Optimizing Irrigation for Water Use Efficiency: A Study of Crop Water Demand Using the Cropwat 8.0 Model

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I. INTRODUCTION

In many developing countries, particularly India, the availability of water for agricultural use is becoming increasingly constrained due to climatic variability, population growth, and competing sectoral demands (IWMI, 2010; World Bank, 2018). Agriculture is the largest consumer of freshwater resources in India, accounting for nearly 81% of total water withdrawals, making the efficient utilization and scientific management of irrigation water a critical national priority. Although Odisha receives an average annual rainfall of about 1401.9 mm, the effective availability of water for crop production during the growing season has been steadily declining across districts owing to erratic rainfall distribution, prolonged dry spells, and frequent drought events.

These challenges are further aggravated by human-induced desertification, land degradation, deforestation, and excessive extraction of surface and groundwater resources (UNCCD, 2017). Concurrently, rapid population growth, urbanization, and industrial development have intensified competition for water among agricultural, domestic, and industrial sectors, increasing pressure on already stressed water resources (FAO, 2017). In addition to quantity-related scarcity, the quality of water resources has deteriorated significantly due to the indiscriminate use of chemical fertilizers, pesticides, and agro-chemicals, leading to contamination of surface and groundwater and a reduction in usable freshwater supplies (CGWB, 2020).

These growing concerns underscore the urgent need for integrated water resource planning and efficient irrigation management strategies to ensure equitable water allocation and long-term agricultural sustainability. Accurate spatial and temporal application of irrigation water is essential for enhancing water conservation, improving crop yields, and increasing water use efficiency (WUE). Under conditions of increasing water scarcity, achieving higher WUE has become a major challenge, necessitating the adoption of advanced irrigation scheduling tools and decision-support systems that enable precise water application based on crop water demand.

The estimation of crop water requirement (CWR) is fundamental to effective irrigation planning and water resource management and is commonly expressed in terms of evapotranspiration (ET), measured in mm day^{-1} or over specific growth periods. Evapotranspiration represents the combined processes of soil evaporation and crop transpiration, and it serves as a reliable indicator of crop water demand (Allen et al., 1998). Consequently, crop water requirement modeling has become an essential approach for quantifying irrigation needs under diverse climatic, soil, and crop conditions.

Among the widely used models, CROPWAT 8.0, a decision-support tool developed by the FAO Land and Water Development Division, is extensively employed for estimating reference evapotranspiration (ETo), crop evapotranspiration (ETc), effective rainfall, irrigation requirements, and yield response to water stress through a soil–water balance approach (Smith, 1992; FAO, 1998). The model integrates climatic, crop, and soil parameters and supports the development of irrigation schedules under different management practices, as well as the estimation of scheme-level water supply for various cropping patterns.

CROPWAT 8.0 includes standard crop and soil databases, which can be updated using site-specific field data, and can be supplemented with climatic data obtained from CLIMWAT, a global climatic database comprising records from more than 5,000 meteorological stations worldwide (FAO, 2015). Irrigation scheduling within CROPWAT is based on a daily soil–water balance, enabling accurate determination of both the timing and quantity of irrigation applications. This is particularly important because studies indicate that only about 40–60% of applied irrigation water is effectively utilized by crops, while the remaining portion is lost through evaporation, surface runoff, and deep percolation (Michael, 2010; Pereira et al., 2015).

The primary objective of this study is to estimate reference evapotranspiration (ETo) using CLIMWAT climatic data and the FAO Penman–Monteith method, which is internationally recognized as the standard approach for ETo estimation (Allen et al., 1998). Additional objectives include the estimation of effective rainfall, determination of net irrigation requirements, and the development of optimal irrigation schedules that ensure timely and adequate water supply during critical crop growth stages while minimizing water losses due to over-irrigation, runoff, and deep percolation. The final objective is to support sustainable and efficient water resource management by evaluating water use under different climatic and management scenarios and by tailoring irrigation strategies to soil characteristics and water-scarce conditions, thereby enhancing water productivity, reducing environmental impacts, and ensuring long-term agricultural sustainability.

II. STUDY AREA & METHODOLOGY

The study area selected for the present work is Brazil (Station A513), located at a latitude of 20°31′46.20″ S and a longitude of 43°41′52.65″ W, within the state of Minas Gerais in southeastern Brazil. Minas Gerais is a large inland state, covering an area of 226,460 square miles (586,528 km²), renowned for its rich mineral resources and hence referred to as the “General Mines” of Brazil. It is the fourth largest state in the country, has the second-largest population after São Paulo, and its capital city is Belo Horizonte, situated in the south-central region of the state.

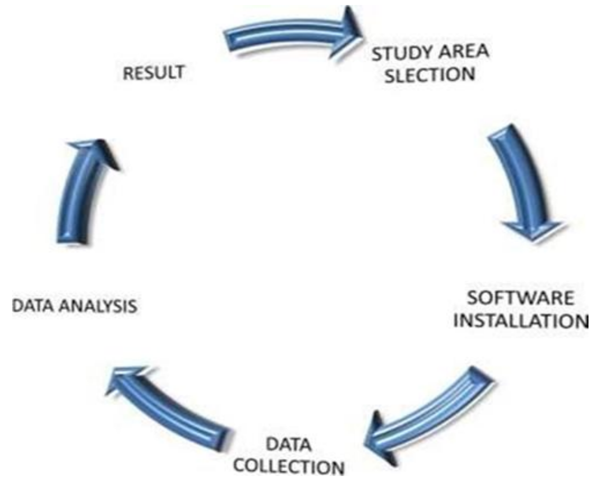

Fig1: Flow chart of Methodology

Climatic data required for the present study, including minimum and maximum temperature, relative humidity, wind speed, sunshine hours, atmospheric pressure, and rainfall, were obtained from multiple reliable sources. These included the FAO CLIMWAT database integrated with CROPWAT 8.0, the Brazilian National Institute of Meteorology (INMET) website (http://tempo.inmet.gov.br), and the NASA climate data portal. INMET provides station-specific meteorological observations in CSV format, and data for Station A513 in Minas Gerais were collected for the period from 2006 to 2023. The collected data were analyzed and processed using Microsoft Excel, where six-monthly datasets were consolidated into annual averages. CROPWAT modeling requires climatic, soil, and crop data; while climatic data were sourced externally, crop and soil parameters were adopted from the standard database available within the CROPWAT software and selected according to the study area. The climatic characteristics of the region indicate moderate temperatures with no extreme cold, minimum temperatures ranging from about 16.5 °C to 22.4 °C, relatively low humidity levels (29–55%), and representative sunshine hours obtained from INMET, which are essential for estimating evapotranspiration.

Monthly Average 2006 to 2023	JAN		21.73	22.42	21.09	76.78	79.82	73.54	17.01	17.60	16.44	897.70	897.93	897.46	2.14	170.25	5.47	39221.44	262.98
	FEB		21.49	22.20	20.85	76.26	79.35	72.98	16.70	17.29	16.13	898.19	898.43	897.96	2.06	157.28	5.27	31383.34	169.57
	MAR		21.15	21.82	20.53	78.42	81.33	75.31	16.90	17.45	16.36	898.48	898.72	898.24	1.94	155.25	5.01	34748.96	166.33
	APR		18.65	19.27	18.09	74.35	76.94	71.49	14.79	15.29	14.31	846.47	846.68	846.26	1.83	145.10	4.57	25447.56	54.28
	MAY		17.97	18.63	17.35	76.92	79.73	73.97	13.45	13.97	12.95	900.43	900.66	900.21	1.90	168.66	4.57	22444.78	27.26
	JUN		17.13	17.82	16.51	76.38	79.18	73.42	12.49	13.02	11.99	902.10	902.30	901.88	1.89	166.41	4.55	24320.01	14.60
	JUL		17.62	17.79	16.37	70.57	73.53	67.41	11.01	11.54	10.47	902.70	902.91	902.49	2.13	155.69	5.03	1093.70	4.93
	AUG		17.94	18.68	17.23	67.15	70.10	64.15	10.92	11.45	10.39	902.18	902.40	901.95	2.33	140.95	5.54	1246.25	12.72
	SEP		20.24	21.01	19.48	65.24	68.15	62.27	12.52	13.08	11.95	900.69	900.95	900.45	2.46	140.16	5.91	1345.56	38.79
	OCT		21.15	21.87	20.47	72.56	75.43	69.58	15.26	15.83	14.72	898.56	898.82	898.30	2.39	149.32	5.94	1286.49	130.44
	NOV		20.48	21.12	19.85	78.38	81.29	75.47	16.16	16.71	15.65	897.14	897.40	896.90	2.30	164.28	5.83	1199.48	213.09
	DEC		21.22	21.89	20.60	79.92	82.81	76.80	17.25	17.81	16.72	896.84	897.08	896.59	2.13	177.64	5.52	1191.98	230.42

Table1: Average data of Jan to Dec

III. RESULTS AND DISCUSSION

The effective rainfall for Brazil Station A513 was estimated as 929.7 mm using the USDA Soil Conservation method. Effective rainfall represents the portion of total rainfall that is stored within the crop root zone and is available for crop use, excluding losses due to runoff, deep percolation, and evaporation. In this study, effective rainfall accounts for 70.15% of the Crop Water Requirement (CWR), indicating that a substantial portion of crop water demand is met naturally by rainfall. This high contribution demonstrates that rainfall plays a major role in satisfying crop water needs in the study area. Consequently, the irrigation requirement is significantly reduced, leading to improved water-use efficiency and lower irrigation costs.

Crop	Eff. rainfall (%oftotal rainfall)	CWR
Corn (Maize)	60–75%	500–800
Vegetables	40–60%	300–600
Millets (Sorghum)	30–50%	400–500

Table2: Major crops and CWR

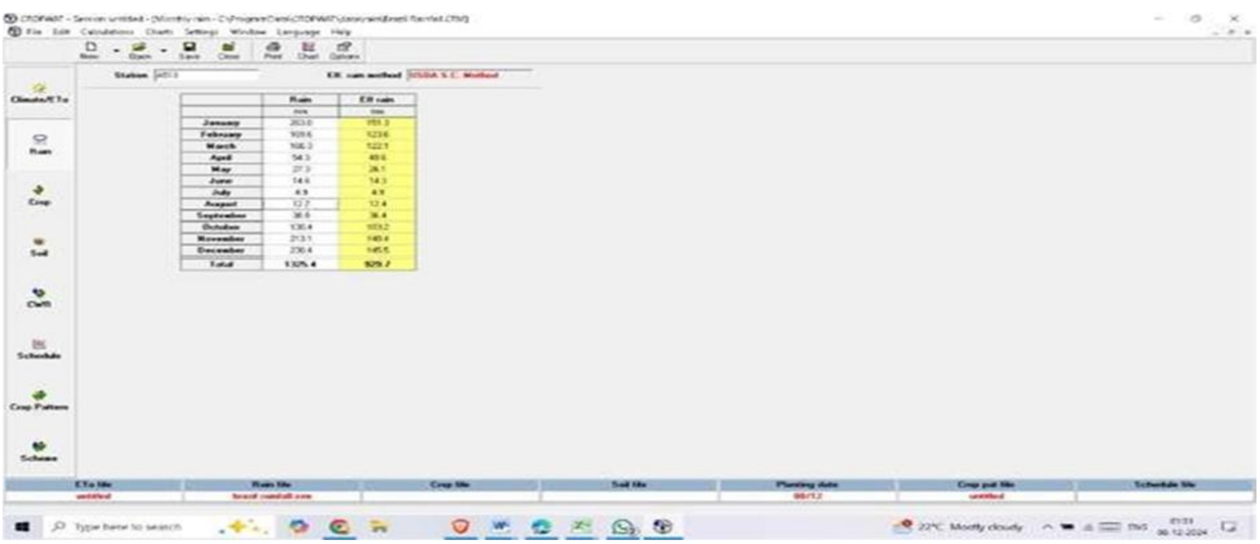

Fig1: software operation

Example Calculation of Irrigation Requirement Percentage of CWR met by Effective Rainfall = 70.15%

$$\text{Effective Rainfall (ER)} = 500 \times 0.7015 = 350.75 \text{ mm}$$

$$\text{Net Irrigation Requirement (NIR)} = \text{CWR} - \text{ER}$$

$$\text{NIR} = 500 - 350.75 = 149.25 \text{ mm}$$

Thus, an irrigation depth of 149.25 mm is required to meet the remaining crop water demand

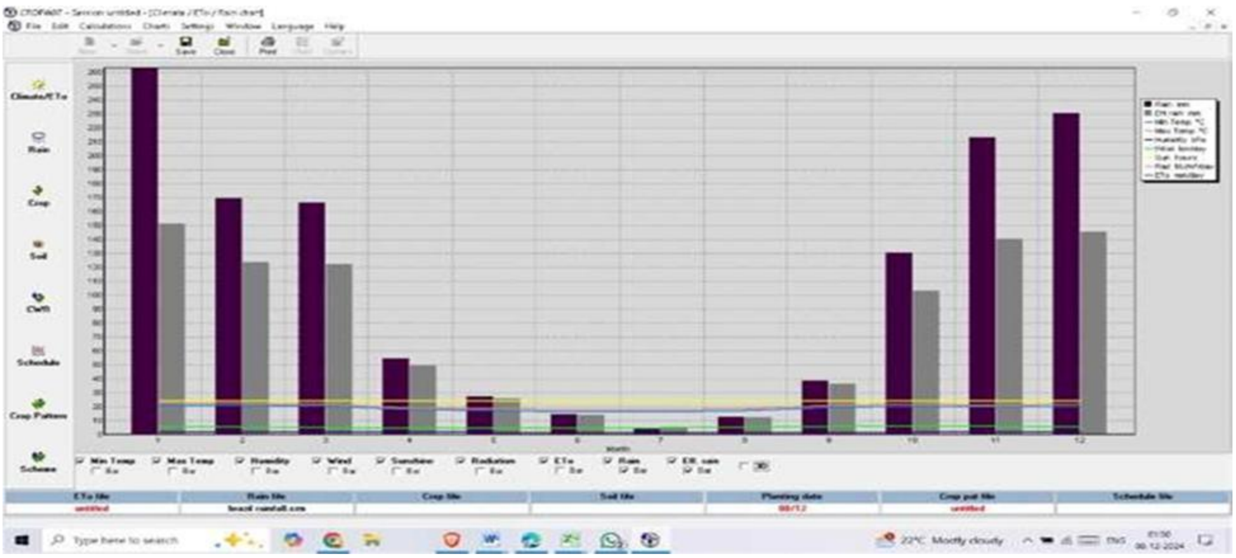

Fig 2: Graphical representation of weather values of studied area in CROPWAT8.0

Crop CWR (mm)	Effective Rainfall	Irrigation Needed (Deficit)
Wheat 450–650	70.15% (~316–456 mm)	29.85%(~134–194mm)
Maize (Corn) 500–800	70.15% (~351–561 mm)	29.85%(~149–239mm)
Vegetables 300–600	70.15% (~211–421 mm)	29.85% (~89–179 mm)
Millets 400–500	70.15% (~281–351 mm)	29.85% (~119–149 mm)

Table3: Effective Rainfall of each crop

Maize and corn, having shallow root systems, require frequent irrigation even when moderate effective rainfall of 351–561 mm is available. Vegetable crops generally need 300–600 mm of water per growing season, depending on the crop type. For example, tomatoes have a crop water requirement of about 400–600 mm, of which nearly 70% may be met by effective rainfall. However, despite this rainfall contribution, regular and timely irrigation remains essential, particularly during critical growth and fruit development stages, to ensure optimum yield and quality.

III. CONCLUSION

The results clearly indicate that the CROPWAT model effectively estimates crop-wise effective rainfall with high reliability, supporting accurate irrigation planning for different crops. Crops such as maize, vegetables, and millets are relatively preferable under limited water conditions, as they require lower crop water requirements (CWR) during their growing period; however, their shallow root systems still necessitate timely and controlled irrigation. Although effective rainfall meets about 70.15% of the crop water demand, crops with high water requirements such as rice and sugarcane continue to depend heavily on irrigation due to their need for sustained moisture, especially during critical stages like flowering. In contrast, drought-tolerant crops such as millets can perform satisfactorily with this level of effective rainfall, making them suitable for water-scarce regions. Overall, the study highlights that while effective rainfall significantly reduces irrigation demand, crop type, root depth, and growth stage must be carefully considered to ensure optimal water management, improved productivity, and sustainable use of water resources.

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