



## Optimization of performance measures in Doroodzan Irrigation Network

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**ABSTRACT**-In this research, the performance measures of water equity and productivity have been optimized in the entire Doroodzan Irrigation Network by using genetic algorithms. Results indicated that irrigation water management improvement at field scale [increasing irrigation application efficiency ( $E_a$ ) and water reduction fraction (WRF)] has much more impressive impact on raising the performance measures than the improvement of conveyance efficiency of channels ( $E_c$ ). Increments of  $E_a$  (40% to 90%) and  $E_c$  (70% to 90%) resulted in maximum and minimum incremental effects on water equity (on average 48.2% and 17.7%, respectively) and productivity (on average 92.0% and 10%, respectively). The incremental effect of WRF (0.0 to 0.8) on water equity and productivity was on average 31.4% and 10%, respectively. Furthermore, the values of performance measures decreased from wet water year to drought water year. Tape irrigation system was considered as the best choice at low quantities of WRF ( $\leq 0.4$ ); however, for higher values of WRF ( $\geq 0.6$ ), sprinkler irrigation system was considered as the best choice for achieving higher values of water equity and productivity. Meanwhile, when equity and productivity were considered together for a specific method of deficit irrigation scheduling, under specified quantity of irrigation water, with increasing equity, the water productivity reduction was negligible.

### INTRODUCTION

Water resources management in agriculture (the main consumer of fresh water resources around the world) at farm scale plays a key role in sustainable management of water resources especially during summer crop season. Appropriate assessment tools that help water resources managers to find suitable water policy frameworks are water equity and water productivity. Water equity and productivity are two socioeconomic performance measures that affect the water allocation decision parameters and help managers to efficiently manage water resources and save water. Among the management methods, an appropriate deficit irrigation scheduling can be the most effective procedure that immediately affects the performance measures. When water is more scarce than land, the irrigation water productivity measure (e.g. crop yield per unit of irrigation water used) is a useful tool to achieve suitable water resources management in irrigated agriculture (Pereira et al., 2002). In many irrigation networks, water distribution, particularly under drought conditions, fails to achieve one of the objectives like water equity or productivity while trying to improve another, especially in unlined canal networks with a high seepage rate (Kalu et al., 1995).

Water productivity and equity are perhaps the two most frequently mentioned performance goals in irrigation management (Steiner and Walter, 1992). On the basis of dealing with the performance measures such as water productivity and equity, the methodologies can

be classified into three categories as: 1) methodologies aiming for only optimum water productivity; 2) methodologies aiming for optimum water productivity while addressing the issue of water equity; and 3) methodologies aiming for optimum water productivity and/or maximum water equity (Gorantiwar et al., 2006). Clearly, because they are closely linked, strategies designed to maximize one of these performance goals will have an impact on the other goals due to their linkage (Steiner and Walter, 1992).

Among the variables that influence the performance measures at irrigation networks, methods of deficit irrigation scheduling are the most effective (Rodrigues and Pereira, 2009). One of the promising irrigation strategies to achieve optimum water equity and productivity is deficit irrigation (DI). DI is deliberately applying irrigation depths smaller than those required to satisfy the crop water requirements at certain periods in the growing season (Rodrigues and Pereira, 2009). It has been widely investigated as a valuable and suitable production strategy in drought conditions (Pereira et al., 2002; Sepaskhah and Akbari, 2005; Kloss et al., 2012). In this regard, irrigation systems with higher irrigation application efficiencies have the key role that resulted in better implementation of deficit irrigation and achieving higher values of performance measures. Meanwhile, application of different irrigation systems for winter and summer crops may lead to different results due to winter precipitation occurrence.

In this study, we are looking for the methodologies that optimize the two performance measures (water equity and productivity) related to dominant summer crop (Maize) irrigated with different irrigation systems, irrigation application efficiencies ( $E_a$ ) and several methods of deficit irrigation scheduling (DIS) under different climatic conditions and water costs by using Genetic Algorithm (GA) in Doroodzan Irrigation Network in the south of Iran.

## MATERIALS AND METHODS

This study was conducted for summer crop season (for dominant summer crop Maize in all Doroodzan Irrigation Network with area of approximately 53159 ha located at the south of Iran). The transmission channels between fields are mostly lined by concrete that mostly required maintenance. The summary of the characteristics of the network used in this study is presented in Table 1 and Fig. 1.

**Table 1.** Summary of characteristics of the network used in this study

Field	Area (ha)	Distance to entrance of the main channel (km)	Length of distributor channels in fields (km)	Distribution efficiency of water in fields (%)
MU1	2156	5.3	45.1	84.2
MU2	1435	12.1	16.1	94.4
MU3	2116	15.3	26.5	90.7
MU4	2523	21.4	46.9	83.6
MU5	3845	26.7	61.7	78.4
MU6	1256	27.4	33.5	88.3
MU7	3708	29.8	57.5	79.9
MU8	3827	30.7	62.4	78.1
MU9	1339	34.6	30.8	89.2
MU10	4843	35.0	85.7	70.0
MU11	3620	36.6	44.1	84.6
MU12	1104	38.4	24.5	91.4
MU13	2545	41.0	38.7	86.5
MU14	1241	42.8	19.3	93.2
MU15	2281	53.9	47.1	83.5
MU16	2728	59.5	49.9	82.5
MU17	2154	65.2	34.3	88.0
MU18	2579	67.4	62.6	78.1
MU19	3337	79.4	49.5	82.7
MU20	2144	83.3	39.7	86.1
MU21	951	87.4	12.9	95.5
MU22	1427	90.0	35.3	87.6

In a previous study (Moghimi and Sepaskhah, 2014), crop irrigation requirement, grain yield and net income per unit area (ha) for maize (dominant summer crop of the study area) were determined for different irrigation systems,  $E_a$  and methods of DIS under different climatic conditions (wet, normal and drought) and water costs (current and real). Then, for different scenarios (different irrigation systems,  $E_a$  and methods of DIS under different climatic conditions and water costs) and different conveyance efficiencies of the main channel (70%, 80% and 90%), two performance measures (water equity and productivity) were simultaneously

optimized by using genetic algorithm (gamultiobjective) under optimization toolbox of MATLAB9 software. Optimization Tool (optimtool) is a graphical user interface (GUI) for selecting a toolbox function, specifying optimization options, and running optimizations. It provides a convenient interface for all optimization routines, including those for genetic algorithms. Optimization Tool makes it easy to: a) Define and modify problems quickly; b) Use the correct syntax for optimization functions; c) Import and export from the MATLAB workspace; d) Generate code containing the configuration for a solver and options and e) Change parameters of an optimization during the execution of certain genetic algorithm.

For running the optimization by using the optimization tool of graphical user interface (GUI), the following steps should be taken: 1) Making an M-file that contains the objective functions (fitness functions); 2) Starting the optimization tool and problem setup which includes the solver selection, entering the fitness function that is created in step 1, numbering the variables and entering the constraints and 3) Entering the options which usually includes entering the population size (300), selection function (Tournament), number of generations (3000) and numbering the stall generations (200). In this study, water equity was considered in the form of modified in terquartile allocation ratio (Smout et al., 2006) and water productivity was considered in the form of economic water productivity ratio (EWPR); that is, the ratio of the value of total actual yield to the cost of irrigation water used. Decision variable is the fraction of total volume of water allocated to  $k^{\text{th}}$  management unit ( $X_k$ ). As a general and powerful procedure, the genetic algorithm (GA) can be applied to many complex problems that are difficult to solve using traditional techniques such as linear and non-linear programming or methods based on gradient calculations (Michalewicz, 1994).

Based on the literature review, it can be stated that traditional optimization methods have limitations in finding global optimization results and are difficult to apply to a complex irrigation planning problem since they search from point to point for the optimization. On the other hand, the genetic algorithm method searches the entire population instead of moving from one point to the next and can, therefore, overcome the limitations of the traditional methods (Kuo et al., 2000). Furthermore, this technique is very suitable for optimal solution of non- derivative problems (functions) using random selection procedures, which simulate natural selection process.

For applying deficit irrigation (DI) for maize, four water reduction fractions (WRF, i. e., 0.2, 0.4, 0.6 and 0.8) and several methods of deficit irrigation scheduling (DIS) (1, 2, 3, 4 and 5) were used that are described as follows:

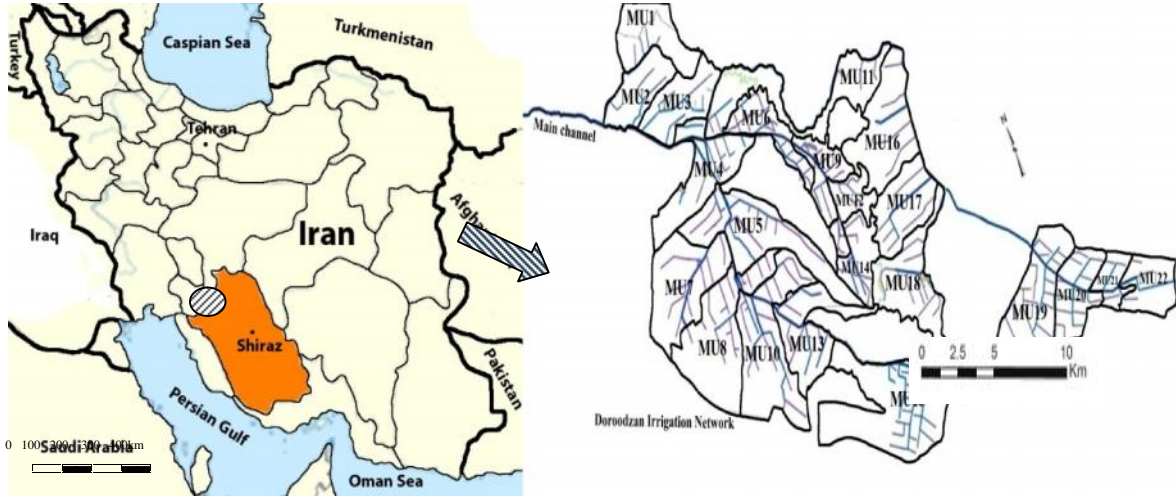


Fig. 1. Location of the study area

Method 1: Relative applied water (1-WRF), i.e., 0.8, 0.6, 0.4 and 0.2 are multiplied by the quantity of each irrigation event calculated for stages after establishment in spring or summer.

Method 2: Relative applied water (1-WRF) are multiplied by the total number of irrigation events obtained for stages after establishment. However, full irrigation was applied at the reduced number of irrigation events.

Methods 3, 4 and 5: Full irrigation was applied at vegetative stage in method 3, at vegetative and flowering stages in method 4 and at flowering stage in method 5. For other stages, (1-WRF) are multiplied by the quantity of water at each irrigation event.

In this study, different irrigation systems with various  $E_a$  in the field were considered as surface irrigation ( $E_a= 40\%$ ,  $50\%$  and  $60\%$ ), solid-set sprinkler irrigation ( $E_a= 60\%$ ,  $70\%$  and  $80\%$ ) and tape irrigation ( $E_a= 70\%$ ,  $80\%$  and  $90\%$ ).

**Water Equity**

One of the objective functions was performance measure of water equity that is defined as modified inter quartile allocation ratio [Eqs. (1-4)] (Smout et al., 2006):

$$E = \frac{\overline{R^{bq}}}{\overline{R^{pq}}} \tag{1}$$

$$R_k = \frac{\} x_k}{\} d_k} \tag{2}$$

$$\} x_k = \frac{\Delta x_k}{\sum_{k=1}^{nk} \Delta x_k} \tag{3}$$

$$\} d_k = \frac{\Delta d_k}{\sum_{k=1}^{nk} \Delta d_k} \tag{4}$$

where E is the modified interquartile allocation ratio (water equity),  $\overline{R^{bq}}$  is the average of allocation ratios of the best quarter,  $\overline{R^{pq}}$  is the average of allocation ratios of the poorest quarter,  $R_k$  is the allocation ratio of  $k^{th}$  management unit,  $x_k$  is the actual allocation proportion for  $k^{th}$  management unit,  $d_k$  is the desired allocation proportion for  $k^{th}$  management unit,  $A_k$  is the cultural command area of  $k^{th}$  managementunit (ha), nk is the total number ofmanagementunits, and  $x_k$  is the value of net income, computed for  $k^{th}$  management unit that is calculated as follows:

$$\Delta x_k = NI_m \times A_k \tag{5}$$

where  $A_k$  is the area allocated to irrigation or irrigated of  $k^{th}$  management unit (ha), and  $NI_m$  is the net income per unit area (Rls/ha) expected or generated from  $m^{th}$  method of irrigation scheduling.  $A_k$  was calculated as follows:

$$A_k = \frac{X_k \times V_0 \times E_c \times E_{dk}}{V_m} \tag{6}$$

where  $X_k$  is the fraction of total volume of water allocated to  $k^{th}$  management unit,  $V_0$  is the total volume of water allocated to Doroodzan Irrigation Network from Doroodzan dam reservoir ( $m^3$ ),  $E_c$  is the conveyance efficiency of main channel,  $E_{dk}$  is the distribution efficiency of water related to  $k^{th}$  management unit and  $V_m$  is the volume of water per unit area ( $m^3/ha$ ) expected or generated from  $m^{th}$  method of irrigation scheduling.

### Water Productivity

Another objective function was the performance measure of water productivity that was considered in the form of economic water productivity ratio (EWPR) that is defined as the ratio of the value of actual yield to the cost of irrigation water used (Rodrigues and Pereira, 2009):

$$EWPR = \frac{Value(Y_a)}{Cost(IWU)} \quad (7)$$

where value ( $Y_a$ ) is the value of total actual yield obtained from fields under the irrigation network, in Rls, and cost (IWU) is the cost of irrigation water used allocated to irrigation network from dam reservoir, in Rls. Value ( $Y_a$ ) was calculated as follows:

$$Value(Y_a) = A_k \times Y_{am} \times P \quad (8)$$

where  $A_k$  is the area allocated to irrigation or irrigated of  $k^{th}$  management unit (ha),  $Y_{am}$  is the grain yield per unit area (kg/ha) expected or generated from  $m^{th}$  method of irrigation scheduling and  $P$  is the cost per kilogram of actual yield of maize (Rls  $kg^{-1}$ ).

Use of EWPR provides the possibility of comparing the effects of real and current cost of water and obtaining better decisions in different conditions.

In this study, two scenarios of irrigation water cost are considered; i.e., current cost and real cost of irrigation water (current cost was calculated as 84 Rls  $m^{-3}$  and real cost was calculated as 1150 Rls  $m^{-3}$ ) (Moghimi and Sepaskhah, 2014).

### Constraints

Restrictions include the volume of available water and the area of available land that are defined as follows:

$$0 \leq X_k \leq 1 \quad (9)$$

$$\sum_{k=1}^n X_k = 1 \quad (10)$$

$$\frac{X_k * V_0 * E_c * E_{dk}}{V_m} \leq A_k \quad (11)$$

where  $X_k$  is the fraction of total volume of water allocated to  $k^{th}$  management unit,  $V_0$  is the total volume of water allocated to irrigation network from dam reservoir ( $m^3$ ),  $E_c$  is the conveyance efficiency of main channel,  $E_{dk}$  is the distribution efficiency of water related to  $k^{th}$  management unit and  $V_m$  is the volume of water per unit area ( $m^3/ha$ ) expected or generated from  $m^{th}$  method of irrigation scheduling.

## RESULTS AND DISCUSSION

The cropping water years of 1978, 1986 and 1994 were considered as wet, normal and drought water years, respectively (Moghimi and Sepaskhah, 2014). The volumes of given water allocated to the area used in this research (The entire irrigation network) were  $377.28 \times 10^6$ ,  $293.80 \times 10^6$  and  $194.95 \times 10^6$   $m^3$  for wet,

normal and drought water years, respectively at the entrance of the main channel with no consideration of water loss in transmission channels.

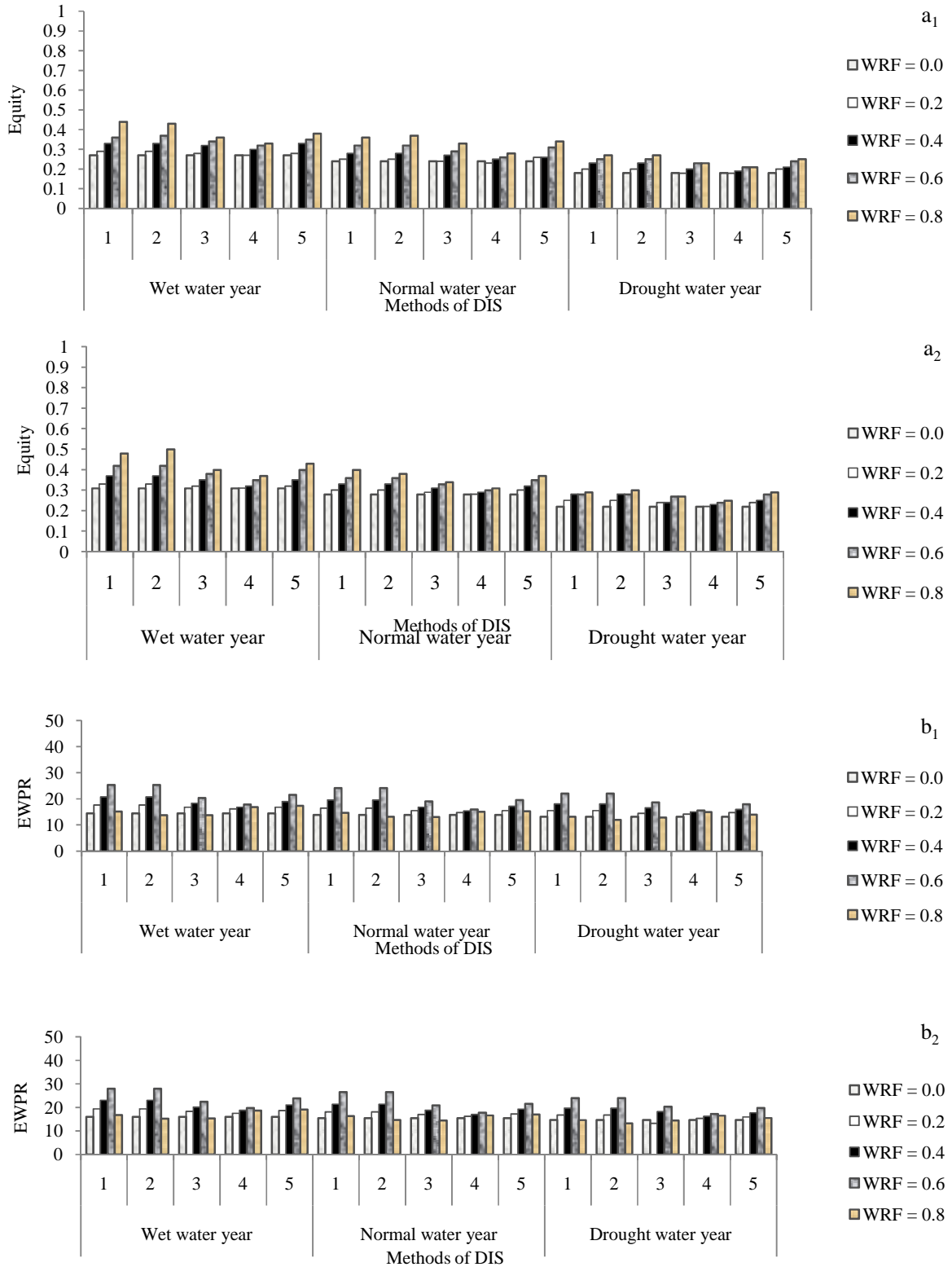
Results of performance measure of water equity [modified inter quartile allocation ratio (E)] and water productivity [economic water productivity ratio (EWPR)] for different conditions calculated by using Eq. (1) and Eq. (7) are given in Fig. 2-4. Results indicated that by increasing  $E_a$  and  $E_c$ , the values of E and EWPR increased and by increasing WRF, the values of E increased and the values of EWPR initially increased and then decreased and by increasing  $E_a$ , the maximum value of EWPR occurred at lower quantities of WRF. Meanwhile, insofar as EWPR rises, E will slightly increase especially at low values of  $E_a$  (surface irrigation). However, the values of E and EWPR decreased from wet water year to drought water year. Furthermore, the increments of E and EWPR due to increasing WRF at most cases were considerably high. This means that by applying deficit irrigation, the establishment of justice in water allocation and higher water productivity at irrigation networks can easily be achieved. Meanwhile, for current and real cost of water in the cases that net income was positive, the mentioned variations were almost the same (cases with negative income are not shown in Figs. 2 to 4).

### Surface Irrigation

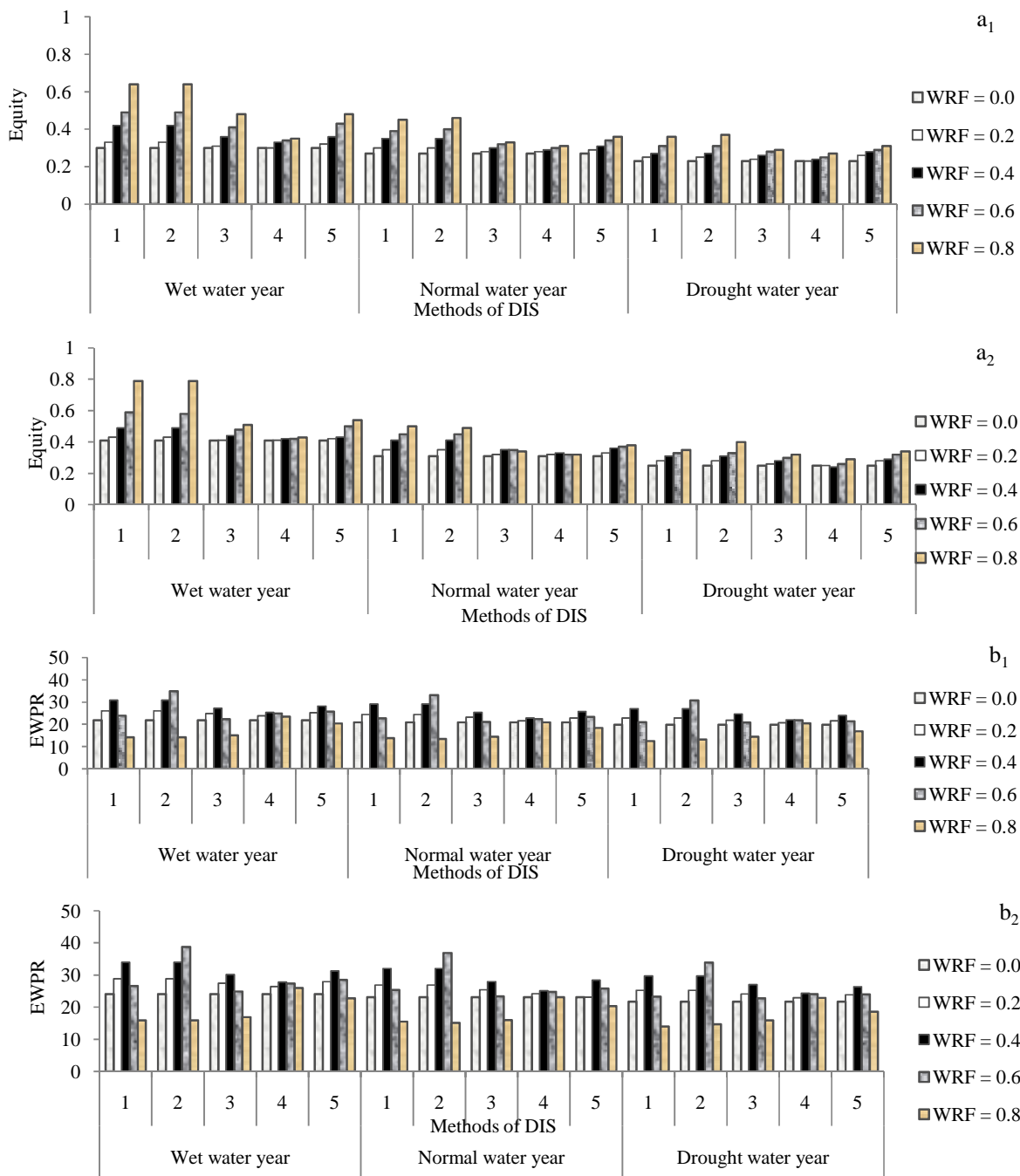
For surface irrigation system with application efficiency of 40% and current cost of water, the values of E for  $E_c=70\%$  were 0.27-0.44, 0.24-0.37 and 0.18-0.27 for wet, normal and drought water years, respectively and the values of EWPR were 13.8-25.4, 13.1-24.2 and 12.0-22.1 for wet, normal and drought water years, respectively. For  $E_c=90\%$ , these values for E were 0.31-0.50, 0.28-0.40 and 0.22-0.30 and for EWPR were 15.2-28.0, 14.4-26.5 and 13.2-24.0, respectively (Fig. 2). By increasing irrigation application efficiency to 60%, the values of E were 0.31-0.67, 0.26-0.48 and 0.23-0.36 and the values of EWPR were 14.3-35.1, 13.5-33.4 and 13.3-30.7 for  $E_c=70\%$  for wet, normal and drought water years, respectively and for  $E_c=90\%$ , these values were 0.40-0.79, 0.34-0.55 and 0.25-0.39 for E and 15.9-38.8, 15.1-36.9 and 14.7-33.6 for EWPR, respectively (To save space, the fig. is not shown).

### Sprinkler Irrigation

For sprinkler irrigation system with application efficiency of 60% and current cost of water, the values of E for  $E_c=70\%$  were 0.30-0.64, 0.27-0.46 and 0.23-0.37 for wet, normal and drought water years, respectively and the values of EWPR were 14.3-35.0, 13.5-33.2 and 12.6-30.8, respectively. For  $E_c=90\%$ , these values for E were 0.41-0.79, 0.31-0.50 and 0.25-0.40 and for EWPR were 15.9-38.8, 15.1-36.9 and 14.0-33.9, respectively (Fig. 3).



**Fig. 2.** Modified inter quartile allocation ratio and economic water productivity ratio of surface irrigation system ( $E_a = 40\%$  and  $E_c = 70\%$ ) ( $a_1$  and  $b_1$ ), ( $E_a = 40\%$  and  $E_c = 90\%$ ) ( $a_2$  and  $b_2$ ) for different water years (wet, normal and drought), water reduction fractions (WRF), methods of deficit irrigation scheduling (DIS) and current cost of water



**Fig. 3.** Modified inter quartile allocation ratio and economic water productivity ratio of sprinkler irrigation system ( $E_a=60\%$  and  $E_c=70\%$ ) ( $a_1$  and  $b_1$ ), ( $E_a=60\%$  and  $E_c=90\%$ ) ( $a_2$  and  $b_2$ ) for different water years (wet, normal and drought), water reduction fractions (WRF), methods of deficit irrigation scheduling (DIS) and current cost of water

By increasing irrigation application efficiency to 80%, these values were 0.37-0.66, 0.33-0.48 and 0.28-0.41 for E and 16.3-38.7, 15.6-36.7 and 15.7-33.9 for EWPR at  $E_c=70\%$  for wet, normal and drought water years, respectively and at  $E_c=90\%$ , these values re 0.47-0.81, 0.40-0.61 and 0.33-0.44 for E and 18.1-43.0, 17.2-40.4 and 17.2-37.5 for EWPR, respectively (To save space, the fig. is not shown).

### Tape Irrigation

For the current cost of water, in some cases, with high values of WRF, the net income was negative because of

low values of grain yield. At other cases, for irrigation system application efficiency of 70%, the values of E for  $E_c=70\%$  were 0.33-0.48, 0.30-0.37 and 0.26-0.31 for wet, normal and drought water years, respectively and

these values for EWPR were 23.2-34.7, 22.1-32.9 and 20.6-30.7, respectively. For  $E_c=90\%$ , these values for E were 0.43-0.52, 0.37-0.42 and 0.30-0.34 and for EWPR, they were 25.8-38.5, 24.4-36.2 and 22.8-33.7, respectively (To save space, the fig. is not shown).

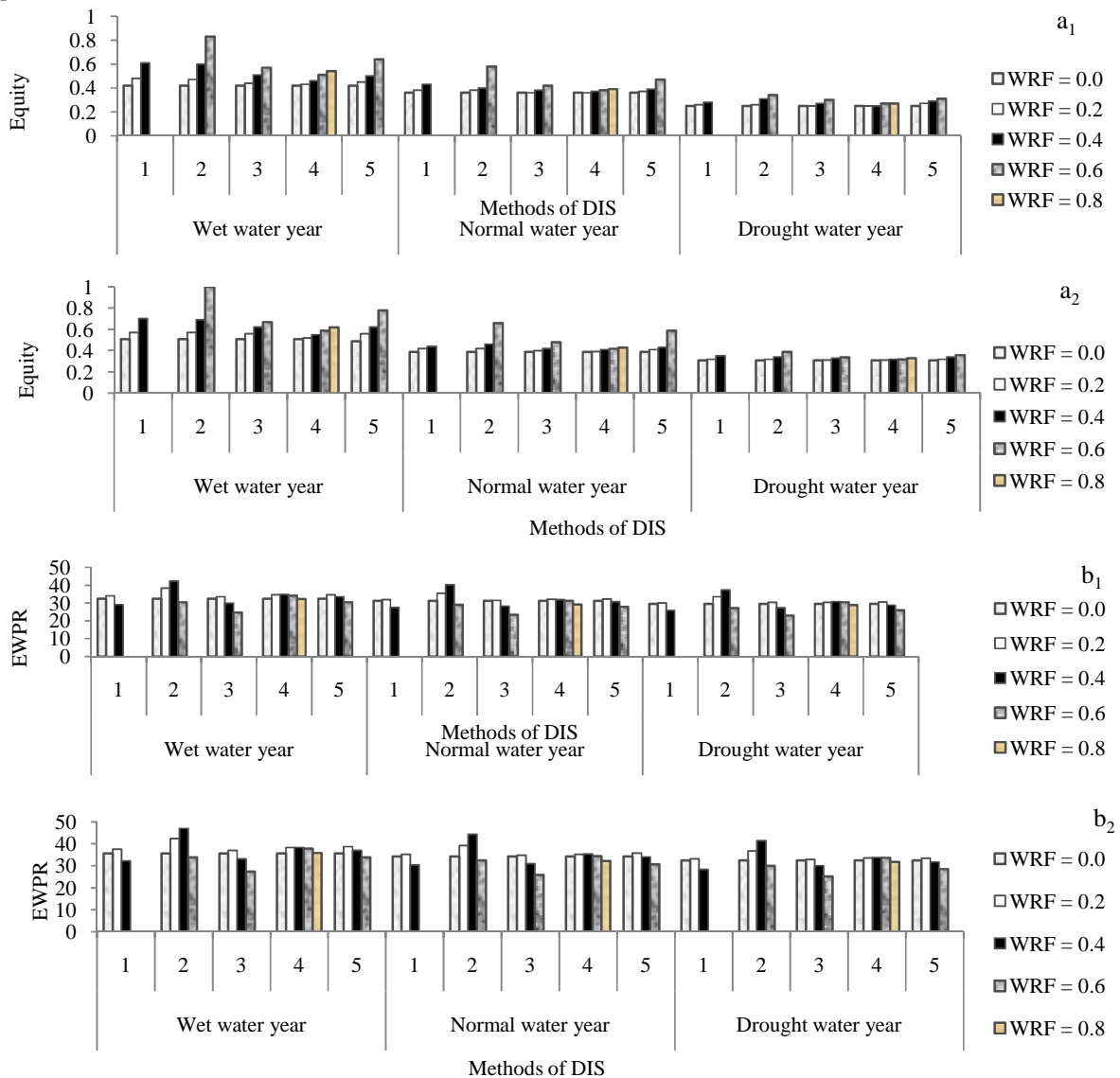
By increasing irrigation application efficiency to 90% at  $E_c=70\%$ , these values for E were 0.42-0.61, 0.36-0.43 and 0.25-0.31 for wet, normal and drought water years, respectively and for EWPR, they were 24.7-42.4, 23.4-40.2 and 23.0-37.4, respectively. For  $E_c=90\%$ , these values for E were 0.51-0.70, 0.39-0.46 and 0.31-0.35 and for EWPR, they were 27.4-47.0, 25.9-44.3 and 25.2-41.3, respectively (Fig. 4).

**Effect of  $E_a$ ,  $E_c$  and WRF on Performance measures**

Increasing  $E_a$ ,  $E_c$  and WRF has the incremental effect on performance measures (Tables 2 and 3) such that, in

general, the incremental effect of WRF was higher. These incremental effects decreased from wet water year to drought water year such that this decrease for EWPR was lower especially at higher values of  $E_a$ ,  $E_c$  and WRF. By increasing  $E_a$  and  $E_c$ , in general, the value of the increment due to increasing WRF, for E increased and for EWPR, it was decreased.

By increasing WRF, the incremental effect of increasing  $E_a$  and  $E_c$  on E and EWPR increased such that this incremental effect on EWPR was lower, so that at tape irrigation system, there was no increase in EWPR. This is because of occurring maximum value of EWPR at lower values of WRF (WRF= 0.4-0.6 for surface and WRF=0.2-0.4 for sprinkler and tape irrigation systems) compared with E (WRF=0.8 for all irrigation systems).



**Fig. 4.** Modified inter quartile allocation ratio and economic water productivity ratio of tape irrigation system ( $E_a = 90\%$  and  $E_c = 70\%$ ) ( $a_1$  and  $b_1$ ), ( $E_a = 90\%$  and  $E_c = 90\%$ ) ( $a_2$  and  $b_2$ ) for different water years (wet, normal and drought), water reduction fractions (WRF), methods of deficit irrigation scheduling (DIS) and current cost of water

**Table 2.** Maximum increase in the values of water equity (E) and EWPR due to increasing WRF

Performance measure	Irrigation system	E <sub>a</sub> (%)	E <sub>c</sub> (%)	Increment of performance measures due to increasing WRF <sup>1</sup> (%)		
				Wet water year	Normal water year	Drought water year
E	Surface	40	70	63.0 <sup>2</sup>	54.2	50.0
		60	90	97.5	61.8	56.0
	Sprinkler	60	70	113.3	70.4	60.9
		80	90	78.7	52.5	33.3
	Tape	70	70	66.7	30.0	26.9
		90	90	96.1	69.2	25.8
EWPR	Surface	40	70	75.2	74.1	67.4
		60	90	61.0	59.7	54.8
	Sprinkler	60	70	59.8	58.1	54.8
		80	90	34.4	32.0	29.3
	Tape	70	70	36.6	36.5	32.9
		90	90	31.7	29.2	27.4

1. From 0.0 to the value of WRF related to maximum performance measures (0.8 for surface irrigation and 0.4-0.8 for sprinkler and tape irrigation systems).
2. These values occurred at DIS method of 1 for surface and sprinkler and 2 for tape irrigation system.

**Table 3.** Maximum increase in the values of water equity (E) and EWPR due to increasing E<sub>a</sub> and E<sub>c</sub>

Performance measure	Irrigation system	WRF	Increment of performance measures due to increasing E <sub>a</sub> <sup>1</sup> and E <sub>c</sub> <sup>2</sup> (%)		
			Wet water year	Normal water year	Drought water year
E	Surface	0.0	48.1	41.7	38.9
		0.8 <sup>3</sup>	83.7	48.6	44.4
	Sprinkler	0.0	56.7	48.1	43.5
		0.8	71.4	69.4	48.3
	Tape	0.0	54.5	30.0	19.2
		0.6	85.2	69.2	21.2
EWPR	Surface	0.0	66.2	66.2	64.4
		0.4-0.6	66.2	66.7	65.5
	Sprinkler	0.0	46.1	45.7	45.7
		0.2-0.4	46.6	48.6	46.8
	Tape	0.0	40.6	42.3	40.7
		0.2-0.4	40.6	42.3	40.7

1. From 40% to 60%, 60% to 80% and 70% to 90% for surface, sprinkler and tape irrigation system, respectively.
2. From 70% to 90%
3. The value of WRF in which maximum performance measure was occurred.

### Considering Real Cost of Water

By considering the real cost of water, for surface irrigation system at E<sub>a</sub>=40% in many cases and at E<sub>a</sub>=60% in some cases with higher values of WRF, the net income was negative because of the high cost of irrigation water.

For sprinkler and tape irrigation systems, the net income in some cases was negative. In cases with positive net income, the values of E were not considerably different from those obtained for the current cost of water; however, the values of EWPR were considerably lower than those obtained for the current cost of water (about 13.7 times).

### Comparison Between Irrigation Systems

Among irrigation systems, in cases with positive net income, tape and surface irrigation systems resulted in higher and lower E and EWPR (Tables 4 and 5).

Application of sprinkler irrigation and tape irrigation systems resulted in minimum and maximum cases with negative net income, respectively (See Fig. 3 and 4). In general, results of this study showed that for achieving the higher values of water equity and productivity, the tape irrigation system is the best choice for low quantities of WRF (0.0-0.4). This is due to the lower volume of applied irrigation water and consequently lower irrigation water cost and higher cultivated area compared with surface and sprinkler irrigation. For high quantities of WRF (0.6-0.8), the sprinkler irrigation system is the best choice. This is due to the lower volume of applied irrigation water compared with surface irrigation and higher grain yield obtained in this system and lower fixed and variable costs and consequently higher gross income compared with tape irrigation.



**Table 4.** Maximum and minimum values of water equity (E) for different irrigation systems

Irrigation system		E	Water year	E <sub>a</sub> (%)	E <sub>c</sub> (%)	WRF	Method of DIS
Surface	Maximum	0.79	Wet	60	90	0.8	2
	Minimum	0.18	Drought	40	70	0.0	-
Sprinkler	Maximum	0.84	Wet	80	90	0.6	1
	Minimum	0.23	Drought	60	70	0.0	-
Tape	Maximum	1.00	Wet	90	90	0.6	2
	Minimum	0.26	Drought	70	70	0.0	-

**Table 5.** Maximum and minimum values of economic water productivity ratio (EWPR) for different irrigation systems

Irrigation system		EWPR	Water year	E <sub>a</sub> (%)	E <sub>c</sub> (%)	WRF	Method of DIS
Surface	Maximum	38.8	Wet	60	90	0.6	2
	Minimum	12.0	Drought	40	70	0.8	2
Sprinkler	Maximum	43.0	Wet	80	90	0.4	2
	Minimum	12.6	Drought	60	70	0.8	1
Tape	Maximum	47	Wet	90	90	0.4	2
	Minimum	20.6	Drought	70	70	0.6	1

### Methods of Deficit Irrigation Scheduling

Water equity as a performance measure of water distribution and water productivity as a performance measure of water consumption are heavily influenced by the method of deficit irrigation scheduling especially in summer crop water year with no precipitation in arid and semiarid regions such as the research area in this study. For all values of WRF, the values of E and for WRF ≤ 0.6, the values of EWPR obtained for DIS methods of 1 and 2 were higher than other DIS methods because in these methods, generally less water is used and higher volume of water is received at downstream management units (Tables 4 and 5). Furthermore, the cultivated area of each management unit increased and higher grain yield was obtained. For WRF = 0.8, the values of EWPR obtained for DIS method of 4 (full irrigation at vegetative and flowering stages) at all cases with the exception of E<sub>a</sub> = 40%, related to wet and normal years, was higher than other DIS methods because of the higher volume of irrigation water applied in this method.

In general, the maximum values of E and EWPR occurred at DIS method of 2 [reduction in the number of full irrigation events] because in this method, generally less water was used and higher volume of water was received at downstream management units and higher grain yield was obtained per consumption of unit volume of water. Meanwhile, by increasing E<sub>a</sub>, the maximum values of E and EWPR increased. The minimum values of E occurred at DIS method of 4 because in this method, the depth of irrigation water was higher than that of other methods. The minimum values of EWPR at low quantities of WRF (≤ 0.4) and low values of E<sub>a</sub> (≤ 60%) occurred at DIS method of 4 and for high values of E<sub>a</sub>, occurred at DIS method of 3. For high quantities of WRF (WRF ≥ 0.6), the minimum values of EWPR occurred at DIS method of 3 and at most cases, the values of EWPR related to DIS method of 4 were maximum. The fluctuation of the values of EWPR in DIS method of 4 was minimum and in DIS methods of 1 and 2, it was maximum because of higher

and lower depth of irrigation water applied in these methods, respectively. Among DIS methods of 3 and 5 (full irrigation at vegetative and flowering stages, respectively), in general the values of E and EWPR obtained in method 5 were higher because of higher sensitivity of the flowering stage to water deficit compared with the vegetative stage.

### Relationship between Water Equity and Productivity

Increasing irrigation system application efficiency, conveyance efficiency of the main channel and water reduction fraction resulted in a simultaneous increase in performance measures [modified inter quartile allocation ratio (water equity) and economic water productivity ratio (EWPR)]. When water equity and water productivity were considered together for a specific method of irrigation scheduling with specified irrigation application efficiency (for example for normal water year, tape irrigation system, E<sub>a</sub> = 90%, E<sub>c</sub> = 90%, DIS method of 3 and WRF = 0.4), by increasing E, EWPR decreased. Meanwhile, these variations increased from wet water year to drought water year. This is because of a decrease in the volume of water allocated to the irrigation network (V<sub>0</sub>) and an increase in net irrigation requirement. However, the increment in E was considerable and decrement in EWPR was very low and by increasing E<sub>a</sub> and WRF, it became much lower. By increasing E, the fractions of total volume of water allocated to management units (X<sub>k</sub>) were close to the fractions assigned by the cultivated area and by decreasing E, these fractions for management units at the upstream of irrigation network became higher and for management units at the downstream of the irrigation network, they became lower.

### Effects of Enlargement of the Study Area

Results of this study showed that by enlarging the study area from single channel level (Moghimi and Sepaskhah, 2016) to the network level, the values of

water equity and productivity decreased. However, decrement of water productivity was very low. This decrement was lower for wet water year compared to drought water year and it decreased by increasing WRF,  $E_c$  and  $E_a$  with higher effect of increasing WRF. Decrement in E values was because of higher water losses due to enlarging the study area and more water deficit at fields located at downstream of the network. Decrement in EWPR values was because of lower applied volume of water at farm level due to the increase in water loss in the study area at the network level and thus decrement of grain yield. Meanwhile, decrement of water equity due to enlarging the study area in DIS methods with lower volume of applied water (DIS methods of 1 and 2) was lower and in DIS methods with higher volume of applied water (DIS method of 4), it was higher. Maximum decrement in E (55.4%) was obtained in tape irrigation, drought water year, WRF=0.4, DIS method of 4,  $E_a=90\%$  and  $E_c=70\%$ . Minimum decrement (10.7%) was obtained in surface irrigation, wet water year, WRF=0.8, DIS method of 4,  $E_a=60\%$  and  $E_c=70\%$ .

## CONCLUSIONS

Results indicated that the influence of increasing irrigation application efficiency on water equity (E) and economic water productivity ratio (EWPR) is higher than conveyance efficiency. By increasing water reduction fraction (i.e., more deficit irrigation), water equity (E) increased and economic water productivity ratio (EWPR) initially increased and then decreased. The values obtained for these two performance measures reduced from wet water year to drought water year. Also, the values of increments in performance measures due to increasing water reduction fraction decreased from wet water year to drought water year. The increments of E due to increasing  $E_a$  and  $E_c$  increased from wet water year to drought water year for lower values of  $E_a$  (surface irrigation) and decreased for higher values of  $E_a$  (sprinkler and tape irrigation). In

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general, the maximum values of E occurred at DIS method of 2 (reduction in the number of full irrigation events) and the maximum values of EWPR at WRF lower than or equal to 0.6 occurred at DIS method of 2 at  $E_a < 80\%$  and for  $E_a \geq 80$ , it occurred at DIS method of 4. At WRF=0.8, the maximum values of EWPR occurred at DIS method of 4 (full irrigation at vegetative and flowering stages).

Combined consideration of variation in E and EWPR in a specific case indicated that by increasing E, EWPR decreased. These variations become higher in the wet water year compared to the drought water year. The increment in E was considerable; however, the decrement in EWPR was low and by increasing  $E_a$  and WRF, it became lower. By considering the real cost of water at higher values of  $E_a$ , fewer cases led to negative income for surface, sprinkler and tape irrigation systems. In the cases with positive net income, the values of E were not considerably different from those considering the current cost of water. However, the values of EWPR were considerably higher (about 13.7 times). On-farm water management has a significant impact on the improvement of performance measures including water equity and productivity in irrigation networks. This impact is more important than distribution channel design and lining that resulted in higher conveyance and distribution efficiencies especially in summer crop and drought conditions.

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## بررسی معیارهای کارایی تحت سناریوهای مختلف برنامه‌بندی آبیاری در شبکه آبیاری سد درودزن

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#### واژه‌های کلیدی:

مدیریت آب در مزرعه

بهینه‌سازی

الگوریتم ژنتیک

عدالت در توزیع آب

بهره‌وری آب

**چکیده-** در این تحقیق بهینه‌سازی همزمان معیارهای کارایی (عدالت و بهره‌وری) برای انتخاب روشهای بهینه مدیریت آب در مزرعه، با استفاده از الگوریتم ژنتیک در شبکه آبیاری سد درودزن مورد بررسی قرار گرفته است. نتایج این تحقیق نشان داد که تأثیر بهبود مدیریت آب آبیاری در مقیاس مزرعه (افزایش راندمان کاربرد آبیاری و کسر کاهش آب) روی افزایش معیارهای کارایی نسبت به اثر بهبود راندمان انتقال آب در کانال‌ها روی این معیارها بسیار بیشتر است. افزایش راندمان کاربرد آب در مزرعه (از ۳۰ درصد به ۹۰ درصد) و راندمان انتقال در کانال‌ها (از ۷۰ درصد به ۹۰ درصد) منتهی به اثر افزایشی حداکثر و حداقل روی عدالت در توزیع آب (به طور میانگین به ترتیب ۴۸/۲ درصد و ۱۷/۷ درصد) و بهره‌وری (به طور میانگین به ترتیب ۹۲ درصد و ۱۰ درصد) می‌شود. اثر افزایشی کسر کاهش آب (۰/۰ تا ۰/۸) روی عدالت و بهره‌وری به طور میانگین به ترتیب برابر با ۳۱/۴ درصد و ۱۰ درصد است. مقادیر معیارهای کارایی از سال آبی مرطوب به سال آبی خشک نیز کاهش یافت. برای دستیابی به عدالت و بهره‌وری بالاتر، سیستم آبیاری قطره‌ای در مقادیر کم کسره‌های کاهش آب (کمتر از و یا مساوی ۰/۴) و سیستم آبیاری بارانی برای مقادیر بیشتر کسره‌های کاهش آب (بزرگتر از و یا مساوی ۰/۶) بهترین سیستم تشخیص داده شدند. ضمناً وقتی که معیارهای کارایی عدالت و بهره‌وری بطور همزمان بررسی می‌شود، برای یک روش خاص برنامه‌بندی کم‌آبیاری و تحت یک مقدار مشخص آب آبیاری، با افزایش عدالت، کاهش در بهره‌وری آب قابل صرف‌نظر کردن است.