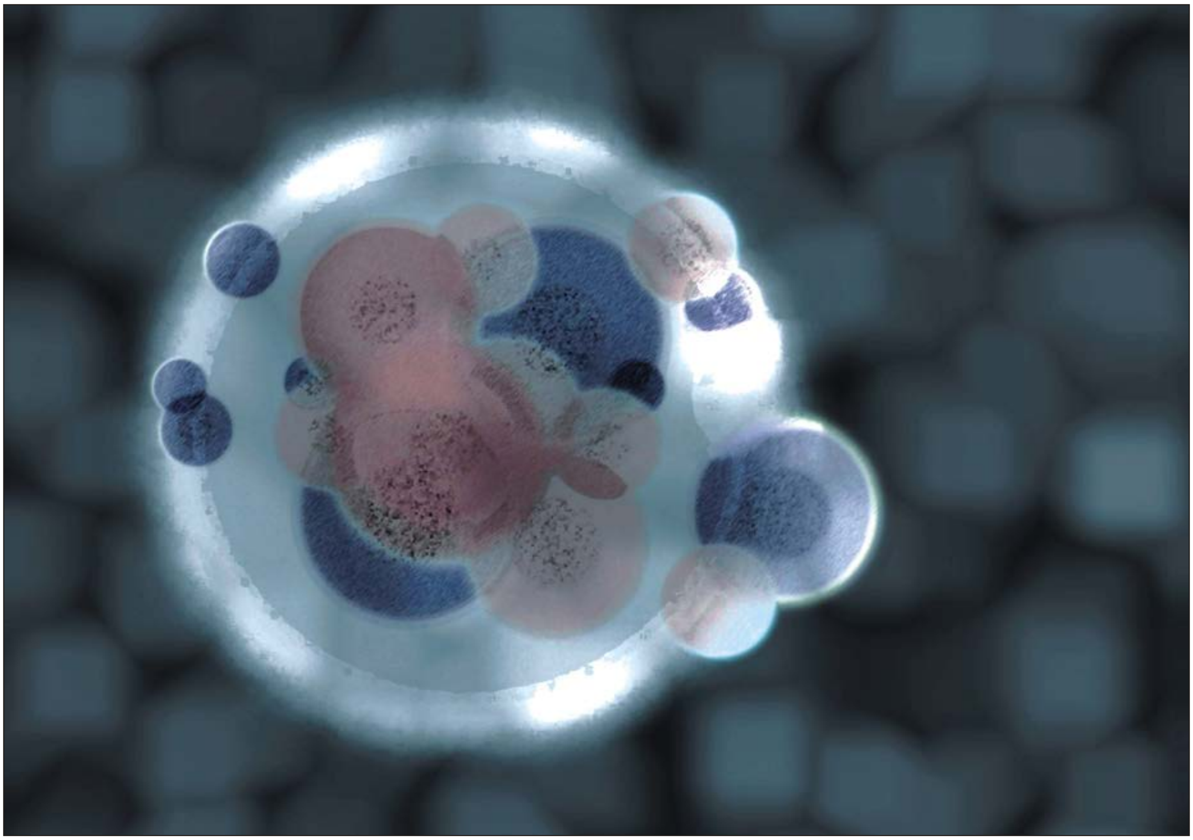

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Water Use Efficiency of Winter Wheat Under Deficit Irrigation

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Abstract: The relationships between crop yield and water applied such as water use efficiency and water production function are necessary for application in planning, design and management of irrigation schemes. This study was conducted to determine Water Use Efficiency (WUE) of wheat obtained from irrigation cutting off after stem elongation (IC1), flowering (IC2), dough (IC3) stages and full irrigation (IC4) with treatments of 1.00 (I1), 0.75 (I2) and 0.50 (I3) for ratio of water amount (IW) to Cumulative Pan Evaporation (CPE) for two winter varieties. Results revealed that with increasing irrigation events from two to five, the WUE decreased. Generally, average WUE varied from 0.581 to 1.894 kg m^{-3}. The WUE of two wheat varieties were nearly identical. Applying IC4 to IC1 as well as I1 to I3 treatments caused an increasing pattern in the WUE. The WUE from IC1, IC2 and IC3 were increased about 58.3, 56.9 and 31.2% relative to that of IC4 with average of 0.923 kg m^{-3}, respectively. The WUE from I2 and I3 were increased about 20.6 and 43.6% comparative to that of I1 with average of 1.04 kg m^{-3}, respectively. Using grain yield and other independent variables measured during two cropping years, several water production functions were worked out so that more than 93% of the variability in the achieved grain yield can be explained by water applied, levels of irrigation cutting off during wheat growth stage and wheat varieties. The comparison of grain yield from developed model with measured values revealed a satisfactory agreement between them.

Key words: Water use efficiency, water production function, deficit irrigation

INTRODUCTION

Winter wheat (*Triticum aestivum* L.) is the principal food grain produced in Iran being grown on some 5.5 million hectars (www.fao.org). Winter wheat is planted in December and harvested for grain in June of the next year in Moghan plain located at north-west part of Iran (39° 39' N, 47° 55' E). The winter and spring-occurred rainfall is insufficient to provide wheat water requirement in Moghan climate conditions. Consequently, irrigation is required for obtaining the potential grain yield. A measure called water use efficiency is applied to compare the efficiency of water use and identifying factors that limit the efficiency of use of soil water content or rainfall, (Robinson and Freebarin, 2005). Water use efficiency is defined as the yield obtained per unit of water consumed as evapotranspiration (ET) by the crop under consideration (Doorenbos and Pruitt, 1977). Water amount and proper time of an irrigation corresponding to the Optimum Water Use Efficiency (OWUE) is significant in the semiarid regions because stored water resulting from utilizing OWUE can be applied to increase cultivated areas or irrigating other crops.

Doorenbos and Kassam (1979) reported that the water use efficiency for harvested yield for grain is about 0.8 to 1.00 kg m^{-3}. Also, some studies have resulted that the range of the WUE for wheat is from 0.8 to 1.00 kg m^{-3} (Musick *et al*., 1984; Shawcroft, 1983), from 1.00 to 1.20 kg m^{-3} (Aggarwal *et al*., 1986; Bunyolo *et al*., 1985; Cooper, 1980; Lal, 1985), from 1.20 to 1.60 kg m^{-3} (Ehling and Le Mert, 1976; Fischer, 1970) and from 1.50 to 1.90 kg m^{-3} (Rao and Bhardwaj, 1981). English and Nakamura (1989) found that the highest water use efficiencies of wheat were 1.77 and achieved with irrigation intervals of four weeks. Under deficit irrigation WUE are higher, on applying irrigation at critical growth stages (Rao and Bhardwaj, 1981; Lal, 1985). Zhang *et al*. (1998) concluded that the WUE for total water consumption of one-irrigation was increased by 24-30% from four-irrigation. They reported the WUE ranged from

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0.93 to 1.55 g mm^{-1} m^{-2}. The average WUE of dryland wheat is about one-half the WUE of irrigated wheat (Musick *et al*., 1984). Nasseri (1999) applied agro-ecological zone method to calculate potential yield and estimated the WUE of wheat to be from 0.54 to 1.22 kg m^{-3} in Moghan plain.

The water production function represents relationship between crop yield and water applied. Crop water production functions are necessary in defining the marginal crop production required in the computation of the maximum profit for management and economic analyses (Hoffman *et al*. 1992). In this case, de Wit (1958) related crop yield and transpiration (TR) for dry, high-radiation climates conditions. Hanks (1974) included a maximum yield corresponding to maximum TR to the de Wit's Model. Hexem and Heady (1978) reported that water production function can be expressed as a second or third order polynomial. Doorenbos and Kassam (1979) suggested relating percent yield reduction to percent ET deficit as a production function. Al-Jamal *et al*. (2000) described onion yield as a linear and second order polynomial functions of evapotranspiration. The objectives of the present study were to determine water use efficiencies of wheat on applying irrigation cutting off during growth stages with different water amounts for two winter varieties and to develop the crop water production functions for winter wheat.

MATERIALS AND METHODS

The field experiments were conducted during 1998-99 and 1999-2000 at the Agricultural Research Center of Moghan, Iran (latitude 39° 39' N, longitude 47° 55' E and 31.9 m above mean sea level). The average maximum and minimum temperature during the growing seasons were 17° C (9.8° to 30.3° C) and 6.1° C (0° to 16°C) in 1998-99 and 16.6°C (8.9 to 31°C) and 5.4°C (-0.8 to 16°C) in 1999-2000, respectively. The field soil was loamy-clay with average Wilting Point (WP), Field Capacity (FC) and acidity (pH) of 16, 25.4% and 7.9 in 1998-99, respectively. In the next year soil was clay-loam with average WP, FC and pH of 22.36, 31.51% and 7.2 in 1999-2000, respectively. During the crop growing season of 1998-99, cumulative pan evaporation and rainfall were 496 and 128 mm, respectively. During of 1999-2000

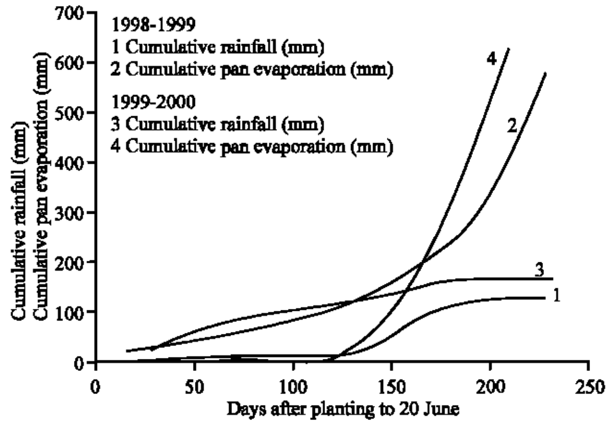

Fig. 1: Cumulative rainfall and pan evaporation during two cropping years

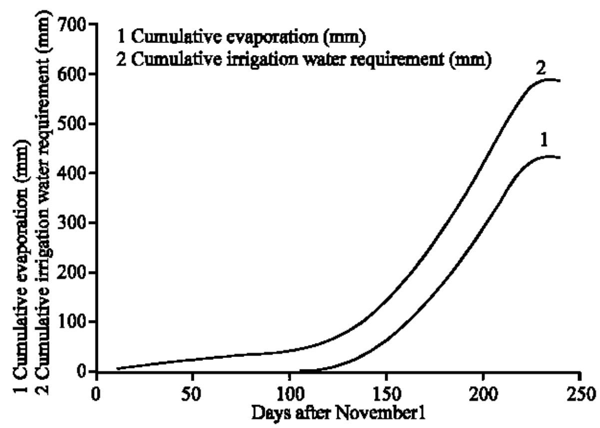

Fig. 2: Estimated evapotranspiration and irrigation water requirement of wheat for Moghan climate conditions (Farshi *et al*., 1997)

Table 1: Plot designation and treatment combinations

Treatments	Plot designation
	Main plots (IC)
Irrigation cutting off after stem elongation stage (with two irrigation)	IC1
Irrigation cutting off after flowering stage (with three irrigation)	IC2
Irrigation cutting off after dough stage (with four irrigation)	IC3
Full irrigation (without cutting off and with five irrigation)	IC4
	Sub-plots (I)
IW:CPE* of 1.00	I1
IW:CPE of 0.75	I2
IW:CPE of 0.50	I3
	Sub-sub plots (V)
Tajan	V1
Shiroudi	V2

*IW:CPE is ratio of irrigation water to cumulative pan evaporation these were 640 and 165 mm, respectively (Fig. 1). Evapotranspiration (ET) and Irrigation Water Requirement (IWR) of wheat for Moghan climate conditions that estimated by Farshi *et al.* (1997) were presented in Fig. 2. Total ET and IWR during wheat growing season are 5935 and 4311 m^3 ha^{-1}, respectively. Winter wheat was sown on 5 Dec. 1998 and 23 Dec. 1999 on six rows 8 m long and 20 cm apart (8×1.2 m^2 plots) at seeding rate of 160 kg ha^{-1}. To prevent any possible water stress during the vegetative stage of wheat growth, sown site were irrigated with 100 and 74 mm of water after seeding for the consecutive two years, respectively. Twenty four treatments were laid out in completely randomized blocks with a split-split plots design with three replications. Treatment combinations comprised 4 levels of irrigation-cutting off during wheat growth stages, 3 levels of irrigation water amount and 2 varieties of wheat. Treatment combinations were enumerated in Table 1 in details. Water requirement for each irrigation was calculated based on pan evaporation. The calculated amount of water was applied to the plots by means of siphons from the ditchs. The water measurement at the entrance of each ditch was made by a flow-meter. All plots were blocked-end. N in the form of urea was applied to the soil prior to 2nd and 3rd irrigation events up to 100 and 200 kg ha^{-1}, respectively. The crop was managed well with respect to weed and disease control. After maturity, plots in 6×1.2 m^2 on 20 June 1999 and in 5.5×0.8 m^2 on 24 June 2000 were harvested for grain. In the present study, the calculation of the WUE was modified by taking in to account the total amount of water applied and calculated as grain yield per total water applied, in which WUE, grain yield and total water applied are in kg m^{-3}, kg ha^{-1} and m^3 ha^{-1}, respectively.

RESULTS AND DISCUSSION

Water use efficiency of wheat from irrigation cutting off during growth stages: Table 2 shows that interactive influence of cropping year and irrigation cutting off during wheat growth stages on water use efficiency were statistically significant ($p\leq0.010$). The affected WUE averaged as 1.262 kg m^{-3}. It ranged from 0.757 to 1.738 kg m^{-3} achieved from full irrigation in 1999-2000 and irrigation cutting off after flowering stage in 1998-99 (Fig. 3). Results for full irrigation is accordance with those reported by Doorenbos and Kassam (1979), Musick *et al.* (1984) and Shawcroft (1983). The WUE of 1.738 kg m^{-3} is accordance with those English and Nakamura (1989). Results show that the WUE in the first year (average = 1.473 kg m^{-3}) was more than that in the second year (average = 1.05 kg m^{-3}). Because proportionate to the cumulative pan evaporation (CPE were 496 and 640 mm during 1998-99 and 1999-2000) water applied in the second year was more than first year. Also, Figure 3 shows that with increasing irrigation events from two to five, the WUE decreased. The replications-average of affected WUE by irrigation cutting off after stem elongation averaged 1.462 kg m^{-3} and ranged from 0.966 to 1.795 kg m^{-3}. Both of them obtained from plots cultivated with Shiroudi variety in 1999-2000 (Fig. 3 and 4a). Qualifying cumulative distribution of the WUE in relation to irrigation cutting off after stem elongation (Fig. 5a) show that 25, 50 and 75% of distributions were 1.342, 1.467 and 1.589 kg m^{-3}, respectively.

The WUE of irrigation cutting off after flowering stage averaged 1.452 kg m^{-3} with range going from 0.731 to 1.894 kg m^{-3}. These ranges obtained from Tajan and Shiroudi in 1999-2000 and 1998-99, respectively (Fig. 3 and

Table 2: Mean squares and significance levels from the analysis of variance on WUE of winter wheat under irrigation cutting off during crop growth stages, water amounts and varieties treatments during two cropping years

Two years	1999-2000	1998-1999	
0.163	0.087	0.582*	Replication
6.430	-	-	Cropping years
2.317**	1.321**	1.347**	Irrigation cutting off
0.359**	-	-	Interaction of cropping years and irrigation cutting off
2.465**	2.089**	0.607**	IW:CPE
0.228**	-	-	Interaction of cropping years and IW:CPE
0.036 ns	0.057 ns	0.089 ns	Interaction of irrigation cutting off and IW:CPE
0.111*	-	-	Interaction of cropping years and Irrigation cutting off and IW:CPE
0.067 ns	0.066 *	0.015ns	Wheat varieties
0.008ns	-	-	Interaction of cropping years and varieties
0.072ns	0.022 ns	0.144 ns	Interaction of irrigation cutting off and varieties
0.091ns	-	-	Interaction of cropping years and irrigation cutting off and varieties
0.034ns	0.004 ns	0.047ns	Interactions of IW:CPE and varieties
0.016ns	-	-	Interaction of cropping years and IW:CPE and varieties
0.026 ns	0.025 ns	0.035 ns	Interaction of Irrigation cutting off and IW:CPE and varieties
0.033 ns	-	-	Interaction of cropping years and Irrigation cutting off and IW:CPE and varieties

**, *, ns Significantly different at 1 and 5% and insignificantly different at 10% level of probability, respectively

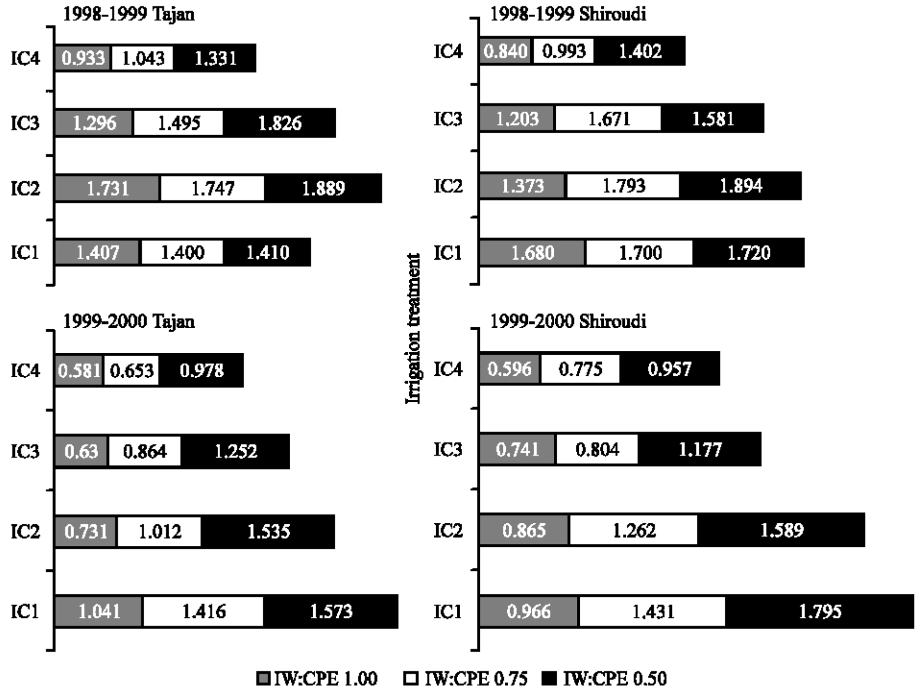

Fig. 3: Replications-average water use efficiency for two wheat varieties achieved with applying irrigation cutting off and water amounts treatments in the two cropping years of 1998-1999 and 1999-2000

4a). The highest value is accordance with those found by Rao and Bhardwaj (1981). Cumulative distribution of the WUE in relation to IC2 (Fig. 5a) show that 25, 50 and 75% of distribution were 1.012, 1.392 and 1.795 kg m^{-3}, respectively. The WUE subjected to irrigation cutting off after dough stage with average of 1.212 kg m^{-3} ranged from 0.630 to 1.826 kg m^{-3}. Both of them achieved from Tajan cultivated in 1999-2000 and 1998-99. Distribution of the WUE from IC3 (Fig. 5a) demonstrate that 25, 50 and 75% of cumulative distribution were 0.85, 1.164 and 1.529 kg m^{-3}, respectively. As seen in Fig. 3 and 4a, the WUE corresponding to applying full irrigation with average of 0.923 kg m^{-3} ranged from 0.581 to 1.402 kg m^{-3}. These ranges acquired in 1999-2000 and 1998-99 for Tajan and Shiroudi. The average value is accordance with results that found by Doorenbos and Kassam (1979), Musick *et al*. (1984) and Shawcroft (1983). Figure 5a show that 25, 50 and 75% of cumulative distribution of the WUE from full irrigation were 0.695, 0.912 and 1.045 kg m^{-3}, respectively.

According to averages and minimums of the WUE subjected to the irrigation cutting off during wheat growth stages can be shown with increasing irrigation events from two (IC1 with average of 1.462 and minimum of 0.966 kg m^{-3}) to five (IC4 with average of 0.923 and minimum of 0.581 kg m^{-3}), the WUE decreased. The WUE averages obtained from IC1 and IC2 were nearly identical. The highest and least WUE acquired from applying IC2 for Shiroudi and IC4 for Tajan. Accordingly, it is found that irrigating before and at the flowering stage play an effective role on grian yield and irrigating can be discontinued after dough stage to increase water use efficiency of wheat. Irrigation cutting off after growth stages of stem elongation, flowering, dough and full irrigation caused a decreasing pattern in water use efficiency so that the WUE acquired from IC1, IC2 and IC3 were increased as 58.3, 56.9 and 31.2% relative to that of IC4 (Fig. 6a) with average of 0.923 kg m^{-3}, respectively. The WUE from IC1 and IC2 were both increased about 20% of that from IC3. This finding is approximately accordance with those found by Zhang *et al*. (1998) reporting that water use efficiency of one-irrigation was increased by 24-30% from four-irrigation.

Water use efficiency of wheat from applying different water amount: As seen in Table 2 interactive influence of cropping year and irrigation water amount on the WUE were significant ($p \leq 0.010$). Figure 3 and 4b show that the WUE with average of 1.262 kg m^{-3} ranged from 0.769 to 1.629 kg m^{-3}.These ranges obtained from applying IW:CPE of 1.00 and 0.50 treatments in 1999-2000 and 1998-99, respectively. The average value is equal with those found by Nasseri (1999) for Moghan plain as maximum WUE. Evidently, The WUE of wheat in the first

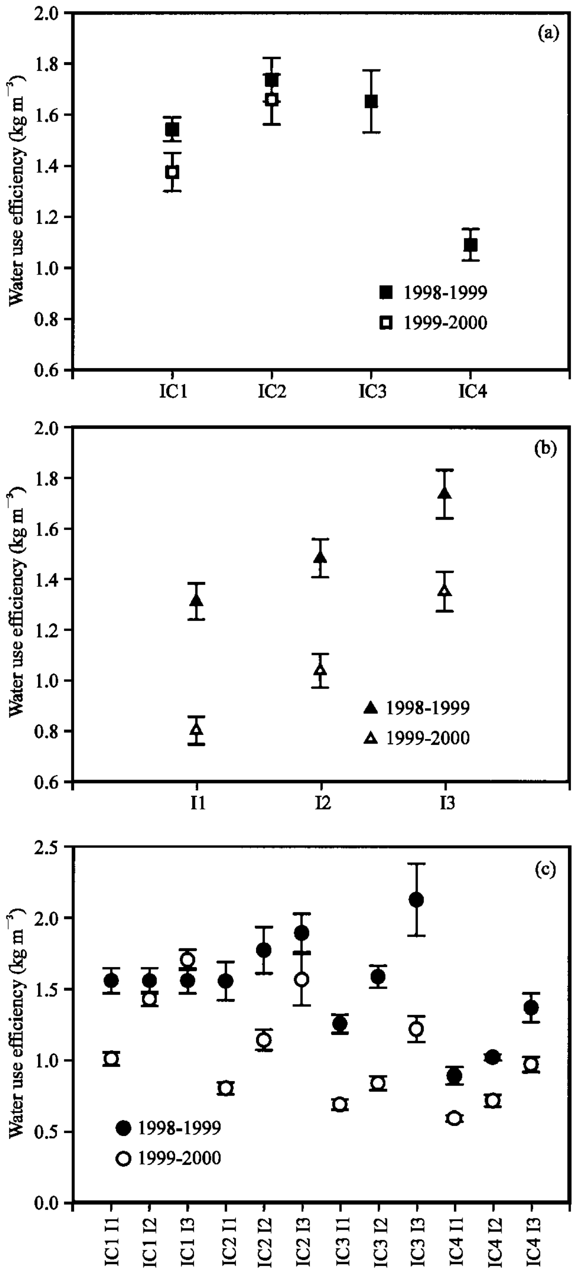

Fig. 4: WUE averages with ± standard errors acquired from (a) irrigation cutting off, (b) water amounts treatments and (c) them interactions for years of 1998-99 and 1999-2000

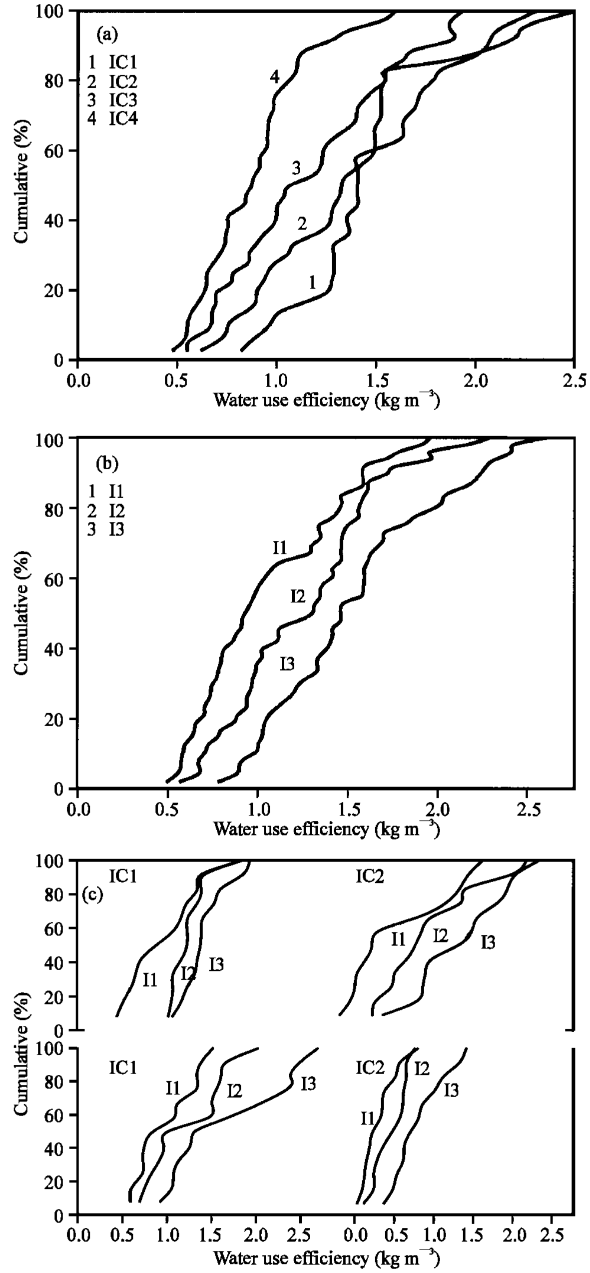

Fig. 5: Cumulative distribution of water use efficiency of wheat from (a) irrigation cutting off treatments (b) water amounts and (c) them interactions

year with average of 1.473 kg m^{-3} was more than that in the second year with average of 1.051 kg m^{-3} because water applied in the second year was more than that in the first year proportionate to the cumulative pan evaporation. Also, with decreasing ratio of irrigation water to cumulative pan evaporation, the WUE increased because the WUE subjected to IW:CPE of 0.75 and 0.50 were 1.33 and 2 times that acquired from IW:CPE of 1.00 treatment.

The replications-average of the WUE resulting from IW:CPE of 1.00 averaged 1.040 kg m^{-3} with range going from 0.581 to 1.731 kg m^{-3}. These ranges obtained from full irrigation in the second cropping year and applying

IC2 in the first cropping year for Tajan (Fig. 3). The highest value is approximately accordance with those reported by English and Nakamura (1989). Cumulative distribution of the WUE in relation to IW:CPE of 1.00 (Fig. 5b) show that 25, 50 and 75% of distribution were 0.732, 0.944 and 1.379 kg m^{-3}, respectively. The produced WUE by IW:CPE of 0.75 averaged 1.254 kg m^{-3} with range from 0.653 to 1.793 kg m^{-3}. These obtained from full irrigating Tajan in 1999-2000 and applying IC2 for shiroudi in 1998-99 (Fig. 3). Distribution of the WUE from IW:CPE of 0.75 (Fig. 5b) show that 25, 50 and 75% of cumulative distribution were 0.945, 1.309 and 1.529 kg m^{-3}, respectively. The WUE corresponding to IW:CPE of 0.50 averaged 1.493 kg m^{-3} and ranged from 0.957 to 1.894 kg m^{-3}. Both of ranges acquired from Shiroudi cultivated under full irrigation in the second cropping year and irrigation cutting off after flowering stage in the first cropping year (Fig. 3). The average and highest value are accordance with those reported by Rao and Bhardwaj (1981). Also, Figure 5b show that 25, 50 and 75% of cumulative distribution of acquired the WUE from IW:CPE of 0.50 were 1.175, 1.465 and 1.837 kg m^{-3}, respectively.

Applying IW:CPE of 0.50, 0.75 and 1.00 caused a decreasing pattern in water use efficiency so that the WUE acquired from IW:CPE of 0.750 and 0.50 were increased about 20.6 and 43.6% comparative to that of I1 (Fig. 6b) with average of 1.04 kg m^{-3}. The highest and least WUE acquired from applying IW:CPE of 0.50 for irrigating Shiroudi with applying IC2 treatment and IW:CPE of 1.00 for irrigating Tajan with applying IC4 treatment.

As shown in Table 2, interactive influence of cropping year, irrigation cutting off during wheat growth stages and irrigation water amount on the WUE were significant ($p \leq 0.050$). The average of the WUE ranged were from 0.588 to 1.891 kg m^{-3}. The WUE ranges achieved from full irrigating by IW:CPE of 1.00 in 1999-2000 and irrigation cutting off flowering stage in 1998-99 by IW:CPE of 0.50 (Fig. 4c). The average WUE of 0.588 kg m^{-3} is less than all reported values and is accordance with minimum values that reported by Nasseri (1999). The WUE increased by applying IC1 to IC4 and decreasing ratio of IW to CPE in two cropping years.

Cumulative distribution of the WUE in relation to interactions of irrigation cutting off after stem elongation and water amounts treatments (Fig. 5c) show that 25, 50 and 75% of distribution were as 0.966, 1.267 and 1.510 kg m^{-3} for IW:CPE of 1.00 and as 1.343, 1.467 and 1.572 kg m^{-3} for IW:CPE of 0.75 and as 1.499, 1.586 and 1.733 kg m^{-3} for IW:CPE of 0.50, respectively. Distribution of the WUE from interactions of irrigation cutting off after

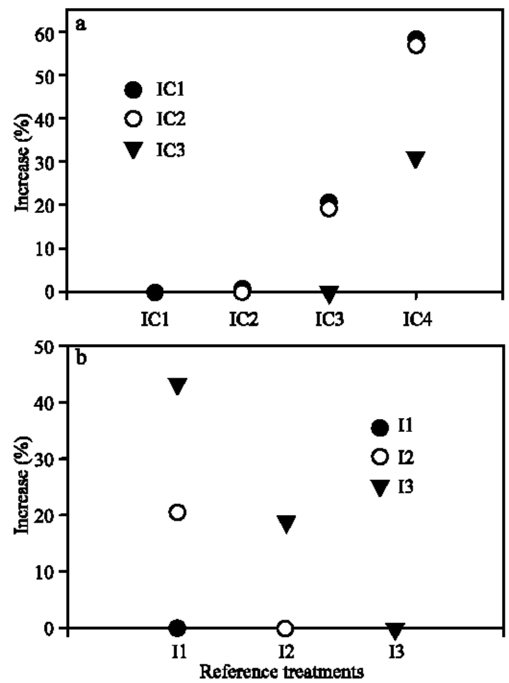

Fig. 6: WUE increase relative to (a) irrigation cutting off stages and water amounts as reference treatments

flowering stage and water amounts (Fig. 5c) explain that 25, 50 and 75% of cumulative distribution were as 0.792, 0.963 and 1.644 kg m^{-3} for IW:CPE of 1.00 and as 1.117, 1.342 and 1.738 kg m^{-3} for IW:CPE of 0.75 and as 1.392, 1.752 and 2.078 kg m^{-3}, respectively. Figure 5c demonstrate that 25, 50 and 75% of cumulative distribution of acquired the WUE from interaction of irrigation cutting off after dough stage and water amounts were as 0.704, 0.931 and 1.288 kg m^{-3} for IW:CPE of 1.00 and as 0.846, 1.194 and 1.529 kg m^{-3} for IW:CPE of 0.75 and as 1.073, 1.447 and 2.295 for IW:CPE of 0.50, respectively. Distribution of the WUE achieved from interactions of full irrigation and water amounts (Fig. 5c) show that 25, 50 and 75% of cumulative distribution were as 0.589, 0.703 and 0.852 kg m^{-3} for IW: CPE of 1.00 and as 0.695, 0.910 and 1.011 kg m^{-3} for IW: CPE of 0.75 and as 0.956, 1.109 and 1.373 kg m^{-3} for IW:CPE of 0.50, respectively. Figure 3 shows that the replications –average of the WUE for Tajan averaged 1.240 kg m^{-3} and ranged from 0.581 to 1.889 kg m^{-3} obtained by full irrigation with IW:CPE of 1.00 in the second cropping year and irrigation cutting off after flowering stage with IW:CPE of 0.50 in the first year, respectively. Figure 3 shows that the WUE of Shiroudi averaged 1.284 kg m^{-3} and ranged from 0.596 to 1.894 kg m^{-3} achieved by full irrigation with IW:CPE of 1.00 in the second year and applying IC2 with IW:CPE of 0.50 in the first year. So, the

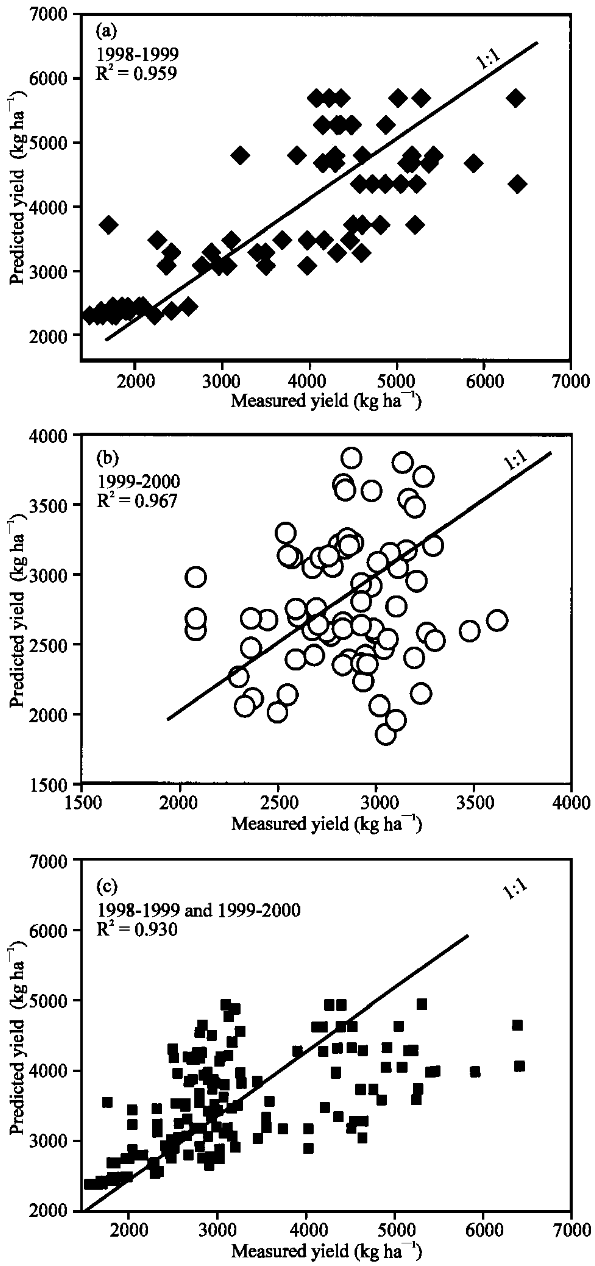

Fig. 7: Measured grain yield versus predicted values (a) for first cropping year, (b) for second cropping year and (c) for two cropping years

maximum and minimum WUE originated from applying IC2 with IW:CPE of 0.50 in 1998-99 and applying IC4 with IW:CPE of 1.00 in 1999-2000. The WUE averaged 1.241 and 1.284 kg m^{-3} for Tajan and Shiroudi. So, there was no difference between the mentioned varieties in water use efficiency.

Wheat water production functions: The water production function that relates water applied to crop yield is non-linear in nature. The water production functions were worked out for measured data in two cropping years by multiple regression and the least squares procedure (Moghaddam, 1999). Acquired-models were as follow:

(1) for 1998-1999 $R^2 = 0.959$ n = 72 $Y = 47.594\ W^{0.51} + 446.770\ A$
(2) for 1999-2000 $R^2 = 0.967$ n = 72 $Y = 52.896\ W^{0.51} + 135.037\ A$
(3) for two years $R^2 = 0.930$ n = 144 $Y = 36.829\ W^{0.51} + 264.702\ A + 333.846\ C$

where Y and W are grain yield (kg ha^{-1}) and water applied (m^3), respectively.

Levels of irrigation cutting off during wheat growth stages are represented by A which can be chosen as 1, 2, 3 and 4 for IC1, IC2, IC3 and IC4 treatments, respectively. Also, C is wheat varieties viz. Tajan (C = 1) and Shiroudi (C = 2).

The R-squared of models indicating that fitted models explain about 96, 97 and 93% of the variability in the grain yield under conditions of conducted experiments in 1998-99, 1999-2000 and two cropping years. The water production function varied from a water application of 1194.0 m^3 and a yield of 1602.11 kg ha^{-1} to an application of 5736.198 m^3 and a yield of 2879.687 kg ha^{-1} in the two cropping years. The grain yield from developed models compared with measured values and displayed in Fig. 7. The agreements were satisfactory.

The water use efficiency of two varieties of winter wheat were estimated on cutting off irrigation during crop growth stages with water amounts treatments. This study supports the following conclusions:

- The WUE averages obtained from irrigation cutting off after stem elongation and flowering stages were nearly identical.
- The highest WUE acquired from applying irrigation cutting off after flowering stage for Shiroudi variety.
- Resulted WUE averaged from 0.581 to 1.894 kg m^{-3}.
- In comparative to full irrigation, the WUE achieved from cutting off irrigation after stem elongation and flowering were identically increased more than one-half and that increased about one-third after dough stage.
- The highest WUE acquired from applying IW:CPE of 0.50 for irrigating Shiroudi with applying IC2 treatment.
- The WUE subjected to IW:CPE of 0.75 and 0.50 were 1.33 and 2 times that acquired from IW:CPE of 1.00 treatment.

- The WUE increased by applying IC1 to IC4 and decreasing ratio of IW to CPE in two cropping years.
- The developed models for estimating wheat yield in the basis of water applied, irrigation cutting off during wheat growth stages and crop varieties had a satisfactory agreement with measured values that more than 93% of grain yield variations can be explained by mentioned variables.

Further study is required to investigate effects of deficit irrigation managements on kernel quality and straw yield.

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