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Estimation of Crop Water and Irrigation Requirement for Major Cereals and Vegetable Crops Using FAO CROPWAT 8.0 Model in the Terai Region of Nepal

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Abstract

To optimize food production and meet the needs of the ever-increasing population, there is a need to utilize agricultural water economically and scientifically. There are barely enough scientific studies done on agricultural water requirements in Nepal resulting in a lack of information available to Nepalese farmers regarding agricultural water management. This study utilizes the CROPWAT 8.0 model to estimate the Crop Water Requirement (CWR) and Irrigation Requirement (IR) for key crops, including rice, maize, wheat, potato, and cauliflower, in Nepal's Terai region. Agro-climatic data, encompassing rainfall, maximum and minimum temperatures, sunlight hours, humidity, and wind, were sourced from the NASA power tool. Crop data were obtained from FAO statistics, and soil data were derived from the Nepal Agricultural Research Council (NARC) soil map. The study revealed significant variations in CWR, ranging from 321.70 mm for potatoes in Dang to 1009.10 mm for paddy in Kailali, and IR, ranging from 86.80 mm for maize in Morang to 802.30 mm for paddy in Kailali. This research study indicates that the seasonal and ecological features of the location necessitate crop water requirements and irrigation schedules that are specific to them. The knowledge on crop water demand help farmers to determine the optimal timing and quantity of irrigation for various crops, thereby mitigating water wastage. These findings offer valuable insights for farmers and researchers to enhance irrigation water management practices in agricultural contexts, promoting sustainable water management.

Keywords: Irrigation requirement, irrigation scheduling, location-specific, waterwastage

Introduction

Approximately 87% of water used and 70% of water withdrawn globally are currently used for agricultural purposes, mostly for irrigated crop cultivation (Taye et al., 2021). Irrigated agricultural land, though makes up less than 5% of all cultivated areas, generates about 40–45% of the world's food supply (Solangi et al., 2022). Water is a renewable resource, however, its unequal distribution with rising demand may have a severely impact its supply and cause freshwater shortage shortly (Tarjuelo et al., 2010) making food and water security critical issues for growing population; freshwater needs might rise by 80% by the year 2050 (Flörke et al., 2018). One of the sustainable ways to combat such problems is the wise use of irrigation water (Ahmadi et al., 2019).

Scientific irrigation requires sufficient knowledge of evapotranspiration, crop water requirements, and net irrigation water requirements (Dingre & Gorantiwar, 2020). An increase in ETo leads to an increase in crop water demand increasing irrigation water requirement (Rahman et al., 2021) and is calculated with the help of the Penman-Monteith method, which is globally one of the most precise method for calculating water requirements and evapotranspiration (Vozhehova et al., 2018). Various models have been developed however CROPWAT requires comparatively less input data and hence is most widely used for defining crop water requirements (Solangi et al., 2022). Developed by the FAO's Land and Water Development Division. The model employs the FAO Penman-Monteith Equation for calculating reference evapotranspiration (ETo), crop water requirements (ETc), and irrigation schedules (Saha et al., 2018).

Agricultural water management is crucial for optimizing crop production, ensuring food security, and enhancing the livelihoods of farmers in an agarian nation like Nepal (Rahman et al., 2018). A false assumption that more water equates to higher yields exists among Nepalese farmers leading to over-irrigation. In this study, the water requirements computed through CROPWAT for the previous years have been compared with the actual irrigation supplied in the corresponding years. This study aims to enhance understanding of the water demands of key crops, facilitating more informed and sustainable water management prac-tices in agriculture.

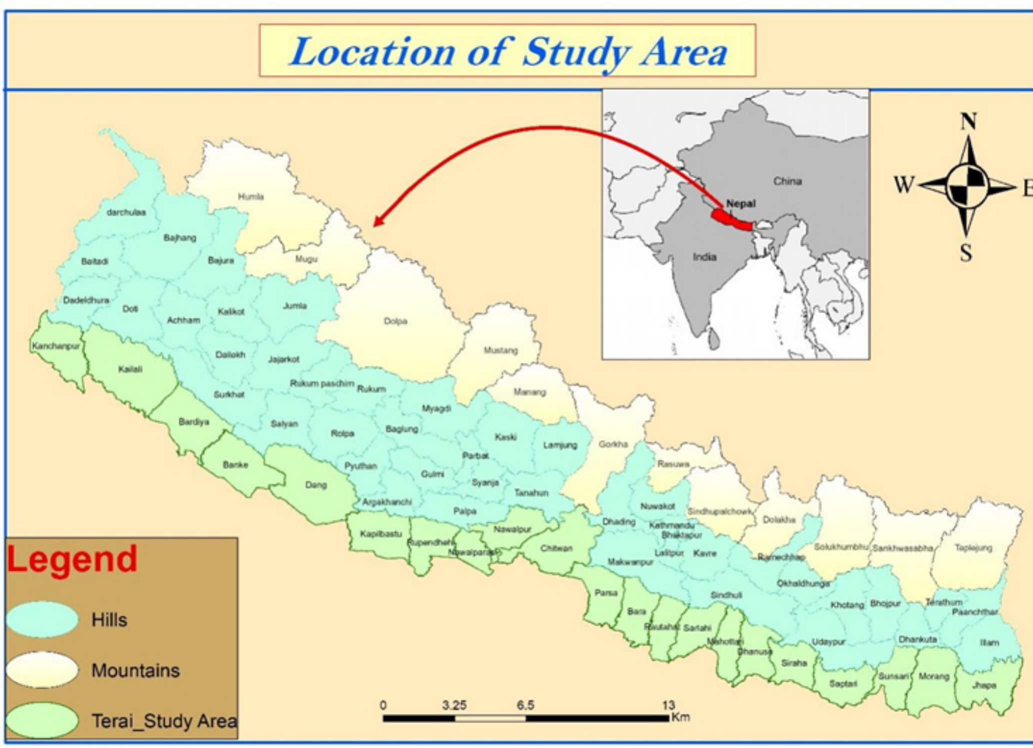
Research Methodology

Description of the Study Area

The area selected for the study is the Terai region which constitutes 21 districts and occupies 23.1% of the total area of Nepal. This flat region lying in the northern belt of the Gangetic plain, is located below 600m elevation (Chhetri & Easterling, 2010). The region has a tropical savanna climate, with hot summers and dry winters. The average annual temperature is 20–28 °C (68–82 °F), and the average annual rainfall is 2,500–3,000 mm (98–118 in) in the east and 1,600–1,800 mm (63–71 in) in the west (Karki et al., 2016). This region experiences high temperature and heavy rainfall during the monsoon season. Known as the "granary (breadbasket) of Nepal," it produces an abundance of food products. Major crops include rice, wheat, maize, potato, sugarcane, ginger, turmeric, cardamom, garlic, peas, and lentils.

Figure 1

Map of the study area



Input data for CROPWAT

The CROPWAT model requires three different categories of data: soil, crop, and climate data.

Climate Data. The climatic data included mean monthly maximum and minimum temperature, relative humidity, monthly rainfall, wind speed, and sunshine hours. These were obtained from NASA's Prediction of Worldwide Energy Resources and employed in the software to estimate monthly evapotranspiration (ETo) for all twenty-one districts of the Terai region.

Reference Evapotranspiration (ETo). The term crop evapotranspiration often referred to as "ET crop," refers to the amount of water required to compensate for the combined loss from evaporation and transpiration. Crop evapotranspiration is the product of reference evapotranspiration and crop coefficient. It is computed using the FAO Penman-Monteith method using daily maximum and lowest temperature, wind speed, daily sunlight hour, and relative humidity.

$$\text{ETo} = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_{2(e_s - e_a)}}{\Delta + \gamma\,(1 + 0.34\,\text{u2})} \tag{1}$$

Where, ET_0 = reference evapotranspiration (mm/day), Rn=net radiation at the crop surface (MJ $m^{-2}day^{-1}$), G=soil heat flux density (MJ $m^{-2}day^{-1}$), T=mean daily air temperature at 2 m height (^{0}C), U_2=wind speed at 2 m height (ms^{-1}), e_s=saturation vapor pressure (KPa), e_a=actual vapour pressure (KPa), e_s-e_a=saturation vapour pressure deficit (KPa), Δ=slope vapour pressure curve (KPa ^{0}C-1) and γ=psychrometric constant (KPa ^{0}C-)

Effective Rainfall. Rainfall data plays a crucial role in determining the necessity of crop watering. Rain data were taken from NASA Power and effective rainfall was determined using the USDA Soil Conservation Service approach, as shown in Equations (2) and (3) (Allen et al., 2005).

$$P_{eff} = \frac{P_{tot}(125 - 0.2 * P_{tot})}{125} for\ P_{tot} < 250mm\ (per\ month) \tag{2}$$

$$P_{eff} = 125 + 0.1\ P_{tot}\ for\ P_{tot} > 250mm\ (per\ month) \tag{3}$$

Where, P_{eff} = effective rainfall (mm); P_{tot} = total rainfall (mm).

Soil Data. The NARC soil map was utilized to determine the percentages of sand, silt, and organic matter concentration in the soil. Based on texture analysis and organic matter, the soil properties were estimated using the SPAW Software utilizing the Pedo transfer function (Saxton & Rawls, 2006). The studied region has a loamy type soil with a Saturation (% vol) of 45, Field Capacity (% vol) of 26.8, Available water (cm/cm) of 0.14, and Drainage Porosity (%) of 18. These required soil parameters were employed in the software.

Crop Data. Sharing of input data might reduce costs and time expenditure, will increase its uptake and improve overall quality of water resources assessments. The crops under study include three major cereal crops: paddy, maize, and wheat, and two major vegetables: potato and cauliflower. The default crop file was already there in the software which was adjusted to the local conditions. The planting and harvesting dates of the studied crops were derived from MODIS NDVI data as suggested by Rimal 2018.

Table 1

Planting and harvesting dates of selected crops using MODIS NDVI data (Rimal et al., 2018)

Crop	Terai	
	Planting Date*	Harvesting Date
Maize	16-Apr	23-Oct
Paddy*	16-Jun	2-Nov
Wheat	1-Nov	20-Mar
Potato	30-Oct	16-Feb
Cauliflower	15-Aug	7-Dec

Note. *-In case of paddy, PD means transplanting date.

Crop Water Requirement (CWR)

The amount of water needed to fulfill a crop's evapotranspiration needs for optimal development is known as crop water requirement. Once ET_o is established, CWR is derived by adjusting ET_o based on crop-specific factors like the crop coefficient (Kc), which accounts for the actual evapotranspiration relative to ET_o in standard conditions. Thus, CWR quantifies the water volume required by the crop throughout its growth stages, informed by local climate and crop characteristics.

$$CWR = ET_o * Kc \quad (4)$$

Where Kc (crop coefficient) is the ratio of the studied crop's evapotranspiration to the reference crop's evapotranspiration under identical conditions, Kc varies according to crop type, crop development stage, and overall plant health (Allen et al., 1998). Crop coefficient represents crop specific water use and is essential for accurate estimation of irrigation requirements of different crops in the area. Although there are published Kc values for different crops, these values are commonly used in places where local data are not available. As these values vary from place to place and from season to season, there is a strong need for local calibration of crop coefficients under given climatic conditions. The Kc is affected by a number of factors, which include: the type of crop, stage of growth of the crop and the cropping pattern. Doorenbos and Pruitt (1979) indicated that plant height and total growing season influence crop coefficient value (Chalmers et al., 2022). The higher the plant height and the longer the growing season the higher the crop coefficient values and vice versa (Kalle Hirvonen, Elia Machado, 2024).

Irrigation Water Requirement (IR)

The quantity of water needed to be delivered through the irrigation system to fulfill the crop water needs for a disease-free crop growing on expansive fields with unrestrictive soil and water conditions and sufficient fertility, is known as the irrigation water requirement, or IWR (Alemayehu et al., 2009). The CROPWAT Model can compute the irrigation water requirement by the following equation.

$$IWR = ET - ER \quad (5)$$

Where, IWR= Irrigation Water Requirement, ET=Evapotranspiration, ER= Effective rainfall.

Results and Discussion

Reference Evapotranspiration (ETo)

Using the Penman-Monteith equation, agro-climatic data were used to compute the reference evapotranspiration (ETo) for the cultivated crops paddy, maize, wheat, cauliflower, and potato. The mean daily evapotranspiration ranges from 3.6 mm/day for potato in Dang to 8.4 mm/day to 10.95 mm/day for maize in Kailali. Also, the highest monthly evapotranspiration was observed in June and the lowest in December. The increased ETo values were attributed to the rise in temperature, extended sunshine duration, and high wind speeds from May to August. The peak temperature was recorded in July, averaging 42.5^0C, contributing to high radiation, maximum sunshine hours, and accelerating ETo. At the beginning and end of the year, ETo values were lower due to cooler temperatures, reduced sunshine, and lower wind speeds. Similar results were obtained Solangi et al. in 2022 indicating that ETo is higher in the summer owing to the high temperature and solar radiation and vice versa.

Crop Water Requirement and Irrigation Requirement

Table 2 illustrates the max ETc, crop water and irrigation requirements derived from CROPWAT for the selected crops. As anticipated, there is a considerable variation in crop water and irrigation needs between crops and locations. The study shows that crop water requirement in mm/day ranges from 321.70 mm for potatoes in Dang to 1009.10 mm for paddy in Kailali. This is because even within the same agro-ecological region, different locations experience different temperature, different amounts of precipitation and soil characteristics. Correspondingly, the crop water requirement varies in paddy, with a minimum of 754.4 mm per season in Jhapa and a peak of 1009.1 mm in Kailali, while wheat has the lowest CWR in Dang at 393.5 mm contrasting with Rautahat's maximum requirement of 449.5 mm. Jhapa again records the minimum CWR of 358,7 mm, while Kailali registers a maximum of 422.3 mm for cauliflower. Maize CWR spans from a minimum of 600.7 mm in Morang to a high of 801.8 mm in Kailali. Moreover, seasonal water requirement fluctuates between 321.7 mm in Dang and 364.4 mm in Rautahat for potatoes. All the studied crops demonstrated their maximum water consumption during the mid-growth phase, compared to both the initial nursery stage and the subsequent maturation phase. The growth stage involves significant biomass accumulation, and increased leaf area development, which leads to higher transpiration rates. Additionally, critical developmental processes such as flowering, fruit setting, and grain filling also occur during this stage, necessitating adequate water supply to ensure optimal yield and quality (Suryadi et al., 2019). These findings are in line with Solangi, who asserts that the growth stages of the crop exhibit elevated reference evapotranspiration values, consequently resulting in a higher water requirement (Solangi et al., 2022).

Similarly, the Irrigation Water Requirement (IWR) displays significant variability across different locations. It represents the additional water needed from irrigation sources beyond natural precipitation. Throughout the growing season, the total IWR ranges from 86.80 mm for maize in Morang to 802.30 mm for paddy in Kailali. The IWR ranges from 431.3 mm to 802.3 mm for paddy, 86.8 mm to 546.6 mm for maize, 230.9 mm to 399.1 mm for wheat, 93.2 to 179.2 for cauliflower, and 220.2 to 474.7mm for potato, respectively. The IWR values ranged from a minimum of 86.80 mm for maize in Morang to a maximum of 802.30 mm for paddy in Kailali. This reflects the crop's varying dependency on external irrigation, influenced by local rainfall patterns and crop growth stages. These irrigation schedules were designed to minimize water usage without compromising crop yields, especially in the dry season when water scarcity is more pronounced (Dawadi et al., 2022). The water requirement of paddy is comparatively higher due to its cultivation method, which involves maintaining flooded fields throughout much of its growing season and the hot, humid conditions it is often grown (Salman et al., 2022). Paddy consistently exhibited highest CWR across the regions which aligns closely with findings from similar studies in Surkhet district that require 950 mm of net irrigation in the entire cropping season (Adhikari et al., 2023). Maize, on the other hand, exhibited a much lower IWR, which can be attributed to higher rainfall in areas like Morang, where maize's water requirements can be largely met by precipitation. However, dry season crops like wheat and potato need regular irrigation to meet their water demands, as rainfall is minimal during this period. The study further indicates that the irrigation water requirements for the examined crops are significantly higher during the arid months of December, January, and February. This peak in irrigation water demand arises primarily because approximately 75-80% of Nepal's annual rainfall is concentrated in the monsoon season. Consequently, farmers who rely on rainfall face substantial risks during the dry months, underscoring the necessity for effective irrigation management as a critical measure towards sustainable agriculture.

The findings of this study cannot be comprehensively compared due to a lack of analogous research across the entire Terai region of Nepal. However, a study conducted by Debi Prasad Bhattarai, which estimated the water requirements for similar crops in the Jhapa district of eastern Nepal, yielded results consistent with the current research. Additionally, in 2021, the Department of Water Resources and Irrigation (DWRI) published a report titled "Procedural Guideline for Integrated Crop Water Management Program," which delineates the proposed crop water requirements. It recommends water needs for rice, wheat, maize, potato, and cauliflower at 900-1500 mm, 450-600 mm, 500-800 mm, 500-700 mm, and 350-500 mm, respectively. The model's results closely align with government standards for the selected crops, demonstrating its accuracy and application to established agricultural recommendations.

Table 2

Max ETc, CWR and IR for different crops

Crop / District	Paddy			Wheat			Potato			Cauliflower			Maize		
	Max ETc (mm/day)	CWR (mm/season)	IR (mm)	Max ETc (mm/day)	CWR (mm/season)	IR (mm)	Max ETc (mm/day)	CWR (mm/season)	IR (mm)	Max ETc (mm/day)	CWR (mm/season)	IR (mm)	Max ETc (mm/day)	CWR (mm/season)	IR (mm)
Banke	8.45	924.7	645.5	5.17	427.4	335.2	3.89	347.6	284.7	4.09	392	171.7	9.92	738	225.4
Bara	7.46	887.4	604.4	5.51	437.4	386.9	4.15	341.6	307.8	4.18	362.6	162.5	8.76	679.7	167.6
Bardiya	8.48	934.8	705.4	4.94	421.8	303.7	3.89	347.3	266.4	4.09	395.5	171.4	10.05	741.1	246.5
Chitwan	7.21	835.1	497.5	5.28	427.1	352.2	3.93	343.3	295.8	3.83	373.7	159.5	8.25	644.9	112.1
Dang	7.46	835.2	583.7	4.71	393.5	306	3.6	321.7	262.7	3.77	361.8	154.1	8.63	655.5	168.5
Dhanusha	6.74	801.8	599.1	4.82	408.3	371.8	3.78	334.7	316.3	3.79	364.7	180.1	7.73	608.4	131.3
Jhapa	5.93	754.4	431.3	5.28	421.8	364.4	3.93	336.3	319.8	3.68	358.7	144.9	6.7	630.1	546.6
Kailali	9.2	1009.1	802.3	5.05	442.1	308.6	3.89	357.3	268.5	4.38	422.3	179.2	10.95	801.8	312.4
Kanchanpur	7.92	912.3	708.9	4.59	395.7	230.9	3.64	331	220.3	4.08	390.9	143.8	9.41	707.3	231.8
Kapilbastu	8.38	927.3	601.3	5.51	446.7	376.5	4.09	362.5	313.8	4.23	406.9	183.2	9.79	728.6	217.1
Mahottari	7.31	864.2	606.1	5.4	439.5	392.7	4.04	357.4	330.7	4.01	388.4	196.6	8.38	662.1	162.7
Morang	6.6	813	501.2	5.28	432.9	394.1	4	350.5	336.9	3.9	380	171.8	7.47	600.7	86.8
Nawalparasi_E	7.88	887.9	541.6	5.4	436.2	359.6	4.04	350.8	301.5	4.09	391	168.6	9.15	691.2	159.9
Nawalparasi_W	7.88	887.9	541.6	5.4	436.2	359.6	4.04	350.8	301.5	4.09	391	168.6	9.15	691.2	159.9
Parsa	7.67	893.6	610.8	5.51	447.2	396.8	4.15	361	327.3	4.12	397.4	197.3	8.76	691.3	175.5
Rautahat	7.67	890.1	607.3	5.51	449.5	399.1	4.15	364.4	330.6	4.12	398.2	198.2	8.76	687.6	172.2
Rupandehi	8.38	927.30	601.30	5.51	446.70	376.50	4.09	362.7	313.8	4.23	406.9	183.2	9.79	728.6	217.1

Saptari	7.03	837	522.3	5.28	427.3	389.9	3.93	341.9	328.2	3.87	378.3	167.9	7.99	630.7	111.4
Sarlahi	7.42	867.6	609.9	5.28	435	388.2	4	352.4	325.8	4.01	387.5	195.8	7.41	608.4	131.3
Siraha	6.74	801.8	599.1	4.82	408.3	371.8	3.78	334.7	316.3	3.79	364.7	180.1	7.73	608.4	131.3
Sunsari	7.03	837	522.3	5.28	427.3	389.9	3.93	341.9	328.2	3.87	378.3	167.9	7.99	630.7	111.4

Figure 2

Water Requirements for Paddy

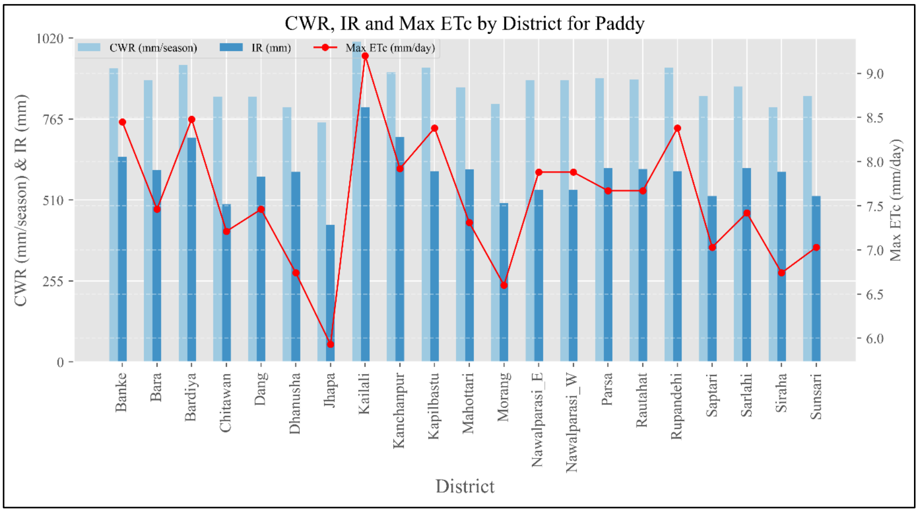


Figure 3

Water Requirements for Wheat

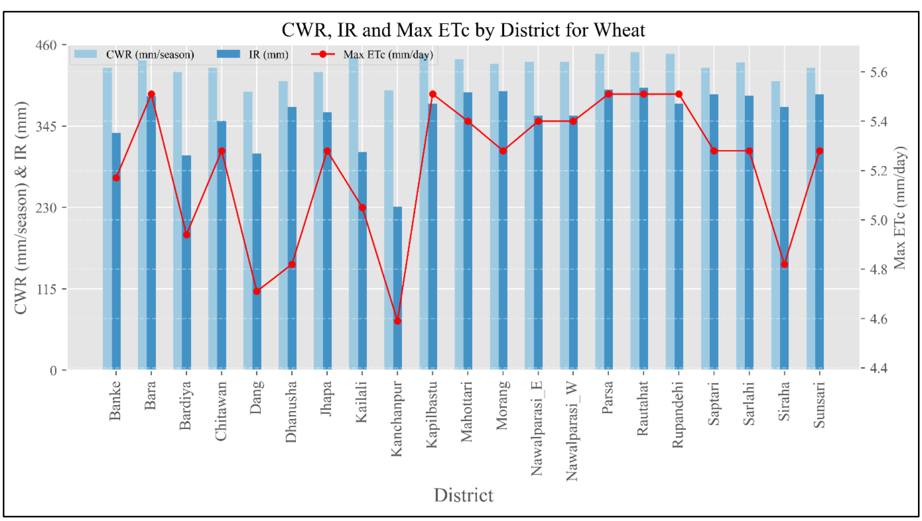


Figure 4

Water Requirements for Potato

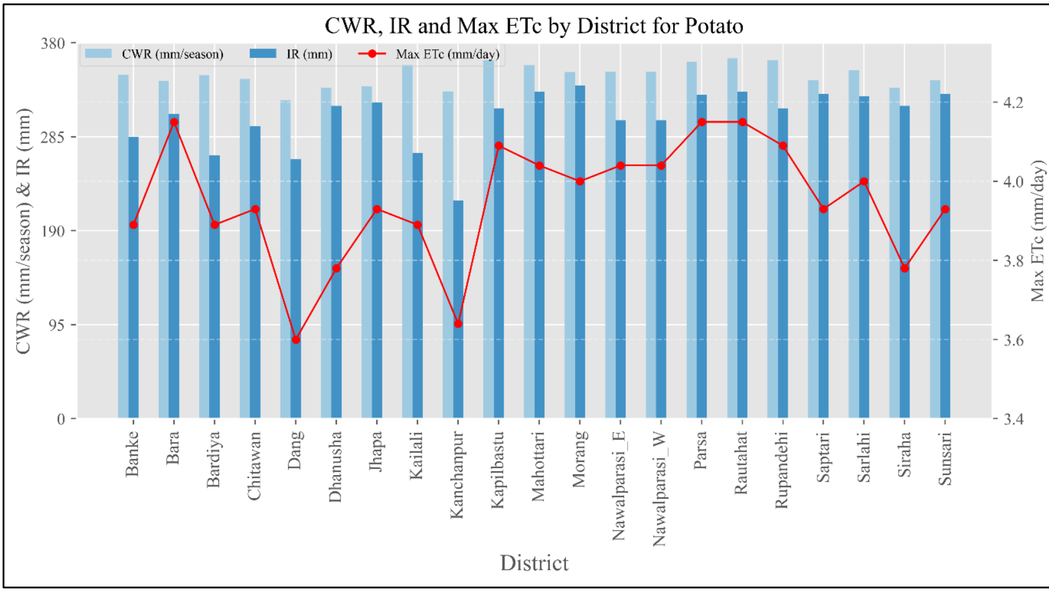


Figure 5

Water Requirements for Cauliflower

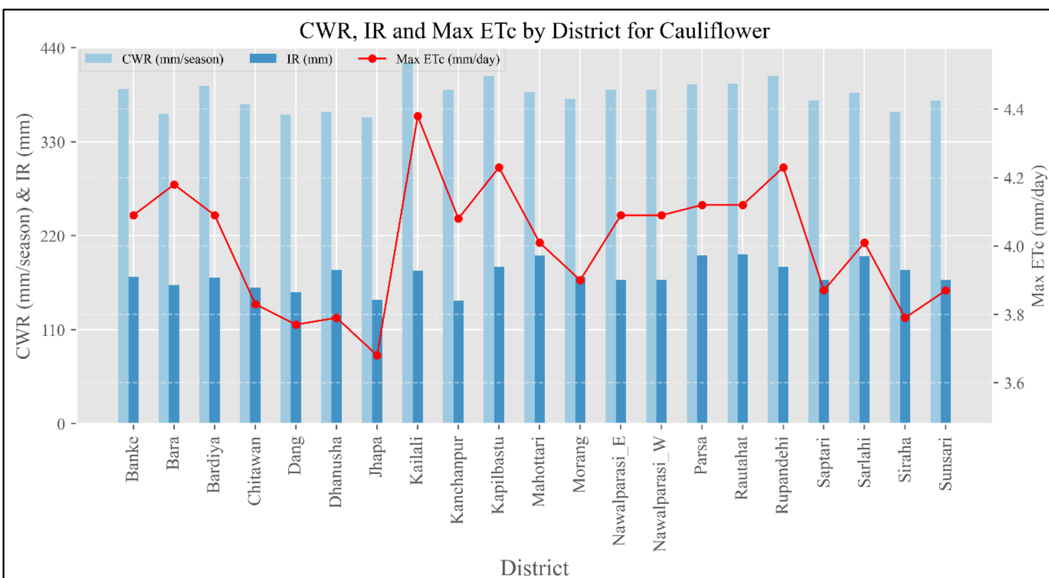
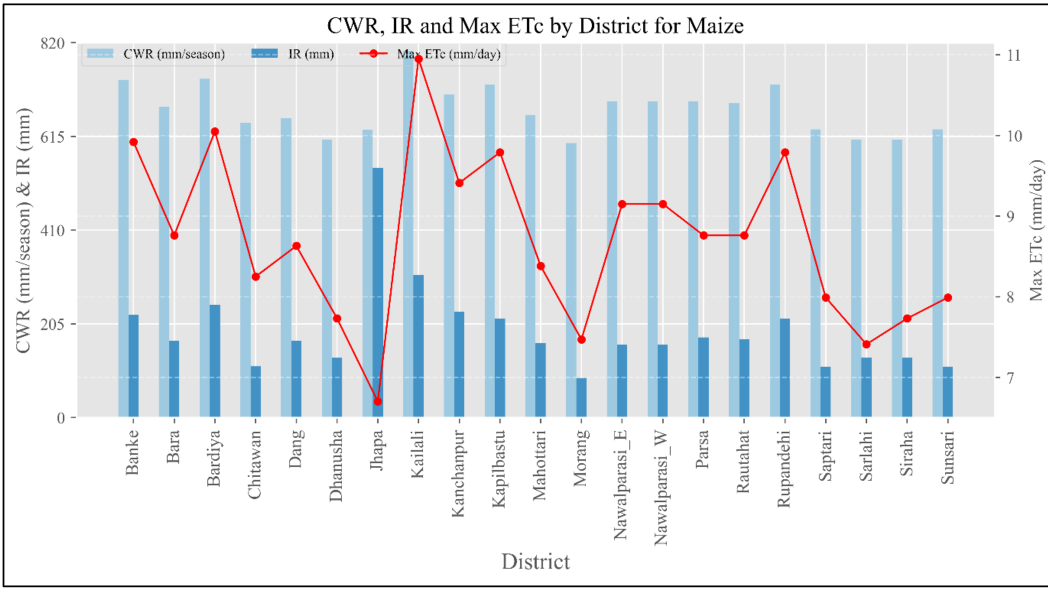


Figure 6

Water Requirements for Maize



Conclusion

The amount of evapotranspiration for rice cultivated in the spring and summer is greater than the amount for four other crops grown in the winter. Similarly, compared to wheat, cauliflower, and potato, maize has a greater water requirement among winter crops. Given the substantial variations in CWR and IR across different crops and locations, it is essential to adopt irrigation schedules that reflect the specific seasonal and ecological conditions. Advanced irrigation techniques, such as drip and sprinkler systems can be beneficial to mitigate water wastage. Another water saving technique is development and utilization of rainwater harvesting systems to collect and store rainfall during the monsoon season. The data obtained can also be used as a reference for research scientists and water resource planners to conserve water for sustainable agriculture. The analysis is based on five years' worth of local climate data. It is recommended that data from a longer period (30 years) can be used to derive more precise and accurate results.

Author's Contributions

All the authors involved in conducting the experiments, analysis, data interpretation and drafting of the manuscript. All authors listed have made a substantial, direct and intellectual contribution to the study, and approved it for publication.

Conflict of Interest

The authors have no relevant financial or non-financial interests to disclose.

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