Environment Conservation Journal 25 (1):308-326, 2024

Journal homepage:https://www.environcj.in/

Environment Conservation Journal

ISSN 0972-3099 (Print) 2278-5124 (Online)

Estimating crop water requirement in Madhya Pradesh's agro climatic regions: A CROPWAT and CLIMWAT software case study

Venkatesh Gaddikeri
Division of Agricultural Engineering, ICAR-IARI, New Delhi, India

Jitendra Rajput ✉
Division of Agricultural Engineering, ICAR-IARI, New Delhi, India

Dimple
College of Agriculture, Kishangarh Bas, Alwar, Rajastham, India

Malkhan Singh Jatav
Division of Agricultural Engineering, ICAR-IARI, New Delhi, India

Arti Kumari
ICAR Research Complex for eastern Region, Patna, Bihar, India

Lalita Rana
Department of Agronomy, SRI, RPCAU; Pusa, Samastipur, Bihar

Ashish Rai
Krishi Vigyan Kendra Parsauni, East Champaran, Dr Rajendra Prasad Central Agricultural University, Pusa, Samastipur, Bihar, India

Anshu Gangwar
Krishi Vigyan Kendra Parsauni, East Champaran, Dr Rajendra Prasad Central Agricultural University, Pusa, Samastipur, Bihar, India

ARTICLE INFO

Received : 18 May 2023
Revised : 25 September 2023
Accepted : 27 October 2023

Available online: 19 January 2024

Key Words:
Crop coefficient
Effective rainfall
Irrigation scheduling
Net irrigation requirement
Evapotranspiration

ABSTRACT

Estimating actual crop evapotranspiration is vital in water-scarce environment affected by climate change, particularly for optimizing irrigation and enhancing crop yield. This research focuses on assessing crop water and irrigation requirement for major crops across six districts of Madhya Pradesh, India, spanning diverse agro-climatic regions. Employing CLIMWAT 2.0 and CROPWAT 8.0 software, calculated crop evapotranspiration and devised irrigation strategies tailored to local climatic conditions. The FAO-Penman-Montieth (FAO-PM) equation for reference evapotranspiration (ET_0), aiding in crop water requirement computation and irrigation planning. Our findings reveal substantial variations in crop water requirements across crops and districts. For instance, soybean in Indore requires the highest water input at 380 mm, while in Guna, was least at 303 mm. Wheat, on the other hand, register the highest water needs in Khandwa at 510.6 mm and the lowest in the Neemuch district at 370.8 mm, particularly during the *rabi* season. Besides that, this study underscores the need for district-specific considerations, taking into account climate and soil characteristics when formulating water management strategies. Employing efficient irrigation practices and techniques to manage water stress becomes imperative for optimizing crop yield and achieving economic returns. Implementing customized approaches to enhance water use efficiency and promote sustainability in agricultural production is crucial. These research outcomes provide valuable insights for policymakers, agricultural practitioners, and water resource managers to develop context-specific water management strategies.

Introduction

Water, a precious and scarce natural resource, is essential to life, livelihood, food security, and long-term sustainable development. "Potential changes in climate can impact agriculture and water resources" (Ludwig *et al.*, 2014). With the prolonged drought, declining water level in dams, sedimentation of rivers, and water restrictions due to constant competition from other sectors, the need for judicious use of available water for sustainable development of agriculture. Agriculture consumes

Corresponding author E-mail: *jitu.caepht@gmail.com*
Doi:https://doi.org/10.36953/ECJ.26022353

the most water in India (81 per cent); thus, making the most effective use of water in agriculture should be a top focus (Surendran *et al..,* 2013; Dhawan, 2017; Kumar and Gautam, 2014). Soil moisture comprises a little portion (0.15%) of the world's available freshwater (Dobriyal *et al..,* 2012). The water available in the form of soil moisture is used to help produce crops and support plant growth. Management of soil water is critical to numerous hydrological, ecological, and biogeochemical activities. For effective resource planning, accurate information on evapotranspiration, crop water requirements, and net irrigation requirements is essential (Levidow *et al..,* 2014). As a result, profitability and long-term viability might improve. Effective water resources management impact agricultural productivity, water usage efficiency, and reduces the negative impact on the environment through nutrient leaching, eutrophication, waterlogging, and pollution of surface and groundwater (Scanlon *et al..,* 2007).“Crop water requirement (CWR) is defined as the depth of water (millimetres) required to meet the water consumed by evapotranspiration (ET_c) by a disease-free crop growing in fields under non-restrictive soil conditions, including soil water and fertility, and achieving full production potential under the given growing environment”. Accurate CWR estimation is a vital part of proper water management in agriculture. Such assessment requires specific instrumentation and methodologies (Rafeet, 2002). The most common criteria for assessing CWR are currently based on the climatic water balance (i.e., evapotranspiration, lysimeter), plant physiological properties, soil water status measurements, remote sensing, surface energy balance algorithm, or a combination of these factors (Gaddikeri *et al.*., 2022). Where meteorological data are available, assessing the CWR is based on the atmospheric water demand called reference evapotranspiration (ET_0) is used. Under limited weather data condition, CROPWAT may used for assessing the ETo, crop water requirement and irrigation scheduling. It is a decision support tool developed by the Land and Water development division of the Food and Agriculture Organization (FAO). CROPWAT is a computer-based software that calculate agricultural water and irrigation needs based on soil, climate, and crop data. CLIMWAT is a climatic database to be used in combination with the computer program CROPWAT. Besides, both the software combinedly used to develop irrigation practice guidelines, the creation of irrigation schedule under diverse water allocation needs, and estimates under rainfed or shortfall irrigation situations. Khan *et al..,* 2021 applied CROPWAT software in the Al-Qassim Province, Saudi Arabia, to estimate the topographical sustainability of the crop water requirement. Furthermore, they explored the utility of CROPWAT and CLIMWAT software for irrigation scheduling of the main crops. Several studies were conducted using CROPWAT software for estimation of crop water requirements for various purposes like evaluating the performance of canal command system (Rajput *et al..,*2017;Vibhute *et al..,* 2016), estimating the potential command area of pulp and paper mill effluent (Rajput *et al..,* 2021), Irrigation scheduling (Prattoyee *et al..,* 2021; Rahman and Sarma, 2019; Ratnaraju *et al..,* 2016), deficit irrigation scheduling (Diro and Tilahun, 2009), climate change impact on crop water (Naik *et al..,* 2015), and water footprint studies (Ewaid *et al..,* 2019) and Reference evapotranspiration modelling (Pawar *et al..,* 2021). CROPWAT uses meteorological data from over 5000 climate stations worldwide to crop water requirements, and helps in crop planning. The CLIMWAT provides data for estimating ET_0, including daily maximum (Tmax) and minimum temperatures (Tmin), relative humidity (RH), daylight hours/solar radiations (SR), wind speed (WS), and precipitation (P). In the CROPWAT model, the FAO-Penman Monteith equation was used to estimate ET_0 using data from the CLIMWAT. Using this data, an attempt was made to estimate crop water requirements of main crops in Madhya Pradesh's Agro-climatic zones using long-term climatic data and developing strategies for the appropriate use of existing water resources.

Material and Methods

The detailed methodology of data collection, its analysis and application of the model to the study area have been discussed in the following heads:

Study Area

The research was carried out in the Indian state of Madhya Pradesh. This includes the districts of Bhopal, Guna, Indore, Khandwa, Neemach, and

Sagar. Table 1 displays the geographic coordinates of the districts and its agro-climatic zones. The location map of the study area is given in Figure 1. Madhya Pradesh rainfall varies significantly, and the climate ranges from sub-humid in the central region to semi-arid in the north. According to all six meteorological station observations, a hot, dry summer lasts from April to June, followed by monsoon rains, with average monthly rainfall increasing dramatically from mid-June to mid-September (Figure 2). And the winter months (November to February) are cool and dry. As a result, the temperature fluctuates from 33°C to 44°C in the summer and 10°C to 27°C in the winter. Furthermore, relative humidity was at its lowest in May and June. The various climatic parameters and ET_0 values for selected districts are presented in Table 2.

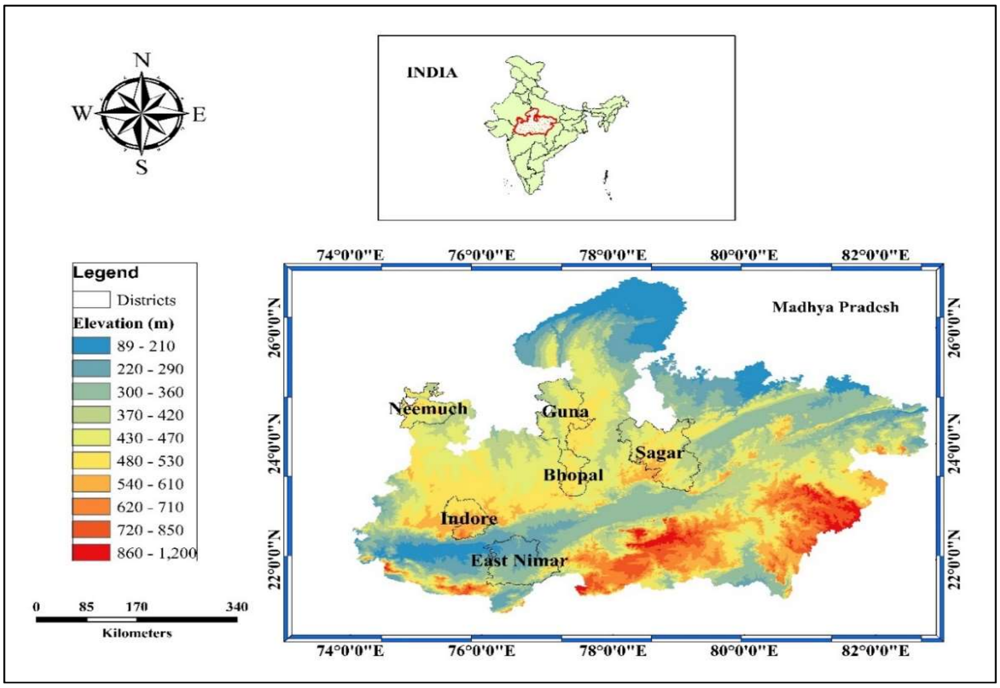

Figure 1: The location map of the study area districts.

Table 1: The geographical information as well as the agro-climatic zone of the study area

SN	Meteorological Station	Latitude (N)	Longitude (E)	Altitude (m)	Agro-climatic Zone
1	Bhopal	$23^0$15'35	77^0 24'45	427	Malwa Plateau (46%) and Vindhya Plateau (42%)
2	Guna	24^0 34'	77^0 21'E	474	Gird Zone
3	Indore	22 ^{0} 43'31	75 ^{0} 51' 56	602	Malawi plateau Agro-climatic
4	Khandwa (East Nimar)	24^0 00'10	80^0 42'56	432	Nimar valley Agro climatic
5	Neemuch	24^o27'55	74^o52'15	534	Malwa plateau
6	Sagar	23° 10'	78° 40'	810	Vindhya Plateau

Table 2: Average climatic data in the study region

District	Tmin (^{0}C)	Tmax (^{0}C)	RH (%)	A.A.R. (mm)	WS (m/s)	SR (MJ/m²/day)	ET_0 (mm/day)
Bhopal	18.5	31.5	47	1099	1.7	18.7	4.65
Guna	17.6	31.8	49	1116	1.43	18.4	4.35
Indore	17.9	31.9	48	980	3.19	18.6	5.67
Khandwa	19.6	33.6	46	948	2.04	18.8	5.2
Nimuch	18.6	31.5	44	870	1.81	17.8	4.67
Sagar	19.5	31.1	46	1218	1.75	18.5	4.73

(Note: Tmin: Minimum Temperature, Tmax: Maximum temperature, RH: Relative Humidity, A.A.R.: Average Annual Rainfall, WS: Wind Speed, SR: Solar Radiation)

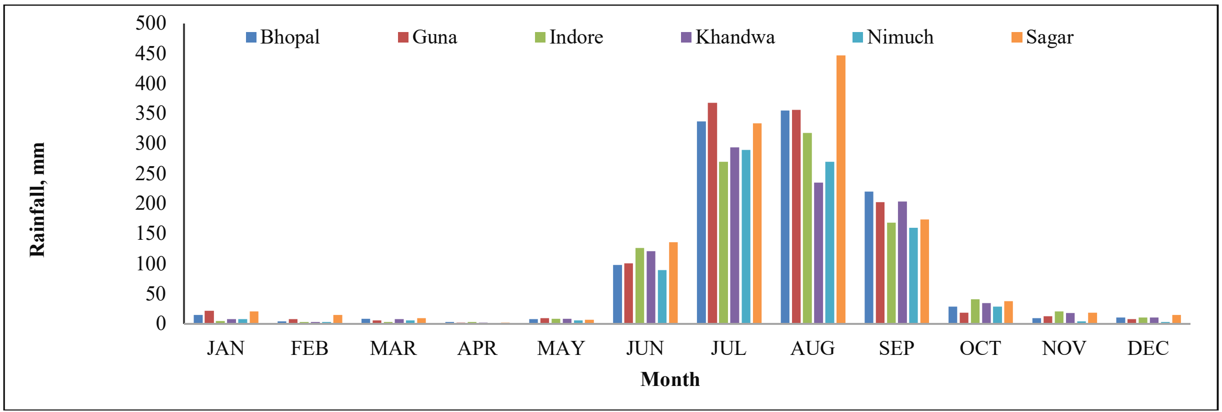

Figure 2: Monthly rainfall received in different districts

Data collection

Daily meteorological data such as rainfall, Tmax, Tmin, RH, and SR, WS information were collected from the CLIMWAT 2.0 software for several districts in MP over a 30-year period. These were utilized to compute the reference evapotranspiration. The principal crop planted in each area was considered when estimating crop water requirement, irrigation scheduling, and water management. Figure 3: Monthly effective rainfall received in different districts. The data needed for the CROPWAT 8.0 model as input, such as date of sowing, development stages and its crop coefficients, harvesting date, and duration of crops, were obtained from ICAR and FAO (Allen *et al.*., 1998) published reports. Average annual rainfall in the districts varied from 870 mm (Neemuch district) to 1278 mm (Sagar district). District wise, effective rainfall obtained were 631.1, 630.1, 625.5, 627, 560.5, and 682.5 mm for Bhopal, Guna, Indore, Khandwa, Neemuch, and Sagar, respectively.

Crop water requirement estimation

Crop water requirements were estimated using climatic parameters, crop, and soil parameters (FAO, 2009; George *et al.*., 2000). The crop coefficient and reference evapotranspiration value are the major factors influencing CWR values. Using climatological data, reference evapotranspiration was computed using an FAO-PM equation and multiplied by crop coefficient to get actual crop evapotranspiration (ET_C). The major soil and crop grown in the study regions are presented in the Table 3 and 4. Reference crop evapotranspiration (ET_0) represents the amount of water that a theoretical grass reference crop would release through a combination of evaporation and transpiration. This reference crop is envisioned with consistent attributes, including a height of 0.12 meters, a surface resistance of 70 s m^{-1}, and an albedo of 0.23. Alfalfa grass is considered to be the reference crop for ET estimation (Allen *et al.*.,1998). Firstly, the FAO-Penman Monteith equation (Equation 1.) was used to determine the ET_0 using the CROPWAT 8.0 model based on FAO Irrigation and Drainage Paper 56. The FAO-PM equation necessitates climatic data, including Tmax, Tmin, RH, SR, and WS, for the estimation of ET0..

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

Where,
Rn is net solar radiation (MJ m^{-2} day^{-1})
λ is the latent heat of evaporation (MJ kg^{-1})
T is the daily mean temperature (°C)
U_2 is the mean daily wind speed at 2meter height (m/s)
$e_s and e_a$- Saturation and actual vapour pressure (kPa)
G - Soil heat flux (MJ m^{-2} day^{-1})
Δ-the slope of saturated water vapor pressure curve (kPa/c)

The actual crop evapotranspiration of different crops can be determined through the Equation. 2.

$$ET_c = Kc * ET_0 \quad \text{……..2}$$

where, ET_c, actual crop evapotranspiration; ET_0, reference crop evapotranspiration; Kc = crop coefficient.

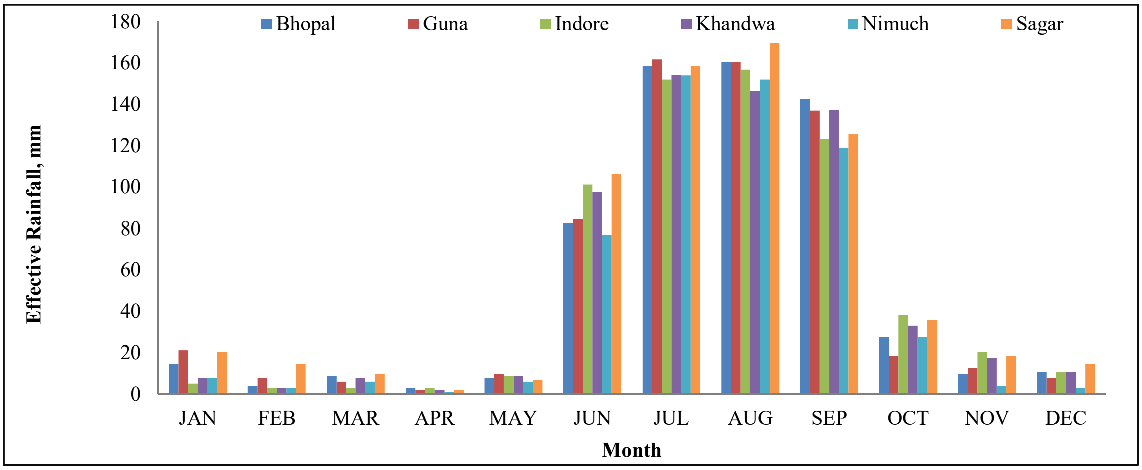

Figure 3: Monthly effective rainfall received in different districts.

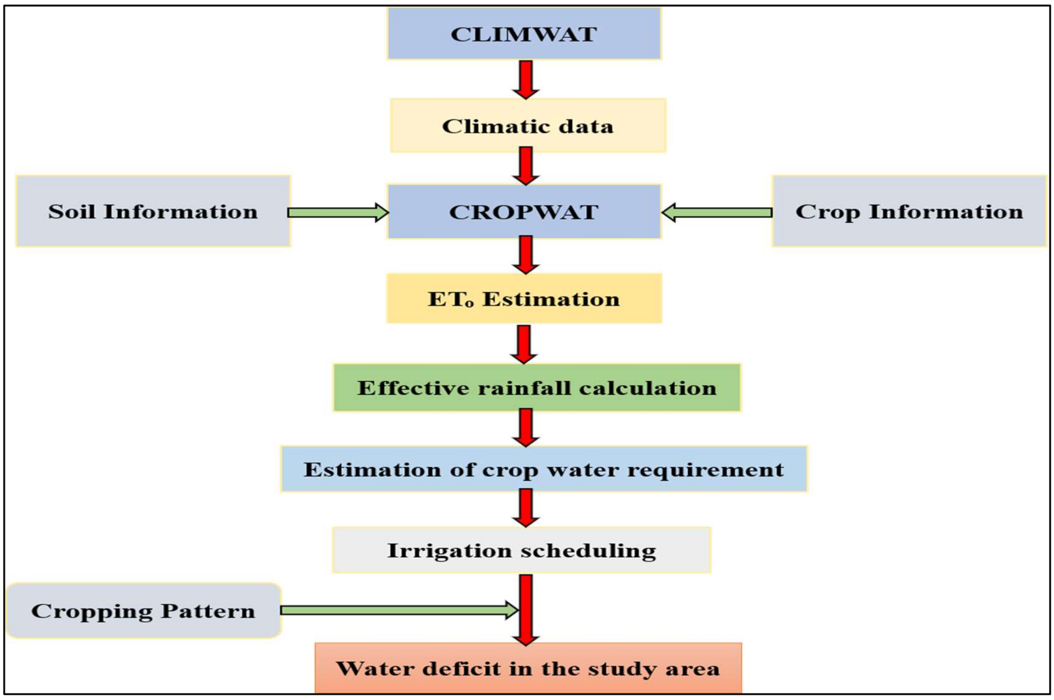

Figure 4: CROPWAT model flow chart for calculating crop water requirements

CROPWAT model uses soil, climate, and crop information as input factors. Furthermore, the soil water balance equation was used to estimate the seasonal crop water requirement on a daily basis. The flow chart (Figure 4) depicts the entire approach for estimating crop water with CROPWAT. The major crops cultivated in the study area are soybean, wheat, chickpea, maize, paddy, mustard, lentil, cotton, green gram, sunflower, and sorghum. The Kc values used to estimate ET_c from ET_0 for major crops grown in the study area were derived from the literature (Allen *et al..*, 1998; Doorenbos and Pruitt, 1977). The Kc for the crop will vary over the growing period, which can be divided into four distinct stages: initial, crop development, mid-season, and late season. Hence ET_c simultaneously varies with crop growth stages. The details of the crop coefficients for the major crops grown in the study districts are presented in Table 5.

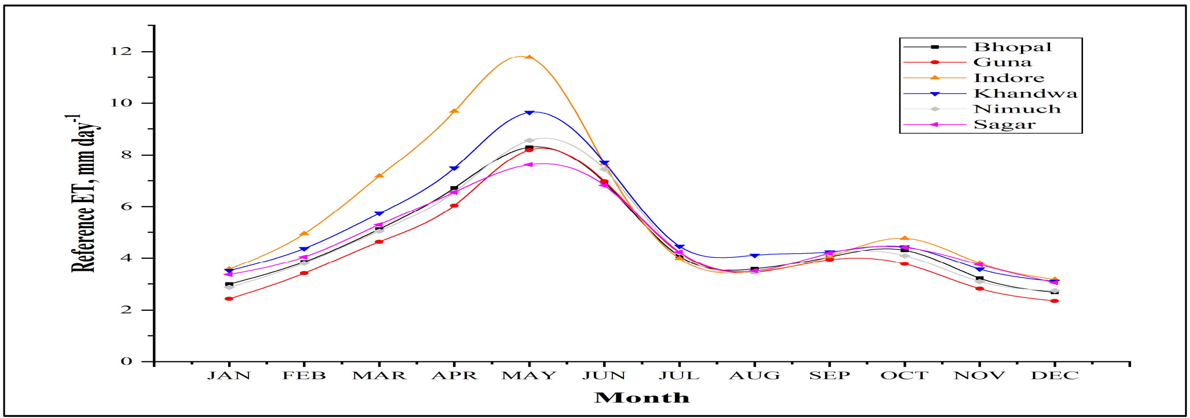

Figure 5: Reference evapotranspiration (ET_0) variation in different districts

Table 3: Major soil and crops grown in study regions

SN	Districts	Major Soil	Major Crops
1	Bhopal	Medium Black	Soybean, Wheat, Gram
2	Guna	Medium and Deep Black	Jowar, Maize, Soybean, Wheat, Gram, Mustard
3	Indore	Medium Black	Soybean, Wheat, Gram
4	Khandwa	Medium Black	Jowar, Soybean, Wheat, Gram, Cotton
5	Neemach	Medium Black	Maize, Soybean, Wheat, Gram, Mustard
6	Sagar	Medium and Deep Black	Urd, Soybean, Wheat, Gram, Lentil

Source:DoLR.gov.in(chrome-extension://oemmndcbldboiebfnladdacbdfmadadm/https://dolr.gov.in/sites/default/files/Madhya%20Pradesh_SPSP.pdf)

Table 4. Water Requirement of various crop in MP districts

SN	Crop	Crop water requirement (cm)
1	Soybean	45-70
2	Wheat	45-65
3	Gram	40-50
4	Rice	120-160
5	Maize	50-80
6	Jowar	45-55
7	Mustard	30-40
8	Cotton	70-130

Source: http://www.angrau.ac.in/media/7380/agro201.pdf

Table 5: Details of the crop coefficients for the major crops

Sl. No	Crop	Max root depth (m)	Kc values of the crop at different stages		
			Initial	Mid	Final
1	Wheat	1	0.3	1.15	0.25
2	Soybean	0.6	0.4	1.15	0.5
3	Chickpea	0.6	0.4	1	0.35
4	Maize	1	0.45	1.11	0.95
5	Lentil	0.6	0.4	1.1	0.3
6	Sunflower	0.80	0.52	1.11	0.41
7	Mustard	1	0.35	1.15	0.35
8	Sorghum	1	0.3	1.05	0.55
9	Cotton	1	0.5	1.15	0.65
10	Green gram	0.6	0.27	1.1	0.67

Net irrigation requirement (NIWR):
The water that must be given via the irrigation system to ensure that the crop receives its complete water requirements is NIWR. If irrigation water is the only source of water supply for the plant, the irrigation need must be larger than the crop water requirement to ensure irrigation system efficiency. However, if the crop gets part of its water from rainfall, deep seepage, the demand for irrigation water will be slightly lower than the demand for crop water.
Therefore, NIWR is calculated as,

NIWR = ET_c - Effective rainfall (ER)

For this study, effective rainfall was computed according to the "USDA Soil Conservation Services Method" using CROPWAT 8.0 model on a monthly basis using the following criteria (USDA, 1967),
1) If total rainfall is less than 250 mm, then ER is given by the following equation

ER=Total Rainfall (TR)*(125-0.2*Total Rainfall) / 125

2) If total rainfall is more than 250 mm, ER is given by the following equation;

ER=125+0.1 * Total Rainfall

Results and Discussion

Reference evapotranspiration variation

There was variation in the ET_0 among districts. It begins to rise in January and reaches a peak in May. Also, from July through August, ET_0 rises and peaks in October then falls and reaches its lowest point in December. ET_0 was greatest in the Indore district and lowest in the Guna district. Figure 5. depicts the variation in theET_0in different months in selected districts.

Crop evapotranspiration of Major crops in the Bhopal districts

The results of decadal ET_c, ER and irrigation requirement (IR) for the major *Kharif* and *Rabi* crops cultivated in the Bhopal district have been shown in Tables 6-9. The seasonal crop water requirement of soybean was determined to be 367.8 mm, while the total effective rainfall received throughout the growing soybean season was 420.4 mm. A significant proportion of crop water demand is met by effective rainfall, but delayed sowing results in a shortage of soil moisture availability during the late season stage, hence, necessitating irrigation. Furthermore, wheat is also dominating crop in the district during the *rabi* season. From the analysis, it was found that the seasonal crop water requirement of wheat was 378 mm. Conversely, effective rainfall meets just a small portion of the overall crop evapotranspiration. Additionally, Maize and Chick Pea (Chana) crops are the other two main crops in the district during the *Kharif* and *Rabi* seasons, with seasonal crop water requirements of 286.4 mm and 270.9 mm, respectively. The analysis found that in the district, the proportion of effective rainfall used by soybean, wheat, maize, and mustard crops to fulfil crop evapotranspiration requirements was 63, 11, 88, and 13 per cent, respectively. According to the effective rainfall used by different crops, the maize crop was superior in utilizing ER. In contrast, the wheat crop exhibited the lowest percentage of effective rainfall usage. Although *kharif* crops consume a higher proportion of ER due to the onset of monsoon season matching the *kharif* crop's sowing/transplanting dates than *rabi* season crops, still, there was substantial heterogeneity among *kharif* crops in utilizing effective rainfall because of crop characteristics, growth duration, and sowing dates. Daily crop evapotranspiration rose from 1.51 mm/day (during the starting stage) to a maximum ET of 4.75 mm/day (during the mid-season stage) for the soybean crop. The seasonal average crop evapotranspiration rate was 3.18, 2.90, 3.20, and 2.39 mm/day for soybean, wheat, maize, and chick, respectively.

Crop evapotranspiration of major crops in the Guna district

In Guna district, soybean and wheat are the dominate crops during the *Kharif* and *Rabi* seasons. Additionally, other crops like maize, chickpeas, and mustard are cultivated. Table 10 presents data on ET_c, ER, and IR for the primary crops in Guna district. The estimation indicates that seasonal crop evapotranspiration for soybean, wheat, maize, chickpea, and mustard stood at 303 mm, 372.1 mm, 275.2 mm, 217.7 mm, and 289.7 mm, respectively. Notably, effective rainfall

Table 6: Decadal crop water requirement, effective rainfall, and irrigation requirement of Soybean in the Bhopal district

Month	Decade	Stage	Kc	ET_c	ET_c	Eff rain	Irr. Req.
			Coefficient	mm/day	mm/dec	mm/dec	mm/dec
Jul	2	Init	0.4	1.51	9.1	33.8	0
Jul	3	Init	0.4	1.48	16.3	55.4	0
Aug	1	Dev	0.48	1.76	17.6	53.9	0
Aug	2	Dev	0.76	2.63	26.3	54.4	0
Aug	3	Mid	1.04	3.81	41.9	52.1	0
Sep	1	Mid	1.11	4.32	43.2	52.6	0
Sep	2	Mid	1.11	4.49	44.9	52.1	0
Sep	3	Mid	1.11	4.58	45.8	37.8	8
Oct	1	Mid	1.11	4.75	47.5	18.9	28.6
Oct	2	Late	1	4.39	43.9	4.6	39.2
Oct	3	Late	0.67	2.69	29.6	4.2	25.4
Nov	1	Late	0.48	1.73	1.7	0.5	1.7
Total					**367.8**	**420.4**	**103**

Init- Initial stage, Mid-Middle stage, Dev-Development stage, late –Late stage

Table 7: Decadal crop water requirement, effective rainfall and irrigation requirement of Wheat in the Bhopal district

Month	Decade	Stage	Kc	ET_c	ET_c	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Nov	1	Init	0.7	2.51	25.1	4.7	20.4
Nov	2	Init	0.7	2.26	22.6	2.4	20.1
Nov	3	Dev	0.72	2.19	21.9	2.8	19.1
Dec	1	Dev	0.83	2.39	23.9	3.4	20.5
Dec	2	Dev	0.96	2.58	25.8	3.5	22.3
Dec	3	Mid	1.1	3.05	33.6	4	29.6
Jan	1	Mid	1.15	3.31	33.1	4.9	28.3
Jan	2	Mid	1.15	3.43	34.3	5.5	28.8
Jan	3	Mid	1.15	3.76	41.4	4.1	37.2
Feb	1	Late	1.14	4.05	40.5	2	38.5
Feb	2	Late	0.92	3.55	35.5	0.6	34.9
Feb	3	Late	0.65	2.79	22.3	1.4	20.9
Mar	1	Late	0.38	1.81	18.1	2.7	15.4
Total					**378**	**42.2**	**335.9**

Table 8:Decadal crop water requirement, effective rainfall and irrigation requirement of Maize in the Bhopal district

Month	Decade	Stage	Kc	ET_c	ET_c	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Jul	2	Init	0.45	1.7	10.2	33.8	0
Jul	3	Init	0.45	1.67	18.4	55.4	0
Aug	1	Dev	0.52	1.89	18.9	53.9	0
Aug	2	Dev	0.74	2.58	25.8	54.4	0
Aug	3	Mid	0.97	3.57	39.3	52.1	0
Sep	1	Mid	1.03	4.02	40.2	52.6	0
Sep	2	Mid	1.03	4.18	41.8	52.1	0
Sep	3	Late	1.03	4.24	42.4	37.8	4.6
Oct	1	Late	0.97	4.14	41.4	18.9	22.4
Oct	2	Late	0.92	4.05	8.1	0.9	8.1
Total					**286.4**	**412**	**35.2**

sufficiently met the entire crop evapotranspiration demand for *Kharif* crops, specifically soybean and maize, rendering irrigation is minimal for these crops. However, during the *Rabi* season, effective rainfall contributed only 12.2%, 22.1%, and 18.0% of the crop evapotranspiration demand for wheat, chickpea, and mustard, respectively. This suggests that without irrigation, these crops could experience abiotic stress, potentially reducing their yields. Interestingly, mustard exhibited a relatively higher reliance on effective rainfall to meet a substantial portion of its ET_c requirements. From the

Table 9: Decadal crop water requirement, effective rainfall and irrigation requirement of Chickpea in the Bhopal district

Month	Decade	Stage	Kc	ET_c	ET_c	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Nov	2	Init	0.4	1.29	7.7	1.5	6.5
Nov	3	Dev	0.4	1.22	12.2	2.8	9.4
Dec	1	Dev	0.51	1.46	14.6	3.4	11.2
Dec	2	Dev	0.68	1.83	18.3	3.5	14.8
Dec	3	Dev	0.86	2.4	26.4	4	22.4
Jan	1	Mid	0.99	2.87	28.7	4.9	23.8
Jan	2	Mid	1	2.98	29.8	5.5	24.3
Jan	3	Mid	1	3.27	36	4.1	31.8
Feb	1	Mid	1	3.55	35.5	2	33.5
Feb	2	Late	0.88	3.39	33.9	0.6	33.3
Feb	3	Late	0.59	2.53	20.3	1.4	18.9
Mar	1	Late	0.4	1.87	7.5	1.1	6.1
Total					**270.9**	**34.9**	**236**

Table 10: Seasonal crop evapotranspiration (ET_c), effective rainfall (ER), and irrigation requirements (IR) of crops in Guna Districts

Crop	ET_c, mm	ER, mm	IR, mm
Soybean	303	303	0
Wheat	372.1	45.4	326.9
Maize	275.2	275.2	0
Chickpea	217.7	47.4	169.9
Mustard	289.7	52.2	237.5

observation it was found that on average, the daily ET_c rates were 3.1 mm/day for soybean, 2.8 mm/day for wheat, 3.1 mm/day for maize, 1.9 mm/day for chickpea, and 2.2 mm/day for mustard crops. The daily average crop evapotranspiration can be valuable for planning irrigation scheduling in such regions and the design of irrigation systems. The variation in crop water requirements among the crops can be attributed to the diverse characteristics of these crops, including their growth cycles, root depths, and transpiration rates. Furthermore, it was found that the mustard crop has the potential to be a water-efficient crop in the region.

Crop evapotranspiration of major crops in the Indore district

The ET_c, ER, and IR of the major crops grown in the Indore district are shown in Table 11. As per the table, soybean, wheat, and chickpea exhibited seasonal crop evapotranspiration rates of 380 mm, 440.7 mm, and 311.1 mm, respectively. Notably, a significant portion of the soybean crop's (major *Kharif* crop) evapotranspiration requirement, approximately 85 percent, was satisfied by effective rainfall, while the remaining 15 percent necessitated irrigation. Effective rainfall contributed 12 percent and 12.3 percent to the total seasonal crop water requirement for *Rabi* season crops, specifically wheat and chickpea, respectively. It was found that there is slight difference in chick pean and wheat ER usage however, due to less of CWR for chickpea than wheat from this reason underscore the superior performance of the chickpea crop in efficiently utilizing effective rainfall during the *Rabi* season. The daily crop evapotranspiration needs to be estimated to estimate the seasonal crop water requirement and irrigation design. It was found that soybean, wheat, and chickpea were 380, 440.7, and 311.1 mm, respectively.

Crop evapotranspiration of major crops in the Khandwa district

According to Table 12, the seasonal crop evapotranspiration for soybean, wheat, sorghum, cotton, and chickpea amounts to 320.4 mm, 510.6 mm, 392.9 mm, 610.4 mm, and 311.1 mm, respectively. Effective rainfall significantly contributed to soybean water requirement, accounting for approximately 98.4%, whereas for wheat, sorghum, cotton, and chickpea, this contribution accounts at 6%, 73.2%, 55.4%, and 5.9%, respectively. This study underscores the superior efficiency of soybean in utilizing effective rainfall compared to other *Kharif* season crops. This

Table 11: Seasonal crop evapotranspiration (ET_c), effective rainfall (ER), and irrigation requirements (IR) of crops in Indore district

Crop	ET_c, mm	ER, mm	IR, mm
Soybean	380	323.9	56.1
Wheat	440.7	53	388.8
Chickpea	311.1	38.3	272.7

Table 12: Seasonal crop evapotranspiration (ET_c), effective rainfall (ER), and irrigation requirements (IR) of cropsin Khandwa district

Crop	ET_c, mm	ER, mm	IR, mm
Soybean	320.4	315.3	5.1
Wheat	510.6	30.1	388.8
Sorghum	392.9	287.5	105.4
Cotton	610.4	333	277.4
Chickpea	311.1	38.3	272.7

discrepancy highlights the exceptional ability of soybean to harness and utilize available rainfall efficiently. It also suggests that soybean is well-suited to the region's climate conditions, making it a viable and sustainable crop option, particularly during the *Kharif* season. The average daily crop evapotranspiration rates for soybean, wheat, sorghum, cotton, and chickpea were 3.3 mm/day, 3.8 mm/day, 3.1 mm/day, 3.5 mm/day, and 2.8 mm/day, respectively, providing valuable insights for design of irrigation system and management in the study region.

Crop evapotranspiration of major crops in the Neemuch district

In the Neemuch district, soybean, wheat, maize, mustard, and chickpea crops showed average crop evapotranspiration rates of 2.3, 2.8, 3.2, 2.3, and 2.2 mm/day, respectively. The seasonal crop evapotranspiration values for soybean, wheat, maize, mustard, and chickpea were determined to be 362.5 mm, 370.8 mm, 284.1 mm, 309.8 mm, and 252.1 mm, respectively, as presented in Table 13. The effective rainfall contribution to the soybean crop water requirement was approximately 86.1 per cent, with the remainder met by irrigation. In contrast, the effective rainfall contribution to the season crop water requirements of wheat, maize, mustard, and chickpea, respectively, was 19.9, 100, 11.4, and 8.8 per cent. This result shows that the maize crop was superior to the soybean crop in *kharif* season crops in terms of effective use of rainfall.

Crop evapotranspiration of major crops in the Sagar district

Table 14 contains effective rainfall, irrigation requirement, and crop evapotranspiration in the Sagar district. The Table found that soybean, wheat, black gram, lentil, and chickpea had seasonal crop evapotranspiration of 365.8, 415.2, 270.8, 309.1, and 284.5 mm, respectively.

Table 13: Seasonal crop evapotranspiration (ET_c), effective rainfall (ER), and irrigation requirements (IR) of crops in Neemuch

Crop	ET_c, mm	ER, mm	IR, mm
Soybean	362.5	312.3	50.2
Wheat	370.8	19.9	350.9
Maize	284.1	284.1	0
Mustard	309.8	35.4	274.4
Chickpea	252.1	22.4	229.7

Table 14: Seasonal crop evapotranspiration (ET_c), effective rainfall (ER), and irrigation requirements (IR) of crops in Sagar District

Crop	ET_c, mm	ER, mm	IR, mm
Soybean	365.8	321.3	44.5
Wheat	415.2	72.1	343.1
Blackgram	270.8	270.8	0
Lentil	309.1	66.7	272.4
Chickpea	284.5	62.9	221.6

The effective rainfall contribution to the soybean crop water demand was around 87.8%, while the effective rainfall contribution to the season crop water requirements of wheat, maize, mustard, and chickpea, respectively, was 17.3, 100, 21.5, and 22.1 per cent. Wheat has the highest irrigation demand, followed by lentils and chickpeas. In terms of effective usage of the rainfall, this data reveals that maize was superior to soybean in *kharif* season crops. The average crop evapotranspiration rate in the Sagar district for soybean, wheat, black gram, lentil, and chickpea crops was 3.3, 3.2, 3.0, 2.6 and 2.5 mm/day.

District-specific analysis of maximum crop evapotranspiration rates

The determination of peak consumptive usage rates for crops in the selected regions is a pivotal aspect in the quest for efficient irrigation system design. This analysis revealed notable variations in the maximum crop evapotranspiration rates across the districts under the prevailing *Kharif* and *Rabi* cropping pattern. Specifically, Khandwa district exhibited the highest rate at 6.24 mm/day, followed by Indore, Bhopal, Sagar, and Guna, while Neemuch district registered the lowest rate at 4.59 mm/day. These findings, as illustrated in Figure 6, hold significant implications for the development of water management strategies and infrastructure. The observed differences in peak consumptive usage rates underscore the need for tailored approaches to irrigation system design and crop management in each district. In regions with higher evapotranspiration rates, such as Khandwa, there is a heightened demand for water resources during the crop growing seasons. This necessitates the development of robust water storage structures and advanced irrigation systems capable of meeting these demands efficiently. Conversely, districts with lower peak consumptive usage rates, like Neemuch, may require less intensive irrigation infrastructure. However, it is crucial to strike a balance between conserving water resources and ensuring that crops receive adequate moisture during critical growth stages. This involves the strategic design and management of irrigation systems that consider factors such as soil characteristics, crop varieties, and local climate conditions. Moreover, these findings provide a valuable foundation for the formulation of region-specific crop management strategies. Farmers and policymakers can use this data to optimize crop planting schedules, irrigation timing, and water allocation practices. Ultimately, the goal is to maximize agricultural productivity while minimizing water wastage and promoting sustainable resource management.

Water stress management strategies

Given the rising water scarcity, agriculture is of critical importance to the global food supply (Sun *et al..,* 2012; Li *et al..*, 2017). Global warming and erratic rainfall patterns, on the other hand, are too responsible for the scarcity of water resources, which limits agricultural productivity in arid and semi-arid regions (Qin *et al..*, 2015; Li *et al..,* 2017). As a result, conservative and effective water usage has been practised successfully and needs to be implemented. These water management strategies (Figure 7.) are detailed in the following sections.

Water harvesting for supplemental irrigation

The potential of supplemental irrigation through rainwater harvesting as a means to enhance agricultural productivity and improve livelihoods in arid and semi arid rainfed regions. The concentration of rainfall during a specific period, from mid-June to mid-September, often leads to issues like runoff, waterlogging, sedimentation and soil erosion. To harness this precious resource, rainwater harvesting structures must be employed for effective storage and utilization of rainfall in crop cultivation. This practice aligns with the findings of Oweis and Hachum (2006), highlighting the significance of supplemental irrigation in optimizing crop yields in such environments. Interestingly, despite the importance of rainwater harvesting, there has been a relative scarcity of studies focusing on its effectiveness for deficient supplemental irrigation, especially in the context of macro-catchment rainwater harvesting systems (Assefa *et al..,* 2016). Nevertheless, numerous experimental studies conducted in rainfed agricultural settings have consistently demonstrated that rainwater collection structures can alleviate water constraints throughout the entire crop growth cycle (Jo and Garry, 2003; Singandhape *et al..,* 2003; Xu and Mermoud, 2003; Khan *et al..,* 2021; Patrick *et al..,* 2004). These

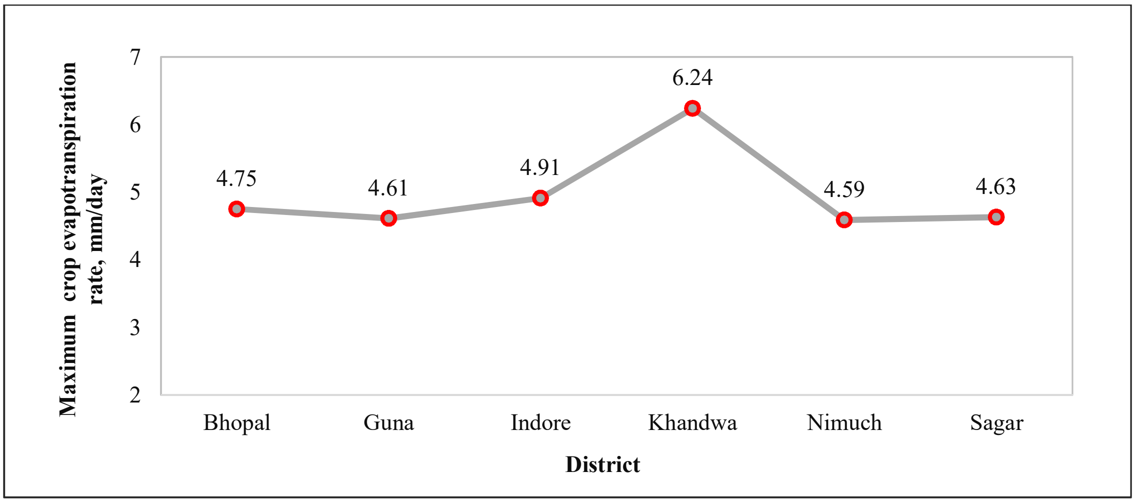

Figure 6: Maximum crop evapotranspiration rate for various districts

Figure 7. Water stress management strategies under water scarce conditions

findings underscore the viability of rainwater harvesting as a sustainable solution to enhance agricultural water availability. Despite the benefits of rainwater harvesting, it's important to acknowledge the inevitability of drought conditions during specific crop developmental stages (Kang *et al.*., 2002; Pan *et al.*., 2003). In response to such challenges, the utilization of water collected in small ponds for additional irrigation, as suggested by Xiao *et al.*., (2005), emerges as a viable option in such circumstances. This demonstrates the need for a multifaceted approach to water management, ncombining rainwater harvesting with other irrigation strategies to address varying water availability throughout the crop's growth cycle. In our study it was suggested that such interventions is required to harvest the excess rainfall and store and use it for critical irrigation in rabi season in order to avoid crop stress, eventually to get optimal yield.

Altering sowing/transplanting dates

Modifying the timing of planting or transplanting can have favourable impact on optimizing the efficient utilization of rainfall resources, leading to a reduction in the demand for irrigation or supplemental irrigation without compromising crop productivity. Research in the context of wheat cultivation, as exemplified by the study conducted by Bana *et al..,* (2022), demonstrates that sowing wheat during the initial fortnight of November can result in a notable reduction, approximately 20-25%, in blue water requirements compared to sowing it toward the end of December. Beyond a certain planting date, a dual challenge emerges, characterized by a decrease in crop yield (approximately 20-22%) and an increased demand for irrigation water. Similarly, observations from a study on paddy transplanting in Punjab, as conducted by Mahajan *et al.*., (2009), indicate that delaying the transplanting date from June 15th to July 5th led to yield reductions ranging from 7% to 16%. Aligning crop sowing and transplanting schedules with the onset of the monsoon season could potentially Mitigating crop stress, along with optimizing the utilization of effective rainfall, results in a diminished need for irrigation. Rajput *et al.*., 2022 estimated crop water requirement of the rice, wheat, sugarcane and sunflower for Kurukshetra district, Haryana. They reported that the date of sowing/transplanting has a great influence on crop water requirements and thus water demand. Therefore, it is highly desirable to match the optimum date of sowing/transplanting for lesser crop water demand and thus efficient management of the water demand.

.

Soil moisture conservation techniques

Enhanced agronomic techniques, including intercropping, mulching, contour farming, crop residue management, and mechanical procedures like laser land leveling, offer valuable for Soil moisture conservation technique. These practices yield several benefits such as the even distribution of irrigation water, reduced usage of fertilizers and chemicals, expanded coverage for irrigation due to enhanced application and distribution efficiency, conservation of soil and water resources, and enhanced crop development and yield (Whitney *et al..,* 1950; Brye *et al..,* 2005). The adoption of zero-tillage methods has been observed to result in significant water savings, ranging from 20% to 35% reduction in irrigation water usage (Nagarajan *et al..,* 2002). As a consequence, issues related to waterlogging and wheat crop yellowing following initial irrigation are minimized (RWC, 2004). Furthermore, zero-tillage practices decrease the necessity for single irrigation events (Laxmi *et al..,* 2003; Malik *et al..,* 2002; Mehla *et al..,* 2000). When wheat crops are cultivated on raised beds, a substantial reduction in irrigation water consumption of approximately 30-40% is achieved in comparison to conventionally seeded crops. Additionally, this approach leads to increased yields and reduced concerns related to pests and diseases (Jat *et al..,* 2005).

Micro irrigation systems

Adopting a micro irrigation system will enhance the irrigation conveyance efficiency and reduce the losses compared to surface irrigation. A study was conducted by (Meena *et al..,* 2015) to improve water use efficiency (WUE) in rice-wheat cropping systems through a micro-irrigation system. The WUE of the check basin approach was the lowest (1.32 kg/m^3). Conversely, drip combined with rain port irrigation (5545 kg/ha) yielded the maximum yield, followed by drip irrigation (5475 kg/ha) with WUEs of 1.57 and 1.55 kg/m^3. In rice, drip irrigation produced significantly better grain yields (4028 and 4683 kg/ha) than sprinkler irrigation. The study found that the highest WUE in wheat was achieved using a drip and rainport treatment, whereas the highest WUE in rice was achieved using drip irrigation. Another study was conducted using drip and sprinkler irrigation systems installed in the onion field; it was found that 37.8 and 32.5 % of water saving was done in drip and sprinkler irrigation, respectively. Furthermore, a significant increase in the yield was also observed (Lawande, 2008). According to the findings of such adoption strategies are essential in the study region in both season where that area is under water scares condition, such interventions will help us improve WUE and crop yield by minimizing water-related stress and maintaining optimal soil moisture at the root level.

Adoption of drought tolerance varieties

The adoption of drought-tolerance cultivars, especially within the realm of agriculture, carries substantial consequences for enhancing productivity, mitigating risks, and improving overall well-being. Dasgupta *et al.*., (2015) conducted a study examining the impact of water stress on drought resistance in rice cultivation. Their findings unveiled that the utilization of drought-tolerant rice cultivars led to a notable increase in crop yield, ranging from 8% to 44%. Furthermore, this induced water stress resulting from a limited water supply presented an opportunity to devise an efficient water-saving approach for lowland rice farming. Additional irrigation techniques capable of inducing water-related stress include deficit irrigation (DI) and partial root drying (PRD). DI involves maintaining minimal water usage, with the resulting minor stress exerting limited influence on crop yield. Conversely, PRD entails watering only half of the root system while allowing the other half to become desiccated. In comparison to full irrigation, the application of PRD conserved approximately 30% of water resources and significantly enhanced crop water use efficiency (WUE) by nearly 60%, all without incurring any significant loss in tuber yield (Jensen *et al..,* 2010). In the rabi season, it is imperative to consider implementing these measures for enhancing crop water productivity, particularly for maize and jowar cultivation in regions where water resources are limited. Various studies have indicated that the adoption of certain stress-inducing techniques may not only improve crop quality but also enhance oil content and aroma in specific crops. However, it is essential to apply these methods in a scientifically validated manner. In a study conducted by Surendran *et al*.. (2015) in the Palakkad district of Kerala, the CROPWAT 8.0 model was utilized to assess future water demands for irrigation, drinking, and industrial purposes. The findings revealed that the projected total water demands for these purposes were estimated to be 3841 Mm^3. However, the available water resources were insufficient to meet this demand. As a result, the study suggests that under such conditions, deficit irrigation strategies could be adopted to optimize water use for irrigation while still aiming for higher crop yields. Such type of deficit irrigation may be adopted in the water scare regions of MP for crop production in both seasons. Such type of intervention may improve the quality and quantity of irrigation. Again, this type of approach needs to be scientifically tested for each district and then standard operating procedure need to be established before adopting deficit irrigation in MP district. Chakravrti *et al*.. (2022) revealed that the month of February necessitated the most substantial water supply. Consequently, the utilization of drought-tolerant crops and the implementation of deficit irrigation methodologies offer viable alternatives in water-stressed or arid regions characterized by acute water scarcity. These approaches hold promise for augmenting crop yields while simultaneously conserving water resources. The research identifies the maximum consumptive usage rate for crops in each selected area, with the most elevated rate observed in the Khandwa district and the lowest in the Neemuch district. These findings hold valuable implications for the design of efficient irrigation systems, planning of water storage structures, and formulation of crop management strategies. In a study conducted by Gangwar *et al..,* (2017) within the Bina command area of Sagar district, wheat, gram-pulses, and mustard were found to exhibit crop water requirements of 349.8 mm, 304.1 mm, and 316.9 mm, respectively. These results suggest that farmers in these districts can capitalize on effective rainfall to fulfil a substantial portion of the water needs for maize cultivation, thus diminishing the necessity for irrigation. In the research conducted by Chakravrti *et al*.. (2022) in MP district, an investigation was undertaken to evaluate the water requirements of various crops. Their findings indicated that wheat exhibited the highest demand for water, whereas maize demonstrated the lowest water requirement consistently across different time periods. Likewise, Rajput *et al*.., 2022 estimated crop water requirements of principal crops *Kharif* and *Rabi* season crops Bhimsagar Canal Command area in Jhalawar, Rajasthan. The crop water requirements of wheat, mustard, coriander, and garlic were found to be 345.2 mm, 323.9 mm, 273.7 mm and 515.1 mm, respectively. They also found that the crop water requirements were varied in different years mainly due to variation in the weather parameters. The crop water requirement is influenced by the crop characteristics, soil properties, and climatic factors. In our current study we found varying crop water requirement for different in different districts which is mainly due to variation in the climatic condition prevailing. Therefore, it is desirable to estimate crop water requirements precisely for a given location for better irrigation planning. In a similar study conducted by Kumar Shaw *et al..,* (2019) in Kurnool district, which experiences hot and arid climatic conditions, it was observed that maize had a NIR

(Net Irrigation Requirement) value of 220 mm. The findings revealed that maize had the highest dry yield, with a significant yield of 13.586 tonnes per hectare, indicating that maize may be the potential best-performing crop where the similar climatic condition observed in the MP districts similarly

Yadav *et al..*, (2018) conducted a study on water needs for crops in *rabi* and *kharif* seasons across twenty diverse districts of MP. They found that Jabalpur had the highest daily water requirements for chickpea (1.73 lpd), wheat (0.70 lpd), and lentil (0.49 lpd) during the *rabi* season. The results presented in the report differ from our own findings, and this disparity could be attributed to variations in factors such as altered sowing dates, distinctive crop attributes, soil conditions, and local climatic parameters within the study area. In Narsinghpur, sugarcane had the highest water requirement during the mid-season, at 13.56 lpd. In the *kharif* season, Harda stood out with cotton requiring 6.53 lpd, while sesame and groundnut needed 2.75 lpd and 2.46 lpd in Datia. Furthermore, Singh *et al..*, (2013) findings revealed that the CWR for soybean amounted to 401.6 mm, while for wheat, it was calculated to be 352.2 mm. Specifically, during the *kharif* season, soybean cultivation necessitated at least one irrigation event (especially in the event of an early monsoon withdrawal) to meet the crop's water requirements, primarily in September during the critical pod development stage. For the *rabi* season, wheat cultivation required irrigation from November to March, underscoring the imperative of rainwater runoff storage within the region to ensure a sustainable water supply for agricultural practices. Both studies are highlighting the irrigation management strategies more essential in the *rabi* season. Similar findings are also reported from our study.Thimmareddy *et al..,* (2022) conducted a study on chick pea using CROPWAT to assess the water requirement under climate changing condition and found that yield under rainfed condition and average number of irrigations reduced by 18.5 % and 42.9 %, respectively, under such condition suitable crop management practice is necessary for enhancing yield. In a similar study conducted by Gabr *et al..*, (2019) in Tina Plain and East South ElKantara regions of North Sinai, Egypt, the net irrigation requirements of different crops were examined using FAO-CROPWAT 8.0 and CLIMWAT 2.0 models. The results revealed variations in net irrigation requirements across crops and regions. In Tina Plain (AER 1), berseem clover, barley, and cotton had net irrigation requirements of 612 mm, 283 mm, and 901 mm, respectively. In East South ElKantara (AER 2), the corresponding values were 738 mm, 287 mm, and 1113 mm, indicating a 19% increase compared to AER 1. Thomas *et al..*, (2014) suggested irrigation strategies to support sustainable rain-fed agriculture in a drought-vulnerable environment. Their analysis of dry spell patterns during crop growing season highlighted the necessity of implementing supplementary irrigation practices to ensure the viability of agricultural operations. The study further involved the estimation of supplemental irrigation needs during critical dry spell periods for every development block across all districts. These findings underscore the importance of implementing better water management practices, focusing on improving irrigation efficiency, and cultivating crops with lower water requirements, such as green beans, wheat, barley, sugar beet, and tomato. In light of the comprehensive examination of research and discoveries, it becomes evident that embracing sustainable irrigation and rainwater harvesting is imperative to bolster agricultural resilience in the face of climate change, effectively addressing its adverse effects on both agriculture and water resources.

Conclusion

In conclusion, this study aimed to assess crop water requirements and irrigation needs in six districts across diverse agro-climatic regions in Madhya Pradesh, employing CLIMWAT 2.0 and CROPWAT 8.0 software. These tools were instrumental in estimating crop evapotranspiration, formulating irrigation schedules, and customizing irrigation strategies based on local climatic conditions. Our findings revealed the prevalence of the soybean-wheat cropping pattern across all districts, alongside notable variations in crop water requirements attributable to differences in climatic parameters, soil characteristics, and crop varieties. Particularly, the Khandwa district exhibited the highest seasonal evapotranspiration for cotton, attributed to its extended growing season (150 to 180 days) and unique climatic attributes. Conversely, the Indore district demonstrated the highest crop water requirement for soybean, while the Guna district exhibited the lowest. In a similar vein, for wheat, Khandwa registered the highest seasonal crop evapotranspiration, while Neemuch reported the lowest value. In addition, this study underscored the reliance of specific crops, such as maize and soybean, on effective rainfall during the *Kharif* season, while others, including wheat, chickpea, and mustard, leaned more heavily on irrigation due to inadequate rainfall during the *Rabi* season. Which was displayed the highest irrigation water requirement during the *Rabi* season. These findings emphasize the critical need for tailored water management strategies to enhance crop water use efficiency and reduce dependence on irrigation, especially in drought-prone regions. The significance of district-specific considerations, encompassing climate and soil attributes, is evident. Promoting practices such as crop diversification, efficient irrigation, and rainwater harvesting, alongside supporting research, financial incentives, and monitoring, will further advance sustainable water management in water-scarce regions.

Acknowledgement

Authors are greatly thankful to ICAR-Indian Agricultural Research Institute for research support.

Conflict of interest

The authors declare that they have no conflicts of interest.

References

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56, FAO-Food and Agriculture Organisation of the United Nations, Rome (http://www. fao. org/docrep).

Assefa, S., Biazin, B., Muluneh, A., Yimer, F., & Haileslassie, A. (2016).Rainwater harvesting for supplemental irrigation of onions in the southern dry lands of Ethiopia," *Agricultural Water Management,* 178(C), 325-334.

Bana, R. S., Bamboriya, S. D., Padaria, R. N., Dhakar, R. K., Khaswan, S. L., Choudhary, R. L., & Bamboriya, J. S. (2022). Planting Period Effects on Wheat Productivity and Water Footprints: Insights through Adaptive Trials and APSIM Simulations". *Agronomy*, *12*(1), 226.

Brye, K.R., Slaton, N.A., & R. J. (2005). Norman. Penetration resistance as affected by shallow-cut land levelling and cropping". *Soil Tillage Research.,* 81:1–13.

Chakravarti, A., Rohilla, K., Singh, S. P., Singh, S. K., & Adeba, D. (2022). Estimation of crop water requirement for Bargi left bank canal command area-Jabalpur MP India. Energy Nexus, 6, 100068.

Dasgupta, P., Das, B. S., & Sen, S. K. (2015). Soil water potential and recoverable water stress in drought tolerant and susceptible rice varieties". *Agricultural Water Management*, *152*, 110-118.

Dhawan, V. (2017). Water and agriculture in India. In *Background paper for the South Asia expert panel during the Global Forum for Food and Agriculture*, 28.

Diro, S.B., & Tilahun, K. (2009). Evaluation of the FAO CROPWAT model for defi cit-irrigation scheduling for onion crop in a semiarid region of Ethiopia". *Journal of Applied Horticulture*, 11(2): 103-106.

Dobriyal, P., Qureshi, A., Badola, R., & Hussain, S. A. (2012). A review of the methods available for estimating soil moisture and its implications for water resource management". *Journal of Hydrology*, *458*, 110-117.

Doorenbos, J., & Pruitt, W.O. (1977). Crop water requirements. *Irrigation and drainage paper*, *24*, 1-144.

Ewaid, S.H., Abed, S.A., & Al-Ansari, N. (2019). "Crop Water Requirements and Irrigation Schedules for Some Major Crops in Southern Iraq". *Water* 11, 4: 756. https://doi.org/10.3390/w11040756

FAO (Food and Agriculture Organization). (2009). CROPWAT Software, Food and Agriculture Organization, Land and Water Division; Available at: 2009. http://www.fao.org/nr/water/infores_databases_cropwat.html . accessed on 26/03/2022.

Gabr, M. E. (2022). Modelling net irrigation water requirements using FAO-CROPWAT 8.0 and CLIMWAT 2.0: a case study of Tina Plain and East South ElKantara regions, North Sinai, Egypt. Archives of Agronomy and Soil Science, 68(10), 1322-1337.

Gaddikeri, V., Hasan, M., Kumar, D., Sarangi, A., & Alam, W. (2022). Performance Analysis and Measurement of Soil Moisture Content by Piezoresistive Sensor. *MAPAN*, *37*(1), 149-160.

Gangwar, A., Nayak, T. R., Singh, R. M., & Singh, A. (2017). Estimation of crop water requirement using CROPWAT 8.0 model for Bina command, Madhya Pradesh. Indian journal of Ecology, 44(4), 71-76.

George, B. A., Shende, S. A., & Raghuwanshi, N. S. (2000). “Development and testing of an irrigation scheduling model". *Agricultural water management*, *46*(2), 121-136.

Jat, M. L., Singh, S., Rai, H.K., Chhokar, R. S., Sharma, S. K., & Gupta, R.K. (2005). Furrow irrigated raised bed planting technique for diversification of rice-wheat system of Indo-Gangetic Plains." *Journal of Japan Association for International Cooperation for Agriculture and Forestry* 28, no. 1: 25-42.

Jensen, C. R., Battilani, A., Plauborg, F., Psarras, G., Chartzoulakis, K., Janowiak, F., & Andersen, M. N. (2010). Deficit irrigation based on drought tolerance and root signalling in potatoes and tomatoes”. *Agricultural Water Management*, *98*(3), 403-413.

Jo, L., & Garry, J.O.L. (2003). Long-term comparison of rotation and fallow tillage system of wheat in Australia”. *Field crops research*, 83, 111–222.

Kang, S.Z., Zhao, L., Liang, Y.L., Hu, X.T., Cai, H.J., & Gu, B.J. (2002). Effects of limited irrigation on yield and water use efficiency of winter wheat in the Loess Plateau of China”. *Agricultural Water Management*. 55, 203–216.

Khan, W.A., Rahman, J.UI., Mohammed, M., Alhussain, Z.A., & Elbashir, M.K. (2021). Topological sustainability of crop water requirements and irrigation scheduling of some main crops based on the penman-monteith method", *Journal of Chemistry*, Vol. 2021, 12 Pages.

Kumar, R., & Gautam, H. R. (2014). “Climate change and its impact on agricultural productivity in India”. *Journal of Climatology & Weather Forecasting*. 2:1.

Kumar, S., Sharma, A., Kumar, K., & Oliveto, G. (2021). An Integrated Approach to Evaluating Crop Water Requirements and Irrigation Schedule for Optimizing Furrow Irrigation Design Parameters in Kurnool District, India. Water, 13(7), 925.

Lawande, V. S. K. (2008). Effect of micro irrigation on growth, yield and water-use efficiency of onion (Allium cepa) under western Maharashtra conditions”. *Indian Journal of Agricultural Sciences*, *78*(7), 584-8.

Laxmi, V., Gupta, R.K., Swarnalatha, A., & Perwaz, S. (2003). “Environmental impact of improved technology - farm level survey and farmers’ perception on zero tillage (Case Study)”. Presented at *Roles of Agriculture Workshop* 20–22 October, 2003 - Rome, Italy.

Levidow, L., Zaccaria, D., Maia, R., Vivas, E., Todorovic, M., & Scardigno, A. (2014). Improving water-efficient irrigation: Prospects and difficulties of innovative practices”. *Agricultural Water Management*, *146*, 84-94.

Li, C., Wang, C., Wen, X., Qin, X., Liu, Y., Han, J., & Wu, W. (2017). Ridge–furrow with plastic film mulching practice improves maize productivity and resource use efficiency under the wheat–maize double–cropping system in dry semi–humid areas”. *Field crops research*, *203*, 201-211.

Ludwig, F., van Slobbe, E., & Cofino, W. (2014). Climate change adaptation and Integrated Water Resource Management in the water sector. *Journal of Hydrology*, *518*, 235-242.

Mahajan, G., Bharaj, T.S., & Timsina, J. (2009). Yield and water productivity of rice as affected by time of transplanting in Punjab, India”. *Agriculture Water Management*., 96: 525-532.

Malik, R.K., Mehla, R.S., &B.K. Singh, B.K. (2002). Conservation tillage technologies and farmers participatory research, extension approaches in Haryana - A case study”. In RWC (ed.), Proceedings of the International Workshop on Developing an Action Program for Farm-level Impact in Rice-Wheat Systems of the Indo-Gangetic Plains, 25–27 September 2000, New Delhi, India. Rice-Wheat Consortium Paper Series 14. New Delhi, India: RWC. Pp. 31–45.

Meena, R. P., Sharma, R. K., Chhokar, R. S., Chander, S., Tripathi, S. C., Kumar, R., & Sharma, I. (2015). Improving water use efficiency of rice-wheat cropping system by adopting micro-irrigation systems”. *International Journal of Bio-resource and Stress Management*, *6*(3), 341-345.

Mehla, R. S., Verma, J.K., Gupta., R. K., & Hobbs, P.R. (2000). Stagnation in the productivity of wheat in the Indo-Gangetic Plains: Zero-till-seed-cum-fertilizer drill as an integrated solution”. Rice-Wheat Consortium Paper Series 8. New Delhi, India: RWC.

Nagarajan, S. A., Singh, R., & Singh, S. (2002). Impact evaluation of zero-tillage in wheat through farmers’ participatory mode”. In R.K. Malik, R.S. Balyan, A. Yadav, and S.K. Pahwa (eds.), Herbicide resistance management and zero tillage in rice-wheat cropping system. Hisar, India: CCSHAU, Pp. 150-154.

Naik, B.R., Latha, T.H., & Babu, C.M. (2015). Command area development by using FAO CROPWAT 8.0 model and impact of climate change on crop water requirement-a case study on Araniar reservoir basin (Pichatur dam)”. *International Journal of Applied Research*; 1(13): 142-155.

Oweis, T., & Hachum, A. (2006). Water harvesting and supplemental irrigation for improved water productivity of dry farming systems in West Asia and North Africa”, *Agricultural Water Management*, 80, 1–3:57-73.https://doi.org/10.1016/j.agwat.2005.07.004.

Pan, X.Y., Wang, G.X., Yang, H.M., & Wer, X.P. (2003). Effect of water deficits on within-plot variability in growth and grain yield of spring wheat in northwest China. Field Crops research. 80, 195–205.

Patrick, G., Chales, G., Joseph, M., & Edword, M. (2004). Effects of soil management practices and tillage system on surface soil water conservation and crust formation on a sandy loam in semi-arid Kenya". *Soil and Tillage Research*. 75, 99–186.

Pawar, S. V., Patel, P. L., & Mirajkar, A. B. (2021). Estimation of Potential Evapotranspiration in command area of New Mutha Right Bank Canal, Pune, Maharashtra, India. HYDRO 2020 INTERNATIONAL, 25th International Conference on Hydraulics, Odisha, India, March 26-28.

Prattoyee, F. T., Hasan, F. R. M. R., Nahid, I. K., & Faruq, M. O. (2021). "Modelling Net Irrigation Water Requirements and Irrigation Scheduling of Boro Rice Using FAO-CROPWAT 8.0 and CLIMWAT 2.0: A Case Study of Rajshahi Regions, Bangladesh". *Journal of Global Ecology and Environment,* 13(2),1-11.

Qin, W., Hu, C., & Oenema, O. (2015). Soil mulching significantly enhances yields and water and nitrogen use efficiencies of maize and wheat: a meta-analysis. *Scientific reports*, *5*(1), 1-13.

Rafeet, M. A. (2002). *Salinity management under a trickle irrigation system*. Colorado State University.

Rahman, J., &Sarma. B. (2019). Assessment of crop water requirements and irrigation scheduling of dhanshiri basin". *Jetir,* 6, 1:685-694.

Rajput, J., Kothari, M., & Bhakar. S.R. (2017). Performance Evaluation of Water Delivery System for Command Area of Left Main Canal of Bhimsagar Irrigation Project, Rajasthan". *Journal of Agricultural Engineering*, 54 (3):57-66.

Rajput, J., Mishra, A.K., Dwivedi, N., Sharma, D. K., Singh, Y. V., Kumar, S., Rosin, K. G., & Mani, I. (2021). Potential irrigation command of pulp and paper mill treated effluent under conventional and pressurized irrigation techniques- A Case Study. *International Journal of Tropical Agriculture,* 39(4):329-333.

Rajput, J., Kushwaha, N. L., Sikka, Alok., Alam, M. F., Mahapatra, S., Sena, D. R., Singh, D. K., & Mani, I. (2022). Water accounting of Kurukshetra district and assessing effects of sustainable interventions on water saving. *Indian Journal of Soil Conservation*. 50(2):91-10.

Ratnaraju, C., Yella reddy, K., Satyanarayana, T.V., & Yogitha, P. (2016). Estimation of Crop Water Requirement Using CROPWAT Software in Appapuram Channel Command under Krishna Western Delta". *International Journal of Agriculture Sciences*. 8,31:1644-1649, ISSN: 0975-3710 & E-ISSN: 0975-9107.

RWC (Rice-Wheat Consortium of the Indo-Gangetic Plains). Highlights 2003–2004. New Delhi, India: Rice-Wheat Consortium for the Indo Gangetic Plains. 2004.

Scanlon, B. R., Jolly, I., Sophocleous, M., & Zhang, L. (2007). Global impacts of conversions from natural to agricultural ecosystems on water resources: Quantity versus quality". *Water resources research*, *43*(3).

Singandhape, R.B., Rao, G.G.S.N., Patil, N.G., & Brahmanand, P.S. (2003). Fustigation studies and irrigation scheduling in drip irrigation system in tomato crop. *European. Journal of Agronomy*. 19, 327–340.

Singh, R., Singh, K., & Bhandarkar, D. M. (2014). Estimation of water requirement for soybean (Glycine max) and wheat (Triticum aestivum) under vertisols of Madhya Pradesh. Indian J Agr Sci, 84, 190-197.

Sun, H., Shao, L., Liu, X., Miao, W., Chen, S., & Zhang, X. (2012). Determination of water consumption and the water-saving potential of three mulching methods in a jujube orchard". *European Journal of Agronomy*, *43*, 87-95.

Surendran, U., Sandeep, O., Mammen, G., & Joseph, E.J. (2013). A novel technique of magnetic treatment of saline and hard water for irrigation and its impact on cow pea growth and water properties". *International Journal of Agriculture, Environment and Biotechnology* 6: 85-92.

Surendran, U., Sushanth, C. M., Mammen, G., & Joseph, E. J. (2015). Modelling the crop water requirement using FAO-CROPWAT and assessment of water resources for sustainable water resource management: A case study in Palakkad district of humid tropical Kerala, India. *Aquatic Procedia*, *4*, 1211-1219.

Thimmareddy, Hemareddy & Kg, Sumesh & Patil, R.H. & G., Dr & Haroli, Mahesh. (2022). Effect of Changing Climate on Water Requirement of Chickpea in North Interior Karnataka: Cropwat Model based Assessment. *Legume research - an international journal*. 10.18805/LR-4951.

Thomas, T., Nayak, P. C., & Ghosh, N. C. (2014). Irrigation planning for sustainable rain-fed agriculture in the drought-prone Bundelkhand region of Madhya Pradesh, India. *Journal of water and climate change*, 5(3), 408-426.

USDA. (1967). Irrigation water requirements. Tech. Release No. 21, United States Dept. of Agr., *Soil Manage*. 59 :67–75.

Vibhute, S. D., Sarangi, A., & Singh, D.K. (2016). "Development of Crop Water Demand Based Water Delivery Schedule for a Canal Command". *Journal of Agricultural Engineering* 53,2:12-23.

Whitney, R.S., Gardner, R., and Robertson, D.W. (1950). The effectiveness of manure and commercial fertilizer in restoring the productivity of subsoils exposed by levelling". *Agronomy Journal.,* 42: 239–245.

Xiao, G.J., Liu, W.X., Xu, Q., Sun, Z.J., & Wang, J. (2005). Effects of temperature increase and elevated CO2 concentration, with supplemental irrigation, on rain-fed spring wheat yield in semiarid areas of China". *Agricultural Water Management*. 74, 243–255.

Xu, D., & Mermoud, A. (2003). Modeling the soil water balance based on time-dependent hydraulic conductivity under different tillage practices". *Agricultural Water Management*,. 63, 139–151.

Yadav, D., Awasthi, M. K., & Nema, R. K. (2018). Study on crop water requirement of field crops under different climatic conditions of Madhya Pradesh. *Agricultural Science Digest-A Research Journal*, 38(2), 81-87.