Optimal Allocation of Irrigation Water Under Different Flow Scenarios Using Multi-stage Stochastic Programming by Emphasizing Economic Productivity

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Abstract

This study investigated the optimal management and allocation of irrigation water under different flow scenarios focusing on economic water productivity (EWP) index. In this study, the aim was to allocate and distribute water between networks and lower crops of Maroon reservoir dam The multi-stage stochastic programming method was used to develop the optimization model under three scenarios of arid, normal and wet years in two management modes and the results were compared with the traditional management figures. For this purpose, hydrometric data was sourced from the Marun network station for the 2006–2016 periods. Finally, the results of the second run provided a better irrigation program with a 19% increase in the total area under cultivation and a 7% increase in objective function profit. Moreover, the highest mean EWP in the three scenarios was obtained in the second run for the North network at 9% more than the first run.

Keywords: optimal management ,irrigation water, scenario, , economic water productivity.

Introduction

Water shortage is an important factor limiting agricultural improvement in several arid and semi-arid territories worldwide (Sun et al., 2015). Especially for arid agricultural regions, it is necessary to plan sustainable agricultural water management strategies for improving water use efficiency(Zhang et al., 2020). Using optimization strategies for deciding optimal supply and demand options was a viable way to handle the matters of a coupled water resources-irrigation system (Moghaddasi et al., 2010). In another study, A stochastic dynamic programming (SDP) model is developed. Simulation of the derived optimal policies shows the significance of the proposed methodology compared with a deterministic linear programming-based approach (Anvari et al.,2017). This paper aimed to consider the variations of both water supply and water demand in the Aharchay basin (Iran) by coupling a hedging rule (HR)-based reservoir operation model (HRROM) with a climate-based irrigation scheduling model (CBISM) at the farm level (Anvari et al.,2023). This study showed a review of literature on agricultural water allocation based on MSP, considering crop yield as the main farmers' profits of suffice water allocation, four prominent water allocation problems, and four different uncertain sources.(Juan Marquez et al., 2022). A non-linear programming (NLP) optimization model with an integrated soil water balance was developed. Therefore, the results are directly applicable to real-world conditions.(Ghahraman & Sepaskhah.,2004). The introduced case study, showed that a 10% profit increase could be gained by taking the corn price and irrigation water availability uncertainties into consideration using two-stage stochastic programming. (Li & Hu., 2020). Moreover, a genetic algorithm (GA) and harmony search (HS) are employed in another study to construct an integrated reservoir–farm system (IRFS), (Ranjbar et al.,2021). This study aims to investigate the performance of Zarrineh Rud reservoir by implementing strategies for adaptation to climate change. Results showed a significant decrease in the annual reservoir inflow compared to the baseline for all future periods (Moghaddasi et al.,2022). In another research, a model was proposed to maximize the total gross benefit of the irrigation networks of Marun. The findings indicated a benefit increase of 7–67% in the second sub-model (Amanat Behbahani et al., 2020).The research approach of this study involved a multi-stage stochastic programming method with interval parameters to investigate optimal management and allocation of irrigation water under different flow scenarios focusing on economic productivity. Accordingly, two management modes—namely optimal management from the network in the existing situation (Intra-network) and optimal management from the reservoir outlet to the network (Inter-network)—were tested and the results were compared to the actual management conditions. Therefore, in this study, the aim was to allocate and distribute water between networks and lower crops of Maroon reservoir dam.The difference between this study and previous research lies primarily in the model used, which considers various stochastic irrigation water flow scenarios and uncertainties in water resources. Among the reviewed studies, only Dai Li (2013) have addressed this issue. However, the key distinction of the present study from Dai Li (2013) is that this research considers the economic water productivity (EWP) as optimal allocation indice. Furthermore, such a study has not been conducted in Iran to date, which simultaneously addresses stochastic irrigation system flows during different growth seasons, uncertainties in available water resources, and the resulting economic productivity index.

Methodology

Case study and data

Marun reservoir dam is in Khuzestan province, southeastern Iran, built on the Marun river. It is located about 19 km to the northeast of Behbahan and 220 km from Ahvaz.This study investigated two plains in Behbahan (13,500 hectares) and Jayzan (3,000 hectares) (Figure 1). Irrigation efficiency was 36–75% in the north and south networks and 32–36% in the Jayzan network (Technical Report of Exploitation Company of Marun Irrigation Network, 2016).The predominant cropping patterns were wheat, colza, and alfalfa, with a maximum yield of 4700, 2300, and 22,000 kilograms per hectare, respectively. The range of changes in the area under cultivation is presented in Table (1). The irrigation area of current crops under cultivation is presented in Table (2). The crops' benefit and cost ratios were presented in Table (3) (Document on Syncing Water Requirement of Crops and Garden Plants in Iran (2016) (case study: Khuzestan province).

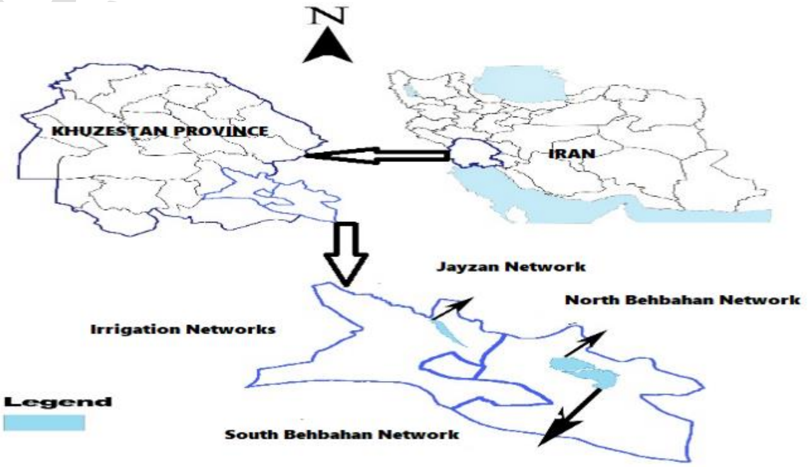

Fig. 1- Map of the case study areas

Table 2- Irrigation area of current crops under cultivation (ha)

Crop / Network	North	South	Jayzan
Wheat	3667	2635	1865
Colza	38	109	206
Alfalfa	461.4	2144	-

Table 3- Crops net benefit and penalties (IRR/ha)

CROP	Network	NB	C
Wheat	North	$[1.8(10)^4 -3.4(10)^4]$	$[1.5(10)^7 -2.6(10)^7]$
Wheat	south	$[1.8(10)^4 -3.4(10)^4]$	$[1.5(10)^7 -2.6(10)^7]$
Wheat	Jayzan	$[1.1(10)^4 -2.5(10)^4]$	$[8.7(10)^6 -1.8(10)^7]$
Colza	North	$[1.9(10)^3 -2.9(10)^4]$	$[1.5(10)^7 -2.6(10)^7]$
Colza	south	$[1.9(10)^3 -2.9(10)^4]$	$[1.5(10)^7 -2.6(10)^7]$
Colza	Jayzan	$[4.2(10)^3 -6.3(10)^4]$	$[8.7(10)^6 -1.8(10)^7]$
Alfalfa	North	$[9.6(10)^4 -1.6(10)^5]$	$[2.6(10)^7 -4.1(10)^7]$
Alfalfa	south	$[9.6(10)^4-1.6(10)^5]$	$[2.6(10)^7 -4.1(10)^7]$
Alfalfa	Jayzan	-------------------	-------------------------

Materials and Methods

At first, by using the Thomas-Fiering model, the simulation of water flows during different seasons was done, and by calculating the probability of occurrence, the flows were categorized into three categories of high, medium and low intensity. Then, by utilizing the two developed optimization models, optimal allocation and distribution of water between networks and crops under different flow scenarios was done.

Artificial data production

One of the parametric methods of artificial data production is that of Thomas and Fiering (1962). By using the Markov chain of formulas, they introduced a functional relationship for determining monthly flow. The equation is as follows:

$$Q_{i+1} = \overline{Q_{J+1}} + b_j\left(Q_i - \overline{Q_J}\right) + e_i S_{j+1}\sqrt{1 - r_j^2} \qquad (1)$$

$$b_j = r_j\left[\frac{S_{j+1}}{S_j}\right] \qquad (2)$$

Where:

Q_i and Q_{i+1}: monthly inflows produced in periods i and i + 1.

$\overline{Q_J}$ and $\overline{Q_{J+1}}$: average monthly inflows in J and J + 1 months.

b_j: least squares correlation coefficient for calculating the inflows of J + 1 month in the inflow of J month, which is obtained from the second equation.

r_j: Correlation coefficient between inflows of J and J +1 months.

S_j and S_j+ 1: standard deviation for J and J + 1 months.

e_i : is a random variable of normal standard distribution with an average of 0 and a standard deviation of 1.

Irrigation Water Requirements

In this study, the crop water requirement was calculated using net irrigation water requirement data and by factoring in effective precipitation obtained from the 2016 Document on Syncing Water Requirement of Crops and Garden Plants in Iran (case study: Khuzestan province).

Modeling

The model for the Marun agricultural water system involved two separated sub-models whose initial idea was from Dai and Li (2013). One difference here was that the model was implemented in two stages, namely (1) actual intra-network optimal allocation and (2) optimal supply and allocation of the reservoir output to the network, and these two modes were compared with the actual management.The model was explained later.

Sub-model 1: Intra-network water allocation and distribution optimization

Following the process of calculations, water was distributed and allocated to intra-networks to irrigate crops. The objective function in the first sub-model was to obtain the highest system gross benefit resulting from the transfer of water during one irrigation year (i.e., four growing seasons: fall, winter, spring, and summer) for scenarios of different inflows. The researcher calculated it using the following formula:

$$
\begin{aligned}
&Max\ z^{\pm} \\
&= \sum_{a=1}^{A}\sum_{b=1}^{B}\sum_{p=1}^{P} NB^{\pm}{}_{abp} ST^{\pm}{}_{abp} \\
&- \sum_{a=1}^{A}\sum_{b=1}^{B}\sum_{p=1}^{P}\sum_{s=1}^{S_t} P_{ps} C^{\pm}{}_{abp}\, SD^{\pm}{}_{abpS}
\end{aligned} \tag{3}
$$

a= crops, a=1, 2… A, and A=3 (Wheat, a=1; Colza, a=2; Alfalfa, a=3)

b=network irrigation, b=1, 2… B=3 (North network, b=1; South network, b=2; Jayzan network, b=3)

p=planning period time, p=1,2,…,P, and P=4 (Fall, p=1; Winter, p=2; Spring, p=3; Summer, p=4)

s= scenarios, s=1,2…S,and S=3 (High, s=1; Moderate, s=2; Low,s=3)

z = total gross benefit per irrigation year (IRR)

±: interval parameters under uncertainty

NB_{abp}= net benefit of crop a in network b (IRR/ha).

ST_{abp}= fixed planting area of crop a in subarea b per irrigation year (ha);

P_{sp}= probable occurrence of scenario s in period p.

C_{abp}= cost of an unirrigated rental area per hectare for crop a in network b

SD_{abps}= uncovered area by surface water irrigation target (ST_{abp}) in Q_p inflow (ha)

Q_p= availability of surface water random parameter for irrigation through period p (mm^3). Q_p = stands for q_{ps} amounts of the probability levels of P_{ps} for scenario s in period p.

Considering the following constraints:

There were five limitations for the optimization model developed in the first run. The first one was the limitation of the available water. It meant that the total water allocated to the irrigated planting areas in each network should be less than or equal to the volume of water supplied to each network plus surplus water of the previous irrigation season. This equation was calculated for each network, period and scenario.

$$
\begin{aligned}
&\sum_{a=1}^{A} W^{\pm}{}_{abp}\left(\mathrm{ST}^{\pm}{}_{\mathrm{abp}} - \mathrm{SD}^{\pm}{}_{\mathrm{abps}}\right) \\
&\qquad \le \mathrm{Q}^{\pm}{}_{\mathrm{bps}} + \varepsilon^{\pm}{}_{b(\mathrm{p}-1)\mathrm{k}}, \\
&\qquad \forall \mathrm{b,p,s}
\end{aligned} \tag{4}
$$

The second limitation was related to the amount of surplus water from the previous irrigation season of each network, which was defined as follows. The total water allocated to the irrigated planting areas, and the surplus water from the previous two irrigation seasons were summed up and the result was subtracted from the volume of water supplied to each the network. This equation was calculated for each network, period and scenario.

$$
\begin{aligned}
\varepsilon^{\pm}_{b(p-1)s} = Q^{\pm}_{b(p-1)s} &- \sum_{a}^{A} W^{\pm}_{ab(p-1)}\left(ST^{\pm}_{ab(p-1)} - SD^{\pm}_{ab(p-1)s}\right) \\
&+ \varepsilon^{\pm}_{b(p-2)s} \quad \forall \mathrm{b}, p, s
\end{aligned} \tag{5}
$$

The third constrain was related to the amount of planting area. The minimum irrigated planting areas, in addition to the area of crops, which was not irrigated with existing surface water, must be greater than or equal to zero. Moreover, the calculated optimal cultivation area must be between the maximum and minimum of the cultivated area investigated in the statistical period of this research. This equation was calculated for each product, network, period and scenario.

$$0 \leq SD^{\pm}{}_{abps} + ST^{\pm}{}_{abp\min} \leq ST^{\pm}{}_{abp} \leq ST^{\pm}{}_{abpmax} \quad ,\forall a, b, p, s \tag{6}$$

The fourth limitation was due to the sameness of the planting area in each irrigation season with the previous irrigation season. This equation was calculated for each product, network and period.

$$\mathrm{ST}^{\pm}{}_{\mathrm{abp}} = \mathrm{ST}^{\pm}{}_{\mathrm{ab(p-1)}}\,, \ ,\forall \mathrm{a,b,p=2,,3,\ldots,P} \tag{7}$$

The fifth constraint indicated that the planting area, which was not irrigated by the available surface water, should be greater than or equal to zero. This equation was calculated for each product, network, period and scenario.

$$SD^{\pm}{}_{abps} \geq 0, \quad \forall a, b, p, s \tag{8}$$

W_{abp}= Gross water demand for crop *a* in network *b* in period *p* (m^3);
$\varepsilon_{(p-1)}$ = surplus flow, when period *p-1* contains delivery of water (mm^3);
$\varepsilon_{(p-2)}$ = surplus flow, when period *p-2* contains delivery of water (mm^3);
ST_{abpmax}= maximum planting area in an investigated statistical period for crop *a* in network *b* (ha);
ST_{abpmin}= minimum planting area in an investigated statistical period for crop *a* in network *b* (ha);

Sub-model 2: Intra-network and inter-network water allocation and distribution optimization

In the presented model, water was allocated and distributed between crops of irrigated intra-networks s. The objective function was the highest water transfer gross benefit.

$$Max\ z^{\pm} = \sum_{a=1}^{A}\sum_{b=1}^{B}\sum_{p=1}^{P} NB^{\pm}{}_{abp} ST^{\pm}{}_{abp} - \sum_{a=1}^{A}\sum_{b=1}^{B}\sum_{p=1}^{P}\sum_{s=1}^{S_t} P_{PS} C^{\pm}{}_{abp}\, SD^{\pm}{}_{abps} \tag{9}$$

The developed optimization model of the second run included six constraints. Except the limitation of the current profit in equation 13, which showed that the net profit of the irrigated planting areas in the networks for crops in all periods and scenarios should be greater than or equal to the current net profit in a water year, the rest were similar to the limitations of the first run of the model. It should be explained that in this sub-model, the volume of water supplied from the output of the reservoir (in total for all networks) was considered. In addition, the surplus water was calculated for all networks in total.
Subject to:

$$\textstyle\sum_{a=1}^{\mathrm{A}} \sum_{\mathrm{b=1}}^{\mathrm{B}} \mathrm{W}^{\pm}{}_{\mathrm{abp}} \left(\mathrm{ST}^{\pm}{}_{\mathrm{abp}} - \mathrm{SD}^{\pm}{}_{\mathrm{abps}}\right) \leq \mathrm{Q}^{\pm}{}_{\mathrm{ps}} + \varepsilon^{\pm}{}_{\mathrm{(p-1)s}} \quad ,\forall p, \forall s \tag{10}$$

$$\varepsilon^{\pm}_{(p-1)k} = Q^{\pm}_{(p-1)k} - \sum_{a=1}^{A}\sum\nolimits_{b=1}^{B} W^{\pm}_{ab(p-1)}\left(ST^{\pm}_{ab(p-1)} - SD^{\pm}_{ab(p-1)S}\right) + \varepsilon^{\pm}_{(p-2)S} \quad ,\forall P, S \tag{11}$$

$$0 \leq SD^{\pm}{}_{abps} + ST^{\pm}{}_{abpmin} \leq ST^{\pm}{}_{abp} \leq ST^{\pm}{}_{abpmax} \quad ,\forall a, b, p, s \tag{12}$$

$$\sum_{a}^{A}\sum_{b}^{B}\sum_{p}^{P}\sum_{s}^{S} NB^{\pm}_{abps}\, ST^{\pm}_{abps} \geq \sum_{a}^{A}\sum_{b}^{B}\sum_{p}^{P} ST^{\pm}_{curabp} * NB^{\pm}_{abp} \tag{13}$$

$$ST^{\pm}{}_{abp} = ST^{\pm}{}_{\boldsymbol{ab(p-1)}}\,, \quad \forall \boldsymbol{a,b,p=2,3,\ldots,P} \tag{14}$$

$$SD^{\pm}{}_{abpS} \geq 0, \quad \forall a, b, p, s \tag{15}$$

ST_{cur} = current planting area of crop a in subarea b per irrigation year (ha);

Then, the multistage irrigation water allocation model (MIWA) was applied using the research sub-models based on the two-module cooperative algorithm in order to calculate the upper and lower bounds of $z^{\pm}$. Despite the importance of the maximization of the gross benefit of the system, the sub-model which resulted in z^{+} was first defined. Here, z^{+} was a combination of the upper bound benefit and lower bound loss coefficients; $SD^{-}{}_{abps}$ were decision variables, and $SD^{-}_{abpsopt}$ were the solutions of the sub-model. The model was nonlinear. The z^{-} Sub-model was calculated by linear programming (LP); where $SD^{+}{}_{abps}$ were decision variables, $SD^{+}{}_{abpsopt}$, $z^{-}{}_{opt}$ were the sub-model's solutions.

The response of the main model based on the solution of these two sub-models was illustrated below:

$$\mathrm{z_{opt}}^{\pm} = \left[\mathrm{z^{-}}_{\mathrm{opt}}, \mathrm{z^{+}}_{\mathrm{opt}}\right] \tag{16}$$

$$\mathrm{SD^{\pm}}_{\mathrm{abpsopt}} \;\; \left[\mathrm{SD^{-}}_{\mathrm{abpsopt}}, SD^{+}{}_{abpsopt}\right] \quad \forall\, a, b, p, s \tag{17}$$

The actual irrigation plan over the complete programming horizon equation;

$$\mathrm{SA^{\pm}}_{\mathrm{abpsopt}} = \mathrm{ST^{\pm}}_{\mathrm{abpopt}} - \mathrm{SD^{\pm}}_{\mathrm{abpsopt}} \quad \forall \mathrm{a, b, p, s} \tag{18}$$

Programming

According to project objectives, the optimization was performed through a multi-stage stochastic programming (MSP) model using interval parameters under uncertainty in the GAMS 24.1.2 environment.

A Multi-stage Stochastic Programming for Water Resources Management

The decision-making process for a temporal period can be aided by the multi-stage stochastic programming model (MSP). Accordingly, the amount of water scarcity in a temporal period was estimated and performed to enable the system manager and consumers to adopt policies to combat the water crisis. Moreover, it performed the final water allocation among different crop types based on the goal of maximizing the system's total benefit. This model made a relation between the initial operating aim—i.e., supplying the irrigation network demand to the extent possible—and economical aims (Wang and Huang, 2012).

It was formulated as follows;

$$Maxf = \sum_{i=1}^{I}\sum_{t=1}^{T} NB_{it}T_{it} - \sum_{i=1}^{I}\sum_{t=1}^{T}\sum_{k=1}^{K} P_{tk}C_{it}S_{itk} \tag{19}$$

$$\sum_{i=1}^{I}(T_{it} - S_{it})(1+\delta) \leq q_{ht} + \varepsilon_{(t-1)k} \quad \forall t, h = 1, 2, \ldots, k-1 \tag{20}$$

$$\varepsilon_{(t-1)k} + \sum_{i=1}^{I}(T_{it} - S_{it})(1+\delta) \leq q_{ht} + \varepsilon_{(t-1)k} \quad \forall t-1, h; k = 1, 2, \ldots, k-1 \tag{21}$$

$$T_{imax} \geq T_{it} \geq S_{itk} \geq 0 \quad \forall i, t, k \tag{22}$$

Subject to

An Interactive Algorithm

To attain upper and lower bounds of $z^{\pm}$ (the system total benefit), both of the sub-models of multistage irrigation water allocation based on two temporal stages of the interactive algorithm were divided into two exact sub-models. The upper bounds optimization model was calculated by NLP, and CONOPT4 was used for its algorithm. LP was used for lower bounds optimization and according to the objective function and its conditions; the lower bounds algorithm was done the same as for the upper bounds.

Economic Water Productivity (EWP) Index

In terms of physical productivity, crop per drop (CPD) was the yield per unit volume of water consumed (kg/m^3). In terms of economic productivity, the benefit per drop (BPD) was the income or yield value per unit volume of water consumed (Molen et al., 1998).

$$CPD = Q/W \tag{23}$$

Where Q is the amount of yield (kg) and W is the volume of water consumed (m^3). Therefore, this index shows the amount of yield per cubic meter of water.

$$BPD = GR/W \tag{24}$$

Where GR was the gross value of production (IRR) and W was the volume of water consumed (m^3). Therefore, this index showed the amount of income (IRR) per cubic meter of water consumed.

$$NBPD = R/W \tag{25}$$

Where R is the net benefit per drop (NBPD), (IRR) and W is the volume of water consumed (m^3). This was one of the best indices for measuring agricultural water productivity, which was used here to assess economic productivity. Figure 2 has been depicted the flowchart of this research and its components

Results

Estimation of the probability of inflow intensity and scenario

Based on the mean and the standard deviation of the produced artificial data, the probability of inflow intensity in the input of irrigation network channels was divided into three levels of low, medium, and high. (Table 4).

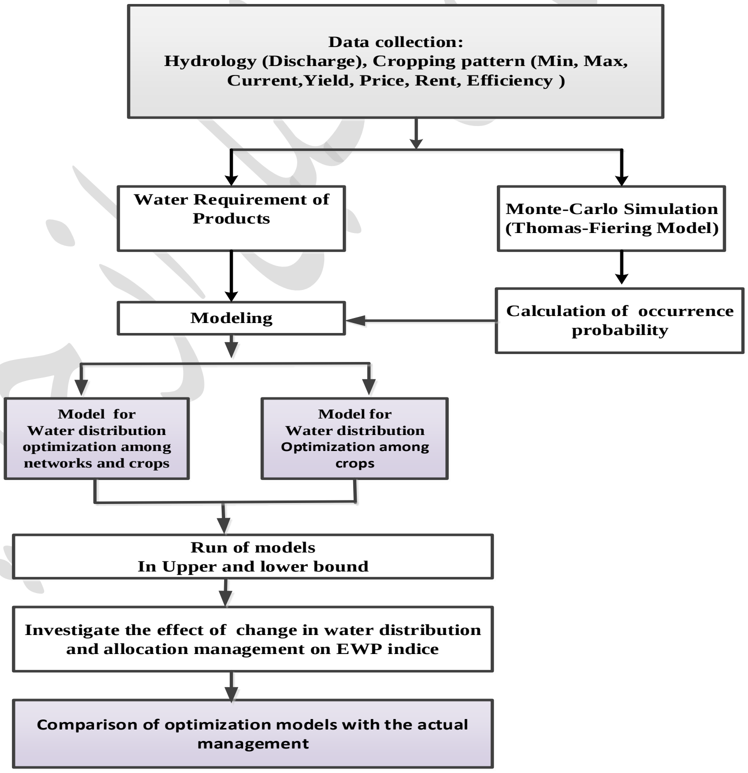

Fig. 2- Flowchart of the research

Table 4- The stochastic input inflow to the networks for irrigation under 3 scenarios of inflow intensity in 4 seasons of crop growth (MM^3)

Available Water													
t		Fall			Winter			Spring			Summer		
Scenario	P%	North	South	Jayzan	North	South	Jayzan	North	South	Jayzan	North	South	Jayzan
Low	20	(0.02-0.03)	(1.5-3)	(0.02-0.03)	(4-10)	(3-9)	(1.3-2.4)	(4-9)	(1.4-3)	0	0	0	0
moderate	60	(10-16)	(13-21)	(7-14)	(10-16.5)	(13-21)	(8-19)	(10-16)	(14-24)	(2-3)	(7-8)	(18.5-28)	0
High	20	(14-21)	(32.5-54)	(23-41)	(13-23)	(16-25)	(20.5-27)	(10-19)	(19-49.5)	(5.4-10.3)	(12-20)	(24-35)	(14-20)

** P=Probability*

Reference: Research findings

Table 5-Optimized irrigation area in networks(Ha) (INOM)

Network	ST^{-}_{abp}		
	Wheat	Colza	Alfalfa
North	2400	10	291
south	1850	4.5	2022
Jayzan	1300	0	0

Reference: Research findings

Optimization Model Implementation

Decision variables in stage p were calculated based on $[a * b * \pi_{s=1}^{p} S_s]$, this value was calculated as 27, 81, 243 and 243 respectively for period 1 to 4, these variables supplied the irrigation water allocation of various crops for scenarios of different inflows.

The first run: INOM

Given the regional social issues and the canal capacity, optimal water allocation and distribution were done separately in irrigation networks. The segregated discharge of each network was fed to the model separately.

Irrigation target setting

The cropping pattern area of all crops in all networks made itself compatible with the optimization lower bounds as illustrated in table (5).

Low amount of benefit was the result of $ST^{\pm}_{abp}$ approaching its lower bounds, and consequently its outcome was disturbing imagined functions with less risk. In such circumstances if the irrigation target was provided, there would be the least benefit, and if not there would be the least penalty too. So the manager had a conservative view for available water. The results indicated that firstly wheat and then alfalfa got higher position in benefit and penalty amounts than colza which indicated they were more competitive.

$$ST^{\pm} = {ST_{abp}}^{-} \tag{26}$$

Irrigation water allocation

Considering the multiplicity of decision variables in this study, the results were presented for 12 random states and four growing seasons to better illustrate the changes. These results had effects on the optimal allocation of irrigation water and the optimal cropping patterns in the irrigation networks of the case study. In table (6), the actual crop irrigation areas with different inflow scenarios were presented in four seasons of growth in the networks. The illustrations were related to different periods (i.e.,SA_{abps}^{-}) in different scenarios for the lower bounds considering the given irrigation targets (i.e.,ST_{abpopt}^{-}) and water shortage (i. eSD_{abpk}^{-}). Water shortage solutions were essential, and the uncertainties in the system were presented using interval values. This value also demonstrated the intra-period and inter-period challenges concerning insufficient water resources for different crops grown in networks during different stages of growth. The water allocation results (12 random states) showed that in most states, the area under cultivation in the model increased by changing the flow intensity from low to high. In the first period, the area under wheat cultivation in the North, South, and Jayzan networks dropped by 97-64-94 percent for the low scenario and by 0-0-36 percent for the medium scenario compared to the high scenario. The area under alfalfa cultivation in the North and South networks decreased by 99 and 72 percent, respectively, for the low scenario and by 91 and 50 percent for the medium scenario compared to the high scenario. In the second period, the area under wheat cultivation in the North, South, and Jaizan networks dropped by 100-100-100 percent, respectively, for the low-low scenario and by 0-64-36 percent for the medium-medium compared to the high-high scenario. The area under alfalfa cultivation in the North and South networks decreased by 100-90 percent, respectively, for the low-low scenario and by 54-50 percent for the medium-medium scenario compared to the high-high scenario. In the third period, the area under wheat cultivation in the North, South, and Jaizan networks decreased by 100-100-100 percent, respectively, for the low-low-low scenario and by 0-0-36 percent for the medium-medium-medium scenario compared to the high-high-high scenario. The area under alfalfa cultivation in the North and South networks dropped by 100-100 percent, respectively, for the low-low-low scenario and by 54-50 percent for the medium-medium scenario compared to the high-high-high scenario. In the fourth period, the area under alfalfa cultivation in the North and South networks decreased by 100-100 percent, respectively, for the low-low-low-low scenario and by 54-54 percent for the medium-medium-medium-medium scenario compared to the high-high-high-high scenario. The wheat cultivation area did not exist for any of the scenarios in the fourth period.

Table 6- The actual irrigation area of crops with different inflow scenarios in four seasons in networks (Ha) (INOM)

		P=1		P=2		P=3		P=4	
Subarea	Crop	Scenario	SA	Scenario	SA	Scenario	SA	Scenario	SA
North	Wheat	L	62	LL	0	LLL	0	LLLL	0
North	Colza	L	5	LL	5	LLL	5	LLLL	0
North	Alfalfa	L	5	LL	0	LLL	0	LLLL	0
South	Wheat	L	667	LL	0	LLL	0	LLLL	0
South	Colza	L	4.5	LL	4.5	LLL	4.5	LLLL	0
South	Alfalfa	L	290	LL	101.5	LLL	0	LLLL	0
Jayzan	Wheat	L	76	LL	0	LLL	0	LLLL	0
Jayzan	Colza	L	0	LL	0	LLL	4.5	LLLL	0
Jayzan	Alfalfa	L	0	LL	0	LLL	0	LLLL	0
North	Wheat	M	2400	MM	2400	MMM	2400	MMMM	0
North	Colza	M	5	MM	5	MMM	5	MMMM	0
North	Alfalfa	M	94	MM	94	MMM	94	MMMM	94
South	Wheat	M	1850	MM	667	MMM	1850	MMMM	0
South	Colza	M	4.5	MM	4.5	MMM	4.5	MMMM	0
South	Alfalfa	M	523	MM	523	MMM	523	MMMM	523
Jayzan	Wheat	M	825.6	MM	826	MMM	826	MMMM	0
Jayzan	Colza	M	0	MM	0	MMM	0	MMMM	0
Jayzan	Alfalfa	M	0	MM	0	MMM	0	MMMM	0
North	Wheat	H	2400	HH	2400	HHH	2400	HHHH	0
North	Colza	H	5	HH	5	HHH	5	HHHH	0
North	Alfalfa	H	1065	HH	205	HHH	205	HHHH	205
South	Wheat	H	1850	HH	1850	HHH	1850	HHHH	0
South	Colza	H	4.5	HH	4.5	HHH	4.5	HHHH	0
South	Alfalfa	H	1065	HH	1065	HHH	1065	HHHH	1065
Jayzan	Wheat	H	1300	HH	1300	HHH	1300	HHHH	0
Jayzan	Colza	H	0	HH	0	HHH	0	HHHH	0
Jayzan	Alfalfa	H	0	HH	0	HHH	0	HHHH	0

Reference: Research findings

Note: P=Period, SA= actual irrigation lands high-moderate-low
L=Low , M= Moderate , H= High
LL=Low Low, MM= Moderate Moderate, HH= High High
LLL=Low Low Low, MMM= Moderate Moderate Moderate, HHH= High High High
LLLL=Low Low Low Low, MMMM= Moderate Moderate Moderate Moderate, HHHH= High High High High

The second run: RO-IN OM

Optimal management of reservoir output to the network was run and the discharge was added collectively.

Irrigation target setting

The cropping pattern area of all crops in all networks made itself compatible with the optimization lower bounds (Table 7).

Table 7- Optimized irrigation area in networks(Ha) (RO-IN OM)

Network	ST^{-}_{abp}		
	Wheat	Colza	Alfalfa
North	2569	10	291
south	2582	4.5	1743
Jayzan	1891	0	0

Reference: Research findings

Irrigation water allocation

In Table (8), the actual irrigation area of crops with different scenarios were presented in four growing seasons in three networks (i.e., North, South, and Jayzan).The water allocation results (12 random states) showed that the area under cultivation in the model increased by changing the flow intensity from low to high. In the first period, the area under wheat cultivation in the North, South, and Jayzan networks dropped by 62-100-3 percent for the low scenario compared to the high scenario; whereas no differences were found for the medium scenario. The area under alfalfa cultivation in the North and South networks decreased by 0-84 percent, respectively, for the low scenario, whereas for the medium scenario it increased by 98% in the North network and decreased by 67% in the South network compared to the high scenario. In the second period, the area under wheat cultivation in the North, South, and Jayzan networks dropped by 78-100-99 percent, respectively, for the low-low scenario, whereas no changes were seen for the medium-medium scenario compared to the high-high scenario. The area under alfalfa cultivation decreased by 0-84 percent in the North and South networks, respectively for the low-low scenario, whereas it increased by 98% in the North network and decreased by 67% in the South network for the medium-medium scenario, compared to the high-high scenario. In the third period, the area under wheat cultivation in the North, South, and Jayzan networks decreased by 78-100-100 percent, respectively, for the low-low-low scenario compared to the high-high-high scenario. Meanwhile, no changes were observed for the medium-medium-medium scenario. The area under alfalfa cultivation in the North and South networks decreased by 100-100 percent for the low-low-low scenario, whereas it increased by 98% in the North network and decreased by 67% in the South network for the medium-medium-medium scenario compared to the high-high-high scenario. In the fourth period, the area under alfalfa cultivation in the North and South networks decreased by 100-100 percent respectively for the low-low-low-low scenario, whereas it increased by 98% in the North network and decreased 67% in the South network for the medium-medium-medium-medium scenario compared to the high-high-high-high scenario. The wheat cultivation area did not exist for any of the scenarios in the fourth period.

Table 8-The actual irrigation area of crops with different inflow scenarios in four seasons in networks (Ha) (RO-IN OM)

		P=1		P=2		P=3		P=4	
Subarea	Crop	Scenario	SA	Scenario	SA	Scenario	SA	Scenario	SA
North	Wheat	L	978	LL	562	LLL	562	LLLL	0
North	Colza	L	5	LL	5	LLL	5	LLLL	0
North	Alfalfa	L	3	LL	3	LLL	0	LLLL	0
South	Wheat	L	0	LL	0	LLL	0	LLLL	0
South	Colza	L	4.5	LL	4.5	LLL	4.5	LLLL	0
South	Alfalfa	L	283.6	LL	284	LLL	0	LLLL	0
Jayzan	Wheat	L	1884	LL	5	LLL	0	LLLL	0
Jayzan	Colza	L	0	LL	0	LLL	0	LLLL	0
Jayzan	Alfalfa	L	0	LL	0	LLL	0	LLLL	0
North	Wheat	M	2569	MM	2569	MMM	2569	MMMM	0
North	Colza	M	5	MM	5	MMM	5	MMMM	0
North	Alfalfa	M	291	MM	291	MMM	291	MMMM	291
South	Wheat	M	2582	MM	2582	MMM	2582	MMMM	0
South	Colza	M	4.5	MM	4.5	MMM	4.5	MMMM	0
South	Alfalfa	M	579	MM	579	MMM	579	MMMM	579
Jayzan	Wheat	M	1891	MM	1891	MMM	1891	MMMM	0
Jayzan	Colza	M	0	MM	0	MMM	0	MMMM	0
Jayzan	Alfalfa	M	0	MM	0	MMM	0	MMMM	0
North	Wheat	H	2569	HH	2569	HHH	2569	HHHH	0
North	Colza	H	5	HH	5	HHH	5	HHHH	0
North	Alfalfa	H	3	HH	3	HHH	3	HHHH	3
South	Wheat	H	2582	HH	2582	HHH	2582	HHHH	0
South	Colza	H	4.5	HH	4.5	HHH	4.5	HHHH	0
South	Alfalfa	H	1784	HH	1784	HHH	1784	HHHH	1784
Jayzan	Wheat	H	1891	HH	1894	HHH	1891	HHHH	0
Jayzan	Colza	H	0	HH	0	HHH	0	HHHH	0
Jayzan	Alfalfa	H	0	HH	0	HHH	0	HHHH	0

Reference: Research findings

Comparison of EWP Index under Different Flow Scenarios in two Optimization Sub-models

A graph of mean economic productivity in all scenarios in the networks was also provided for both sub-models. Figure (3) shows the economic productivity index under three scenarios for both sub-models in the North network. In the first run, the highest EWP was obtained for the medium-medium-medium scenario at 4651 IRR/m^3. The EWP index in the high-high-high and low-low-low scenarios, respectively, decreased by 6% and 2% compared to the above scenario. The comparison of the scenarios in the North network showed that the volume of water released in winter and summer did not improve the economic productivity of the water network, whereas it played an effective role in fall and spring. The high-high-high scenario in all seasons was not a suitable approach for improving the economic water productivity. In the second run, the highest EWP was obtained for the high-high-high and low-low-low scenarios at 4997 IRR/m^3. The EWP index in the medium-medium-medium scenario decreased by 15% compared to the above scenario. The comparison of the scenarios indicates that the volume of water released in winter, spring, and summer did not improve the economic water productivity in the North network. Figure (4) shows the EWP index under three scenarios for both sub-models in the South network. In the first run, the highest economic productivity was obtained for the high-high high scenario at 3503 IRR/m^3. The EWP index in the medium-medium-medium scenario decreased by 2% and in the low-low-low scenario by 13% compared to the above scenario. The comparison of the scenarios showed that the volume of water released in the low and medium scenarios in all seasons was more effective than the high scenario in the South network. In the second run, the highest EWP was obtained for the medium-medium-medium scenario at 3907 IRR/m^3. It decreased by 11% in the high-high-high scenario and by 1% in the low-low-low scenario compared to the above scenario. The comparison of the scenarios showed that the volume of water released in the low and medium scenarios in all seasons was more effective than the high scenario in the South network. Figure (5) shows the EWP index under three scenarios for both sub-models in the Jayzan network. In the first run, economic productivity was equal in two scenarios of medium-medium-medium and high-high-high, standing at 1736 IRR/m^3. The comparison of the scenarios showed that the volume of water released in different scenarios and seasons did not improve the economic productivity of the Jayzan network. In the second run, the economic productivity was the same in medium-medium-medium and high-high-high scenarios, standing at 1736 IRR/m^3. The comparison of the scenarios showed that the volume of water released in the high scenario did not improve the economic productivity of the Jayzan network.

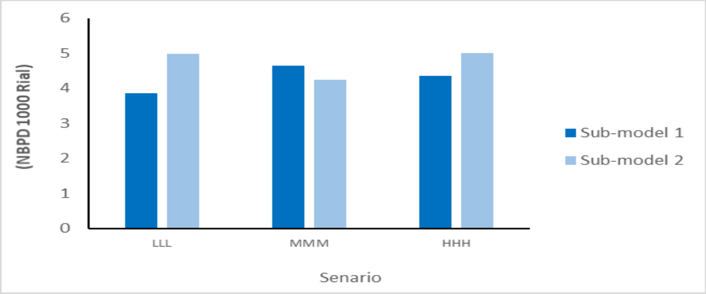

Fig 3 - Economic productivity index under three scenarios in the North network in two optimization sub-models

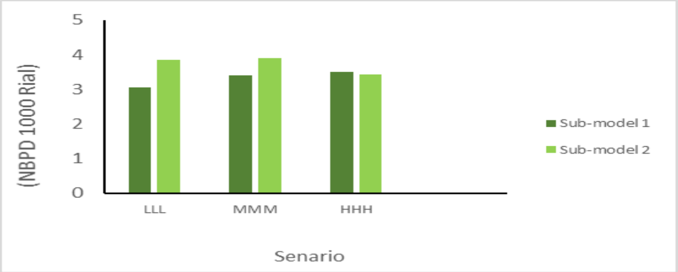

Fig . 4 - EWP index under three scenarios in the South network in two optimization sub-models

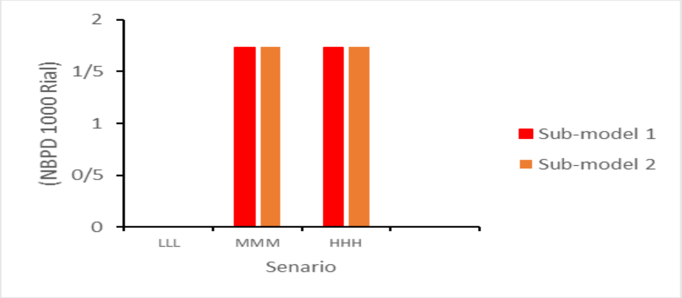

Fig. 5 - EWP index under four scenarios in the Jayzan network in two optimization sub-models

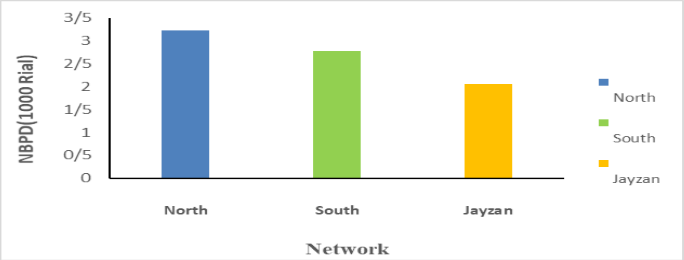

Fig. 6- EWP index in networks under the actual management

Comparison of EWP Index in the Actual Management

Figure (6) shows the EWP index in networks. The highest level of EWP was obtained in the North network at 3228 IRR/m^3 and the lowest at 2064 IRR/m^3 in the Jayzan network.

Optimization Assessment under Two Management Modes

The highest average EWP values in the three scenarios were 4294 and 4744 IRR/m^3 in the North network, and the lowest value in both runs was 1157 IRR/m^3 in the Jayzan network. Considering the 19% increase in the actual irrigation areas (cropping areas) and the 7% increase in the profit of the objective function in the second run compared to the first (Amanat Behbahani et al., 2020), the model's second run had a better performance in water consumption. Moreover, the highest mean EWP in the three scenarios was obtained in the second run for the North network at 9% more than the first run.

Comparison of Optimization Models against the Actual Management

In order to compare the performance of the EWP index in different senarios, the results of the optimization model under two management modes and 12 flow scenarios were compared with the actual management conditions in the Marun network in the 2006–2016 period. The flow rate supplied in the actual management was assumed to be fixed. The EWP index results in the comparison of the optimization model in two management modes and three flow scenarios with the actual management showed that the highest mean value was obtained for the North network, which was 8% (first run) and 20% (second run) higher than current figures in the three scenarios. The lowest mean value was obtained for the Jayzan network, which was 44% lower than the actual figures in both runs.

Conclusion

In this study, the water requirements of crops have been assumed to be constant over the years analyzed, which should be noted as a limitation. In future studies, it is recommended to investigate the effects of the hydrological cycle and climate change on the water needs of crops.The results showed the applicability of this developed model in the study area.The mentioned results were compatible with the results of Dai and Li (2013). The general findings were as follows:

1. Considering the 19% increase in the total area under cultivation and the 7% increase in the profit of the objective function in the second run compared to the first, the optimization model's second run had a better performance in water consumption. Moreover, the highest mean EWP in the three scenarios was obtained in the second run for the North network at 9% more than the first run.
2. The highest EWP in the North network and under three scenarios was obtained in the first run for the medium-medium-medium scenario at 4651 IRR/m^3 and in the second run for the high-high-high and low-low-low scenarios at 4997 IRR/m^3.
3. The highest EWP in the South network and under three scenarios was obtained in the first run for the high-high-high scenario at 3503 IRR/m^3 and in the second run for the medium-medium-medium scenario at 3907 IRR/m^3.
4. The highest EWP in the Jayzan network and under three scenarios was obtained in the first and second runs for medium-medium-medium and high-high-high scenarios at 1736 IRR/m^3.
5. The highest mean EWP index value was obtained in the North network, which was 8% (first run) and 20% (second run) higher than the actual management figures. The lowest mean EWP index value was obtained for the Jayzan network, which was 44% lower than the actual management in both runs.

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