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ORIGINAL ARTICLE

Effects of agro-climatic indices on wheat yield in arid, semi-arid, and sub-humid regions of Iran

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Abstract

This study aimed to analyze the impact of variations of drought-related agro-climatic indices including cumulative precipitation, cumulative potential evapotranspiration, cumulative actual evapotranspiration, cumulative crop evapotranspiration, cumulative water stress, and cumulative water deficit during nine consecutive phenological stages (emergence to physiological maturity) on wheat yield in arid, semi-arid, and sub-humid regions of Iran during 1999–2018. Principal component analysis was used to recognize the main components that largely explained the variations of agro-climatic indices during different stages of the crop growing period. Then, the relationships between the major components, retrieved from principal component analysis, and the crop yield were assessed. Wheat irrigation requirements were also calculated to investigate the regional water supply–demand patterns during the crop growing period. The findings highlighted increasing impacts of cumulative precipitation, cumulative potential evapotranspiration, cumulative crop evapotranspiration, and cumulative actual evapotranspiration and decreasing impacts of cumulative water stress and deficit on wheat yield, particularly in arid and semi-arid regions. The crop yield was more affected by variations of the agro-climatic indices during the reproductive phase than the vegetative phase. Accordingly, booting to flowering in the arid region, flowering in the sub-humid region, and stem elongation to booting in the semi-arid region were the most sensitive periods of wheat to agro-climatic indices variations. Wheat irrigation requirements in arid and semi-arid regions started earlier than in the sub-humid region. From the findings, it was concluded that adjusting the irrigation schedule based on wheat irrigation requirements during the wheat growing period could help farmers to achieve a favorable wheat yield.

Keywords Drought · Grain filling period · Impact analysis · Climate adaptation · Water stress · Irrigation

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Introduction

The climate in the arid and semi-arid regions has spatiotemporally changed. For example, the temperature has increased, and precipitation has decreased at annual and inter-annual scales (Ashraf et al. 2014; Kheiri et al. 2021a; Thakur et al. 2012). Drought, as the main limiting abiotic factor for crop production, plays a crucial role in these regions (Mousavi-Baygi et al. 2016). The intensity of greenhouse gases (GHG) emission is expected to increase due to population growth and economic development during the twenty-first century resulting in more pressure on water resources, changes in precipitation patterns, loss of total annual precipitation (around 10–20%), and exacerbation of drought, especially in developing countries (IPCC 2018).

Drought caused by inadequate precipitation and/or warm temperature is considered the most effective environmental factor determining the growth and development of various crops throughout the world (Hasanuzzaman et al. 2012; Kheiri et al. 2021b; Rahimi-Moghaddam et al. 2021; Vogel and Olivier 2019). Drought caused by inadequate precipitation and/or warm temperature is considered the most effective environmental factor determining the growth and development of various crops throughout the world (Hasanuzzaman et al. 2012; Kheiri et al. 2021b; Rahimi-Moghaddam et al. 2021; Vogel and Olivier 2019). By decreasing photosynthesis, leaf area, set of seeds and weight, and the mobilization of assimilate reserves, drought has an impact on growth and crop productivity (Shah and Paulsen 2003). When possible annual evapotranspiration exceeds yearly precipitation in a certain region, drought stress frequently occurs (Langridge and Reynolds 2021). Thus, weather drought can directly (i.e., transpiration) and indirectly (i.e., evaporation) affect crop growth and yield. Drought stress also shortens the crops' development period and advances their phenological stages, resulting in lower crop yield (Dietz et al. 2021). This phenomenon can result in a 9–10% decrease in grain harvests (Lesk et al. 2016), with a 21% decrease in wheat yield (Daryanto et al. 2016). The negative impacts of drought on agricultural production could be more destructive for the areas located in developing countries (Ahmed et al. 2020). According to the reports of Kheiri et al. (2023) and Segnon et al. (2021), agricultural lands located in developing countries are more exposed to climate change and extreme events such as drought. In addition, due to the socioeconomic condition of these areas, the farmers have a higher sensitivity to climate change while their adaptive capacity is very limited. However, the intensity of crops' vulnerability to drought stress depends on the crop phenological stage in which the drought occurred (Abid et al. 2018). Therefore, to better consider the impacts of drought stress on crop production, it is necessary to pay attention to related agro-climatic indices during the crop growing period. These indices derived directly from weather data better show the link between drought and crop growth, and also provide a clear point of view for decision-makers in the agriculture sector (Mathieu and Aires 2018). According to Rivington et al. (2013), the use of agro-climatic indices is an easy way to distinguish between appropriate and inappropriate mitigation and adaptation strategies to deal with climate change based on specific crop requirements. In other words, by using agro-climatic indices and evaluating their impacts on crop yield, users could design an appropriate water management plan for crops (Caubel et al. 2015). In this regard, agro-climatic indices, especially some types of drought indices, have long been used for crop yield predictions (Mathieu and Aires 2018).

There are several methods available to assess the effects of agro-climatic indices on crop growth attributes and yield formation. Each method has its advantages and limitations. Due to their capacity to handle complex, high-dimensional information, machine learning algorithms like Random Forest, Support Vector Machines (SVM), and Gradient Boosting have become more widely utilized for identifying drought variables (Zhao et al. 2022). Considering the advantages of this method, machine learning algorithms can handle vast and varied datasets, spotting complex relationships that conventional statistical methods would overlook. However, overfitting is a problem with machine learning models, which causes them to perform well on training data but fall short on new data. Additionally, they might not be interpretable, making it difficult to determine the precise causes of their predictions (Bouaziz et al. 2021). Multivariate analysis tools, such as factor analysis (FA), hierarchical cluster analysis (HCA), and canonical correlation analysis (CCA), are also powerful in dealing with inter-correlated data (Arshad and Umar 2022), such as agro-climatic indices limiting crop yields (Qian et al. 2009). PCA is one of the appropriate multivariate analysis techniques, which allows users to transform a complex set of mutually correlated variables into new variables. PCA can identify the primary causes of drought by highlighting underlying patterns and linkages in a vast dataset of meteorological and hydrological variables (Prajapati et al. 2022). PCA allows us to identify the key factors influencing drought variability by transforming the original variables into a new set of uncorrelated variables (principal components) that have a linear relationship with the original ones (Merabti et al. 2023). PCA has been used in many previous studies to analyze and recognize factors affecting crop production such as spring wheat yield (Qian et al. 2009), barley yield (Abi Saab et al. 2019), cotton morphology and yield (Sun et al. 2021), and wheat biomass, yield, and radiation use efficiency (Reynolds et al. 2007).

In a study, wavelet and PCA methods were employed to model crop yield as a function of climate-related indices for 40 agricultural regions during 1976–2006 in Canadian Prairies and it was concluded that PCA had an advantage over the wavelet method (Bornn and Zidek 2012). Alonso et al. (2019) evaluated the crops' sensitivity and adaptive capacity of agriculture systems to drought events in Portugal and reported the higher suitability of PCA for analyzing the vulnerability to drought events compared to other methods. Mousavi-Baygi et al. (2016) investigated the impacts of different water-related agro-climatic indices on rainfed wheat yield using PCA in the northwest of Iran and demonstrated that actual evapotranspiration (AET) and crop evapotranspiration (ETc) were the most effective components that are associated with crop yield. Therefore, PCA makes complex datasets simpler and helps in the extraction of useful information by reducing the dimensionality of the data and can assess the impacts of drought variables on the agricultural systems in different regions, especially where there are water shortages such as in Iran (Choubin et al. 2014).

Iran, a developing country with a serious water crisis (Madani 2014), has a varied climate, including dry to humid weather with an approximately average precipitation of 210 mm, about 25% of the global average precipitation (860 mm) (Kheiri et al. 2017). Alteration of annual precipitation is high and can range from 100 to 500 mm throughout Iran. Furthermore, temperature variations vary from 9 to 27 °C (Mesgaran et al. 2017). According to Modarres et al. (2016), Iran has experienced many severe drought events in the last and current century due to increased evaporation and decreased soil moisture caused by the increase in air temperature. In addition, Mansouri Daneshvar et al. (2019) estimated that Iran will experience a 2.6 °C increase in annual mean temperature and a 35% decline in total precipitation by the end of 2050. Such climate conditions can exacerbate the risk of drought and unstable crop production, thereby enhancing food insecurity in the country. Among the arable crops, wheat is the most strategic crop for food security in Iran with an approximate cropping area of 6.2 million hectares (nearly 60% of the total country's arable lands) (Karimi et al. 2018) and the total production of about 13×10^6 t year^{-1} (Tahmasebi et al. 2018), which emphasizes the heavy dependence of the agriculture sector of the country on the production of this crop. In this regard, any opportunity that can help farmers achieve greater crop yields and reduce the destructive effects of drought in the country is essential. Therefore, this study aims to achieve a comprehensive and better understanding of the impacts of drought via agro-climatic indices during the growing period on wheat yield in different regions to enhance or prevent a reduction in wheat production in Iran. It is assumed that drought in this study is only due to non-anthropogenic factors that could be offset by recognizing the main drivers and the most sensitive stages of the crop growth period. Accordingly, the objectives of the study are (i) to detect the most drought-sensitive stage(s) of the crop growing period in terms of wheat yield and (ii) to provide a water supply–demand pattern for each phenological stage of wheat in each region.

The novelty of the current study lies in several key aspects: (i) comprehensive understanding of drought impacts, which goes beyond merely identifying the presence of drought and examines the effects of agro-climatic indices during nine consecutive phenological stages (emergence to physiological maturity) on wheat yield over 20 years (1999–2018), (ii) region-specific study, which accounts for the variability in conditions in Iran's arid, semi-arid, and sub-humid regions that can greatly alter wheat's drought response, and (iii) comprehensive method, which is deemed transferrable to other regions facing limited access to water. By applying a replicable approach, the current study offers insights into regions dealing with similar drought-related challenges.

Materials and methods

Study area, weather, and crop data

Iran with 1,648,000 km^2 is located between 25 and 40° latitudes and between 44 and 63° longitudes (Fig. 1) and is bordered by the Caspian Sea to the north and Oman Sea and the Persian Gulf to the south. Alborz and Zagros are the two main mountain ranges of the country (Ashraf et al. 2014). The country covers heterogeneous climates consisting of arid (60%), semi-arid (28%), sub-humid (4%), semi-humid (1%), humid (2%), very humid (3%), and extremely humid (2%) climates (Tabari et al. 2014). The distance from the oceans and the direction of the northern mountain range of Alborz and the western and southern mountain range of Zagros and being adjacent to the hot and dry deserts of Saudi Arabia are the most important reasons for Iran's different climates. This study was done at four agrometeorological sites in Iran including Hashem Abad (located in Golestan province), Karaj (located in Alborz province), and Zarghan and Darab (located in Fars province) (Table 1). The site selection was made based on (i) the availability of historical weather and crop data in detail and (ii) the differences in climatic conditions across the country. In this study, the sites of Darab and Zarghan were selected because Fars province is one of the most important hubs of wheat production in Iran. Moreover, the share of Fars province in the country's annual wheat production is about 11%. Furthermore, this province covers about 7% of the wheat production area of the country (MAJ 2020). Besides, considering that this province has a high diversity in terms of climate conditions, wheat production in Fars province could be influenced by different

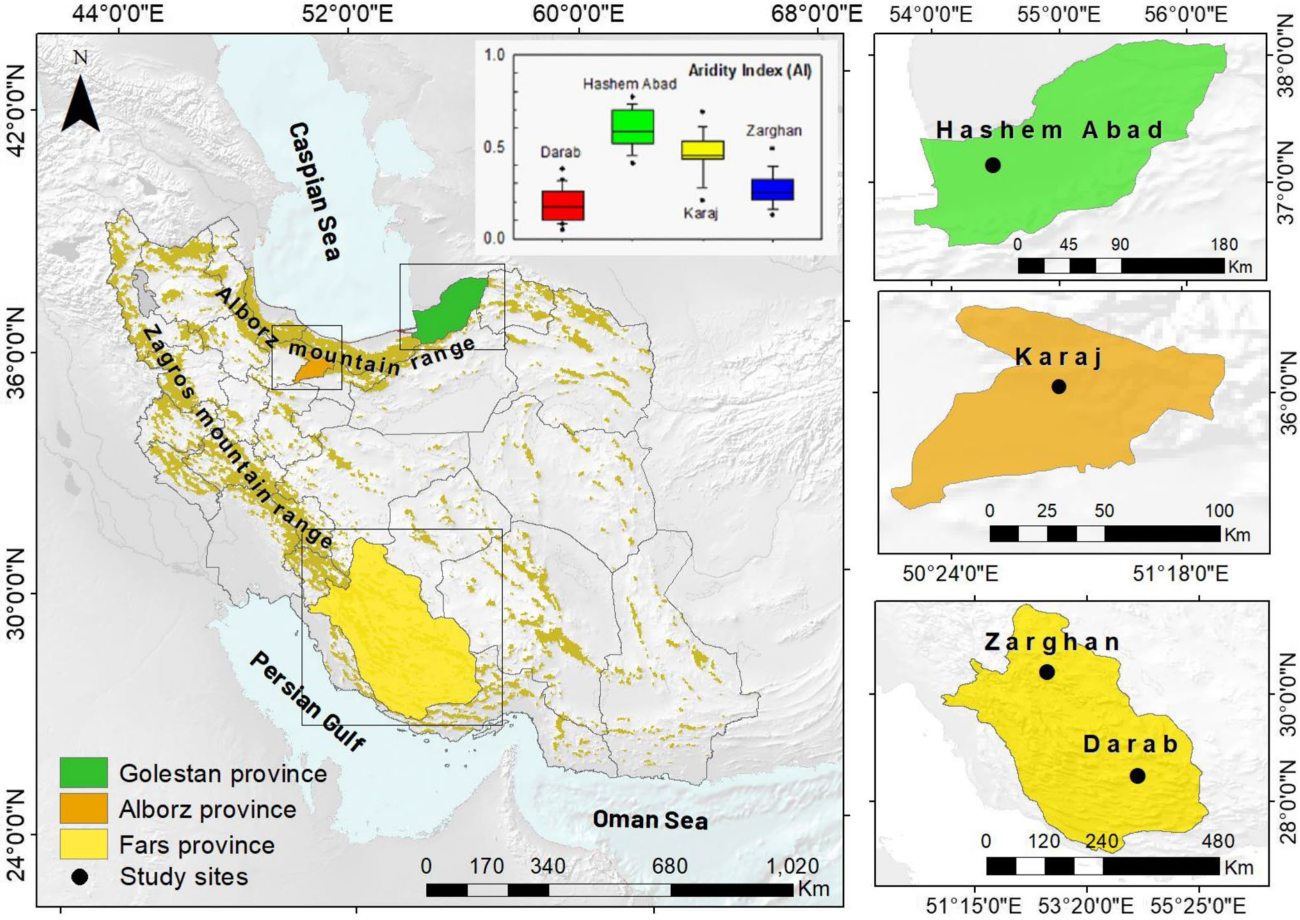

Fig. 1 Geographical situation and annual aridity index (AI) of the study sites in Iran

Table 1 Latitude, longitude, altitude, climate class, weather variables, and wheat yield of the selected sites during the study timespan (1999–2018)

Study site	Altitude (masl)	Climate class*	Annual cumulative precipitation (mm)	Annual mean temperature (°C)	Annual minimum temperature (°C)	Annual maximum temperature (°C)	Wheat yield (t ha^{-1})
Karaj	1312	Semi-arid	273.8	16.1	9.4	21.9	6.21
Darab	1180	Arid	241.5	22.6	14.4	29.8	6.15
Zarghan	1600	Semi-arid	360.3	15.9	7.9	24.9	4.6
Hashem Abad	160	Sub-humid	565.5	18.1	12.8	23.1	4.3

*The climatic classification is based on Eq. 1

agro-climatic indices (Jahangir et al. 2022). Accordingly, Darab and Zarghan were selected as the arid and semi-arid sites, respectively.

Long-term crop data (1999–2018) consists of different development stages, and the yield of wheat for the study sites was collected from the agrometeorological research institute of Iran. The institute's experiments seek to investigate the sensitivity of different crops such as wheat to weather variations in different climates. The experiments also measure and record crop growth stages (phenology and biometrics) from sowing to harvest in response to different atmospheric parameters at different regions every year. Wheat is cultivated under the rainfed condition in Hashem Abad and under the irrigated condition in Karaj, Darab, and Zarghan. The sowing dates were different in the studied sites: late-Nov to early-Dec in Zarghan, late-Oct to early-Nov in Karaj, late-Dec to early-Jan in Hashem Abad, and late-Dec in Darab. In addition, wheat is harvested from the late-spring to mid-summer in the study sites. Given that the main goal of this study is to find more effective agro-climatic indices that affect wheat yield during the crop growing period, the effects of any non-climatic/anthropogenic factors (i.e., genetic and technical improvements) were removed by means of double exponential smoothing method (Bannayan et al. 2010; Kheiri et al. 2017). According to Kheiri et al. (2021c), although double exponential smoothing does not entirely eliminate the impacts of anthropogenic factors on crop yield, it is the most appropriate method to smooth such kind of information. As shown in Table 1, the average wheat yield in Karaj and Darab (~ 6.2 t ha^{-1}) was higher than in Hashem Abad and Zarghan (4.6 and 4.3 t ha^{-1}, respectively).

The sites are classified into arid (Darab), semi-arid (Karaj and Zarghan), and sub-humid (Hashem Abad) climates according to Eq. 1. The range of each box plot shows differences among the studied years (1999–2018). As indicated in Table 1, the range of daily temperature variations in Zarghan (17 °C) is higher than in Karaj (12.5 °C). In addition, the annual precipitation in Zarghan is ~ 90 mm higher than in Karaj. This shows that although Zarghan and Karaj are located in semi-arid climates, there are some differences between the two selected sites. Therefore, these two sites have been considered in this study to show how wheat yield responded in two stations that are in the same climatic class but have different conditions in terms of climatic components.

Weather data including sunshine hours (h); minimum, maximum, and mean temperatures (°C); relative humidity (%); precipitation (mm); and wind speed (m s.$^{-1}$) were gathered from the synoptic station of each site for 1999–2018. The quality of weather data was checked by the Iranian Meteorological Organization (IMO). Study sites are classified into arid (Darab), semi-arid (Karaj and Zarghan), and sub-humid (Hashem Abad) regions, according to United Nations Development Program aridity index (Fig. 1):

$$Aridity index = \frac{P}{PET}\left\{\begin{array}{c} Sub-humid if 0.5-0.65 \\ Semi-arid if 0.2-0.5 \\ Arid if 0.05-0.2 \end{array}\right\} \quad (1)$$

where P indicates the cumulative annual precipitation (mm) and PET refers to the reference or potential evapotranspiration. The aridity index ranges between 0 and ∞, with higher values indicating wetter climate conditions (Rodrigo-Comino et al. 2021).

Calculation of the agro-climatic indices

Given that the main aim is to find more effective agro-climatic indices that affect wheat yield during the crop growing period, six agro-climatic indices including the cumulative amounts of precipitation (P), reference/potential evapotranspiration (PET), actual evapotranspiration (AET), evapotranspiration of crop (ETc), crop water stress (S) calculated as [1 – (AET/PET)], and soil water deficit (D) calculated as [PET–AET] were considered during nine consecutive phenological stages of wheat including emergence (1), three leaves (2), tillering (3), stem elongation (4), booting (5), flowering (6), milk development (7), dough development (8), and physiological maturity (9).

PET (mm) is defined as evapotranspiration from a short green crop that entirely covers the soil surface, shades the ground, and has no limiting water intake. According to Jensen and Allen (1990), PET was measured through the Penman–Monteith method and then it was applied to obtain ETc (mm) based on Allen et al. (1998). ETc is the evapotranspiration in standard conditions (Sultan et al. 2010) which was widely used to recognize the main drought-related agro-climatic indices affecting crop yield and to determine the optimal crop water supply–demand for achieving potential yield (Mousavi-Baygi et al. 2016; Rinaldi and He 2014). In other words, the wheat evaporating demand is grown in optimum soil water and best management practices, to achieve potential production in the given climatic conditions (Farg et al. 2012).

$$ETc = PET \times Kc \quad (2)$$

The winter wheat crop coefficient (*Kc*) was adjusted based on FAO guidelines (Doorenbos and Pruitt 1977). AET (mm) refers to the actual amount of water uptake from the soil, which includes evaporation losses from the soil surface and transpiration from the crop surface. AET is calculated based on the Eagleman (1971) polynomial function (Sultan et al. 2010):

$$\begin{aligned} AET = {} & 0.732 - 0.05ETc + \left(4.97ETc - 0.661ETc^2\right) \\ & \times MR - \left(8.57ETc - 1.56ETc^2\right) \times MR^2 \\ & + \left(4.35ETc - 0.88ETc^2\right) \times MR^3 \end{aligned} \quad (3)$$

The moisture ratio (MR) is an index to explain soil water content ranging between 0 and 1 and is calculated as:

$$MR = \frac{P}{AWC} \quad (4)$$

where P (mm) indicates the amount of precipitation in the considered period and AWC (mm) refers to the available water capacity of the soil. It demonstrates the amount of available water stored in the rhizosphere zone for the crop during the growing period to avoid water stress (Mousavi-Baygi et al. 2016). Whenever the amount of P is higher than AWC, the MR value is equal to 1. Equation 4 shows how the AWC is obtained:

$$AWC = pF \times TAW \quad (5)$$

pF is defined as the proportion (%) of TAW (mm) which refers to the drainable water from the rhizosphere zone before the beginning of moisture stress. TAW refers to the total available water stored between the soil field capacity (θ_{FC}) and its permanent wilting point (θ_{PWP}). The type of soil and rooting depth (R_d) are two main factors affecting the content of soil TAW (FAO 1998):

$$TAW = 1000 \times \left(\theta_{FC} - \theta_{PWP}\right) \times R_d \tag{6}$$

In the end, the outcomes of the mentioned equations were 216 variables, which were obtained from the calculation of six indices at four study sites and during the nine phenological stages of wheat. They can be applied in future analyses.

Principal components analysis (PCA)

PCA, a statistical multivariate procedure, uses an orthogonal conversion for the summarization of the data and provides linear non-correlated relations between two or more variables that are called principal components (PCs). PCA also provides dimension reduction with the highest variance on the first coordinate (called the first PC), the second highest variance on the second coordinate, and so on.

In this study, PCs were created through 54 variables in Karaj, Darab, Zarghan, and Hashem Abad during the study period. Then, the correlations between current PCs and crop yield were estimated to explain how these variables affect wheat yield.

Irrigation requirements (IRs)

The irrigation requirements (IRs), defined as the difference between wheat evapotranspiration demand and cumulative precipitation [ETc – P], were considered another index to assess the crop water supply–demand pattern during different phenological stages of wheat at each site. In this regard, the sum of the crop IRs during different phenological stages gives an overview of the total IRs of the crop during the growth period of each site.

Computation and analysis

In this study, the calculation of cumulative potential evapotranspiration via the Penman–Monteith method was made by means of CropWat8.0 software. Furthermore, the spatial situation of study sites was mapped by Arc-GIS10.8. PCA technique and Pearson's correlation between agro-climatic indices and wheat yield were performed using Minitab18. Finally, the graphs of IRs and temporal distribution of six agro-climatic indices (i.e., P, PET, AET, ETc, S, and D) as well as mean temperature (T) during the phenological stages of study sites were designed in R software.

Results

Analysis of agro-climatic indices variations

To receive an easier and more understandable interpretation of the agro-climatic indices variations during nine consecutive phenological stages of wheat, standardized values of all indices were investigated at each site and are shown in Fig. 2. The standard value shows how far the original values are from the mean in terms of standard deviations.

Evaluation of variations of mean temperature during the crop growing period shows that the highest and the least variations in mean temperature occurred in Hashem Abad (ranging from – 1.21 to 1.49 of standard values) and Darab (ranging from – 0.4 to 1.3 of standard values), respectively. In addition, compared with the vegetative phase (emergence to booting), the mean temperature during the reproductive phase (flowering to physiological maturity) had more variation toward the mean value in all sites (Fig. 2).

As expected, cumulative precipitation variability in all sites follows a completely inverse pattern into mean temperature in which the standard values of cumulative precipitation were higher and lower than the mean value during the vegetative (emergence to booting) and reproductive phases (flowering to physiological maturity), respectively (Fig. 2). The highest and the least range of cumulative precipitation variations during the crop growth period were observed in Darab and Karaj with the standard values of 3.04 and 2.68, respectively. Moreover, the highest cumulative precipitation occurred during the stem elongation stage in all sites. However, the least cumulative precipitation has been observed during the physiological maturity stage in Karaj and Darab, during the flowering stage in Hashem Abad, and during the last three stages (after flowering) in Zarghan (Fig. 2).

The results also show that crop evapotranspiration has remarkable coordination to both mean temperature and cumulative potential evapotranspiration, while it did not show a notable likeness to cumulative precipitation pattern during different phenological stages in study sites (Fig. 2). The greatest cumulative crop evapotranspiration was observed during the booting stage in Karaj, the dough development stage in Darab, and the flowering stage in Hashem Abad and Zarghan (Fig. 2).

The temporal distribution of cumulative actual evapotranspiration follows a completely inverse pattern compared to cumulative crop evapotranspiration in all sites. For instance, the least amounts of cumulative actual evapotranspiration were illustrated during the booting stage in Karaj (– 1.87), dough development stage in Darab (– 1.67), and flowering stage in Hashem Abad

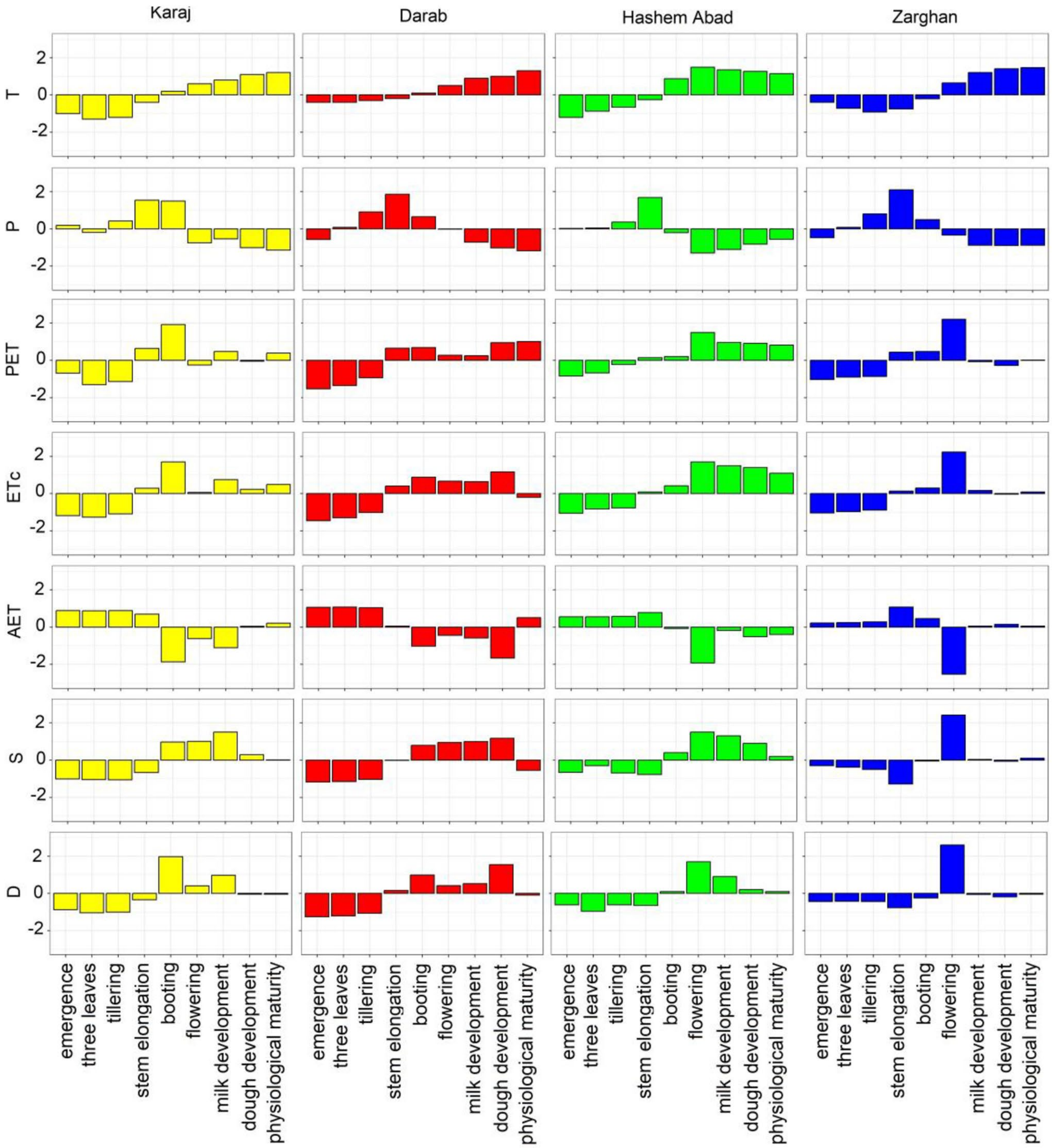

Fig. 2 The standardized values distributions of seven indices during nine consecutive phenological stages of wheat for study sites. T: mean temperature; P: cumulative precipitation; PET: cumulative potential evapotranspiration; AET: cumulative actual evapotranspiration; ETc: cumulative crop evapotranspiration; S: cumulative water stress; D: water deficit

and Zarghan (– 1.93 and – 2.53). Estimation of cumulative actual evapotranspiration is a very beneficial way to assign irrigation schedules for improving crop production, especially in water scarcity conditions (Oweis and Hachum 2006; García-Vila and Fereres 2012; Marek et al. 2016).

Principal components analysis of agro-climatic indices

The principal components (PCs) which had eigenvalues higher than 1 were considered the main PCs (McGowan et al. 2021) to decrease the number of selected variables. Therefore, in this study, the measured 54 indices were classified into 11 groups in Darab and Zarghan and 9 groups in Karaj, and 36 calculated indices were classified into 7 groups in Hashem Abad. The selected PCs covered approximately 95% of the variance of calculated indices in each site. Table 2 and Table 3 show the percentage and contribution of each principal component to wheat yield in different sites. The differences in the number and type of effective components are related to the regional weather condition of each site.

In Darab, a positive association was observed between the wheat yield and cumulative crop evapotranspiration at

Table 2 Proportion (%) of explained variance of each principal component (PC) for four study sites

Study sites	Order of PC										
	1	2	3	4	5	6	7	8	9	10	11
Karaj	26.1	15.4	14.6	11.5	10.5	7.5	5.4	3.5	2.2	–	–
Darab	21.6	17.1	12.2	11.9	8.4	5.7	4.6	4.4	3.3	2.8	2.1
Hashem Abad	24.9	22.6	15.8	12.8	8.1	5.9	3.7	–	–	–	–
Zarghan	21.6	17.2	14.6	10.6	7.9	6.7	5.4	4.1	4	2.5	2

Table 3 The relationship between the selected PCs and wheat yield for four sites in Iran

Karaj		Darab		Hashem Abad		Zarghan	
Index	*r*	Index	*r*	Index	*r*	Index	*r*
P2	−0.19	P3	0.28	P1	−0.42	P2	0.35
P5	0.49	P6	0.21	P3	0.31	P3	0.30
P8	−0.28	P7	0.21	P6	−0.35	P5	−0.53*
PET1	−0.25	P8	0.24	PET4	−0.25	P6	−0.40
PET4	0.10	P9	−0.23	PET5	−0.13	P8	−0.29
PET5	0.25	PET5	0.37	PET6	0.64*	P9	0.31
PET6	0.18	PET6	0.45*	ETC3	0.41	PET4	0.86**
PET9	0.34	PET7	−0.36	ETC4	−0.23	PET5	−0.15
ETC1	−0.25	ETC3	−0.14	ETC9	0.22	PET6	−0.46
ETC3	−0.30	ETC5	0.40	AET1	0.42	ETC4	0.87**
ETC6	0.17	ETC6	0.46*	AET3	0.43	ETC5	−0.30
ETC8	0.29	ETC8	0.16	AET6	0.46	ETC6	−0.44
ETC9	0.21	AET5	0.43	AET9	0.41	AET2	0.28
AET2	0.41	AET6	0.21	S1	0.40	AET3	0.38
AET3	0.30	AET8	−0.30	S3	−0.49	AET4	0.47
AET5	0.34	S5	0.41	S9	0.17	AET5	0.42
AET6	0.12	S8	0.29	D3	−0.31	AET8	0.31
S1	−0.14	S9	−0.21	D6	−0.53*	S2	−0.40
S2	−0.40	D5	−0.45*	D9	0.37	S3	−0.38
S5	−0.44	D6	0.26	–	–	S4	−0.30
D6	−0.22	D8	0.29	–	–	S8	−0.30
D9	−0.30	–	–	–	–	S9	0.30
–	–	–	–	–	–	D2	−0.31
–	–	–	–	–	–	D3	−0.35
–	–	–	–	–	–	D4	−0.31
–	–	–	–	–	–	D5	0.38

* and ** indicate significance at 5% and 1% probability levels, respectively. 1: emergence; 2: three leaves; 3: tillering; 4: stem elongation; 5: booting; 6: flowering; 7: milk development; 8: dough development; 9: physiological maturity. *P*, cumulative precipitation; *PET*, cumulative potential evapotranspiration; *AET*, cumulative actual evapotranspiration; ETc, cumulative crop evapotranspiration; *S*, cumulative water stress; *D*, water deficit; for example, P2 represents the amount of precipitation during three leaves stage

the flowering stage (from PC3) with a correlation coefficient of + 0.46. Furthermore, water deficit at the booting stage (from PC2) showed a significantly negative relationship with the crop yield ($r = -0.45$; Table 3).

The association between cumulative potential evapotranspiration at the physiological maturity stage (from PC3) and the crop yield was significant in Hashem Abad ($r = +0.64$). Furthermore, an increase in cumulative water deficit at the flowering stage (from PC2) significantly decreased the crop yield in this site ($r = -0.53$; Table 3).

Although the association between cumulative precipitation at the booting stage (from PC8) and crop yield was significant with a correlation coefficient of − 0.53 in Zarghan (Table 3), it could not be the desired result for yield prediction due to its weak contribution to the total variance (4.1%; Table 2). In addition, meaningful positive associations were observed between cumulative potential evapotranspiration at the stem elongation stage (from PC5), cumulative crop evapotranspiration at the stem elongation stage (from PC6), and wheat yield ($r = +0.86$ and $r = +0.87$, respectively; Table 3). As shown in Fig. 2, the amount of cumulative precipitation during the stem elongation stage was higher than that of other stages with the least cumulative water stress and water deficit in Zarghan.

Our results represent no significant relationship between agro-climatic indices and wheat yield in Karaj (Table 3). Generally, cumulative precipitation and different types of evapotranspiration (i.e., cumulative potential evapotranspiration, cumulative crop evapotranspiration, and cumulative actual evapotranspiration) showed positive associations with crop yield, while the correlations between cumulative water stress, cumulative water deficit, and wheat yield were mostly negative. In addition, the significant correlations between agro-climatic indices and wheat yield mostly belonged to the first PCs which possess strong variances (more than 12%).

Determination of irrigation requirements

The difference between the amounts of crop water requirement (ETc) and cumulative precipitation, which refers to the irrigation requirements, during the reproductive phase was more than the vegetative phase for all sites (Fig. 3). In this regard, the cumulative irrigation requirements during the reproductive phase were 135.2, 137.7, 49.8, and 273.3 mm in Karaj, Darab, Hashem Abad, and Zarghan, respectively. In addition, cumulative irrigation requirements for the total crop growth period were 166.2, 169.9, 49.8, and 300 mm in Karaj, Darab, Hashem Abad, and Zarghan, respectively (Fig. 3). Zarghan has a semi-arid climate and was anticipated to require lower irrigation than Darab, which has an arid climate (Fig. 1). Figure 3 also shows that the irrigation requirements in arid and semi-arid regions (i.e., Karaj, Darab, and Zarghan) occurred earlier (during the booting stage) than in the sub-humid region (i.e., Hashem Abad; during flowering stage).

Discussion

The present study investigated the wheat yield response to the variations of six drought-related agro-climatic indices. First, PCA was used to recognize the main components that largely explained the variations of agro-climatic indices during different stages of the crop growing period. Then, the relationships between the major components, retrieved from PCA, and wheat yield were assessed. Finally, wheat irrigation requirements were measured to evaluate the regional water supply–demand patterns during the crop growing period to design an appropriate irrigation management schedule separately for each studied site.

Agro-climatic indices

The results showed that the highest and the most minor variations in mean temperature occurred in Hashem Abad and Darab, respectively. Cumulative precipitation variability in all sites followed a completely inverse pattern into mean temperature. The biggest and lowest ranges of cumulative precipitation changes during the crop growth period were found in Darab and Karaj, respectively, during the crop growth period. In Hashem Abad, where wheat is cultivated under the rainfed condition, the lowest cumulative precipitation and the highest mean temperature occurred during the flowering stage, as the most important stage in terms of water stress (Kheiri et al. 2021b), which could impose irreversible effects on final yield by reducing pollination, grain weight, and grain number and shortening the grain filling period (Rezaei et al. 2015; Bannayan and Sanjani 2011).

The findings also reveal that crop evapotranspiration is highly correlated with both mean temperature and cumulative potential evapotranspiration, which was not valid for cumulative precipitation patterns at different phenological stages. These results are in line with those of Mousavi-Baygi et al. (2016) who revealed that the temporal distributions of cumulative precipitation and cumulative crop evapotranspiration did not have significant likeness together. Furthermore, Nistor et al. (2016) explained that the inter-seasonal variations of cumulative crop evapotranspiration are primarily attributed to the alterations in ambient air temperature.

The highest cumulative crop evapotranspiration was recorded in Karaj during the booting stage, Darab during the dough development stage, and Hashem Abad and Zarghan during the flowering stage. It should be considered that cumulative crop evapotranspiration during different phenological stages refers to the environmental capacity in extracting water from the soil root zone via the root system and is

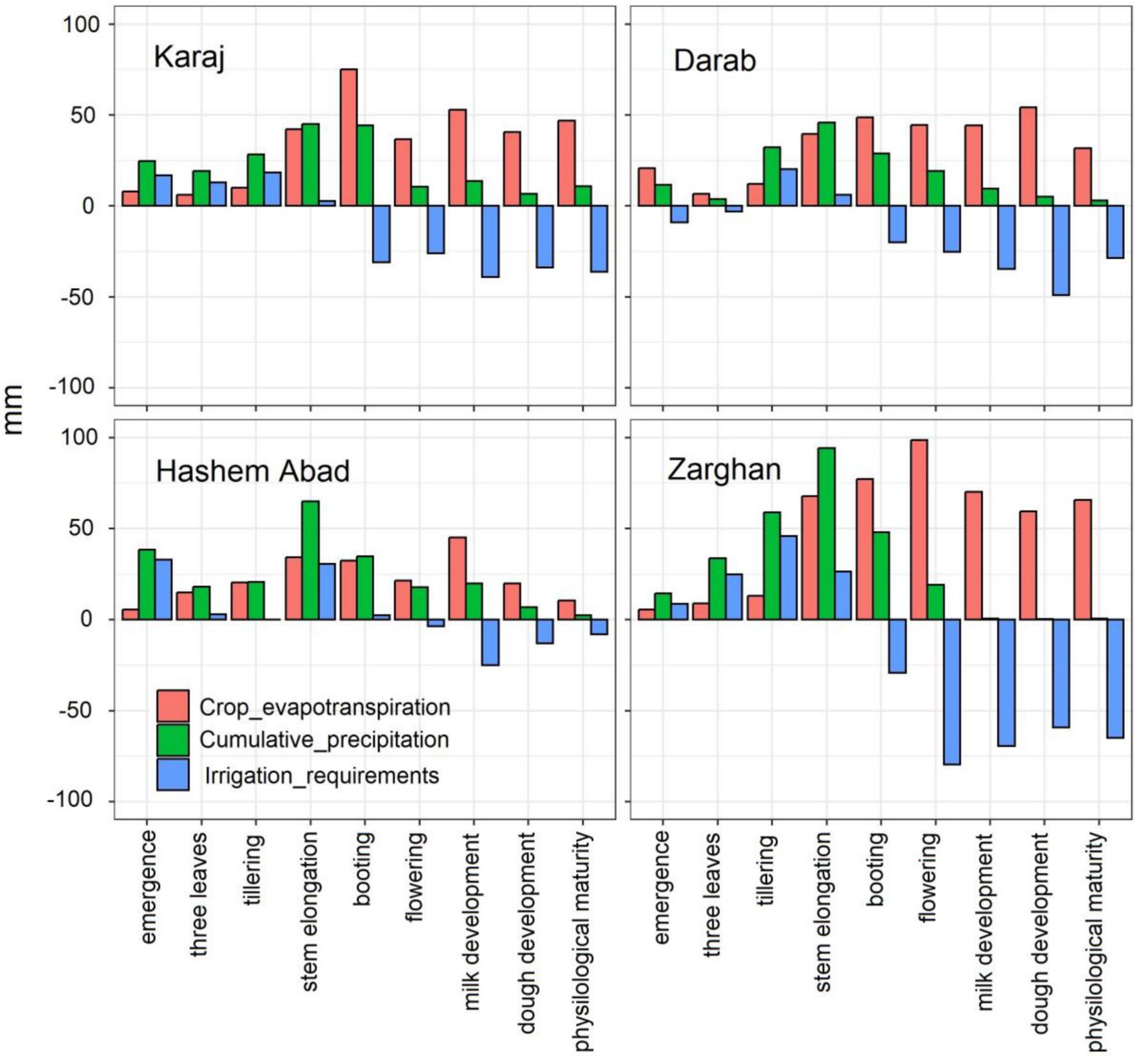

Fig. 3 Temporal variations of cumulative precipitation, crop evapotranspiration, and irrigation requirements during nine consecutive phenological stages of wheat in the study sites

known as the crop water demand supplied by precipitation and/or irrigation. Adequate soil water supply at the same time as the crop water demand eliminates the risk of drought stress, allows appropriate crop growth and development, and consequently results in favorable crop yield. However, drought stress during the crop water demand periods causes disproportionate damage to the final yield due to the abortion of flowers, reduction of pod production, and shrinking of grain size (Hussain et al. 2019).

Considering both cumulative crop evapotranspiration and cumulative actual evapotranspiration patterns, it could be interpreted that the highest water demand (the highest cumulative crop evapotranspiration) of wheat coincided with a severe shortage of water supply (the least cumulative actual evapotranspiration) in each site. In other words, existing air humidity and/or soil moisture could not meet the crop water requirements during the water-sensitive periods in the study sites. Such conditions would lead to an irreversible reduction in the length of phenological stages and hinder the formation of proper crop yield (Sehgal et al. 2018). These results were made more plausible when the highest cumulative water stress and cumulative water deficit were also observed during the stages similar to that obtained for cumulative crop evapotranspiration. Although these two indices (i.e., cumulative water stress and deficit) indicate the water shortages regarding cumulative potential evapotranspiration, they help achieve an overview of the climatic conditions of the study sites during different phenological stages.

Overall, the findings illustrated that wheat faced intense water shortage within the reproductive phase in all of the studied sites which could deleteriously affect crop development and final wheat yield. Consistent with this finding, Nadeem et al. (2019) reported that during the crop growing period, flowering to physiological maturity (reproductive phase) is highly vulnerable to water scarcity. In another study, Farooq et al. (2019) indicated that under water deficit conditions, particularly during the reproductive phase, the reduction in crop growth and productivity is attributed to the slowness of physiological processes, which in turn slows down the growth processes. Many reports also demonstrated that water shortage (i.e., drought stress) in the reproductive phase severely decreased the photosynthetic activity, damaged oxidative metabolism, increased membrane instability, disrupted stomatal conductance, and accelerated leaf senescence in cereals (Suzuki et al. 2014; Alghabari et al. 2015; Zheng et al. 2016; Fahad et al. 2017; Zarei et al. 2020).

Principal components analysis

As the results showed, wheat production and cumulative crop evapotranspiration during the flowering stage were positively related in Darab. Furthermore, water shortage at the booting stage was found to have a substantial negative link with crop yield. These findings are in line with those of Ihsan et al. (2016), who recognized the booting stage as one of the most sensitive stages to water shortage and reported that the absence of water shortage in this stage is necessary to achieve acceptable wheat yield. In addition, Alghabari et al. (2016) demonstrated that drought stress at the booting stage of wheat negatively affected the wheat yield by decreasing the number of grains per spikelet.

According to the findings, in Hashem Abad, the relationship between cumulative potential evapotranspiration at the physiological maturity stage and crop output was substantial. Moreover, an increase in cumulative water deficit at the flowering stage reduced crop production significantly at this site. In general, the flowering stage is the most crucial stage in crop yield formation, and the water limitation during this stage leads to reduced grain number and subsequently yield reduction, particularly in rainfed conditions (Bannayan and Sanjani 2011; Semenov et al. 2014). Comparing the current results with worldwide studies, Kheiri et al. (2017) investigated the association between weather variables and dryland wheat yield in northwestern Iran and illustrated the positive and significant correlations between De Martonne aridity index and crop yield at the flowering stage (April to May). Chen et al. (2016) evaluated the influence of drought stress on crop production changes in northern China by characterizing the variability of drought stress at the post-heading phases of winter wheat. They discovered that extreme drought stress reduced yield significantly in most of the study region. However, adequate humidity during the flowering stage can delay leaf senescence because it has an impact on how much terminal drought is reduced or eliminated, which is the greatest risk to rainfed wheat production globally and results in chlorosis and membrane breakdown in the leaves (Farooq et al. 2014), which increases grain yield (Nio et al. 2011).

Cumulative potential evapotranspiration at the stage of stem elongation, cumulative crop evapotranspiration at the stage of stem elongation, and wheat yield all showed substantial positive relationships. In Zarghan, the stem elongation stage experienced more cumulative precipitation than previous phases, which had the least degree of water stress and water shortage. In such conditions, an increase in evapotranspiration results in a higher accumulation of dry matter which would ultimately enhance the final yield (Whitechurch et al. 2007). These findings are supported by Hlaváčová et al. (2018), who evaluated the integrated effects of heat and drought stresses on winter wheat yield during the crop growth period and concluded that the number and weight of grain per spike substantially went down due to drought stress during the stem elongation stage.

From the findings of this study, many of the significant correlations occurred in the reproductive phase, which emphasizes the higher sensitivity of crop yield to the agro-climatic indices variations during the reproductive phase. To be more specific, booting to flowering in the arid region (Darab), flowering in the sub-humid region (Hashem Abad), and stem elongation to booting in the semi-arid region (Zarghan) were the most sensitive periods of wheat to agro-climatic indices variations, and water shortage in these periods can lead to wheat yield reduction. Although wheat is cultivated under irrigation conditions in arid and semi-arid regions (e.g., Darab and Zarghan), these regions have experienced more water limitations than the sub-humid region (Hashem Abad), where wheat is cultivated under rainfed conditions. Identifying the most crucial water demand periods of the crop helps farmers to apply a set of suitable methods to optimize the use of scarce water and to enhance crop water use efficiency, particularly in drier regions.

Irrigation requirements

In this study, the irrigation requirements of wheat were measured at nine consecutive phenological stages during the wheat growing period. As reported by Rinaldi and He (2014), assessing irrigation requirements is a vital and effective operation for the agronomic and economic viability of small farms in terms of both (i) water savings and (ii) improved crop yields. According to Pereira et al. (2020), adopting adequate irrigation programs that should result in optimal yields and agricultural and irrigation techniques that enable a decrease but optimization of water consumption, specifically non-useful ones, are both very important. In general, our findings revealed that the irrigation requirements during the reproductive phase were more than the vegetative phase. Furthermore, Zarghan as an area with a semi-arid climate showed the highest irrigation requirements among the studied sites. It can be attributed to Zarghan's higher altitude of 1680 masl, showing that it is exposed to flows of stronger winds (Archer and Caldeira 2009), which increases the evapotranspiration rate and consequently exacerbates crop water demand (Dinpashoh et al. 2011). The results also showed that the irrigation requirements in arid and semi-arid regions occurred earlier (during the booting stage) than in the sub-humid region (during the flowering stage). These findings are consistent with those obtained by Sarvestani et al. (2008), Singh (1981), and Yang et al. (2019), who demonstrated that booting to flowering is the most critical period of wheat growth during a water shortage, and controlled irrigation in this period could significantly improve wheat yield (Shao et al. 2014). The results obtained in this section could help farmers to adjust the irrigation schedule based on wheat irrigation requirements during the crop growth period to eliminate the negative effects of water shortage on wheat yield.

Regarding the limitations of this study, the effect of agro-climatic indices on wheat yield in Mediterranean and humid climates was not investigated due to a lack of access to long-term crops and climatic information in these two climates. Given that these climates account for 19.5% of Iran's agricultural areas (Kheiri et al. 2023), future research should focus on the response of wheat yield to fluctuations in agro-climatic indices in these locations. Furthermore, as previously indicated, due to a lack of sufficient and reliable information, the primary focus of this research was solely on calculating irrigation requirements and optimizing irrigation management for wheat in Iran. Considering that water access is a serious crisis in Iran's agricultural sector (Madani 2014), it is recommended that future studies investigate the effects of variations in agro-climatic indices on other major crops (e.g., corn and barley) in order to properly allocate water resources in the agricultural sector. The lack of access to information on different wheat cultivars in the studied sites was another limitation of the present study. Therefore, it is suggested that to identify the best drought-tolerant cultivars in each site, further studies focus on the evaluation of the impacts of the agro-climatic indices on various wheat cultivars' yield in these regions.

Conclusions

Drought stress, as the main limiting abiotic factor for wheat production, plays a crucial role in Iran. Changes in annual mean temperature and cumulative precipitation are temporally and spatially high across Iran, which leads to exacerbating the risk of drought and unstable crop production. The findings highlighted that the studied agro-climatic indices variations were more dependent on seasonal mean temperature compared with seasonal precipitation. More importantly, wheat is undergoing severe water shortages during the reproductive phase compared with the vegetative phase in all studied regions. Furthermore, wheat irrigation requirements in arid and semi-arid regions start from the booting stage (earlier) while in the sub-humid region, they begin from the flowering stage (later). The findings of this study could help decision-makers to adjust the irrigation schedule based on wheat irrigation requirements during the crop growth period, appropriately manage water resources, and mitigate the harms of drought stress to wheat yield, particularly under water shortage conditions. As ~ 92% of the agricultural lands of Iran have arid, semi-arid, and sub-humid climates, without thoughtful adaptation measures, these areas may be exposed to more severe drought stress due to the forthcoming climate change, which will lead to limited wheat production. Finally, our method could be adopted in other regions that are exposed to similar problems to improve the adaptive capacity of the agricultural sector and diminish its vulnerability to drought events.

Data availability Data is available upon request.

Declarations

Ethical approval None.

Consent to participate All authors contributed equally to the preparation of this manuscript.

Consent for publication All authors have read the manuscript and agreed to its publication.

Conflict of interest The authors declare no competing interests.

Research involving human participants and/or animals None.

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