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Investigation of Changes in the Green and Blue Water Footprint of Wheat in Drought and Rainy Seasons (A Case Study on Wheat under the Dez Irrigation Network, Southwestern Iran)

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Abstract

Water resource management in agriculture, especially in arid and semi-arid regions, is a major global challenge. This study examines the impact of drought and wet periods on the blue water footprint (WFblue) and green water footprint (WFgreen) of wheat within the Dez irrigation network in Southwest Iran (1993–2023). The objective is to analyze variations in the water footprint using 30 years of meteorological data, wheat yield, and water input to the Dez network. Data were evaluated through WFblue/WFgreen models and ANOVA Results show that severe drought significantly increases WFblue by approximately 121.07% (375.20 m^3ton^{-1}) compared to the normal condition (169.59 m^3ton^{-1}), while reducing WFgreen, exerting substantial stress on groundwater and surface water resources. Variance analysis indicates that drought indices (RDI, SPI) significantly affect water resources, with SPI as the primary driver of variability. This study builds on Hoekstra's water footprint theory by integrating adaptive management strategies for drought and wet periods, emphasizing temporal variations in water use. The findings highlight the urgent need for smart water management and advanced meteorological forecasting to guide policies that mitigate drought impacts and enhance water-use efficiency.

Introduction

Approximately half of global agricultural production relies on irrigation systems, with agriculture consuming 71% of freshwater resources, making it the largest water consumer worldwide, compared to 18% for industry and 8% for urban use (Nalbantis and Tsakiris, 2009; Burton, 2010). Optimizing water management in agriculture can significantly alleviate water shortages in other sectors and improve agricultural productivity.

Climate change, reduced precipitation, and altered rainfall patterns have heightened the need for optimized water management strategies. Traditional water management methods are no longer sufficiently effective. Agricultural water management comprises two main components: supply management (e.g., harnessing surface water, utilizing groundwater, and transferring water via irrigation channels) and demand management (e.g., modifying consumption patterns, input adjustments, and stakeholder participation). Given water resource constraints, demand management has become a key strategy for improving efficiency.

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he water footprint concept, introduced by Hoekstra in 2002, serves as a metric to assess water consumption in producing goods, particularly in agriculture, and has been applied to evaluate water security (Hoekstra et al., 2011; Veettil and Mishra, 2016). However, initial water footprint models, such as those developed by Hoekstra and colleagues before the standardized framework of 2011, often relied on annual average data, neglecting seasonal and inter-annual variations in blue and green water resources (Borzoo et al., 2024). For instance, these models typically overlooked fluctuations in precipitation and evapotranspiration, leading to inaccurate estimates of crop water requirements and inefficient irrigation planning, particularly during drought and wet periods. Evaluating crop water requirements and their variations under these conditions is essential for effective water management. The blue water footprint (WFblue) represents freshwater directly sourced from surface and groundwater, while the green water footprint (WFgreen) refers to rainwater stored in soil and vegetation. Assessing these resources can significantly enhance sustainable water management. This study examines changes in the blue and green water footprints of wheat over a 30-year period (1993–2023) in the Dez irrigation network, addressing a research gap in the region where prior studies, such as Panahi and Malik Muhammadi (2008) and Salarian (2014), focused on general water consumption and irrigation development but overlooked temporal variations in blue and green water footprints under drought and wet conditions. The main research question is: Can the network's water supply during drought compensate for green water shortages and prevent yield reductions?

Materials and Methods

Study Area

The study was conducted in the modern Dez irrigation network, located in northern Khuzestan Province, Iran, recognized as one of the largest and oldest modern irrigation networks in the country. Construction began in 1957 and was fully operational by the 1976–1977 agricultural season, aimed at supplying agricultural water and controlling floods from the Dez River, utilizing water from the Dez Dam. It is bounded by the northern Dezful hills to the north, Haft-Tappeh lands and the Shavoor River to the south, the Shoor River (Gelal Kohnag) to the east, and the Karkheh River to the west, covering the cities of Dezful, Andimeshk, and Shush. The network spans a gross area of approximately 111,674 hectares and a net area of 93,599 hectares, divided into three regions: Sabili (6,000 hectares, with water pumped due to elevated lands, featuring five pumping stations and a 12.8 km main canal), East Dez (37,000 hectares), and West Dez (50,000 hectares), based on the agricultural lands' positions relative to the Dez River and the regulating dam (North Khuzestan Irrigation Networks Operation Company). The region experiences a semi-arid climate with an average annual rainfall of 327 mm, a potential evapotranspiration of about 2,460 mm, and an average annual temperature of 24.6°C, based on 30-year data (1993–2023) from the Safiabad Dezful station (Details are provided in Table (1). The Dez River exhibits a perennial hydrological regime with seasonal fluctuations, with higher flows in the wet season (spring) and lower flows in the dry season (summer). Wheat constitutes approximately 36% of the cropping pattern in the Dez irrigation network (not the entire northern Khuzestan region), making it the dominant crop, based on cultivated area data from the North Khuzestan Irrigation Networks Operation Company and corroborated by the Khuzestan Agricultural Organization's statistical yearbook (NKINOC, n.d.; Khuzestan Agricultural Organization, 2023). Wheat planting in the Dez network typically occurs from mid-November to mid-December, with harvesting from late April to mid-May. The average irrigated wheat yield in the Dez network, used for water footprint calculations on an annual basis (1993–2023), is approximately 4,000 kg/ha (NKINOC, n.d.). The network employs diverse structures such as regulating dams, diversion dams, canals, and drains, including concrete-lined canals and 76 irrigation gates in the Sabili region, making it a distinguished and efficient irrigation system. Its selection for this study was driven by its historical significance, vast coverage, progressive farmers facilitating better

cooperation in surveys, and the need to redefine cropping patterns due to aging infrastructure, potential structural damage, and reduced water inflow caused by climate change, upstream water transfers, and multiple upstream dams. Meteorological data were collected from the Safiabad Dezful station (48°38'24"E, 32°40'12"N, 143 m above sea level), chosen for its proximity and reliable long-term data. The location of the network is shown in Figure (1).

Table 1- Average 30-Year Meteorological Data (1993–2023) from Safiabad Dezful Station

Year	Tmin (°C)	Tmax (°C)	RH (%)	Wind (Km/day)	Sun (hours)	Rain (mm)	Evaporation (mm)
1993-2023	16.5	32.6	55.25	329	3.4	327	2459.6

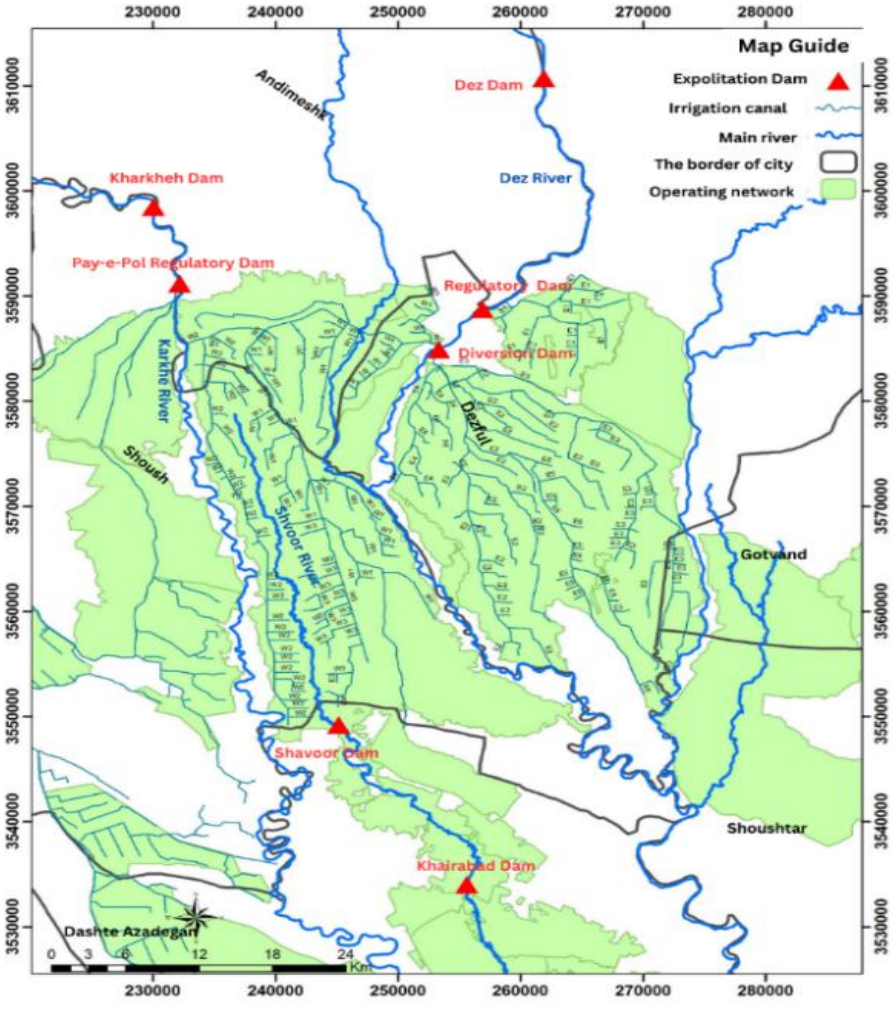


Fig.1- location of Dez network

Data and Tools

The study utilized a dataset comprising climatic parameters (maximum and minimum temperature, precipitation, wind speed, sunshine hours, and evaporation), 30-year meteorological data (1993–2023) from Safiabad Dezful station, 30-year wheat yield data (1993–2023) from the Khuzestan Agricultural Organization, and water input data to the Dez irrigation network from the North District Irrigation and Drainage Operation Company.

Data were processed using two software tools:

DrinC (version 1.7) to calculate drought indices (RDI, SPI, SDI) and assess wet and dry conditions, and Cropwat (version 8.0) to compute blue and green water footprints (WFblue and WFgreen).

Blue and Green Water Footprint Calculation

The blue and green water footprints were calculated following the global water footprint standard by Hoekstra et al. (2011). Cropwat was used to determine WFblue and WFgreen based on crop yield data from the Khuzestan Agricultural Organization. The calculations followed these equations:

$$WF_{Blue} = \frac{ET_{Blue}}{Y} \times 10 \quad (1)$$

$$WF_{Green} = \frac{ET_{Green}}{Y} \times 10 \quad (2)$$

Where:

WF_{Blue}, WF_{Green}: Blue and green water footprints ($m^3 ton^{-1}$).

ET_{Blue}, ET_{Green}: Blue and green evapotranspiration (mm), calculated using:

Y: Crop yield (ton ha^{-1}).

$$ET_{Blue} = \begin{cases} 0, & Eff \geq ETc \\ ETc - Eff\ Rain, & other\ wise \end{cases} \quad (3)$$

$$ET_{Green} = \begin{cases} ETc, & Irr.Req = 0 \\ Eff\ Rain, & other\ wise \end{cases} \quad (4)$$

Where:

ETc: Crop evapotranspiration (mm day^{-1}).

$Eff\ Rain$: Effective rainfall (mm), calculated using the USDA SCS method as configured in Cropwat (version 8.0). This method estimates effective rainfall based on total rainfall (P) by accounting for runoff and deep percolation, following the approach outlined by Allen et al (1998). The average effective rainfall over the 30-year period (1993–2023) was 162.2 mm.

Equation (1) states that if effective rainfall exceeds crop evapotranspiration, the blue evapotranspiration (ET_{Blue})is considered zero; otherwise, it equals the difference between crop evapotranspiration (ETc) and effective rainfall ($Eff\ Rain$).

Equation (2) indicates that the green evapotranspiration (ET_{Green}) equals the crop water requirement when irrigation demand is zero; in all other cases, it is equivalent to the effective rainfall ($Eff\ Rain$).

The parameter ETc (crop evapotranspiration) in the above equations was estimated using the reference evapotranspiration (ET_o) as described by Allen et al. (1998) and supported by alternative methods evaluated by Fisher and Pringle (2013); (Equation 6).

$$ET_C = ET_o \times Kc \quad (5)$$

Where:

Kc: Crop coefficient, adjusted based on local planting and harvesting dates and climatic parameters for wheat over 30 years, as per FAO guidelines (Allen et al., 1998).

ET_o: Reference evapotranspiration, calculated using the Penman-Monteith equation (Allen et al., 1998).

$$ET_0 = \frac{0.408(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.3u_2)} \quad (6)$$

Where:

Rn:Net radiation (MJ $m^{-2} day^{-1}$).

G: Soil heat flux (MJ $m^{-2} day^{-1}$).

γ: Psychrometric constant (kPa°C^{-1}).

T:Air temperature (°C).

u_2:Wind speed at 2 m height (m s^{-1})

e_s, e_a:Saturation and actual vapor pressure (kPa)

Δ: Slope of the vapor pressure curve (kPa°C^{-1})

Drought and Wet Period Assessment

Drought intensity was evaluated using three indices:

Reconnaissance Drought Index (RDI): Calculated using cumulative precipitation (P) and potential evapotranspiration (PET) to assess water balance (Hargreaves & Samani, 1985; Tsakiris et al., 2007). PET was computed using the Hargreaves method, as implemented in the DrinC software (version 1.7), due to its simplicity and reduced data requirements compared to the Penman-Monteith method. The Hargreaves method estimates PET as follows:

$$PET = 0.023(0.408) \times (T_{mean} + 17.8) \times \sqrt{T\,max - T\,min} \times R_a \quad (7)$$

Where:

PET: Potential evapotranspiration (mm day^{-1})

T_{mean}: Mean daily temperature (°C)

T max, T min: Maximum and minimum daily temperatures (°C)

R_a:Extraterrestrial radiation (MJ m^{-2}day^{-1}), calculated based on latitude and calendar day of the year as per Hargreaves and Samani (1985).

0.408: Conversion factor from MJ m^{-2} to mm.

The classification of climatic and hydrological conditions based on SPI, RDI, and SDI indices is presented in Table (2).

Note: Potential evapotranspiration (ET_0) was calculated using the Penman-Monteith method, and effective rainfall (Eff. rain) using the USDA SCS method (average Eff. rain: 162.2 mm). ET_0 represents annual values, whereas crop evapotranspiration (ETc) for wheat during the growing season (approximately 600 mm) is lower due to the crop coefficient (Kc).

Positive values indicate wet periods, while negative values indicate dry periods. RDI was computed for 3, 6, 9, and 12-month periods within a hydrological year. RDI was selected over alternatives like the Standardized Precipitation Evapotranspiration Index (SPEI) due to its direct compatibility with DrinC software and its focus on water balance, as outlined by Tsakiris et al. (2007). Additionally, the meteorological monitoring network design for RDI was optimized based on approaches by Tsakiris et al. (2008).

Standardized Precipitation Index (SPI): A statistical tool based on long-term precipitation data, fitted to a gamma distribution and transformed to a normal distribution (Hayes et al., 2007). Positive SPI values indicate above-average precipitation, while negative values indicate drought. SPI was chosen for its simplicity and standardized approach to analyzing precipitation and identifying climatic droughts.

Streamflow Drought Index (SDI): Used to assess hydrological drought based on cumulative streamflow volume (Vangelis et al., 2013). Due to data availability constraints, only 20 years of streamflow data (2001–2021) were available for computing SDI, compared to the 30-year period (1993–2023) used for climatic indices (RDI and SPI). This shorter timeframe may limit capturing long-term hydrological drought trends in the earlier (1993–2000) and later (2022–2023) years, but SDI was included as a complementary index to evaluate hydrological drought, enhancing the climatic analyses provided by RDI and SPI. In this study, climatic drought and water footprint data were analyzed using the SPI and RDI indices over a 30-year period (1993–2023). Precipitation data and related information for these indices were fully available for this period. On the other hand, to analyze hydrological drought and assess water inflow in the irrigation network, the SDI index was used. Due to limitations in the availability of water inflow data for the network, these analyses were conducted based on a 20-year dataset (2001–2021). The difference in time periods reflects data availability constraints but does not compromise the primary focus on climatic drought impacts, as SDI serves as a supplementary index.

Table 2- Classification of Climatic and Hydrological Conditions Based on SPI, RDI, and SDI Indices

Classification	SPI, RDI, SDI Value
Extremely wet	≥ 2.0
Very wet	1.5 to 1.99
Moderate wet	1.0 to 1.49
Near normal	-0.99 to 0.99
Mild drought	-1.0 to -1.49
Moderate drought	-1.5 to -1.99
Severe drought	≤ -2.0

Note: Classification criteria are based on global standards (McKee et al., 1993 for SPI; Tsakiris et al., 2007 for RDI; Nalbantis and Tsakiris, 2008 for SDI) and applied to SPI, RDI, and SDI indices calculated using DrinC software (version 1.7) for the October–September period. SPI is based on precipitation, RDI on the precipitation-to-potential evapotranspiration ratio (P/PET), and SDI on river flow. Data normalization for SPI and RDI was performed using DrinC's standard process, fitting precipitation (for SPI) and P/PET ratios (for RDI) to a gamma distribution and transforming them to a normal distribution(Abramovitz and Stegun, 1965; Thom, 1958).
SDI normality was confirmed through visual inspection (histograms and Q-Q plots), supported by the Central Limit Theorem due to the large sample size (20 years). SDI data are available for 2001–2021.

Methodology

Statistical analysis was performed using a two-way ANOVA to evaluate the individual and interactive effects of drought indices on water resources. The independent variables were the drought indices (RDI, SPI, and SDI), while the dependent variables were the blue and green water footprints (WFblue and WFgreen). The interactive effects between SPI and RDI, as well as other combinations of indices (e.g., SPI-SDI, RDI-SDI), were examined to understand their combined impact on the water footprints. All climatic data (e.g., precipitation, temperature, wind speed, sunshine hours, and potential evapotranspiration) used as inputs to compute SPI and RDI were normalized by the DrinC software (version 1.7) as part of its standard computation process. This process ensures robust statistical analysis by fitting precipitation (for SPI) and P/PET ratios (for RDI) to a gamma distribution and transforming them to a normal distribution, meeting the normality assumptions required for ANOVA. For SDI, which relies on streamflow data, normality was assessed through visual inspection using histograms and Q-Q plots, and the large sample size (20 years) supported the assumption of approximate normality based on the Central Limit Theorem. The analysis also assumed homogeneity of variances (confirmed using Levene's test) and independence of observations (ensured by the study design and data collection across different years). Post-hoc tests, such as Tukey's test, were not conducted, as the study focused on the overall significance of main and interactive effects; however, such tests could be considered in future studies for pairwise comparisons of drought severity levels.

Results and Discussion

The use of a 20-year period (2001–2021) for SDI, compared to the 30-year period (1993–2023) for RDI and SPI, may have limited the ability to capture long-term hydrological drought trends in the earlier (1993–2000) and later (2022–2023) years. In this research, SPI and RDI were employed to assess climatic drought and its impact on the water footprint, while SDI was used to evaluate hydrological drought and the water inflow to the irrigation network, complementing the climatic analyses. Since SDI was used as a complementary index, its shorter time frame is unlikely to have significantly impacted the overall findings, which primarily focus on water footprint dynamics influenced by climatic variations.

Comparison of SPI and RDI

Comparison of the SPI and RDI indices in (3) revealed that both indices generally provide similar interpretations of drought and wet conditions in most years. For instance, in 2019, which experienced widespread flooding in Khuzestan, both indices indicated wet conditions (SPI = 1.80, Very Wet; RDI = 1.50, Very Wet), consistent with a decrease in the blue water footprint (WFblue = 50.0 m^3ton^{-1}) and an increase in the green water footprint (WFgreen = 376.5 m^3ton^{-1}). However, in drought years such as 1995 (SPI

= -1.83, Moderate Drought; RDI = -1.75, Severe Drought) and 2021 (SPI = -2.58, Severe Drought; RDI = -2.57, Extremely Drought), the RDI index indicated a greater severity of drought.

Water Footprint and Drought Analysis

The blue and green water footprints (calculated using Cropwat 8.0) and drought/wet conditions (assessed using DrinC 1.7) are summarized in Table (3) and illustrated in Figure (2).

Figure (2) illustrates a consistent increase in WFblue, indicating greater reliance on blue water resources (groundwater and surface water). Reduced effective precipitation is a primary driver of this trend, increasing pressure on blue water to compensate for deficits. This raises concerns about overexploitation of groundwater and sustainable management. Conversely, WFgreen shows a declining trend, reflecting limited access to effective rainfall during wheat planting, possibly due to reduced soil infiltration, uneven rainfall distribution, or suboptimal farm management practices (e.g., non-optimal crop rotation delaying planting).

Table 3 - Exit code of DrinC and Cropwat

Year	SPI	RDI	SPI interpretation	RDI interpretation	Wfblue ($m^3\ ton^{-1}$)	Wfgreen ($m^3\ ton^{-1}$)
1993	1.12	1.21	Moderately Wet	Moderately Wet	133.2	220.1
1994	0.92	0.97	Near Normal	Near Normal	123.5	220
1995	-1.83	-1.75	Moderate Drought	Moderate Drought	222.3	139
1996	0.73	0.71	Near Normal	Near Normal	58.4	351.7
1997	1.37	1.4	Moderately Wet	Moderately Wet	43.6	324
1998	0.37	0.3	Near Normal	Near Normal	57.3	306.3
1999	0.63	0.56	Near Normal	Near Normal	112.6	279.6
2000	0.18	0.16	Near Normal	Near Normal	111.7	360.2
2001	0.37	0.3	Near Normal	Near Normal	174	236.5
2002	-0.04	-0.03	Near Normal	Near Normal	119.5	254.5
2003	-0.64	-0.61	Near Normal	Near Normal	212.2	204.6
2004	0.55	0.56	Near Normal	Near Normal	112.4	280.1
2005	-0.05	-0.06	Near Normal	Near Normal	86.6	260.9
2006	1.12	1.09	Moderately Wet	Moderately Wet	80.8	281.8
2007	-0.04	-0.04	Near Normal	Near Normal	79	284.2
2008	-1.38	-1.37	Mild Drought	Moderate Drought	314.2	88.7
2009	-0.6	-0.53	Near Normal	Near Normal	267.5	124
2010	-0.7	-0.73	Near Normal	Near Normal	265.2	151.8
2011	0.06	0.07	Near Normal	Near Normal	200.6	227.7
2012	-0.09	-0.09	Near Normal	Near Normal	211.3	192.4
2013	-0.56	-0.52	Near Normal	Near Normal	318.9	132.6
2014	0.21	0.26	Near Normal	Near Normal	152	249.9
2015	-0.17	-0.14	Near Normal	Near Normal	243.6	202.1
2016	-1.28	-1.25	Mild Drought	Mild Drought	202.8	178.9
2017	-1.33	-1.4	Mild Drought	Mild Drought	402.3	108.3
2018	1.41	1.32	Moderately Wet	Moderate Drought	188	281.1
2019	1.8	1.50	Very Wet	Very Wet	0.4	376.5
2020	0.81	0.76	Near Normal	Near Normal	197.5	252.7
2021	-2.58	-2.57	Severe Drought	Severe Drought	331.9	101.1
2022	-1.38	-1.43	Mild Drought	Mild Drought	375.2	174.5
2023	-135	-1.4	Mild Drought	Mild Drought	464.9	79.4

Note: Interpretation based on standard thresholds; WF values in m^3/ton. RDI calculations adapted from (Tsakiris et al., 2008)

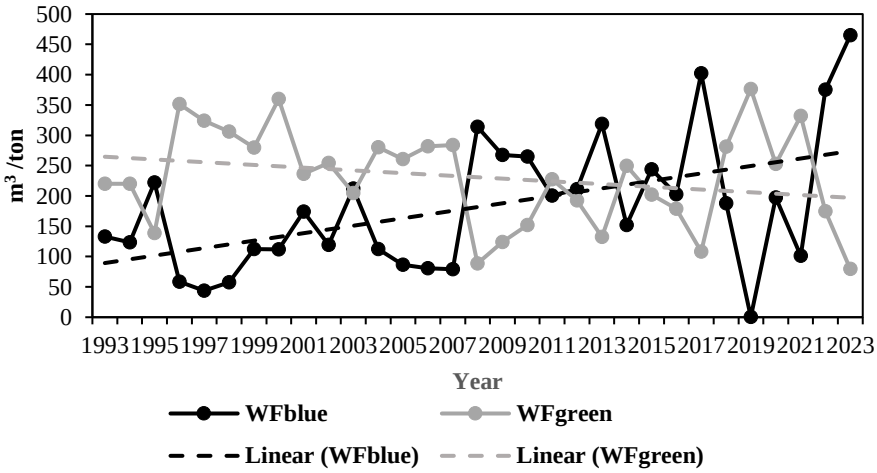


Fig. 2- 30-year changes in the blue and green water footprint of wheat in the cultivated lands of the Dez irrigation network

Table 4- Correlation analysis and relationship between drought indicators and blue and green footprints

Indicators	SPI	RDI	WFblue	WFgreen
SPI	1	0.998505	-0.58726	0.380326
RDI	0.998505	1	-0.58075	0.362443
WFblue	-0.58726	-0.58075	1	-0.88924
WFgreen	0.380326	0.362443	-0.88924	1

The results indicated a significant interactive effect between SPI and RDI on the blue water footprint (WFblue) of wheat, particularly during drought periods Table (4). The underlying mechanism of this relationship stems from the reduction in effective rainfall (Eff. rain) during drought conditions, as reflected by negative SPI and RDI values. When Eff. rain decreases below the crop evapotranspiration requirement (ETc), the shortfall in water availability must be compensated through irrigation, thereby increasing ETblue. As per the water footprint calculation framework (Equations 3 and 4), ETblue is calculated as ETblue = ETc − Eff. rain when Eff. rain < ETc. For instance, in a drought year like 2008 (SPI = -1.2), the effective rainfall (Eff. rain) was 169.2 mm, significantly below the average crop evapotranspiration (ETc) during the growing season of approximately 600 mm Table (1), resulting in a higher ETblue to meet the water needs of wheat. This increased ETblue directly contributes to a higher WFblue, indicating a greater reliance on blue water resources (e.g., river water from the Dez River or groundwater) to sustain crop production under water-scarce conditions. Conversely, in wetter years like 2018 (SPI = 1.4), Eff. rain increased to 211.9 mm, reducing the irrigation demand and consequently lowering ETblue. This mechanism underscores the vulnerability of wheat production in the Dez Irrigation Network to climatic variations, emphasizing the need for adaptive water management strategies—such as optimizing irrigation scheduling or enhancing water storage—to mitigate the increased stress on blue water resources during drought periods. The details presented in Table (4) are clearly reflected in Figures (2) and (3). Figure (3) illustrates the trends in the drought indices RDI and SDI, annual rainfall (Rain), and network water input (NIW) over a 20-year period. The alignment between the table values and figures enables a comprehensive examination of the impacts of rainfall and drought on water resources. Figure (4) compares rainfall (mm) and net irrigation water (NIW, $m^3 year^{-1}$) requirements under three climatic conditions (dry, normal, and wet), highlighting increased irrigation demand as rainfall decreases.

Table 5 - Regional and accounting parameters of the country during the 30th period

Year	Tmin ℃	Tmax ℃	RH %	Wind Km/day	Sun hours	Rain mm	Eff.rain mm	Etblue mm/day	Etgreen mm/day	Y Kg/ha
1993	15.5	31.3	50.6	131.4	2	230.8	220.1	133.2	220.1	2781.07
1994	15.8	31.6	50	165.9	2.6	265.8	220.1	123.5	220	2922.84
1995	15.1	31.9	51.6	152.9	2.4	254	139.2	222.3	139	4558.79
1996	16.4	32.6	48.8	169	2.6	379.8	289.7	58.4	289.7	4282.57
1997	15.6	31.5	48.2	159.6	2.5	257.4	333	43.6	324	5314.69
1998	16.6	33.3	47.2	153.4	2.4	252.9	306.4	57.3	306.3	3538.01
1999	16.7	33.1	46	168.1	2.6	266.5	279.8	112.6	279.6	4670.31
2000	16	32.3	47.2	183.2	2.8	281.6	208	111.7	360.2	4252.72
2001	16.4	33.1	48.2	176.8	2.7	277.3	236.7	174	236.5	4294.45
2002	13.3	28	57.1	210.2	3.3	311.9	254.5	119.5	254.5	3598.68
2003	16.5	32.5	47.7	179.6	2.8	279.1	204.6	212.2	204.6	4151.45
2004	16.2	32.2	53.3	177.7	2.8	282.2	280	112.4	280.1	4346.1
2005	16.2	32.6	51.3	198.5	3.1	301.7	260.9	86.6	260.9	4379.5
2006	16.7	32.3	53.2	241.2	3.7	347	281.8	80.8	281.8	4445.78
2007	16.3	32.5	53.8	242.8	3.8	349.1	284.4	79	284.2	4031.95
2008	16.8	33	52.2	244.1	3.8	349.8	88.7	314.2	88.7	3050.32
2009	16.9	32.4	56.8	256.5	4	366.6	124	267.5	124	3365.71
2010	17.8	34	48.2	254.4	3.9	358.3	151.8	265.2	151.8	2986.01
2011	16.4	32.3	47.5	245.3	3.8	345.3	222.7	200.6	227.7	3021.55
2012	17	32.7	46.5	223	3.5	322.6	192.3	211.3	192.4	2892.62
2013	16.1	32.3	50.4	220.3	3.4	322.4	132.6	318.9	132.6	3961.41
2014	16.9	32.3	51.4	238.9	3.7	343.3	249.9	152	249.9	4857.76
2015	17.7	32.9	72.2	228.4	3.5	354.6	202.1	243.6	202.1	4807
2016	16.7	32.8	72.1	237.9	3.7	363.2	179	202.8	178.9	5693.6
2017	16.9	34	68.3	315.2	4.9	439.2	108.3	402.3	108.3	5190.9
2018	17.5	33.4	74.1	363.4	5.6	494.1	281.1	188	281.1	4841.1
2019	16.7	32.6	74.7	236.2	3.7	363.9	376.5	0.4	376.5	4480
2020	16.7	32.8	74.1	200.2	3.1	326.8	252.7	197.5	252.7	3761
2021	17.2	34.6	68.4	207.6	3.2	331	79.4	101.1	331.9	3816
2022	17.3	33.9	49.1	272.8	4.2	377.3	174.5	375.2	174.5	-
2023	17.6	33.7	52.4	335.3	5.2	444.2	79.4	464.9	79.4	-

Table 6-Descriptive status of drought indices (RDI and SDI), annual rainfall, and water input to the irrigation network during the wheat growing season over a 20-year period

Year	NIW (m3 year^{-1})	Rain (mm)	RDI	SDI	RDI Interpretation	SDI Interpretation
2001-2002	12723.1	292.7	-0.03	-0.19	Near Normal	Near Normal
2002-2003	17561.7	235.9	-0.61	0.42	Near Normal	Near Normal
2003-2004	13453.5	357.8	0.56	0.17	Near Normal	Near Normal
2004-2005	13330.4	292.0	-0.06	0.17	Near Normal	Near Normal
2005-2006	16663.0	428.3	1.09	1.08	Moderately Wet	Moderately Wet
2006-2007	16838.2	292.7	-0.04	0.68	Near Normal	Near Normal
2007-2008	15591.8	176.0	-1.37	-1.56	Moderate Drought	Moderate Drought
2008-2009	7030.2	239.2	-0.53	-2.39	Near Normal	Severe Drought
2009-2010	17525.0	230.2	-0.73	0.45	Near Normal	Near Normal
2010-2011	16217.8	303.6	0.07	0.55	Near Normal	Near Normal
2011-2012	18753.7	287.6	-0.09	0.24	Near Normal	Near Normal
2012-2013	18195.3	242.7	-0.52	1.14	Near Normal	Moderately Wet
2013-2014	20672.5	319.0	0.26	1.32	Near Normal	Moderately Wet
2014-2015	17960.9	279.5	-0.14	0.80	Near Normal	Near Normal
2015-2016	15084.4	183.2	-1.25	0.22	Mild Drought	Near Normal
2016-2017	18266.8	179.8	-1.40	0.68	Mild Drought	Near Normal
2017-2018	10850.5	468.1	1.32	-1.52	Moderately Wet	Moderate Drought
2018-2019	9311.8	434.9	1.50	-0.36	Very Wet	Near Normal
2019-2020	15234.1	389.4	0.76	0.61	Near Normal	Near Normal
2020-2021	16673.3	103.4	-2.57	-0.80	Severe Drought	Near Normal

Note: RDI values are calculated for the hydrological year (October–September) using DrinC, reflecting annual climatic conditions, except for 2018–2019, where RDI is based on localized data reflecting the severe flooding in Khuzestan, classified as Very Wet. SDI, annual rainfall, and network water input (NIW) are calculated for the wheat growing season (October–May) for 2001–2021. RDI values were previously misaligned by one year in earlier versions and have been corrected using validated DrinC outputs. These values may differ from water footprint calculations Table (7), which تare based on calendar year data (January–December) from Cropwat.

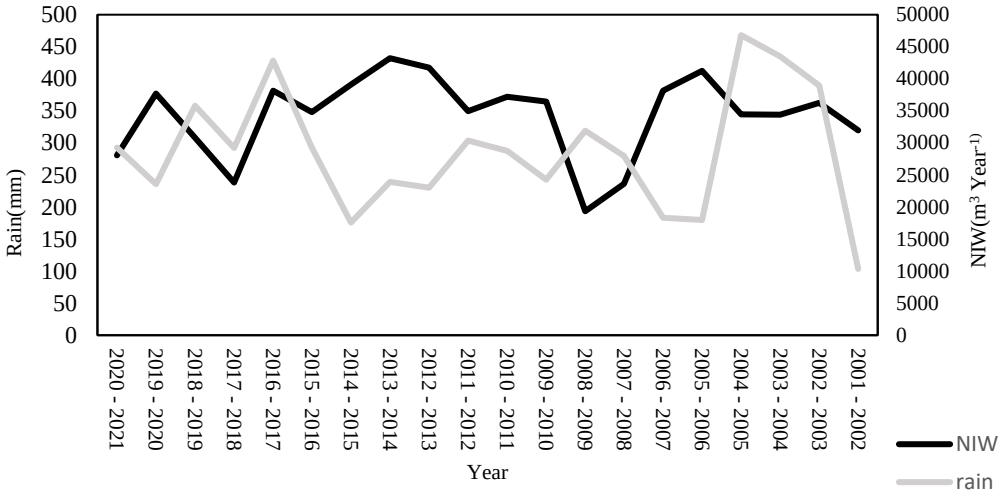


Fig. 3 - Trends in changes in water entering the Dez irrigation network and rainfall over a 20-year statistical period

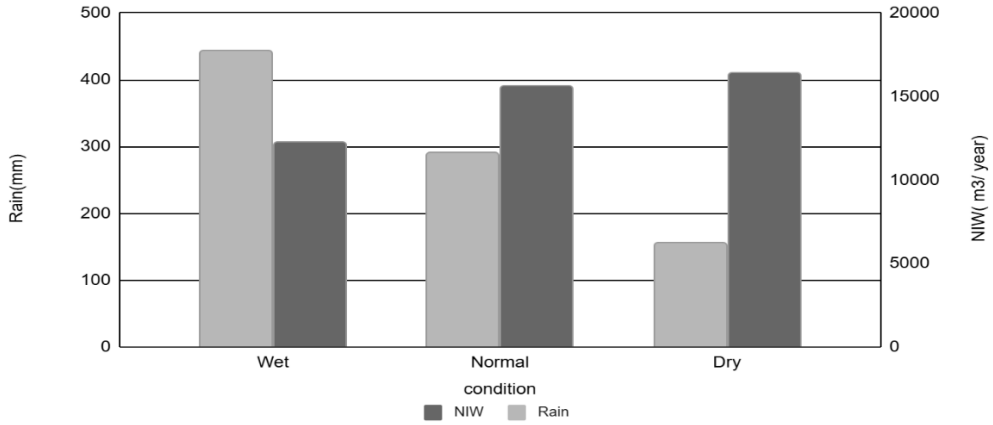


Fig. 4- compares rainfall and net irrigation water (NIW) requirements under three climatic conditions (dry, normal, and wet)

Impact of Climatic Variations on Water Footprints

The RDI reflects precipitation deficits. In years with negative RDI (e.g., 2008–2009, RDI = -0.42), insufficient rainfall led to reduced NIW (7030.2 m³). The SDI indicates hydrological drought severity (e.g., 2008–2009, SDI = -2.39), exerting significant pressure on water resources. In wet years (e.g., 2005–2006, rainfall = 428.3 mm, RDI = -0.02), NIW increased to 16,663 m³, reflecting favorable conditions.

To evaluate the individual and interactive effects of the drought indices SDI and RDI on water resources, a statistical analysis of variance (ANOVA) was conducted. This analysis enabled the assessment of each index's impact independently as well as their interactions under varying climatic conditions. The results of these analyses are presented in Table (7) and visualized in Figures (5) and (6) to clarify the relationships between the indices and water resources with greater precision.

Figures (5,6) provide a comparative analysis of the blue and green water footprints of wheat under varying climatic conditions. Figure 5 compares the average WFblue (99.12 m^3ton^{-1}in wet conditions vs. 202.78 m^3ton^{-1} in dry conditions) and WFgreen (296.7 m3ton-1 in wet conditions vs. 223.49 m^3ton^{-1}in dry conditions), highlighting the increased reliance on blue water resources during dry periods. Figure (6) illustrates the trends in WFblue and WFgreen across a spectrum of conditions from Very Wet to Severe Drought, showing a clear upward trend in WFblue and a

corresponding decline in WFgreen as drought intensity increases. These visualizations underscore the vulnerability of wheat production in the Dez Irrigation Network to climatic variations, emphasizing the need for adaptive water management strategies.

ANOVA Results for the Blue Water Footprint

The ANOVA results presented in Table (7) indicate that the Standardized Precipitation Index (SPI) has a highly significant effect on the blue water footprint (WFblue) (P-value ≈ 0.000206), suggesting that variations in standardized precipitation play a critical role in the utilization of blue water resources within the Dez Irrigation Network. In contrast, the individual effect of the Reconnaissance Drought Index (RDI) was not statistically significant (P-value = 0.3). This does not necessarily indicate a lack of effect but rather suggests uncertainty in the result, potentially due to factors such as the sample size or high variance in the data. For instance, the 30-year dataset (1993–2023) for RDI may include variability influenced by local climatic fluctuations (e.g., severe flooding in 2019), which could affect the statistical power of the analysis. The interaction between SPI and RDI, however, approached statistical significance under certain climatic conditions, indicating a potential combined influence that warrants further investigation with a larger or more controlled dataset.

ANOVA Results for the Green Water Footprint

The results obtained from the statistical analyses Table (8) indicate that the Standardized Precipitation Index (SPI) has a significant effect on the green water footprint (WFgreen), whereas the Reconnaissance Drought Index (RDI) exhibits a lesser impact. These findings highlight the critical role of effective rainfall and its temporal distribution in meeting crop water requirements. As drought intensity increases, reliance on blue water resources intensifies, exerting considerable stress on water resources. Figure (5) illustrates the green and blue water footprints of wheat during drought and wet periods over the 30-year study period, showing a clear pattern of increased WFblue and decreased WFgreen during drought conditions.

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Table 7 -ANOVA analysis of variance of simple and interaction effects of drought indices SDI and RDI on blue water footprint

Term	Df	Sum Sq	Mean Sq	F Value	Pr (>F)
SPI	1	136780	136780	18.384	0.000206*
RDI	1	8234	8234	1.107	0.302125
SPI: RDI	1	23422	23422	3.148	0.087294
Residuals	27	200880	7440	-	-

** signification in 0.01, * signification in 0.05

Table 8 - ANOVA analysis of variance of simple and interaction effects of drought indices SDI and RDI on green water footprint

Term	Df	Sum Sq	Mean Sq	F Value	Pr (>F)
SPI	1	65998	65998	16.814	0.000339*
RDI	1	3622	3622	0.923	0.345296
SPI:RDI	1	19666	19666	5.010	0.033639*
Residuals	27	105978	3925		

** signification in 0.01, * signification in 0.05

Table 9- Average green and blue water footprints under different drought and wet conditions based on RDI and SPI drought indices

Year's Drought Condition	Frequency	Ave.WFgreen	Ave.WFblue	WFgreen/WFblue
Very Wet	1	376.5	50.0	7.53
Moderately Wet	4	276.63	111.4	2.48
Near Normal	19	241.7	152.8	1.22
Mild Drought	5	125.96	351.88	0.36
Moderate Drought	1	139	222.3	0.63
Severe Drought	1	101.1	331.9	0.30

Note: Values are based on calendar year data (January–December) from Cropwat, aligned with drought conditions derived from RDI and SPI in Table 3. For 2018–2019, RDI and SPI are based on localized data reflecting the severe flooding in Khuzestan. Frequencies reflect the number of years within each drought condition category over the study period (1993–2023).

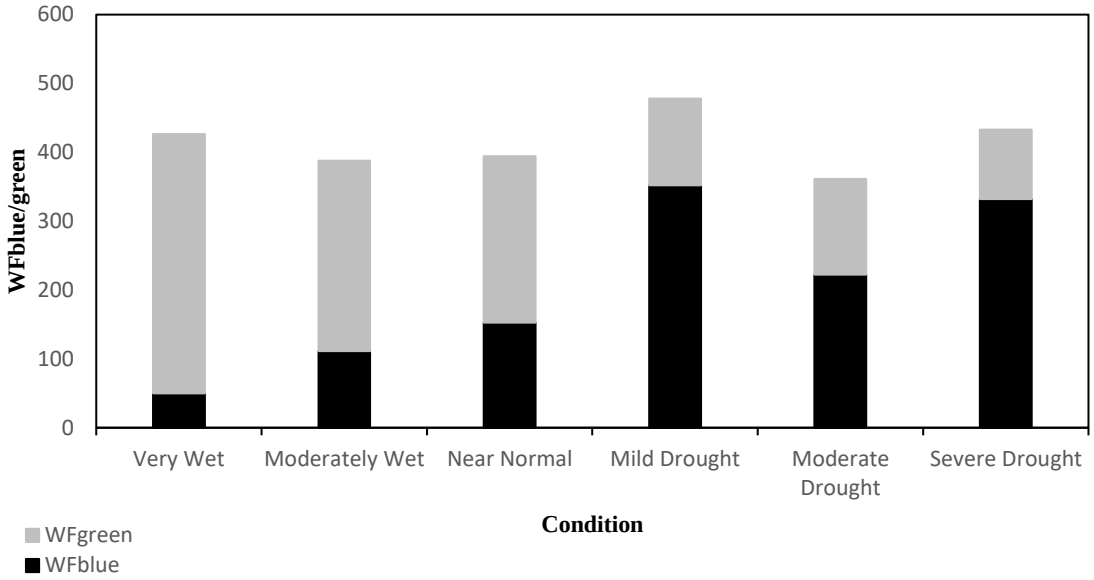


Fig. 5 - Green and blue water footprint of wheat during drought and wet periods over a 30-year statistical period

Blue Water Footprint of Wheat in Severe Drought

The analyses reveal that severe drought significantly increases the blue water footprint (WFblue) while reducing the green water footprint (WFgreen). In severe drought conditions, WFblue reached 375.20 m^3ton^{-1}, an increase of approximately 121.07% compared to normal conditions (169.59 m^3ton^{-1}), exerting substantial stress on blue water resources. This increase reflects a heightened dependence on water resources, underscoring the critical need for precise water management during severe drought. Indeed, this represents the most sensitive condition for water resource management.

The findings derived from the analysis of Table (9) highlight significant challenges and opportunities in water resource management under varying climatic conditions. In low-precipitation and drought years, dependence on blue water resources increases substantially, indicating greater stress on stored water reserves and elevated water inputs to the Dez irrigation network to compensate for deficits. The reduction in the green water footprint (WFgreen) during these conditions is associated with decreased precipitation, reduced soil water infiltration, and limited access to natural water resources, potentially causing severe impacts on agriculture without artificial irrigation. Concurrently, the increase in the blue water

footprint (WFblue) during severe drought reflects heightened extraction from groundwater or surface water sources and greater reliance on artificial irrigation systems. This underscores the critical need for precise planning and the development of efficient management strategies to ensure the sustainable use of water resources in the face of drought.

Blue Water Footprint of Wheat in Moderately Wet Conditions

In moderately wet conditions, WFgreen peaked at 276.63 m^3ton^{-1}, indicating effective utilization of green water resources. These conditions impose the least stress on irrigation systems and represent the optimal scenario for meeting crop water requirements.

Blue Water Footprint of Wheat in Near Normal, Mild and Modearte Drought Conditions

Over the 30-year study period (1993–2023), the prevalence of 'moderately wet' (4 years), 'near normal' (19 years), and 'mild drought' (5 years) conditions indicates a relative balance between wet and mildly dry years. However, a notable shift occurs in 'mild drought' conditions, where WFblue sharply rises to 351.88 m^3ton^{-1}—more than double the 163.36 m^3ton^{-1} observed in 'near normal' years—while WFgreen drops to 125.96 m^3ton^{-1}. This significant increase in blue water footprint underscores the heightened dependence on irrigation during these periods, highlighting the urgent need for enhanced resource management strategies to sustainably address water stress. Figure (4) illustrates that as drought intensity increases, the average WFblue exhibits an upward trend, while WFgreen declines. These changes reflect reduced effective rainfall and increased stress on storage and irrigation systems, as well as higher water inputs to the Dez irrigation network during drought conditions. These findings emphasize the importance of developing management strategies tailored to climatic variations.

Conclusion

The findings of this study demonstrate that climatic variations significantly influence wheat production in the Dez Irrigation Network, challenging the ability of irrigation systems to fully address water deficits during drought. In response to the research question—whether the network's water supply and release can compensate for effective rainfall shortages and maintain crop yields—the results indicate that this is not feasible. Drought affects water resources through two primary mechanisms: heightened reliance on irrigation due to diminished rainfall and reduced availability of soil moisture from natural precipitation. These dynamics reveal the limitations of even advanced irrigation networks in sustaining normal cultivation levels under drought conditions, as the increased demand for irrigation water places substantial pressure on available resources. The study underscores the critical need for adaptive water management strategies that prioritize efficient use of rainfall and innovative resource allocation to mitigate drought impacts and ensure agricultural sustainability in arid and semi-arid regions. For future research, the following investigations are recommended: first, evaluating the economic implications of the increased WFblue during severe drought to determine whether the additional water use and associated pumping costs are justified by the market value of wheat; second, replicating the current analysis for other irrigation networks located in different basins with more severe water resource constraints and higher temperature stress both within the province and in other regions of the country, to enhance understanding of challenges and potential solutions in diverse environmental conditions. Additionally, future studies should incorporate climate change projections to further refine water management strategies. These results underscore the critical need for precise water management, emphasizing rainfall quality, temporal distribution, and intelligent resource use to mitigate drought impacts and sustain agricultural productivity in arid and semi-arid regions like Southwestern Iran.

Conflict of Interest

The authors declared no potential conflicts of interest concerning the research,

authorship, and publication of this article. Confirmation.

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Data Availability Statements

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Authors' contribution

First Author: Mahkameh Mansoori, Writing and executing articles-60%

Second Author: Esfandiar Fateh, Study of the article and revised-30%

Third Author: Amir Aynehband, Giving advice-5%

Fourth Author: Ali Shahbazi, Giving advice-5%

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References

1- Abramowitz, M. and Stegun, I.A., 1965. With formulas, graphs, and mathematical tables. *National Bureau of Standards Applied Mathematics Series. e*, *55*, p.953.

2- Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. 1998. *Crop evapotranspiration: Guidelines for computing crop water requirements* (FAO Irrigation and Drainage Paper 56). Food and Agriculture Organization.

3- Borzoo, F., Ramezani Etedali, H., Kaviani, A., and Kalanaki, M.2024. Investigating green water footprint in spring wheat under climate change conditions and different crop dates. *Iranian Journal of irrigation and drainage*, 18(3),pp. 393-408.

4- Burton, M. 2010. Irrigation management principles and practices. *CABI Publishing*. https://doi.org/10.1079/9781845935160.0000

5- Fisher, D.K. and Pringle III, H.C., 2013. Evaluation of alternative methods for estimating reference evapotranspiration. *Agricultural Sciences*, *4*(8), pp.51-60. https://doi.org/10.4236/as.2013.48A008

6- Hargreaves, G. H., & Samani, Z. A. 1985. Reference crop evapotranspiration from temperature. *Applied Engineering in Agriculture*, 1 (2), 96–99. https://doi.org/10.13031/2013.26773.

7-Hayes, M. J., Alvord, C., & Lowrey, J. 2007. Drought indices. *Intermountain West Climate Summary*, 3 (6), 2–6.

8- Hoekstra, A. Y., Chapagain, A. K., Aldaya, M. M., & Mekonnen, M. M. (2011). *The water footprint assessment manual: Setting the global standard*. Routledge. https://doi.org/10.4324/9781849775526

9- McKee, T. B., Doesken, N. J., & Kleist, J. 1993. The relationship of drought frequency and duration to time scale. In *Proceedings of the Eighth Conference on Applied Climatology* (pp. 179–184). American Meteorological Society.

10- Nalbantis, I., & Tsakiris, G. 2009. Assessment of hydrological drought revisited. *Water Resources Management, 23(5), 881–897. https://doi.org/10.1007/s11269-008-9305-1.

11- Panahi, F., & Malik Muhammadi, A. 2008. Optimization of agricultural water in the region. In *Proceedings of the National Conference on Water Harvesting* (pp. 489–498). (In Persian).

12- Ramezani Etedali, H., Kalanaki, M., & van Oel, P. 2022. Evaluation of future climate component changes from north to southwest Iran. *Journal of Ecohydrology, 9*(2), 373–386. https://doi.org/10.22059/ije.2022.90424.

13- Salarian, M. 2014. Development of water resources and transformations in modern irrigation. **Water Harvesting Journal*, 2, 83–90. (In Persian).

14- Thom, H. C. S. 1958. A note on the gamma distribution. *Monthly Weather Review*, 86(4), 117–122. https://doi.org/10.1175/1520-0493(1958)086<0117:ANOTGD>2.0.CO;2.

15- Tsakiris, G., Loukas, A., Pangalou, D., Vangelis, H., Tigkas, D., Rossi, G., & Cancelliere, A. 2007. Drought characterization. In A. Iglesias et al. (Eds.), Drought Management Guidelines Technical Annex (pp. 85–102). CIHEAM / ECMEDA Water, Zaragoza.

16- Tsakiris, G., Nalbantis, I., Pangalou, D., Tigkas, D., & Vangelis, H. 2008. Drought meteorological monitoring network design for the reconnaissance drought index (RDI). In A. Franco Lopez (Ed.), Proceedings of the 1st International Conference "Drought Management: Scientific and Technological Innovations" (pp. 57–62). Zaragoza, Spain: Option Méditerranéennes, Series A, No. 80, 12-14 June 2008.

17- Vangelis, H., Tigkas, D., & Tsakiris, G. 2013. The effect of PET method on Reconnaissance Drought Index (RDI) calculation. *Journal of Arid Environments*, 88, 130–140. https://doi.org/10.1016/j.jaridenv.2012.09.002.

18- Veettil, A. V., & Mishra, A. K. 2016. Water security assessment using blue and green water footprint concepts. *Journal of Hydrology*, 542, 589–602. https://doi.org/10.1016/j.jhydrol.2016.09.034

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