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Optimality and water conservation under non-system and system tank commands of Andhra Pradesh, India

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ABSTRACT

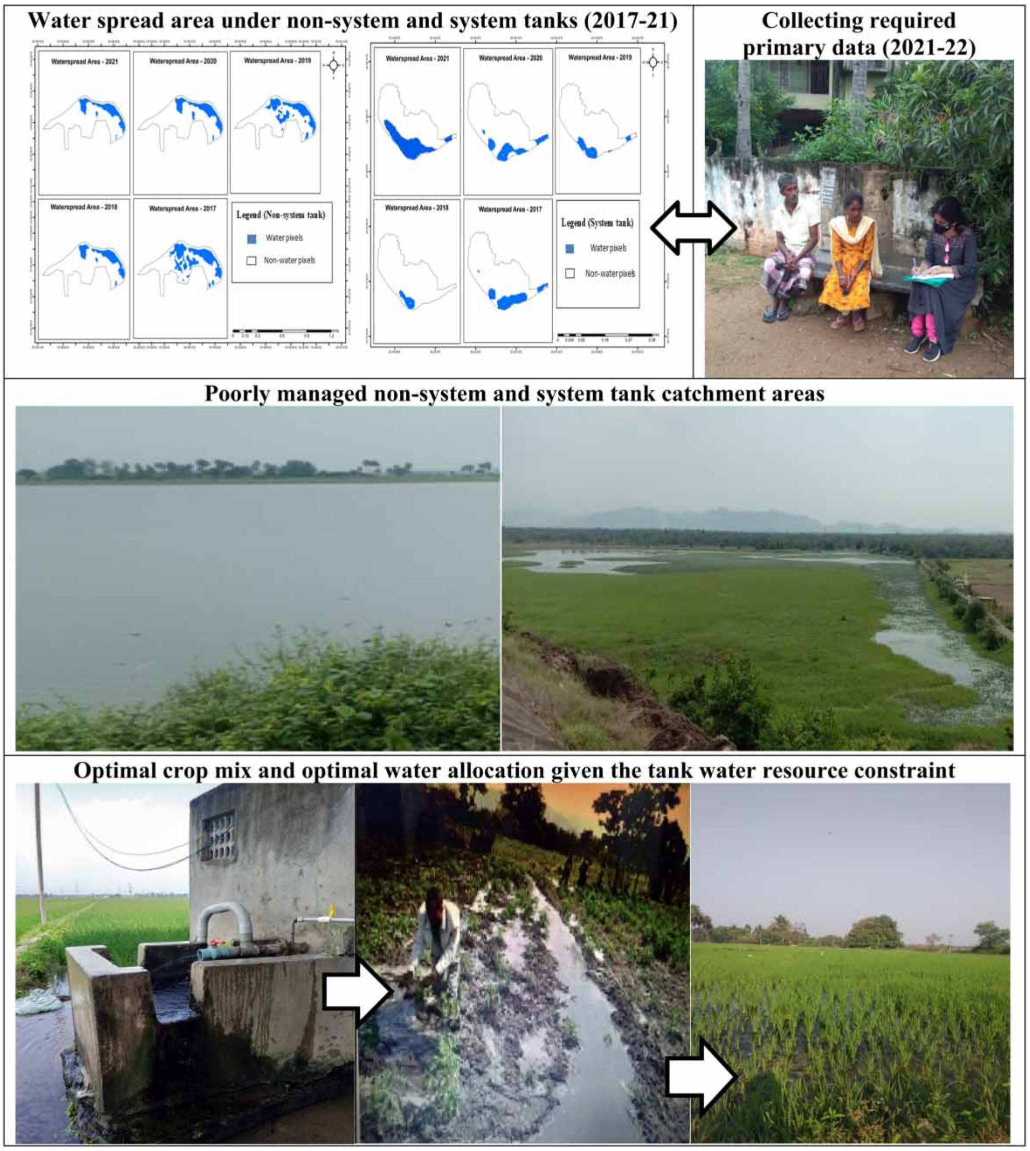
Indian agriculture relies on irrigation. India's net irrigated area has tripled in 60 years, although tank-irrigated regions suffered a large decline. This study examines the potential for improving tank irrigation performance through linear programming by developing individual optimal plans for two different tank irrigation systems (non-system and system tank) in the Chittoor and Srikakulam districts of Andhra Pradesh, India. The optimal plans under non-system tanks allocated less land under paddy while improving groundnut areas to optimally reorganize resources among head, middle, and tail ends. Net returns were maximized to ₹ 2.63, ₹ 2.52, and ₹ 1.92 lakhs. The system tank optimal plans advised less water-intensive crops like pulses and sesame over sugarcane with maximized net returns of ₹ 5.35, ₹ 2.61, and ₹ 1.71 lakhs. Both physical (kg/m^3) and economic water productivity (₹/m^3) were highest among optimal crop mix under non-system and system tank command farms. Participatory water management, adoption of less water-intensive crops, and promotion of pressurized technologies were highly recommended in the study area and similar agro-climatic conditions

Key words: Cropping pattern, Linear programming, Net returns, Optimization, Tank irrigation, Water productivity

HIGHLIGHTS

- Optimization maximized the total net returns from ₹ 4.84 lakhs to ₹ 7.07 lakhs among head, middle and tail end tank commands of non-system tank.
- System tank command regions can maximize the total net farm returns of ₹ 9.67 lakhs from ₹ 8.88 lakhs in the existing situation.
- Optimal crop mix, a shift from water-intensive crops to less-water-intensive crops.
- Improvement in physical and economic water productivity.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Over time, India's net irrigated area has increased significantly from 24.66 million hectares (mha) in 1960 to 71.55 mha in 2018, with the almost tripled net irrigated area. A significant rise in groundwater irrigation occurred quickly, increasing from 29.56% (7.29 mha) to 63.93% (45.75 mha) (Figure 1). The main forces behind the expansion of groundwater irrigation were green revolution technologies and other significant irrigation changes in agriculture. Additionally, throughout time, the area covered by other irrigation sources such as tank irrigation

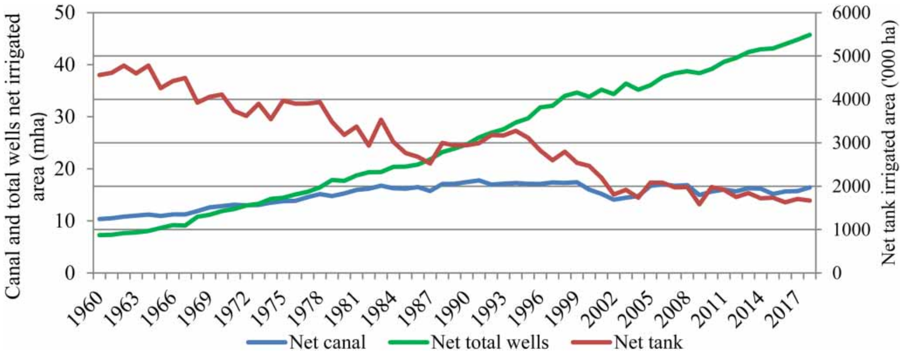


Fig. 1 | Trends in all India source-wise net irrigated area during 1960–2018.

shrunken from 4.56 mha (18.49%) to barely 1.66 mha, or 2.36% (Agricultural Statistics at a glance, DES, GOI, 2021).

Nevertheless, while having many benefits, the area irrigated by tanks has been steadily decreasing since independence. Surprisingly, even in years with normal or above-average rainfall, a decrease in net tank-irrigated area has been noted. While the area irrigated by tanks decreased from 4.56 mha in 1960–61 to 2.71 mha in 1999–2000, its proportion of the net irrigated area substantially decreased over this time from 18.49 to 4.73% on a national scale. In states like Andhra Pradesh, Karnataka, and Tamil Nadu where tank irrigation is still a significant source of irrigation (Narayanamoorthy, 2002; Raju *et al.*, 2004), this reduction is shown to be more pronounced. Social and human-induced factors contributing to a decline in tank performance are encroachment, poor maintenance of surplus weirs and sluices, population density, social forestry, siltation, conflicts over water distribution (Palanisami & Meinzen-Dick, 2001; Palanisami, 2006; Suresh Kumar, 2016; Suresh Kumar & Palanisami, 2020).

While several regions of the country practice tank irrigation, it is mostly dominant in peninsular South Indian states, viz. Andhra Pradesh (13.3%), Tamil Nadu (16.57%), Telangana (10.63%), and Karnataka (6.16%) (Dhawan, 2000; Narayanamoorthy, 2007). Andhra Pradesh state's irrigation pattern has changed over time, improving groundwater irrigation with declining tank water resources, while canals remain the main source of irrigation to date accounting for 46.19% of the state's gross irrigated area. In the 1970s, tanks contributed 0.66 mha to the state's irrigation demands while in the 2020s; they contributed 0.30 mha in 13 districts as depicted in Figure 2. In 2020, the state's net groundwater contribution to agricultural water needs grew 3.5 times to 1.17 mha (Statistical abstracts of Andhra Pradesh 1970–2020). Since the state has most of the nation's tank irrigation area, farmer-friendly and eco-friendly supplies may soon disappear. Studies found that many districts in Andhra Pradesh, particularly in the Rayalaseema region where non-system tanks (rainfed tanks) dominate for irrigation requirements, registered a sharp decline over the decades due to groundwater irrigation which had a negative impact on tank irrigation (Narayanamoorthy *et al.*, 2022).

Despite tank rehabilitation programmes, the tank revival strategies continue to fail mainly due to lack of effective water user associations, erratic rainfall, destructible physical structures, poor maintenance of tanks and weak bunds (Bardhan, 2000; Agarwal *et al.*, 2001; Sakthivadivel, 2005; ADB, 2006; Chakravarthy *et al.*, 2006; Shah, 2009; Kiran Kumara & Kumar, 2019).

Water is a finite resource. In 2001, the per capita water availability was 1,820 m^3 and by 2025, it was predicted to be 1,341 m^3 and by 2050, 1,150 m^3 (Bhattacharyya *et al.*, 2015; Kumari *et al.*, 2017a, 2017b). Due to water

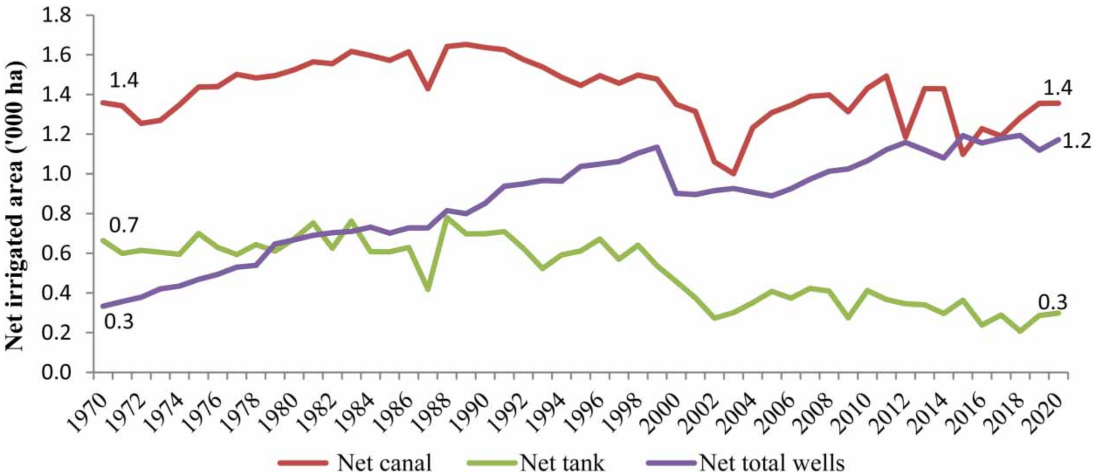


Fig. 2 | Trends in source-wise net irrigated area in Andhra Pradesh (1970–2020).

shortages, Indian farmers dig new wells and compete to deepen open wells (Shaheen & Shiyani, 2005; Devi *et al.*, 2022). Many countries, including India, have a serious water deficit. Agriculture consumes most of India's water; hence water conservation must be prioritized, particularly to conservation of eco-friendly resources like tank irrigation structures.

Water productivity is defined as crop production per cubic meter of water consumption, including 'green' water (effective rainfall) for rainfed areas and 'green' and 'blue' water (diverted water from water systems) for irrigated areas (Cai & Rosegrant, 2003). Water productivity depends on crop patterns, climate (if rainfall supports crop growth), irrigation technology, field water management, land and infrastructure, and inputs like labour, fertilizer and machinery. Water productivity along with effective water allocation will make farming a secure occupation (Zwart *et al.*, 2010). Farm specific crop water requirement and supply estimates with the help of Geographic Information System (GIS) spatial imagery and data set will enhance to design reliable optimal plans (Vibhute *et al.*, 2016). CROPWAT modelling estimates will ease the process by taking location specific climatic spatial data to produce net irrigation water requirements (Sharma & Tare, 2022).

1.1. Research gap and significance

Many studies have concentrated on highlighting the reasons for the decline in tank irrigation and ways to reclaim through different ways and optimization programmes, but this study will find its way to bring optimality among two different scenarios of tank irrigation systems (non-system and system tanks) situated at different agro-climatic zones, among different locations of water reach under tank command like head, middle, and tail end regions, so have broader scope for the results at farm level with similar agro-climatic parameters.

With this background, given constraints in the existing scenario; bringing the available land area under optimal tank irrigation among head, middle and tail end command regions of both tank systems is deemed necessary. Also, maximized net returns for the improved well-being of farming communities with better resource allocation and achieving high water productivity are felt as prime requirements of the study. Consecutively, the study was taken up under two different agro-climatic zones of Andhra Pradesh to represent two different tank irrigation systems, i.e. system tank and non-system tanks in Srikakulam and Chittoor districts to highlight the measures to reclaim tank irrigation structures with changes in resource allocation and optimization of activities under each tank command area (TCA) zone (head, middle, and tail).

1.2. Objectives of the study

This study has four main objectives listed as follows:

i To study the socio-economic conditions of sample farms under each TCA;
ii To evaluate the existing scenario of cropping pattern and net farm returns in the tank command farms;
iii To optimize the irrigation water allocation and net farm returns with optimal crop mix at different locations of water reach and
iv To evaluate water productivity at existing and optimal scenarios with necessary recommendations.

2. METHODS

The present section discusses the conceptual framework of the study, the sampling procedure and data collected for the analysis of the study. The development of optimal models using linear programming techniques separately for non-system and system tank scenarios under head, middle and tail tank commands were discussed. The selection of crop activities under each tank command for *kharif* and *rabi* seasons, given the linear constraints, was also elaborated.

2.1. Study area selection

Andhra Pradesh has the highest net tank-irrigated state with system and non-system tank irrigation systems. System tanks are filled by canals connected to rivers and precipitation, while non-system tanks are only filled by precipitation. This changes the filling pattern, cropping pattern and agricultural production system under tank irrigation. The districts with the highest net tank-irrigated area, i.e. Srikakulam and Chittoor, representing two different tank irrigation systems, and two different agro-climatic zones (North Coastal zone and Southern zone) were selected purposively to delineate the differences in tank irrigation systems.

The system tank is located at 83° 75′ E longitude and 18° 60′ N latitude in the Srikakulam district recharged from Thotapalli left canal of Nagavali river while a non-system tank in the Chittoor district is located at 79°70′ E longitude and 13°75′ N latitude and gets recharged from annual precipitation. To account for changes in cropping patterns, resource endowments and agricultural production from each TCA three villages to represent head, middle, and tail end regions were stratified. Thirty farmers were randomly selected from each region, totalling 90 farmers and 180 farmers from both tank command zones (Table 1).

Table 1 | Sampling of study tank regions based on the type of tank irrigation.

Type of tank irrigation	Sample districts	Sample mandals	Sample villages	Sample respondents
System tank	Srikakulam	Palakonda	Lumburu (Head)	30
			Garugubilli (Middle)	30
			Palakonda (Tail)	30
Non-system tank	Chittoor	Srikalahasti	Uranduru (Head)	30
			Guntakindapalli (Middle)	30
			Maddiledu (Tail)	30
Total				180

2.2. Conceptual framework

The present study assessed and compared the levels of land allocation to the crop mix given the resource constraints and to identify the optimal crop mix for the existing resources so that net farm returns, crop mix and optimal tank water allocation among head, middle, and tail end regions of two different tank systems is achieved. The conceptual framework of the aforesaid model is presented in the flowchart in Figure 3.

2.3. Data and methodology

For the 2021–22 agricultural year, 180 respondents provided primary data for socio-economic analysis, including demographics, farming details, resource use, constraints and production information. The study collected technical coefficients via surveys and estimated irrigation demands and supply using CROPWAT based on 20-year climatic averages (2001–2021). Additionally, remote sensing and GIS methods, including MODIS for cropping intensity and SENTINEL-1 SAR for water spread area were employed to analyze tank systems (Karunakaran & Madhurima, 2024).

2.4. Linear programming and resource optimization

Given the resource use pattern and constraints, attaining more than two objectives simultaneously using linear programming is most desirable among other optimization methods. Attaining economic and allocative efficiencies through maximized net returns and efficient reorganization of resources has always been the major goal of the farming community which can be effectively obtained through linear programming. Hence in the existing scenario, given the linear constraints and activities, linear programming was used to obtain optimal crop mix over the existing cropping pattern, maximum net farm returns over existing scenarios and maximum net irrigable area

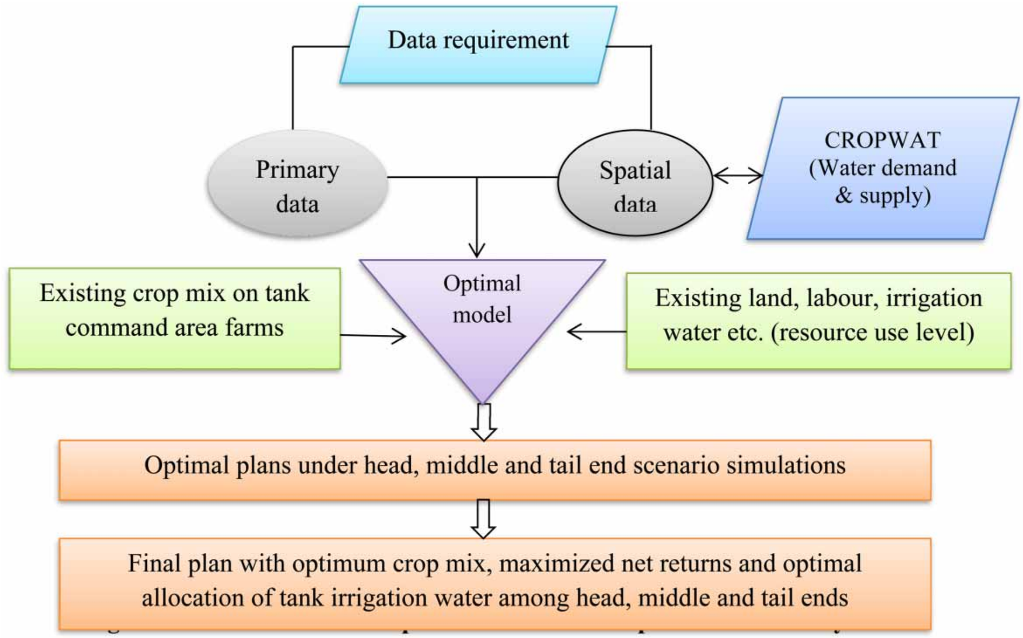


Fig. 3 | Conceptual framework.

with available water resources was done as given by Karunakaran (2004), Karunakaran *et al.* (2012), Muthuraja (2016), Madhurima *et al.* (2023):

$$\text{Maximize } Z = \sum_{i=1}^{n} C_j\ X_j \tag{1}$$

where Z indicates the objective function to be maximized in the year; C_j indicates net returns from jth crop activity in rupees during *kharif* and *rabi* seasons of the year; X_j indicates level of jth crop activity. Crops cultivated in both seasons were considered as separate crop activities in the model; j indicates crop activities considered in the model, such as *Kharif* groundnut, *Kharif* paddy and *Rabi* paddy under non-system tank of head, middle, and tail end regions; and *Kharif* paddy, *Rabi* groundnut, Greengram, Blackgram, Sesame and Planted sugarcane under the system tank of head, middle, and tail end regions.

In the present study, optimization models were implemented separately for head, middle, and tail end regions under both tank systems by following the average farm model approach.

2.4.1. Selection of processes or activities

Using linear programming, optimal solutions require a thorough understanding of the agricultural system in each zone of two tank irrigation systems. Resource availability and enterprise combination under restricted resources are also significant. In the *kharif* season, sample farmers of the system tank followed paddy, groundnut or pulses (greengram and blackgram) or oil seed crop sesame in all head, middle and tail regions. Only head and middle-reach farms followed annually planted sugarcane. In non-system TCA farms, groundnut and 1st paddy in *kharif* and 2nd paddy crop in *rabi*.

2.4.2. Resource constraints

2.4.2.1. Land. In the study, all land-related activities were measured in terms of hectares. Since returns from land vary from season to season, a crop cultivated on the land during a specific season was treated as a separate activity. The head, middle, and tail end sections of both tank command areas were divided into separate irrigated lands:

$$\sum_{j} a_{ij} X_j \leq b_i \tag{2}$$

where a_{ij} indicates the amount of ith land resource required per unit of jth crop activity; b_i indicates total availability of ith land resource on the farm; b_1 is total irrigated area once (same for both seasons); b_2 is rainfed land area; X_j indicates level of jth crop activity in both the seasons; $i = 1$ and 2 for irrigated land and rainfed land.

2.4.2.2. Labour. Family labour along with hired labour was used for all agriculture operations under each region of TCA. Because of this, limitations were placed on the availability of overall labour requirements:

$$\sum_{j} L_j X_j \leq \text{TLA} \tag{3}$$

where L_j indicates the actual amount of labour both hired and family labour used for jth crop activity; TLA indicates the total amount of labour available (both hired and family labour) in a year.

2.4.2.3. Irrigation water. The head, middle, and tail end command farms may not have enough tank irrigation water and other irrigation sources. If irrigation or precipitation fails to meet crop water needs, demand–supply gaps will occur. CROPWAT model determined irrigation water requirements and supply predictions were used as irrigation water constraints:

$$\sum_j X_j \, \mathrm{WD}_j \leq \ \mathrm{WS} \tag{4}$$

where X_j indicates the area under jth crop activity under command area farms; WD_j indicates the irrigation water demand by jth crop activity; WS indicates the irrigation water supply to the jth crop activity.

2.4.2.4. Cash availability. The availability of working capital may not always be adequate to satisfy the needs of diverse agricultural operations. However, it may restrict the scope for implementing enhanced production processes. Due to the impossibility of directly estimating the availability of funds at the beginning of the year (*kharif*), it was determined to use the farm's variable expenses (paid out costs) as a proxy:

$$\sum_j X_j \, E_j \ \leq \ \mathrm{TEA} \tag{5}$$

where X_j indicates the area under jth crop activity; E_j indicates the variable expenses required for the jth crop activity; TEA indicates the total cash available for variable expenses as estimated from the sample farms.

2.4.2.5. Maximum and minimum constraints. Maximum and minimum constraints were employed in the model to get rid of such practically unsatisfactory solutions. The study addresses the minimum area allotted for paddy crops and the maximum area for commercial crops like groundnut and sugarcane under both tank command areas:

$$X_j \ \geq \ A_{\mathrm{min\,j}}$$
$$X_j \ \leq \ A_{\mathrm{max\,j}} \tag{6}$$

where A_j indicates the area under jth crop activity.

2.4.2.6. Non-negativity constraints. Since the resources are real, the values should not be negative for the crop activities (X_j):

$$X_j \ \geq 0 \tag{7}$$

3. RESULTS

This section presents survey estimates of socio-economic conditions, current crop mixes in *kharif* and *rabi* seasons, optimized crop mix for efficient allocation of water resources and maximizing net returns in head, middle, and tail regions. It also discusses improved physical and economic water productivity in optimal plans compared to the existing situation.

3.1. Socio-economic conditions of TCA farms

From the survey estimates (Table 2), it was noticed that system TCA farms have larger average family sizes. Head, middle and tail end farms had an average of four, five, and six members under the non-system command area and five, seven, and eight members under the system TCA, respectively. Tail end farmers had more males, females and children under both the tank commands than middle and head end farmers.

Farm size was found to be the most critical factor affecting production efficiency and average farm family income. Head, middle and tail end farms of both tank systems constituted an average land size of 1.55–4.60 ha, and 1.32–4.0 ha, respectively. The head region farms of both the tank systems had 2.7 (58.69%) and 2.4 ha (60%) of rainfed land, whereas the middle and tail end farms had 1.7 and 1.4 ha and 1.05 and 1.02 ha, respectively.

Head region farms were found to have more irrigated land than middle and tail end tank command farms. Tail-end farms had less access to tank irrigation water and relied more on micro-irrigation. Due to tank irrigation water shortages, dry land farming was found to dominate the tail ends of both command area farms.

3.2. Cropping pattern and net farm returns under existing scenario

The study found that non-system TCA farms followed specialized or double-cropping while system TCA farms diversified or had multiple cropping patterns. Tables 3 and 4 show the cropping pattern and cropping intensity on head, middle and tail end farms of both TCAs.

3.2.1. Existing cropping pattern in non-system TCA farms

The existing crop production programme of head, middle and tail end farmers included groundnut alone on dry land in the *kharif* season. The *kharif* dry land area utilized for groundnut was 2.70, 1.70 and 1.05 ha accounting for 100% of the total *kharif* dry land on all three regions of the command area farms, respectively.

Head, middle and tail end farmers followed groundnut on *kharif* dry land in the existing scenario on 2.70, 1.70 and 1.05 ha of *kharif* dry land accounting for 100% of land under groundnut (Table 3). Paddy was the only *kharif* crop grown on irrigated land by head, middle and tail end non-system TCA farms, which occupied 1.9, 0.9 and 0.5 ha, respectively.

Table 2 | Socio-economic characteristics of the sample farmers.

	Non-system TCA farms				System TCA farms			
Item	**Head ($n = 30$)**	**Middle ($n = 30$)**	**Tail ($n = 30$)**	**All farms ($n = 90$)**	**Head ($n = 30$)**	**Middle ($n = 30$)**	**Tail ($n = 30$)**	**All farms ($n = 90$)**
Family size								
Men	2.0 (50.00)	2.0 (40.00)	2.0 (33.33)	2.0 (40.00)	2.0 (40.00)	3.0 (42.86)	3.0 (37.50)	3.0 (42.86)
Women	1.0 (25.00)	2.0 (40.00)	2.0 (33.34)	2.0 (40.00)	2.0 (40.00)	2.0 (28.57)	3.0 (37.50)	2.0 (28.57)
Children	1.0 (25.00)	1.0 (20.00)	2.0 (33.33)	1.0 (20.00)	1.0 (20.00)	2.0 (28.57)	2.0 (25.00)	2.0 (28.57)
Total	4.0 (100.0)	5.0 (100.0)	6.0 (100.0)	6.0 (100.0)	5.0 (100.0)	7.0 (100.0)	8.0 (100.0)	7.0 (100.0)
Average farm size (ha)								
Dry land	2.70 (58.69)	1.70 (65.38)	1.05 (67.75)	3.41 (73.00)	2.40 (60.00)	1.40 (70.00)	1.02 (77.27)	3.21 (78.00)
Irrigated land	1.90 (41.31)	0.90 (34.62)	0.50 (32.25)	1.26 (27.00)	1.60 (40.00)	0.60 (30.00)	0.3 (22.73)	0.89 (22.00)
Total	4.60 (100.0)	2.60 (100.0)	1.55 (100.0)	4.67 (100.0)	4.00 (100.0)	2.00 (100.0)	1.32 (100.0)	4.10 (100.0)

Note: TCA, tank command area, figures in parentheses indicate percentages.

Table 3 | Existing cropping pattern under non-system tank command area farms (hectares).

Item	Head	Middle	Tail
Kharif rainfed land			
Groundnut	2.70 (100.00)	1.70 (100.00)	1.05 (100.00)
Total *Kharif* rainfed land	2.70 (100.00)	1.70 (100.00)	1.05 (100.00)
Kharif irrigated land			
Paddy	1.90 (100.00)	0.90 (100.00)	0.5 (100.00)
Total *kharif* irrigated land	1.90 (100.00)	0.90 (100.00)	0.5 (100.00)
Rabi-irrigated land			
Paddy	1.90 (100.00)	0.90 (100.00)	0.5 (100.00)
Total *rabi*-irrigated land	1.90 (100.00)	0.90 (100.00)	0.5 (100.00)
Gross cropped area (ha)	6.50	3.50	2.05
Net cropped area (ha)	4.60	2.60	1.55
Cropping intensity (per cent)	141.30	134.61	132.25

Note: Figures in parentheses are percentages to the total.

Table 4 | Existing cropping pattern under system tank command area farms (Hectares).

Item	Head	Middle	Tail
Kharif irrigated land			
Paddy	1.2 (75.00)	0.5 (83.33)	0.3 (100.00)
Sugarcane	0.4 (25.00)	0.1 (16.67)	-
Total *kharif* irrigated land	1.6 (100.00)	0.6 (100.00)	0.3 (100.00)
Rabi rainfed land			
Groundnut	2.4 (100.00)	1.40 (100.00)	1.02 (100.00)
Total *rabi* rainfed land	2.40 (100.00)	1.40 (100.00)	1.02 (100.00)
Rabi-irrigated land			
Greengram	0.5 (41.67)	0.2 (40.00)	0.1 (33.33)
Blackgram	0.5 (41.66)	0.2 (40.00)	0.1 (33.33)
Sesame	0.2 (16.67)	0.1 (20.00)	0.1 (33.34)
Total *rabi*-irrigated land	1.2 (100.00)	0.5 (100.00)	0.3 (100.00)
Gross cropped area (ha)	5.2	2.5	1.62
Net cropped area (ha)	4.0	2.0	1.32
Cropping intensity (per cent)	130.00	125.00	122.72

Note: Figures in parentheses are percentages to the total.

Head, middle and tail end farmers chose paddy crop alone as the second crop on *rabi*-irrigated land. It occupied the entire irrigated land by 1.9, 0.9 and 0.5 ha in head, middle, and tail end farms accounting for 100%. From Table 3 it was observed that double-cropping of paddy was being followed under irrigated conditions of non-system TCA farms. *Rabi* dry land was held fallow under non-system TCA farms.

In the existing situation, head region farms had 141.30% cropping intensity, followed by middle (134.61%) and tail end farms (132.25%). Groundnut was the main oil seed crop on *kharif* dry land. Paddy inhabited entire *kharif* and *rabi*-irrigated areas of head, middle and tail end farms.

The input usage with average women labour was found highest in the head region with 160 woman days, the average yield of groundnut under the existing scenario was 27.53 quintals/ha, *kharif* paddy – 68.11 quintals/ha and 72.28 quintals/ha for *rabi* paddy. Cattle pairs were found only for groundnut, recorded 4.12 pair days for middle end farms with an average groundnut yield of 28.25 quintals/ha. Tail end farms were found to be resource-poor. Due to lack of resources and less irrigated land under crops, realized average yields were 27.12 quintals/ha for groundnut and 65.24 and 69.24 quintals/ha for two paddy crops. (*Note:* Data on crop-wise, growth-wise and tank-wise irrigation water requirements and supply estimates are given in Supplementary material).

3.2.2. Existing cropping pattern system TCA farms

The farming community under system TCA farms followed multiple cropping or diversified cropping due to assured water supply from both tank and canal systems. Tail end farmers grew paddy alone on *kharif* irrigated land (sugarcane was absent due to high variable expenses and irrigation water constraints) whereas head and middle end farmers followed paddy along with annually planted sugarcane. It can be noted from Table 4 that paddy occupied 1.2, 0.5 and 0.3 ha on head, middle and tail end farms, whereas sugarcane occupied 0.4 (25%) and 0.1 (16.67%) in head and middle region farms of the TCA.

All farms in the command area followed groundnut in *rabi* dry land. *Rabi*-irrigated land had pulses, sesame and sugarcane. Blackgram and greengram took up 40 and 33.33% of land in middle and tail end farms, respectively, and 41.67% in the head region.

Head farms had the highest cropping intensity (130%), followed by middle (125%) and tail ends (122.72%). Tail end cropping intensity was lower due to reduced tank and canal water supplies than head and middle regions. The input usage was highest with an average number of men labour for the annual crop sugarcane followed by *kharif* paddy (410 and 76.12 man days) among head farms with an average jaggery yield of 1,231.1 quintals/ha. Pulses and sesame required the lowest inputs among all the regions. Average yields realized were high and similar among head and middle regions, while tail end regions recorded lower average yields for all crops, i.e. 50.42, 30.12, 13.38, 10.27 and 6.14 quintals/ha (*kharif* paddy, groundnut, greengram, blackgram and sesame).

3.2.3. Net farm returns under non-system tank

According to the estimates on sample farms (Table 5), the overall cost of cultivation for *kharif* groundnut was found to be higher among head end farms by ₹ 83,512, followed by middle and tail end farms in *kharif* rainfed situations. However, average net farm returns realized were lowest in head farms (₹ 2,888), followed by tail end farms (₹ 6,216), and highest among middle command area farms (₹ 8,130).

Variable costs have increased due to increasing per-hectare manpower, fertilizer usage and other cash expenses, lowering the net returns in the head region. While the cost of cultivation for head end *kharif* paddy crop was high (₹ 1, 31,955), the net farm returns realized were ₹ 17,645 due to a minor fall in yields, resulting in two-fold loss of yield and net farm returns. The tail end region realized total net farm returns of ₹ 15,444 and ₹ 26,100 for the two paddy crops.

3.2.4. Net farm returns under system tank scenario

From the results of Table 6 it was observed that the net farm returns and costs scenario were unique among head, middle and tail end farms of the system tank.

Table 5 | Costs and returns (in ₹/hectare) under non-system tank command area crops.

	***Kharif* Groundnut**			***Kharif* Paddy**			***Rabi* Paddy**		
Costs and returns	**Head**	**Middle**	**Tail**	**Head**	**Middle**	**Tail**	**Head**	**Middle**	**Tail**
Total variable costs	67,202	65,360	64,424	101,955	99,695	98,106	95,280	95,690	96,250
Total fixed costs	16,310	16,110	15,760	30,000	29,800	29,450	30,000	29,800	29,450
Total costs	83,512	81,470	80,184	131,955	129,495	127,556	125,280	125,490	125,700
Total yield (quintals/ha)	27.53	28.25	27.12	68.11	68.12	65.24	72.28	73.23	69.24
Gross margin (TR – TVC)	19,198	24,240	21,976	47,645	49,905	44,894	63,120	64,910	55,550
Net profit (TR – TC)	2,888	8,130	6,216	17,645	20,105	15,444	33,120	35,110	26,100

Table 6 | Costs and returns (in ₹/hectare) under system tank command area crops.

	***Kharif* Paddy**			***Rabi* Groundnut**			***Rabi* Greengram**		
Costs and returns	**Head**	**Middle**	**Tail**	**Head**	**Middle**	**Tail**	**Head**	**Middle**	**Tail**
Total variable costs	128,905	126,595	109,156	77,652	78,260	74,274	30,820	29,725	29,750
Total fixed costs	30,000	29,800	29,450	16,310	16,110	15,760	10,810	10,610	10,260
Total costs	158,905	156,395	138,606	93,962	94,370	90,034	41,630	40,335	40,010
Total yield (quintals/ha)	55.21	55.11	50.42	33.21	32.18	30.12	13.25	12.16	13.38
Gross margin (TR – TVC)	36,095	38,405	40,844	37,848	33,740	30,726	47,180	42,275	48,250
Net profit (TR – TC)	6,095	8,605	11,394	21,538	17,630	14,966	36,370	31,665	37,990
	***Rabi* Blackgram**			**Sesame**			**Sugarcane**		
Costs and returns	**Head**	**Middle**	**Tail**	**Head**	**Middle**	**Tail**	**Head**	**Middle**	
Total variable costs	30,520	29,625	29,650	27,620	25,825	24,200	392,180	383,990	
Total fixed costs	10,810	10,610	10,260	10,810	10,610	10,260	67,800	67,400	
Total costs	41,330	40,235	39,910	38,430	36,435	34,460	459,980	451,390	
Total yield (quintals/ha)	12.25	12.33	10.27	8.25	8.11	6.14	1,231.3	1,202.1	
Gross margin (TR – TVC)	29,480	30,375	20,350	28,380	30,175	17,800	99,820	96,010	
Net profit (TR – TC)	18,670	19,765	10,090	17,570	19,565	7,540	32,020	28,610	

Despite water supply and average land area limits, tail end farms *kharif* paddy produced the greatest net farm returns of ₹ 11,394, followed by middle and head end farms (₹ 8,605 and ₹ 6,095). More micro-irrigation water resources in tail end farms alleviated tank water limitations.

Net returns from pulses were prominent among all the command area farms due to the lower cost of cultivation. The total costs were highest among head end region farms (except for *rabi* groundnut) followed by middle and tail end farms.

Though sugarcane was present among head and middle regions, the net farm returns of pulses (greengram) outweighed those from sugarcane (₹ 32,020 and ₹ 28,610) because sugarcane occupied less area with higher total variable costs (including maintenance and crusher costs).

3.3. Cropping pattern and net farm returns under optimal situations

The study examined how optimality can be achieved with an increase in net returns through a variety of activities and capital conditions by simulating the basic models of head, middle, and tail end areas with total borrowing constraint relaxation. Tables 7 and 8 and Figure 4 show optimal cropping patterns and net farm returns for both tank command zones.

3.3.1. Non-system tank scenario

3.3.1.1. Head, middle and tail end TCA farms. The head end farms optimal plan emphasized resource reorganization and income enhancement via two-crop activities with available tank water. It suggested reducing *kharif* groundnut to 0.5 ha, allocating 0.99 and 0.81 ha for irrigated *kharif* and *rabi* paddy, and enhancing cropping intensity to 153%. With 1.5 ha net sown area and 2.3 ha gross cropped area, it achieved

Table 7 | Cropping pattern for non-system tank command area farms under optimal plans (hectares).

	Head		Middle		Tail	
Crop	**Existing**	**Optimal**	**Existing**	**Optimal**	**Existing**	**Optimal**
Kharif dry land						
Groundnut	2.70 (100.00)	0.5 (100.00)	1.7 (100.00)	1.7 (100.00)	1.05 (100.00)	1.00 (100.00)
Total	2.70 (100.00)	0.5 (100.00)	1.7 (100.00)	1.7 (100.00)	1.05 (100.00)	1.00 (100.00)
Kharif irrigated land						
Paddy	1.90 (100.00)	0.99 (100.00)	0.9 (100.00)	0.8 (100.00)	0.50 (100.00)	0.50 (100.00)
Total	1.90 (100.00)	0.99 (100.00)	0.9 (100.00)	0.8 (100.00)	0.50 (100.00)	0.50 (100.00)
Rabi-irrigated land						
Paddy	1.90 (100.00)	0.81 (100.00)	0.9 (100.00)	0.8 (94.44)	0.50 (100.00)	0.50 (100.00)
Total	1.90 (100.00)	0.81 (100.00)	0.9 (100.00)	0.8 (100.00)	0.50 (100.00)	0.50 (100.00)
Net sown area	4.6	1.5	2.6	2.5	1.55	1.50
Gross cropped area	6.5	2.3	3.5	3.3	2.05	2.00
Cropping intensity (per cent)	141.30	153.0	134.62	132.0	132.26	133.33
Net farm returns for total cultivated area (in ₹ lakh)	2.46	2.63	1.64	2.52	0.74	1.92
Net returns per hectare of cultivated area (in ₹ lakh)	0.53	1.14	0.63	0.76	0.47	0.96
Per cent change in optimal plan to existing plan net returns	–	6.91	–	53.27	–	160
Net returns/TVC for the net sown area	0.21	0.66	0.24	0.38	0.18	0.5
Monthly net returns (in ₹/month/hectare)	4,417	9,500	5,250	6,333	3,917	8,000

Note: Figures in parentheses are percentages to the total.
Source: Linear programming technique and author's estimates from the survey.

Table 8 | Cropping pattern for system tank command area farms under optimal plans (hectares).

	Head		Middle		Tail	
Crop	**Existing**	**Optimal**	**Existing**	**Optimal**	**Existing**	**Optimal**
Kharif irrigated land						
Paddy	1.2 (75.00)	1.45 (90.63)	0.5 (83.33)	0.44 (73.33)	0.3 (100.00)	0.3 (100.00)
Sugarcane	0.4 (25.00)	0.15 (9.97)	0.1 (16.67)	0.16 (26.67)	–	–
Total	1.6 (100.00)	1.6 (100.00)	0.6 (100.00)	0.6 (100.00)	0.3 (100.00)	0.3 (100.00)
Rabi dry land						
Groundnut	2.4 (100.00)	2.4 (100.00)	1.4 (100.00)	1.4 (100.00)	1.02 (100.00)	1.02 (100.00)
Total	2.4 (100.00)	2.4 (100.00)	1.4 (100.00)	1.4 (100.00)	1.02 (100.00)	1.02 (100.00)
Rabi irrigated land						
Greengram	0.5 (31.25)	1.25 (86.22)	0.2 (40.00)	0.24 (30.76)	0.1 (33.34)	0.1 (33.34)
Blackgram	0.5 (31.25)	0.1 (6.89)	0.2 (40.00)	0.1 (12.82)	0.1 (33.33)	0.1 (33.33)
Sesame	0.2 (12.5)	0.1 (6.89)	0.1 (20.00)	0.44 (56.42)	0.1 (33.33)	0.1 (33.33)
Total	1.2 (100.00)	1.45 (100.00)	0.5 (100.00)	0.78 (100.00)	0.3 (100.00)	0.3 (100.00)
Net sown area	4.0	4.0	2.0	2.0	1.32	1.32
Gross cropped area	5.2	5.45	2.5	2.78	1.62	1.62
Cropping intensity (per cent)	140.0	136.25	130.0	132.25	122.72	122.72
Net farm returns for total cultivated area (in ₹ lakh)	5.29	5.35	2.51	2.61	1.08	1.71
Net farm Returns per hectare of cultivated area (in ₹ lakh)	1.32	1.33	1.25	1.30	0.81	1.29
Per cent change in optimal plan to existing plan net returns	–	1.14	–	3.68	–	58.03
Net returns/TVC for the net sown area	0.192	0.194	0.186	0.193	0.307	0.485
Monthly net returns (in ₹/month/hectare)	11,000	11,083.3	10,416.7	10,833.3	6,750	10,750

Source: Linear programming technique and author's estimates from the survey.

higher yields using fewer resources. Average net farm returns improved by 6.91%. Monthly returns rose significantly, from ₹ 4,417 thousand in the existing scenario to ₹ 9,500 thousand with optimal allocation.

The optimal model for middle end tank command farms proposed keeping groundnut production constant with the existing scenario. The optimal plan suggested reducing paddy production under *kharif* and *rabi*-irrigated lands from 0.9 to 0.8 ha in both seasons. The optimal plan resulted in lowering the cropping intensity from 134.62 to 132.62%, but with sufficient funds (both owned and borrowed), planning and reorganization of minimum land and water resources, net farm returns for the cultivated area increased from 1.64 lakh rupees to 2.52 lakh rupees.

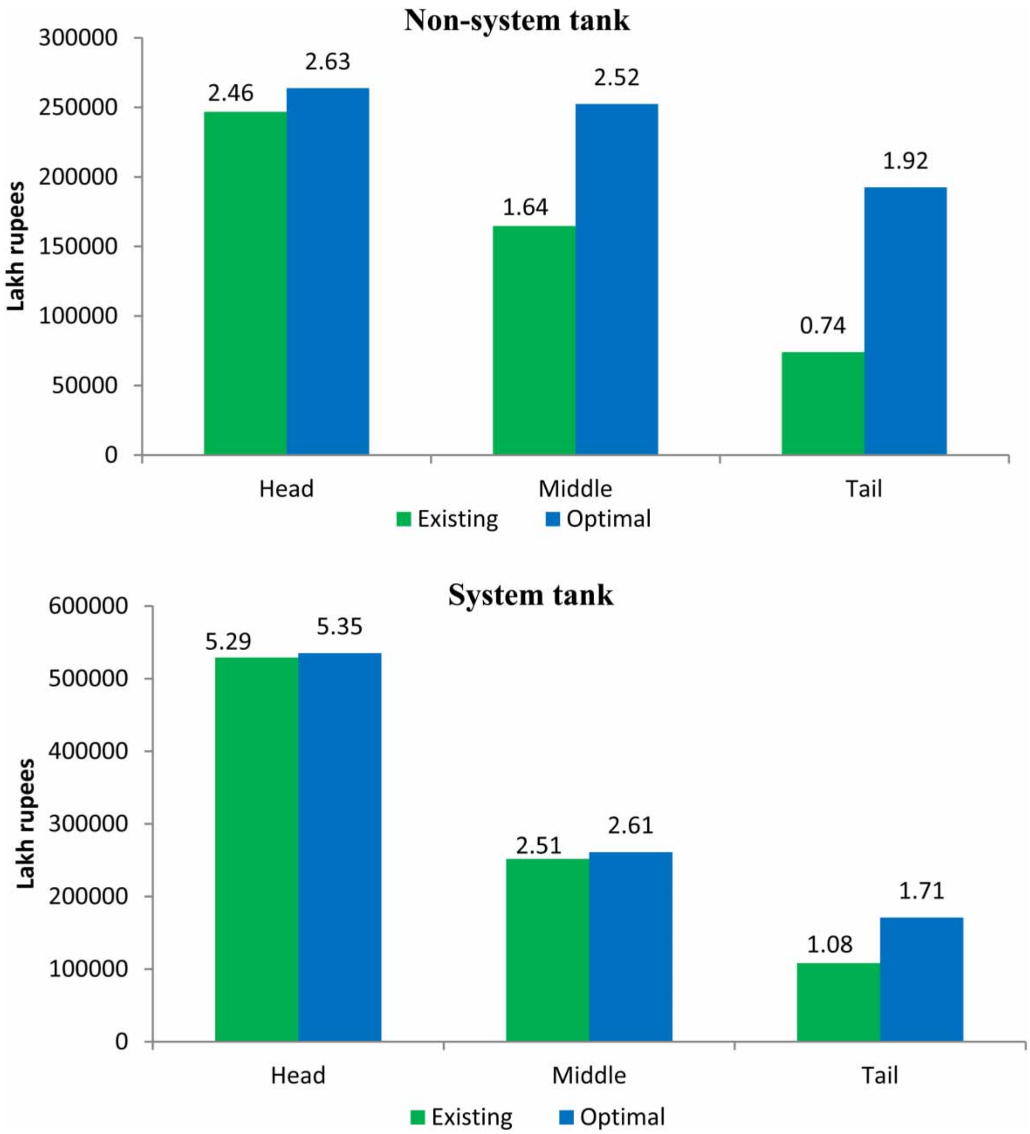


Fig. 4 | Net farm returns of head, middle, and tail end regions under non-system and system tank command area farms.

Tail end command area farms under non-system tank scenarios were found to be resource deprived. The optimal solution has not reduced paddy crop activities under irrigated conditions. Under *kharif* dry land groundnut area is suggested to be 1.00 ha as against 1.05 ha in the existing situation. The cropping intensity increased from 132.26% in the existing plan to 133.33% in the optimal solution. The net farm returns/ha realized were 0.96 lakh rupees under optimal solution over 0.47 lakh rupees under the existing situation.

The per cent change in net farm returns was found to be highest in tail end farms by 160% followed by middle and head regions. Net returns to the total variable expenses for the net sown area under optimal plans were found to be highest in the head end by 0.66 followed by the tail end by 0.5 and middle region farms by 0.38, respectively.

The realization of monthly net returns contributed more than 100% change under tail end farms from ₹ 3,917 to ₹ 8,000 with optimization.

From the foregoing discussion, it can be deduced that there was improper resource allocation in the existing plans. Optimization resulted in the improvement of net farm returns in the head, middle (less land, more returns) and tail end farms under the TCA.

3.3.2. System tank scenario

3.3.2.1. Head, middle and tail end TCA farms. In the *kharif* season, the head region's optimal plan recommended increasing irrigated paddy area to 1.45 ha and reducing sugarcane cultivation to 0.15 ha from 0.4 ha. *Rabi* rainfed conditions maintained groundnut at 2.4 ha. The optimal plan prioritized green gram, raising its area to 1.25 ha while reducing black gram and sesame to 0.1 ha each. Resource optimization maintained a 4.0-ha net sown area, yielding ₹ 5.35 lakhs in net farm returns. The dominance of groundnut, paddy and green gram resulted in monthly net returns rising to ₹11,083.3 from ₹11,000 under head end scenarios.

In the middle end optimal model, 0.44 ha of *kharif* irrigated land was recommended for paddy crop, down from 0.5 ha. The ideal strategy raised sugarcane acreage to 0.16 ha from the current 0.1 ha. Groundnut was maintained the same at 1.4 ha under the optimal plan. As in head end farms, greengram was found to be the most profitable enterprise on *rabi*-irrigated land. The improvement in cropping intensity was observed from 130% in existing situations to 132.25% in optimal solution with the realization of ₹ 2.61 lakh net farm returns.

Tail end farms were resource-poor; therefore no enterprise was eliminated and existing crop combination was redistributed according to plan. The net sown and gross cropped areas remained the same by 1.32 and 1.62 ha in optimal plans. Relaxed borrowing and credit availability can increase net farm returns to ₹ 1.71 lakhs from ₹ 1.08 lakhs. Net returns to total variable expenses were highest in the tail end by 0.485, followed by head (0.194) and middle (0.193).

From the previous explanation it was inferred that, though system TCA farms followed a multi-cropping pattern, due to resource misallocation, head and middle end regions had larger cropping intensity than tail end regions.

3.4. Water productivity under TCA crops

Water productivity for non-system and system tanks was calculated in both physical and monetary terms. Per-unit-water-used plans are compared from existing to optimal solutions. From Table 9 it was clear that under the non-system tank scenario, the water used per kg of groundnut crop was 1,810 m^3/ha under the existing scenario than the optimal use of 574 m^3/ha. By reducing the overusage and allocating minimal land area, the optimal plan realized 2,915.2 kg/ha and ₹ 21,481/ha of groundnut yield and net farm returns with 5.07 kg/m^3 of physical water productivity. Due to less allocation of the irrigated area under optimal plans for both paddy crops, yield and net returns realized were 5,114.33 kg/ha and ₹ 39,686.5/ha which led to reduced water productivity.

Under the system tank scenario, for all the crops the yield per unit of water used was improved except for sugarcane, as the optimal plan does not consider the enterprise feasible. As the tank system is dependent on canal and precipitation, the area under paddy was suggested to be more in optimal plans than existing plans so that the water productivity improved by 1.44 kg/m^3 and 5.94 ₹/m^3 as against 0.96 kg/m^3 and 3.24 ₹/m^3. The area under sugarcane was reduced as the requirement for irrigation water was highest among all other crops. The water productivity for less water-consuming crops like pulses (0.11 kg/m^3 and 9.24 ₹/m^3 against 0.1 kg/m^3 and 6.67 ₹/m^3) were improved with improvement in yield and net returns in optimal plans against existing scenarios to the extent of 392.33 kg/ha against 320 kg/ha and ₹ 30,856.8/ha against ₹ 21,307/ha. The comparison also revealed that water productivity was improved for sesame and groundnut enterprises.

Table 9 | Water productivity under non-system and system tank scenario.

TCA	Crops	Water used (m^3/ha)		Yield (kg/ha)		Net farm returns (₹/ha)		Physical water productivity (kg/m^3)		Economic water productivity (₹/m^3)	
		Existing	Optimal	Existing	Optimal	Existing	Optimal	Existing	Optimal	Existing	Optimal
Non-system tank	*Kharif* Groundnut	1,810	574	4,964.95	2,915.2	32,185.8	21,481	2.74	5.07	17.78	37.42
	Kharif Paddy	4,670	4,702	7,370.00	5,114.33	59,342	39,686.5	1.57	1.08	12.71	8.44
	Rabi Paddy	7,140	8,721	7,846.66	5,016.87	107,577	67,965.2	1.09	0.57	15.06	7.79
System tank	*Kharif* Paddy	4,640	2,697	4,444.44	3,893.33	15,034.7	16,042.15	0.96	1.44	3.24	5.94
	Rabi Groundnut	4,760	3,749	5,087.77	5,087.77	152,132.7	152,132.7	1.06	1.35	31.96	40.57
	Pulses	3,190	3,337	320.00	392.33	21,307	30,856.8	0.10	0.11	6.67	9.24
	Sesame	2,370	2,916	97.77	156.44	6,224.5	11,119.6	0.04	0.05	2.62	3.81
	Sugarcane	11,480	10,467	3,037.5	1,883.25	15,669	9,380.6	0.26	0.17	1.36	0.89

4. DISCUSSION

Non-system tank scenario was found to be dominated by paddy crops and very less of groundnut in the command area farms of the study tank which was found to be in conformity with the studies by Palanisami (1993) where the tank-irrigated regions were found to primarily grow rice, with non-rice crops in the second season of Tamil Nadu, India due to pure dependence of tank systems on rainfall. Studies by Kiran Kumara *et al.* (2022) depicted that cropping pattern in *kharif* under tank command farms in the Ananthapur district of Andhra Pradesh occupied majorly by rice and maize followed by groundnut and mulberry and in *rabi* maize, groundnut and rice were adopted. Studies by Ramyaa *et al.* (2023) revealed that in Khammam and Warangal districts of Telangana state, paddy was the only crop followed under tank commands in *kharif* with annual crops cotton and chillies, while in *rabi* paddy, pulse crops and vegetable crops (onion, brinjal and tomato) were followed under irrigated dry conditions under the TCA farms.

The optimality improved cropping pattern under groundnut compared to paddy under the non-system tank scenario of the present study while greengram (pulse crops) dominated with improvement in cropping pattern under system tank scenario along with the significant area under paddy crops (as the canal water supply is supplemented with tank irrigation) under head, middle, and tail end regions in both the seasons. The results were compatible with the studies of Palanisami (1993) where optimality with 25% rice and 75% non-rice crops, were more effective than the existing 100% rice practice and studies of Ramyaa *et al.* (2023) where cropping pattern change from paddy to irrigated dry crops improved the cultural command area of the tanks by 79%.

Due to effective reorganization of resources and optimal cropping patterns, net returns in the existing scenario of study tank tail, middle and head command regions of ₹ 0.74, ₹ 1.64 and ₹ 2.46 lakhs were significantly maximized by ₹ 1.92, ₹ 2.52 and ₹ 2.63 lakhs under non-system tank farms and system tank command farms realized maximized net returns by ₹ 1.71, ₹ 2.61 ₹ 5.35 lakhs, respectively. The results are in conformity with studies of Singh *et al.* (2001) where the optimal cropping pattern for the 11,818-ha command area of Shahi distributary canal and groundwater control can maximize net farm returns to ₹ 185 million. Studies by Karunakaran *et al.* (2012) developed a suitable crop-land-use pattern which maximized net returns for the Western zone of the Bhavani river basin in Tamil Nadu by ₹ 6.14–₹ 8.25 billion yearly.

Work by Kumari *et al.* (2017a, 2017b) have shown that an optimized cropping plan has increased farm income by 7% with a net reduction in 6% of irrigation water use in Eastern Uttar Pradesh. Shreedhar *et al.* (2015) show that using a multi-crop model, optimal cropping pattern for the Markandeya command area in Karnataka state can improve net farm returns from ₹ 53.2 crores for 2,000 ha-m of water availability to ₹ 78 crores for 5,000 ha-m of water. Munas & Pathirana (2019) estimates for maximized net farms were ₹ 60 million over the traditional cropping methods with net farm returns ₹ 26 million for the Kalugal Oya project in Ampara District, Sri Lanka. Ramyaa *et al.* (2023) have discovered that the substitution of paddy with irrigated dry crops in tank command farms with water-saving technologies can improve net farm returns by 43%. Works of Kiran Kumara *et al.* (2022) have proved that improved tank irrigation methods can enhance the net farm returns by 25% and overall gross cropped area by 9%, respectively.

Optimality in the cropping pattern and available tank water reorganization showed that water productivity can be improved both in physical and monetary terms for less water-intensive crops like groundnut under a non-system tank and pulses under a system tank which were found compatible with collateral studies of Sathish Kumar *et al.* (2012) where minimum water productivity of ₹ 1.34/m^3 can be achieved by paddy crop alone while maximum water productivity of ₹ 3.77/m^3 to ₹ 4.61/m^3 with optimal cropping patterns under tank systems and the studies of Kumar *et al.* (2009) show that economic water productivity can be improved by optimal input use and enhanced quality of irrigation water from ₹ 4.61/m^3 to ₹ 5.61/m^3.

The study was conducted within two tank command systems with specific socio-economic and agro-climatic variables, thus any generalization of the results may be prejudiced. Crop enterprises alone are analyzed for optimal plans on an average farm. Farmer interviews based on memory recall provided primary data on input costs, yield and output prices, irrigations per crop and growth stage, etc., had inherent limitations.

5. CONCLUSIONS

The study of non-system and system tanks in Andhra Pradesh shows how variations in agricultural production, human-induced, and climatic factors affect tank water supply to head, middle, and tail ends. Linear programming approach optimized resource misallocation given the resource constraints. Double-cropping with 100% paddy and groundnut in *kharif* and *rabi* seasons was practiced under non-system tanks. Command area farms' double-cropping pattern was mainly due to encroachment and rainfall variability. System TCA farms followed a multi-cropping pattern with no sugarcane in the tail end region due to irrigation water constraints. Head regions had the highest cost of cultivation and net returns under both tank command farms, followed by middle and tail ends.

In the non-system tank scenario, optimal plans reduced high-water-consuming paddy in both seasons, but tail end farms did not remove cropping due to resource scarcity. Optimization improved net farm returns highly under tail end farms (159.89%), followed by middle (53.27%) and head end farms (6.91%) through resource reorganization. In system tank optimal plans, pulses and sesame were enhanced, greegram was found to be the best enterprise (75, 43.32 and 33.34%), and sugarcane occupied very little. Tail end net returns were maximized to 58.03% followed by middle and head regions. As the system utilizes canal and tank water systems, optimal plans for paddy, sesame and pulses were larger than existing plans both in physical and monetary terms as proved in water productivity.

Farmer's participatory approach and strengthening water user's associations for efficient tank water management, adoption of less water-intensive crops under study tank commands to improve water productivity and water conservation, especially under non-system tanks and adoption and promotion of pressurized irrigation technologies for effective tank water utilization measures were highly recommended. However, the study can be extended to the regional and state levels for further research to draw explicit policy measures for water conservation and revival of tank irrigation.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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