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Changes in Climatic Variables and Their Effect on Wheat Water Requirement in Urmia Lake Basin

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ABSTRACT

Climate change and low water use efficiency are the main reasons for reducing the water entering the Urmia Lake. Therefore, water use management via irrigation scheduling can be an effective strategy to restore this lake. This research was conducted to investigate the effect of climatic variables on water requirements, identify water-sensitive growth stages, and prepare irrigation scheduling guidelines for wheat, which is one of the main crops in the studied region. For this purpose, crop Evapotranspiration (ET_c) and Net Irrigation Requirement (NIR) of wheat growth stages were estimated by computing the daily soil water balance of the root zone for a period of 32 years (1985-1986 to 2016-2017). Dividing wheat growth period into nine phenological stages was performed using Growing Degree Days (GDDs) and Zadoks scale. These stages included intervals of [Sowing-Emergence (StE)], [Emergence-Trifoliate (EtT)], [Trifoliate-Double ridge (TtD)], [Double ridge-Jointing (DtJ)], [Jointing-Booting (JtB)], [Booting-Heading (BtH)], [Heading-Anthesis (HtA)], [Anthesis-Maturity (AtM)] and [Maturity-Harvesting (MtHa)], whose mean ET_c was estimated to be 2.30, 1.33, 1.03, 3.63, 4.69, 5.13, 6.53, 7.09 and 1.35 mm d^{-1}, respectively. The mean ET_c, Effective Precipitation (Eff. P) and NIR of wheat during its growth period were estimated to be 774, 349, and 425 mm, respectively. Results showed that wheat sensitivity to water stress is high from booting to maturity, is low from sowing to double ridge and from maturity to harvesting, and is moderate in other stages. Therefore, increasing the irrigation interval in the first three stages of growth and eliminating the end-stage irrigation are recommended for water saving.

Keywords: Dual K_c, FAO Penman-Monteith, GDD, Mann-Kendall test, Zadoks scale.

INTRODUCTION

Urmia Lake, in north-western Iran, is the largest saltwater lake in the Middle East (Zoljoodi and Didevarasl, 2014). Over a period of 20 years (1995-2015), the lake water level has decreased more than 8 m (Khazaei *et al.*, 2019). This decline in the lake water level has caused a significant decrease in lake surface area and its water volume. Continuation of the drying up of Urmia Lake will cause serious damages to health, hygiene, livelihood, and destruction of its basin ecosystem.

The drying process of this lake is the consequence of negative impacts of human activities and natural factors. Unbalanced and unsustainable development of agricultural activities and excessive and undesirable water use in this sector are the most important reasons for over-harvesting of the renewable water resources in the Urmia Lake Basin (Khazaei *et al.*, 2019).

Irrigation scheduling is one of the most important practices to manage water use in agriculture. In numerous studies, the effectiveness of different irrigation scheduling methods in reducing water use and increasing water productivity has been evaluated (Rosa *et al.,* 2012; Zhao *et al.,* 2013; Gao *et al.,* 2014; Incrocci *et al.,* 2014; Goosheh *et al.,* 2018; Zhang *et al.,* 2018; Ewaid *et al.,* 2019; Jha *et al.,* 2019; Mehmood *et al.,* 2019; Zhou *et al.,* 2019; Taromi Aliabadi *et al.,* 2019; Erken and Yildirim 2019; Dindarlou *et al.,* 2019; Singh *et al.,* 2019).

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Irrigation scheduling involves methods that are based on plant stress indices, soil moisture budget, crop water use (ET), or a combination of these approaches (Hill, 2002). Applying these methods requires field measurements and experiments, or the use of simulation models. Field experiments have some limitations (including cost and time consuming, unable to perform multiple and complex irrigation management options, and generalization of test findings to other conditions and regions (external validity)). Simulation models are used to overcome these limitations. Among the most used ones are FAO Penman-Monteith (P-M), CERES, and AquaCrop models. The effectiveness of these models has been studied and approved for irrigation scheduling of different crops, reducing water use and increasing water productivity in different parts of the world (Rosa *et al.*, 2012; Zhao *et al.*, 2013; Gao *et al.*, 2014; Incrocci *et al.*, 2014; Goosheh *et al.*, 2018; Zhang *et al.*, 2018; Ewaid *et al.*, 2019; Zhou *et al.*, 2019).

In Saqqez County, located in the Urmia Lake basin, farmers do not use the scientific method for irrigation scheduling. The vastness of the area is an obstacle to generalize the results of field experiments to the whole region. This research was conducted to prepare irrigation scheduling guidelines for wheat using FAO P-M model and dual K_c approach, as well as investigate the effect of climatic variables on water requirements and identifying water-sensitive growth stages of wheat.

MATERIALS AND METHODS

Study Area

The study area is Saqqez County in Kurdistan province, located in the southern part of the Urmia Lake basin of Iran (Figure 1). Saqqez has a cold semi-humid climate. The climate of Saqqez was determined using Emberger method (Arkian *et al.*, 2018). Daily minimum and maximum temperatures of Saqqez in the coldest and warmest months of the year are -36 and 43°C, respectively. Mean annual precipitation of

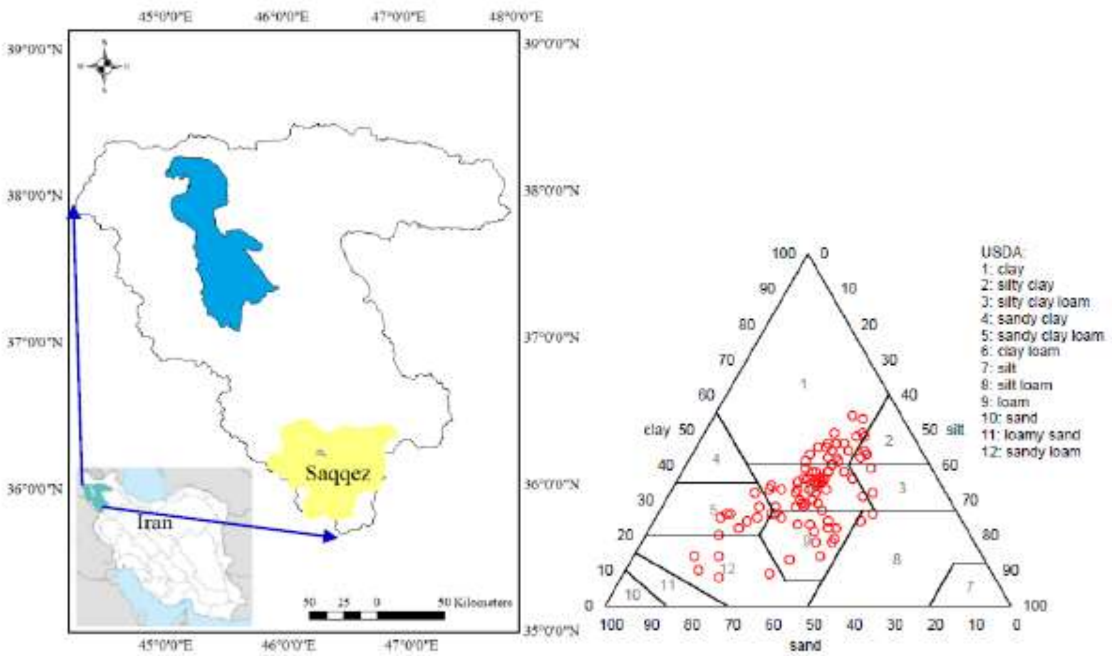

Figure 1. Location of Urmia Lake basin and Saqqez County and the textural classes of 94 soil samples of the study area in the USDA soil texture triangle.

Saqqez is about 450 mm. In this county, approximately 118,000 ha of the land is cultivated. On average, wheat is planted in 83000 ha (70%) of these cultivated lands. Therefore, wheat is one of the main crops of this county.

The textural classes of 94 soil samples of the study area are presented in Figure 1. According to this figure, Saqqez soils include clay loam (41.5%), clay (21.3%), loam (14.9%), sandy clay loam (9.6%), sandy loam (5.3%), silty clay (3.2%), silty clay loam (2.1%) and silty loam (2.1%). These data were obtained from Kurdistan Agricultural and Natural Resources Research and Education Center.

FAO P-M Equation

In this method, reference ET (ET_0) is estimated by Equation (1). The required climate variables to calculate daily ET_0 by this method were obtained from the Saqqez Synoptic Station. This station has a longitude of 46° 16′ E, a latitude of 36° 15′ N, and an altitude of 1,522.8 m above mean sea level.

$$ET_0 = \frac{0.408 \cdot \Delta \cdot (R_n - G) + \gamma \cdot \frac{900}{T + 273} \cdot u_2 \cdot (e_s - e_a)}{\Delta + \gamma \cdot (1 - 0.34 \cdot u_2)} \qquad (1)$$

Where, ET_0 is reference ET (mm d^{-1}), Δ is slope of the saturation vapor pressure curve (kPa °C^{-1}), γ is psychrometric constant (kPa °C^{-1}), u_2 and T are wind speed (m s^{-1}) and mean air temperature (°C) at 2 m height, e_a and e_s are actual and saturation vapor pressures (kPa), G is soil heat flux density (MJ m^{-2} d^{-1}), and R_n is net Radiation at the crop surface (MJ m^{-2} d^{-1}).

Crop Growth Stages

Every plant needs a certain amount of heat to pass a growth stage, which is referred to as the heat requirement and is expressed in terms of Growing Degree Days (GDDs). Table (1) presents the GDDs required for some wheat growth stages (Bowden *et al.*, 2008). In this study, the GDDs were calculated using Equation (2).

$$GDD = \sum_{j=1}^{n}\left(\left(\frac{1}{m} \cdot \sum_{i=1}^{m} T_i\right) - T_b\right) \qquad (2)$$

Where, T_i is hourly air Temperature (°C), m is number of daily air temperature records, n is number of days after sowing, and T_b is the base Temperature. The base temperature, or physiological zero, is the minimum temperature at which the plant grows, and its value varies for each plant. For wheat, T_b was set to zero degrees Celsius (Bowden *et al*., 2008).

Based on the K_c approach, the plant growth period is divided into four stages including initial (L_{ini}), development (L_{dev}), mid (L_{mid}) and late (L_{end}) season. The GDDs required for wheat to pass through the initial (trifoliate), crop development (heading), mid-season (maturity), and late-season (harvesting) stages were considered 300, 1400, 2,200, and 2,500°C, respectively (Allen *et al.*, 1998; Bowden *et al.*, 2008).

Table 1. Generic GDDs required for wheat growth stages (Bowden *et al.*, 2008).

Row	growth stage (Code[a])	GDDs (°C)	Row	growth stage (Code[a])	GDDs (°C)
1	Seeding (00) to emergence (09)	100	7	Flag leaf to heading (59)	140
2	Emergence to 3 leaves unfolded (Trifoliate) (13)	200	8	Heading to anthesis (69)	75
3	Trifoliate to double ridge (29)	305	9	Anthesis to maturity (89)	800
4	Double ridge to terminal spikelet (30)	150	10	Maturity to harvested product (99)	300
5	Terminal spikelet to jointing (36)	105			
6	Jointing to flag leaf (49)	300		Total	2475

[a] The decimal code is based on the well-known cereal code developed by Zadoks *et al.*, (1974).

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Dual K_c Method

K_c is a coefficient that is multiplied by the reference crop ET (ET_0) to get the ET_c. The K_c is used in the form of single (Equation 3) or dual (Equation 4) approaches. In real-time irrigation scheduling, dual K_c is more accurate than single K_c (Allen *et al.*, 1998). Therefore, in this study, dual K_c method was used to calculate daily ET of wheat ($ET_{c\text{-}w}$):

$$ET_c = K_c \cdot ET_0 \quad (3)$$

$$ET_c = (K_{cb} + K_e) \cdot ET_0 \quad \text{always} \quad (K_{cb} + K_e) \le K_{c-max} \quad (4)$$

In Equations (3) and (4), ET_c is crop ET (mm d^{-1}) and ET_0 is reference crop (grass or alfalfa) ET (mm/d), K_c, K_{cb}, and K_e are single K_c, basal K_c, and soil evaporation coefficient, respectively. The dual K_c is always smaller than the maximum value of K_c ($K_{c\text{-}max}$). The $K_{c\text{-}max}$ can be obtained using Equation (5). The K_{cb} of mid and late season stages ($K_{cb\text{-}mid}$ and $K_{cb\text{-}end}$) must be modified by using Equation (6) for local weather conditions (Allen *et al.*, 1998).

Where, u_2 is mean wind speed at 2 m height (m s^{-1}), RH_{min} is mean minimum Relative Humidity (%), $K_{cb\text{-}adj}$ is modified K_{cb}, max ( ) is maximum amount of the parameters in the braces { }, separated by the comma.

K_e describes the evaporation component of ET_c. To estimate K_e, it is necessary to calculate daily water balance for the surface soil layer using Equations (7) to (14). For this purpose, the process of evaporation from bare soil exposed to air is divided into two steps. In the first step, topsoil is moist after rainfall or irrigation. Soil evaporation has maximum rate, which is limited only by energy availability. During step 1 of soil drying, the evaporation reduction coefficient (K_r) is constant (K_r= 1).

In the second step, topsoil is apparently dry, and evaporation decreases in proportion to the amount of water remaining in the topsoil. During stage 2 of drying, the evaporation rate decreases and K_r is smaller than one (Equation (9)) (Allen *et al.*, 1998).

$$K_e = K_r \cdot (K_{c-max} - K_{cb}) \le f_{ew} \cdot K_{c-max} \quad (7)$$

$$D_{e,j-1} = TEW = 1000(\theta_{FC} - 0.5 \cdot \theta_{WP}) \cdot Z_e \quad (8)$$

$$K_r = \frac{TEW - D_{e,j-1}}{TEW - REW} \qquad D_{e,j-1} > REW \quad (9)$$

$$D_{e,j} = D_{e,j-1} - (P_j - RO_j) - \frac{I_j}{f_w} + \frac{E_j}{f_{ew}} + T_{ew,j} + DP_{e,j} \quad (10)$$

$$E_j = K_e \cdot ET_0 \quad (11)$$

$$DP_{e,j} = (P_j - RO_j) + \frac{I_j}{f_w} - D_{e,j-1} \ge 0 \quad (12)$$

$$f_{ew} = \min(1 - f_c, f_w) \quad (5)$$

$$f_c = \left(\frac{K_{cb} - K_{c-min}}{K_{c-max} - K_{c-min}}\right)^{(1+0.5\cdot h)} \quad (6)$$

In Equations (7) to (14), $K_{c\text{-}min}$ is minimum K_c for dry bare soil, f_w is mean fraction of topsoil wetted by irrigation or rainfall, f_{ew} is fraction of the soil wetted and exposed to air or soil fraction having maximum evaporation, f_c is the effective fraction of topsoil covered by vegetation, θ_{FC} and θ_{WP} are soil water content at Field Capacity (FC) and wilting point (m^3 m^{-3}), Z_e is depth of the topsoil layer that is subject to drying by evaporation [0.1-0.15m], TEW (Total Evaporable Water) is cumulative depth of evaporable water during a complete cycle of topsoil drying (mm), REW (Readily

$$K_{c-max} = \max\left(\left\{1.2 + [0.04 \cdot (u_2 - 2) - 0.004 \cdot (RH_{min} - 45)] \cdot \left(\frac{h}{3}\right)^{0.3}\right\}, \{K_{cb} + 0.05\}\right) \quad (5)$$

$$K_{cb-adj} = K_{cb} + [0.04 \cdot (u_2 - 2) - 0.004 \cdot (RH_{min} - 45)] \cdot \left(\frac{h}{3}\right)^{0.3} \quad (6)$$

$$D_{r,j} = D_{r,j-1} - (P - RO)_j - I_j - CR_j + ET_{c,j} + DP_j \quad , \quad 0 \le D_{r,j} \le TAW \tag{15}$$

Evaporable Water) is cumulative depth of evaporation at the first stage of drying soil (mm), and h is average plant height (m). Also, in these equations, the j subscript represents day j, D_e is cumulative evaporation at the end of the day (mm), P is Precipitation (mm), RO is Runoff (mm), I is Irrigation (mm), E is Evaporation (mm), T_{ew} is transpiration from the fraction of the topsoil exposed to air and moisture (mm), and DP_e is Deep Percolation (mm) when the soil moisture content is above FC.

As long as the soil moisture content in the evaporation layer is less than FC (i.e., $D_{e,j} > 0$), $DP_{e,j}$ is zero. The amount of Transpiration from evaporating soil layer (T_{ew}) is not very effective in calculating daily moisture balance and can be ignored. The $K_{c\text{-}min}$ coefficient is usually the same as the $K_{cb\text{-}ini}$ used for annual crops (0.15 for wheat) in bare soil conditions (Allen *et al.*, 1998).

Time and depth of subsequent irrigation are determined by computing daily soil water balance of the root zone using Equations (15) to (18). To avoid water stress, irrigation should be done before or at the moment when Readily Available Water (RAW) is depleted (i.e. $D_{r,j} \le RAW$). Also, to avoid deep percolation, which leads to leaching of soil nutrients, the net irrigation depth should be smaller than or equal to the amount of water depleted ($I_j \le D_{r,j}$) (Allen *et al.*, 1998).

$$D_{r,j-1} = 1000 \cdot (\theta_{FC} - \theta_{j-1}) \cdot Z_r \tag{16}$$

$$TAW = 1000 \cdot (\theta_{FC} - \theta_{WP}) \cdot Z_r \tag{17}$$

$$RAW = p \cdot (TAW) \tag{18}$$

Where, the j subscript represents day j, D_r is root zone Depletion at the end of the day (mm), P is Precipitation (mm), RO is Runoff (mm), I is net Irrigation (mm), CR is Capillary Rise from the groundwater table (mm), ET_c is crop ET (mm), DP is water loss out of the root zone by Deep Percolation (mm), Z_r is root Zone depth, θ_{FC} is soil water content at FC ($m^3\ m^{-3}$), θ is average soil water content for Z_r ($m^3\ m^{-3}$), TAW is Total Available soil Water in Z_r (mm), RAW is Readily Available soil Water in Z_r (mm), and p is average fraction of TAW that can be depleted from Z_r before moisture stress occurs [0-1].

After heavy rainfall or irrigation, it can be assumed that θ_{j-1} is about FC and $D_{r,j-1}$ is zero. Also, in the region where water table is more than about 1 m below the bottom of root zone (such as in Saqqez), CR can be assumed to be zero (Allen *et al.*, 1998). In this study, RO was estimated using the Curve Number method (Schmit and Scott, 2019).

Mann-Kendall Trend Test

The M-K statistical test is applied to evaluate the significance of trend in the data time series. The M-K statistic, S, is calculated using Equation (19). The mean of S is zero and its variance is calculated by Equation (20). Using the Z-transformation [i.e. Equation (21)], distribution of the S

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(X_j - X_i) \quad , \quad \operatorname{sgn}(X_j - X_i) = \begin{cases} -1 & \text{if } (X_j - X_i) < 0 \\ 0 & \text{if } (X_j - X_i) = 0 \\ 1 & \text{if } (X_j - X_i) > 0 \end{cases} \tag{19}$$

$$Var(S) = \frac{1}{18} \cdot [n \cdot (n-1) \cdot (2n+5) - \sum_{i=1}^{m} t_i \cdot (t_i - 1) \cdot (2t_i + 5)] \tag{20}$$

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statistic will be an approximately normal distribution.

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{\mathrm{Var}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \dfrac{S+1}{\sqrt{\mathrm{Var}(S)}} & \text{if } S < 0 \end{cases} \quad (7)$$

Where, X_j is data value, n is number of data points, m is number of tied groups (a tied group is a set of sample data having the same value), and t_i is number of data points in the *i*th tied group. If calculated |Z| value is greater than $Z_{1-\alpha/2}$, obtained from the standard normal distribution table with the significance level of α, the data follow a monotonic trend (Yue and Wang 2004; Pohlert 2020).

In this study, ET_c, Eff.P, and NIR were calculated by programming in the Excel spreadsheet. The calculation process included determining L_{ini}, L_{dev}, L_{mid}, L_{end}, K_{cb}, K_e, ET_0, ET_c, Eff.P, and NIR. To use Equations (7) to (18), it was necessary to determine K_{cb-ini}, K_{cb-mid}, K_{c-end}, K_{c-min}, p, f_w, REW, TEW, TAW, Z_r, and h. The K_{cb-ini}, K_{cb-mid}, K_{c-end}, K_{c-min} and p for winter wheat were set as 0.15, 1.10, 0.15, 0.15, and 0.55, respectively. Based on the irrigation type (sprinkler) and soil texture f_w, REW, TEW, and TAW were considered 1, 8 (mm), 20 (mm), and 170 (mm), respectively (Allen *et al.*, 1998). Maximum crop height (h) and root development depth (Z_r) were 0.8 and 1.2 m, respectively, according to the experts from Kurdistan Agricultural and Natural Resources Research and Education Center.

RESULTS AND DISCUSSION

Trends in ET_0 and Climatic Variables

The monthly means and M-K statistics of climatic data and ET_0 in Saqqez County during 1985-1986 to 2016-2017 are presented in Table 2. It is observed that ET_0 has an upward trend at significant levels of less than 1% in all months of the year, except for November. The significant increase trend in ET_0 for northwestern Iran, where Urmia Lake basin is located, is also found in the studies of Dinpashoh *et al.* (2011) and Kousari and Ahani (2012). Precipitation declined significantly in February, March, and April. The average air Temperature (T_{mean}) has significantly increased in all months of the year, except

Table 2. Monthly means and M-K statistics of climatic data and ET_0 in Saqqez County during 1985-1986 to 2016-2017.

Month	ET_0 (mm d^{-1})		P (mm d^{-1})		S (h d^{-1})		T_{mean} (°C)		RH_{mean} (%)	
	Mean	Z	Mean	Z	Mean	Z	Mean	Z	Mean	Z
Jan.	0.8	6.66^{***}	1.8	-1.25^{ns}	4.5	9.90^{***}	-2.2	2.65^{**}	73.8	0.58^{ns}
Feb.	1.2	7.72^{***}	2.0	-4.73^{***}	5.5	5.28^{***}	-0.3	5.44^{***}	70.5	-6.41^{***}
Mar.	2.3	4.24^{***}	2.3	-4.26^{***}	6.4	4.90^{***}	4.9	5.65^{***}	63.9	-2.35^{*}
Apr.	3.5	4.21^{***}	2.2	-4.50^{***}	7.6	3.13^{**}	10.3	2.58^{**}	59.7	0.49^{ns}
May	4.7	2.62^{**}	1.1	-0.08^{ns}	9.5	-0.33^{ns}	14.3	3.32^{***}	55.5	1.06^{ns}
Jun.	6.1	5.01^{***}	0.2	-1.67^{ns}	11.9	1.44^{ns}	19.1	3.25^{**}	43.6	-0.66^{ns}
Jul.	6.6	4.09^{***}	0.2	1.31^{ns}	11.7	0.74^{ns}	23.6	2.35^{*}	36.1	-2.17^{*}
Aug.	6.1	2.82^{**}	0.1	2.77^{**}	11.3	1.08^{ns}	23.4	6.43^{***}	31.6	-1.15^{ns}
Sep.	4.6	3.68^{***}	0.1	1.06^{ns}	10.5	1.45^{ns}	18.7	5.73^{***}	32.7	1.81^{ns}
Oct.	2.8	2.94^{**}	1.0	0.78^{ns}	8.1	1.77^{ns}	13.0	2.49^{*}	47.1	-1.46^{ns}
Nov.	1.3	0.95^{ns}	2.1	0.54^{ns}	6.0	-0.31^{ns}	6.2	-0.11^{ns}	62.8	2.63^{**}
Dec.	0.8	3.10^{**}	1.9	-0.03^{ns}	4.5	5.26^{***}	0.6	-0.46^{ns}	70.7	0.38^{ns}
Annual	3.4	3.72^{***}	1.2	-4.00^{***}	8.1	3.92^{***}	11.0	5.11^{***}	53.9	-0.63^{ns}

*, ** and ***: Indicate a trend at the significance level of 5% (Z_C= 1.96), 1% (Z_C= 2.576), and 0.1% (Z_C= 3.291), respectively.

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for November and December. The Sunshine (S) had a significant increase in 5 months of the year (December to April). At the annual scale, ET_0, S, and T_{mean} variables had a significant incremental trend. The trend of annual precipitation and relative humidity was decreasing. However, the decreasing trend of relative humidity was not significant.

Changes in the Length of the Growth Stages

Date of planting was set to October 12 by reviewing the literature and according to the experts from Kurdistan Agricultural-Jahad Organization (Bazgeer *et al.*, 2008). Also, using Table 1 and Eq. (2), L_{ini}, L_{dev}, L_{mid}, and L_{end} of winter wheat in Saqqez County for 32 years (1985-1986 to 2016-2017) were estimated. Results are presented in Figure (2). Coefficient of Variation (CV) for L_{ini}, L_{dev}, L_{mid}, and L_{end} was 35.0%, 6.74%, 6.52% and 7.52%, respectively. The higher value of CV for L_{ini} was due to higher fluctuations in air temperature in the initial stage than in other stages. Mean L_{ini}, L_{dev}, L_{mid}, and L_{end} for winter wheat were obtained as 31, 195, 39 and 12 days, respectively. Allen *et al.* (1998) reported 30, 140, 40, and 30 days for L_{ini}, L_{dev}, L_{mid}, and L_{end} for winter wheat, respectively. Therefore, the length of wheat growth period determined in this study is longer than that suggested by Allen *et al.* (1998).

Changes in K_c and K_e

Figure 3 shows the daily variations of K_{cb-adj}, K_e, (K_{c-adj}+K_e), and K_{c-max} in 2015-2016. Due to low vegetation cover at the beginning of the growing season (initial stage), K_e will be very high if the soil gets wet by irrigation or rain. As the crop grows and vegetation cover is completed, K_e decreases. According to Figure 3, it can be said that K_e has a decreasing trend during the growth period and its fluctuations are related to the wetting of the soil surface. This result is consistent with field experiments by Zhao *et al.* (2013).

Figure 4 shows the mean K_{cb-adj}, K_e, (K_{c-adj}+K_e), and K_{c-max} at nine growth stages of the winter wheat for 2015-2016. Due to the low vegetation cover in the initial growth stage (planting to trifoliate), K_e is high and K_{cb-adj} is low. Thus, in the initial growth

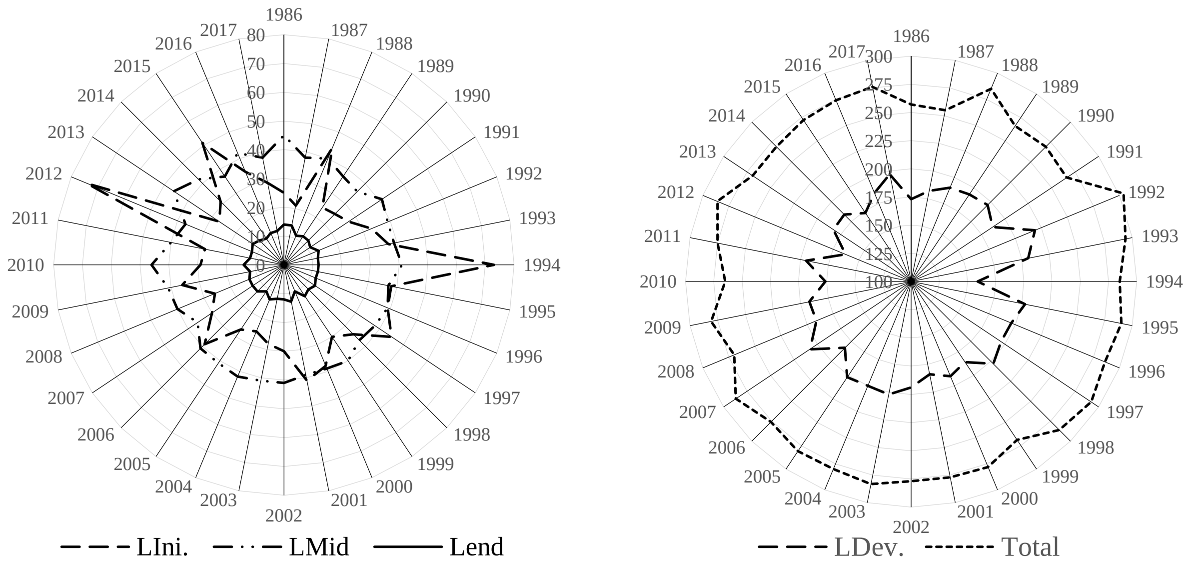

Figure 2. Length of the wheat growth stages in Saqqez (1985-1986 to 2016-2017).

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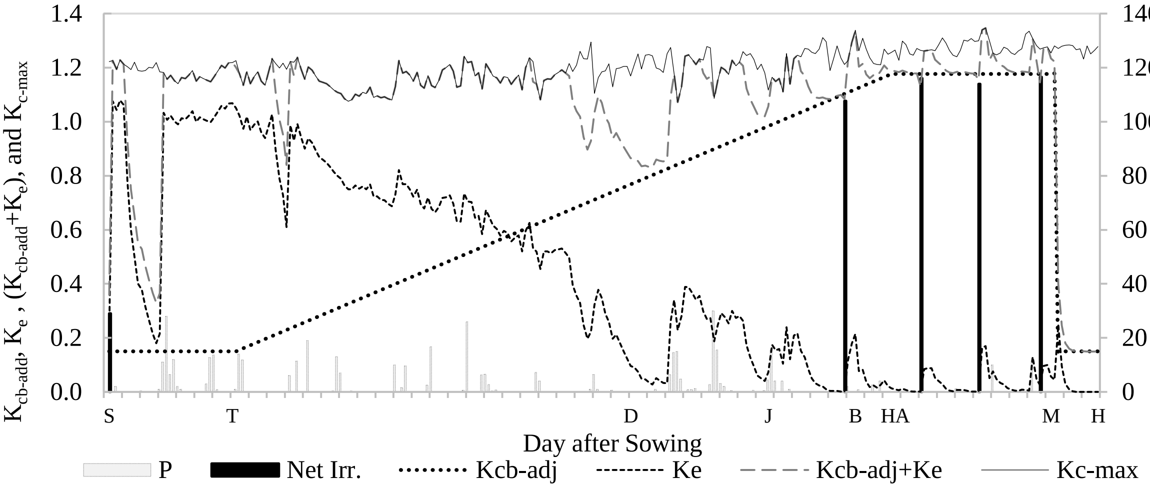

Figure 3. Daily $K_{cb\text{-}adj}$, K_e, $K_{cb\text{-}adj}$+K_e, $K_{c\text{-}max}$, and NIR for winter wheat, and precipitation in 2015-2016.

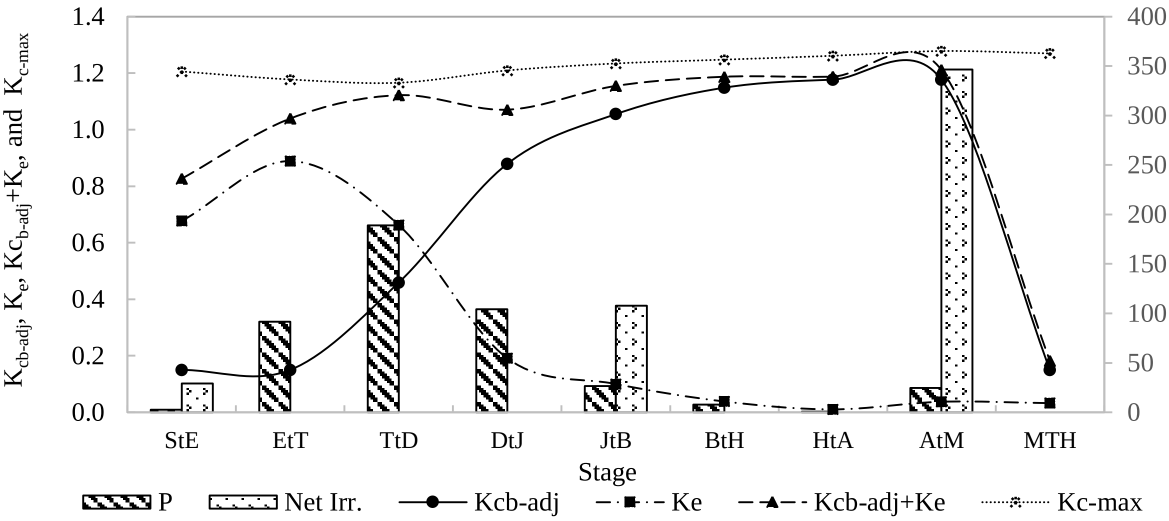

Figure 4. Mean $K_{cb\text{-}adj}$, K_e, ($K_{cb\text{-}adj}$ +K_c), and $K_{c\text{-}max}$, NIR, and P in nine wheat growth stages in 2015-2016.

Table 3. ET_c, NIR, and length of different growth stages of winter wheat in Saqqez region.

Stage	Duration (Day)	ET_c (mm)				Net irrigation (mm)				Nu Of Irr
		Distribution	Confidence level			Distribution	Confidence level			
			50	75	90		50	75	90	
StE	10	Wakeby	23.0	25.1	27.6	Wakeby	23.0	25.1	27.6	1
EtT	21	Johnson SB	27.9	37.3	47.5	Gumbel Max	5.00	13.5	23.3	
TtD	128	Wakeby	132	173	227	Gumbel Max	1.30	7.20	13.9	
DtJ	30	Wakeby	109	121	140	Gumbel Min	14.5	42.3	74.1	1
JtB	23	Johnson SB	108	119	128	Normal	59.1	99.0	135	1
BtH	9	Gen Extreme	46.2	51.1	55.6	Gumbel Max	29.7	67.0	109	1
HtA	4	Wakeby	26.1	29.1	32.7	Gumbel Max	26.1	29.1	32.7	1
AtM	40	Wakeby	284	298	313	Wakeby	266	322	358	3
MtHa	13	Wakeby	17.6	24.0	30.9	Gumbel Max	0.20	13.9	29.4	
Total	278		774	878	1002		425	619	803	8

stage, the E portion in ET_C is on the average more than 80%. With the onset of tillering, due to the increasing trend of green vegetation, the descending trend of K_e begins and continues until the end of the physiological maturity stage. From the physiological maturity to harvesting, due to the partial reduction of vegetation cover, K_e shows a slightly increasing trend.

Figure 5 presents the results of calculating mean daily ($K_{cb\text{-}adj}$+K_e) for initial, mid, and late-season stages of winter wheat growth during the 32-year period (1985-1986 to 2016-2017). The mean daily $(K_{cb\text{-}adj}+K_e)_{ini}$, $(K_{cb\text{-}adj}+K_e)_{mid}$ and $(K_{cb\text{-}adj}+K_e)_{end}$ were 0.79, 1.18, and 0.23, respectively. These coefficients include the effect of both crop transpiration and soil evaporation; therefore, they can be used instead of the single K_c. According to Allen *et al.* (1998), the single K_c of initial, mid and late-season growth stages of winter wheat are 0.4, 1.15 and 0.25, respectively. It can be seen from this figure that $(K_{cb\text{-}adj}+K_e)_{ini}$ and $(K_{cb\text{-}adj}+K_e)_{end}$ vary for each year. But the $(K_{cb\text{-}adj}+K_e)_{mid}$ was almost constant. The $(K_{cb\text{-}adj}+K_e)_{ini}$ and $(K_{cb\text{-}adj}+K_e)_{end}$ are dependent on the topsoil moisture balance, which is strongly affected by the weather conditions. Different weather conditions in each year caused changes in soil moisture balance and, as a result, changes in the $(K_{cb\text{-}adj}+K_e)_{ini}$ and $(K_{cb\text{-}adj}+K_e)_{end}$.

ET_c and NIR

Daily ET_c of wheat ($ET_{c\text{-}w}$) was calculated using Equation (4). The time and depth of irrigation were determined by Equation (15). The calculations were repeated for 32 years (1985-1986 to 2016-2017). The ET_c and NIR of the growth stage were obtained from the sum of the daily data. EasyFit5.5 software was used to select the statistical distribution of the ET_c and NIR data of the wheat growth stages. The ET_c and NIR of wheat were calculated at different probability levels using the selected appropriate distribution. Results of the calculations are presented in Table 3. It can be seen from this table that the ET_c of wheat at 50% probability level is 774 mm. The mean NIR of wheat was estimated to be 425 mm. The number of irrigations per growth stages include StE (once; 27 mm), DtJ (1 time; 16 mm), JtB (1 time; 60 mm), BtH (1 time; 30 mm), HtA (1 time; 26 mm), and AtM (3 times; 266 mm).

According to Equation (14), the evapotranspiration of wheat (ET_c) in Saqqez is supplied by precipitation and irrigation. Therefore, the difference between ET_c (774 mm) and NIR (425 mm) indicates the amount of effective precipitation (i.e. 349 mm). Total evaporation from soil during the wheat growth period (E) was 157 mm, which was 20% of Evapotranspiration (ET_c).

Reference documents for estimating water requirement of main crops in Iran (Farshi *et al.*, 1997; Alizadeh, 2003) cite ET_c and NIR for wheat in Saqqez as (531 and 366 mm) and (375 and 220 mm), respectively. These reported ET_c and NIR values are much less than those estimated in this study (774 and 425 mm). These researchers considered the length of growth stages to be constant each year and did not modify the crop coefficients based on weather conditions. These were the main reasons for the large differences in their results compared to the present study. Other reasons for the discrepancy can be attributed to the differences in the statistical length of the data and the increasing or decreasing trend of some climatic data. This discrepancy in results confirms the necessity of revising and updating the mentioned references.

Mean daily net irrigation requirements, evaporation, transpiration, and evaporation portion of ET (E/ET_c) at wheat growth stages are presented for 32 years in Figure 6. Based on the mean daily ET_c and E/ET_c, each of the nine wheat growth stages can be classified into three groups with low, moderate, and high sensitivity to water stress.

Mean soil evaporation and wheat transpiration in the four stages of Sowing to Emergence (StE), Emergence to Trifoliate

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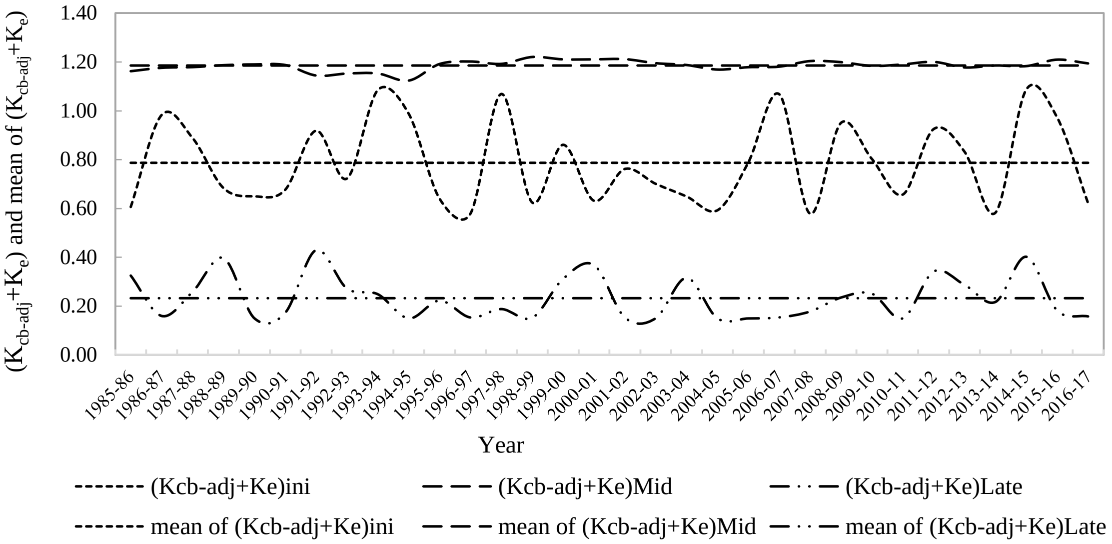

Figure 5. Mean daily $(K_{cb\text{-}adj}+K_e)_{ini}$, $(K_{cb\text{-}adj}+K_e)_{mid}$ and $(K_{cb\text{-}adj}+K_e)_{end}$ of winter wheat during the 32-year period (1985-1986 to 2016-2017).

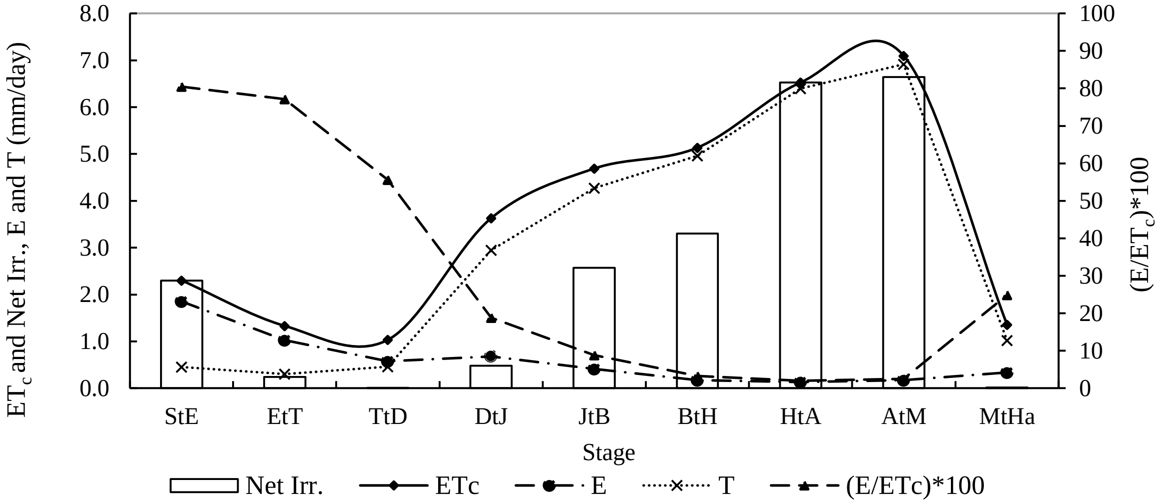

Figure 6. Average daily NIR, T, E, and E/ET$_c$ at wheat growth stages in 32 years (1985-1986 to 2016-2017).

(EtT), Trifoliate to Double ridge (TtD), and Maturity to Harvesting were (1.84, 0.46), (1.02, 0.31), (0.58, 0.45), and (0.34, 1.01) mm d^{-1}, respectively. In these four stages, E/ET$_c$ was high, and ET$_c$ and wheat sensitivity to water stress were low. Therefore, increasing the irrigation interval in the first three stages of growth and eliminating the end-stage irrigation are recommended for saving water and increasing WUE.

Mean E and wheat T in three stages of Booting to Heading (BtH), Heading to Anthesis (HtA), and Anthesis to Maturity (AtM) were (0.15, 4.98), (0.13, 6.40), and (0.14, 6.95) mm d^{-1}, respectively. In these three stages, E/ET$_c$ was low, and ET$_c$ and wheat sensitivity to water stress were high. In these three wheat growth stages in the Saqqez region, precipitation probability is very low and ET$_c$ must be supplied through accurate and timely irrigation.

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Mean E and wheat T in two stages of Double ridge to Jointing (DtJ) and Jointing to Booting (JtB) were (0.73, 2.90) and (0.42, 4.27) mm d^{-1}, respectively. In these two stages, wheat sensitivity to water stress was moderate.

CONCLUSION

Proper identification of wheat water-sensitive growth stages will help planners and farmers in timely irrigation and optimal management of water use. Also, scientific use of deficit irrigation (reducing or eliminating irrigation in growth stages non-sensitive to water stress) and supplemental irrigation methods would be possible. In addition, water use efficiency can also be increased. Results showed that wheat sensitivity to water stress was high from booting to maturity, low from sowing to double ridge and from maturity to harvesting, and moderate in other stages.

Agricultural operations are done based on plant growth stages, which are known to the farmer. However, previous relevant reference documents of Iran have reported crop ET_c and NIR for ten-day periods. Therefore, it is difficult to use the results of these documents in practice. In this study, to solve this problem, wheat irrigation scheduling guideline was developed based on nine principal growth stages of the Zadoks scale, and the sensitivity of each stage to water stress was determined.

Duration and crop coefficients of winter wheat growth stages (i.e. $L_{ini.}$, $L_{dev.}$, L_{mid}, L_{end}, $K_{c\text{-}ini}$ and $K_{c\text{-}end}$) varied each year. Therefore, using a constant value for them in different years will be the main source of error in calculating the water requirement based on the K_c method. This subject has not been addressed in the national water documents of Iran. This result confirms the necessity of revising the reference documents for estimating water requirement of the main plants in Iran. In addition, this study showed a significant increasing trend in ET_0 data, which is a compelling reason for updating former documents.

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تغییر در متغیرهای آب و هوایی و تأثیر آن‌ها بر نیاز آبی گندم در حوضه دریاچه ارومیه

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چکیده

تغییر آب و هوا و کارآیی پایین مصرف آب در بخش کشاورزی، دو عامل اصلی کاهش آب ورودی به دریاچه ارومیه می‌باشند. بنابراین، مدیریت مصرف آب از طریق برنامه‌ریزی آبیاری می‌تواند راه‌کاری موثر برای احیای این دریاچه باشد. این تحقیق با هدف بررسی اثر متغیرهای آب و هوایی بر نیاز آبی، شناسایی مراحل رشد حساس به آب و تهیه دستورالعمل برنامه‌ریزی آبیاری برای گندم، که یکی از گیاهان زراعی اصلی در حوضه دریاچه ارومیه است، انجام شد. برای این منظور، تبخیر-تعرق (ET_C) و نیاز آبیاری خالص (NIR) مراحل رشد گندم با محاسبه بیلان روزانه رطوبت خاک منطقه ریشه برای دوره 32 ساله (1365-1364 تا 1396-1395) برآورد شد. جداسازی دوره رشد به نه مرحله فنولوژی با استفاده از درجه روزهای رشد و مقیاس Zadoks انجام شد. این مراحل شامل فواصل [کاشت تا سبز شدن]، [سبز شدن تا سه برگی]، [سه برگی تا برجستگی دوگانه]، [برجستگی دوگانه تا تشکیل ساقه]، [تشکیل ساقه تا چکمه‌پوش] ، [چکمه‌پوش تا تشکیل خوشه]، [تشکیل خوشه تا گل‌دهی]، [گل‌دهی تا رسیدگی] و [رسیدگی تا برداشت] بودند، که میانگین ET_C آن‌ها به‌ترتیب برابر با 2.30، 1.33، 1.03، 3.63، 4.69، 5.13، 6.53، 7.09 و 1.35 میلی‌متر در روز برآورد شد. میانگین تبخیر-تعرق، بارش مؤثر و نیاز آبیاری خالص گندم در طول دوره رشد آن به ترتیب 774 ، 349 و 425 میلی‌متر برآورد شد. نتایج نشان داد حساسیت گندم نسبت به تنش آبی از چکمه‌پوش تا رسیدگی زیاد، از کاشت تا برجستگی دوگانه و از رسیدگی تا برداشت کم و در سایر مراحل متوسط است. بنابراین افزایش فاصله آبیاری در سه مرحله اول رشد و حذف آبیاری مرحله آخر رشد برای صرفه جویی در مصرف آب توصیه می‌شود.

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