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RESEARCH ARTICLE

Application of simulation-optimization techniques for *Rabi* crop planning in the Bargarh canal command of eastern India

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Abstract

The nation's economic growth relies heavily on agriculture, which in turn depends on water resources, land and crops. Effective optimization and management of these water resources have become essential for sustainable agricultural practices, particularly in irrigated command areas. This study aims to develop a linear programming model for optimizing water resource allocation and crop selection in the Bargarh Canal Command Area (BCCA) to maximize farmers' net returns. We analyzed the existing cropping patterns adopted by farmers and calculated the optimal areas for crop cultivation. Water requirements were assessed using the FAO's CROPWAT model, while groundwater availability was modeled using the Groundwater Modeling System (GMS) with MODFLOW software. Linear programming was employed to optimize both water allocation and crop selection, considering constraints such as available cropland and water resources. Considering the prevailing cropping pattern, the net profit obtained in the *Rabi* season was 4673.18 million rupees and using linear optimization, the net profit was 4837.14 million rupees from the current cropping pattern. This indicates a significant increase in farmers' income. The study examined water availability, crop water requirements and optimal cropping patterns within the BCCA, which covers approximately 130235 hectares irrigated by the Bargarh canal system. The temporal scope included analyzing Canal water availability over the approximately 100-day cropping period during *Rabi* 2023, as well as assessing groundwater conditions. The developed model serves as a valuable tool for policymakers and farmers, enabling them to make informed decisions that could lead to more sustainable and profitable agricultural practices in irrigated command areas.

Keywords: agricultural practices; economic return; irrigation management; linear programming; water resources

Introduction

Effectively managing water resources to achieve agricultural sustainability is a challenge in various regions, especially in command areas where irrigation plays a major role in crop production (1). However, the optimal utilization of water resources in these areas remains a significant concern due to inefficient water distribution, inadequate infrastructure and changing climatic conditions (2). In addition, relying solely on surface water resources from canals can lead to inefficiencies and inequitable distribution (3).

Optimization techniques offer powerful tools for developing effective conjunctive use plans in canal command areas. These techniques, ranging from linear programming to more advanced meta-heuristic evolutionary algorithms, can help decision-makers identify optimal strategies for allocating water resources, scheduling irrigation and managing groundwater extraction while considering various objectives, such as maximizing crop production, minimizing water losses and ensuring equitable access. Conjunctive water use, which involves the integrated management of both surface water (canals) and groundwater resources, has emerged as a challenging approach for enhancing water availability, improving irrigation reliability and ensuring the sustainability of agricultural systems (4-7).

Previous studies have highlighted the significance of efficient water management in canal command areas to improve agricultural productivity and sustainability (8, 9). Net annual groundwater availability is 398 billion cubic meters and the overall level of groundwater development in India is around 63 %, which falls under the safe category. In addition, there is an untapped groundwater potential in the eastern parts of India (10). Optimal cropping patterns have been developed using linear programming to match irrigation supply with crop water needs (11, 12). Many studies have also been conducted and various optimization methods have been compared to obtain desirable results from surface water allocation and conjunctive use planning in the irrigated command areas or its part, showing the importance of irrigated land to maximize yield and profitability (13, 14).

Research has shown that proper irrigation scheduling, crop diversification and adoption of water-optimizing technologies can significantly enhance water-use efficiency and net return (15). Additionally, the implementation of participatory irrigation management approaches has been found to improve water distribution and reduce conflict among farmers in canal command areas (16). Canal irrigation systems are crucial for supporting agriculture and ensuring food security (17).

Although surface water can meet crop demands, its unpredictable availability poses major challenges. Despite these advancements, a significant research gap remains in understanding the challenges and prospects for optimal water use in the canal command areas in parts of the country. Few studies have comprehensively examined the interplay between water availability, irrigation infrastructure, farming practices and agricultural sustainability in this region (18, 19). Moreover, the climate change impact on water resources and their implications for agricultural planning in the canal command areas of Odisha remain underexplored been comprehensively examined (20, 21). In addition, owing to the inadequacy of surface water in meeting the water and food demands of large populations, groundwater must be used along with surface water (22). Previous studies do not explain the optimization model for both surface water and groundwater by analyzing climatic, topographic, crop, groundwater and canal water data to maximize the net benefits from changing cropping patterns (23, 24). Moreover, there has been a lack of attention to volumetric analyses and the significance of groundwater availability in areas predominantly used for agriculture (11, 12). This study can also be useful in arid as well as semi-arid regions, where groundwater usage can be added to reduce irrigation losses, salinization and waterlogging and thereby conserving surface water.

This approach also demonstrates that conjunctive use planning can maintain stable and sustainable water levels in both canals and groundwater systems. To address all the research gaps, it is crucial to develop targeted strategies and plans to enhance water-use efficiency, increase agricultural productivity and sustainability in canal command areas. Accordingly, this study estimates crop water demand using FAO-CROPWAT, assesses groundwater availability with GMS-MODFLOW and develops a simulation-optimization model for conjunctive water use planning.

Materials and Methods

Description of the study area

The Bargarh Canal command area (BCCA) is geographically positioned between 20°43′ to 21°41′N latitude and 82°39′ to 83° 58′E longitude (Fig. 1). The command is situated within the western central table land agro-climatic zone of eastern India which is part of Hirakud canal command and Mahanadi River basin. Canal irrigation is delivered to the command through three major distribution systems, namely Sason main canal, Sambalpur Distributary and Bargarh main canal. The Bargarh canal, originating from the right dyke of Hirakud Dam, with

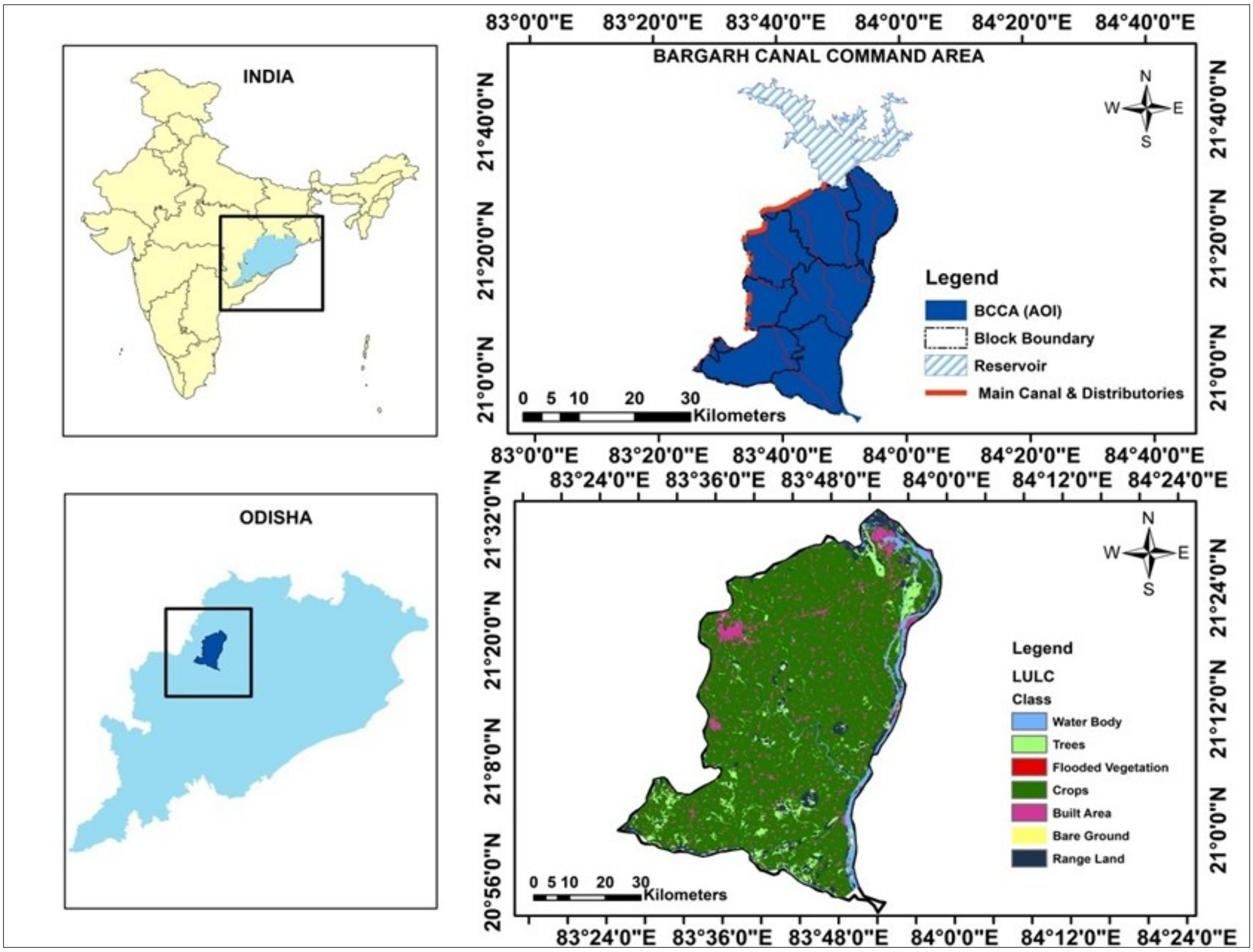

Fig. 1. Land use and canal network of study area.

84.28 km in length and 155 cumec discharge. This system, covering 130235 ha, was selected for surplus-deficit water analysis. The soils in the BCCA generally exhibit average to good fertility, predominantly comprising clay loam. Rice is the principal crop grown in the command area in the monsoon as well as the non-monsoon period. The water supply at different outlets was collected from the Department of Water Resources, Government of Odisha. The release of water from each direct outlet and the current cropping pattern of the command of individual distributaries/branch canals (including the direct outlets) were considered for the analysis. The average elevation of the study area is 171 m and the average annual rainfall is 1660 mm, of which 91 % is accumulated during the monsoon season (mid-June to mid-October). Crop data, such as the net area for different crops, cropping patterns and cost of cultivation for each season, were obtained from the College of Agriculture (COA), Bhubaneswar. Groundwater data such as hydrogeological information, geology and geomorphology were obtained from the Central Groundwater Board (CGWB), Bhubaneswar. The region is characterized by a complex geological configuration, comprising a diverse array of rock types primarily associated with the Archaean Precambrian and Permo-Carboniferous periods. Granites and their variants represent the most prevalent rock type, occupying significant portions of the BCCA (CGWB, 2022). Fig. 2 describes the methodology adopted in this research.

Deficit surplus status

This study emphasizes the assessment of canal water availability along with design discharge at the outlets of different distributaries and branch canals in the BCCA. It also focuses on the water demand of different crops using CROPWAT to minimize the demand-supply gap. Table 1 presents the design discharge and CCA of the direct outlets, distributaries and branch canals that operate in the system. The Department of Water Resources of the Government of Odisha, India, has devised a cropping strategy for the *Rabi* season of 2023, considering the water supply at various outlets. This analysis included the uninterrupted flow of water from the canal, which remained operational throughout the

Table 1. Details of outlets from the Bargarh Canal system

Sl. No.	Name of Distributary/Branch Canal	Discharge (cumec)	CCA (ha)
1	Godbhaga Distributary	10.780	15957.44
2	Telkani Distributary	0.311	507.00
3	Attabira Branch canal	25.540	31468.17
4	Jada Distributary	1.100	1553.00
5	Bargarh Distributary	9.970	2166.00
6	Dang Distributary	0.590	363.00
7	Ambapali Distributary	0.380	497.00
8	Baiman Distributary	0.720	1073.00
9	Behera Distributary	3.020	3863.44
10	Ainthapali Distributary	0.480	518.37
11	Barpali Distributary	1.380	1654.04
12	Retamunda Branch	14.340	16780.00
13	Bisipali Distributary	0.250	562.01
14	Resume Distributary	4.890	6985.50
15	Dhanbasa Distributary	0.022	285.00
16	Sarasmal Distributary	0.254	417.00
17	Rampur Distributary	3.900	5396.00
18	Puturupali Distributary	0.860	141.50
19	Telpali Distributary	0.230	268.00
20	Barkale Distributary	5.490	6459.00
21	Sulei Distributary	0.490	542.00
22	Pandrapali Distributary	0.490	641.00
23	Andharibanji Distributary	16.410	704.00
24	Gania Distributary	0.360	446.00
25	Bhimtikra Distributary	9.510	10692.00
	Total	**111.767**	**109939.47**

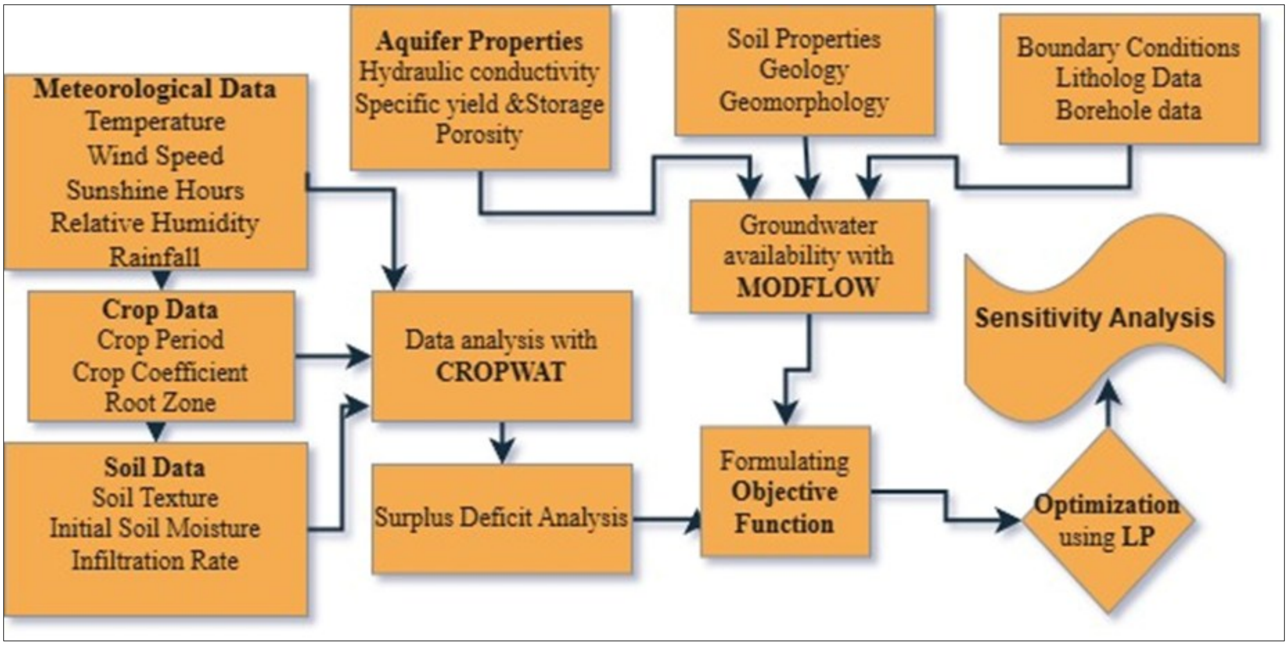

Fig. 2. Flow chart of the methodology.

cropping period and cropping pattern implemented in the BCCA of these outlets during the *Rabi* 2023 season.

During the approximately 100-day cropping period, the canal was kept open continuously, except for a short 3-day shutdown for minor maintenance activities. The water available at each outlet was calculated using Eqn. 1 considering the discharge as well as the duration of the canal opening.

$$WA_i = q_i \times 36 \times 24 \times N \quad (1)$$

Where, WA_i is total water available at each outlet '*i*' (ha cm), q_i is discharge of each outlet '*i*' (cumec) and N is number of canal operations.

A deficit surplus status was performed by comparing the amount of water available at each outlet with crop water requirements in the BCCA. The deficit condition is one in which the outlet operates where $WR_i > WA_i$ (11, 12).

CROPWAT 8.0

CROPWAT 8.0 is a decision-support software tool that uses rainfall, soil, crop and climate data to compute effective rainfall, reference evapotranspiration (ETo), crop water requirements (CWR), net irrigation requirements (NIR) and irrigation schedules. This model, developed by the United Nations Food and Agriculture Organization (FAO), can directly output the evapotranspiration and irrigation water requirements for crops. The FAO Penman-Monteith method is currently regarded as the standard approach for estimating evapotranspiration in agricultural contexts (25). Because of the lack of regulation of water release through the outlets, crops cultivated within the command area have been categorized into three groups based on their water requirements throughout their life cycle: heavy, moderate and low. The water requirements for heavy-duty crops (such as rice and sugarcane), moderate-duty crops (including groundnuts, various vegetables, maize and potato) and low-duty crops (e.g., Green Gram, Black Gram, other pulses, Ragi, Sesamum and Sunflower) were calculated using the CROPWAT software (26, 27). Fig. 3 describes different crops along with growth stages, i.e. initial, development, mid and late, for calculation of crop water requirement. Table 2 summarises the different crops into heavy, moderate and low according to their water requirements, which is further used in the analysis.

Table 2. Details of crop parameters used in the analysis

Crop type	WR (cm)
Heavy Duty	110
Moderate Duty	50
Low Duty	30

The validation of the CROPWAT model is conducted by equating the ETo values generated by the software with the average input pan evaporation data from a Class A pan over a decade (2012-2022) using Eqn. 2 sourced from OUAT, Regional Research and Technology Transfer Station, Chiplima, Odisha, the closest station to the study area. Fig. 4 presents the comparative results of the ETo calculations, demonstrating a strong correlation between the calculated and simulated values. Thus, we can conclude that the CROPWAT software is effective for estimating ETo values and predicting CWR for various crops.

The total surface water requirement for the command at each outlet was calculated using Eqn. 2:

$$Wr_i = A^i_h \times D_h + A^i_m \times D_m + A^i_l \times D_l$$

Where WR_i is total water requirement of the BCCA of each outlet '*i*' (ha cm),A^i_h, A^i_m and A^i_l are areas under heavy, moderate and low duty crops in the BCCA of each outlet '*i*' respectively (ha) and D_h, D_m and D_l are total depth of water required for the heavy, moderate and low duty crops respectively (cm).

Groundwater Modeling System (GMS)

The GMS is an application designed for the development and simulation of groundwater models. It incorporates both two-dimensional and three-dimensional geostatistics, stratigraphic modeling and a distinctive conceptual model. The models currently supported by the application include MODPATH, MODFLOW, MT3DMS, RT3D, SEEP2D, FEMWATER and UTEXAS (28-31). The three-dimensional features of the groundwater flow system are crucial for accurately characterizing hydrogeological properties, developing conceptual models and conducting simulations using the MODFLOW 2000

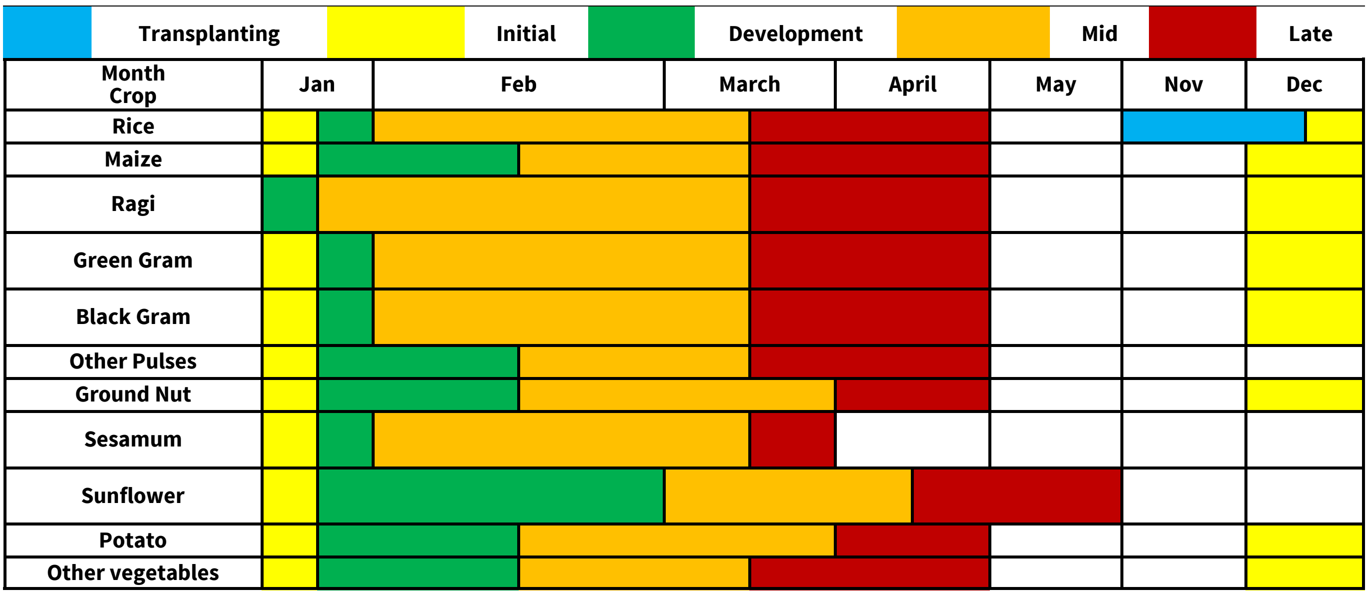

Fig. 3. Crop Growth stages for each crop.

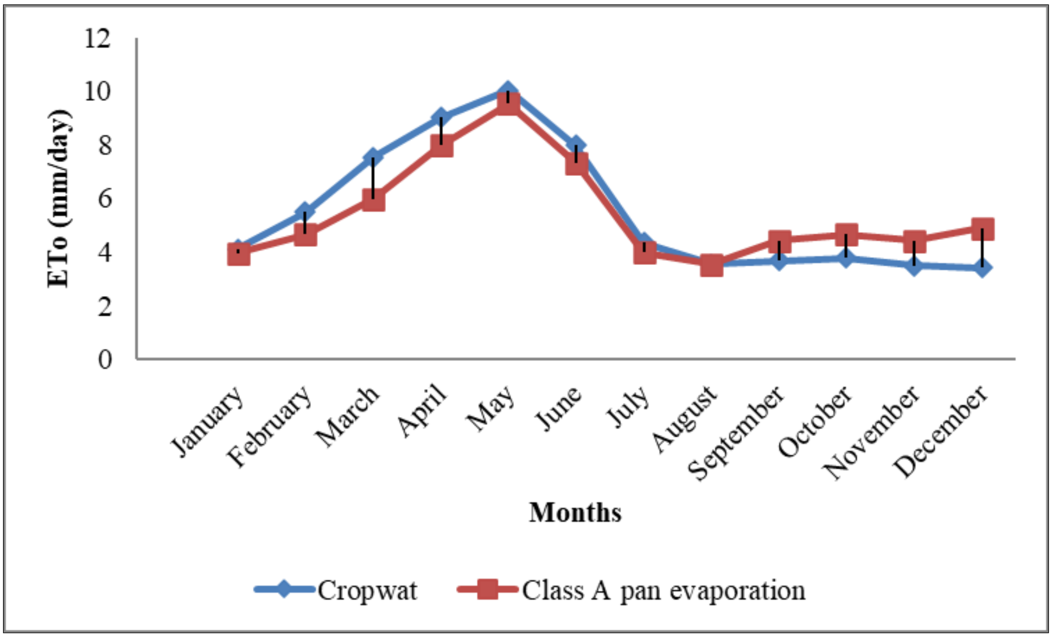

Fig. 4. Validation of ETo between Class A pan evaporation and CROPWAT software.

package within the software uses finite difference approach. Various hydrogeological parameters, such as seasonal groundwater level, boundary conditions, recharge rate, specific yield, porosity and hydraulic conductivity were integrated into the model. Model calibration was achieved by comparing the simulated levels with the observed data from the monitoring wells across the command area. A flow budget analysis was performed to calculate the groundwater availability of the canal command. Similarly, calibration for the GMS-MODFLOW model was done to demonstrate its accuracy. Fig. 5 represents the scatter plot for comparative statistics (R^2) of the simulated groundwater levels against observed groundwater levels.

Linear optimization

Optimization techniques determine the optimal values for the system design and operational policy variables, resulting in the highest system performance. Linear Programming (LP) is employed to either maximize or minimize the objective function while adhering to various constraints. The problem involves maximizing a linear objective function (net economic returns) subject to linear constraints (land area, water availability, crop area limits). This linear structure aligns perfectly with LP's capabilities. While other methods like dynamic programming or metaheuristics could potentially be applied, LP offered an effective and efficient approach for this crop planning optimization context, balancing modeling power, solution quality and ease of implementation and interpretation (23, 24, 32).

Conjunctive use model formulation

In the present study, LP was used to maximize net profits using the objective function (Eqn. 3), subject to the land area constraint (Eqn. 4), surface water constraint (Eqn. 5), groundwater constraint (Eqn. 6), crop area constraint keeping people's affinity and nutritional requirement (Eqn. 7) and non-negativity constraint. Table 3 describes the various constraints for optimization to increase net benefit in the BCCA (11, 14).

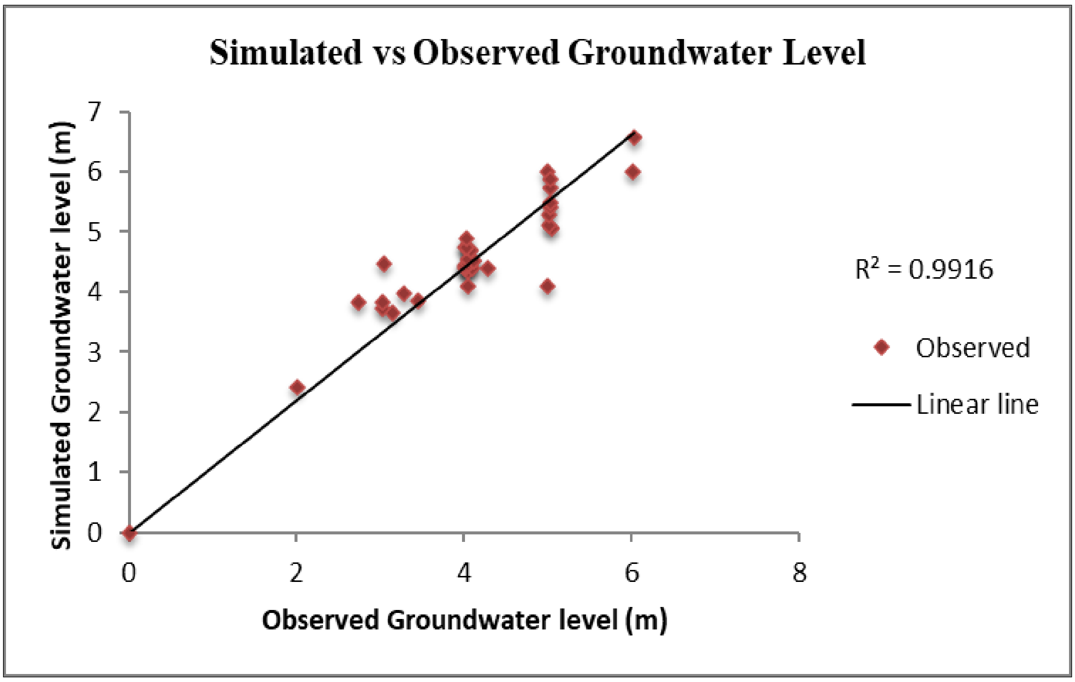

Fig. 5. Scatter plot for simulated against observed groundwater level.

Table 3. Constraints and description used in optimization (11, 14)

SI No	Constraint	Equations		
1.	Land area constraint	$\sum_{i}^{n} A_i^s + A_i^G \leq CCA_i$	Maximum area available for each crop should be less than the total cultivable command area	Eqn. (4)
2.	Surface water constraint	$\sum_{i}^{n} SW_i \leq WA_s \times E_s$	Surface water availability from canal system	Eqn. (5)
3.	Groundwater constraint	$\sum_i^n GW_i \leq WA_G \times E_G$	Groundwater availability estimated using GMS-MODFLOW	Eqn. (6)
4.	Crop area constraint	$L_{bi} \leq A_i \leq U_{bi}$	Minimum area allocations for cereals, pulses, oilseeds to meet nutritional needs	Eqn. (7)
5.	Non-negativity constraint		Crop areas must be non-negative values	

A_i^G: area for each crop (groundwater); CCA_i: total culturable command area; SW_i: surface water requirement; = water requirement for each crop × A_i^s; GW_i : groundwater requirement = water requirement for each crop × A_i^G; WA_s: surface water availability; WA_G : groundwater availability; L_{bi} : lower bound for crop 'i'; U_{bi}: upper bound for crop 'i'; E_s: 70 % (34);E_G : 100 % (35).

Table 4. Constraints on crop areas to fulfill dietary requirements (33)

	Crop	Condition	Suggested least level of cropped area per hectare (%)	Rationales
Cereals	Rice	≥	50.00	To improve the fibre level in the family diet
	Maize	≥	1.61	
	Ragi	≥	1.61	
	Wheat	≥	1.71	
Pulses	Green Gram	≥	1.61	To improve the protein level in family diet
	Black Gram	≥	1.61	
	Other Pulses	≥	9.68	
Oilseeds	Groundnut	≥	0.80	To improve the nourishment in the family diet
	Sesamum	≥	0.48	
	Sunflower	≥	0.81	
Vegetables	Potato	≥	1.94	To improve the nutrition level in the family diet
	Other Vegetables	≥	11.29	
Cash crop	Sugarcane	≥	1.00	To improve the family income

Table 4 illustrates the crop area constraints to meet the dietary requirements in the BCCA (33).

Objective

$$Z = \Sigma^n_i A^s_i \times NR^s_i + A^G_i + NR^G_i \quad (3)$$

Where, NR_i^G: net return for groundwater for each crop; A^s_i: area for each crop (surface water); A^G_i: area for each crop (groundwater).

Surface water irrigation efficiency typically ranges from 50 % to 80 %, depending on factors like the irrigation method, soil type and management practices. The 70 % assumption for surface water efficiency falls within this typical range. Groundwater irrigation efficiency is often higher than surface water, as there are fewer conveyance losses. Efficiencies of 70-100 % are common for groundwater irrigation systems. The 100 % assumption for groundwater efficiency is at the high end but could potentially be achieved with very efficient irrigation methods and management (34, 35). All the optimizations were analyzed using extension tool "Excel solver".

Results and Discussion

Deficit surplus status

The cropping pattern proposed by the Agriculture Department of the Government of Odisha (India) for *Rabi* 2023 is detailed in Table 5. This table also includes information on water availability and demand under the command of each distributary and branch canal of the Bargarh Canal System. According to the prevailing cropping pattern and farmers' preferences, 60 % of the total CCA for each outlet was allocated to crops with a high-water demand like rice and sugarcane. Similarly, 20 % of the total CCA was allocated to moderate water demand crops like groundnut, various vegetables, maize and potato and 20 % to low water demand crops like Green Gram, Black Gram, other pulses, Ragi, Sesamum and Sunflower. A deficit was observed for most of the distributaries and branch canals, whereas a surplus of water was noted in the Bargarh, Dang, Puturupali and Andharibanji Distributaries. This presents potential for expanded irrigation or growing more water-intensive crops in those water surplus areas. Given the deficit in surface water availability, groundwater use may be necessary to meet crop water demands. In the deficit-surplus analysis, an assessment was made between the water requirements of the actual cropped area and the theoretical design of the water supply for each outlet. Subsequently, a water deficit was observed in the analysis of the tail-end outlets. There is

Table 5. Deficit-surplus analysis of the Bargarh Canal command

Sl. No.	Name of Distributary/ Branch canal	Cropping Pattern (ha) Rabi 2023				Water Status		
		Heavy	Moderate	Low	Total	WR (ha-cm)	WA (ha-cm)	Status
1	Godbhaga Distributary	11170.21	1595.744	3191.488	15957.44	1404254.72	931392	Deficit
2	Telkani Distributary	354.9	50.7	101.4	507	44616	26870.4	Deficit
3	Attabira Branch Canal	22027.72	3146.817	6293.634	31468.17	2769198.96	2206656	Deficit
4	Jada Distributary	1087.1	155.3	310.6	1553	136664	95040	Deficit
5	Bargarh Distributary	1516.2	216.6	433.2	2166	190608	861408	Surplus
6	Dang Distributary	254.1	36.3	72.6	363	31944	50976	Surplus
7	Ambapali Distributary	347.9	49.7	99.4	497	43736	32832	Deficit
8	Baiman Distributary	751.1	107.3	214.6	1073	94424	62208	Deficit
9	Behera Distributary	2704.408	386.344	772.688	3863.44	339982.72	260928	Deficit
10	Ainthapali Distributary	362.859	51.837	103.674	518.37	45616.56	41472	Deficit
11	Barpali Distributary	1157.828	165.404	330.808	1654.04	145555.52	119232	Deficit
12	Retamunda Branch	11746	1678	3356	16780	1476640	1238976	Deficit
13	Bisipali Distributary	393.407	56.201	112.402	562.01	49456.88	21600	Deficit
14	Resume Distributary	4889.85	698.55	1397.1	6985.5	614724	422496	Deficit
15	Dhanbasa Distributary	199.5	28.5	57	285	25080	1900.8	Deficit
16	Sarasmal Distributary	291.9	41.7	83.4	417	36696	21945.6	Deficit
17	Rampur Distributary	3777.2	539.6	1079.2	5396	474848	336960	Deficit
18	Puturupali Distributary	99.05	14.15	28.3	141.5	12452	74304	Surplus
19	Telpali Distributary	187.6	26.8	53.6	268	23584	19872	Deficit
20	Barkale Distributary	4521.3	645.9	1291.8	6459	568392	474336	Deficit
21	Sulei Distributary	379.4	54.2	108.4	542	47696	42336	Deficit
22	Pandrapali Distributary	448.7	64.1	128.2	641	56408	42336	Deficit
23	Andharibanji Distributary	492.8	70.4	140.8	704	61952	1417824	Surplus
24	Gania Distributary	312.2	44.6	89.2	446	39248	31104	Deficit
25	Bhimtikra Distributary	7484.4	1069.2	2138.4	10692	940896	821664	Deficit
	Total	76957.63	10993.95	21987.89	99247.47	9674673.36	9656668.8	Deficit

insufficient surface water to meet crop demands in many parts of the command area. This necessitates groundwater supplementation and water conservation measures a three-dimensional groundwater flow model was established for BCCA and Fig. 6 shows the head distribution, Digital Elevation Model (DEM) and Triangulated Irregular Network (TIN) map representing 3D meshes. Total inflow and outflow of water were found to be 89075.03 ha-cm, indicating a balanced water budget.

In surplus areas, farmers might expand irrigated land or grow more water-intensive, high-value crops. In deficit areas, farmers may need to supplement canal water with groundwater by installing tube wells or borewells. They could adopt water-efficient irrigation methods like drip or sprinkler systems and shift to less water-intensive crops. Collective actions like forming water user associations and coordinating planting schedules could help manage water distribution more equitably. Infrastructure improvements, such as lining canals and installing flow measurement devices, could enhance water use efficiency. Capacity building through training on efficient irrigation practices and access to weather forecasts would help farmers optimize water use and adapt to varying water availability.

Derivation of optimal cropping pattern using linear programming

The optimization model was formulated with different constraints, such as water availability, land availability, crop area and land area for the *Rabi* season. The final iteration shows that all constraints and optimality conditions are satisfied. The net benefit per crop is shown in Fig. 7. Considering the cost of cultivation, water requirements and net return per crop, rice, other vegetables, green grams and other pulses are highly profitable crops. In addition, according to the soil, climate, water availability and cost of cultivation, rice and vegetables are preferable in the canal command to obtain maximum benefits and we can also increase the allocated crop area for those crops. While the specific numerical results differ, the overall findings of increased economic returns, crop diversification, conjunctive water use, improved efficiency and policy relevance are consistent with other studies in similar regions. The novelty lies in the specific application to the Bargarh Canal Command Area and the integration of multiple modeling approaches (CROPWAT, GMS-MODFLOW and LP) to develop a comprehensive optimization framework.

Throughout the year, local farmers consistently cultivated rice as their main crop, yet the profits they gained were not satisfactory. This study focuses on improving water use and crop choices in the BCCA to increase farmers' profits. A linear programming model was used to find the best combination of crops and water usage. The optimized cropping pattern derived from linear programming resulted in a total net economic return of 4837.14 million rupees, compared to 4673.18 million rupees from the prevailing cropping pattern. This represents a substantial increase of 163.96 million rupees in farmers' income compared with current practices.

Sensitivity analysis

The study conducted a sensitivity analysis to assess the impacts of changes in cropping pattern on net profit for the BCCA. It was performed considering one parameter change at a time for the objective function change and constraint changes to assess the impacts of the cropping pattern on net profit for BCCA. Shadow prices were calculated to determine the rate of change in the optimal value of the objective

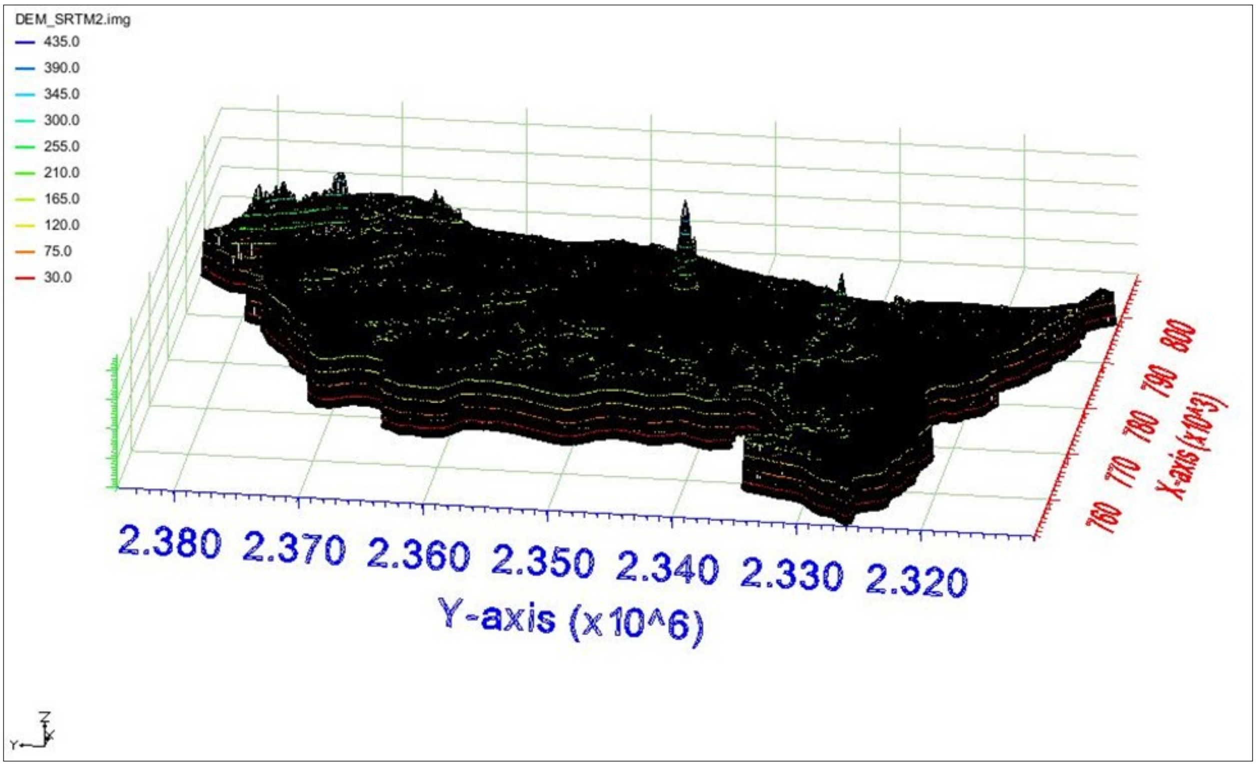

Fig. 6. Digital elevation model map of BCCA in GMS.

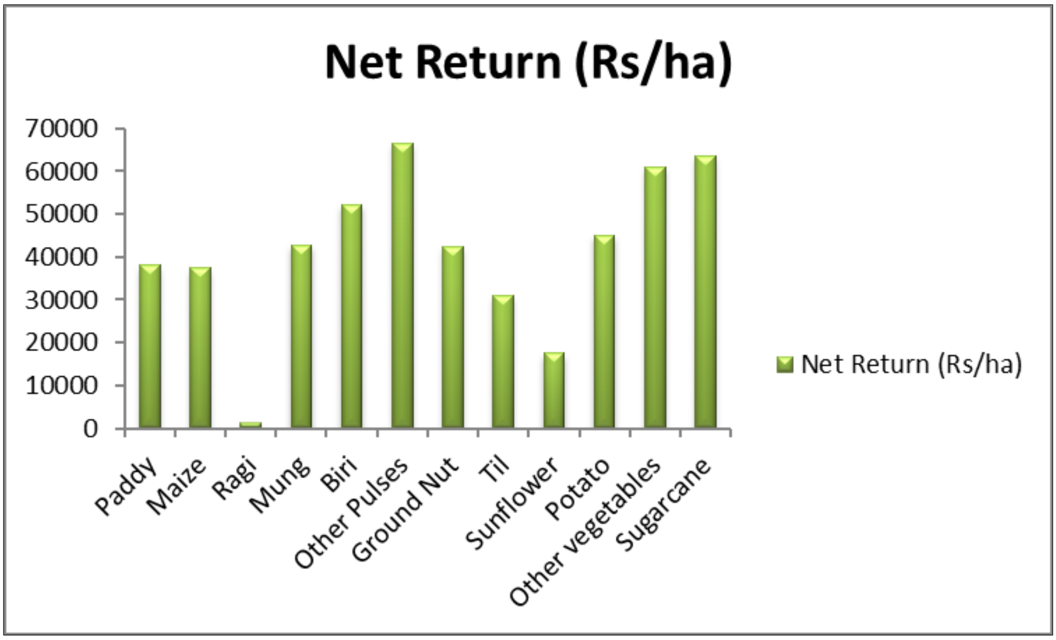

Fig. 7. Net benefit analysis per crop.

Table 6. Sensitivity analysis for constraints total area (ha) used in linear optimization

Sl No	Name	Final Value	Shadow Price	Constraint R.H. Side	Allowable Increase	Allowable Decrease	Maximum value	Minimum Value
1	Groundnut	2880	30806	2880	5123.07	2843.57	8003.07	36.43
2	Other Pulses	5320.02	54906	5320.02	5123.07	5234.37	10443.09	85.65
3	Black Gram	539.51	40506	539.51	5123.07	530.82	5662.58	8.69
4	Green Gram	8550	31006	8550	5123.07	8412.35	13673.07	137.66
5	Ragi	11.44	5656	11.44	133.56	9.11	145.00	2.33
6	Maize	320	25637	320	5123.07	314.85	5443.07	5.15
7	Rice	74782.21	26306	74782.21	5123.07	37391.11	79905.28	37391.11
8	Sugarcane	10.12	51918.22	10.12	5123.07	10.02	5133.19	0.10
9	Other vegetables	16444.75	49306	16444.75	5123.07	14588.14	21567.82	1856.61
10	Potato	550	33393	550	5123.07	505.45	5673.07	44.55
11	Sunflower	73.74	5906	73.74	5123.07	67.84	5196.81	5.90
12	Sesamum	758.96	19306	758.96	0.00	722.53	758.96	36.43

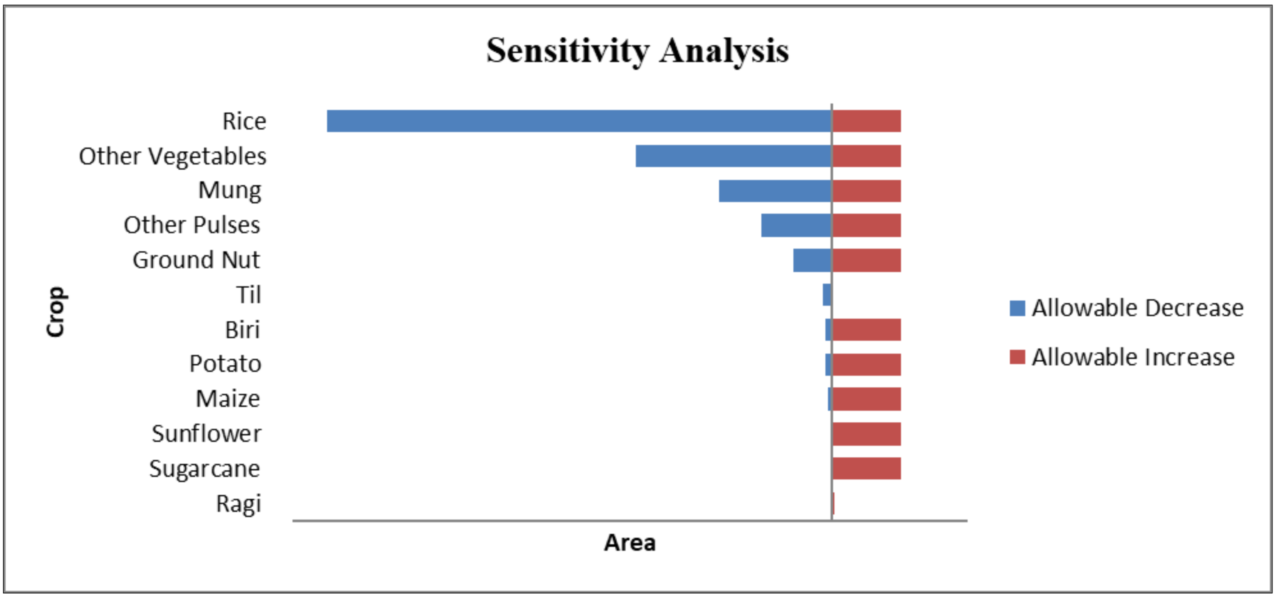

Fig. 8. Sensitivity analysis plot for different crops for total area.

function (net profit) with respect to a one unit change in area constraints. The results for all 12 crops are shown in Table 6 and a tornado graph was plotted (Fig. 8) for maximum allowable increase and decrease in area, i.e., range where optimal solution/maximum profit remains unchanged. The constraints on rice, vegetables, pulses and groundnut areas appear to be the most limiting factors for maximizing profitability. Relaxing these constraints, particularly for rice and vegetables, would likely lead to the largest increases in overall profit. Crops like potato, maize and sugarcane have very low or zero shadow prices, suggesting they are not significantly limiting profitability. Expanding the cultivation of some crops like black gram and sesamum might reduce overall profits. The model suggests focusing on expanding production of these high-value crops where possible, while potentially reducing the area for less profitable crops. This provides valuable insights into the robustness of the optimal solution and its responsiveness to changes in the key parameters. By examining shadow prices, decision-makers can identify the area constraints that have the most significant impact on the overall profitability of the cropping pattern. This information can be particularly useful for prioritizing resource allocation and guiding future agricultural planning decisions within BCCA.

The optimized cropping pattern could significantly boost regional agricultural profitability. This substantial revenue growth could improve farmers' livelihoods, increase agricultural investment, enhance food security, create jobs and promote crop diversity. Implementing this pattern could lead to a more sustainable and profitable agrarian system that benefits farmers and communities. Further research and pilot programs are required to validate these findings.

Conclusion

The analysis of the BCCA reveals inefficiencies in water distribution and gaps between irrigation supply and crop demand. An optimization model using GMS, linear programming and CROPWAT was developed to maximize agricultural sustainability and profit. The model identified a water deficit of 18004.56 ha-cm, with groundwater supplementing 89075.03 ha-cm. While groundwater helps address the surface water deficit, its long-term sustainability depends on recharge rates and extraction levels. The optimal cropping pattern increased net economic returns by 163.96 million rupees compared to the prevailing pattern. This approach shows promises for enhancing agricultural sustainability, improving water management and increasing economic returns in water-scarce regions. Policymakers should consider implementing pilot programs to test and validate the optimized cropping patterns and water allocation strategies identified in this study. Government agencies could provide incentives or subsidies to farmers who adopt more water-efficient crops and irrigation practices aligned with the optimized plans. While the policy recommendations aim to promote sustainable crop planning and water management in the Bargarh Canal Command Area, their implementation may face challenges such as resistance from farmers accustomed to traditional rice cultivation, initial costs of adopting new technologies and potential short-term yield reductions during the transition period. Additionally, the success of these measures depends on factors like consistent policy enforcement, adequate funding for infrastructure improvements and effective coordination among various stakeholders.

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Authors' contributions

PM conducted research, data acquisition, statistical analysis and drafted the manuscript; JCP performed in conceptualization and supervision; DMD participated in data analysis and edited the manuscript; SKR helped in conducting the research work; APS has supervised; and NP performed in data analysis and statistical analysis.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

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