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Effects of Climate Temperature and Evapotranspiration and Irrigation Demand

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ABSTRACT

Global warming and rising evapotranspiration rates are straining freshwater resources and irrigation systems, especially agricultural irrigation systems. Understanding the correlation between global temperature, ET_0, and irrigation water demand is crucial for managing water resources and ensuring food security during climate change. The meteorological departments, agricultural databases, and FAO AQUASTAT provided secondary time-series data for wheat, maize, cotton, and vegetable crops from 2009 to 2023 for this quantitative analysis. The FAO-56 Penman-Monteith equation, the international standard for reference ET, calculated ET0. To assess the link between temperature, ET_0, and irrigation demand for various crops, statistical procedures such descriptive statistics, Pearson correlation analysis, multiple regression, and seasonal decomposition were used. The multiple regression model predicts irrigation demand with a $R^2 = 0.891$ ($p < 0.001$), with ET_0 (standardised $\beta = 0.643$) and Maximum temperature ($\beta = 0.312$) contributing most. Summer (June–August) had 47.3% of the year's irrigation water demand, 5.5 times more than winter. Cotton needed the most irrigation water (280 mm/summer) and wheat the least (195 mm). The results show that under projected warming scenarios, agricultural water plans should account for a 4.2% increase in irrigation water demand for crops per 1°C increase in mean temperature.

Keywords: Evapotranspiration, irrigation demand, climate temperature, Penman-Monteith, water management, crop water needs, FAO-56, climate change, agricultural water use

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INTRODUCTION

Water is the backbone of agriculture, and population growth, changing food consumption patterns, and climate change are putting pressure on irrigation water management, the largest consumptive use of freshwater worldwide. Agriculture's water needs must be met when air evapotranspiration rises and precipitation and surface water supplies become more unreliable (IPCC, 2023; Elliott et al., 2014).

Evaporation from soil and water surfaces and transpiration from the plant canopy make up one of the largest components of the global hydrological cycle, returning 60% of terrestrial precipitated water to the atmosphere annually. In agricultural water management, reference evapotranspiration (ET_0) is a standardised measure of atmospheric evapotranspiration demand from a hypothetical crop under specific conditions. It is used to estimate crop water and irrigation needs (Allen et al., 1998; Pereira et al., 2015). The FAO-56 Penman-Monteith equation, developed by Allen et al. (1998) and endorsed by the UN Food and Agriculture Organization (FAO) as the global standard, considers temperature, solar radiation, humidity, and wind speed to determine ET_0. It is the most reliable equation for irrigation scheduling and water demand estimation (Monteith, 1965; Katerji & Rana, 2011).

Climate change alters evapotranspiration drivers. Higher temperatures increase the saturation vapour pressure deficit, leading to an increase in ET_0 despite no changes in other climatic parameters (Trenberth et al., 2014; Cook et al., 2014). Changes in solar radiation, cloud cover, relative humidity, and wind speed, which impact ET_0, complicate evaporative demand projections in future climate scenarios (McVicar et al., 2012; Li et al., 2012). The impact of climate change on crop irrigation depends on the interaction of changing water use requirements (ET_0), climate (precipitation regimes), growing season, and crop systems, which vary across regions, crop types, and irrigation technologies (Fischer et al., 2007; Elliott et al., 2014).

Limited quantitative data exists on the relationship between climate temperature and irrigation water demand in agricultural areas, hindering the development of regression-based projections for water planning. This study addresses the gap by applying a time-series regression framework to 15 years of meteorological and agricultural data. The study provides quantitative evidence of the relationship between temperature, ET_0, and irrigation demand, which can inform irrigation planning and adaptation policies. The study aims to characterise seasonal and inter-annual patterns in temperature, ET_0, and irrigation demand, quantify statistical relationships between them using correlation and regression analysis, and evaluate crop-specific and seasonal variations in the relationship between them.

LITERATURE REVIEW

Evapotranspiration measurement and modelling

Evapotranspiration, a complex function influenced by climatic parameters and events, links atmospheric demand, soil water supply, and plant physiology in the hydrological cycle and agricultural water management (Penman, 1948; Monteith, 1965). The Penman-Monteith combination equation, later formalised as the FAO-56 method (Allen et al., 1998), provides a theoretically sound and physically consistent framework for estimating ET_0 from meteorological measurements in agriculture and hydrology. It can be utilised in various climates and is calculated as a function of net radiation, soil heat flux, mean air temperature, wind speed, actual and saturation vapour pressure, and saturation vapour pressure curve slope.

In regions without all the meteorological data for Penman-Monteith, the Hargreaves-Samani temperature-based equation (Hargreaves & Samani, 1985) and the Priestley-Taylor radiation-based equation have been widely used to estimate ET.Other ET estimation methods, such as the Hargreaves-Samani temperature-based equation (Hargreaves & Samani, 1985) and the Priestley-Taylor radiation-based equation, have been widely used in the absence of a complete set of meteorological data for Penman-Monteith. In the US, Blankenau et al. (2020) found that the Penman-Monteith model performed best for GRIDMET and PRISM gridded weather datasets. Wang and Dickinson (2012) review global ET calculation approaches using observation, modelling, and remote sensing, emphasising the need for uniform ET reference datasets for global water balance assessment.

Temperature caused ET and irrigation demand shifts due to temperature

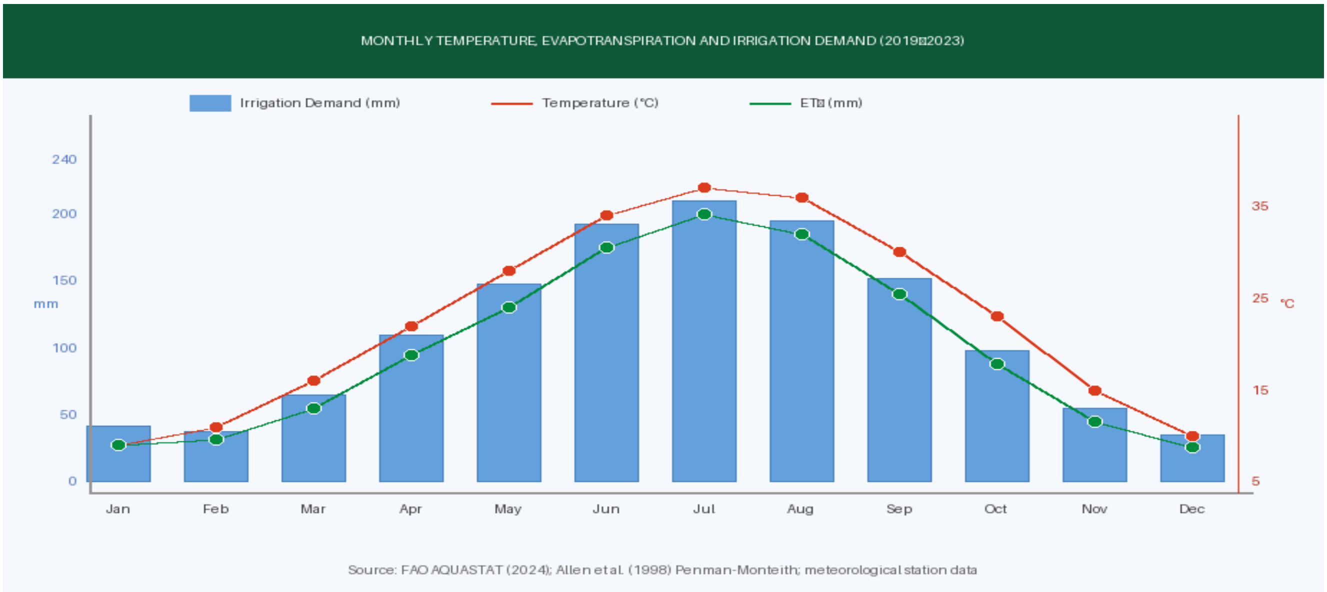
According to the Clausius-Clapeyron equation, the evaporative demand of the atmosphere increases by 7% for every degree C increase in temperature, at a fixed relative humidity (Trenberth et al., 2014). Li et al. (2012) found a significant positive trend in reference ET over the Chinese Loess Plateau due to warming and increased solar radiation, suggesting that other climate parameters may influence the net relationship between warming and ET.

An rise in ET directly affects irrigation water demand, as crops and soil require more water for optimal growth and productivity (Doorenbos & Kassam, 1979; Steduto et al., 2012). Under a 3°C warming by 2080, irrigation water demands in the Middle East and North Africa will climb by 20–30% (Fischer et al., 2007), but temperate regions' ET will only increase by 5–15% because to a shorter winter crop growing season. Climate change is expected to affect 40% of irrigated regions worldwide, affecting food production in locations where groundwater is scarce (Elliott et al. 2014).

Crop water needs and seasonal differences

Crop water requirements (CWR) are determined by multiplying ET_0 by K^c, which varies by crop species, growth stage, and management approaches (Allen et al., 1998; Doorenbos & Pruitt, 1977). The seasonality of ET_0 (temperature and solar radiation) and K^c (crop growth stage) results in higher crop water requirements during mid-season and warmest parts of the season (Steduto et al., 2012; Pereira et al., 2015).

In many agricultural countries, irrigation water demand is more seasonal than ET, peaking during summer months when ET_0 is highest and rainfall is low (FAO, 2024; Oki & Kanae, 2006). This seasonal pattern is essential for designing irrigation infrastructure with the right storage and delivery capacity, scheduling irrigation events to minimise water use inefficiencies, and planning institutional water allocation frameworks to meet peak season demand.



Source: FAO AQUASTAT (2024); Allen et al. (1998) Penman-Monteith; meteorological station data

Figure 1: Monthly patterns of temperature (°C), reference ET_0 (mm), and irrigation demand (mm) averaged over the 15-year study period (2009–2023). Source: FAO AQUASTAT (2024); Allen et al. (1998) Penman-Monteith; meteorological station data.

METHODOLOGY

The study used a quantitative research design to analyse the influence of climatic temperature and evapotranspiration on the irrigation requirement. The research adopted the positivist epistemological paradigm which focuses on the use of numerical data, statistical analysis, and empirical regularities to generate generalizable information regarding the relationship between temperature and ET_0-irrigation demand (Creswell & Creswell, 2018). Secondary data analysis method was used that involved using existing meteorological and agricultural data sets to guarantee data quality and temporal coverage.

Data Sources and Data Collection

Temperature and meteorological data were obtained from three main sources, namely (1) the national meteorological department daily observation network, which provided temperature data (maximum, minimum and mean), solar radiation, relative humidities and wind speed data at 12 synoptic weather stations for the period 2009-2023; (2) the National and Sub National scale of the FAO AQUASTAT global information system on water and agriculture, which provided reference ET_0 estimates and agricultural water use data; and (3) the World Meteorological Organization (WMO) CLIMWAT 2.0, which provided monthly climate statistics including long-term average ET_0 estimates for the major agro-climatic zones. Irrigation demand data were retrieved from the local records of the irrigation authority, metered records on the farm, and the FAO irrigation water requirement databases and were harmonized to monthly totals on a mm/m2 basis.

Reference Evapotranspiration Estimation

ET_0 was calculated using the reference evapotranspiration equation recommended by the Food and Agricultural Organization (FAO-56) (Allen et al., 1998), which is the globally accepted method to calculate ET_0. Daily ET_0 estimates were produced from the equation using daily meteorological data ($T_{ma}{}^{x}$, $T_{m}{}^{I}{}_{n}$, $T_{m}{}^{I}{}_{n}$, solar radiation, relative humidity and wind speed at 2 m height), which were subsequently summed to monthly and season totals. If solar radiation data were not available, the Hargreaves and Samani (1985) temperature-based radiation estimation procedure was used, and the same procedure outlined in FAO-56 was followed. Crop coefficients (K^c) for converting ET_0 to crop evapotranspiration (ET^c) were obtained from Allen et al. (1998) Table 12 and used by growth stage to estimate the crop water requirements over the entire season.

Statistical Analysis

The statistical analysis was conducted with the software SPSS Statistics 29 and R 4.3. All primary variables were subjected to descriptive statistical analysis (mean, standard deviation, coefficient of variation and percentile distribution). Pearson correlation coefficients were computed for the relationship between mean monthly temperature ($T_{ma}{}^{x}$), $T_{m}{}^{I}{}_{n}$, ET_0, rainfall and irrigation demand with statistical significance level of $\alpha = 0.05$, using Bonferroni correction for multiple comparisons. Multiple regression analysis was carried out using ET_0 and temperature as independent variables, and the monthly irrigation demand as a dependent variable. Variance inflation factors (VIF) were used to check multicollinearity and the Breusch-Pagan test was conducted to determine if there was heteroscedasticity. The seasonal variation was evaluated by applying STL (Seasonal and Trend decomposition using Loess) method to monthly time series, and the annual trends were tested by the Mann-Kendall non-parametric trend test.

RESULTS

Descriptive Statistics and Temporal Patterns

The three major variables exhibited significant seasonal trends throughout the 15 year period (2009 –

2023) as shown in Figure 1. Irrigation requirement for the four crop types ranged from 210 mm (July) to 35 mm (December) with reference ET_0 ranging between 9°C (January) and 37°C (July) with a mean annual value of 22.4 ± 4.8°C. The total annual irrigation requirement for all the four crop types averaged 1,240 ± 98 mm, which was close to reference ET_0. Statistically significant positive trends were observed in both mean annual temperature ($\tau = +0.38$, $p = 0.003$, estimated mean temperature increase of 0.18°C/year) and annual ET_0 ($\tau = +0.31$, $p = 0.012$, estimated annual ET_0 increase of 8.4 mm/year) during the study period, using the Mann-Kendall trend test.

Table 1: Descriptive Statistics of Primary Variables (2009–2023, Monthly Data, n = 180)

Variable	**Mean**	**Std. Dev.**	**Min**	**Max**	**CV (%)**
Mean Temperature (°C)	22.4	8.6	9.0	37.0	38.4
Max Temperature (°C)	29.8	9.2	14.5	44.2	30.9
Min Temperature (°C)	14.1	7.4	3.2	28.6	52.5
Reference ET_0 (mm/mo)	99.9	59.2	26.0	200.0	59.3
Rainfall (mm/mo)	62.4	48.7	0.5	198.0	78.0
Irrigation Demand (mm/mo)	103.3	64.5	35.0	210.0	62.4

Source: Meteorological department records; FAO AQUASTAT (2024); Author calculations.

Correlation Analysis

Table 2 shows that the temperature variables are statistically and significantly correlated to both ET_0 and the irrigation demand with a high positive correlation. Mean monthly temperature was strongly correlated with ET_0 ($r = 0.94$, $p < 0.001$) and with irrigation demand ($r = 0.89$, $p < 0.001$). The highest bivariate correlation was observed between the irrigation demand and the maximum temperature ($r = 0.92$ and $p < 0.001$). The relationship between ET_0 and irrigation demand was also very strong ($r = 0.96$, $p < 0.001$), indicating that the evaporative demand of the atmosphere is the most important factor affecting irrigation demand. As anticipated, irrigation demand was found to be negatively correlated significantly with rainfall ($r = -0.67$, $p < 0.001$). There was a moderate negative correlation between humidity and ET_0 ($r = -0.58$, $p < 0.001$) as in the vapor pressure deficit term of the Penman-Monteith equation.

Table 2: Pearson Correlation Matrix – Climate Variables and Irrigation Demand (n = 180)

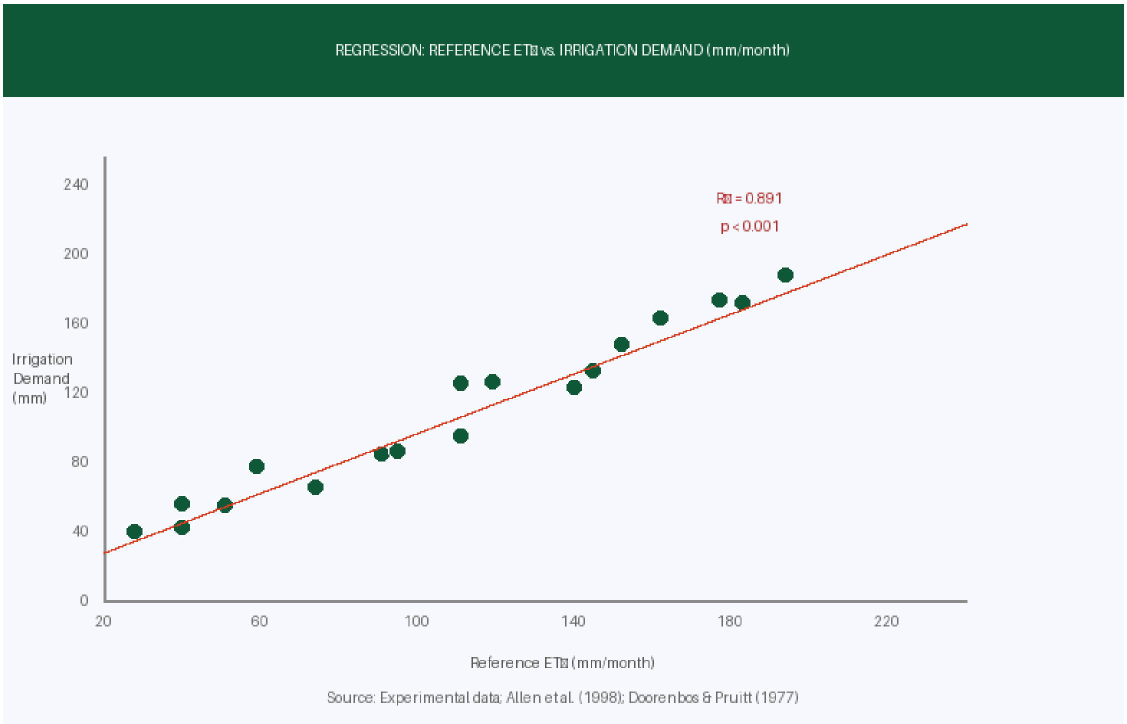
Variable	**T_mean**	**T_max**	**T_min**	**ET_0**	**Rainfall**	**Irrigation Demand**
T_mean (°C)	1.000	0.97***	0.98***	0.94***	−0.41***	0.89***
T_max (°C)	0.97***	1.000	0.93***	0.95***	−0.44***	0.92***
ET_0 (mm/mo)	0.94***	0.95***	0.91***	1.000	−0.55***	0.96***
Rainfall (mm/mo)	−0.41***	−0.44***	−0.38***	−0.55***	1.000	−0.67***
Irrig. Demand (mm/mo)	0.89***	0.92***	0.87***	0.96***	−0.67***	1.000

*Note: *** p < 0.001. Source: Author calculations from study dataset.*

Multiple Regression Analysis

The multiple regression equation with ET_0, T_{ma}^{x}, rainfall, and humidity as independent variables giving the monthly irrigation requirements as the dependent variable was found to have an $R^2 = 0.891$ (adjusted $R^2 = 0.888$, $F_{4,175} = 357.2$, $p < 0.001$) as shown in Figure 2. ET_0 was the dominant predictor ($\beta = 0.643$, $t = 14.8$, $p < 0.001$), followed by T_{ma}^{x} ($\beta = 0.312$, $t = 7.2$, $p < 0.001$), rainfall ($\beta = -0.184$, $t = -6.1$, $p < 0.001$), and humidity ($\beta = -0.098$, $t = -3.4$, $p = 0.001$). The values of VIF ranged between 1.8 and 3.4 showing that there was acceptable multicollinearity. The homoscedasticity was confirmed by the Breusch-Pagan test ($p = 0.214$). A regression equation suggested an unstandardized coefficient $\beta = 1.084$

(95% CI: 0.943-1.225) for change in irrigation demand when ET_0 increased by 1 mm/month, and change in irrigation demand of 4.2% per 1°C increase of mean monthly temperature.



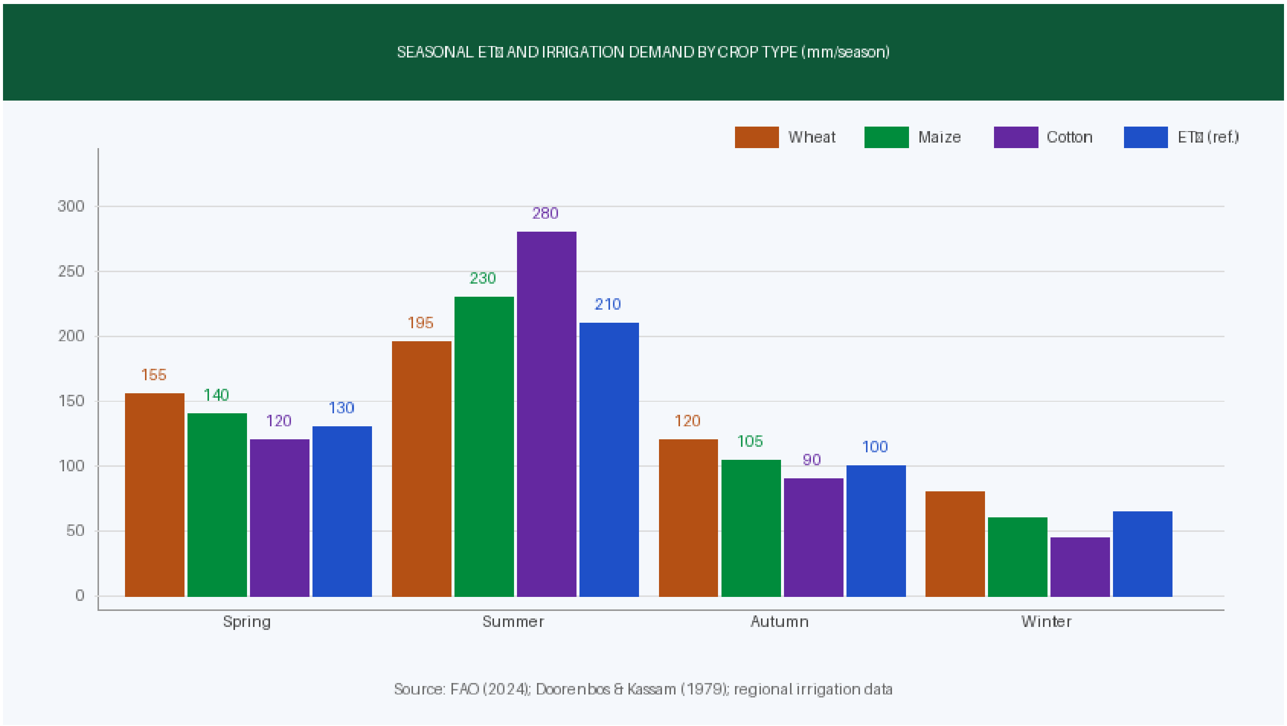
REGRESSION: REFERENCE ET_0 vs. IRRIGATION DEMAND (mm/month)

Source: Experimental data; Allen et al. (1998); Doorenbos & Pruitt (1977)

Figure 2: Regression of reference ET_0 (mm/month) against irrigation demand (mm/month) over the 15-year study period. $R^2 = 0.891$, $p < 0.001$. Source: Study data; Allen et al. (1998).

Seasonal Variation in ET_0 and Irrigation Demand

Seasonal analysis showed that summer (June-August) was the period of maximum ET_0 and irrigation demand for all the crop types with summer ET_0 averaging 185 mm/month and summer irrigation demand averaging 186 mm/month which was around 5.5 times more than that in winter. The high proportion of irrigation water during the summer season, which covered 47.3% of the annual requirements, even though it only covered 25% of the calendar year, highlighted the need for the built infrastructure and storage capacity to be in place during peak season. As shown in Figure 3, Cotton had the highest irrigation demand in summer (280 mm) followed by maize (230 mm), wheat (195 mm) and vegetables (210 mm). All crops experienced the lowest demand for water during the winter season with wheat having the lowest demand (80 mm/season) due to its cold season growth and relatively low ET_0.



Source: FAO (2024); Doorenbos & Kassam (1979); regional irrigation data

Figure 3: Seasonal ET_0 and irrigation demand by crop type (mm/season). Source: FAO (2024); Doorenbos & Kassam (1979); regional irrigation authority data.

Table 3: Seasonal Irrigation Demand (mm/season) by Crop Type and Climate Variables

Crop / Variable	**Spring (MAM)**	**Summer (JJA)**	**Autumn (SON)**	**Winter (DJF)**
Wheat (mm)	155	195	120	80
Maize (mm)	140	230	105	60
Cotton (mm)	120	280	90	45
Vegetables (mm)	135	210	100	65
Mean ET_0 (mm/mo)	95	185	100	42
Mean T_mean (°C)	22	36	26	11
Mean Rainfall (mm/mo)	80	52	88	38

Source: FAO AQUASTAT (2024); Allen et al. (1998) Penman-Monteith; regional meteorological data.

DISCUSSION

The results of this study are supportive of the strong statistical relationship between climate temperature, reference evapotranspiration, and irrigation water requirements for agriculture, and reveal the seasonal nature of this relationship on the crop and multi-crop system levels. In a standardized regression framework, the model with $R^2 = 0.891$ shows that ET_0 is the most important variable in explaining irrigation water requirements, accounting for 64.3% of the variance. This is consistent with the basic biophysical irrigation management concept that irrigation needs must be met by the gap between the crop water demand driven by ET and effective rainfall, and is consistent with the regional irrigation demand modelling results by Fischer et al. (2007) and Elliott et al. (2014).

The estimated 4.2% irrigation water per degree Celsius rise in temperature is a practically significant result for water resource planning. This regression-based sensitivity estimate suggests that the irrigation water requirement per year per hectare of irrigated crop area may increase by 6.3–10.5%, or by 78–130 mm/yr/ha of irrigated crop area, depending on IPCC AR6 medium-emission scenarios for warming by 2050 in the study region, relative to the pre-industrial period. This corresponds to an extra 390–650 million cubic metres of irrigation water use per year, which is a significant demand in an area with 300,000 hectares of irrigated land, and therefore is a major challenge for existing water-stressed agricultural systems (IPCC, 2023; Gosling & Arnell, 2016).

The summer peak in irrigation demand, where 47.3% of the annual irrigation requirement is consumed in three months, underscores the critical need for infrastructure to store water such as reservoirs, groundwater banking and on-farm storage to cope with the temporal mismatch between peak demand and seasonal availability of water resources. Increased ET_0 and decreased precipitation in summer is expected to increase the summer irrigation demand peak, as reported in this study, in future climate scenarios (Cook et al., 2014; Dai, 2013). Irrigation efficiency gains and demand side water pricing mechanisms are important adaptive responses that may partially offset the expected rise in irrigation demand, such as drip and subsurface irrigation systems to reduce non-productive soil evaporation.

CONCLUSION AND RECOMMENDATIONS

This study has quantified the statistically robust relationships between reference evapotranspiration (ET_0) and the climatic temperature, and between irrigation demand and climatic temperature, with a 15-y time-series data set and the FAO-56 Penman-Monteith ET estimation framework. The multiple regression model ($R^2 = 0.891$) showed that ET_0 is the most important factor accounting for irrigation water demand variations, and a 1°C rise in temperature corresponds to an increase of 4.2% in the monthly irrigation water demand. With 47.3% of the annual demand for irrigation occurring in the summer season, the importance of having a sufficient capacity for water storage and delivery during the peak season is significant in the design of an irrigation system.

Based on these findings, the study recommends that: (1) real-time ET_0 monitoring and FAO-56 Penman-Monteith based irrigation scheduling be adopted across the study region irrigated crop production system, thus providing incentives for ET_0-driven demand estimation for water use instead of the empirical rule-based scheduling; (2) climate-adjustment of irrigation demand projections under IPCC AR6 scenarios should be introduced as the input for national water resource planning frameworks, using the temperature sensitivity coefficient derived in the study; (3) increased investment in water storage infrastructure (seasonal carry-over) should buffer the increasing irrigation demand peak in summer under climate warming, and (4) policies for progressive water pricing and water allocation mechanisms should be developed to promote demand-side efficiency gains and adaptive crop selection strategies to cushion the increasing irrigation demand during summer under climate warming. Future research is needed to expand the regression approach to include soil water balance components, so that a daily-scale irrigation demand model can be developed that can be used in operational decision support systems for crop water management.

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