

Role of Deficit Irrigation in Sustaining Wheat and Maize Cultivation Under Harsh Climatic Conditions in Iraq

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ABSTRACT

Water scarcity and climate variability threaten the sustainable production of strategic crops such as wheat and maize in arid regions like Iraq. Conventional irrigation methods are increasingly insufficient to satisfy crop water requirements due to rising evapotranspiration and reduced effective rainfall. Therefore, Deficit Irrigation (DI), which involves applying water below full crop water requirements, has become an important strategy for improving water use efficiency. This paper aimed to evaluate irrigation water requirements and crop responses to different DI levels in arid conditions, selecting the Al-Raed Research Station in Iraq as the study area. Climatic data were analyzed using the CROPWAT 8 model to estimate crop evapotranspiration, effective rainfall, net irrigation requirement, and gross irrigation requirement at full irrigation and DI levels ranging from 5% to 25% in steps of 5%, with 5% across four growth stages. The results showed that wheat had relatively low sensitivity to water deficit, with no yield reduction at DI5% during most growth stages and a maximum reduction of 2.0% at DI25%, mainly during the mid-season stage. In contrast, maize was more sensitive to water deficits, particularly during development and mid-season, with yield reductions of 4.3% and 4.0%, respectively, under DI25%. However, under DI5%, maize showed only minor yield reduction, not exceeding 0.3%. Overall, DI5% can be recommended during the initial and development stages for both crops due to their low water demand and limited sensitivity to water stress during early growth.

Keywords: Deficit irrigation, Wheat, Maize, Semi-arid, Growth stages, CROPWAT 8 software.

1. INTRODUCTION

In the arid and semi-arid areas, water shortage and climatic variability pose significant limitations to agricultural production at a sustainable level. Over the past, the pressure on the limited water resources has been aggravated by growing air temperatures, decreased precipitation, augmented evapotranspiration, and heightened climatic variability, especially in the Middle East and Iraq. Some of the most strategic food security and livestock-helpful

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crops are wheat and maize, which are extremely susceptible to irrigation management and climatic stress. The efficiency of water utilization has become a critical issue of concern that scientifically efficient irrigation methods need to be developed to ensure stability in yields with minimal use of water (**Ehdaie et al., 1995; Zhang et al., 1998**). In Iraq, conventional full-irrigation approaches rarely account for crop-specific water sensitivity across different growth stages, leading to inefficient water use and avoidable yield and resource losses. Previous research has shown that, when used correctly, DI can increase water-use efficiency, but it should not be used to reduce yield relative to that of water-use efficiency (**Ferri and Faci, 2006; Fereres and Soriano, 2007**). Studies on wheat have indicated that moderate water stress at the less sensitive periods can enhance assimilate remobilization and grain filling and save water (**Payero et al., 2008; Okten, 2008**). Equally, maize productivity has been reported to have a strong reaction to irrigation timing, wherein it is very sensitive to irrigation during the elongation, flowering, and grain-filling periods (**Chai et al., 2016**). Nonetheless, much of the available literature was carried out under climatic, soil, and management conditions that are not comparable with those of arid regions such as central Iraq, and as such, the applicability cannot be made directly. Various studies have emphasized the significance of the physiological behavior of crops to water stress. The availability of soil moisture influences root development, the stomatal conductance, canopy expansion, as well as crop coefficients (K_c) in a direct relationship with evapotranspiration and the formation of yield (**Xu et al., 2021**). In arid and semi-arid areas, research has also shown that wheat is usually more tolerant to moderate water stress than maize because it has a more extensive root system and higher carbon remobilization capacity (**Wang et al., 2026**). However, one area has not yet been covered: locally calibrated and stage-specific irrigation recommendations on wheat and maize in Iraqi climatic situations, especially those that consider effective rainfall and inefficiencies caused by irrigation systems and seasonal climatic drivers (**Pereira et al., 2021**).

In order to fill these knowledge gaps, several methodological techniques have been used in the irrigation research, such as field experimentation, soil-plant-atmosphere modeling, and decision-support systems. The FAO CROPWAT model is one of the commonly used tools in estimating crop water requirement, reference evapotranspiration (ET_0), crop evapotranspiration (ET_c), and irrigation scheduling under different climatic and management conditions (**Geerts and Raes, 2009**). Also, irrigation scheduling represents a fundamental approach for optimizing agricultural water management, particularly under conditions of increasing water scarcity, which has become a critical challenge for sustainable agricultural production, particularly in arid and semi-arid regions. Therefore, adopting efficient irrigation scheduling and management strategies is essential to optimize water use and improve crop productivity (**Al-Aridhee and Mahdi, 2022; Farooq et al., 2009**).

The increasing scarcity of freshwater resources has driven the adoption of advanced irrigation systems such as drip and subsurface drip irrigation to enhance water use efficiency. These systems improve soil moisture distribution within the root zone, reduce water losses, and significantly increase crop yield and productivity (**Abdul-Razak et al., 2016**). The model combines the climatic variables, including temperature, solar radiation, wind speed, and humidity, with crop coefficients and soil properties and allows the net and gross irrigation needs to be assessed systematically. Other researchers have been able to apply CROPWAT to calculate irrigation efficiency, deficit cases, and water productivity of wheat and maize under semi-arid conditions (**Omran et al., 2025; Maria et al., 2025**). Also, the Global Climate Models (GCMs) showed no significant changes in the short and medium-



term future climate change on rainfall amounts in arid and semi-arid regions, particularly in Baghdad (Olewi et al., 2023).

Through agro-climatological modeling aimed at assessing the spatial and temporal sensitivity of the net irrigation water requirement (NIWR) for sixteen crops in arid and semi-arid regions of Iraq, using the LARS-WG model and five global climate models to predict temperature and rainfall for the period 2021–2080 under three emission paths (RCP 2.6, 4.5, and 8.5), data were entered into CROPWAT 8 software based on reference data (1990–2019). The results showed an expected increase in water requirements, with barley being the most vulnerable to climate change, while maize demonstrated better resilience. This provides a scientific basis for improving spatial and temporal irrigation planning and promoting sustainable water resource management in the future (Saeed et al., 2021).

This case study was conducted utilizing the FAO CROPWAT 8 by using the local climatic, soil, and crop growth factors in order to determine the irrigation water requirements of wheat and maize in the case under full and various levels of DI. The study aims to offer a more realistic and location-specific knowledge of crop water demand and stress response by assessing several levels of deficit at various critical phenological stages. It is based on the prior theoretical and experimental results and discusses its deficiencies in the regional scope and stage-specific evaluation, and contributes to quantifying crop-stage water requirements and deficit irrigation responses of wheat and maize in the arid climate, such as in Al-Raed Research Station, Iraq. This study provides locally calibrated, growth-stage-specific irrigation thresholds that offer practical guidance for optimizing water-use efficiency while safeguarding the productivity of strategic crops such as maize and wheat under water-limited conditions.

2. MATERIALS AND METHOD

2.1 Study Area

Fig. 1 shows the study area, which was conducted at Al-Raed Research Station, which is administratively affiliated with the Iraqi Ministry of Water Resources in the Abu Ghraib District, located approximately 20 km west of Baghdad within the Baghdad Governorate, central Iraq. The area lies between latitudes 33.3373N and 44.2114E, at an average elevation of about 34 m above sea level. According to the Koppen-Geiger (BWh) classification, the climate of the Baghdad region, such as Abu Ghraib, is categorized as a hot desert climate. It is typified by high temperatures in the summer season and a low amount of rainfall per year, which is only 150-160 mm, and the majority of the rainfall occurs in the winter (Climate-Data, 2024). Due to this climate trend, the rates of evaporation and the humidity of the atmosphere are higher, which puts the region in the arid to semi-arid climate zone. These climatic features are limiting their agricultural activity since agriculture in the area is mainly dependent on auxiliary irrigation because rainfall is not enough to support the water demands of crops (Gao et al., 2023). The region is a large irrigated farmland in the central part of Iraq and is highly planted with strategic products, especially wheat during the winter period and maize during the summer period. Such properties render the area viable in assessing crop behavior in deficit irrigation techniques in arid and semi-arid environments. By 2024, the amount of wheat that was planted on land in Baghdad was estimated at around 35,029 dunams (CSO, 2024). Conversely, the Baghdad area under maize production remains very low, with 232 dunams being the reported area under cultivation in 2023 (CSO, 2023).

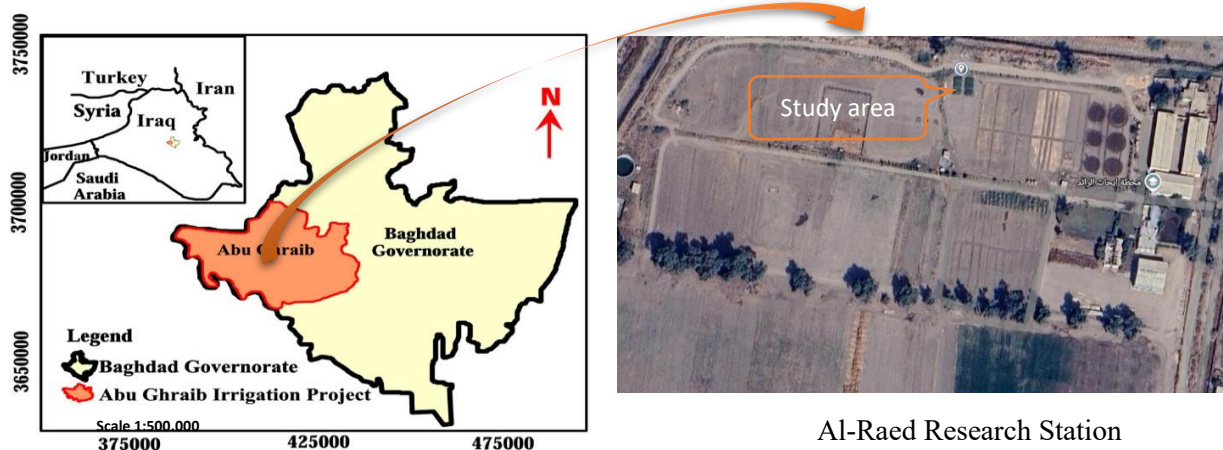


Figure 1. Study area location.

2.2 Soil and Water Quality

The capacity to retain water and provide it to the crops after irrigation is based on the physical and hydro-hydraulic characteristics of the soil. Fine-textured soils contain more water and require fewer and deeper irrigations, whereas sandy soils demand less frequent and smaller applications because they drain out fast. In Baghdad, where water shortage and high rate of water percolation are major concerns, knowledge on the availability of moisture in soils, their capacity to absorb water, and water content within soils is important to optimize the irrigation time, minimize the losses of water, and enhance the efficiency of water utilization in the production of maize. Besides this, the quality of irrigation water is also a direct determinant of its appropriateness to the agricultural sector.

Soil samples were collected from the field at a depth of 0–30 cm prior to the initiation of the experiment. Soil physical properties were determined following standard procedures aligned with USDA guidelines. Particle size distribution was measured using the hydrometer method with temperature correction based on Stokes' law, and soil texture was classified according to the USDA textural classification system. The USDA particle sizes were used to classify the soil texture based on the sieve analysis and hydrometer method, and categorize it based on the triangular diagram of soil textural classes (**Waller and Yitayew, 2016**). The results indicated that the soil was silty clay loam (36% clay, 45% silt, and 19% sand), with an estimated available water content of approximately 200 mm/m, based on gravimetric moisture content and bulk density, and a maximum rain infiltration rate at 40 mm/day. Soil pH values were within the neutral to slightly alkaline range, which is generally considered suitable for most crops. The electrical conductivity (EC) of the soil indicated moderate salinity levels. Soils with EC values of 2–4 dS/m are considered slightly saline and may affect sensitive crops, whereas soils with EC > 4 dS/m are classified as saline (**FAO, 2021**).

Besides that, the quality of irrigation water was also subjected to testing and evaluation using the FAO and US Salinity Laboratory (USSL) specifications (**Kramer, 1983**). The measured pH was within the acceptable range for agricultural use. The EC value of irrigation water was relatively low and falls within the category of water suitable for the irrigation of moderately salt-tolerant crops. Based on FAO guidelines (**Ayers and Westcot, 1985**), irrigation water with EC values below 0.7–1.0 ds/m generally poses a low salinity hazard and can be used safely under proper management practices. Planting was done in the heavy-textured, silty clay loam soil that was described as having good aeration and sufficient



drainage of water. The soil characteristics of the study area, previously described, were evaluated against FAO suitability criteria (FAO, 2021) and found to be appropriate for both wheat and maize cultivation due to adequate drainage, moderate water-holding capacity, and favorable PH conditions, and the maize does not tolerate stagnant water. The maize field had a range of 6.8 to 7.4 in soil PHs. The values of electrical conductivity of the wheat and the maize soils were 3-4 dS/m. The estimated field capacity and permanent wilting point values (0.39 and 0.23 $\text{m}^3 \text{m}^{-3}$, respectively) are consistent with the typical range reported for silty clay loam soils (Saxton and Rawls, 2006). Irrigation water used for both crops was of pH 7.8 and 0.78 ds/m electrical conductivity (Gao et al., 2023). Soil properties play a crucial role in irrigation efficiency and water availability. Soil texture, field capacity, permanent wilting point, and available water capacity were incorporated into the model to reflect local conditions. Medium-textured soils with moderate water-holding capacity necessitate frequent but controlled irrigation to avoid surface runoff and deep percolation losses. In Fig. 2, the characterization profile of the soil is shown, and it gives the necessary information about the soil's total available soil moisture, maximum infiltration rate, and initial available soil moisture.

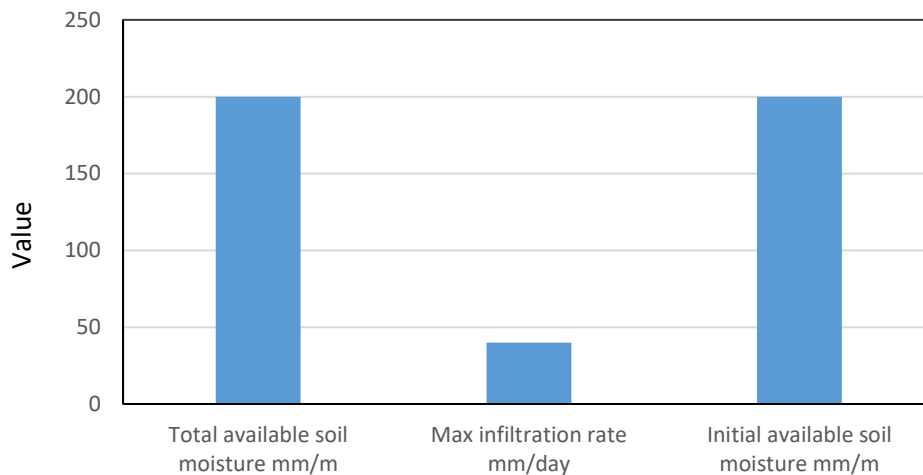


Figure 2. Values of soil parameters.

The paper will make the following assumptions: soil property homogeneity, constant irrigation efficiency, and the lack of biotic stress factors. Yet, these assumptions are in line with the general FAO modeling convention and provide a comparison with other studies of the same kind.

2.3 Climatic Data

The research location has an average semi-arid, hot, and dry climate. The Abu Ghraib Meteorological Station, the nearest to the study area, provided climatic data, including maximum and minimum air temperatures, relative humidity, wind speed, sunshine duration, solar radiation, and precipitation. Climate data for 2024 was officially obtained from (Iraqi Meteorological Organization and Seismology, 2025). Ensuring the reliability and authenticity of the recorded measurements. There are distinct seasonal fluctuations in temperature, rainfall, relative humidity, sunshine duration, wind speed, and solar radiation throughout the year. Maximum air temperature gradually increased from 20.2 °C in January to a peak of 45.9 °C in June and July, then declined to 18.7 °C in December. The same pattern



was seen in the minimum temperature, which ranged from 4.5 °C in December to 28.3 °C in July.

Rainfall was concentrated in the winter and spring, with April recording the most precipitation (127.7 mm). June through October had no precipitation. Due to high temperatures and dry conditions, relative humidity was lowest in summer, while it was often higher in the cooler months, reaching 64% in both February and November.

During the summer, both solar radiation and sunshine duration increased significantly, peaking in June at 27.9 MJ/m²/day and 12.0 hours/day, respectively. December, on the other hand, had the lowest solar radiation value (10.6 MJ/m²/day). Throughout the year, wind speed ranged from 2.9 to 3.9 m/s, with little monthly variation.

Overall, the study area's climate is typical of the semi-arid climate that predominates in central Iraq, with hot, dry summers and warm, comparatively moist winters. The climatic conditions of the study area strongly influence both ET_o and ET_c, which together determine the irrigation requirements of maize and wheat. These conditions significantly increase ET_o, which in turn raises ET_c for maize, especially during the elongation, flowering, and grain-filling stages, when the crop is most sensitive to water stress. Under such conditions, even moderate DI leads to rapid soil moisture depletion and yield reduction unless irrigation is carefully scheduled. In contrast, during the winter season (December–March), when wheat is grown, ET_o and ET_c decrease, indicating that wheat depends partially on effective rainfall. This means that deficit irrigation can be used more safely on wheat than on maize, particularly during vegetative stages, without severe yield repercussions. Due to almost zero rainfall in the study area from June to October, maize crops are entirely dependent on irrigation, whereas wheat crops rely on seasonal rainfall. That is why maize is more sensitive to deficit irrigation, whereas wheat is more tolerant.

In Baghdad, with hot summers and cool winters, rising temperatures have increased ET_o and ET_c, particularly for summer crops. However, elevated atmospheric CO₂ concentrations may partially mitigate these impacts by improving photosynthetic activity, crop growth, and water-use efficiency. Future climate projections also indicate continuous increases in temperature and crop water demand under different CO₂ emission scenarios, reflecting the combined influence of climate warming and elevated CO₂ levels on agricultural productivity and irrigation requirements. Therefore, understanding the interaction between temperature dynamics and atmospheric CO₂ concentration is essential for explaining variations in evapotranspiration, irrigation demand, and crop performance under arid and semi-arid conditions (**Hasan and Abed, 2024**).

Relative humidity, wind speed, sunshine duration, solar radiation, and rainfall are key climatic factors controlling evapotranspiration and crop water requirements in Baghdad. Higher relative humidity reduces vapor pressure deficit (VPD) and evapotranspiration, while low humidity increases water loss and irrigation demand, particularly for maize under semi-arid conditions. Higher wind speeds enhance atmospheric turbulence, increasing evaporation and reducing irrigation efficiency, whereas lower wind speeds help conserve soil moisture. Extended sunshine duration and higher solar radiation promote photosynthesis but also increase evapotranspiration and crop water demand. Conversely, reduced radiation lowers irrigation requirements, especially during early growth stages. Rainfall in Baghdad is low, averaging about 150mm annually, and is highly seasonal, occurring mainly during winter and early spring, with almost no precipitation in summer (**Climate-Data, 2024**). This climatic pattern, combined with high temperatures and



evaporative demand, necessitates efficient irrigation management to sustain crop production.

2.4 Software and Tools

The primary instrument of analysis was the FAO CROPWAT 8 program, which was employed to estimate ET_o based on climatic data, including temperature, relative humidity, wind speed, and sunshine duration, following the FAO Penman–Monteith method. Crop water requirements were calculated by applying crop coefficients (K_c) corresponding to different growth stages to ET_c . The model also integrates soil characteristics and effective rainfall to determine net and gross irrigation requirements and to develop optimal irrigation schedules under semi-arid conditions. In addition, the program was utilized to assess the impact of DI levels on crop productivity by estimating the corresponding reduction in crop yield. The analysis was further supported by supplementary calculations and the generation of figures using spreadsheet tools and statistical processing software.

2.5 Conceptual Framework and Theoretical Background

The theory of Soil-Plant-Atmosphere Continuum (SPAC) is the basis of the research, and the conceptualization of crop water use is presented as a dynamic and interrelated process, based on the needs of the atmosphere, the supply of soil moisture, and the physiological activities of plants. The SPAC theory states that the water is constantly transported through the plant to the atmosphere by the soil, water, and plant through gradients in the water potential. The water needs of crops are derived as a result of the interplay of ET_o , K_c , effective rainfalls, and irrigation efficiency. Evapotranspiration plays the most significant role in the agricultural water balance of arid and semi-arid areas like central Iraq, and therefore, its correct estimation is very important in sustainable irrigation planning (Allen et al., 1998). The methodological scheme is based on the FAO-56 approach of estimating crop water requirement, in which ET_c is estimated as:

$$ET_c = K_c \times ET_o \quad (1)$$

This relationship enables the conversion of climate-driven reference evapotranspiration into crop-specific water demand using phenology-dependent crop coefficients. The ET_c was the combined effect of ET_o and K_c , which rose gradually during the early growth phases and rose to a high during the mid-season of the two crops. ET_c s values were greatest at the times of peak temperature, radiation, and when canopies were developing. Maize had always recorded more ET_c compared with wheat; that is, it had a higher water demand and was more sensitive to climatic stress.

The irrigation requirement followed the changes in ET_c closely, but was somewhat moderated in the intervals of efficient rainfall. The time series analysis showed that the most important water demand times were the maize elongation, tasseling, fine-tuning stages, and wheat stem elongation and heading phases. Failure to supply adequate water during these windows would likely result in irreversible yield losses. The FAO-56 method has been extensively validated and widely applied in irrigation research under water-limited conditions, forming the theoretical foundation of this study (Allen et al., 1998).



2.5.1 Reference Evapotranspiration (ET_o) Estimation

ET_o was computed using the FAO Penman–Monteith method, which is widely accepted as the international standard technique of estimating the evaporative demand in the atmosphere, based on measured climatic data obtained from the Abu Ghraib Meteorological Station, including air temperature, relative humidity, wind speed, and solar radiation.

$$ET_o = \frac{0.408 \Delta (R_n - G) + \gamma \left(\frac{900}{T+273} \right) U_2 (e_s - e_a)}{\Delta + \gamma (1 + C_d U_2)} \quad (2)$$

Where, ET_o is the reference evapotranspiration (mm day^{-1}), R_n is net radiation at the crop surface ($\text{MJ m}^{-2} \text{day}^{-1}$), G is soil heat flux density ($\text{MJ m}^{-2} \text{day}^{-1}$), T is mean daily air temperature ($^{\circ}\text{C}$), U_2 is wind speed at 2 m height (m s^{-1}), e_s is saturation vapor pressure (kPa), e_a is actual vapor pressure (kPa), Δ is the slope of the saturation vapor pressure curve ($\text{kPa } ^{\circ}\text{C}^{-1}$), γ is the psychrometric constant ($\text{kPa } ^{\circ}\text{C}^{-1}$) (Waller and Yitayew, 2016).

The approach incorporates solar radiance, air temperature, wind speed, and relative humidity, hence offering a physically grounded and climatologically strong support of ET_o . The Penman-Monteith model presumes the existence of a hypothetical reference grass surface with an equal height and sufficient water supply, and this factor makes this model applicable in the process of analyzing the water demand of various crops comparatively.

Daily climatic data were processed within the CROPWAT 8 software environment to generate ten-day (decadal) and seasonal ET_o values. Variations in ET_o throughout the growing season reflect changes in climatic drivers such as increasing temperature, solar radiation, wind speed, and declining humidity, which are particularly pronounced in the Abu Ghraib region.

2.5.2 Crop Coefficient (K_c) Evolution

The K_c integrates the effect of characteristics that distinguish a specific crop from the reference crop. It is influenced mostly by crop type and, to a minor extent, by climate and soil evaporation. Moreover, the K_c for a given crop varies over the crop growing stages, since ground cover, crop height, and leaf area change as the crop develops. The changing values of the K_c of maize and wheat were an indicator of the physiological growth and the canopy formation. The value of K_c during germination and early establishment was the lowest, whereas the value increased at a sharp rate during vegetative growth and peaked at mid-season when the covers of the canopy and transpiration were highest. K_c started to decrease towards maturity because transpiration demand decreased due to senescence. The K_c were selected based on FAO-56 guidelines and adjusted to reflect local climatic and agronomic conditions. K_c values differ in four significant phenological stages, including initial (germination), development, mid-season (maximum canopy cover), and late season (maturity and senescence). These variants reflect the change in the canopy cover, root depth, rate of transpiration, and physiological activities. Temporal variation of K_c was simulated in CROPWAT in order to match observed wheat and maize growth levels at the test site. Peak K_c values are those associated with the optimal leaf area index and transpiration demand, whereas decreasing ones are related to the early establishment and late-season leaf senescence (Xu et al., 2021).



2.6 Irrigation Requirement and Scheduling

Net irrigation requirement (NIR) was calculated as the difference between ET_c and effective rainfall (ER).

$$NIR = ET_c - ER \quad (3)$$

The gross irrigation requirement (GIR) was determined by taking into consideration the efficiency of irrigation systems to show the losses incurred due to irrigating water through the conveyance/distribution non-uniformity, water through evaporation, and deep percolation. The correlation between NIR and GIR takes the form of:

$$GIR = NIR/E_i \quad (4)$$

In which E_i is the total irrigation efficiency in the form of a decimal. It is imperative to distinguish net and gross irrigation needs in order to measure guaranteed water application at the field level and detect system inefficiency when irrigation takes place in practicable conditions (**Allen et al., 1998**).

Irrigation schedules were prepared at daily, decadal, and monthly levels to capture the short-term climatic variation and seasonal water demand patterns. The volumetric flow rate was calculated using the relationship:

$$Q = I \times A \times t \times 10^4 \quad (5)$$

Q = discharge rate ($L s^{-1} ha^{-1}$), I = Irrigation depth (mm), A =irrigated area (ha), t =irrigation time (s). This conversion made it possible to combine crop water needs and hydraulic system capacity and helped in the realistic planning of irrigation and system design (**Allen et al., 1998**).

2.6.1 Effective Rainfall (ER)

Total rainfall is the total of the rainfall that has fallen within a certain time, whereas effective rainfall is the amount of rainfall that is stored in the soil and can be used to water the crops. The effective rainfall is without losses of canopy interception, surface runoff, deep percolation, root zone and direct evaporative losses. Such loss occurs especially in semi-arid conditions, e.g., in Baghdad, when high temperatures, relative humidity, and high solar radiances considerably decrease rainfall activity.

The usefulness of precipitation was estimated by reporting the daily rainfall measurements at the Abu Ghraib Meteorological Station. This data was computed by the FAO effective rainfall technique that is incorporated within the CROPWAT 8.0 model, which takes into consideration rainfall losses as a result of runoff, deep percolation, and evaporation. Since the study area has semi-arid climatic conditions, effective rainfall was a more realistic input to the contribution of rainfall to soil moisture than the total precipitation (**Allen et al., 1998**). The effective rainfall did not contribute to the maize crop due to a mismatch between the timing of rainfall and the planting date. In contrast, the wheat crop benefited significantly, as the heavy rainfall coincided with its critical growth stages, leading to improved growth and higher productivity (**Alsamarray et al., 2025**). Effective rainfall and decadal comparison between a daily and decadal effective rain and ET_c , compared the water



surplus and deficit periods. Such analyses are critical in the determination of the irrigation timing and the amount of supplemental irrigation needed.

Each of the rainfall (R) calculation options is based on the estimation of the effective rainfall of the actual rainfall records. The formula available to calculate effective rainfall has been developed by the USDA, and the effective rainfall can be calculated as follows:

$$ER = R_{\text{month}} \times (125 - 0.2 \times R_{\text{month}}) / 125 \quad (R_{\text{month}} \leq 250 \text{ mm}) \quad (7)$$

$$ER = 125 + 0.1 \times R_{\text{month}} \quad (R_{\text{month}} > 250 \text{ mm}) \quad (8)$$

2.6.2 Deficit Irrigation (DI)

Deficit irrigation (DI) is premised on the fact that crops are able to endure moderate to minimal water stress during specific phases of development, without generating serious yield losses. Sensitivity of crops to water stress changes during the phenological stages, and the most sensitive ones are flowering and grain filling, whereas the tolerability to water scarcity is generally lower in vegetative development and late maturity stages. During these less sensitive stages, irrigation can be cut strategically to enable the conservation of irrigation water and its efficient use.

2.7 Investigated Scenarios of Deficit Irrigation

There were five DI scenarios (5%, 10%, 15%, 20, and 25%) compared to full irrigation. These conditions were implemented in four critical growth phases (germination, vegetative growth (elongation), flowering, and grain filling) for the two crops to determine sensitivity and tolerance to water stress.

The analysis was aimed at determining the crop growth stages where water reduction causes the least threat to yield and stages where DI causes a severe reduction in crop performance. Such a seasonal reduction of water is impractical and less adaptive to the development of an irrigation strategy than this stage-based evaluation. Based on this, DI scenarios were implemented individually on a growth stage that included germination, vegetative growth (elongation), flowering, and grain filling to determine each stage in isolation and the particular effect of water stress on the stage. Moreover, DI was also carried out at each of the growth stages simultaneously in each scenario to determine the net impact on the performance of the crop. Water productivity indicators, which include crop yield per unit applied water, are usually used to assess the success of DI. In contrast to the traditional irrigation methods that are designed to achieve maximum yield, DI is designed to achieve maximum economic returns per unit of water and therefore enhances the overall efficiency of irrigation.

Climate change conditions usually lead to an increased scarcity of water because of the rise in temperatures, changes in precipitation patterns, and the rate of evapotranspiration. In this regard, DI is a significant adaptive mechanism that helps farmers with the scarcity of water. DI can increase agricultural system resilience and sustainability by improving water productivity and decreasing the irrigation needs of agricultural systems in a changing climate. The key benefits of DI are efficiency and water productivity, lower cost and energy usage in irrigation, better sustainability of water resources in agriculture, and in certain situations, the quality of crops is improved. By and large, DI is a promising water-saving technology that is capable of boosting water productivity in agricultural activities, especially in water-stressed areas, significantly. When it is well managed, the company is able to attain



reasonable crop production at lower levels of water. Due to the ever-growing pressures caused by water shortage and climate change, DI will become an increasingly important part of sustainable agricultural development. However, additional studies and field research need to be made on how to perfect irrigation timing and to adjust DI techniques to the regional environmental and agronomic conditions.

3. RESULTS AND DISCUSSION

3.1 Reference and Crop Evapotranspiration

ET_0 was calculated using the standardized FAO-56 methodology, which is highly recommended for estimating ET_0 across a variety of climatic conditions. This method is consistent and reliable for measuring atmospheric evaporative demand throughout the growing season. **Fig. 3** indicates the change over time of the ET_0 , which is the amount of water demanded in the atmosphere independently of the type of crop, and it acts as a reference point when computing ET_c .

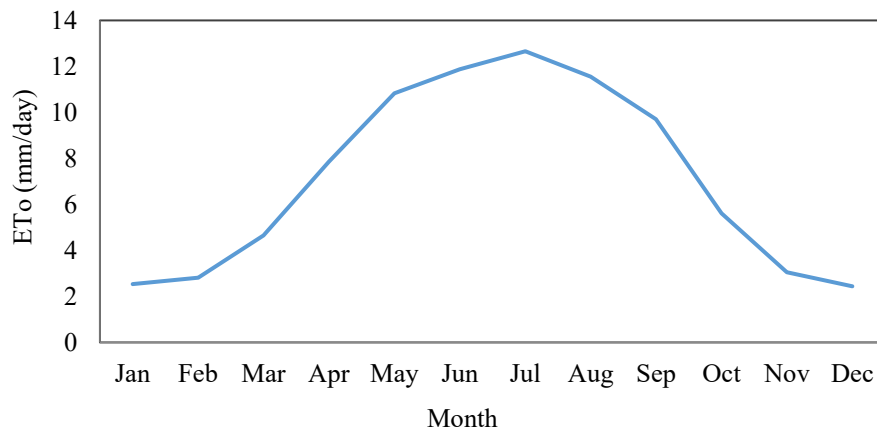


Figure 3. Change in ET_0 with change in climatic conditions.

The ET_0 calculations depicted greater ET_0 values in intervals of high temperatures, high sun radiation, low relative humidity, and increased wind speeds. The findings in **Fig. 3** show that ET_0 also exhibits a distinct seasonal cycle whereby low values are recorded in winter months and then progressively increase after March and reach high values in mid-summer (June-July) and then decrease towards the end of the year. The very large ET_0 values in summer indicate the times of water demand in the atmosphere, meaning that the soil moisture is more rapidly depleted and that crops consume more water. On the other hand, the low ET_0 during the winter is associated with less evaporation demand and interim lower irrigation demands. This great seasonal change in ET_0 indicates the existence of critical periods of blocky crop water demand and the basis of changing irrigation timing and water distribution during the growing season. These findings are consistent with recent studies, (**Waller and Yitayew, 2016; FAO, 2021**), which indicate that atmospheric evapotranspiration ET_0 is a key factor controlling irrigation scheduling and water use efficiency. Proper alignment of irrigation with periods of high evaporative demand can improve water productivity without significant yield reduction. The results of the study support the conclusion that seasonal changes in ET_0 are an important factor in explaining the dynamics of crop water demand, especially in arid and semi-arid areas. The significant rise in ET_0 values in summer periods indicates that the pressure of water on the atmosphere is increased, which results in the

rapid loss of soil moisture and high-water demand by crops. The low values in winter months, on the other hand, are linked to decreased water demand and the possibility of reducing the irrigation without adversely affecting the growth of crops. These results indicate that a valid irrigation water management practice must be based on seasonal ET_c changes to predict water needs and arrange irrigation, particularly in the use of water-efficient methods like controlled DI.

In Baghdad, maize is typically planted between mid-July and mid-August. **Fig. 4** indicates that ET_c of maize exhibits a significant change over time that depicts the development of the crop and the water requirements. The values of ET_c during the first month of the season are lower, as this is the period when there is minimal water utilization due to the lack of canopy cover and the development of transpiration rates.

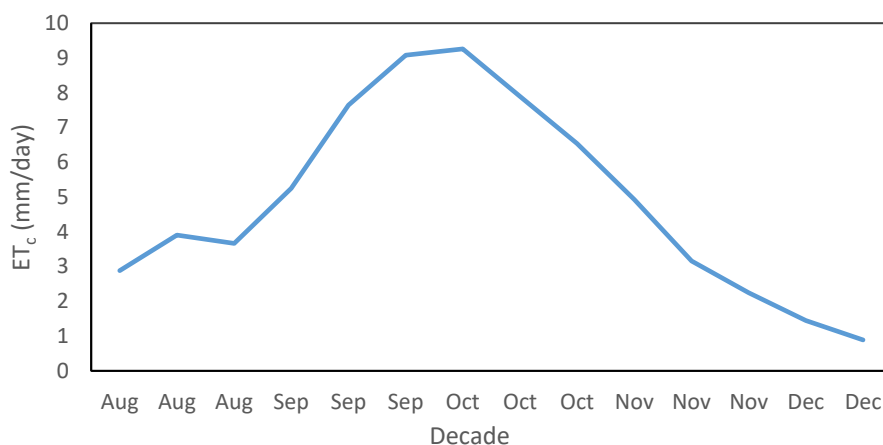


Figure 4. ET_c of Maize (in a decade, Aug 2025 - Dec 2025).

The crop advances into the month of September, and the ET_c shoots up to the highest peak in late September to early October. This peak is equal to the growth stage in the middle of the season, when maize acquires its complete canopy and its maximum rates of transpiration and evapotranspiration. ET_c values start to decrease slowly during October and further through the late-season stage, where the leaf area is smaller, physiological maturity and overall water consumption of the crop also increase steadily. During November and December, ET_c will be minimal because the evapotranspiration is low since the crop is towards harvest or the end of its life cycle.

A study of (FAO, 2021) has demonstrated a clear temporal variation in crop ET_c of maize throughout the growing season. The values of ET_c s were low at the start of the season, then increased steadily with the growth of the crop, reaching a maximum in the middle of the season, the same time when the vegetative growth was completed, and water demand was maximum. Then, the ET_c rate steadily decreased because the crop was approaching physiological maturity at the end of the season. The changes in seasonal ET_c data were dependent on the available water, and water stress decreases the actual evapotranspiration rate as compared to the non-stressful conditions. And it verified that the alterations in the maize ET_c in semi-arid conditions are strongly connected with the degree of irrigation, and that the linear correlation between the ET_c and yield turns ET_c into a significant element in efficient irrigation planning and management.

The recommended planting period for wheat in Baghdad extends from mid-October to mid-December. **Fig. 5** depicts ET_c of wheat as it has a pronounced seasonal trend, which indicates the growth stages of the crop and the current climatic conditions.

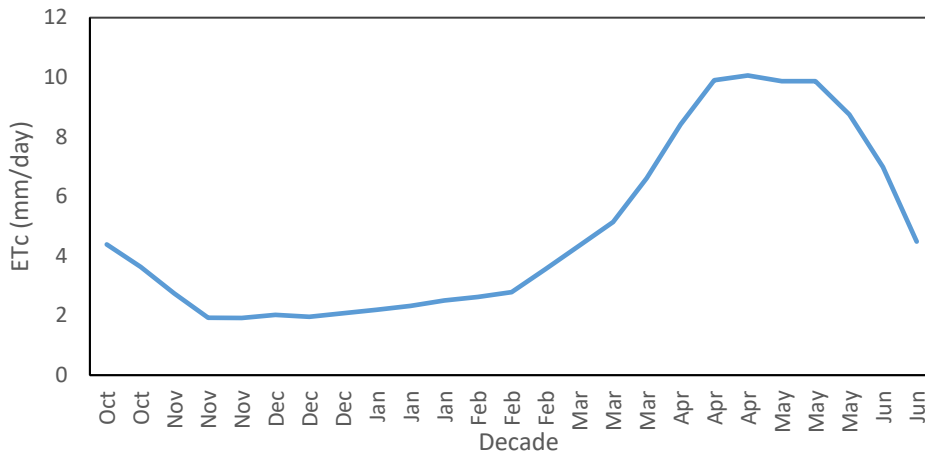


Figure 5. ET_c for Wheat over a decade (Oct 2025 – Jun 2026).

At the beginning of the season (October–November), ET_c values are relatively moderate, then decrease to their lowest levels during early winter (November–December), indicating limited water use during the initial establishment stage and low atmospheric demand. Starting in January, ET_c gradually increases as the crop enters the vegetative growth stage and temperatures begin to rise. A sharp increase in ET_c is observed from March onward, reaching its peak during April and early May, which coincides with the flowering and grain-forming stages, when wheat reaches its highest water requirement. After this peak, ET_c declines rapidly as late May and June approach physiological maturity and senescence. (Pereira et al., 2015) results showed that the wheat growth period in the spring constitutes the critical stage in which the demand for water reaches its peak, and that providing sufficient water supplies during this period is necessary to maintain the crop and improve water use efficiency, which is entirely consistent with the results of this research related to wheat water consumption in arid and semi-arid regions.

3.2 Crop Coefficient (K_c) and Its Role in Irrigation Requirements

The time-dependent change in the K_c of maize and wheat over 10 days in every month, which is the impact of physiological maturation of the crop on the water-use pattern of the crop over the growing period, is shown in Fig. 6. As the cycle starts, the values of K_c are low, which means that the canopy is sparse, the root systems are shallow, and the rate of transpiration is low.

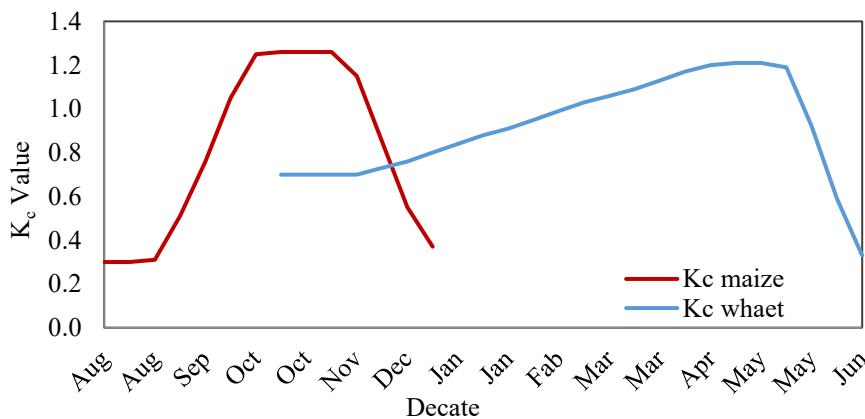


Figure 6. K_c for Wheat and maize over the decade (Aug 2025 – Jun 2026).



When the crop enters its rapid vegetative growth period, K_c increases drastically, and it is a sign of increased leaf area, stomatal activity, and increased sun radiation interception. The highest K_c values in the full canopy phase, where the crop has the highest evaporative demand and is the most sensitive to water stress. Senescence and a slowing of physiological activity can be indicated by the decrease in K_c at the end of the season, with transpiration decreasing as the canopy degrades and grain development comes to an end. The trend in the figure is critical in the accurate conversion of ET_o to ET_c and, hence, scheduling irrigation appropriately based on the actual water requirement of the plant under the climatic conditions of the study area in Baghdad.

Maize had a higher peak K_c value than wheat; thus, it has a transpiration demand and water stress sensitivity. The K_c transition was smoother in wheat, which indicated that the water-use behavior showed greater stability during the growth stages. This physiological variation is the cause of the different reactions of the two crops to the deficit irrigation conditions.

The trends in K_c observed prove the theories of crop growth in FAO and support the appropriateness of irrigation scheduling on a stage-by-stage basis. Using homogeneous irrigation without considering the changes in K_c would either use up water when the demand is low or cause stress at the time of the critical growth stages.

The results of (Okten, 2008) demonstrate that the K_c is a fundamental criterion for estimating crop water requirements and plays a pivotal role in irrigation scheduling according to the FAO56 K_c - ET_c methodology. The study confirms that standard K_c values vary systematically with the crop's growth stages (initial, growth, mid-season, and end-season) and accurately reflect changes in vegetation growth, crop height, ground cover, and soil evapotranspiration. Proper choice of K_c value makes it possible to obtain a reliable estimate of ET_c and avoid over- and under-irrigation. Incorrect or locally derived K_c values may result in substantial inaccuracies in estimating the water requirements, causing inefficient use of water, excessive deep seepage, or water stress in crops. Therefore, accurate determination and proper adjustment of the K_c value are essential for optimizing irrigation timing, improving water use efficiency, and supporting sustainable water management in arid and semi-arid regions.

3.3 Crop Evapotranspiration (ET_c) and Irrigation Requirement Analysis

The variations of NIR and ET_c for wheat and maize crops on a ten-day (decadal) basis are shown in Fig. 7. This figure depicts the tendency of rising and falling irrigation demand and the actual plant evapotranspiration. ET_c and NIR must coordinate in order to establish the irrigation schedule. This comparison unveils the time when irrigation is necessary to satisfy the demand of crops. When the maximum irrigation needs always fall short of the peaks of ET_c , then crops can be under moisture stress at crucial stages of growth. The change in irrigation demand NIR and ET_c depicts the degree to which the irrigation demand follows the process of evapotranspiration over successive ten-day intervals. ET_c rises when the crop is changing between emergence and full development of the canopy due to rising temperatures, increased solar radiation, and an increase in the leaf area. This curve normally reflects the irrigation requirement curve, which is slightly lower at the time that the rainfall is effective in supplying water to the soil. NIR is also maximized at the peak of the mid-season when ET_c is also at peak levels, which signifies the high necessity of ensuring irrigation is done at the right time so that the crop does not face water stress at its most sensitive stages of growth. Both ET_c and NIR decrease towards the end of the season as the plant matures and the physiological activity of the plant decreases.

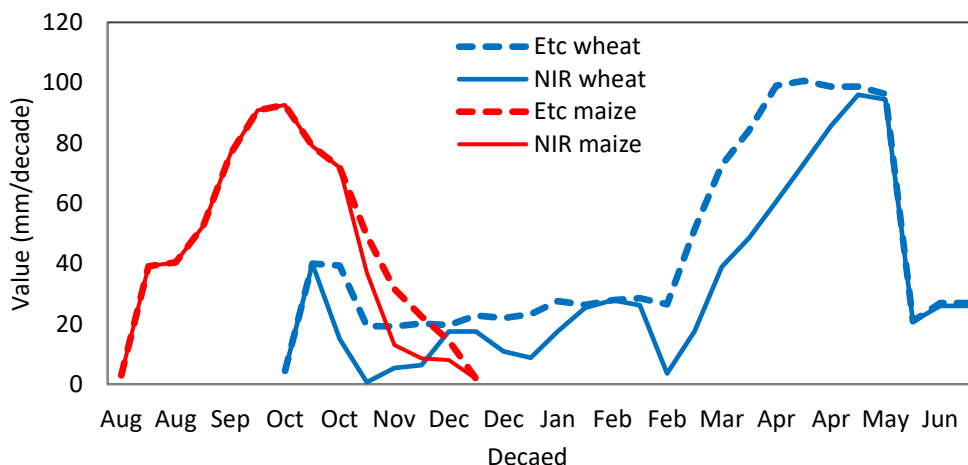


Figure 7. Variation of NIR and ET_c for wheat and maize crops.

Altogether, the figure indicates the significant role of decadal monitoring of ET_c to adjust the irrigation schedule and guarantee the water deliveries that should correspond to the changing demands of the crop during the semi-arid season in Baghdad. The germination stage is usually characterized by a low evapotranspiration rate of the ET_c and low irrigation requirements, when canopy cover is limited. In regions such as Baghdad, winter rainfall during this period can partially or fully satisfy crop water requirements, thereby reducing the need for supplemental irrigation. As wheat enters the tillering, stem elongation, and heading stages, both ET_c and NIR increase at high rates, which are the consequences of the enlargement of the leaf area, the increase in the rate of transpiration, and exposure to the warmer temperatures. The peak values of ET_c calculated on a decadal basis closely correspond to the peak irrigation requirements over the same periods, highlighting the times when supplemental irrigation is essential to prevent soil moisture stress and potential yield reduction. At the end of the season, ET_c decreases because canopy activity decreases, and therefore, GIR also decreases in line with the decadal variations in ET_c due to the need to ensure that water is delivered efficiently at the high-demand phases to maximize wheat production in the semi-arid environment of Baghdad.

3.4 Integrated Water Balance and System Performance

Integrative analysis of the water balance components indicates a strong seasonal water demand in terms of a low level of water demand during the spring growth phase, a sharp rise in water demand during the active vegetative and mid-season growth period, and slow growth of the crop as it attains maturity. This combined view supports the idea that the proper planning of irrigation must be founded on cumulative seasonal processes and not on specific hydrological or agronomic measures. **Fig. 8** contains a combined representation of the dynamics of the irrigation system of the crops in Abu Ghraib under consideration. It integrates the main agronomic and hydrological signals, e.g., K_c and effective root depth, to show the effect of crop development on water demand and soil water uptake capacity during the growing period. Setting a percentage of the maximum root depth of crops monthly is a flexible and effective irrigation management tool. It allows for a precise balance between the amount of irrigation water applied and the water saved, while minimizing deep drainage losses and improving the utilization of total available water and readily available water for the plant. Changes in root depth reflect the plant's development and its ability to utilize soil



moisture. In the same context, (Al-Haddad and Bakr, 2013) showed that controlling irrigation frequency and timing based on the effective root depth can improve WUE and enhance productivity while minimizing water losses.

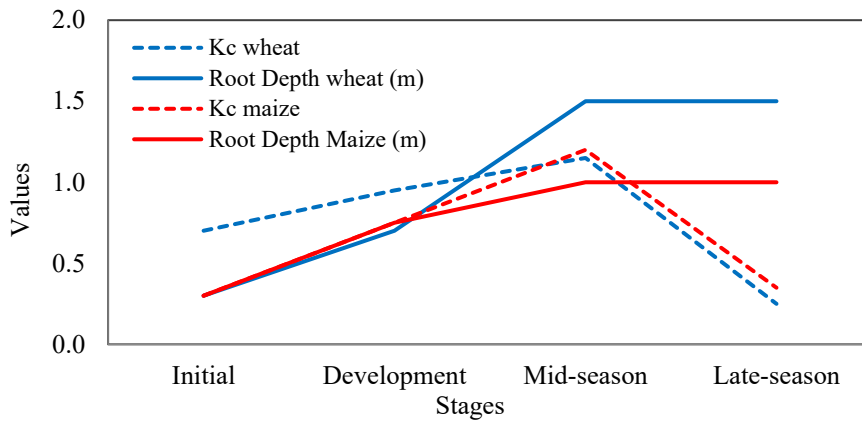


Figure 8. Seasonal Variation of Kc and Root Depth for Wheat and Maize.

This trend reveals the interaction of the climate-driven factors, such as temperature, solar radiation, and variability of rainfall, on crop water use. Altogether, it is a diagnostic tool that summarizes the seasonal patterns of crop water demand and aids in the determination of irrigation scheduling efficiency and resource distribution in the semi-arid climate of Baghdad.

3.5 Estimated Effective Rainfall (ER)

Fig. 9 indicates the manner in which the total rain and ER, with particular emphasis on the difference between the total precipitation and the amount of precipitation that could be utilized to fill soil moisture. The figure makes a comparison of total and effective rainfall during the growing season in the study area in Baghdad. There are two different curves that are presented, one depicting the variation between the actual rainfall levels and the proportion that is actually used by crops. The separation of these curves differs by season, and it shows variations in the effectiveness of rainfall at the varied climatic conditions.

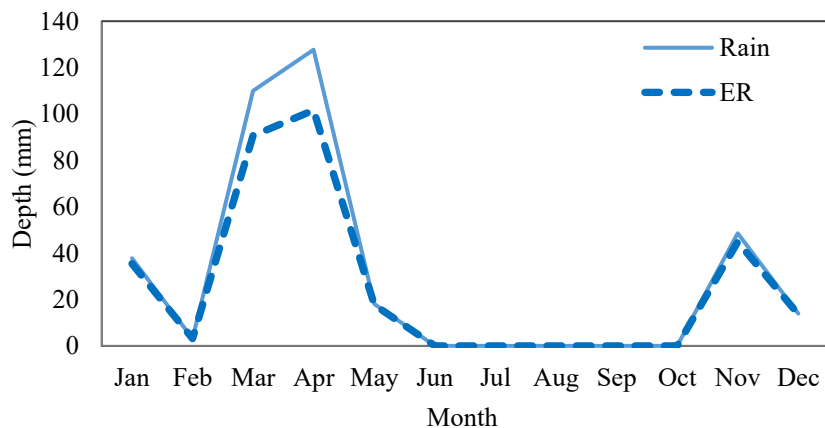


Figure 9. Effective Rainfall.

These findings indicate that due to the semi-arid climatic conditions in Baghdad, a significant portion of the rainfall is not converted to effective rainfall. This is the reason why

supplemental irrigation is always necessary even after the rainfall events have taken place. Low effective rainfall periods create a need to have higher inputs of irrigation, whereas high terms of effective rainfall can temporarily lower the level of irrigation needs.

The observed results show strong similarity to those reported by **(Geerts and Raes, 2009)**, which clearly indicated that a relatively small fraction of the total rainfall was useful in supplying water to maize in rainfed maize. The least grain production and water use efficiency was recorded in rainfed maize, suggesting that a large amount of rainfall was lost through evaporation, run-off, and deep percolation, and inefficient coordination between rainfall and crop water demand. The scenario analysis also revealed that dry seasons resulted in the yield being 30.8% lower than that obtained in rainy seasons and that the effective rainfall was highly dependent on the quantity and the seasonal variation of the precipitation.

Conversely, drip irrigation reduced water wastage and increased the efficiency of both rainfall and irrigation water applied on the soil, and thus, improved the efficiency of water **(Al-Aridhee and Mahdi, 2022)**. Also, **(Abdul-Razak et al., 2016)** studied the effect of surface drip (DI) and subsurface drip (SDI) irrigation systems on maize yield. A field experiment was conducted during the autumn season of 2013 at the experimental field of the Field Crops Department, College of Agriculture, University of Baghdad. The results showed that subsurface irrigation was superior in increasing grain yield (5.55 tons/ha) by 3.2% compared to surface irrigation. Therefore, the study recommended adopting subsurface drip irrigation at a pressure of 21 kPa and a depth of 0.31 m for maize fields in the central region of Iraq.

Fig. 10 shows the decade variation of ER and ET_c of maize and wheat, which shows the importance of the contribution of natural rainfall to the amount of water required by the atmosphere for the crop. Rainfall contributes partially to replenishing soil moisture; however, under the semi-arid conditions of the study area in Baghdad, ET_c generally exceeds effective rainfall, creating a persistent water deficit. Maize exhibits high water demand from late summer, peaking during September–October (>90 mm/decade) under high temperature and evaporative conditions, with negligible rainfall, making irrigation essential.

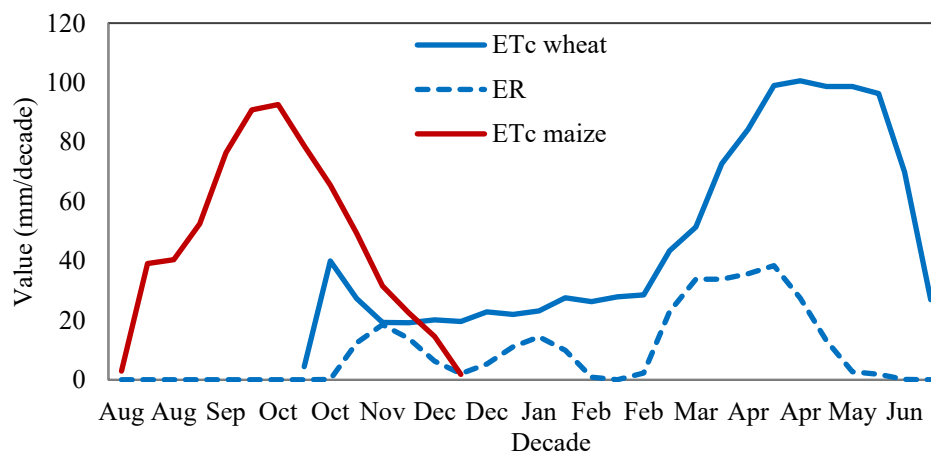


Figure 10. The variation of ER and ET_c for wheat and maize by ten-day/month.

In contrast, wheat begins in autumn with relatively low ET_c (20–30 mm/decade) during winter, where rainfall partially meets crop demand. As temperatures rise in spring, wheat ET_c increases sharply, peaking in April–May (~100 mm/decade), while rainfall declines,

resulting in significant irrigation requirements. Overall, the temporal mismatch between rainfall and crop water demand highlights the necessity of supplemental irrigation, particularly during critical growth stages such as stem elongation, heading, and grain filling, to avoid moisture stress and ensure optimal productivity.

3.6 Net and Gross Irrigation Requirements and System Efficiency

The monthly variation of NIR and GIR for maize and wheat is illustrated in **Fig. 11**. Both NIR and GIR increase progressively from August for maize, reflecting rising crop water demand associated with crop establishment and vegetative growth.

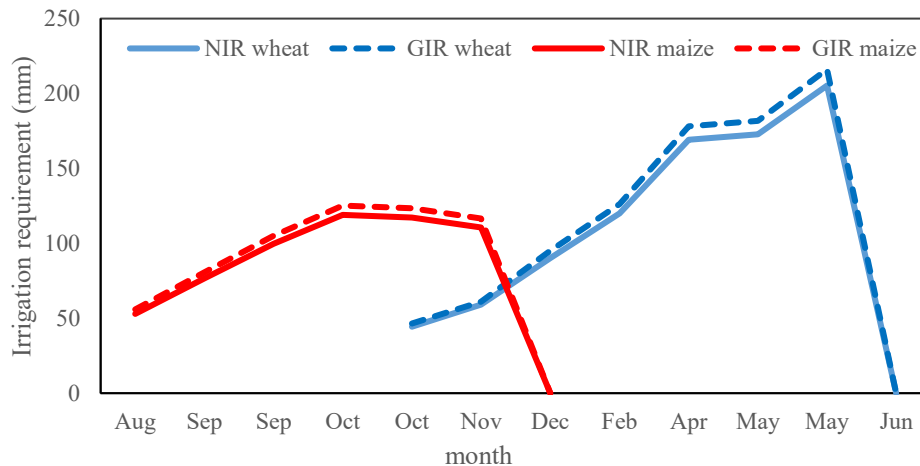


Figure 11. Variation of NIR and GIR for maize and wheat.

The irrigation requirements peak during October, which corresponds to the period of maximum crop evapotranspiration and full canopy development, when maize is most sensitive to water stress. The irrigation requirements were estimated assuming a drip irrigation system. The GIR is also constantly greater than NIR over the growing season, and this suggests that there is water loss to field application inefficiencies, including conveyance losses, runoff, or deep percolation. Both NIR and GIR start to fall in November, following the onset of October as the crop attains physiological maturity and the rate of evapotranspiration reduces. The irrigation demands also reduce to close to zero by December, which implies that crop water demands are low, or the growing season is over. Generally, the trend shows the dire need to properly irrigate during the mid-season period of growth, especially in October, to prevent moisture stress and loss of yield in maize due to climatic conditions within the study area.

The irrigation needs of wheat at the onset of the season in October are relatively low due to the reduced rates of evapotranspiration and partial fulfillment of crop water requirements by the early season rainfall. Both NIR and GIR are increasing significantly after February, which is related to the increase in vegetative growth, expansion of stems, and the increase in atmospheric demand. The highest irrigation needs are in the month of May when the reproductive and grain-filling phases of wheat are in full swing, and the demand and sensitivity to moisture stress are at their peaks. Just like maize, the GIR values are always greater than those of NIR during the season because of the loss of irrigation application. Subsequent to the peak season in May, the need for irrigation decreases drastically in June, with the crop attaining physiological maturity and evapotranspiration reducing, which means there will be little or no necessity for additional irrigation. In general, the findings



underscore the need to have proper irrigation at the late vegetative and reproductive phases, especially during spring months, to achieve the best wheat production as per the climatic conditions of the study region.

3.7 Deficit Irrigation Scenarios and Yield Reduction

The impact of administering varying concentrations of DI (5, 10, 15, 20, and 25%) of the total water requirement on the reduction in yield of maize at various growth stages (initial, developmental, and mid-season) was researched. The findings presented in **Table 1** indicate that yield decline is gradually increasing with increased reduction in irrigation water, but the extent of effect is different at the various levels of growth stages at which deficiency of water is imposed.

As shown in the initial stage data in **Table 1**, the impact of DI on yield is quite small at simple deficit levels, and yield decreases are observed at 5% of the water requirement. But this decrease grows dramatically with the increase in DI and peaks at 25%, which proves the fact that early water stress is an important determinant of plant establishment and future growth potential.

Table 1. DI on the reduction of yield in maize.

Maize season stage	Yield reduction% corresponding to the deficit irrigation level				
	DI 5%	DI 10%	DI 15%	DI 20%	DI 25%
Initial	0.1	0.2	0.4	0.6	0.8
Development	0.3	1.0	1.9	3.0	4.3
Mid-season	0.2	0.8	1.7	2.0	4.0
End-season	0.0	0.0	0.0	0.0	0.0

Maize is moderately sensitive to water stress during the stage of development. Although the effect of under-irrigation is not as dramatic as that of the mid-season stage, it influences the development of foliage and the number of leaves, which also influence the efficiency of photosynthesis, dry matter production, and eventually yield. The mid-season phase, which involves flowering and grain development, is the most vulnerable to under-irrigation. The maximum losses in yield were observed when DI levels were used, especially at 20% and 25% of the total water requirement. This is because water stress at this stage has a direct consequence on the set and filling of the grain, which results in a significant reduction in productivity. The current results align closely with those obtained in **(Waller and Yitayew, 2016)**. Maize is somewhat vulnerable to water stress, especially when water is unavailable, in some sensitive stages of reproduction, like flowering and grain formation. Losses in crops can be as much as 30%-40%. The study observed that moderate irrigation and limited irrigation, as well as partial root zone irrigation, can increase water use efficiency by about 10%-42% and reduces 11%-32% of irrigation water, mainly by lowering transpiration as well as promoting root growth. Limited irrigation also promotes deeper and more extensive root systems, increasing the root-to-stem ratio and improving the plant's ability to access soil moisture and nutrients.

Overall, the results confirm a direct relationship between DI levels and yield reduction; that is, increasing the DI leads to increased yield loss, although the degree of impact varies depending on the growth stage. The results also show the possibility of applying controlled DI in less sensitive stages (such as the start or vegetative development stage (End season)) to save water, provided that DI is avoided during the mid-season stage, in order to achieve a balance between rationalizing water consumption and maintaining maize productivity.



For wheat, computation of yield reduction versus DI, **Table 2**, shows that the effects of applying different levels of DI compared to full irrigation on yield reduction during various growth stages, including the initial stage, the development stage, the mid-season stage (including elongation and flowering), and the late stage, were investigated.

Table 2. The effect of DI on yield reduction for wheat.

Wheat season stage	Yield reduction% corresponding to the deficit irrigation level				
	DI 5%	DI 10%	DI 15%	DI 20%	DI 25%
Initial	0.0	0.0	0.0	0.0	0.1
Development	0.0	0.0	0.1	0.2	0.4
Mid-season	0.0	0.0	0.4	1.1	2.0
End-season	0.0	0.0	0.0	0.0	0.0

These results show that reducing irrigation water leads to a gradual increase in yield reduction, although the severity of the effect varies significantly depending on the growth stage. Data indicate that applying DI during the initial stage results in a relatively limited yield reduction, especially at low deficit levels, as wheat has a partial capacity to compensate for early water stress by improving growth in later stages. Nonetheless, an augmentation of the severity of the DI at this phase may have an adverse impact on the plant density and spike amount, which in turn influences yield. In the developmental phase, wheat is moderately vulnerable to water stress; DI reduces the vegetative cover and the rate of vegetative growth, limiting the photosynthetic efficiency and dry matter accumulation.

The yield losses become more important as the DI levels get higher, but they are not as substantial as the influence in the mid-season stage. The period of mid-season, which includes elongation, flowering, and grain filling, is the most sensitive to DI in wheat and is the one that shows the greatest yield losses when water deficits are imposed at this stage. This has been explained by direct effects of water stress regarding the quantity of grains per spike and grain weight, which are the two most crucial constituents of yield in wheat. Nonetheless, the effect of DI at the ripening phase is relatively lower in yields than at earlier phases, particularly at low deficit levels, since most of the yield situations are predetermined, and the impact of water stress can only be manifested on grain filling. Altogether, the findings support the existence of a direct correlation between the power of DI and the decrease in wheat yield, as well as the fact that the sensitivity of the crop to water stress depends on the stage of its development. It is also seen in the results that controlled DI can be adopted in a less sensitive period, like early growth or ripening, but it is important not to experience water shortage in the middle of the season to obtain the optimal balance between water saving and maintaining wheat yields.

These findings were in line with those of (**Payero et al., 2008; Okten, 2008; Geerts and Raer, 2009**), which show that regulated DI leads to the progressive decline in grain yield as water stress intensifies, but moderate water stress does not lead to the crop being affected. The findings show that the efficiency of water use (WUE) and irrigation water use efficiency (IWUE) is enhanced in the mild deficit conditions and is accompanied by significant savings in irrigation water as compared to complete irrigation. The deeper and more developed root systems were encouraged by water stress as part of physiological adaptation, which increases the capacity of the plant to draw moisture further down in the soil. The reproductive growth phases were found to be the most sensitive to the water stress, and the prevention of the water shortages in the reproductive growth phases was effective in

reducing the losses in yield. More so, the value of yield response factors indicates that even minimal water deficits can be considered agronomically acceptable, since yield decline is proportionately less compared to the relative decline in water usage. In general, the research finds that DI is a sustainable crop production method that is both practical and effective in the semi-arid areas when it comes to saving on the use of water. These findings are consistent with previous studies (Farooq et al., 2009), which indicate that wheat demonstrates greater tolerance to deficit irrigation compared to maize. This resilience is primarily attributed to wheat's adaptive root system and higher physiological plasticity. Under moderate water stress, wheat can develop deeper and more extensive root systems, allowing it to effectively utilize moisture from deeper soil layers. This adaptation enhances its ability to sustain transpiration and grain filling under limited water conditions. Consequently, wheat can maintain relatively stable yield levels while improving water use efficiency under deficit irrigation.

3.8 Yield Reduction Analysis

The impact of DI on the maize and wheat growth phases is summarized in **Fig. 12**. This figure shows how each maize and wheat growth stage is processed separately under DI conditions (5, 10, 15, 20, 25%) reduction in comparison to full irrigation and the obtained results show the influence of various levels of DI on maize yield reduction in the 4 growth stages (Initial, Development, Mid-season and End). The general direction of yield reduction with an increase in DI at a growth stage is nonlinear at all stages, which implies the presence of a distinct dose-response association between water stress intensity and yield loss.

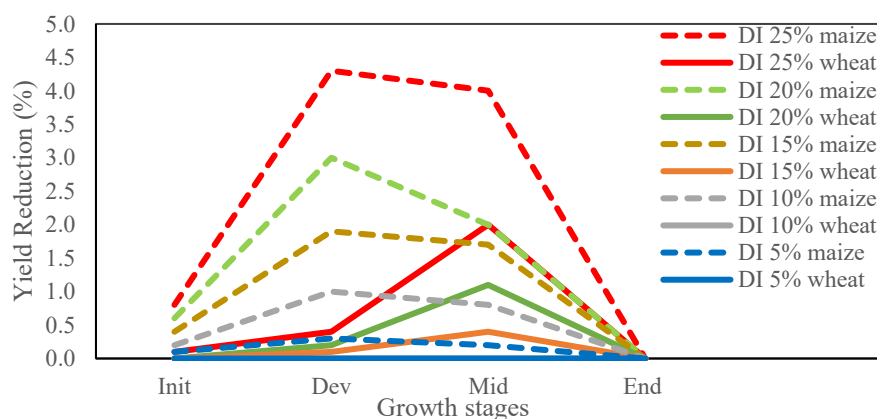


Figure 12. Effect of applying different DI levels at different growth stages on the yield reduction of maize and wheat.

The stages that are most sensitive to DI are the Development (Dev) and Mid-season (Mid) stages. Peaks of the maximum decline in yield occur at DI25% with a peak value of approximately 4.3%, and 4.0% of yield reduction in Development and Mid-season, respectively, indicating that these two seasons are very important in the maize water needs. Even moderate deficits (DI 15 to 20%) have significant losses on the yield (around 1.7-3.0%), which is proof that any stressful conditions that arise even in these stages can have a great impact on productivity. By contrast, the Initial (Init) stage is quite insensitive to deficit irrigation, with the yield decreases not exceeding 1% even at DI 25%. The End stage displays no significant yield decrease regardless of the level of deficit, implying that water stress

during some parts of the season (late in the season) does not have a major effect on the final yield. All in all, the findings show that deficit irrigation can be utilized with minimal yield penalty at the first and last stage of maize growth, but sufficient irrigation at the developmental and mid-season stages is essential to prevent significant yield losses. The observation confirms stage-specific deficit irrigation approaches to enhance the efficiency of water use in water-limited situations. Nevertheless, in the case of maize aimed at all its development phases and deficit irrigation cases, the yield is considerably lowered by a particular percentage.

In the case of wheat, the results obtained illustrate the impact on yield reduction of various DI levels (5%-25%) on wheat in four growth stages (Initial, Development, Mid-season, and End). On the whole, the yield decrease is more with higher concentrations of DI, thus a clear-cut negative correlation between water availability and wheat productivity is observed. The most water stress-sensitive stage is the mid-season one. At DI25%, yield loss is about 2.0%, and moderate levels of deficit (DI 15%-20%) also result in significant yield losses (about 0.4-1.1%). This underscores the relevance of proper supply of water in the reproductive and grain-filling phases of wheat, which are critical.

The development stage is moderately sensitive, with the yield decrease less steep with the increase in DI, but the first stage is very low sensitive, as there is a slight decrease in yields even with higher deficit levels. The end stage exhibits an insignificant reduction in the yield, with all the irrigation treatments depicting that there is little influence of water stress on end yield. In general, the findings indicate that wheat can withstand mild DI with low yield loss, especially at the early and late developmental phases.

Nonetheless, enough irrigation in the mid-season stage is crucial to avoid a significant loss of yield. These results advocate the use of stage-specific DI measures to enhance the use of water more efficiently and maintain wheat production under water-limited conditions.

The relationship between DI levels and the reduction in lifespan yield of maize and wheat is illustrated in **Fig. 13**. An almost linear increasing trend is noted to be clear in maize, with the irrigation deficit increasing by 5% to 25%. The yield decreases gradually with the level of DI5% to about 13% at DI25%, which suggests that maize yield is highly sensitive to escalating levels of water stress.

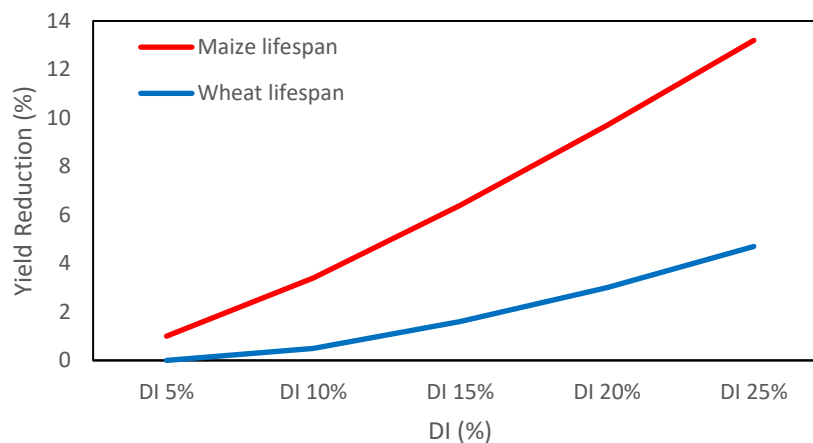


Figure 13. Influence of DI levels on the yield reduction during the lifespan of maize and wheat.

Low deficit irrigation (DI 5%-10%) causes relatively high yield reductions, implying that a relatively weak water stress can be imposed with few effects on productivity. Nevertheless, after DI15%, there is an increased rate of decrease in the yield, which is an indication of a



threshold that maize is highly susceptible to water scarcity. In general, the findings indicate that a moderate level of DI can result in water use efficiency with reasonable yield loss, but severe DI ($\geq 20\%$) causes severe yield loss and must be avoided, particularly in arid and semi-arid environments. This shows that there is a need to optimize DI levels carefully to create a balance between water savings and yield stability. Such outcomes are mostly in tandem with the findings of (Ibrahim et al., 2023; Omran et al., 2025), which explored the impact of climate change and deficit irrigation on the maize irrigation demand and production in Egypt, on the basis of the FAO-Penman-Monteith equation and the CROPWAT model. Meteorological data at Al-Gharbiya, Assiut, and Aswan showed that there was a steady rise in ETo, which reflects the escalating influences of the rising temperatures. Also, the findings indicated that there was an evident negative correlation between DI and the yield of the crop, with the yield decreasing with the degree of water deficit. Also, (5%-10%) DI resulted in minimal yield losses, moderate to severe deficits (15%-25%) resulted in considerable losses of yield, particularly when water stress was experienced in the development and mid-season phases, which were found to be the most sensitive phases of growth. A simple and increasingly growing tendency can be witnessed in the form of wheat because the percentage of DI increases with an increment in the percentage of DI to 5% and to 25%, which implies a high adverse effect of water stress on the wheat yield. The yield reduction at the lower levels of deficit (DI 5%-10%) is also low (around 0%-0.5%), which indicates that wheat can endure light water stress with no or little impact on the yield. But the stronger the DI gets, to moderate levels (DI 15%-20%), the more the yield will be reduced, which is approximately 1.5%-3.0%. In extreme DI 25%, the loss in yield rises dramatically to about 4.7%, which is an indication of the high sensitivity of wheat to significant limitation of water. In general, the findings show that mild DI may be implemented with a minimum yield penalty, but moderate to severe water shortages will cause the yield of wheat to decrease considerably.

These findings align with the requirements modeling on evapotranspiration, effective rainfall, and irrigation requirements in (Maria et al., 2025), which suggested that winter wheat needs an extra four more irrigations within the growing season, mainly in the months of April, May, and July. This study identified the necessity to optimize the water needs of winter wheat irrigation in the Belt of Romania in a region of huge agricultural output. Irrigation at the crucial levels of deficit had a hundred percent efficiency in alleviating crop deficits, particularly in the mid-season and late-season stages, which are the most sensitive to water stress. Moreover, the findings showed a significant negative correlation between DI and crop yield, and crop loss was increasing with the deterioration of water shortages. Moderate DI caused a slight loss of yield, whereas moderate to severe water stress caused serious losses in crops, especially in the growing and mid-season periods.

4. CONCLUSIONS

In this paper, the importance of deficit irrigation (DI) in supporting the production of wheat and maize within an arid to semi-arid region was assessed, considering a case in Baghdad in central Iraq. Through the incorporation of the local climatic, soil, and crop data in the FAO CROPWAT 8 model, crop water requirements, efficient rainfall, and irrigation demands were measured at complete and different DI levels. The findings showed obvious variations in crop responses to water stress. Wheat was very tolerant to moderate water shortage with low to moderate yield losses, with too low to moderate levels of DI (5%-10%), especially when stress was not experienced during the critical developmental phases, such as stem



elongation, flowering, and grain filling. Conversely, at most development stages, particularly tasseling and grain-filling stages. For maize, though, DI is only to be applied with caution, wary of the stages that are least sensitive, so that the yield would not be greatly lost. It was very sensitive to DI, with the most pronounced yield loss (3%–4.3%) for DI (20%–25%). Rainfall played a small role in satisfying the crop water demands, especially that of maize, which emphasized the high reliance of agricultural production within the study region on supplemental irrigation. Seasonal changes in reference evapotranspiration and crop coefficients were used to confirm that the mid-season stages are the highest level of water demand and the most important times of water management in irrigation. Overall, this research enhances current knowledge by framing irrigation management as a threshold-based optimization rather than a simple maximization. The results offer practical evidence that mild to moderate deficit irrigation, DI5–DI10, can be an effective strategy to improve water productivity and economic efficiency in water-scarce scenarios.

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Credit Authorship Contribution Statement

Ahmed Nadhir and Khalid Shemal performed the data collection and analysis, interpreted the results, and wrote the draft of the manuscript. Mahmoud S. Al-Khafaji reviewed the manuscript and prepared the final version. All authors have read and agreed to the published version of the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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دور الري الناقص في استدامة زراعة القمح والذرة في ظل الظروف المناخية القاسية في العراق

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الخلاصة

نقص المياه وتقلبات المناخ يُهدد الإنتاج المستدام للمحاصيل الاستراتيجية كالقمح والذرة في المناطق القاحلة كالعراق. وتتزايد أوجه قصور أساليب الري التقليدية في تلبية احتياجات المحاصيل المائية نتيجة ارتفاع معدل النتح والتبخر وانخفاض معدل هطول الأمطار الفعال. لذا، أصبح الري الناقص، الذي يتضمن استخدام كميات من المياه أقل من احتياجات المحاصيل المائية الكاملة، استراتيجية مهمة لتحسين كفاءة استخدام المياه. هدفت هذه الدراسة إلى تقييم احتياجات مياه الري واستجابة المحاصيل في ظل مستويات مختلفة من الري الناقص في ظروف قاحلة، باستخدام محطة الرائد للبحوث في العراق كمنطقة للدراسة. وتم تحليل البيانات المناخية باستخدام نموذج CROPWAT 8 لتقدير معدل النتح والتبخر، ومعدل هطول الأمطار الفعال، وصافي احتياجات الري، وإجمالي احتياجات الري في ظل الري الكامل ومستويات الري الناقص التي تتراوح من 5% إلى 25% خلال أربع مراحل نمو. وأظهرت النتائج أن القمح يتمتع بحساسية منخفضة نسبيًا لنقص المياه، حيث لم يُلاحظ أي انخفاض في المحصول عند مستوى الري الناقص 5% خلال معظم مراحل النمو، بينما بلغ الحد الأقصى للانخفاض 2.0% عند مستوى الري الناقص 25%، وخاصةً خلال منتصف الموسم. في المقابل، كان الذرة أكثر حساسية لنقص المياه، لا سيما خلال مرحلتي النمو ومنتصف الموسم، حيث بلغ انخفاض المحصول 4.3% و4.0% على التوالي عند استخدام نظام الري الناقص بنسبة 25%. ومع ذلك، عند استخدام نظام الري الناقص بنسبة 5%، لم يُظهر الذرة سوى انخفاض طفيف في المحصول لا يتجاوز 0.3%. عمومًا، يُنصح باستخدام نظام الري الناقص بنسبة 5% خلال مرحلتي الانبات والنمو لكلا المحصولين نظرًا لانخفاض احتياجاتهما للمياه وقلة حساسية المحصول خلال مراحل النمو المبكرة.

الكلمات المفتاحية: الري الناقص، القمح، الذرة، المناطق شبه القاحلة، مراحل النمو.