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Maximizing net income and economic water productivity in a canal command through conjunctive use of canal water and groundwater

A. Dalai[1,*], A. Mishra[2], M.P. Tripathi[1], V.K. Pandey[1] and R.R. Mohanty[3]

[1]Department of Soil and Water Engineering, Swami Vivekanand College of Agricultural Engineering and Technology and Research Station, Indira Gandhi Krishi Viswavidyalaya, Raipur, Chhattishgarh; [2]ICAR-Indian Institute of Water Management, Bhubaneswar; [3]Agro Polytechnic Centre, Rourkela, Odisha University of Agriculture and Technology, Bhubaneswar.

**Corresponding author:*
E-mail: dalaiabinash500@gmail.com (A. Dalai)

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ABSTRACT

This study was taken up in the Phulnakhara distributary command of Puri main canal system located partly in Cuttack and partly in Khurda districts of Odisha at 20^{0}19'15.6"N to 20^{0}14'56.4"N latitudes and 85^{0}52'51.6"E to 86^{0}0'0"E longitudes and 28 m above mean seal level (amsl). In the said command area, an optimization model was formulated for finding optimal cropping pattern with conjunctive use of surface and groundwater. Based on the goal programming (GP), the optimization model maximized the net annual income and economic water productivity from the canal command area. Along with the optimal cropping pattern for the command area, groundwater draft required to meet the irrigation demand of the crops in conjunction with surface water was obtained from the optimization model. After maximizing the net annual income and economic water productivity from the command area, no groundwater was required to meet the irrigation water requirement in *kharif* for the dry year (2015-16), normal year (2016-17) and the wet year (2017-18), respectively. Whereas, the highest and the lowest irrigation water requirement met from the groundwater in *rabi* were 210.14 lakh m^3 (2015-16) and 176.80 lakh m^3 (2016-17), respectively. The 10-years average irrigation water requirement met from the groundwater in *rabi* obtained from the optimization model for the canal command was 182.33 lakh m^3. The highest and the lowest obtained net annual income were ₹ 101.01 crores in 2017-18 (wet year) and ₹ 98.75 crores in 2015-16 (dry year), respectively. The highest and the lowest obtained economic water productivity were ₹ 16.92 m^{-3} (normal year) and ₹ 15.51 m^{-3} (dry year).

1. INTRODUCTION

Soil and water are the essential resources for all forms of life on earth. Water resource takes into account both the surface water and groundwater resources. Conjunctive use of water in a canal command area refers to the combined use of surface water and groundwater for crop production. The water productivity in a canal command area should be maximized by efficient utilization of water resources for sustainable production and productivity. Timely water supply to crops as per the requirement is the prime factor for enhancing productivity. Swift industrialization, rapid urbanization, exponentially rising population coupled with increasing demand for food grains are the major components placing more and more constraint on land and water resources. Now, numerous parts of the globe are putting up with water paucity and water allocation to irrigation sector is dropping. The production per unit area needs to be maximized from limited water resources combining both surface water and groundwater.In the eastern part of India, specifically in the coastal districts of Odisha, during *kharif* season, more than the required amount of water is delivered in the canal system as the irrigation systems are mostly runoff-the-river scheme (Mishra *et al.,* 2008). On the contrary in *rabi* season, the canals do not flow at their full supply level as a result of which the total irrigation demand of the command areas are not met leading the poor productivity and cropping intensity. Since plenty of groundwater is available in the command area, conjunctive use of surface water along with groundwater thought to be an ideal water management solution to meet the crop water requirement of *rabi* season. A suitable optimization model is also thought to be appropriate tool in deciding the optimal cropping pattern and thereby the groundwater requirement to be used in conjunction with available canal water for meeting the crop water requirement.

A monthly irrigation planning model was formulated for determining the optimal cropping pattern and the ground water abstraction requirement in an existing groundwater development project under uncertainty of rainfall (Mainuddin *et al.*, 1997). A multi-objective model was formulated for the optimal allocation of resources like land, crop and water resources of Kosi irrigation system in Nepal. Weighted goal programming (GP) technique is employed for optimal allocation of resources for a compromising solution to decision makers for economic, health and environmental goal (Jha and Singh, 2008). An optimal crop planning model was developed, to find net return for different seasons and for different years *viz.,* wet, normal, dry and conjunctive use of water resources in a coastal river basin. The net annual return of the basin is the highest for the wet years and the optimal cropping pattern, net return for different seasons and groundwater management plan were formulated (Rejani *et al.,* 2009). An optimization model was formed to determine optimal cropping pattern and groundwater allocation from private and government tube wells according to different soil types (saline and non-saline), type of agriculture (rainfed and irrigated), seasons (monsoon and winter) and for wet, normal and dry years. (Sethi *et al.*, 2002). A GP approach for watershed planning of Mandakini Balinala watershed No.1 was solved. The maximization in production helped to increase the net return from this watershed, thereby improving the socio-economic condition of the farmers (Paul *et al.*, 2015). Irrigation planning and scheduling are essential components of water management in irrigated agriculture, which involves optimal allocation of land and water by optimizing cropping pattern of the Barna irrigation project under a set of limitations (Vivekanandan and Viswanathan, 2007). A multi objective optimization model was developed to determine the optimal size of auxiliary storage reservoir and optimal cropping pattern (Mishra *et al.,* 2009). A linear programming model was formulated to suggest the optimal cropping pattern giving the maximum net return at different water availability levels (Singh *et al.,* 2001). An interactive multi-objective linear programming has been developed for optimal utilization of the land, water and human resources of Mandakini Balinala watershed No. 1. (Mohanty *et al.*, 2015).

In this paper, a multi objective optimization model was formulated; net annual income and economic water productivity were maximized and the optimal cropping pattern along with groundwater draft required to meet the irrigation demand of the crops in conjunction with surface water, during both the season was found out in a run-off-the-river based canal system of Phulnakhara distributary of Puri main canal in eastern Odisha. So that abundantly available ground water resources in the studied area can be utilized in conjunction with surface water during deficit canal water supply period.

2. MATERIAL AND METHODS

Study Area

The study was conducted in the Phulnakhara distributary command of Puri main canal system located partly in Cuttack and partly in Khurda districts of Odisha with $20^0$19' 15.6"N to $20^0$14'56.4"N latitudes and $85^0$52'51.6"E to $86^0$0' 0"E longitudes and 28 m amsl (Fig. 1). The Phulnakhara distributary off takes from Kakatpur branch canal of Puri main canal system and run for 21.41 km. It has verified cultivable command area of 4903.29 ha and design discharge of 6.03 cumec. The command area consisted of 3 blocks of Cuttack district *viz.,* Cuttack Sadar, Kantapada and Baranga and 2 blocks of Khurda district *viz.,* Balianta and Bhubaneswar. The command area of the distributary is dominated by clay loam soil at its middle and tail reaches. The soils of the head reach are comparatively heavier than the middle and tail reaches. The bulk density of the soil ranged from 1.42 to 1.64 gm cm^{-3} (Mishra *et al.*, 2008). The average annual rainfall of the study area is about 1530 mm. In the Phulnakhara distributary command area, during *kharif* season, more than the required amount of irrigation water is delivered (Mishra *et al.*, 2008). While in *rabi* season, the canal flow was substantially below the full supply level, thereby the irrigation demand of the crops could not be met. Mishra *et al.* (2008) revealed that as the canal water during *rabi* and summer is not adequate enough to meet the crop water demand, due to which a sizeable area remained under fallow within the command.

Data Requirement and Processing

Meteorological data like daily rainfall, maximum and

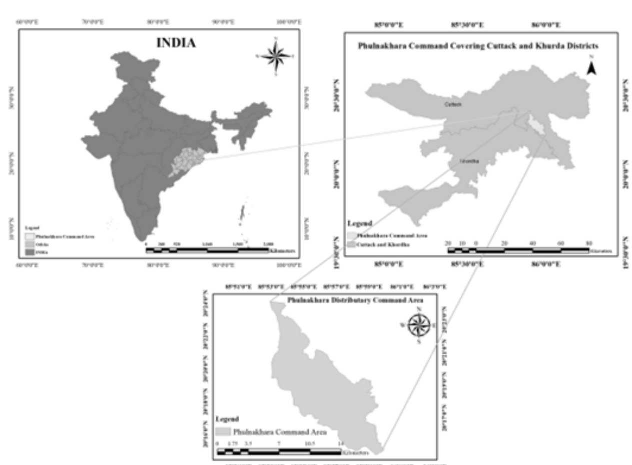

Fig. 1. Locations of study area

minimum temperature, relative humidity, sunshine hour and average wind speed, collected from OUAT agromet observatory to calculate the crop water requirement, and subsequently calculate the irrigation water requirement. Daily canal discharge data at the head regulator of Phulnakhara distributary was collected from the sub-division office of Water Resources Department, Government of Odisha for understanding the canal delivery schedule and quantum of canal water delivered**.** Block wise agricultural data *viz.,* cropping practices, crop coverage, yield and production were collected from the office of Deputy Director of Agriculture, Cuttack and Khurda, Govt. of Odisha for assessing the crop water requirement. Cost of cultivation for both *kharif* and *rabi* crops for the year 2018, minimum support price (MSP) were collected from OUAT for calculation of net benefit from different seasonal crops.

Assessment of Irrigation Water Requirement

Based on the existing cropping pattern, crop water requirement, subsequently the irrigation water requirement was calculated using the meteorological parameters, involving Penman-Monteith method (Allen *et al.*, 2004). Daily canal flow release at the head regulator of the study distributary *i.e.* the surface water was used for assessing the irrigation water supply quantum and pattern. The area under different crops over the years in the study command was used to calculate the irrigation water demand of the command.

Development of Conjunctive Use Plan for Optimal Utilization of Water Resources

An optimization model was developed for finding out the optimal cropping pattern for the study command. The groundwater draft required to fulfill the irrigation need of the optimal cropping pattern in wet, normal and dry years was also determined.

Multi-objective Models

Multi-objective programming (MOP) model is a mathematical method associated with a problem, in which different functions are to be optimized at a time under a set of management and operational constraints.

The general description of a MOP problem having, 'm' objectives, 'n' decision variables and 'o' constraints can be expressed as:

$$\text{Max } Z(x) = [Z_k(x), \text{for } k = 1, 2, ... m] \quad ...(1)$$

$$\text{Subjected to: } g_i(x) \ (\leq = \geq) \ b, \text{ for } i = 1,2,.......o \quad ...(2)$$

$$\text{and } x \geq 0 \quad ...(3)$$

Where, 'Z' is a vector valued function consisting of the objective functions $Z_k(x)$, for k = 1,2, ..., m and 'x' is a vector consisting of decision variables, they are x_1, x_2, x_3, ..., x_n. eq. 2 is a set of constraints, defining the feasible regions of the decision variables.

If, $Z_k(x)$ and $g_i(x)$ for i = 1, 2,.........,x and k = 1, 2,............,p are linear ,the MOP formulation is termed as multiple objective linear programming (MOLP).

The concept of optimal solution as used in single objective optimization has a different interpretation in MOP.

Formulation of a Multi-Objective Optimization Model

A multi objective optimization model is formulated to determine the optimal cropping pattern in the command and also to determine the quantum of annual groundwater draft, which is needed to bring the entire command under crop coverage. Two objective functions are considered in our case. The objective functions are described as follows:

a) **Maximization of the net annual income:** The net annual income from the study command is to be maximized by maximizing the difference between the gross income from the produce and the cost of cultivation / production of crops.

$$\text{Max } Z_1 = \sum_{i=1}^{m}\sum_{j=1}^{n}(I_{ij} \times X_{ij}) \quad ...(4)$$

Where, Z_1 = objective function for maximization of net income (₹); I_{ij} = Net income from 'j'[th] crop in 'i'[th] season (₹ ha^{-1}); X_{ij} = area allocated for 'j'[th] crop in 'i'[th] season (ha); m = total number of seasons; and n = total number of crops.

b) **Maximization of the economic water productivity:** The economic water productivity is maximized by maximizing the crop output value in a specific season divided by the total amount of water (both surface and groundwater) used by the crop.

$$\text{Max } Z_2 = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n} Y_{ij} \times X_{ij} \times C_{ij} - \sum_{i=1}^{m}\sum_{j=1}^{n} X_{ij} \times P_{ij}}{W_{ij}} \quad ...(5)$$

Where, Z_2 = objective function for maximization of economic water productivity (₹ m^{-3}); Y_{ij} = Yield from 'j'[th] crop in 'i'[th] season (t ha^{-1}); C_{ij} = Price of produce from 'j'[th] crop in 'i'[th] season (₹ t^{-1}); P_{ij} = Cost of crop production for 'j'[th] crop in 'i'[th] season (₹ ha^{-1}); and W_{ij} = Total water required to cultivate the crops in the entire command in all the seasons (m^3). X_{ij} = area allocated for 'j'[th] crop in 'i'[th] season (ha).

The following constraints are considered in the optimization model:

i) **Water allocation constraints (surface water and groundwater):** The amount of irrigation water required during *kharif* season should be less than or equal to the total water available from both the sources (surface water and groundwater).

$$\sum_{j=1}^{n} X_j \times IWR_j \leq [(SW)_K + (GW)_K], \quad \text{for } \textit{kharif} \text{ season,} \quad ...(6)$$

Where, IWR_j = irrigation water requirement for *kharif* crops (mm); $(SW)_K$ = surface water released in the canal during *kharif* season (m^3); $(GW)_K$ = groundwater withdrawal during *kharif* season (m^3); n = total number of crops during *kharif*; X_j = area under 'j'th crop (ha).

Similarly, for *rabi*, amount of water required, should be less than equal to the total available water resources.

$$\sum_{j=1}^{n} X_j \times IWR_j \leq (SW)_R + (GW)_R, \quad \text{for } rabi \text{ season,} \quad ...(7)$$

Where, IWR_j = irrigation water requirement for *rabi* crops (mm); $(SW)_R$ = surface water released in the canal for *rabi* (m^3); $(GW)_R$ = groundwater withdrawal in *rabi* (m^3).

ii) **Land availability constraint:** Total cropped area during a season 'i' should be within or same as that of total culturable command area.

$$\sum_{j=1}^{n} X_j \leq CCA, \quad \forall \text{ 'i'} \quad ...(8)$$

Where, CCA = total culturable command area.

iii) **Maximum and minimum area constraint:** Management considerations restrict some minimum and maximum value for cropped area under certain crops to meet the local food and market requirements. Area under a particular crop should be more than or equal to minimum cropped area and less than or equal to maximum cropped area.

$$\psi_{ij}^{min} \times CCA \leq X_{ij} \leq \gamma_{ij}^{max} \times CCA \quad \forall \text{'i' and 'j'} \quad ...(9)$$

Where, γ_{ij}^{max} = maximum percentage of total culturable command area for different crops during 'i'th season; ψ_{ij}^{min} = minimum percentage of total culturable command area for different crops during 'i'th season.

iv) **Non-negativity constraint:** The area under different crops and the groundwater extraction should be more than or equal to zero.

$$X_{ij} \geq 0; GWi \geq 0 \quad ...(10)$$

The notations for the decision variables for both *kharif* and *rabi* seasons are given in Table 1.

The yearwise annual rainfall is given in the Table 2.

Based on the yearwise annual rainfall, the year 2015 year is categorized as dry year, 2017 as normal year and 2018 as wet year. So, for these above years the cost of cultivation for 2018-19 was considered. The MSP of *kharif*

Table: 2
Yearwise annual rainfall

S.No.	Years	Rainfall (mm)
1.	2008	1744.9
2.	2009	1373
3.	2010	1442.2
4.	2011	1505.1
5.	2012	1227.4
6.	2013	1848.8
7.	2014	1615.4
8.	2015	1074.8
9.	2016	1248.5
10.	2017	1629.6
11.	2018	2121.2

Table: 1
Decision variables with notations

Kharif crops	
X_{11} = Area under *kharif* paddy (ha)	X_{12} = Area under *kharif* maize (ha)
X_{13} = Area under *kharif* other vegetables*(ha)	X_{14} = Area under *kharif* chilly (ha)
X_{15} = Area under ginger (ha)	
Rabi crops	
X_{21} = Area under *rabi* paddy (ha)	X_{22} = Area under *rabi* wheat (ha)
X_{23} = Area under *rabi* maize (ha)	X_{24} = Area under *rabi* greengram (ha)
X_{25} = Area under *rabi* blackgram (ha)	X_{26} = Area under *rabi* gram (chickpea) (ha)
X_{27} = Area under *rabi* field pea (ha)	X_{28} = Area under *rabi* groundnut (ha)
X_{29} = Area under *rabi* sesamum til (ha)	X_{210} = Area under *rabi* sunflower (ha)
X_{211} = Area under *rabi* mustard (ha)	X_{212} = Area under *rabi* potato (ha)
X_{213} = Area under *rabi* onion (ha)	X_{214} = Area under *rabi* other vegetables (ha)
X_{215} = Area under rabichilly (ha)	X_{216} = Area under *rabi* sugarcane[@](ha)
X_{217} = Area under turmeric[#](ha)	

*Note: *Other vegetables mentioned in the above table include spinach, pumpkin, water melon and cassava etc.; [@]The water requirement of sugarcane during kharif is mostly met from the rainfall as, it is grown 1-2 months prior to the rabi season. So, it is categorized as the rabi crop; [#]The water requirement of turmeric during kharif is mostly met from the rainfall as, it is grown 1-2 months prior to the rabi season. So, it is categorized as the rabi crop.*

Table: 3
Minimum support price (MSP) of *kharif* and *rabi* crops (₹ q^{-1})

S.No.	Crops	MSP (₹ q^{-1}) for 2015-16	MSP (₹ q^{-1}) for 2016-17	MSP (₹ q^{-1}) for 2017-18
1.	Paddy	1410	1470	1550
2.	Maize	1325	1365	1425
3.	Wheat	1525	1625	1735
4.	Gram	3425	4000	4400
5.	Mustard	3350	3700	4000
6.	Sesamum	4700	5000	5300
7.	Greengram	4850	5225	5575
8.	Blackgram	4625	5000	5400
9.	Groundnut	4030	4220	4450
10.	Sunflower	3800	3950	4100
11.	Sugarcane	230	230	255

crops and *rabi* crops (rupees per quintal) for the years 2015-16, 2016-17 and 2017-18 are given in Table 3. The MSPs of different seasonal crops for different years were obtained from Directorate of Economics and Statistics, Department of Agriculture, Co-operation & Farmers' Welfare, Ministry of Agriculture and Farmers' Welfare, Government of India.

The MSP for other vegetables, chilly, ginger, field pea, potato, onion and turmeric was obtained from the cost of cultivation for 2018-19 of OUAT, Bhubaneswar (Dean of Research, OUAT through personal communication).

The minimum and maximum area constraint in *kharif* season was decided by considering *kharif* paddy as base crop. So 50% area of the total command is considered as the minimum area for *kharif* paddy and rest 50% area of the command is considered as the maximum area constraint for *kharif* maize, *kharif* other vegetables, *kharif* chilly, and ginger. The minimum area constraint for these *kharif* crops are considered as the least area under respective crops grown in the last 10 years in the canal command. Similarly, the maximum area constraint during *rabi* season was decided by taking greengram and *rabi* other vegetables as base crops. So, 100% area of the total command is considered as the maximum area for greengram and *rabi* vegetables. The actual minimum area for these two crops in last 10 years' period together was found to be about 28% of the total command area. Hence, 72% area of the command is considered as the maximum area constraints for rest of the *rabi* crops. The minimum area constraint for *rabi* crops are considered as the least area under respective crops grown in the last 10 years in the canal command. The maximum and minimum area constraints considered for various crops to be used in the optimization for *kharif* and *rabi* seasons are given in Tables 4 and 5, respectively.

After formulation of the optimization model, the following data sets (Tables 6 and 7) for both the seasons (*kharif* and *rabi*) were prepared for obtaining the optimal solution.

Table: 4
Area constraints for the *kharif* crops

S.No.	Crops	Minimum area (ha)	Maximum area (ha)
1.	Paddy	2451	3843
2.	Maize	5	2452
3.	Other vegetable	236	2452
4.	Chilly	18	2452
5.	Ginger	4	2452

Table: 5
Area constraints for the *rabi* crops

S.No.	Crops	Minimum area (ha)	Maximum area (ha)
1.	*Rabi* paddy	49	3527
2.	Wheat	0	3527
3.	Maize	3	3527
4.	Greengram	727	4903
5.	Blackgram	403	3527
6.	Gram	3	3527
7.	Fieldpea	4	3527
8.	Groundnut	49	3527
9.	Sesamum	6	3527
10.	Sunflower	2	3527
11.	Mustard	20	3527
12.	Potato	75	3527
13.	Onion	18	3527
14.	Other vegetable	649	4903
15.	Chilly	48	3527
16.	Sugarcane	22	3527
17.	Turmeric	10	3527

Solving of Multi-objective Optimization Model Using WinQSB

The optimization model was solved using Windows Quantitative System Business (WinQSB) software. After formulating the model in standard linear programming form, all constraints had variables on the left side and a constant on the right. Then from the WinQSB software linear programming option was selected. All the parameters

Table: 6
Data requirement for the optimization routine for *kharif* season

S.No.	Crops	MSP (₹ q^{-1}) (avg. of 10 yrs)	Yield for 2018 yr (q ha^{-1})	Avg. area under diff. crops for 10 yrs (ha)	MSP×Yield (₹ ha^{-1})	Cost of cultivation for 2018-19 (₹ ha^{-1})	Benefit (₹ ha^{-1})	Total water required to cultivate the crops in field coverage of 10 yrs (mm)	IWR (mm) at field avg. of 10 yrs	IWR (mm) at head regulator (avg. of 10 yrs)	Total water required to cultivate the crops (avg. of 10 yrs) (m^3)
1.	Paddy	1238	40	3843	49520.0	44726	4794.0	1353.6	628.0	897.2	52021434.1
2.	Maize	1145	52	14	59540.0	61226	-1686.0	314.5	17.2	24.5	42938.4
3.	Other vegetable	1000	200	845	200000.0	128728	71272.0	182.0	76.9	109.9	1537417.3
4.	Chilly	10000	20	37	200000.0	128109	71891.0	435.6	14.7	21.0	162732.2
5.	Ginger	3500	150	6	525000.0	314600	210400.0	577.1	109.1	155.9	36720.1

Note: IWR = Irrigation water requirement

Table: 7
Data requirement for the optimization routine for *rabi* season

S.No.	Crops	MSP (₹ q^{-1}) (avg. of 10 yrs)	Yield for 2018 yr (q ha^{-1})	Avg. area under diff. crops for 10 yrs (ha)	MSP×Yield (₹ ha^{-1})	Cost of cultivation or 2018-19 (₹ ha^{-1})	Benefit (₹ ha^{-1})	Total water required to cultivate the crops in field coverage of 10 yrs (mm)	IWR (mm) at field avg. of 10 yrs	IWR (mm) at head regulator (avg. of 10 yrs)	Total water required to cultivate the crops (avg. of 10 yrs) (m^3)
1.	*Rabi* Paddy	1238	45	210	55710.0	58476	-2766.0	1344.9	1268.2	1811.7	2824359.54
2.	Wheat	1376	45	3	61920.0	46293	15627.0	357.1	325.6	465.1	10713.96
3.	Maize	1145	58	6	66410.0	68376	-1966.0	267.6	248.8	355.4	16053.88
4.	Greengram	4110	8.5	962	34935.0	37301	-2366.0	187.6	171.6	245.2	1804700.40
5.	Blackgram	3922	8.5	678	33337.0	37301	-3964.0	187.9	172.4	246.2	1273964.00
6.	Gram	2986	15	4	44790.0	43384	1406.0	249.3	227.0	324.3	9970.01
7.	Fieldpea	3500	20	11	70000.0	43470	26530.0	241.6	223.5	319.3	26580.77
8.	Groundnut	3360	25	233	84000.0	57865	26135.0	248.6	231.2	330.3	579343.66
9.	Sesamum	4020	9	37	36180.0	40120	-3940.0	138.5	125.9	179.9	51232.32
10.	Sunflower	3258	20	11	65160.0	66528	-1368.0	201.6	183.2	261.7	22173.12
11.	Mustard	2823	15	30	42345.0	49300	-6955.0	193.2	175.8	251.1	57974.12
12.	Potato	900	280	108	252000.0	177606	74394	96.7	87.7	125.3	104421.41
13.	Onion	900	250	27	225000.0	136257	88743	348.9	322.4	460.5	94201.19
14.	Other Vegetable	1000	200	1243	200000.0	128728	71272	155.7	143.2	204.5	1935474.61
15.	Chilly	10000	20	69	200000.0	128109	71891	304.4	285.2	407.4	210053.65
16.	Sugarcane	188	1000	111	188000.0	171897	16103.0	800.9	673.4	962.0	888998.93
17.	Turmeric	3000	140	15	420000.0	273091	146909	689.1	573.5	819.2	106089.12

were filled in all respect to have a spreadsheet form, where the column headings reflected the new variable names, the lower bound of each variable was '0' and the upper bound was the largest number. Then the objective functions and constraints were entered. The spreadsheet cells also contained the coefficients of each decision variable in the objective function and each constraint, which were entered. Then using the 'solve the problem' option the formulation was solved.

3. RESULTS AND DISCUSSION

The optimization model determined the optimal cropping pattern for the command area. As well, it also determined the groundwater draft which was required to meet the irrigation demand of the crops in conjunction with surface water and the net annual income from the command area. By maximizing the net annual income and economic water productivity from the command area, no groundwater was required to meet the irrigation water requirement in *kharif* for the dry year (2015-16), normal year (2016-17) and the wet year (2017-18), respectively. Whereas, the highest and the lowest irrigation water requirement met from the groundwater in *rabi* were 210.14 lakh m^3 (2015-16) and 176.80 lakh m^3 (2016-17), respectively (Table 8). The highest and the lowest obtained net annual income were ₹ 101.01 crores in 2017-18 (wet year) and ₹ 98.75 crores in 2015-16 (dry year), respectively. The highest and the lowest obtained economic water productivity were ₹ 16.92 m^{-3} (normal year) and ₹ 15.51 m^{-3} (dry year). The 10-years average irrigation water requirement met from the groundwater in *rabi* obtained from the optimization model for the canal command was 182.33 lakh m^3. From the Tables 8 and 9, it is evident that year 2017-18 registers the highest net annual income amongst the dry year (2015-16) and normal year (2016-17) by allocating 2451 ha to *kharif* paddy, 5 ha *kharif* maize, 236 ha *kharif* vegetables,18 ha *kharif* chilly, 2193 ha ginger, 49 ha *rabi* paddy, no area under *rabi* wheat, 3 ha *rabi* maize, 728 ha greengram, 403 ha blackgram, 3 ha gram, 4 ha field pea, 50 ha groundnut, 6 ha sesamum til, 1 ha sunflower, 20 ha mustard, 76 ha potato, 18 ha onion, 649 ha *rabi* vegetables, 48 ha *rabi* chilly, 22 ha sugarcane and 2824 ha turmeric. The dry year (2015-16) registers the lowest net annual income and economic water productivity. The difference between these two years occurred as the MSP values were less for the year 2015-16. Similarly, the groundwater draft both combined during *kharif* and *rabi* seasons in the dry year (2015-16) have also more than that of wet year (2017-18).

The annual groundwater draft during the dry, normal and wet year for *kharif and rabi*, which was obtained from the optimization model are given in Table 8. The optimization model was solved using WinQSB software.

The optimal cropping pattern, net annual income, EWP for the study command were found out and are given in Table 9.

The 10-years average irrigation water requirement met from the groundwater in *rabi,* net annual income and economic water productivity obtained from the optimization model for the canal command were 182.33 lakh m^3, ₹ 96.12 crore and ₹ 15.06 m^{-3}, respectively (Table 8). Among the crops ginger has the highest economic water productivity of ₹ 7.23 m^{-3} followed by turmeric (₹ 6.5 m^{-3}). Similar results have been found by Sethi *et al.* (2002); Rejani *et al.* (2009). The results have been corroborated with the findings of Vivekanandan and Viswanathan, 2007, who revealed, the cropping pattern of GP was found to be best as compared to the linear programming and GP approach was recommended for optimization of multi-objective cropping pattern by considering high values of net return for Barna irrigation project. A multi objective optimization routine successfully optimized the size of the auxiliary storage reservoir and the cropping pattern considering various constraints. Similar results have been found by Upadhyaya *et al.* (2022a,b) *i.e.* the results were useful in suggesting an optimum land allocation plan under different crops that gave maximum net return, land productivity and water productivity under different canal and ground water use scenarios and affinity levels.

4. CONCLUSIONS

The scope of conjunctive use of canal water and groundwater was assessed in a runoff from the river canal system. The existing canal water availability and its utilization pattern was found out. A multi-objective optimization model was formulated to maximize the net annual income and economic water productivity of the canal command area. Optimal cropping pattern for the command area and

Table: 8
Yearwise groundwater draft for *kharif* and *rabi* season for maximizing net annual income and economic water productivity

S.No.	Years	IWR from GW_k (m^3) during *kharif* season	IWR from GW_r (lakh m^3) during *rabi* season	Net annual income (crore ₹)	EWP (₹ m^{-3})
1.	2015-16 (dry year)	0	210.14	98.75	15.51
2.	2016-17 (normal year)	0	198.96	99.75	16.92
3.	2017-18 (wet year)	0	176.80	101.01	16.89
4.	10 years average obtained from optimization	0	182.33	96.12	15.06

Note: EWP = Economic water productivity

Table: 9
Optimal solution obtained from the multi-objective programming model

S.No.	Goal level	Decision variable	Solution value (ha)	Total contribution (crore ₹)	Solution value (ha)	Total contribution (crore ₹)
			Priority-1 (Max = Net Annual Income)		Priority-2 (Max = EWP)	
1.	G1	Paddy (X_{11})	2,451.00	1.18	2,451.00	0.00
2.	G1	Maize (X_{12})	4.66	0.00	4.66	0.00
3.	G1	Other vegetable (X_{13})	236.19	1.68	236.19	0.00
4.	G1	Chilly (X_{14})	18.19	0.13	18.19	0.00
5.	G1	Ginger (X_{15})	2,193.25	46.15	2,193.25	0.00
6.	G1	*Rabi* paddy (X_{21})	49.03	-0.01	49.03	0.00
7.	G1	Wheat (X_{22})	0.16	0.00	0.16	0.00
8.	G1	Maize (X_{23})	3.43	0.00	3.43	0.00
9.	G1	Greengram (X_{24})	727.65	-0.17	727.65	0.00
10.	G1	Blackgram (X_{25})	403.05	-0.16	403.05	0.00
11.	G1	Gram (X_{26})	2.94	0.00	2.94	0.00
12.	G1	Field pea (X_{27})	3.92	0.01	3.92	0.00
13.	G1	Groundnut (X_{28})	49.52	0.13	49.52	0.00
14.	G1	Sesamum (X_{29})	6.37	0.00	6.37	0.00
15.	G1	Sunflower (X_{210})	1.47	0.00	1.47	0.00
16.	G1	Mustard (X_{211})	19.61	-0.01	19.61	0.00
17.	G1	Potato (X_{212})	75.51	0.56	75.51	0.00
18.	G1	Onion (X_{213})	18.14	0.16	18.14	0.00
19.	G1	Other vegetable (X_{214})	648.71	4.62	648.71	0.00
20.	G1	Chilly (X_{215})	47.56	0.34	47.56	0.00
21.	G1	Sugarcane (X_{216})	22.06	0.04	22.06	0.00
22.	G1	Turmeric (X_{217})	2,824.14	41.49	2,824.14	0.00
23.	G1	GW_K	0	0	0	0.00
24.	G1	GW_R	182.33	0	182.33	0.00
25.	G2	Paddy (X_{11})	2,451.00	0.18	2,451.00	1.18
26.	G2	Maize (X_{12})	4.66	0	4.66	0.00
27.	G2	Other vegetable(X_{13})	236.19	0.26	236.19	1.68
28.	G2	Chilly (X_{14})	18.19	0.02	18.19	0.13
29.	G2	Ginger (X_{15})	2,193.25	7.23	2,193.25	46.15
30.	G2	*Rabi* paddy (X_{21})	49.03	0	49.03	-0.01
31.	G2	Wheat (X_{22})	0.16	0	0.16	0.00
32.	G2	Maize (X_{23})	3.43	0	3.43	0.00
33.	G2	Greengram (X_{24})	727.65	-0.03	727.65	-0.17
34.	G2	Blackgram (X_{25})	403.05	-0.03	403.05	-0.16
35.	G2	Gram (X_{26})	2.94	0	2.94	0.00
36.	G2	Field pea (X_{27})	3.92	0	3.92	0.01
37.	G2	Groundnut (X_{28})	49.52	0.02	49.52	0.13
38.	G2	Sesamum (X_{29})	6.37	0	6.37	0.00
39.	G2	Sunflower (X_{210})	1.47	0	1.47	0.00
40.	G2	Mustard (X_{211})	19.61	0	19.61	-0.01
41.	G2	Potato (X_{212})	75.51	0.09	75.51	0.56
42.	G2	Onion (X_{213})	18.14	0.03	18.14	0.16
43.	G2	Other vegetable (X_{214})	648.71	0.72	648.71	4.62
44.	G2	Chilly (X_{215})	47.56	0.05	47.56	0.34
45.	G2	Sugarcane (X_{216})	22.06	0.01	22.06	0.04
46.	G2	Turmeric (X_{217})	2,824.14	6.5	2,824.14	41.49
47.	G2	GW_K	0	0	0	0
48.	G2	GW_R	182.33	0	182.33	0
	G1	Goal	Value (Max.) =	96.13	Value (Max.) =	15.06
	G2	Goal	Value (Max.) =	15.06	Value (Max.) =	96.13

Note: GW_K = irrigation water requirement met from the groundwater in kharif (lakh m^3); GW_R = irrigation water requirement met from the groundwater in rabi (lakh m^3)

groundwater draft required to meet the irrigation demand of the crops in conjunction with surface water was obtained. After maximizing the net annual income and economic water productivity from the command area, the obtained optimal irrigation water requirement met from the groundwater both combined during *kharif* and *rabi* seasons was the highest for the dry year and the lowest for the wet year, respectively. Similarly, the net annual income was the highest in wet year and the lowest was in dry year, respectively. The 10-years average irrigation water requirement met from the groundwater in *rabi* was less as compared to the dry year and net annual income obtained from the optimization model for the canal command was less as compared to the wet year, respectively. The net annual income for the wet year is more than that of dry year, as the groundwater draft, both combined during *kharif* and *rabi* seasons in dry year is more than that of wet year. Based on the optimized crop coverage, it is recommended for the farmers of the study area that, they should go for *kharif* paddy, *kharif* vegetables, ginger, *rabi* paddy, greengram, blackgram, groundnut, mustard, potato, *rabi* vegetables, *rabi* chilly, sugarcane and turmeric for better net benefit and high economic water productivity throughout the year.

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