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Mapping irrigation requirements of major crops in the coastal agro-climatic zone of Odisha using CROPWAT 8.0 and geospatial techniques

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ABSTRACT

The demand for water in agriculture sector is increasing due to the need for higher crop production to feed the growing population. The east and south-eastern coastal plain agro-climatic zone (ACZ) of Odisha is one of the fertile zones that demands sustainable water resource management in agriculture. A study was carried out during 2023 at College of Agricultural Engineering and Technology (Odisha University of Agriculture and Technology), Bhubaneswar, Odisha to determine the crop water requirement (CWR), irrigation requirement (IR) and irrigation scheduling of major crops grown in different districts of east and south-eastern coastal plain ACZ of Odisha using CROPWAT model and GIS software. Based on 10-years of the meteorological data from 7 districts (Kendrapara, Khordha, Jagatsinghpur, Puri, Nayagarh, Cuttack and part of Ganjam) and the soil condition of the coastal region, daily evapotranspiration was found to range from 3.73–4.86 mm/day and the effective rainfall ranged from 778.6–986 mm. The crop water requirement for *kharif* rice was the greatest at 850 mm, followed by maize at approximately 400 mm. During *kharif*, no irrigation was required for pearl millet or finger millet in this region. A map of crop water requirements and irrigation needs in the zone would be very useful for sustainable irrigation planning for different crops in seven different districts of the east and south-eastern coastal plain ACZ of Odisha. These findings offer valuable insights for optimizing water allocation in the agricultural sector which will contribute to more effective water resource management and agricultural planning in the region.

Keywords: Coastal plain, CROPWAT 8.0, Crop water requirement, Evapotranspiration, Effective rainfall

In India, agriculture consumes about 80% of available freshwater, yet the water use efficiency of the flow irrigation systems is only around 40% (Poddar *et al.* 2021). The main reason behind this is the inefficiencies in estimating crop water requirements (CWR) and losses of irrigation water. Accurate CWR estimation is essential for better water management, as it varies with respect to climate, location, crop type, soil and growing season (George *et al.* 2000). Improved water management in agriculture is crucial for addressing the ever growing water scarcity, risk from climate variability and food security (Padhee 2018). Remote sensing and modelling techniques are now widely used to predict agricultural water needs, optimizing irrigation supply and conserving the fresh water resources (Kamel *et al.* 2012).

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The rationale of this study is based on the increasing demand for water in the agricultural sector due to the need for higher crop production to meet the food requirement of the growing population. In particular, the east and south-eastern coastal plain ACZ of Odisha is a fertile region that faces critical challenges in sustainable water resource management. There is limited research focusing on region-specific crop water requirements, particularly for the diverse cropping patterns in coastal agro-climatic zones of Odisha. Additionally, existing studies often lack comprehensive irrigation scheduling tailored to different crops across seasons in the state (Khatua 2017, Mohanty *et al.* 2020). Filling this research gap is critical for supporting sustainable water management practices that address the challenges of both water scarcity and agricultural productivity. It will offer a clear framework for optimizing water allocation in the east and south-eastern coastal plain ACZ of Odisha. This study is focused on addressing the need for accurate, region-specific estimations of crop water requirements (CWR) and irrigation needs for major crops in this zone, which is essential for effective agricultural water management.

MATERIALS AND METHODS

Description of study area: The study was carried out during 2023 at College of Agricultural Engineering and Technology (Odisha University of Agriculture and Technology), Bhubaneswar (19° 30' and 20° 50' N and 86° 41' and 85° E), Odisha. It covered seven districts of Odisha, viz. Kendrapara, Khordha, Jagatsinghpur, Puri, Nayagarh, Cuttack and part of Ganjam. The climate of this zone is hot and humid with 1577 mm annual rainfall; temperatures ranging from 39.0°C in summer to 11.5°C in winter. Predominant soils include alluvial, lateritic, red and saline soils.

Crop data: Four major crop, viz. rice (*Oryza sativa*), finger millet (*Eleusine coracana*), maize (*Zea mays*), and greengram (*Vigna radiata*) were chosen to estimate crop water requirements in the seven districts. Crop data such as planting dates, harvest time, root depth and crop coefficients were gathered from literature, reports and field surveys were taken during the study (Table 1) (Mohan and Arumugam 1994, Tyagi *et al.* 2000, Kar *et al.* 2005, Srinivas and Tiwari 2018).

CROPWAT model: CROPWAT 8.0 is decision support software developed by FAO to calculate crop water requirements and irrigation schedules based on climatic, soil and crop data (Allen *et al.* 1998). CROPWAT employs several methods for estimating reference evapotranspiration (ET_0) and effective rainfall, based on FAO papers. The Penman-Monteith method (FAO 56) is preferred for its ability to account for multiple climatic factors, making it more accurate than simpler empirical methods (Allen *et al.* 1998). It estimates reference evapotranspiration (ET_0) using parameters like rainfall, average maximum and minimum temperature (°C), relative humidity (%), wind speed (km/h) and sunshine duration (h/day) (Kaboosi and Kaveh 2012). Weather data for CROPWAT can be sourced from inbuilt CLIMWAT database or from local stations. The average meteorological data and location of climate stations of the seven districts are given in Table 2.

Table 1 Details of crop data for rice, maize, millet and greengram

Crop	Rice	Maize	Finger millet	Greengram
Planting and harvesting date				
Sowing/Planting date	01 Jun	10 Nov	01 Jul	01 Feb
Harvesting date	28 Oct	27 Feb	08 Oct	11 May
Crop stage (days)				
Initial	30	25	20	20
Development	30	30	15	20
Mid	60	25	25	30
Late	30	20	40	20
Total	150	100	100	90
Rooting depth				
Max. rooting depth (m)	0.8–1.2	1.0–1.5	1.0–1.5	0.8–1.2
Crop coefficient				
Initial	1.15	0.70	0.35	0.45
Mid	1.30	1.15	1.10	1.10
Late	1.10	1.00	0.65	0.50
Critical depletion factor	0.20	0.50	0.55	0.60
Yield response fraction	1.10	1.25	0.70	0.80

Table 2 Meteorological data for different districts of east and south eastern coastal plain of Odisha

District	Lat (°N)	Long (°E)	Max. temp (°C)	Min. temp (°C)	RH (%)	Sunshine duration (h/day)	Annual rainfall (mm)
Khordha	20.1	85.6	32.6	22.2	70	6.7	1500
Puri	19.8	85.8	30.1	23.8	90	8.0	1460
Cuttack	20.4	85.8	32.9	22.4	70	7.0	1491
Kendrapara	20.5	86.4	31.5	22.0	71	6.1	1558
Ganjam	19.3	85.0	30.3	23.0	79	5.9	1068
Jagatsinghpur	20.0	86.1	31.5	22.1	74	5.8	1460
Nayagarh	20.1	85.1	32.5	21.4	60	6.6	1176

The Penman-Monteith Method was used to determine the reference evapotranspiration using the equation (1):

$$ET_0 = \frac{0.408\Delta(Rn\text{-}G) + y(900(T + 273)U_{2m(e_s - e_a)}}{\Delta + Y(1 + 0.34U2m)} \quad (1)$$

where ET_0, Reference evapotranspiration; Rn is the net radiation at the crop surface (MJ/m²/day); T, Mean daily air temperature (°C); Δ, Slope of the saturation vapour pressure curve (kPa/°C); U_{2m}, Wind speed at a height of 2 m (m/s); e_s, Saturation vapour pressure (kPa); γ, Psychrometric constant (0.054 kPa/°C); e_a, Actual vapour pressure (kPa).

Effective rainfall of the study area was calculated using USDA Soil Conservation Service formula given in equation (2) and (3):

$$Peff = \frac{P_t \times (125 - 0.6\,Pt)}{125}, \text{ for } P_t <= \left(\frac{250}{3}\right) mm \quad (2)$$

$$Peff = \frac{125}{3} + 0.1 \times P_t, \text{ for } P_t >= \left(\frac{250}{3}\right) mm \quad (3)$$

where P_{eff}, Effective rainfall and P_t, Total rainfall.

RESULTS AND DISCUSSION

Effective rainfall and evapotranspiration: Fluctuations in effective rainfall and reference evapotranspiration (ET_0) across the 7 districts of the agro-climatic zone (ACZ) (Fig. 1). Effective rainfall was calculated using Eq. (2) and (3). Kendrapara district has the highest annual effective rainfall at 986.0 mm, while Nayagarh has the lowest at 778.6 mm. The highest average ET_0 was recorded in Khordha at 4.86 mm/day, with Puri district having the lowest at 3.77 mm/day. ET_0reaches its minimum in December and maximum in May. Solar radiation and temperature are the main factors affecting ET_0 (Rim 2004). These findings indicated that irrigation needs differ across districts, even within the same ACZs.

Similar trends of regional variability in ET_0 have been observed in the neighbouring coastal zones of West Bengal and Andhra Pradesh where reference ET is found to vary significantly due to distinct micro-climatic factors such as wind speed, humidity, and solar radiation intensity (Sharma *et al.* 2021). In West Bengal, Bhattacharya *et al.* (2019) reported that ET_0 is significantly higher in the dry winter months corroborating the findings in the present study, suggesting that climatic factors in coastal zones exert substantial influence on water demand for crops. Such variation emphasizes the need for micro-level irrigation planning across different districts to optimize water use efficiency.

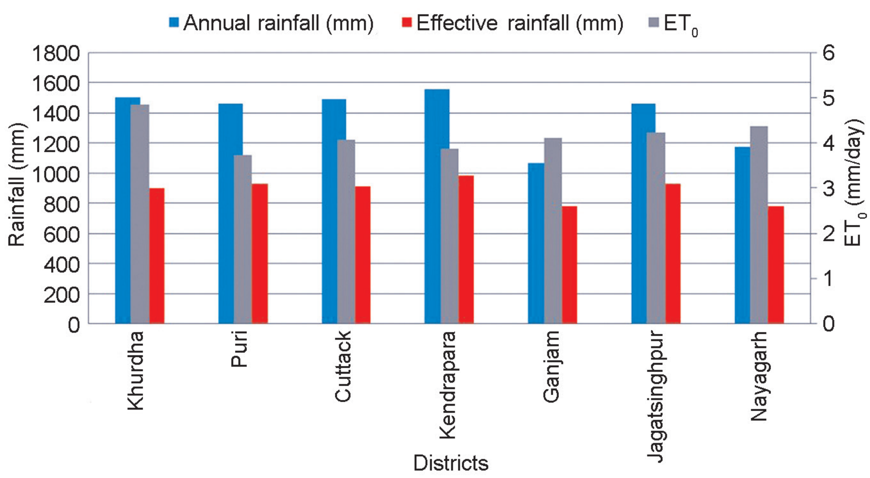

Fig. 1 Graphical representation of variation in effective rainfall and evapotranspiration of various districts.

The relationship between effective rainfall and evapotranspiration (ET) revealed distinct seasonal patterns. ET exceeds effective rainfall on an annual basis, however, during the monsoon season the effective rainfall is more than ET. This leads to minimal irrigation requirement during monsoon and irrigation is only required during dry spells. However, beyond the monsoon season, particularly in *rabi* and summer seasons the ET is higher than effective rainfall that leads to higher irrigation demands to maintain the optimal crop growth. These variations emphasized for the need for seasonal irrigation planning in the study area.

Crop water requirement: The crop water requirement (CWR) and irrigation needs for rice, maize, finger millet, and greengram are presented in Table 3. For rice, the CROPWAT model indicated that Khordha district has the highest CWR at 881.0 mm while Puri district has the lowest at 743.2 mm. The highest irrigation demand for rice was found in Nayagarh district at 184.85 mm and the lowest was recorded in Puri district at 123.85 mm. Monthly analysis showed that rice has the highest water requirements during developing and mid-season stages. Water needs gradually decrease as the crop matures.

In comparison, rice cultivation in Tamil Nadu's coastal region under similar climatic conditions showed slightly higher irrigation requirements, as noted by Raj *et al.* (2022), due to different soil moisture retention capacities and groundwater availability. This suggests that the geographical and soil context within even coastal agro-climatic zones significantly affects irrigation schedules. Research from the Philippines by Garcia *et al.* (2021) also highlights that supplemental irrigation during the dry season for rice can increase yield by up to 15%, which supports the findings here regarding the necessity of irrigation during dry spells.

The highest crop water requirement for maize, measuring 370.8 mm, was found in Khordha district, while the lowest crop water requirement of 266.8 mm was found in Kendrapara district. The irrigation requirement for maize, measuring 325.8 mm, was found to be the highest in Khordha district, whereas the lowest requirement was observed in Kendrapara district at 217.7 mm. When analyzing the crop water requirements of maize throughout the season, it was noted that the highest water demand occurs in January during the mid-season (reproductive) stage. As the time progresses and the plants mature, the water requirement gradually decreases.

The maize crop water requirement variation found here is consistent with studies conducted by Jangre *et al.* (2022) in central India, where similar irrigation demands were reported during the dry winter months. This highlights that the phenological stage of maize is critical in determining water demand. Particularly, water stress during the reproductive stage can significantly reduce yields, as supported by findings in Africa by Waha *et al.* (2020). Such consistency across regions with similar cropping cycles reinforces the need for efficient irrigation scheduling.

The crop water requirement (CWR) for millets, specifically ragi (finger millet), varies significantly across different districts. In Khordha district, the CWR is highest at 342.0 mm, whereas in Jagatsinghpur district, it is the lowest at 296.8 mm. The study indicates that during the *kharif* season, there is no need for additional irrigation for millets in any district within the Agro-Climatic Zone (ACZ) as the effective rainfall is adequate to meet the CWR.

The crop water requirement (CWR) for greengram exhibits significant spatial variation across the seven districts of the Agro-Climatic Zone (ACZ). Khordha district has the highest CWR at 490.0 mm, while Puri district has the lowest at 285.5 mm. Similarly, the irrigation requirement for greengram also varies greatly, with Khordha district needing the most at 412.3 mm and Kendrapara district requiring the least at 197.7 mm. The highest CWR for greengram occurs in April, during its mid-season stage.

Spatial Variation of CWR and IR: Fig. 2A and Fig. 2B illustrate the district wise variability in crop water requirement and irrigation requirement for four major crops grown in the east and southern coastal plain of Odisha, respectively. These figures highlight how the CWR and irrigation needs differ across districts for specific crops,

Table 3 Estimated crop water requirement and irrigation requirement of different crops

	District	May		June		July		August		September		October		Total	
		CWR	IR	CWR	IR	CWR	IR	CWR	IR	CWR	IR	CWR	IR	CWR	IR
Rice (*kharif*)	Khordha	75.0	171	183.7	8	143.2	0	141.4	0	138.5	0	124.2	1	881.0	180.0
	Puri	42.6	115.5	129.1	6.3	131.3	0	136.4	0	139	1	122.4	1	743.2	123.8
	Cuttack	64.1	151.6	158.4	21.3	129.7	0	130.6	0	125.7	0	109.4	1	782.0	173.9
	Kendrapara	60.2	144.2	153.7	11.6	125.4	0	115.8	0	110.3	0	93.5	2	719.4	157.8
	Ganjam	46.9	125.9	139.6	6.3	134.4	1	140.1	1	137.2	6	121	1	766.3	141.2
	Jagatsinghpur	67.6	137.3	168.9	31.3	140.2	0	139	0	130.8	0	98.7	0	812.8	168.6
	Nayagarh	72.4	173.5	178.8	6.3	133.3	0	128.6	0	123.5	4	106.6	1	815.6	184.8
	Districts	November		December		January		February						Total	
Maize (*rabi*)	Khordha	57.4	44.5	99.9	95.8	131.8	119.9	81.7	65.6					370.8	325.8
	Puri	53.6	31.4	85.4	80.4	107.0	102.9	58.0	44.0					304.0	258.7
	Cuttack	50.1	45.3	76.0	71.9	99.3	87.4	58.4	43.7					283.8	248.3
	Kendrapara	43.4	34.2	70.8	57.2	94.3	90.1	58.3	36.2					266.8	217.7
	Ganjam	59.4	29.3	99.4	93.3	127.4	125.4	72.9	62.0					359.1	310.0
	Jagatsinghpur	46.3	30.2	79.1	64.4	107.2	97.3	64.7	33.6					297.3	225.5
	Nayagarh	48.1	38.6	81.5	78.4	111.4	106.4	68.9	52.3					309.9	275.7
	Districts	June		July		August		September						Total	
Millet (*kharif*)	Khordha	72.4	0.0	137.2	0.0	110.6	0.0	21.8	0.0					342.0	0.0
	Puri	51.6	0.0	125.7	0.0	107.0	0.0	21.7	0.0					306.0	0.0
	Cuttack	62.5	0.0	127.1	0.0	107.5	0.0	21.0	0.0					318.1	0.0
	Kendrapara	66.8	0.0	135.4	0.0	110.8	0.0	21.5	0.0					334.5	0.0
	Ganjam	55.7	0.0	128.3	0.0	109.0	0.0	21.5	0.0					314.5	0.0
	Jagatsinghpur	60.6	0.0	122.8	0.0	95.0	0.0	18.4	0.0					296.8	0.0
	Nayagarh	70.3	0.0	130.1	0.0	104.7	0.0	20.4	0.0					325.5	0.0
	Districts	February		March		April		May						Total	
Greengram (*rabi*)	Khordha	65.9	40.9	199.5	172.8	219.7	193.7	4.9	4.9					490.0	412.3
	Puri	46.4	25.2	123.6	107.2	163.1	108.0	2.4	2.4					345.5	242.8
	Cuttack	48.9	25.0	144.0	110.2	151.5	120.2	3.5	3.5					347.9	258.9
	Kendrapara	49.3	12.6	151.9	100.0	157.8	81.6	3.5	3.5					362.5	197.7
	Ganjam	57.8	40.4	161.1	141.9	138.7	127.8	2.9	2.9					360.5	313.0
	Jagatsinghpur	41.8	46.0	158.8	106.9	159.4	103.2	4.6	2.2					364.6	237.3
	Nayagarh	56.7	29.1	169.6	129.6	175.6	143.3	4.1	4.1					406.0	306.1

CWR, Crop water requirement (mm); IW, Irrigation requirement (mm).

which is crucial for effective irrigation planning and optimal utilization of water resources in agriculture. This approach, as reported in (Panme and Sethi 2023), can also be applied to study other vegetable crops.

The ET_0 and effective rainfall for the study region were estimated utilizing the Penman-Monteith method and the USDA Soil Conservation Service calculation in the decision support software CROPWAT 8. The crop water requirement and irrigation requirement of different crops were estimated using various weather, crop and soil information collected from the study area and published literature. The crop water requirement for *kharif* rice was found to range from 719–881 mm, while its irrigation requirement varied from 123–185 mm across different districts of East and South Eastern coastal plain ACZs. This revealed that although there is sufficient rainfall in *kharif*, the occurrence of dry spells causes water stress in rice crop. This hampers both the growth and yield of the crop. Hence, supplemental irrigation is necessary during the dry spells for maximizing the production (Subramanian *et al.* 2023).

The crop water requirement for maize is obtained in range of 266–370 mm, whereas its irrigation requirement ranged from 218–325 mm. Hence, it is suggested to irrigate the maize crop at least with three irrigations during December, January and February when the IR is at its peak. The silking and tasselling stages of the maize should not suffer with water stress as this would lead to a significant reduction in yield (Song *et al.* 2019, Kaur *et al.* 2023). The CWR of millets ranged from 296–342 mm throughout different districts of the ACZs. However, irrigation is not

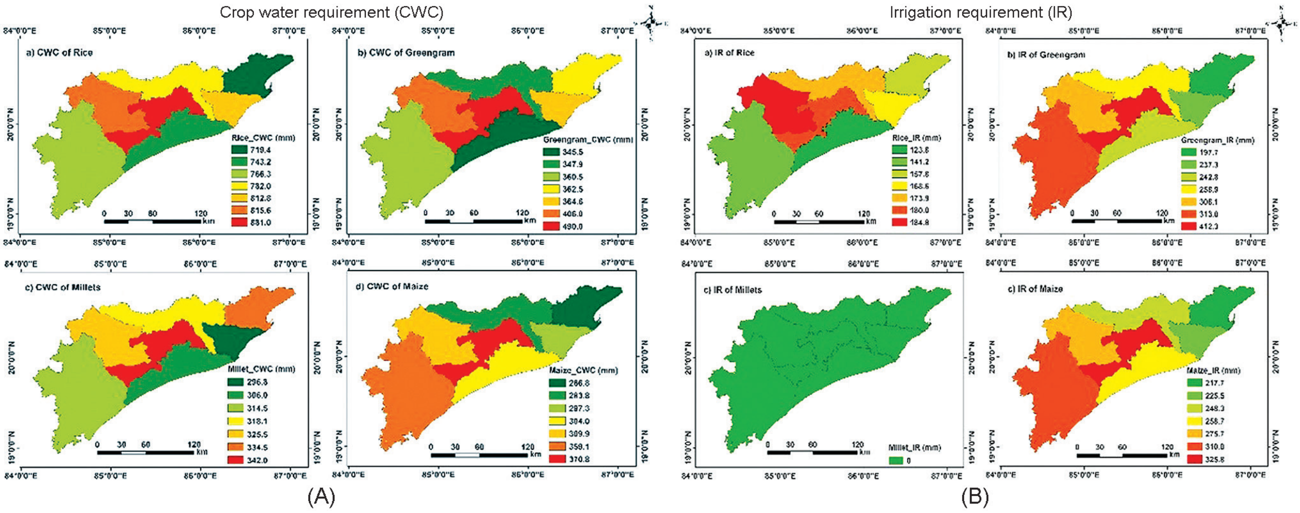

Fig. 2 Map showing (A) crop-water requirement; and (B) Irrigation requirement of a) Rice, b) Greengram, c) Millets, and d) Maize in seven districts of the study area.

required for millets during *kharif*. This revealed that millet is more trustable than rice in absence of irrigation. Hence, it is suggested to cultivate millets in uplands of the ACZs with well-drained soil (Devi *et al.* 2024).

The water required for cultivating greengram ranged from 345–490 mm, whereas the irrigation requirement varied between 197–412 mm across different districts. Generally, farmers do not apply any irrigation to greengram, but the study suggests that irrigation is must for summer greengram for higher productivity. At least two sprinkler irrigation is necessary during March and April when the IR is high. The crop water requirements of all the crops are found to corroborate with the study by Khatua (2017). This supports the argument for targeted irrigation in regions with similar climatic patterns, as observed in coastal Odisha.

A district wise map of crop water requirement and irrigation requirement in East and South Eastern coastal agro climatic zone has been developed, which would be useful for scientific water resources management and optimal irrigation planning in the study area. In districts with higher irrigation demands, like Khordha, farmers may need to adopt more efficient irrigation systems such as drip or sprinkler irrigation to optimize water use. Conversely, in regions with lower irrigation needs, such as Puri, traditional irrigation methods may suffice. Aligning irrigation practices with district-specific water needs would enhance water conservation efforts and improve crop yields. Furthermore, crop wise information of spatial and temporal variability of CWR and IR, has now become a basic requirement for any holistic planning in agriculture sector particularly in the context of climate change (Zhang *et al.* 2023). Such comprehensive research may be conducted in other ACZs of Odisha for better management of the crop and available water resources. Farmers should consider adopting crop diversification strategies such as introducing millets which require no supplemental irrigation during the *kharif* season as a water-saving measure in upland areas. Policymakers should promote the use of advanced irrigation technologies in districts with high irrigation demands and encourage the development of district-specific, crop specific irrigation methods and schedules for optimal water management. This approach would ensure sustainable agricultural practices and efficient water resource management in coastal plains of Odisha.

However, the study has certain limitations. The investigation was based on 10 years of meteorological data which may have not fully capture the long-term trends in climate change. Additionally, the study focused on major crops like rice, maize, millet, and greengram, but further studies are needed to evaluate other crops grown in the region. The accuracy of the CROPWAT model depends on the availability and precision of input data, which may vary across districts. Future research should incorporate a longer time scale, more crops, and advanced hydrological models to better understand the impacts of climate variability on crop water requirements.

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