Compatibility of Crop Patterns with Climate Change for Irrigation Projects in Semi-Arid Regions: The Case Study of the Abu Ghraib Project in Iraq

Rusul S. Alsamarray
Department of Water Resources Engineering, College of Engineering, University of Baghdad, Baghdad, Iraq
rusul.abd2310@coeng.uobaghdad.edu.iq (corresponding author)

Mahmoud S. Al-Khafaji
Department of Water Resources Engineering, College of Engineering, University of Baghdad, Baghdad, Iraq
mahmoud.s@coeng.uobaghdad.edu.iq

Khalid Shemal
State Commission for Irrigation and Reclamation Projects, Ministry of Water Resources, Iraq
dr.khalidshemal@gmail.com

Received: 8 May 2025 | Revised: 1 July 2025 | Accepted: 9 July 2025

DOI: https://doi.org/10.48084/etasr.11967

ABSTRACT

The climate change has become a significant threat to the water security and agricultural productivity, particularly in arid and semi-arid regions. The overall aim of this paper is to demonstrate the compatibility of the current crop patterns with the climate change in the semi-arid areas, using the Abu Ghraib Irrigation Project (AGIP)- one of Iraq's most significant irrigation projects- as a case study. The observed climate data from 1993 to 2023 were used to forecast the climate parameters for 2025–2075 under the Shared Socioeconomic Pathway (SSP) 2-4.5 scenario, utilizing the LARS-WG weather generator and the HadGEM3-GC31-LL model for RCP 5. The CROPWAT 8.0 model was employed to assess the crop water requirements, including the calculations of evapotranspiration and irrigation demands for the summer and winter cropping patterns based on the Penman–Monteith equation. The results indicate a consistent increase in both the maximum and minimum temperatures, accompanied by a slight decline in the annual precipitation. As a result, the Net Irrigation Water Requirements (NIWR) for most crops are projected to have increased by up to 80% by 2075 compared to the historical baselines. Crops, such as wheat, alfalfa, eggplant, and dry onion, exhibited high sensitivity to climatic changes, whereas others, like barley, cowpea, and spinach, demonstrated greater adaptability. The findings indicate that the current cropping patterns are not suitable for the future climate conditions. This highlights the need to modify the farming strategies by selecting drought-resistant crops and adopting modern irrigation techniques. The study also provides valuable information to help improve the water management and support the agriculture in dry and semi-dry regions.

Keywords-climate change; drought-tolerant crops; CROPWAT 8.0; crop water requirement; AGIP; irrigation management

I. INTRODUCTION

One of the most pressing problems is that of global warming, also known as climate change, and the world has begun to recognize its environmental, economic, and social impacts. This has generated an international interest in the climate issues and their potential future implications through the conduct of comprehensive and in-depth studies and research. Therefore, predicting the future climate conditions is crucial for assessing their effects on hydrology, meteorology, and agriculture. The climate change has led to water scarcity issues in semi-arid regions due to increased shortages. As a result, arid and semi-arid areas experience water scarcity for irrigation projects [1]. Thus, the climate change has led to reduced efficiency in agricultural projects. Additionally, some regions face extreme precipitation, while others experience less rainfall, witnessing an increase in the drought frequency, intensity, and duration [2-6]. Consequently, many areas' agricultural systems will be heavily impacted by the land degradation, such as erosion and desertification, which will seriously affect the human activities and food security, prompting the migration from Iraq [7-9]. Iraq, which is characterized by its arid and semi-arid climate zones, remains a concern due to the ongoing climate changes and their potential future effects on the water and food security [10]. Climate change impacts the crop yields because the irrigation needs depend on the climate data, including temperature, rainfall, humidity, and wind speed. To calculate the NIWR, advanced methods, such as the Penman–Monteith equation and crop coefficients (Kc), are used to estimate the actual crop evapotranspiration (ETc), which indicates the crop's water usage [11].

Additionally, the amount of water needed varies depending on the crop type, growth stage, and soil type, necessitating precise irrigation strategies. The accurate water estimates and proper amounts help improve the agricultural productivity and guide the irrigation practices to address the climate change challenges. The climate change primarily impacts the plant growth and development by inducing water stress through altered precipitation patterns and rising temperatures. Each growth stage responds differently. The responses to water stress vary among species, cultivars, and environments, making it crucial to understand these effects for effective water management and improved agricultural water use efficiency. The climate change impacts the crop yields in several ways. As temperatures increase and humidity fluctuates, the crops react differently; some are highly sensitive, leading to increased irrigation needs or significant yield losses [12], while others are more resilient and better suited to tough conditions [13]. The rising temperatures influence the crop productivity in five key ways: higher temperatures accelerate the growth, shorten the growing period, and reduce the yields [14, 15]; they also disrupt photosynthesis, as C4 crops, like maize and sugarcane, tolerate the heat better than C3 crops, like rice and wheat, though both decline under extreme heat [16]. The elevated temperatures increase the Vapor Pressure Deficit (VPD), causing plants to close their stomata, which reduces photosynthesis and increases the canopy temperature [17]. The heat stress during reproduction can increase sterility, decrease yields, and lead to crop failure [18]. Finally, the rising temperatures and CO2 levels enhance the pest survival and facilitate the disease spread, further threatening the crop production [19].

The assessment of the impact of climate change on the global agricultural productivity indicates that the climate change has resulted in a 21% reduction in productivity since 1961, with projections indicating a further decline to 28% by 2060 [20]. The application of the Aqua-Crop model to estimate the yield and water productivity suggests that the irrigation water productivity is expected to have increased by 28% in 2060 under climate change conditions. Iraq, classified within arid and semi-arid climatic zones, is among the most severely affected countries, experiencing longer, more frequent, and more intense droughts [6]. For this reason, Iraq was selected as a case study because it is considered one of the critical cases. The climate change projections derived from multiple General Circulation Models (GCMs) and Representative Concentration Pathways (RCP 2.6, 4.5, and 8.5) indicate increasing annual mean temperatures and evapotranspiration, accompanied by a declining trend in the annual precipitation. Toward the end of the century, temperature increases of 1.86–5.36 °C and fluctuations in precipitation will be observed [21-24]. The AGIP, located in the central region of Iraq, classified as arid to semi-arid, was selected as the case study due to its significance as one of the country's leading irrigation schemes. It features diverse crops and irrigation systems, faces challenges such as water scarcity and desertification, and offers strong potential for improved management. This paper aims to assess the impact of climate change on irrigation requirements for different crops within the cropping patterns in semi-arid regions, with a particular focus on Iraq. The study also evaluated the suitability of the current cropping patterns under changing climate conditions to develop sustainable agricultural strategies that support the food security and resource management. Specifically, it evaluated the crop pattern of the AGIP under the present climate conditions and projected the long-term impacts of the climate change on the agricultural planning. The crop sensitivity, resilience, and adaptability to climate variations were examined to determine their influence on productivity. Furthermore, the crop water requirements were analyzed under different climate scenarios to propose strategies for optimizing the irrigation and improving the water-use efficiency. By generating climate-related agricultural data from a semi-arid region, the study contributes to the global scientific literature. It provides valuable guidance for policymakers and researchers in regions facing similar climate challenges.

II. MATERIALS AND METHODS

A. Study Area

1) Location and Area

Iraq is one of the countries most severely affected by the climate change. It is located between 29.5-37.22 N latitudes and 38.45-48.45 E longitudes. The middle and southern regions of Iraq lie within the arid and semi-arid continental zones of the Middle East. The AGIP is one of the largest and most critical agricultural projects in central Iraq, making it a key example for assessing the impact of the climate change on irrigation and farming. Its strategic position within a semi-arid zone and dependence on the Euphrates River underscore its importance for the national food security and water resource management. AGIP is situated 35 km southwest of Baghdad and bordered by the Saqlawiyah and Radhwaniyah Irrigation Projects, the Main Outfall Drain, and Fallujah's agricultural lands (Figure 1). Covering 515 km2, it is irrigated through the 23 km Abu Ghraib Canal. Its semi-arid climate, characterized by hot, dry summers and cool winters, makes it an ideal model for studying sustainable agricultural practices under the changing climate conditions [25].

2) Climatic Characteristics and Datasets

Iraq's climate is predominantly arid to semi-arid, characterized by hot, dry summers and very low annual rainfall, including in Baghdad. In the Baghdad Governorate, where AGIP is located, the average minimum summer temperature is around 28 °C, with maximum summer values reaching 48 °C. The annual precipitation ranges from 70 to 200 mm, and the dry northwesterly winds are frequent [26]. These climatic conditions, combined with limited rainfall, make AGIP a key location for assessing the effects of the climate change on the cropping patterns and emphasize the need for effective irrigation and agricultural practices.

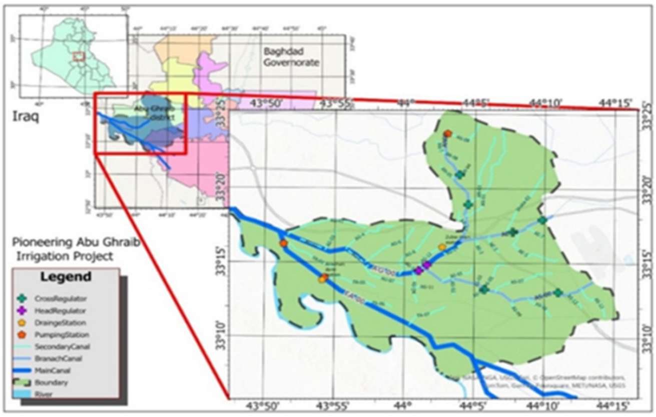

Fig. 1. Location and irrigation network of the AGIP.

Climatological data were collected for the period 1980–2023 in 10-year intervals from the Baghdad Meteorological Station (Table I). The dataset includes daily temperature (°C), wind speed (m/s), relative humidity (%), sunshine duration (hours/day), and precipitation (mm). The accuracy and completeness of the temperature and radiation data were verified using NASA sources [27]. Precipitation records were obtained from the CLIMATE ENGINE platform and the CHIRPS satellite dataset [28] at a spatial resolution of 0.05 × 0.05 degrees. The use of these global datasets is preferable due to their geographical coverage, temporal consistency, and reliability. NASA satellite products have also been widely applied in recent feasibility studies of solar energy projects in Libya to evaluate the solar levels across multiple sites, demonstrating their robustness as a data source for regional, environmental, and energy analyses [29].

TABLE I. SOURCES OF CLIMATIC DATA

No	Data source	Climate variable	Period
1	Ministry of Transport / Iraqi Meteorological Organization and Seismology	Tmax, Tmin, Pr, Humidity, Wind, Sun-S	1980 - 1990 - 2000 - 2010 - 2020 - 2023
2	LARS-WG8.0	Tmax, Tmin, Pr, S-RAD	2025- 2035 - 2045- 2055- 2065 - 2075

Authors in [30, 31] emphasize the importance of providing free, up-to-date information supported by advanced technologies, such as satellites. In this study, climate data were collected over a 30-year period (1993–2023) to calibrate and validate the LARS-WG 8.0 software. This duration was selected as it represents a standard reference period for analyzing the climate variability, reducing the short-term fluctuations, and capturing the recent climate patterns and extreme events, thereby enhancing the accuracy of future projections. The RCP 4.5 was adopted as a moderate stabilization pathway consistent with the global mitigation strategies [32]. The HadGEM3-GC31-LL model was selected for its comprehensive representation of the climate processes and participation in CMIP6, providing reliable climate projections [33]. Additionally, the SSP 2–4.5 was considered a middle-ground scenario, suitable for assessing the future climate impacts. Previous research has highlighted the relevance and importance of these approaches in similar contexts [21, 34, 35].

3) *Soil Information*

Salinity and waterlogging are the main constraints limiting the agricultural productivity in AGIP. The soil has a medium texture and a groundwater table at a depth exceeding 2 m. These issues are primarily attributed to the poor drainage and over-irrigation. Although partial reclamation has been carried out in some areas, salinity remains a persistent challenge (Table II) [25, 36].

TABLE II. MAIN SOIL CHARACTERISTICS IN AGPI

No	Soil name	Heavy (clay)	Light (sand)	Medium (loam)
1	Total available soil moisture (mm / meter)	200	60	290
2	Maximum rain infiltration rate (mm / day)	40	40	40
3	Maximum rooting depth (cm)	900	900	900
4	Initial soil moisture depletion (as % TAM)	0	0	0
5	Initial available soil moisture (mm / meter)	200	60	290

4) *Water Resources and Irrigation Network*

The AGIP is irrigated by the Abu Ghraib Canal, a 23 km concrete-lined canal with three branches (East, North, and South). The unified Al Faluja supplies the Iskandariyah Main Canal, which diverts water from the Euphrates River approximately 20 km downstream of Al Faluja, with a maximum discharge of 28 m³/s. Irrigation mainly relies on gravity, supplemented by five pumping stations that house 18 pumps with a total capacity of 7.35 m³/s.

5) *Crop Patterns*

The cropping pattern in AGIP is balanced between grains and vegetables, with fodder crops accounting for 3.2% of the cultivated area. Summer cultivation accounts for approximately 35% of the annual cropped land, which may be attributed to irrigation water shortages during this period [25]. The selection of a cropping pattern can be viewed as a strategic decision made before the planting season. Table III summarizes the planned crops, planting, and harvesting dates provided by the Ministry of Agriculture and Irrigation, together with the national strategic study for water and land resources. The total planned agricultural area was 51,500 Ha (approximately 515 km²), with planting and harvesting dates subject to slight variations depending on the water availability [25].

6) *Crop Sensitivity Analysis*

Climate change has a significant impact on the plant growth and development, primarily through the water stress resulting from altered precipitation patterns and rising temperatures. Each stage of the plant growth reacts differently to the water stress.

1. Germination Stage: Adequate soil moisture is essential for the seed germination. The water deficiency during this phase can cause lower and delayed germination rates, which can negatively impact the plant density and future yield.
2. Vegetative Growth Stage: In this stage, the plants depend on adequate water to support the photosynthesis and fast growth. Water stress can reduce the vegetative growth, limiting the leaf area for light absorption and impacting the plant's ability to produce essential nutrients.
3. Flowering Stage: This stage is susceptible to water stress. Not enough water during flowering can reduce the number of flowers produced and increase the flower drop, directly affecting the crop yield.
4. Fruit or Grain Development Stage: The water stress during this stage impacts the size and quality of fruits or grains. Insufficient water can lead to smaller fruits, lower sugar content, and an overall decline in the product quality.

TABLE III. PLANTING DATE, HARVESTING DATE, SENSITIVE STAGES FOR WINTER AND SUMMER PLANS OF THE MINISTRY OF AGRICULTURE

Winter crop	Planting period	Harvesting period	Sensitive stage	Summer crops	Planting period	Harvesting period	Sensitive stage
Wheat	Oct- Nov	Apr- May	Flowering and fertilization	Maize	Mar-May	Jun-Sep	Flowering and pollination
Barley	Oct-Nov	Apr- May	Flowering and early grain filling	Eggplant	Feb-May	Jun-Jul	Flowering and fruit setting
Onion green	Sep-Oct	Feb- Mar	Bulb formation	Tomato	Mar-May	Jun-Jul	Flowering and fruit setting
Potato	Sep-Oct	Jan- Mar	Tuber initiation and bulking	Cucumber	Mar-May	Jun-Jul	Flowering and fruit setting
Broad bean	Oct-Nov	Mar- Apr	Flowering and pod setting	Cowpea	Apr-May	Aug-Sep	Flowering and pod setting
Spinach	Sep-Nov	Dec- Jan	Rapid vegetative growth	Watermelon	Mar-May	Jun-Aug	Flowering and fruit setting
Forage mixture	Sep-Oct	Feb- Apr	Rapid vegetative growth	Sweet melon	Mar-May	Jun-Aug	Flowering and fruit setting
Alfalfa[a]	Sep-Oct	Every 60~70 day several Times/Year	Flowering	Millet	Apr-May	Aug-Sep	Flowering and early grain filling
Lettuce	Sep-Nov	Jan- Dec	Head formation	Maize forage	Mar-May	Jun-Aug	Vegetative growth
Vegetables	Sep-Nov	Jan-Dec	Vegetative growth and fruit setting	Onion	Apr-May	Jun-Aug	Bulb formation
				Potato	Mar-May	Jun-Jul	Tuber initiation and bulking
				Pepper	Mar-May	Jun-Jul	Flowering and fruit setting
				Vegetables	Feb-May	May-Sep	Vegetative growth and fruit setting

The plant responses to water stress differ depending on the species, cultivar, and environmental conditions. Understanding how the climate change and water stress impact each growth stage is crucial for developing effective water management strategies and improving the water use efficiency in agriculture. The climate change and rising temperatures affect the crop yields through several mechanisms. First, elevated temperatures accelerate the crop development, leading to shorter growth duration that is often associated with reduced yields [12]. Second, the high temperatures influence physiological processes, such as photosynthesis, respiration, and grain filling. Crops with a C4 photosynthetic pathway, such as maize and sugarcane, have higher optimum temperatures for photosynthesis compared with C3 crops, such as rice and wheat; however, even C4 crops exhibit reduced photosynthetic efficiency under excessive heat [16]. Third, warming increases the saturation vapor pressure of the air exponentially. Under stable relative humidity, this raises the VPD between the air and the leaf, which is defined as the difference between the saturation vapor pressure and the actual vapor pressure. The relative humidity has remained relatively constant over large spatial scales, and it is expected to change minimally in the future. Plants respond to high VPD by closing their stomata, which reduces the photosynthesis and increases the canopy temperature. Fourth, temperature extremes can cause direct cellular damage and increase the probability of heat stress during critical reproductive phases, leading to sterility, reduced yields, or even complete crop failure [18]. Fifth, higher temperatures, combined with increased atmospheric CO_2, favor the proliferation of pests and diseases affecting the crops [19]. The flowering and fruit or grain development stages are among the most sensitive phases to the water stress in a plant's lifecycle. Insufficient water during flowering reduces the number of flowers and increases the flower drop, while deficits during fruit or grain development decrease the size and quality, negatively impacting both the nutritional value and market potential [37].

B. *Determination of Crop Evapotranspiration (ETc) and Irrigation Water Demand*

To estimate the water requirements of the project, the water consumption of each crop must be calculated. CROPWAT 8.0, developed by FAO, is a widely used model for estimating the reference evapotranspiration (ET_0), ETc, and NIWR for multiple crops based on soil, crop, and climate data. The model calculates ET_0 using the Penman–Monteith method, with minimum temperature (Tmin) and maximum temperature (Tmax), wind speeds, sunshine durations, and relative humidities from the designated climate station as inputs [36]. ETc is derived from ET_0 by applying the dimensionless Kc, while adequate rainfall is estimated using the USDA Soil Conservation Service method [38]. ETc is calculated for each crop and across its different growth stages. The analysis of the irrigation demands for both winter and summer cropping plans provides valuable insights for improving the irrigation scheduling and enhancing the water management efficiency.

C. Climate Change and Future Climate Parameters

To predict the future climate change and estimate the key climatic parameters, the LARS-WG 8.0 weather generator was employed to simulate the maximum and minimum temperatures and precipitation based on historical climate data. This software applies advanced statistical techniques to downscale the outputs from global climate models, providing high-resolution and accurate projections. A 30-year dataset (1993–2023) was used for calibration and validation to ensure reliable results. The HadGEM3-GC31-LL global climate model was selected for its strong performance in representing the climate variables in semi-arid regions, while the SSP2-4.5 scenario was adopted as a moderate greenhouse gas emission pathway consistent with the global mitigation efforts. Previous research has successfully applied the LARS-WG model to generate synthetic rainfall and temperature data under both historical and projected climate conditions [39]. The prediction process involved calibrating LARS-WG 8.0 using observed climate data, followed by validation to ensure the accuracy of the projections. Future climate parameters were simulated at 20-year intervals (2025, 2035, 2045, 2055, 2065, and 2075) to identify the long-term trends. The projections were analyzed to assess the impacts of the climate change on the water resources and agricultural sustainability. By integrating LARS-WG 8.0 with a suitable global climate model and emission scenario, this study provides a robust framework for evaluating the potential impacts of climate change on the irrigation projects and cropping patterns in semi-arid regions, such as Iraq.

D. Computation and Evaluation Methodology

CROPWAT was applied to estimate the crop water requirements for different crops during the years 1980, 1990, 2000, 2010, 2020, and 2023, covering both winter and summer growing cycles. Subsequently, future climate data generated with LARS-WG 8.0 were employed to calculate the crop water requirements for 2025, 2035, 2045, 2055, 2065, and 2075. Combining these two models provided a comprehensive assessment of the crop water demand under both historical and projected climate conditions, making CROPWAT a valuable tool for identifying the suitable crop cycles. This analysis helps optimize the cropping patterns in line with the expected climate change and supports sustainable irrigation practices.

III. RESULTS AND DISCUSSION

A. Prediction of Climate Change and Future Climate Parameters

Understanding the future climate trends is crucial for assessing their potential impact on the agriculture, water resources, and the overall stability of irrigation projects. Temperature variations, as a key climate parameter, play a crucial role in shaping the regional climate conditions. Figure 2 shows the annual average maximum temperature records, ranging from 30.2°C in 1980 to 33.0°C in 2010. The trend is expected to continue rising, having reached 34.5°C by 2075. Similarly, the annual averages of the minimum temperatures show a consistent upward trend. In 1980, the average minimum temperature (Tmin) was the lowest, at 14.4°C, and it had increased to 18.0°C by 2010. It was found that the temperature was 16.9°C in 2020; it is expected to have been 19.6°C by 2075, the highest recorded Tmin in the study period.

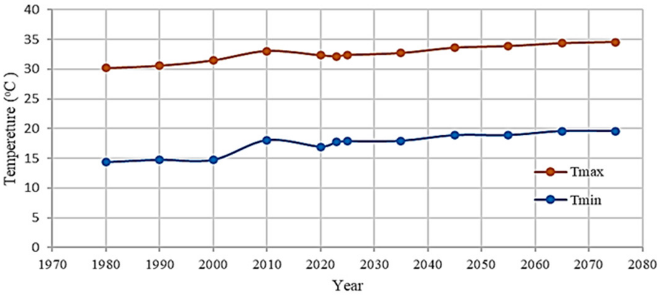

Fig. 2. Average Tmax and Tmin per year (°C).

As illustrated in Figure 3, the total annual precipitation varied considerably across the study period. The lowest value was recorded in 2000 (67.6 mm), while the highest occurred in 2023 (194.4 mm). The maximum temperature increased by 6.22%, the minimum temperature by 17.39%, while the precipitation decreased by 4.63%. These results are consistent with the findings of [40], which reported a 5.88%–6.05% rise in temperature and a 30.68% reduction in precipitation using the multicriteria decision-making technique.

B. Irrigation Water Demand

The AGIP includes two agricultural plans: a winter crop plan and a summer crop plan. As shown in Figure 4, the crops in the winter plan are affected by the climate change. The annual water consumption increased from 1980 to 2020 at 10-year intervals, with 2023 used as a reference year for all crops (barley, onion, green onion, potato, broad beans, spinach, forage mixture, lettuce, and vegetables).

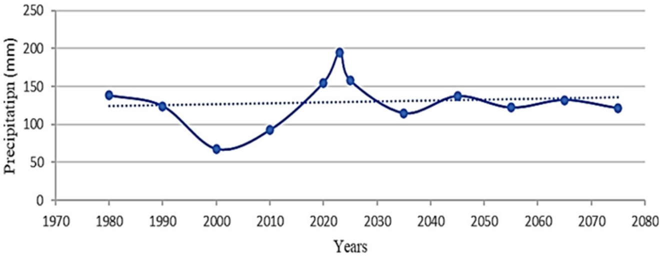

Fig. 3. Total annual amounts of precipitation (mm).

Variations in water use were observed depending on the nature and growth requirements of each crop. These changes are primarily attributed to the influence of the climate change. For example, onion green recorded the lowest water consumption in 2020 due to the abundant rainfall that year, which satisfied most of the plants' water requirements. Among the winter crops, wheat and alfalfa require the highest amounts of water due to their longer growing periods, with wheat averaging 240 days and alfalfa lasting a whole year, making them more vulnerable to the climate variability. Projections for northeastern Iran under the RCP8.5 scenario similarly indicate a significant increase in the crop water demand and a decline in the wheat yields, underscoring the need for adaptive agricultural strategies. The research period was categorized into two temporal groups to facilitate a more comprehensive comparison of the data.

In Group A of the winter plan, as depicted in Figure 4, NIWR in 2000 was among the highest across all crops due to severe rainfall scarcity. In contrast, 2023 recorded the highest rainfall, yet the crop water requirements remained high for a different reason. Although it was a rainy year, the crops did not benefit from the abundance of rain because it was not yet time to plant them. Only certain crops, such as wheat and alfalfa, were able to take advantage of the abundant rainfall since it occurred during critical growth stages for these plants.

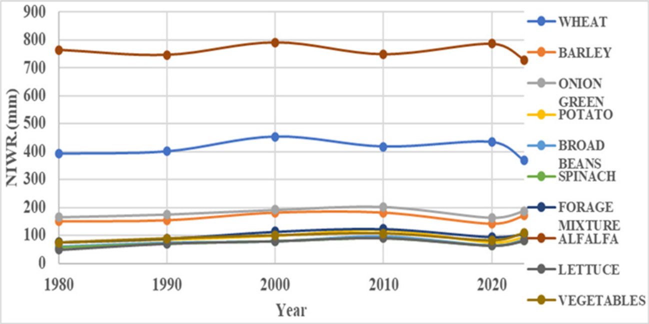

Fig. 4. NIWR of winter plan crops for Group A.

For Group B of the winter plan, as illustrated in Figure 5, the crop water consumption showed a steady increase, nearly doubling that of Group A for most crops. This increase is mainly attributed to the higher maximum and minimum temperatures. Although the annual rainfall was projected to remain within normal ranges, the effect of the rising temperatures on the crop water requirements was considerably more pronounced than the variability in rainfall. These findings are consistent with [41], where significant yield reductions were reported, particularly for wheat, with decreases of approximately 59.95% under climate change scenarios. Among the winter crops, wheat and alfalfa exhibited the highest water requirements due to their longer growing cycles and greater cumulative evapotranspiration throughout the season.

Figure 6 displays the difference in NIWR among strategic crops and their sensitivity to climate change, showing a proportional increase in the water demand under the AGIP summer plan. As shown in Figure 7, Group A crops exhibited increased water requirements with slight decreases in the response to variations in rainfall availability and temperature. Overall, the summer crops in this group exhibited similar responses to the climate change. In 1980, although rainfall was relatively high and temperatures were moderate, the crop water demand remained high because most of the rainfall occurred before the planting period in May.

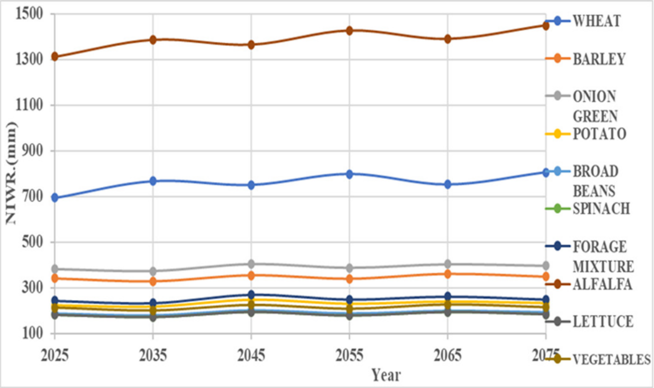

Fig. 5. NIWR of winter plan crops of Group B.

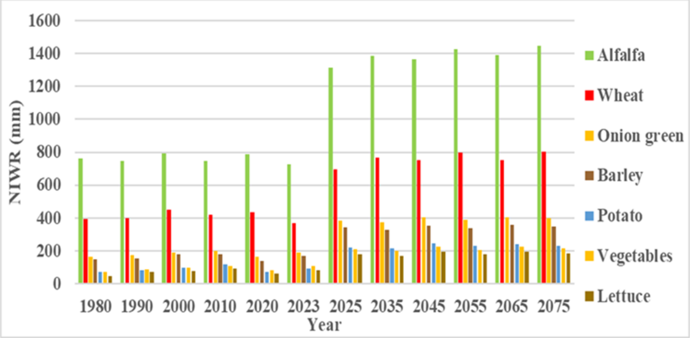

Fig. 6. Sensitivity of winter crops NIWR toward climate change.

Rainfall mainly occurred during the first and last three months of the year, outside the planting season, providing little benefit to the crops. In contrast, although overall rainfall in 2010 was low, some of it coincided with the planting period, allowing crops to benefit and decreasing their net irrigation needs. As a result, the water demand in 2010 was relatively low [42]. These observations confirm that the successive crop production depends not only on the total seasonal or yearly rainfall, but also on its temporal distribution [43].

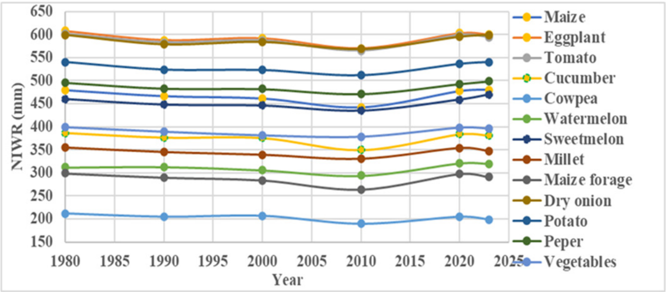

Fig. 7. NIWR of summer plan crops of Group (A).

In Group B of the summer plan crop responses to the climate change remained consistent, showing a gradual but slight increase in the water consumption. This trend reflects the relative adaptability of the agricultural patterns to the evolving climatic conditions, as portrayed in Figure 8. In the summer plan of Group B, the water demand varied among crops depending on their specific characteristics. Between 2065 and 2075, the consumption reached its peak, significantly exceeding the levels observed in 2025. The trend line illustrates a clear upward trajectory, indicating an expected annual increase in the water demand. The most affected aspects include the changes in phenological dates, crop season lengths, crop water requirements, net irrigation requirements, and related yield variations [44]. Among the summer crops, eggplants, tomatoes, and dry onions exhibited the highest net irrigation requirements due to their sensitivity to the water stress and elevated transpiration rates during the peak growth stages (Figure 9).

A comparison between Group B and Group A indicates that the water consumption increased for all crops by approximately 1.8 times, confirming the influence of the climate change on the crop water demand. This pattern is consistent when each crop is evaluated individually and its response is monitored. Table IV summarizes the overall linear and non-linear trends observed for the crops in the winter plan. The results indicate that the coefficient of determination (R^2) ranges from 0.68 to 0.73, reflecting a strong relationship between the plant behavior and water consumption under changing climatic conditions. The most sensitive crops in the winter plan were those with the steepest slopes in the regression index, namely winter wheat, barley, and green onions. The linear relationships provide a straightforward and efficient means of identifying the trends in the crop behavior, such as the progressive increase in the water demand over time. They are helpful for preliminary analysis and forecasting in crops, such as wheat and barley, where the patterns appear relatively stable. Although less precise than nonlinear models, linear equations remain valuable for capturing the general direction of crop–climate responses. The considerable gap in R^2 values for wheat and green onion indicates that their behavior follows a nonlinear pattern. Wheat growth is influenced by multiple factors, including the rainfall distribution and soil quality, while nonlinear models offer a more accurate representation of the seasonal growth curves and environmental variability. The considerable gap in R^2 values for wheat and green onion indicates that their behavior follows a nonlinear pattern. Wheat growth is influenced by multiple factors, including the rainfall distribution and soil quality, while nonlinear models offer a more accurate representation of the seasonal growth curves and environmental variability. Similarly, crops such as potatoes, spinach, and broad beans are highly sensitive to temperature and moisture, which explains the improved accuracy of the nonlinear approaches for these cases.

Table V indicates that all summer crops achieved higher R^2 values under nonlinear models compared to the linear models, suggesting that complex functions better represent their temporal behavior. Maize, eggplant, sweet melon, and potato showed particularly high nonlinear R^2 values (above 0.9), reflecting strong and consistent responses to climatic factors. These crops likely follow stable seasonal cycles that are well captured by sigmoid or Pearson-type models. For tomato, dry onion, pepper, and vegetables, the nonlinear R^2 values were slightly lower (approximately 0.93–0.98), indicating greater variability in the water demand and sensitivity to the environmental stress and timing. This distinction highlights that even within summer crops, the level of predictability differs, underscoring the need for crop-specific modeling approaches. The high R^2 values in nonlinear models further suggest that functions, such as Pearson V or Sigmoid provide more realistic estimates of the crop water demand.

C. Summer and Winter Patterns

For the summer plan, a clear distinction exists between the past and future Groups A and B, with the predicted water consumption in future years expected to have significantly exceeded the historical levels. In agricultural practice, all crops share water allocations and often have overlapping irrigation dates. As shown in Figure 10, the monthly summer consumption pattern for each year demonstrates that, regardless of the crop type, estimating the monthly water requirements provides a comprehensive assessment of the impact of the climate change on the agricultural demand. It is important to note that all consumption is concentrated within a specific period due to the design of the AGIP agricultural plan, with most crops planted in May and the peak water demand occurring in June, July, and August. This period represents the most sensitive stage in a plant's life, encompassing flowering and early fruiting. It is consistent with previous research indicating that the summer annual strategy begins with spring germination, progresses to summer flowering, and is followed by extended seed dormancy.

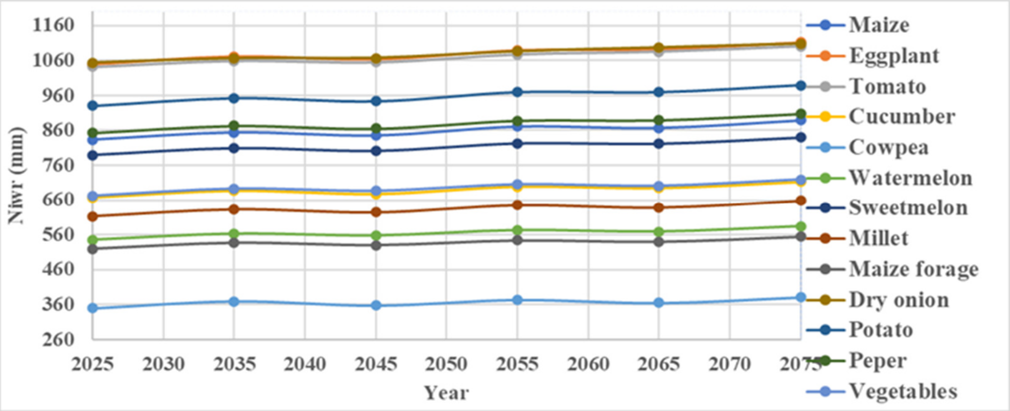

Fig. 8. NIWR of summer plan crops of Group (B).

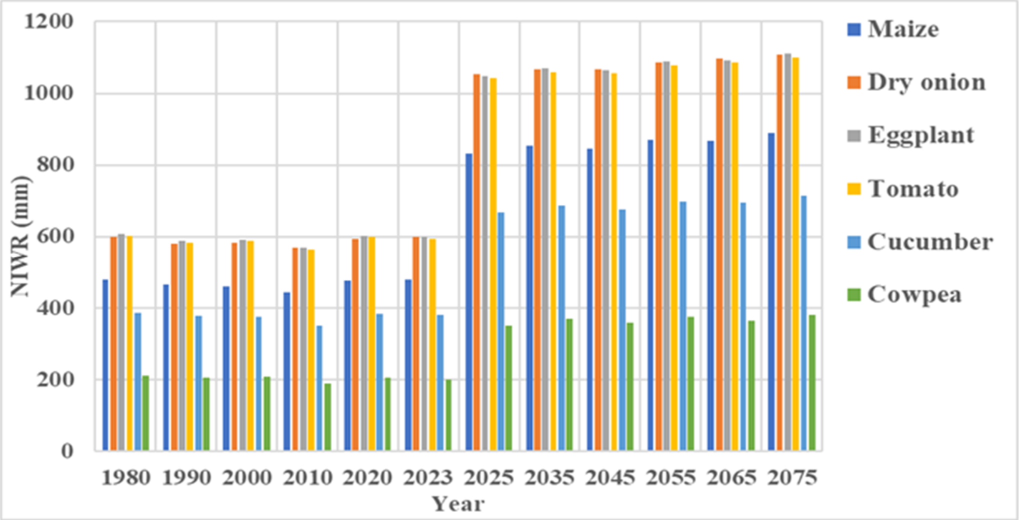

Fig. 9. Sensitivity of summer crops NIWR toward climate change.

TABLE IV. THE GENERAL TREND AND REPRESENTATIVE EQUATION FOR WINTER CROPS

Winter crops	General trend R²	Linear relationship	General trend R²	Nonlinear relationship
Wheat	$R^2 = 0.721$	$y = 5.3515x - 10261$	0.981	$y = (b^\wedge a / \Gamma(a)) * (1 / x^\wedge(a+1)) * e^\wedge(-b/x),\ x > 0$
Barley	$R^2 = 0.699$	$y = 2.729x - 5276.9$	0.979	$y = 1 / (1 + e^\wedge(-x))$
Onion green	$R^2 = 0.709$	$y = 3.1623x - 6123.4$	0.985	$y = (b^\wedge a / \Gamma(a)) * (1 / x^\wedge(a+1)) * e^\wedge(-b/x),\ x > 0$
Potato	$R^2 = 0.706$	$y = 2.1131x - 4122.1$	0.968	$y = (b^\wedge a / \Gamma(a)) * (1 / x^\wedge(a+1)) * e^\wedge(-b/x),\ x > 0$
Broad beans	$R^2 = 0.720$	$y = 1.7396x - 3391.9$	0.970	$y = 1 / (1 + e^\wedge(-x))$
Spinach	$R^2 = 0.719$	$y = 1.6724x - 3261$	0.969	$y = 1 / (1 + e^\wedge(-x))$
Forage mixture	$R^2 = 0.729$	$y = 1.8621x - 3620.2$	0.967	$y = (b^\wedge a / \Gamma(a)) * (1 / x^\wedge(a+1)) * e^\wedge(-b/x),\ x > 0$
Alfalfa	$R^2 = 0.712$	$y = -0.1995x + 1160.3$	0.989	$y = A * \delta(t - t0)$
Lettuce	$R^2 = 0.729$	$y = 1.7116x - 3341$	0.962	$y = (b^\wedge a / \Gamma(a)) * (1 / x^\wedge(a+1)) * e^\wedge(-b/x),\ x > 0$
Vegetables	$R^2 = 0.729$	$y = 1.8621x - 3620.2$	0.972	$y = (b^\wedge a / \Gamma(a)) * (1 / x^\wedge(a+1)) * e^\wedge(-b/x),\ x > 0$

x represents the years, and y indicates the actual water consumption of the crop

TABLE V. R^2 THE GENERAL TREND AND REPRESENTATIVE EQUATION FOR SUMMER CROPS

Summer crops	General trend R²	Linear relationship	General trend R²	Nonlinear relationship
Maize	$R^2 = 0.7056$	$y = 5.849x - 11172$	0.996	$y = 1 - e^\wedge(-((x - c)^\wedge e / b)^\wedge a)$
Eggplant	$R^2 = 0.7021$	$y = 7.2175x - 13793$	0.997	$y = (b^\wedge a / \Gamma(a)) * (1 / x^\wedge(a+1)) * e^\wedge(-b/x),\ x > 0$
Tomato	$R^2 = 0.7012$	$y = 7.1472x - 13658$	0.935	$y = a + b\,x + c\,x^\wedge(1.5) + d\,x^\wedge(0.5)\,ln(x)$
Cucumber	$R^2 = 0.6982$	$y = 4.6568x - 8906.1$	0.995	$y = (b^\wedge a / \Gamma(a)) * (1 / x^\wedge(a+1)) * e^\wedge(-b/x),\ x > 0$
Cowpea	$R^2 = 0.683$	$y = 2.4017x - 4583.3$	0.993	$y = 1 / (1 + e^\wedge(-x))$
Watermelon	$R^2 = 0.7127$	$y = 3.8144x - 7293.1$	0.993	$y = a + b\,x + c\,x^\wedge(1.5) + d\,x^\wedge(0.5)\,ln(x)$
Sweet melon	$R^2 = 0.7122$	$y = 5.4064x - 10325$	0.997	$y = 1 / (1 + e^\wedge(-x))$
Millet	$R^2 = 0.7022$	$y = 4.3161x - 8258.2$	0.996	$y = 1 / (1 + e^\wedge(-x))$
Maize forage	$R^2 = 0.6929$	$y = 3.6947x - 7076.3$	0.994	$y = (b^\wedge a / \Gamma(a)) * (1 / x^\wedge(a+1)) * e^\wedge(-b/x),\ x > 0$
Dry onion	$R^2 = 0.7044$	$y = 7.32x - 14004$	0.952	$y = 1 - e^\wedge(-((x - c)^\wedge e / b)^\wedge a)$
Potato	$R^2 = 0.7069$	$y = 6.4054x - 12239$	0.997	$y = 1 / (1 + e^\wedge(-x))$
Peper	$R^2 = 0.7082$	$y = 5.849x - 11172$	0.987	$y = 1 - e^\wedge(-((x - c)^\wedge e / b)^\wedge a)$
Vegetables	$R^2 = 0.7065$	$y = 4.5664x - 8712.4$	0.962	$y = a + b\,x + c\,x^\wedge(1.5) + d\,x^\wedge(0.5)\,ln(x)$

x represents the years, and y indicates the actual water consumption of the crop

For the AGIP winter plan, the yearly cropping pattern indicates that the water demand peaks in July, followed by a peak in May. This trend reflects the planting schedule, as most crops are sown in November, with green onions and barley planted in October, and some crops beginning as early as September. Consequently, the two peaks in the water consumption coincide with the driest months and the most critical growth stages of winter-planted crops, as shown in Figure 11. High temperatures and limited rainfall characterize June. Despite these conditions, the water consumption decreases significantly because the growing season of most crops ends before June. Each crop has a distinct lifespan, with alfalfa persisting year-round, wheat growing for approximately eight months, and short-cycle crops, such as potatoes, lasting no longer than four months. As illustrated in Figure 12, the agricultural patterns are divided into two groups: historical years (Group A), which require less water, and future years (Group B), where the consumption is expected to increase. This confirms that the water demand and irrigation requirements are projected to rise in response to future climate changes. The application of climate-based irrigation scheduling resulted in nearly 11% water savings compared to the conventional methods, highlighting the importance of selecting cropping patterns that are compatible with the local climatic conditions [45].

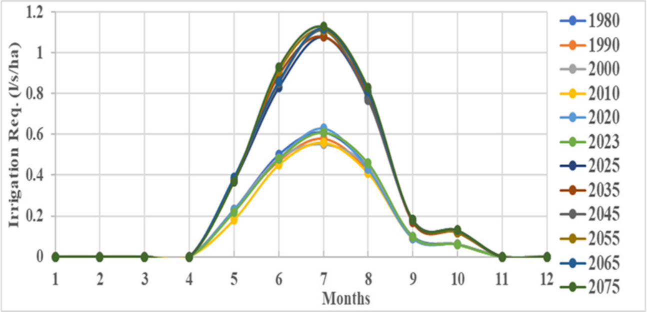

Fig. 10. Monthly irrigation requirement of summer pattern in (l/s/ha) of AGIP.

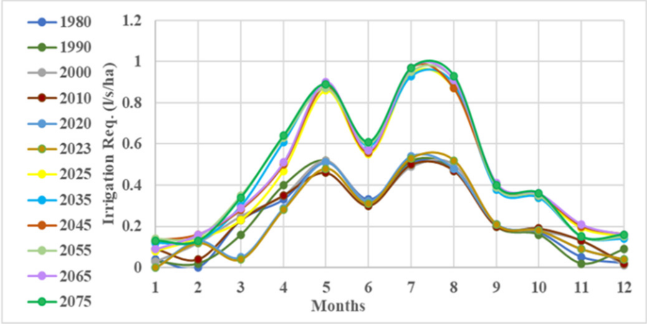

Fig. 11. Irrigation requirement of winter pattern in (l/s/ha) of AGIP.

The seasonal analysis of summer and winter cropping patterns in AGIP confirms that climate-based irrigation scheduling can significantly reduce the water use, particularly under future climate scenarios. These findings are consistent with [13], where a 10–15% reduction in the irrigation demand was reported through adaptive scheduling in central Iraq and strong NIWR sensitivity was highlightedacross 16 crops, with barley and maize identified as particularly climate-sensitive. However, a peak demand was recorded in early spring, in contrast to the mid-summer peak observed in Abu Ghraib. In Jordan, authors in [46] demonstrated that shifting the planting dates by 2–4 weeks reduced the water stress by up to 18% and showed that the wheat and barley were vulnerable to early-season droughts under rainfed conditions. Although the stress peaks in [46] occurred earlier than those of the present study, both studies emphasize the importance of revising the planting calendars to adapt to semi-arid climates. Research in northern Ethiopia, led by authors in [47], found that using 25% deficit irrigation during the initial and late growth stages of potatoes boosted the water productivity and net benefits without a significant yield loss. This aligns with the current work's observation of the reduced irrigation needs in June, as the crop cycle is complete. However, since authors in [47] focused solely on potatoes, their findings may not fully apply to other crops.

The findings of the current study are applicable to other semi-arid regions with comparable climatic and agricultural conditions. The combined use of LARS-WG and CROPWAT has been successfully applied in neighboring arid and semi-arid areas, such as the Diyala Basin in Iraq, where NIWR sensitivity was found to increase by 0.1–44% across 16 crops under future climate scenarios [13]. However, the differences in local soil properties, irrigation infrastructure, and economic factors may affect the model outputs. Local calibration and validation are therefore proposed to ensure a reliable application across different semi-arid settings. This methodology can also be extended to other arid and semi-arid regions of Iraq, such as the irrigation projects of Al-Mussaib, Al-Hussainiya, and Al-Dalmaj. These areas are key agricultural zones characterized by distinct soil textures, water availability challenges, and crop patterns. Applying the proposed approach in these regions while accounting for their specific soil characteristics, irrigation systems, and crop choices could support more accurate planning and strengthen the climate resilience in future irrigation management strategies

IV. CONCLUSION

The findings of this study indicate that the climate change directly influences the agricultural requirements, resulting in a proportional increase in the water demand. Climate prediction models further project a significant temperature rise accompanied by a decline in precipitation, which together are expected to intensify the future irrigation requirements. A significant difference between the historical and future climate conditions underscores the need to adopt modern irrigation strategies and cultivate crop varieties that are more resilient to the climate change. Satellite-based datasets, such as NASA POWER and CHIRPS, have been widely used to analyze the regional climate variability. Several studies in the Middle East and North Africa have examined the temperature and precipitation trends using similar approaches. Previous research in Iraq [13] employed models, such as LARS-WG and CROPWAT 8.0 to assess the irrigation water requirements and crop sensitivity across four irrigation projects from 1990 to 2019, with projections extending to 2080.

A recent study in Wasit Governorate utilized LARS-WG and CROPWAT 8.0 to predict the irrigation water demand for the period 2030–2050 [48]. However, this study focuses on Baghdad, covering a historical period from 1980 to 2023 and including climate projections up to 2050, thereby providing a unique local perspective on the urban climate dynamics. This contribution enhances the scientific understanding of the climate patterns in Iraqi urban environments, which remain underrepresented in the existing literature. The water requirements of winter wheat and alfalfa are higher than those of other crops due to their longer growing periods and greater cumulative evapotranspiration demands. Under conditions of limited irrigation and projected climate change scenarios, this extended growth duration underscores the need for more efficient water management strategies to maintain the yield stability and enhance the irrigation water productivity. Higher cumulative evapotranspiration demands were observed for summer crops, such as eggplants, tomatoes, and dry onions due to their sensitivity to the water stress and high transpiration rates during the peak growth stages. These crops require a continuous and sufficient water supply to prevent significant yield losses. The results further indicate that the current cropping patterns are unsustainable and incompatible with the projected climate change, emphasizing the need for adaptive strategies in the AGIP, located in Iraq's central arid and semi-arid region.

In general, it is proposed to avoid cultivating high-water-demand crops during periods of water scarcity and to prioritize more drought-tolerant species, such as barley and potatoes in winter and maize and peppers in summer. This study enhances the understanding of the impacts of the climate change on the water requirements and provides valuable data to support decision-makers and farmers in improving the irrigation strategies. The proposed methodology can also be applied to other irrigation projects with comparable climatic conditions, particularly in arid and semi-arid regions. It is proposed to adopt modern irrigation strategies, such as sprinkler and drip irrigation systems, to meet the crop water requirements, particularly during sensitive growth stages. Irrigation scheduling should be improved to reduce the pressure during the driest months and to distribute the water demand more evenly across the year. To ensure agricultural sustainability and maintain the food security, the irrigation projects must adapt to the climate change, especially in the arid and semi-arid regions.

ACKNOWLEDGEMENT

The authors would like to express their sincere gratitude to the Ministry of Water Resources in Iraq for providing valuable climate and agricultural data. Special thanks are extended to the Department of Planning and Follow-up at AGIP for their technical support.

REFERENCES

[1] X. Tian, J. Dong, S. Jin, H. He, H. Yin, and X. Chen, "Climate change impacts on regional agricultural irrigation water use in semi-arid environments," *Agricultural Water Management*, vol. 281, May 2023, Art. no. 108239, https://doi.org/10.1016/j.agwat.2023.108239.

[2] V. V. Kharin, G. M. Flato, X. Zhang, N. P. Gillett, F. Zwiers, and K. J. Anderson, "Risks from Climate Extremes Change Differently from 1.5°C to 2.0°C Depending on Rarity," *Earth's Future*, vol. 6, no. 5, pp. 704–715, 2018, https://doi.org/10.1002/2018EF000813.

[3] K. Alsafadi, S. A. Mohammed, B. Ayugi, M. Sharaf, and E. Harsányi, "Spatial–Temporal Evolution of Drought Characteristics Over Hungary Between 1961 and 2010," *Pure and Applied Geophysics*, vol. 177, no. 8, pp. 3961–3978, Aug. 2020, https://doi.org/10.1007/s00024-020-02449-5.

[4] F. H. Saeed, M. S. Al-Khafaji, and F. Al-Faraj, "Hydrologic response of arid and semi-arid river basins in Iraq under a changing climate," *Journal of Water and Climate Change*, vol. 13, no. 3, pp. 1225–1240, Feb. 2022, https://doi.org/10.2166/wcc.2022.418.

[5] A. Mokhtar *et al.*, "Estimation of SPEI Meteorological Drought Using Machine Learning Algorithms," *IEEE Access*, vol. 9, pp. 65503–65523, 2021, https://doi.org/10.1109/ACCESS.2021.3074305.

[6] M. S. Al-Khafaji and R. A. Al-Ameri, "Evaluation of drought indices correlation for drought frequency analysis of the Mosul dam watershed," *IOP Conference Series: Earth and Environmental Science*, vol. 779, no. 1, Mar. 2021, Art. no. 012077, https://doi.org/10.1088/1755-1315/779/1/012077.

[7] D. Mullan, "Soil erosion under the impacts of future climate change: Assessing the statistical significance of future changes and the potential on-site and off-site problems," *CATENA*, vol. 109, pp. 234–246, Oct. 2013, https://doi.org/10.1016/j.catena.2013.03.007.

[8] T. Wheeler and J. von Braun, "Climate Change Impacts on Global Food Security," *Science*, vol. 341, no. 6145, pp. 508–513, Aug. 2013, https://doi.org/10.1126/science.1239402.

[9] A. Molotoks, P. Smith, and T. P. Dawson, "Impacts of land use, population, and climate change on global food security," *Food and Energy Security*, vol. 10, no. 1, 2021, Art. no. e261, https://doi.org/10.1002/fes3.261.

[10] N. Adamo, N. Al-Ansari, V. K. Sissakian, S. Knutsson, and J. Laue, "Climate Change: Consequences on Iraq's Environment," *Journal of Earth Sciences and Geotechnical Engineering*, vol. 8, no. 3, pp. 43-58, 2018.

[11] K. S. Raju and D. N. Kumar, *Impact of Climate Change on Water Resources: With Modeling Techniques and Case Studies*, Springer Climate, Springer Nature Singapore, 2018.

[12] P. Stone, "The effects of heat stress on cereal yield and quality," in *Crop Responses and Adaptations to Temperature Stress*, A. S. Basra, Ed. Boca Raton, FL, USA: CRC Press, 2000, pp. 49.

[13] F. H. Saeed, M. S. Al-Khafaji, and F. A. M. Al-Faraj, "Sensitivity of Irrigation Water Requirement to Climate Change in Arid and Semi-Arid Regions towards Sustainable Management of Water Resources," *Sustainability*, vol. 13, no. 24, Jan. 2021, Art. no. 13608, https://doi.org/10.3390/su132413608.

[14] G. Rasul, Q. Z. Chaudhry, A. Mahmood, and K. W. Hyder, "Effect of temperature rise on crop growth and productivity," *Pakistan Journal of Meteorology*, vol. 8, no. 15, pp. 53–62, 2011.

[15] Y. Kang, S. Khan, and X. Ma, "Climate change impacts on crop yield, crop water productivity and food security – A review," *Progress in Natural Science*, vol. 19, no. 12, pp. 1665–1674, Dec. 2009, https://doi.org/10.1016/j.pnsc.2009.08.001.

[16] S. J. Crafts-Brandner and M. E. Salvucci, "Sensitivity of Photosynthesis in a C4 Plant, Maize, to Heat Stress," *Plant Physiology*, vol. 129, no. 4, pp. 1773–1780, Aug. 2002, https://doi.org/10.1104/pp.002170.

[17] K. M. Willett, N. P. Gillett, P. D. Jones, and P. W. Thorne, "Attribution of observed surface humidity changes to human influence," *Nature*, vol. 449, no. 7163, pp. 710–712, Oct. 2007, https://doi.org/10.1038/nature06207.

[18] E. I. Teixeira, G. Fischer, H. van Velthuizen, C. Walter, and F. Ewert, "Global hot-spots of heat stress on agricultural crops due to climate change," *Agricultural and Forest Meteorology*, vol. 170, pp. 206–215, Mar. 2013, https://doi.org/10.1016/j.agrformet.2011.09.002.

[19] L. H. Ziska, P. R. Epstein, and W. H. Schlesinger, "Rising CO2, Climate Change, and Public Health: Exploring the Links to Plant Biology," *Environmental Health Perspectives*, vol. 117, no. 2, pp. 155–158, Feb. 2009, https://doi.org/10.1289/ehp.11501.

[20] B. F. Hasan and B. Sh. Abed, "Assessment of climate change impact on water productivity and yield of wheat cultivated using developed seasonal schedule irrigation in Euphrates basin," *AIP Conference Proceedings*, vol. 2864, no. 1, Jan. 2024, Art. no. 020012, https://doi.org/10.1063/5.0186954.

[21] M. A. Dheyaa, M. M. Al-Mukhtar, and K. Shemal, "Analyzing the Future Climate Change Impacts on Meteorological Parameters Using the LARS-WG Model," *Civil Engineering Journal*, vol. 10, no. 11, pp. 3754–3778, Nov. 2024, https://doi.org/10.28991/CEJ-2024-010-11-019.

[22] B. M. Hashim, A. N. A. Alnaemi, B. A. Hussain, S. A. Abduljabbar, Z. H. Doost, and Z. M. Yaseen, "Statistical downscaling of future temperature and precipitation projections in Iraq under climate change scenarios," *Physics and Chemistry of the Earth, Parts A/B/C*, vol. 135, Oct. 2024, Art. no. 103647, https://doi.org/10.1016/j.pce.2024.103647.

[23] A. Ortiz-Bobea, T. R. Ault, C. M. Carrillo, R. G. Chambers, and D. B. Lobell, "The Historical Impact of Anthropogenic Climate Change on Global Agricultural Productivity," *Nature Climate Change*, vol. 11, no. 4, pp. 306–312, Apr. 2021, https://doi.org/10.1038/s41558-021-01000-1.

[24] F. H. Saeed, M. Saleh, and F. A. Al-Faraj , "Forecasting of Future Irrigation Water Demand for Salah-addin Province under Various Scenarios of Climate Change," *Journal of Water Resources and Geosciences*, vol. 1, no. 1, pp. 102–116, Mar. 2022.

[25] Ministry of Water Resources of Iraq, *Strategy for Water and Land Resources of Iraq (SWLRI) 2015–2035*, Baghdad, Iraq, 2014.

[26] *Climatological data for Baghdad Governorate (1980–2023)*, Unpublished Report, Iraqi Meteorological Organization and Seismology, 2024.

[27] "NASA POWER Homepage," *Prediction Of Worldwide Energy Resources (POWER)*. https://power.larc.nasa.gov/.

[28] "ClimateEngine." https://app.climateengine.org/climateEngine.

[29] Y. Kassem, H. Camur, and O. A. M. Abughinda, "Solar Energy Potential and Feasibility Study of a 10MW Grid-connected Solar Plant in Libya," *Engineering, Technology & Applied Science Research*, vol. 10, no. 4, pp. 5358–5366, Aug. 2020, https://doi.org/10.48084/etasr.3607.

[30] B. A. Ahmed and R. S. Hadid, "Application of a Vegetation Health Index to Identify Distribution of Agricultural Drought in Diyala Province, Iraq," *Iraqi Journal of Science*, pp. 901–921, Feb. 2025, https://doi.org/10.24996/ijs.2025.66.2.27.

[31] R. A. Q. Saleh, A. S. Oleiwi, and Z. Q. Lateef, "The Impact of Climate Change on Water Quality and Consumption in the Tigris River Basin (Mosul-Baghdad)," *IOP Conference Series: Earth and Environmental Science*, vol. 1374, no. 1, Dec. 2024, Art. no. 012048, https://doi.org/10.1088/1755-1315/1374/1/012048.

[32] W. H. Hassan, B. K. Nile, Z. K. Kadhim, K. Mahdi, M. Riksen, and R. F. Thiab, "Trends, forecasting and adaptation strategies of climate change in the middle and west regions of Iraq," *SN Applied Sciences*, vol. 5, no. 12, Nov. 2023, Art. no. 312, https://doi.org/10.1007/s42452-023-05544-z.

[33] S. Michaelides, "Modes of Atmospheric Energetics Based on HadGEM3-GC3.1-LL Simulations in the Framework of CMIP6," *Advances in Meteorology*, vol. 2023, no. 1, 2023, Art. no. 3956086, https://doi.org/10.1155/2023/3956086.

[34] D. Zhai, J. Zhuo, and R. Wang, "The coupled PLUS-InVEST-XGBoost model explores the response of climate to ecosystem services in SSP scenarios," *Research Square*, Nov. 25, 2024, https://doi.org/10.21203/rs.3.rs-5407564/v1.

[35] O. A. Marzouk, "Adiabatic Flame Temperatures for Oxy-Methane, Oxy-Hydrogen, Air-Methane, and Air-Hydrogen Stoichiometric Combustion using the NASA CEARUN Tool, GRI-Mech 3.0 Reaction Mechanism, and Cantera Python Package," *Engineering, Technology & Applied Science Research*, vol. 13, no. 4, pp. 11437–11444, Aug. 2023, https://doi.org/10.48084/etasr.6132.

[36] R. G. Allen, L. S. Pereira, D. Raes, and M. Smith, *Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements (FAO Irrigation and Drainage Paper No. 56)*. Rome, Italy: FAO, 1998.

[37] M. E. Berman and T. M. DeJong, "Water stress and crop load effects on fruit fresh and dry weights in peach (Prunus persica)," *Tree Physiology*, vol. 16, no. 10, pp. 859–864, Oct. 1996, https://doi.org/10.1093/treephys/16.10.859.

[38] *CROPWAT 8.0: Computer program for calculation of crop water requirements and irrigation requirements*. Rome, Italy: FAO, 2018.

[39] W. A. Abidalla and B. Sh. Abed, "Predicting Future Surface Runoff Delivered to the Euphrates River Using LARSWG and SWAT Models: (Sahiliya Valley in the Iraqi Western Desert as a Case Study)," *Journal of Engineering*, vol. 31, no. 2, pp. 156-176, Feb. 2025.

[40] S. Shayanmehr *et al.*, "The Impacts of Climate Change on Water Resources and Crop Production in an Arid Region," *Agriculture*, vol. 12, no. 7, July 2022, Art. no. 1056, https://doi.org/10.3390/agriculture12071056.

[41] P. Paymard, F. Yaghoubi, M. Nouri, and M. Bannayan, "Projecting climate change impacts on rainfed wheat yield, water demand, and water use efficiency in northeast Iran," *Theoretical and Applied Climatology*, vol. 138, no. 3, pp. 1361–1373, Nov. 2019, https://doi.org/10.1007/s00704-019-02896-8.

[42] T. A. Awchi and A. I. Jasim, "Rainfall Data Analysis and Study of Meteorological Draught in Iraq for the Period 1970-2010," *Tikrit Journal of Engineering Sciences*, vol. 24, no. 1, pp. 110–121, Mar. 2017, https://doi.org/10.25130/tjes.24.1.12.

[43] T. Gebremedhin, G. G. Haile, T. G. Gebremicael, H. Libsekal, and K. W. Reda, "Balancing crop water requirements through supplemental irrigation under rainfed agriculture in a semi-arid environment," *Heliyon*, vol. 9, no. 8, Aug. 2023, Art. no. e18727, https://doi.org/10.1016/j.heliyon.2023.e18727.

[44] S. Saadi, M. Todorovic, L. Tanasijevic, L. S. Pereira, C. Pizzigalli, and P. Lionello, "Climate change and Mediterranean agriculture: Impacts on winter wheat and tomato crop evapotranspiration, irrigation requirements and yield," *Agricultural Water Management*, vol. 147, pp. 103–115, Jan. 2015, https://doi.org/10.1016/j.agwat.2014.05.008.

[45] A. H. Al-Haddad and T. S. Bakr, "Irrigation Scheduling Effect on Water Requirements," *Journal of Engineering*, vol. 19, no. 01, pp. 96–145, Jan. 2013, https://doi.org/10.31026/j.eng.2013.01.07.

[46] J. Al-Bakri, A. Suleiman, F. Abdulla, and J. Ayad, "Potential impact of climate change on rainfed agriculture of a semi-arid basin in Jordan," *Physics and Chemistry of the Earth, Parts A/B/C*, vol. 36, no. 5, pp. 125–134, Jan. 2011, https://doi.org/10.1016/j.pce.2010.06.001.

[47] A. W. Teshome, M. D. Wosenie, and H. K. Addis, "Effects of deficit irrigation on potato yield and water productivity in northern Ethiopia," *PLOS Water*, vol. 3, no. 9, 2024, Art. no. e0000266, https://doi.org/10.1371/journal.pwat.0000266.

[48] F. H. Saeed, "Hydrological and Environmental Impacts of Climate Change on Water Resources in Iraq," Ph.D. dissertation, Univ. of Mosul, Mosul, Iraq, 2022.