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DYNAMIC WATER REQUIREMENTS FOR OPTIMAL CROPPING PATTERN UNDER TANK COMMAND AREAS IN ANDHRA PRADESH, INDIA

Madhurima U[1]*, Karunakaran K R[2], Suresh Kumar D[3], Pazhanivelan S[4] and Panneerselvam S[5]

*[1]*Department of Agricultural Economics, Tamil Nadu Agricultural University, Coimbatore-641 003, India*
[2]Department of Agricultural Economics, Agricultural College and Research Institute, Tamil Nadu Agricultural University, Kudumiyanmalai-622 104, Pudukkottai, India
[3]Centre for Agricultural Research and Rural Development, Tamil Nadu Agricultural University, Coimbatore-641 003, India
[4]Water Technology Centre, Tamil Nadu Agricultural University, Coimbatore-641 003, India
[5]Department of Agronomy, Tamil Nadu Agricultural University, Coimbatore-641 003, India

ABSTRACT

Water conservation must be a priority in Indian agriculture, which is among the largest consumers of water globally. Farmers dependent on tank irrigation are increasingly facing challenges due to the loss of eco-friendly irrigation practices that rely on optimal crop water use. This study assessed crop water demand and supply to propose a net irrigation water scheme under two types of tank irrigation systems: non-system and system tanks, in the Chittoor and Srikakulam districts of Andhra Pradesh, India. Using the CROPWAT 8.0 software, irrigation water requirements were estimated based on primary data collected in 2021–22 and secondary data spanning 2001–2021. Under the non-system tank irrigation system, second-season paddy exhibited the highest irrigation water demand at 872.1 mm/ha during the *rabi* season, while groundnut had the lowest requirement at 57.4 mm/ha during *kharif*. On the other hand, in system tank irrigation, paddy required 266.7 mm/ha, while sugarcane demonstrated the highest water usage at 1046.7 mm/ha. The analysis of demand-supply gaps indicated that irrigation water availability was generally sufficient during agricultural growth phases, except in seasons marked by water deficits. Monthly net irrigation schemes in both tank-command areas were found to optimize crop growth and water distribution. The study highlights the need to reallocate water resources, particularly supplying *rabi* crops with *kharif* water through effective water harvesting techniques. These findings can guide farmers in determining appropriate crop water quantities and irrigation schedules in the study area and other regions with similar agro-climatic conditions.

Keywords: Crop water requirement and supply, Optimality, Tank irrigation, Water scarcity

Tank irrigation remains a predominant method in South Indian states such as Andhra Pradesh, Karnataka, Tamil Nadu, and Telangana. In certain districts within these states, tanks still account for 20–30% of the net irrigated land. This traditional irrigation practice has been integral to Indian agriculture for centuries, playing a vital role in safeguarding rural livelihoods for millennia. Due to their relatively small size, tanks typically possess an irrigable command area of 50–250 hectares (Raju *et al.*, 2003; Vaidyanathan and Sivasubramaniyan, 2001; Narayanamoorthy *et al.*, 2022).

India's tank-irrigated acreage has steadily declined over the decades, despite its significant benefits to farmers and rural communities. In 2013–14, tanks irrigated only 1.89 million hectares, a dramatic 59% decrease from 4.56 million hectares in 1960–61. However, tank irrigation still constitutes a notable share of the irrigated area in southern states such as Tamil Nadu (16.57%), Andhra Pradesh (13.31%), Telangana (10.62%), and Karnataka (6.16%) (Agricultural Statistics at a Glance, 2021; Narayanamoorthy, 2002; Raju *et al.*, 2004).

Water is a finite resource, and its availability is steadily declining. In 2001, per capita water availability in India was 1820 m³, which is projected to decrease to 1341 m³ by 2025 and 1150 m³ by 2050 (Bhattacharyya *et al.*, 2015; Kumari *et al.*, 2017). In response to water shortages, Indian farmers often resort to digging new wells or competing to deepen existing open wells (Shaheen and Shiyani, 2005; Devi *et al.*, 2022). Like many other nations, India faces severe water scarcity, with agriculture accounting for the majority of water consumption. Therefore, water conservation must be a priority. Effective irrigation management in irrigated regions requires a clear understanding of crop water requirements at different growth stages to optimize water use and minimize inefficiencies.

India's major irrigation command regions often suffer from unreliable water supply and significant

*Corresponding author: madhurimaupadhyay@gmail.com
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irrigation potential gaps. Temporal mismatches between water supply and demand, coupled with high seepage losses and rising groundwater tables, contribute to waterlogging and salinity issues. These challenges are further exacerbated by frequent monsoon failures and recurring drought conditions. Inefficient water resource assessment, mismatched irrigation flows relative to rainfall patterns and crop water demands, as well as deviations from planned cropping patterns, are key contributors to these problems (Rao, 1992; Rao and Rajput, 2009).

Effective precipitation (EP), irrigation, and soil moisture collectively fulfill crop water requirements. A crop's potential evapotranspiration (ET) quantifies its total water demand, while the difference between ET and EP determines the agricultural irrigation water requirement. To optimize the distribution of limited water resources and enhance water use efficiency, it is essential to estimate crop water demands based on meteorological, soil, and plant factors. This process is greatly facilitated by CROPWAT modelling, which uses location-specific climatic and spatial data to calculate net irrigation water requirements (Madhurima *et al.*, 2024; Sharma and Tare, 2022).

Engineers and economists commonly use the metric "produced yields per unit of water consumed" (often referred to as "crop per drop") to evaluate agricultural water management efficiency. Identifying inefficient water usage and yield gaps due to water constraints is crucial for improving agricultural water management practices (Kumar *et al.*, 2008). Optimization and simulation models further aid in developing effective irrigation system operation policies, helping conserve scarce water resources (Madhurima *et al.*, 2024).

This study evaluates crop water demand and availability under two tank irrigation systems in Andhra Pradesh, system tanks and non-system tanks, in the context of water scarcity. System tanks are recharged by canal channels linked to rivers and precipitation, whereas non-system tanks rely solely on rainfall. To maximize the effective use of non-system tank water, it is essential to estimate crop water needs in the tank command regions alongside water supply availability. Accurate estimation of crop water demand requires consideration of crop development phases, tank water availability, precipitation, and tank type. Precise, scientific data on crop water requirements at different growth stages and the amount of water needed to achieve crop-specific yields are critical for optimizing water resource planning and allocation. Accordingly, this study aims to: (i) Estimate the crop water requirements for command area crops during each growth phase. (ii) Determine the irrigation water supply schedule for the command areas. (iii) Assess demand-supply gaps and propose a net irrigation water requirement scheme.

MATERIALS AND METHODS

Study Area: The research was conducted on two distinct tank irrigation systems, system tanks and non-system tanks, as illustrated in Figure 1. The system tank is located in Srikakulam at 83°75' E longitude and 18°60' N latitude, while the non-system tank is situated in Chittoor at 79°70' E longitude and 13°75' N latitude. The system tank is connected to the Thotapalli left channel of the Nagavali River in Srikakulam, ensuring its recharge through river-fed canal channels and precipitation. In contrast, the non-system tank in Chittoor is replenished annually through direct rainfall (Karunakaran and Madhurima, 2024).

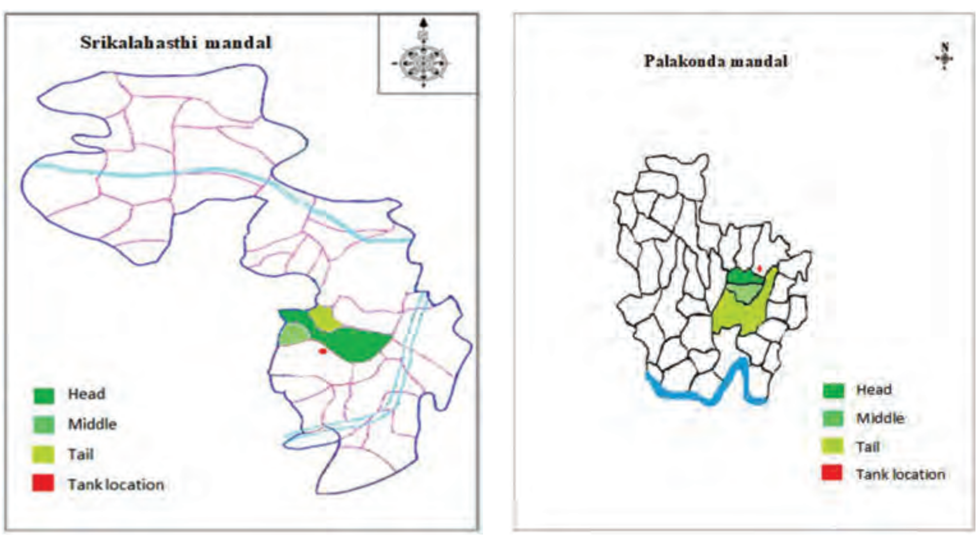


Fig. 1. Study area non-system and system tank locations in Andhra Pradesh

Table 1. Particulars of the study area tank systems in Andhra Pradesh (2020-21)

Particulars	Non-system tank	System tank
Registered command area (ha)	389.49	273.17
Actual command area (ha)	168.22	208.77
Number of wells and micro – irrigation sources in the command areas	264	102
Well density (no of wells/ha)	0.67	-
Micro – irrigation source density (no. of sources/ha)	-	0.37
No. of fillings	1	2.5
Number of farmers benefitted	540	485

Source: Authors' estimates from survey

As presented in Table 1, the registered command area of the non-system tank is 389.49 hectares, while the actual command area is significantly reduced to 168.22 hectares, serving approximately 540 farm households. On average, each farmer operates about 0.31 hectares of land to sustain their agricultural production and support their families. The non-system tank currently receives only one annual filling, whereas the system tank benefits from 2.5 annual fillings, supplied by both the canal system and precipitation. The system tank has an actual command area of 208.77 hectares, shared among 485 farmers, giving each farmer less than 1 hectare of cultivable land. In the non-system tank command areas, well irrigation serves as a supplementary source to meet irrigation demands. In contrast, micro-irrigation techniques are commonly employed in system tank command areas to enhance water use efficiency.

CROPWAT: CROPWAT is a crop water modelling software that calculates reference crop evapotranspiration using the Penman-Monteith method (Smith, 1992). The software utilizes these estimates to determine crop water needs and develop irrigation schedules. CROPWAT computes the monthly irrigation water requirements for a cropping pattern in an irrigated area, accounting for various crop growth phases throughout the growing season (Raju *et al.*, 2016). Additionally, it estimates crop water requirements, scheme water supply, and irrigation schedules under different management scenarios, as well as assessing rainfed production and the effects of drought (Smith, 1992).

It generates reference crop evapotranspiration (ET_0) using the FAO Penman-Monteith method, which aligns with global agricultural water consumption statistics and ensures replicability (Allen *et al.*, 1998; Lopez *et al.*, 2012; Kumar *et al.*, 2017). Several studies have used the CROPWAT model to estimate crop water requirements (Bouraima *et al.*, 2015; Laghari *et al.*, 2014). Crop water requirements are calculated by accumulating crop evapotranspiration (ETc) in millimeters per day throughout the crop's growing season.

Evapo-transpiration (ET_c) formula:

$$ET_c = K_c \times ET_0 \qquad \text{... (1)}$$

where, ET_0 is crop reference evapo-transpiration and K_c is crop coefficient.

K_c compares the real crop canopy and aerodynamic resistance to the hypothetical reference crop. Crop coefficients combine physical and physiological differences between a crop and the reference crop (Kumari *et al.*, 2017). FAO Penman-Monteith equation determined reference crop evapotranspiration:

$$ET_0 = \frac{0.408\Delta(R_n - G) + 900/T{+}273\ U_2\ (e_a - e_d)}{\Delta + \gamma\ (1{+}0.34\ U_2)} \qquad \text{... (2)}$$

where,

ET_0 is Reference crop evapotranspiration (mm/day); Rn is Net radiation at the crop surface (MJ/m^3 /day); G is Soil heat flux (MJ/m^3 /day); T is Average air temperature (^{o}C); U_2 is Wind speed measured at 2 m height (m/s); e_a is Saturation vapour pressure curve (kPa); e_d is Actual vapour pressure (kPa); e_a-e_d is Vapour pressure deficit (kPa); $\Delta$is slope of the vapour pressure curve (kPa/^{o}C) and γ is Psychometric constant (kPa/^{o}C).

Conceptual framework: This study estimates crop water demand and supply using the CROPWAT program to optimally allocate water resources across land resources in both tank command areas. Primary data (2021–22), including crop and soil data, along with secondary data (climatic data), are utilized to predict irrigation water supply and demand, as illustrated in the flowchart (Figure 2).

Climatic data: For the past 20 years, the CRU TS (Climatic Research Unit Gridded Time Series) dataset has collected point data from specific tank command area farms, providing monthly average parameters, including maximum and minimum air temperature, relative humidity (percentage), incoming solar radiation

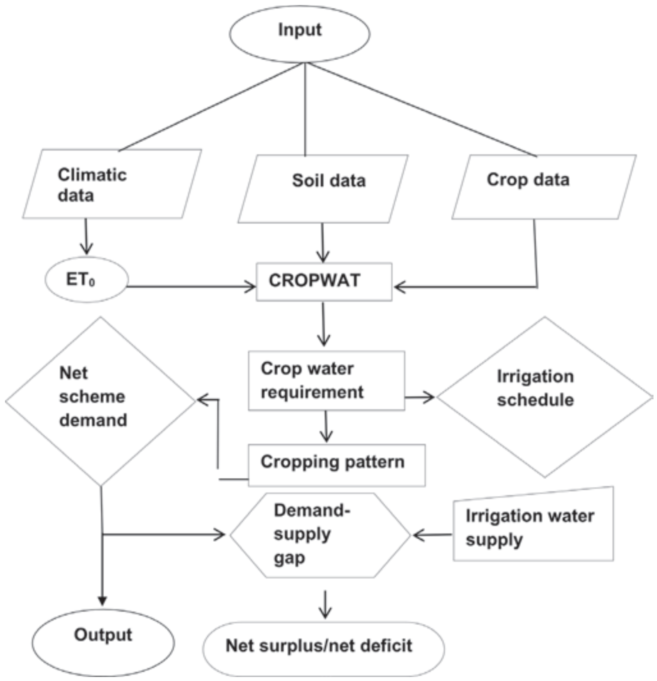


Fig. 2. Flowchart for scheduling net irrigation water and estimation of crop water requirement using CROPWAT

(W/m²), total precipitation (mm), and wind speed (m/s) for the period 2001-2021.

Soil data: Soil data, including soil type, infiltration rate (mm/day), permitted depletion (percentage), rooting depth (m), and total available moisture (mm/m), were collected through observations from the nearest soil testing laboratory and analyzed using CROPWAT 8.0 software.

Crop data: The data collected for each crop are as follows: Type of crop, planting date (day/month) and total growing season (days).

i. Period of crop growth stages (initial, development, mid-season and late season)

ii. Rooting depth (initial and maximum)

iii. Crop coefficient (K_c) values in each crop growth stage

iv. Maximum height of the crop

v. Cropping pattern

The typical cropping patterns followed under the two tank command areas are shown in Table 2. In the non-system tank area, the cropping pattern consists of groundnut followed by paddy (1st crop) during *kharif*, and paddy-paddy (2nd crop) during *rabi*, occupying 100% of the cropped area. In the system tank area, the pattern includes paddy followed by sugarcane during *kharif*, and groundnut or pulses-sesame-sugarcane during *rabi*.

RESULTS AND DISCUSSION

Physiological, climatic, and agronomic factors influence a crop's water requirements, which can vary across farms and regions. Crop water needs are determined by the amount of water required to compensate for evapotranspiration losses, ensuring optimal growth. During the growing season, these needs are met through a combination of precipitation, soil water storage, and irrigation. In the state's *kharif* season, the southwest monsoon provides the majority of the water required for crops, with irrigation supplementing any shortfalls. As water bodies are replenished during *kharif*, irrigation water, combined with reduced precipitation, fulfills the crop water requirements for the *rabi* and summer seasons.

Irrigation water requirement of study area crops

Based on seasonal rainfall, crop management practices, and soil and climatic characteristics, crops during the *kharif* season required less irrigation water. This is primarily because rainfall met a significant portion of crop water needs, with 487 mm of effective

Table 2. Cropping pattern under study tank command area farms in Andhra Pradesh

Tank command area	Crop	Planting date	Harvesting date	Area under crops (percent)
Non-system tank	Groundnut (Rainfed)	25-Jul	11-Nov	90
	1st paddy	25-Jul	21-Nov	10
	2nd paddy	25-Dec	23-Apr	100
System tank	*Kharif* paddy	05-Jul	01-Nov	85
	Groundnut (Rainfed)	05-Nov	14-Mar	10
	Pulses	01-Dec	10-Mar	70
	Sesame	01-Dec	10-Mar	05
	Sugarcane (annual)	25-Jul	24-Jul	15

Source: Authors' estimates from survey

Table 3. Total crop water requirements for study tank command area crops

Crop season	Crop	Total crop water requirement (mm/ha)	
		Non-system TCA*	System TCA
Kharif	Groundnut	57.4	-
	Paddy	470.2	269.7
Rabi	Groundnut	-	374.9
	Paddy	872.1	-
	Pulses		333.7
	Sesame		291.6
	Sugarcane (annual)		1046.7

*TCA: Tank command area
Source: Authors' estimates from CROPWAT 8.0 software

rainfall during the *kharif* season compared to only 92.5 mm during the *rabi* season. Consequently, the irrigation water requirements under the non-system tank scenario were found to be 57.4 mm/ha for groundnut and 470.2 mm/ha for *kharif* paddy. In contrast, under the system tank scenario, the effective rainfall during *kharif* was higher, at 738.6 mm, which reduced the irrigation water requirement for *kharif* paddy to 269.7 mm/ha (Table 3). The irrigation water needs for *kharif* paddy across the two tank command areas were influenced by soil characteristics, climatic conditions, and crop management practices.

In addition to rainfall during the growing season, crops in the study area require substantial irrigation water during the *rabi* and summer seasons (Table 3). Under the non-system tank command areas, the irrigation water requirements were highest for sugarcane (an annual crop) at 1,046.7 mm. For other crops, the requirements were 872.1 mm for *rabi* paddy, 374.8 mm for *rabi* groundnut, 334.3 mm for pulses, and 291.6 mm for sesame.

Crop growth stage irrigation water requirements of TCA crops

Under the non-system tank scenario, the *rabi* paddy crop had the highest irrigation water requirement, with 281.7 mm, 131.5 mm, 325.4 mm, and 133.5 mm needed during the initial (including land development), mid-season, and late stages of crop growth, respectively (Table 4, Figure 4). *Kharif* paddy followed, requiring 319 mm, 86.6 mm, 61.1 mm, and 3.5 mm across its growth stages (Figure 3). Crops grown during the *kharif* season generally require minimal irrigation, as precipitation satisfies most of the agricultural water demand. Among *kharif* crops, groundnut requires the least irrigation water due to sufficient rainfall (Table 4, Figure 3).

Under non-system tank conditions, the first paddy crop occupies 90% of the cropped land during the *kharif* season, while groundnut accounts for the remaining

Table 4. Irrigation water demand based on crop growth stage under non-system tank (mm/ha)

Crop	Stage of development	Development stage period (days)	Average irrigation water demand (mm/ha)	Total irrigation water demand (mm/ha)
Groundnut	Initial	25	0.7	57.4
	Development	30	7.0	
	Mid-season	25	46.1	
	Late season	25	3.6	
Kharif paddy	Initial	30	319	470.2
	Development	35	86.6	
	Mid-season	30	61.1	
	Late season	20	3.5	
Rabi paddy	Initial	30	281.7	872.1
	Development	35	131.5	
	Mid-season	30	325.4	
	Late season	20	133.5	

Source: Authors' estimates from CROPWAT 8.0 software

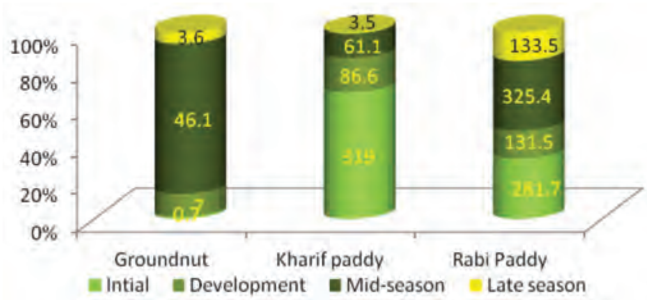


Fig. 3. Crop growth stage irrigation water requirement under non-system TCA farms

10% (Table 6). During the crop growth period, the total seasonal net scheme irrigation water requirements are as follows: 287.1 mm or 1.07 l/s in July, 78.6 mm or 0.29 l/s in August, 56.7 mm or 0.22 l/s in September, 3.1 mm in October, and 3.4 mm in November (Table 6).

During the *rabi* season, 100% of the cropped area is occupied by the second paddy crop (Table 6). The total seasonal net scheme irrigation water requirement for this crop is as follows: 281.7 mm or 1.05 l/s in December, 131.5 mm or 0.49 l/s in January, 136.9 mm or 0.57 l/s in February, 188.5 mm or 0.7 l/s in March, and 133.5 mm or 0.52 l/s in April.

Sugarcane is projected to have the highest water requirement throughout its growth cycle in system tank areas. During the crop germination phase, rainfall is generally sufficient to meet its water needs. However, during the grand growth (mid-season) phase, which lasts approximately six months, sugarcane requires 850.6 mm/ha of irrigation water from November to April (Figures 5, 6, and Table 5).

The system TCA cropping pattern requires irrigation water for 85 percent *kharif* paddy and 15 percent sugarcane crops in the *kharif* season, 10 percent groundnut, 70 percent pulses, 5 percent oil crop sesame, and 15 percent sugarcane in the *rabi* season under net scheme irrigation requirements (Table 6).

In the *rabi* season, groundnut is the second-largest consumer of irrigation water after the annual crop sugarcane, with water requirements of 8.2 mm, 91.2 mm, 158.3 mm, and 117.2 mm across its growth phases. Pulses follow, requiring 333.7 mm of irrigation water, while sesame requires 34.2 mm, 25.7 mm, 146.8 mm, and 84.9 mm during its respective growth stages. In contrast, during the *kharif* season, most agricultural water needs are met through rainfall, resulting in *kharif* paddy crops having the lowest irrigation water requirement of 269.7 mm (Table 5, Figure 6).

Similar studies utilizing the CROPWAT software have provided valuable insights into irrigation water requirements in various regions. Al-Najar (2011) estimated annual irrigation water requirements for citrus, almonds, date palm, and grapes in the Gaza Strip to be 763 mm, 722 mm, 1,091 mm, and 591 mm, respectively. Raju *et al.* (2016) assessed the gross water demand for the Appapuram Channel Command region, estimating it to be 124.39 MCM to irrigate 8,880 ha of registered ayacut, 4,000 ha of unregistered ayacut during the *kharif* season, and 4,000 ha of maize during the *rabi* season. Using CROPWAT 8.0, Sharma and Tare (2022) analyzed the optimal irrigation area and requirements for the Upper Ganga Canal Command. They found that the total crop water requirement in the region was 1,763 MCM, exceeding the available water resources.

Irrigation water supply to TCA crops

The quantity and timing of irrigation water play a crucial role in determining grain yield. Both the frequency and duration of irrigation significantly impact crop productivity. Adequate water availability during critical growth stages is essential for achieving optimal yields.

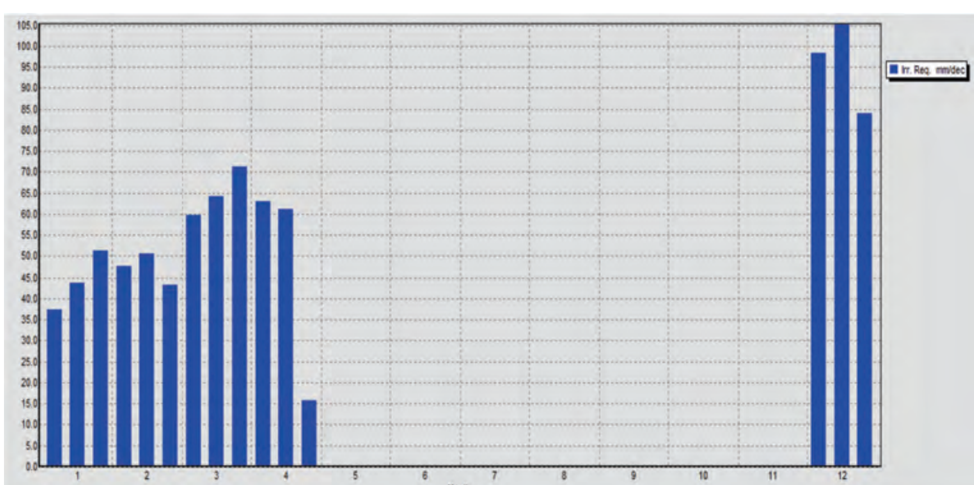


Fig. 4. Monthly irrigation water requirements of *rabi* paddy crop in non-system TCA

Table 5. Irrigation water demand based on crop growth stage under system tank (mm/ha)

Crop	Stage of development	Development stage period (days)	Average irrigation water demand (mm/ha)	Total irrigation water demand (mm/ha)
Kharif paddy	Initial	30	231.6	269.7
	Development	35	14.5	
	Mid-season	30	19.5	
	Late season	20	4.1	
Rabi groundnut	Initial	30	8.2	374.9
	Development	35	91.2	
	Mid-season	35	158.3	
	Late season	30	117.2	
Pulses	Initial	20	27.1	333.7
	Development	30	46.6	
	Mid-season	30	198.3	
	Late season	20	61.7	
Sesame	Initial	20	34.2	291.6
	Development	30	25.7	
	Mid-season	30	146.8	
	Late season	20	84.9	
Sugarcane	Germination	30	-	1046.7
	Tillering	60	20.1	
	Grand growth	180	850.6	
	Ripening	90	176.0	

Source: Authors' estimates from CROPWAT 8.0 software

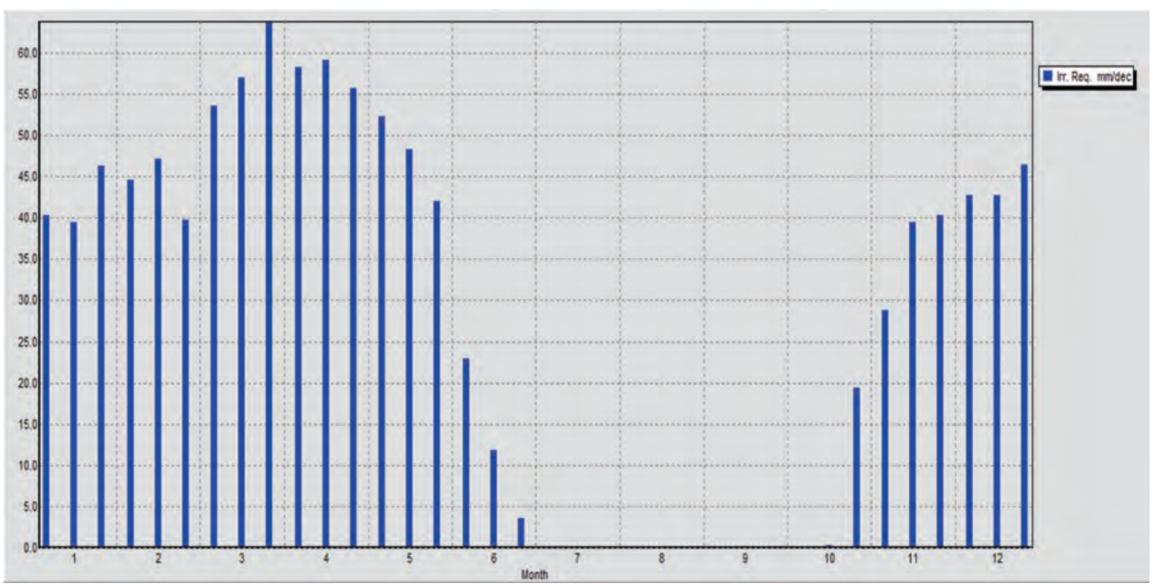


Fig. 5. Monthly irrigation water requirements of sugarcane crop in system TCA

In drought-prone regions, where rainfall is insufficient or erratic, agriculture becomes unviable without irrigation.

Irrigation significantly enhances crop yields in dry regions, allowing farmers to grow crops more consistently. To optimize production, it is essential to analyze crop water demand and supply throughout the growth cycle, identifying periods of net surplus and deficit. Over its growing period, groundnut receives an

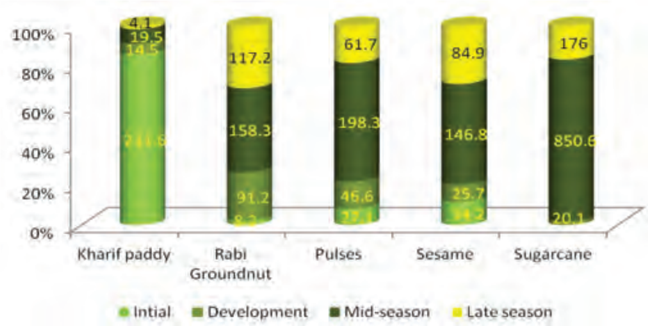


Fig. 6. Crop growth wise irrigation water requirements under system TCA farms

excess of 127.2 mm of irrigation water, despite having a relatively low irrigation requirement of 57.4 mm. Under the non-system tank scenario, paddy crops experienced net deficits during land development (-163 mm, -77.7 mm) and during the mid-season of the second paddy crop (-172.4 mm) (Table 7, Figure 7).

Under the system tank scenario, the paddy crop's field development phase experienced a water shortfall of -57.6 mm. However, with the exception of the paddy crop's land development stage, as well as the mid-season and late stages of pulses, sesame, and the grand expansion phase of sugarcane (-552.6 mm), most crop growth phases received surplus irrigation water (Table 7, Figure 8).

Similar studies have highlighted significant mismatches between irrigation supply and demand. For instance, Al-Najar (2011) estimated a 30 percent supply-demand discrepancy in the Gaza Strip command area, where farmers' irrigation practices exceeded the actual irrigation water requirements. Using CROPWAT, Vibhute *et al.* (2016) determined that the gross irrigation water requirement for wheat was 363.4 mm and for

Table 6. Monthly crop-wise net scheme irrigation water requirement under study tank command area crops

TCA	Particulars	Net Scheme irrigation water requirement											
		JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY
Non-system tank	**Crop**												
	Groundnut	-	0.7	7.0	46.1	1.6	2.0	-	-	-	-	-	-
	Kharif Paddy	-	319	86.6	57.8	3.3	3.5	-	-	-	-	-	-
	Rabi Paddy	-	-	-	-	-	-	281.7	131.5	136.9	188.5	133.5	-
	Net scheme irrigation requirement												
	mm/month	-	287.1	78.6	56.7	3.1	3.4	281.7	131.5	136.9	188.5	133.5	-
	liters/sec (l/s)	-	1.07	0.29	0.22	0.01	0.01	1.05	0.49	0.57	0.7	0.52	-
	Irrigated area												
	per cent of total area	-	100	100	100	100	100	100	100	100	100	100	-
	Irrigation requirement for actual area												
	l/s/ha	-	1.07	0.29	0.22	0.01	0.01	1.05	0.49	0.57	0.7	0.52	-
System tank	Crop												
	Kharif Paddy	161	70.6	14.8	5.3	14.0	4.0	-	-	-	-	-	-
	Rabi Groundnut	-	-	-	-	-	18.2	81.1	116.9	115.7	43	-	-
	Pulses	-	-	-	-	-	-	47.7	102.5	121.8	61.7	-	-
	Sesame	-	-	-	-	-	-	59.9	108.2	106.5	17	-	-
	Sugarcane	34.5	0	0	0	20.1	109.4	132.7	126.9	132.1	175.4	174.1	141.5
	Net scheme irrigation requirement												
	mm/month	142	60	12.6	4.5	14.9	20.7	68.9	106	105.4	41.2	26.1	21.2
	liters/sec(l/s)	0.55	0.22	0.05	0.02	0.06	0.08	0.26	0.4	0.44	0.15	0.1	0.08
	Irrigated area												
	per cent of total area	100	85	85	85	100	100	100	100	100	100	15	15
	Irrigation requirement for actual area												
	l/s/ha	0.55	0.26	0.06	0.02	0.06	0.08	0.27	0.42	0.46	0.16	0.67	0.53

Source: Authors' estimates from CROPWAT 8.0 software

Table 7. Irrigation water supply and net surplus/deficit scenarios of crop water

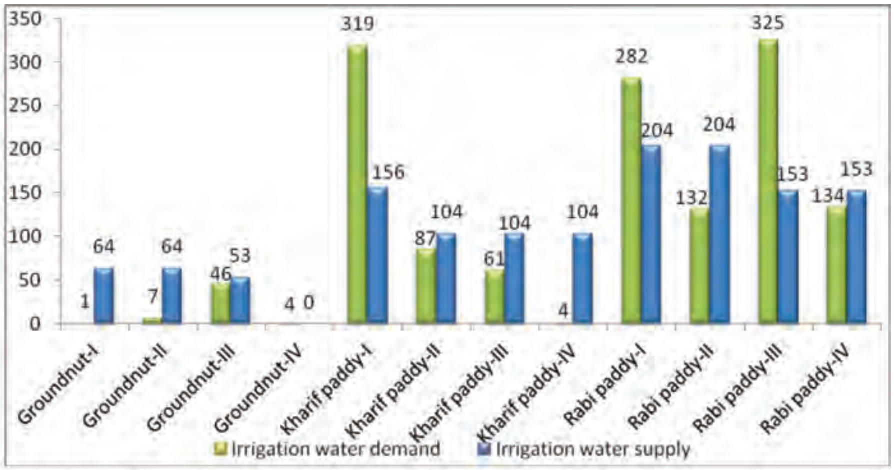
TCA	Crop	Crop growth stage	Period of crop growth stage (days)	Irrigation water supply (mm/ha)	Irrigation water requirement (mm/ha)	Net effect (mm/ha)	Net surplus or deficit
Non-system tank	Groundnut	Initial	25	64	0.7	63.3	surplus
		Development	30	64	7.0	57	surplus
		Mid-season	25	53	46.1	6.9	surplus
		Late season	25	-	3.6	-3.6	deficit
	Kharif paddy	Initial	30	156	319	-163	deficit
		Development	35	104	86.6	17.4	surplus
		Mid-season	30	104	61.1	42.9	surplus
		Late season	20	104	3.5	100.5	surplus
	Rabi paddy	Initial	30	204	281.7	-77.7	deficit
		Development	35	204	131.5	72.5	surplus
		Mid-season	30	153	325.4	-172.4	deficit
		Late season	20	153	133.5	19.5	surplus
System tank	*Kharif* paddy	Initial	30	174	231.6	-57.6	deficit
		Development	35	116	14.5	101.5	surplus
		Mid-season	30	116	19.5	96.5	surplus
		Late season	20	87	4.1	82.9	surplus
	Rabi Groundnut	Initial	30	136	8.2	127.8	surplus
		Development	35	136	91.2	44.8	surplus
		Mid-season	35	204	158.3	45.7	surplus
		Late season	30	-	117.2	-117.2	deficit
	Pulses	Initial	20	106	27.1	78.9	surplus
		Development	30	85	46.6	38.4	surplus
		Mid-season	30	64	198.3	-134.3	deficit
		Late season	20	64	61.7	2.3	surplus
	Sesame	Initial	20	79	34.2	44.8	surplus
		Development	30	79	25.7	53.5	surplus
		Mid-season	30	40	146.8	-106.8	deficit
		Late season	20	40	84.9	-44.9	deficit
	Sugarcane	Germination	30	298	-	298	surplus
		Tillering	60	298	20.1	277.9	surplus
		Grand growth	180	298	850.6	-552.6	deficit
		Ripening	90	255	176.0	79.0	surplus

Source: Authors' estimates from survey and CROPWAT 8.0 software

rice was 1,386 mm during their respective growth seasons (wheat during *rabi* and rice during *kharif*). Effective rainfall depths for these crops were 55.8 mm and 461.8 mm, respectively. Based on the operational canal release schedule of the Jhajjar distributary, the crop water demand-driven protocol developed in this study projected that approximately 25.5 percent of the land area within the distributary could be adequately irrigated.

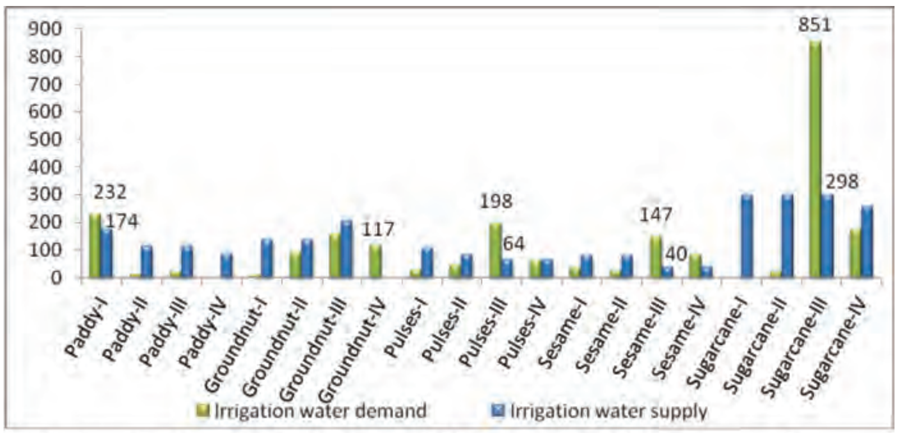
CONCLUSION

In conclusion, this study provides a comprehensive analysis of crop water requirements across two distinct tank command zones in Andhra Pradesh, aiming to optimize water allocation for crops on limited land. The findings highlight significant differences in water demands between the non-system and system tank command areas, with non-system tanks requiring



I-Initial growth phase, II-Development, III-Mid-season and IV-late season phase

Fig. 7. Irrigation water demand-supply gap under non-system tank farms



I-Initial growth phase, II-Development, III-Mid-season and IV-late season phase

Fig. 8. Irrigation water demand-supply gap under system tank farms

1.75 times more irrigation water for *kharif* paddy due to variations in soil, climate, and crop management practices. Groundnut emerged as the most efficient rainfed crop in non-system tank areas, requiring minimal irrigation of 57.4 mm/ha. Sugarcane, while not needing irrigation during germination, exhibited varying irrigation needs during the field development and mid-season stages under the system tank scenario. The study also identified irrigation surpluses and deficits within the command zones, with paddy crops showing substantial water deficits-50 percent during land development and 53 percent during mid-season in the non-system tank scenario. Under the system tank scenario, paddy crops experienced a 25 percent water shortfall during field development. The optimal irrigation requirements were calculated, with monthly net scheme irrigation needs specified for both tank command areas to ensure efficient water use and crop growth. For the non-system tank, the irrigation requirements ranged from 1.07 l/s/ha in July to 0.22 l/s/ha in September, while the system tank showed varied monthly requirements, peaking in May at 0.53 l/s/ha. To optimize water use, the study suggests redirecting *kharif* monsoon irrigation water to meet the needs of *rabi* crops. By offering precise irrigation schedules and crop-specific water needs, this study serves as a valuable guide for farmers in the study area and similar agro-climatic conditions, enabling them to make informed decisions on irrigation water quantity and frequency. Additionally, it encourages further research to help farmers avoid both excess and deficiency in irrigation, ensuring sustainable water resource management and increased agricultural productivity.

Authors' contributions

Conceptualization of research work and designing of experiments (KKR, SKD, PS and PS); Execution of field/lab experiments and data collection (MU); Analysis of data and interpretation (MU); Preparation of manuscript (MU, KKR).

Declaration: The authors declare that no conflicts of interest exist.

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