivers in the northwest of Iran. The volumes of water delivered from Taleghan dam and integrated wells to the command area in the existing cropping pattern are 252 and 46 million m^3 (MCM), respectively. Figure 2 shows the volumes of the allocated water from Taleghan dam and integrated wells over different months of the year in the irrigation network.

Table 1 | Characteristics of major crops in the existing cropping pattern on the Qazvin plain (Ministry of Jihad-e-Agriculture 2015)

	Wheat	Barley	Corn	Tomato	Alfalfa
A_i (ha)	26,927	4,272	906	1,446	4,502
Y_p (Kg/ha)	4,052	3,923	64,853	56,611	12,380
K_y^a	1.2	1.1	1.35	1.09	1.1
P_c (IRR/ha)[b]	6,965,090	6,149,230	8,281,020	9,715,350	8,854,900
W_i (m^3/ha)	5,069	5,103	13,245	31,051	17,086

[a]Najarchi *et al.* (2011).
[b]33,000 Iranian Rials (IRR) = 1 US Dollar.

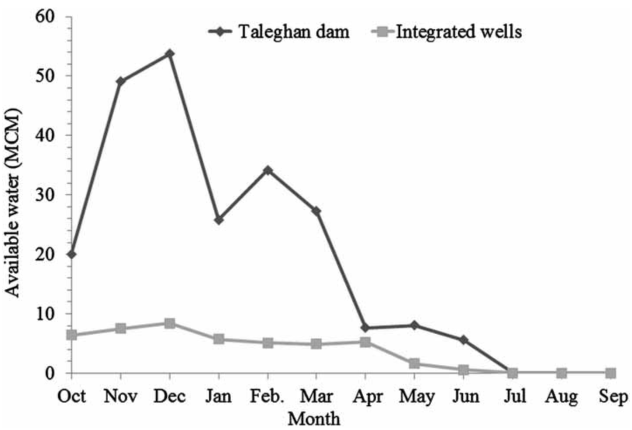

Figure 2 | Monthly volume of available water from Taleghan dam and integrated wells.

Water–yield function

Because the water–yield function is the most important part of the objective function (Tafteh *et al.* 2014), it is necessary to know the relationship between the yield and the amount of water used by the crop. In this study, the best production functions available were selected and calibrated. Ghahraman & Sepaskhah (1997) presented a simple optimization model for water production functions according to the function proposed by Doorenbos & Kassam (1979). The relationship between yield and water is calculated using the following function:

$$1-\frac{Y_a}{Y_p}=K_y\left[1-\frac{W_a}{W_p}\right] \quad (1)$$

where Y_a and Y_p are actual and potential crop yields (kg/ha), W_a and W_p are actual and potential water demands (mm) respectively, and K_y is the yield response factor (dimensionless). Non-linear (second degree polynomial) water–yield functions have been generated from crop yield values obtained from various quantities of irrigation water applied for each crop. Required data of water–yield functions for wheat, alfalfa, barley, tomato, and corn in the Qazvin plain irrigation network were obtained from field experiments, field studies and Jihad-e-Agriculture of Iran (2015). Figure 3 shows the water–yield functions for the crops cultivated in the region.

Optimization of WP

Objective function

A non-linear programming model was formulated to maximize WP under the terms of the existing resources of land and water. The model contained three parts: (1) a non-linear objective function, (2) a set of linear and non-linear constraints, and (3) a set of non-negativity constraints. In this study, the WP index was defined as the objective function (the ratio of total net benefit to the total volume of the crops' water requirement). Net benefit was computed by subtracting crop sale cost from crop production costs including water, seeds, fertilizers, etc.

$$Max(NB)=Max\left(\sum_{i=1}^{5}Y_iA_iP_i-\sum_{i=1}^{5}A_iP_{ci}\right) \quad (2)$$

$$WP=\left(\frac{NB}{Vol}\right)=\left(\frac{Max\left(\sum_{i=1}^{5}Y_iA_iP_i-\sum_{i=1}^{5}A_iP_{ci}\right)}{Vol}\right) \quad (3)$$

where i is crop number, Y_i is the yield of crop i as a function of gross applied water depth (kg/ha), A_i is the cultivated area of crop i (ha), P_i is the price of crop i (IRR/ton), and P_{ci} is the crop production cost of crop i (IRR/ha) (IRR = Iranian Rials). In fact, the term Y_i describes the relationship between the yield of a crop and different irrigation scenarios. The yield of crop i in Equation (2) could be generated according to Equation (1).

Constraints

Water supply constraint

The maximum water allocation from Taleghan storage dam for agricultural use was 298 MCM:

$$\sum_{i=1}^{5}W_iA_i\le Q \quad (4)$$

where W_i is gross water for crop i per unit area (m^3/ha), and Q is the amount of available water for irrigation.

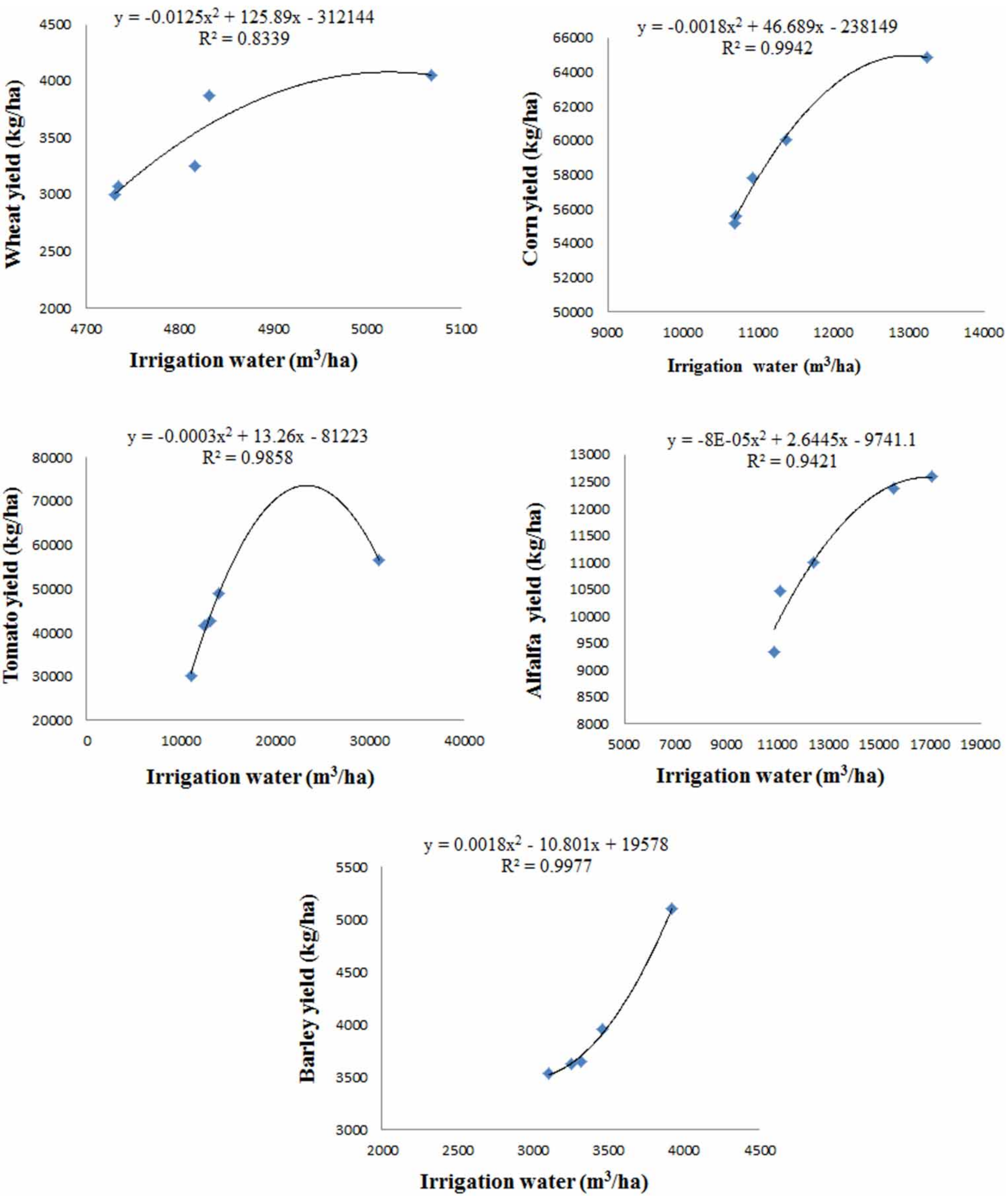

Figure 3 | Water–yield function for the cultivated crops in the study area.

Constraints for total allowable area

The total area of cultivable lands based on the limitation of the Qazvin irrigation network was 60,000 hectares:

$$\sum_{i=1}^{5} A_i \leq A_T \tag{5}$$

$$A_{corn} \geq 906 \tag{6}$$

$$A_i \geq 0 \tag{7}$$

where A_i is the land area available for allocation to crop i, A_T is the total land area allocated for the selected crops (ha), and A_{corn} is the minimum area available for allocation to crop corn due to the supply of primary requirement. The cost information, such as production costs, is presented in Table 1.

RESULTS AND DISCUSSION

In this study, a non-linear optimization model was used which included an objective function of the WP index described as the net benefit to the volume of water allocated to agriculture. Using this model offered the optimal cropping pattern developed for the Qazvin irrigation network under different water supply scenarios, which was compared with the existing cropping pattern. According to Table 2, six water supply scenarios (100%, 90%, 80%, 70%, 60%, and 50% of full irrigation volume) were investigated. The results showed that the highest and lowest cultivated areas belonged to wheat and alfalfa crops with 27,000 and 558 hectares for the water supply scenarios of 100% and 50%, respectively.

The optimal cropping pattern for the sufficient water supply scenario (100%) suggested raising the cultivated area of wheat, barley, tomato, and alfalfa from 26,927, 4,272, 1,446, and 4,502 (existing conditions) to 27,000, 4,475, 1,590 and 4,888 hectares, respectively.

Moreover, by reducing the available amount of irrigation water, the cultivated area and net benefit obtained from the products were reduced, while the volume of saved water was increased. For example, the net benefits for the 100% and 90% water supply scenarios increased by about 11% and 1% and decreased by about 10%, 19%, 28% and 34% in the situation of limited water supply in the 20%, 30%, 40% and 50% scenarios respectively. Figure 4 shows the net profit change compared with the existing situation.

For example, in Figure 4 and Table 2, when the water supply capacity was reduced to 238 MCM (80% of the optimum requirement), the total net benefit was reduced from 888×10^9 IRR to 794×10^9 IRR (89% of the existing condition). In addition, a 30% reduction in water supply capacity decreased the net benefit by only 19% in the condition of the optimum cropping pattern. The analysis of the results showed that performing the optimal cropping pattern in the overall network under the water limitation

Table 2 | Optimum cropping pattern, volume of allocated water, and net benefit under full and limited irrigation water conditions

		Water supply capacity scenarios					
Crop pattern	**Existing conditions**	**100%**	**90%**	**80%**	**70%**	**60%**	**50%**
Wheat (ha)	26,927	27,000	24,600	21,867	19,133	18,223	18,223
Barley (ha)	4,272	4,475	4,028	3,580	3,132	2,685	2,237
Corn (ha)	906	906	906	906	906	906	906
Tomato (ha)	1,446	1,590	1,507	1,339	1,172	1,004	837
Alfalfa (ha)	4,502	4,888	4,127	3,586	3,045	1,942	558
Total area (ha)	38,053	38,859	35,168	31,278	27,388	24,760	22,761
Total available water (MCM)	298	298	268	238	208	178	149
Net benefit (10^9 IRR)	880	973	888	794	699	633	580
Benefit changes (%)	0	+10	+1	−11	−19	−28	−34

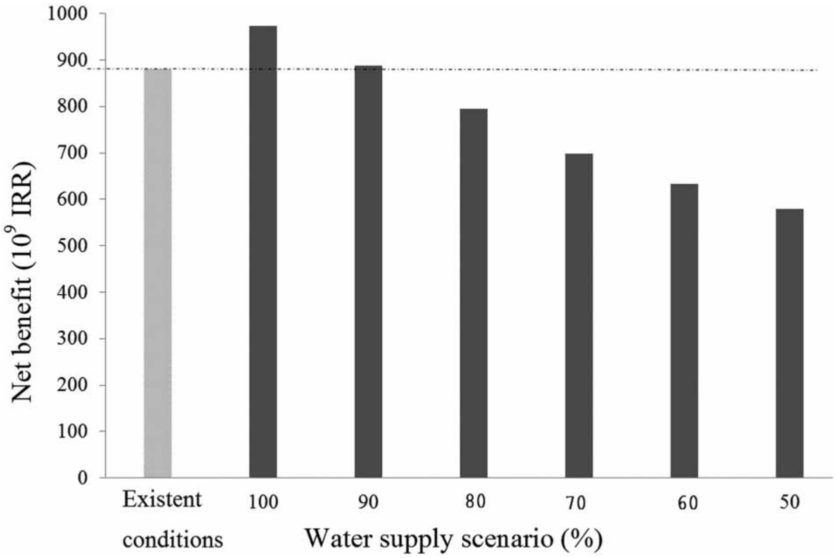

Figure 4 | Comparison of net benefit changes and water supply scenarios.

condition could help achieve the highest volume of water saving in Taleghan dam against the lowest reduction in the net benefit of agricultural products. Below, the WP index was computed for the optimal cropping pattern under different water supply scenarios. The results are presented in Figure 5.

The results showed that when the volume of water allocated for the optimal cropping pattern was reduced to the 100%, 90%, 80%, 70%, 60% and 50% water supply scenarios, the WP index for this condition in comparison with the existing conditions was increased about 7.96%, 8.55%, 8.92%, 9.30%, 9.44% and 9.21%, respectively. The 60% and 100% water supply scenarios had the highest and lowest WP index, respectively. The findings indicated that with the optimization of the cropping pattern, the overall WP index of the irrigation network can be increased to 569.3 IRR/m^3 under the 60% water supply scenario, while the values of net benefit in the 60% and 100% water supply scenarios were obtained as 973×10^9 and 633×10^9 IRR, respectively. Therefore, the highest WP index was obtained for a 60% water supply scenario under 40% limited irrigation. The WP index for the 60% water supply scenario showed an increase of 49.1 IRR/m^3 in comparison with the existing conditions (520.2 IRR/m^3).

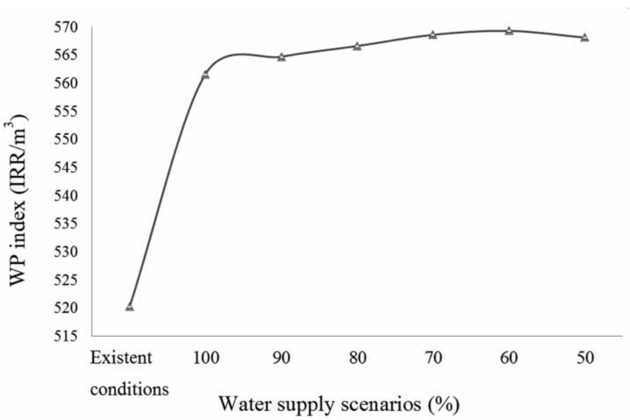

Figure 5 | Comparison of the WP index for different irrigation scenarios under the optimal cropping pattern.

A comparison between our findings and the findings by Benli & Kodal (2003), Najarchi *et al.* (2011), and Singh *et al.* (2001) showed that under the terms of the water supply scenarios, the cultivated area and net benefit obtained from the products were reduced, but the volume of agricultural water saving was increased. The value obtained in the present study was also close to the one observed by Zhang & Oweis (1999). The results of the optimal cropping pattern and optimal allocation of agricultural water demonstrate that the WP index was increased with the application of the water supply scenarios.

In this study, a non-linear optimization model was developed based on the conjunctive effects of WP index and optimal cultivation pattern under the terms of limited water conditions. The WP index was selected as the objective function to motivate farmers to select the optimally cultivated area for each crop and the volume of agricultural water allocated for irrigation with the highest WP index. It is necessary to know the water–yield function to reach the optimal amounts of irrigation water. In particular, the optimization models help gain the highest net benefit considering the relationship between water and crop yields. Optimizing the agricultural WP index is one of the management alternatives that can improve the relationship between land and water under the terms of limited water conditions. Uncertainty in agricultural water management decisions could lead to economic implications. It can be created by many factors such as price, yield and water availability prediction. The dependency on the rainfall in the study area was very low because of the poor annual rainfall of only 269 mm, and agricultural water for the Qazvin plain irrigation network was provided from Taleghan dam. Therefore, the temporal variability in the water requirements of the crops can be taken care of by adjusting the water releases from the Taleghan reservoirs. The analysis of the results indicated that land and water resources were diverted to produce mainly wheat crop as it was giving more net benefits in the optimal mix of crop production as compared with other crops. The price of the wheat crop has not changed during the last few years. Therefore the market values of the crops were kept constant in estimating the net benefits.

CONCLUSIONS

The overall results of the non-linear programming model with the objective of maximizing the WP index and net profit from the sale of agricultural products on the Qazvin plain were as follows:

(1) Cultivation pattern is one of the most important factors in irrigation network management, and has a direct relationship with the WP index.
(2) When water supply resources are limited by droughts or other factors, limited irrigation can be used as an effective method to reduce the use of irrigation water.
(3) The cultivation area and net benefit of agricultural products are reduced by the reduction of the amount of water allocated to the land under the terms of limited irrigation situations, while the volume of saved water is increased.
(4) The general results showed that the non-linear programming method could be used to determine cropping patterns by changing variable parameters such as limited irrigation.
(5) The WP index is the most important index in terms of water management and economic profit.
(6) The optimal WP index, considering maximum net economic benefit and the volume of agricultural water saving, was obtained from a 60% water supply scenario.

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