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ORIGINAL ARTICLE

Optimal cropping pattern for a tail-end distributary canal of Bhadra command area using linear programming model

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Abstract
Agriculture has a major role in the Indian economy. More than 50% population depends on agriculture for livelihood. It is observed that there is a significant difference in farmer preference and the notified cropping pattern by the department in most of the command area. Farmer prefers to grow wet crops/profitable crops. There is a mismatch between demand and supply for notified cropping. To bridge the gap between these two, there is a need for designing of cropping pattern considering the available water in the canal. The present study uses a linear programming model for cropping pattern suggestion considering the rotational policy followed in the canal system. This model considers constraints like area availability, water availability, farmer preference, and soil suitability to design a cropping pattern to maximize the net returns. Conclusions were drawn about the possible cropping pattern in the command area depending on water demand against the notified crops and their corresponding economic benefits. This paper also suggests cropping pattern for deficit supply to the canal system in the range of 100% to 50% for the rotation period.

Keywords Command area · Rotation policy · Optimal crop planning · Surplus–deficit analysis · Linear programming

Introduction

The systematic utilization of available water resources is crucial for a country like India, which shares 17% of the global population with only 2.4% of land and 4% of the water resources (CWC 2015). Canal mode of water supply is very important for most of the crop; however, its frequency is reduced in the recent years alarms the proper irrigation planning. Irrigation planning plays an important role to solve the gap between the supply and demand of water resources in the canal command area. Many researchers highlight the problems related to canal irrigation and a few are addressed here. Moors Eddy et al. (2011) suggested regional adaptation plans to increase the resilience. Here, irrigated area accounts for nearly 48.8 percent, while the remaining 51.2 percent is rain-fed. Sarma and Rao (1997) carried out a case study and found that the major problem encountered in canal irrigation is the timely equitable allocation and maintenance of the system. In India, the overall efficiency of major and medium irrigation projects is below 30% due to poor distribution and management of irrigation water, and hence, there is need of sufficient monitoring and evaluation of performance to improve water management practices to improve efficiency.

Linear programming (LP) is one of the best tools for the optimal allocation of land and water resources. Different researchers have applied LP models to develop an optimal cropping pattern within the available resources and constraints of their study area. Osama et al. (2017) developed the optimization model to maximize the profit in different regions of Egypt. Gadge et al. (2014) developed Linear Optimal Programming (LP) under available water and recommended a varied cropping pattern to ensure maximum profit and compared with the traditional cropping pattern. Rath et al. (2019) developed the optimal cropping pattern model, whose results were compared with the existing adopted

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cropping pattern in the command area and found that the new cropping pattern can enhance the maximum net returns. Hove-Musekwab (2013) developed LP optimal model for cropping of an irrigation scheme in Masvingo, Zimbabwe. The solution indicates that farmer's income could be increased by 87% after adapting the model. Azamathulla et al. (2008) used Genetic algorithm and Linear Programming technique in real-time reservoir operation for optimal assigning of water for the notified crop. Azamathulla et al. (2008) used linear programming technique for irrigation scheduling in real-time reservoir operation for optimal assigning of water for the notified crop. Azamathulla et al. (2011) developed an extension of genetic programming approach with linear programming to find the scour depth. Abdolreza and Azamathulla (2014) applied linear genetic programming (LGP) and M5 tree to predict the flow in compound channel. Azamathulla and Zahiri (2012) used a set of artificial intelligent methods such as LGP to predict the discharge in the channel.

Decision on cropping pattern considering parameters like soil characteristics and the land suitability for the specific crop is considered by some researchers. Ferguson and Rundquist (2018) has suggested the optimal dosage of fertilizers after comparing the soil fertility and the available nutrient factors for the different crops. Cropping decision depends on multi-criteria GIS is a modern tool which will assist in the process. Feizizadeh and Blaschke (2013) used multi-criterion GIS approach to find the optimal land requirement for production. Yalew et al. (2016) used GIS approach to locate the area of soil erosion as well as land degradation. Abdel Rahman et al. (2016) used GIS approach to develop land suitability as well as land capability maps suitable for agriculture. This type of approach is very much useful for the irrigation and agricultural sector to improve agricultural activity to obtain optimal productivity.

Augmenting the cropping area by adopting less water consuming crops, replacing improved variety, and growing short-term crops which yield more profit are some of the techniques to obtain optimal productivity. Aerobic rice can be grown without flooding in unsaturated soil condition is one of the best choices and most effective strategies in terms of efficient use of water. Meena et al. (2019) represented the development with respect to aerobic rice. Xue et al. (2008) represented aerobic rice variety obtained from filed experiment. Singh et al. (2015) explained baby corn crop as one of the short-term crops which requires less water and can be grown as an intermittent crop with more profit.

The objective of present study aims in building a linear programming model to maximize the economic return from the command area considering the constraints appropriate to the command area. The study is undertaken to know the possibilities of improving the net returns for the real-time water schedule of an existing distributary canal where inherent problem of water shortage is observed at tail end. Initial studies investigate the water supply sufficiency for notified crops of the department under ideal rotation periods. Furthermore, this study suggests the suitable change of cropping pattern that can be adapted for the command area to maximize the cropping returns. Estimation of the optimal cropping pattern will take into account some of the constraints concerning to the study area in particular. Keeping the rotation period same as followed by the department for varied deficient supply, model is expected to suggest the new cropping pattern for this deficit supply. The limitation includes: range of objective function, selection of decision variable, derivative information dependency, and deterministic rules need to be addressed to improve the accuracy of the model. The description of the study area, irrigation procedure, and cropping pattern adopted in the command area and the model description with the results are discussed in detail in the next sections.

Study area

The study area shown in Fig. 1, is situated in Karnataka state of South India having 14°21′–14°30′ N latitude and 75°47′–75°57′ E longitude. The area lies in the Agro climatic-4th zone of Karnataka state having notified command area 1478.99 ha with 36 pipe outlets. The command area comprises of black and red type of soil and received an average of 58% rain from south-west monsoon, average of 22% from north-east monsoon, and an average of 20% during summer. The dam constructed across the Bhadra River at Lakkavalli village delivers water through both right and left bank canal irrigates a command area of 121,500 Ha. Harihar branch canal of Bhadra reservoir project is selected for this analysis and a middle distributary (10th distributary) of Harihar branch canal located at 15.3 km. The distributary is of 11.6 km length with discharging capacity 1.76 cumecs with a command area 2715 Ha.

Water allocation policy and cropping pattern under the distributary

The irrigation department considers the water availability in the reservoir and notify crops to be grown in different plots of the distributary. Paddy, Sugarcane, Garden, and semidry crops were the notified crops under 10th distributary with 62.04 ha, 120.21 ha, 34 ha, and 1262.74 ha area, respectively, for the Rabi season 2015 and 2016 (CACP 2015).

A rotational water allocation policy was adopted in the distributary. The rotation period was between 8 and 11 days. The distributary receives water in every alternate rotation. During Rabi season 2015 (January 26th to May

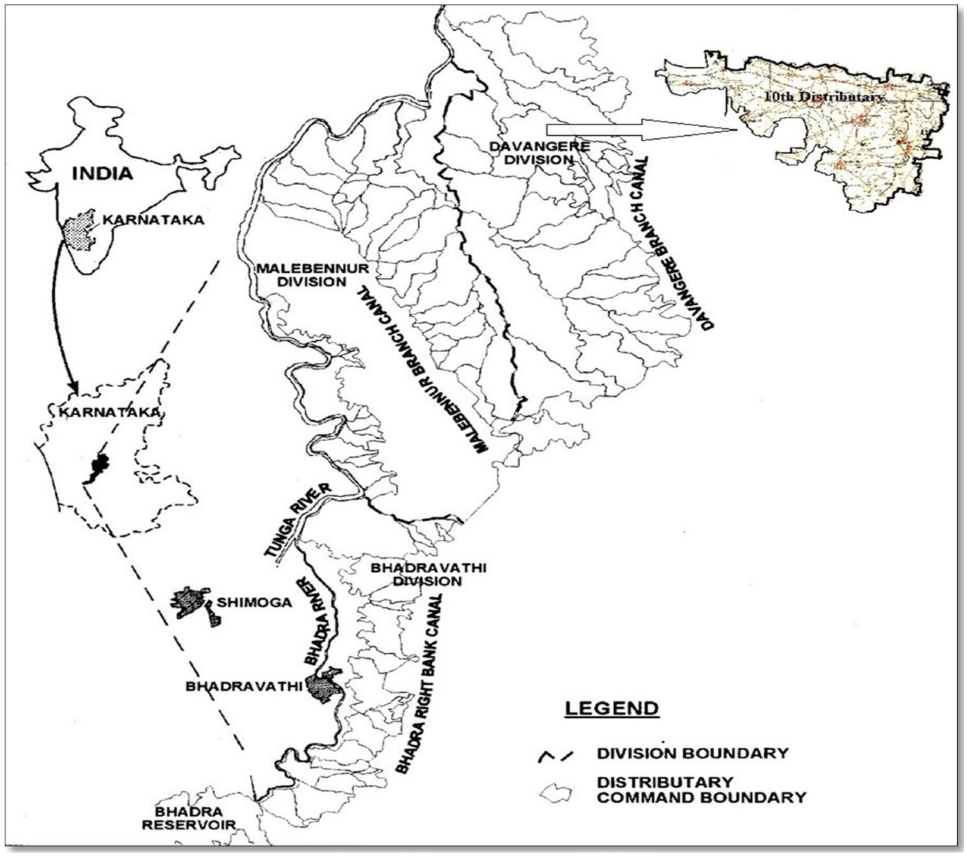

Fig. 1 Location map of the study area

15th 2015), there were 12 rotations with first ten rotations of 10 days and last two rotations of 5 days. However, during Rabi 2016 (10th January to 18th May 16), the canal was run intermittently with only eight rotations of alternate 8 and 9 days. (In between January 26th and February 15th, March 3rd and March 25th, and April 11th and May 1st, canal was closed due to shortage of water.) During these rotation periods of the main canal, the distributary receives the water in alternate rotations.

However, as per records when the reservoir is full, the canal shall run for 120 days with 10 days ON and 10 days OFF and 12 rotations. The climatological data of the command area from 2001 to 2014 were considered and water requirement for the notified crops using the FAO Modified Penman–Monteith method was assessed to understand the sufficiency of water.

The distributary considered in the present study receives water during 1, 3, 5, 7, 9th rotation periods of 10 days each and 5 days in the 11th rotation. This means, the distributary is OFF during 2, 4, 6, 8, 10, and 12th rotation period; therefore, the water requirement for the notified crops has to be matched with the water availability during the ON rotation. The analysis of the water requirement of crops against the water released to the distributary indicated that the distributary release is short of the crop water requirement in different rotations as presented.

The crop water requirement for the notified crops as per the rotational operational policy is presented in Table 1. It is observed that every rotational water requirement cannot be catered by the distributary. Therefore, water required by the crop for the rotation when the operation policy is OFF is balanced by supplying the sum water required in ON rotation to meet the water demand in advance as described in the table below. Sum total of water required for rotation 1 and 2 is supplied during rotation 1 of operation policy (ON Condition); likewise, water required for rotation 3 and 4 is supplied during rotation 3 of operation policy and followed similarly for the rest of the rotations. It is also observed that distributary carrying capacity is less compared to the water demand; therefore, the water supply to the notified crops is insufficient.

It is observed from Table 1 that the distributary cannot cater to the demand during all the rotations, as water requirement for crops is more than its capacity for the rotation period. Furthermore, it can be observed the total release to the canal is always less than the total water requirement for the rotation for the notified crops.

Table 1 Crop water requirement for the notified crops as per the rotational operational policy

Rotation operation	Irrigation water requirement (IWR)					IWR as per operation policy	Distributary water carrying capacity ha-m	*in ha-m* Surplus/deficit
	Paddy	Sugarcane	Garden	semidry	Total			
Rotation-1	8.10	13.00	2.68	77.13	100.91	230.410	152.50	– 77.91
Rotation-2	9.29	14.43	2.98	102.81	129.50	OFF		
Rotation-3	9.29	14.43	2.98	130.35	157.05	335.072	152.50	– 182.58
Rotation-4	10.18	16.07	3.31	148.46	178.03	OFF		
Rotation-5	10.77	17.17	3.53	158.49	189.97	379.943	152.50	– 227.45
Rotation-6	10.77	17.17	3.53	158.49	189.97	OFF		
Rotation-7	10.17	17.06	3.45	156.54	187.23	371.711	152.50	– 219.21
Rotation-8	9.57	16.94	3.37	154.59	184.48	OFF		
Rotation-9	9.57	16.94	3.37	113.30	143.19	256.270	152.50	– 103.77
Rotation-10	9.20	13.25	3.10	87.51	113.08	OFF		
Rotation-11	4.42	4.78	1.42	30.86	41.48	82.961	76.25	– 6.71
Rotation-12	4.42	4.78	1.42	30.86	41.48	OFF		

Table 2 Probable irrigable area with variable water availability in distributary and estimated net returns

Water availability	Paddy	Sugarcane	Garden	Semidry	*Crop area in ha* Net cropping area
100	0.00	0.00	34.00	577.10	611.10
95	0.00	0.00	34.00	546.82	580.82
90	0.00	0.00	34.00	516.53	550.53
85	0.00	0.00	34.00	486.24	520.24
80	0.00	0.00	34.00	455.95	489.95
75	0.00	0.00	34.00	425.67	459.67
70	0.00	0.00	34.00	395.37	429.37
65	0.00	0.00	34.00	365.07	399.07
60	0.00	0.00	34.00	334.78	368.78
55	0.00	0.00	34.00	304.49	338.49
50	0.00	0.00	34.00	274.20	308.20

The extent of notified crops that can be grown for a range of 100–50% of water availability to the distributary is carried out based on priority of water allocation for Garden crops followed by dry crops, sugar cane, and paddy was estimated. Since Garden crops in the command area are coconut and aracanut, the requirement is fully met and semidry is given the second priority as the crop requires less water. The probable cropping pattern is presented in Table 2 (CACP 2015).

The conclusion drawn from the initial analysis is that the supply capacity of the canal cannot cater to the crop water requirement for the notified crops. Hence, there is a need for change of the existing cropping pattern to match the water supplied in the canal.

After considering the outlet structure locations at the site, the command area of each outlet, the distributary is trifurcated into head, middle and tail reach to balance the water distribution till the tail end. The head reach area receives a discharge of 0.680 cumecs covering the area of 1010 ha. Middle reach receives a discharge of 0.420 cumecs covering an area of 697 ha. The tail reach area receives a discharge of 0.659 cumecs covering an area of 1008 ha. A linear programming model is developed for developing the cropping pattern model, which is discussed in the next paragraph.

Methodology

Optimal cropping pattern by linear programming

The water supply for the notified cropping pattern in the distributary is deficient. To bridge the gap of this deficit, there is a need for designing of new cropping pattern. Linear programming considers many constraints and gives the cropping pattern which when adapted can increase the net returns.

The optimal plan model, using the Linear Programming (LP) technique, is developed to allocate available water at the distributary canal with an objective to the aggregate net return from the command during the rabi season.

The constraints of the LP model were the water availability in different rotations, area availability, Farmer's priority, crop allocation on soil fertility, and fertilizer availability in the command area during the season. The model is described below.

Maximization of net returns in the command area with available water resources is the main objective. Mathematically, it is represented in Eq. 1

$$\text{Max } Z = \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} NR_i A_{ij}, \quad (1)$$

where K is the no of rotations varies from 1 to 6. NR is the total net returns from all of the crops in the distributary command area.

NR_i= Net returns per hectare of crop area of ith crop, A_{ij} = Area of the ith crop in jth reach. i = number of crops grown in season [1 = Paddy, 2 = Sugarcane, 3 = Garden (Arecanut), 4 = Maize, 5=Aerobic rice, 6 & 7 is Baby corn (double crop)]. j = Different reaches of the distributary command area. (1 = Head, 2 = Middle, 3 = Tail).

Constraints of water availability

The total water availability during the rotation for the distributary is allocated to three reaches, viz., Head, Middle, and Tail, respectively, in accordance with command area served by the reach.

The following mathematical equation considers water availability as a constraint which is given in Eq. 2:

$$\sum_{i=1}^{I} \sum_{j=1}^{J} A_{ijk} \mathrm{IWR}_{ijk} \le \mathrm{WAR}_k \quad \text{for } k = 1, 2, 3 \ldots 6, \quad (2)$$

where $\mathrm{IWR}_{\mathrm{ijk}}$ is the depth of irrigation water requirement ith crop in jth reach during kth rotation. $\mathrm{WAR}_{\mathrm{k}}$ is the volume of water available at the distributary at the head for different rotation in ha-m. k = rotation number. (1 = First rotation, 2 = second rotation, 3 = third rotation, 4 = fourth rotation, 5 = fifth rotation, 6 = sixth rotation. A_{ijk}= area of the i^{th} crop under j^{th} reach for k^{th} rotation in (ha).

Constraints for area availability

The culturable command areas of Head (H), Middle (M), and Tail (T) reaches are fixed.

The total area of crops under cultivation in any reach shall be less than the notified area for the crops for that reach.

The following mathematical equation considers area availability as a constraint, which is given in Eq. 3

$$\sum_{i=1}^{I} A_{ijk} \le A_j \quad j = 1, 2, 3 \quad \text{for } k = 1, 2, 3 \ldots 6, \quad (3)$$

where A_{j} = command area of jth reach.

Farmers' crop priority constraint

Farmers prefer to grow wet crops or crops yielding higher profits, over semidry crops in the command area as the plot may be suitable for growing crops. However, it may not be possible to grow these crops due to water availability constraints and it may exceed the notified crop area for the season. An interview is conducted to ascertain the crops preferred by the famers in the distributary. Some of the farmers are preferring aerobic rice as an alternative to conventional rice as the crop requires less water.

Therefore, the total area even if the farmers grow the preferred crop under the command during any rotation in any reach shall always be less than the notified crop area for that distributary. Mathematical representation of the constraint can be written as shown in Eq. 4

$$\sum_{i=1}^{I} \sum_{j=1}^{3} APF_{ij} \le A_j, \quad (4)$$

where APF_{ij} = Area of ith crop preferred by the farmer in jth reach.

Crop area constraint-based on natural soil condition

The agricultural department suggests a suitable crops that can be grown with nominal fertilizer dosage in the command area. Soil suitability map for each of the crops suggested by the agriculture department is done through GIS mapping and the constraints are being developed for this model. The total area suggested by the agriculture department, and subsequently, the crop grown by the farmers under each crop shall not exceed the notified crop area for the reach. Mathematical form is represented in Eq. 5

$$\sum_{i=1}^{I} \mathrm{ASF}_{ij} \le A_j \quad J = 1, 2, 3 \ldots J \quad (5)$$

where ASF_{ij} = Area of ith crop suggested based on soil fertility with the optimal dosage of the fertilizer in jth reach. A_j = command area of jth reach.

Crop area constraint

The notified crop area in the command comprises paddy, sugarcane, garden, and semidry crops. The water requirement of the garden crops is to be fully met as these crops are long duration multi-year crops. The area consists of two sugar factories; hence, large area is notified for sugar cane. Since the quantity of water to distributary is not catering to the notified crop requirement for sugar cane, it is restricted to a maximum of 60% of the area proposed under sugar cane. Of the maximum 60%, a proposed maximum of 25% for head and middle reach, and a maximum of 10% for tail reach is allocated to sugar cane.

A semidry crop like maize is not preferred in head reach by farmers. However, a constraint of minimum semidry crops of 10% and a maximum of 25% of the allocated semidry crop area for each reach is adopted. Farmers in the command area prefer to grow rice in the command area. Constraint for conventional rice crop even for farmers preferring wet crops is adopted by introducing water saving aerobic rice crop, which is direct-seeded in nonpuddled, nonflooded aerobic soil. Aerobic rice system can reduce water use in rice production by as much as 50%. Aerobic rice with a minimum of 10% and a maximum of 25% of the notified semidry crop area is implemented.

The water supplied during the rotation period shall cater the demand of crop for full period. If some water left over in any rotation can be utilized for certain intermittent crops of short period, higher profit can be expected. Baby corn is one of the short duration crops (60–80 days) suitable for this command area. This crop can be grown as a double crop (staggering) within the season up to a maximum of 25% of notified semidry crop area.

The following mathematical equation considers crop area as a constraint, which is given as shown in Eqs. 6 and 7:

$$\sum_{J=1}^{J} A_{ijk} \geq CF_{ijk}A_{ij} \tag{6}$$

$$\sum_{J=1}^{J} A_{ijk} \leq CF_{ijk}A_{ij} \quad \text{for } j = 1 \ldots J \tag{7}$$

CF_{ijk}= proposed crop percentage factor for ith crop in jth reach for kth rotation in (ha),where Eq. 6 represents the minimum percentage of area limit for the reach for ith particular crop, and Eq. 7 represents the maximum percentage of area limit for the reach for the particular crop.A_{ijk}= area of the ith crop under jth reach.

Fertilizer as constraint

The government allocates a fixed amount of fertilizer to the particular command area. Also, a particular crop requires a known quantity of fertilizer. Hence, in this model, amount of fertilizer available is equally restricted to each reach in arriving at cropping pattern.

The following mathematical equation considers fertilizer as a constraint, which is given in Eq. 8:

$$\sum_{i=1}^{I} A_{ij}FR_{ij} \leq TFA_j \quad \text{for } j = 1, 2 \text{ and } 3 \tag{8}$$

where FR_{ij} = fertilizer requirement for the ith crop in jth reach. A_{ij} = area with total Fertilizer availability for the j^{th} reach.

Results and discussion

The rotational water supply to the 10th distributary command area of the Harihar branch canal of Bhadra Irrigation project is verified for sufficiency of crop water requirement for the crop period. It is understood that water supply is insufficient to cater to the demand of the notified crops of the department necessitated for newer cropping pattern policy considering the constraints of the system for economic benefits.

The present work carried out to suggest a cropping pattern for maximum revenue, suitable to the command area for a range of water supply varying from 100 to 50% to the distributary.

The restrictions with respect to water release to garden crop which is a multiple year crop in the command area and the sugar cane is attended before planning of cropping pattern. Farmer's priority crop like rice is proposed by replacing with aerobic rice. Due to the application of the change in cropping pattern, some excess water was observed during certain rotations for which intermittent crop of shorter period-baby corn is proposed in the distributary.

The LP modeling for the varied percentage of water availability in each reach [head, middle, and tail] is done separately. The tail-end deprivation are taken care of through continuous operations of laterals. The cropping pattern results for each reach are shown in Table 3 (CACP 2015), Tables 4, and 5. The total cropping pattern for the command is shown in Table 6 and is graphically represented in Fig. 2.

The cumulative yield from all reaches is computed (standard yield per hectare for each crop is obtained from the Commission for Agricultural Costs and Prices, Department of Agriculture, Cooperation and Farmers Welfare, Ministry of Agriculture and Farmers Welfare, Government of India, March 2015–2019) in Table 7 and the graphical representation is shown in Fig. 3.

The financial returns for the newer cropping for command area (standard maximum selling price per 100 kg for each crop is obtained from the Commission for Agricultural Costs and Prices, Department of Agriculture, Cooperation and Farmers Welfare, Ministry of Agriculture and Farmers Welfare, Government of India, March 2019) is shown in Table 8.

Table 3 Cropping pattern through LP model in the head reach for the varying percentage of water availability (WA)

Area in hectares

WA	Paddy	Sugarcane	Garden	Maize	Aerobic rice	Baby corn	Total
100	0.00	30.05	23.80	0.00	62.04	161.01	276.90
95	0.00	30.05	23.80	0.00	62.04	162.09	277.98
90	0.00	30.05	23.80	0.00	62.04	161.42	277.31
85	0.00	30.05	23.80	0.00	62.04	142.01	257.91
80	0.00	30.05	23.80	0.00	62.04	122.57	238.46
75	0.00	30.05	23.80	0.00	62.04	103.12	219.01
70	0.00	23.36	23.80	0.00	62.04	95.61	204.81
65	0.00	0.00	23.80	0.00	62.04	117.83	203.67
60	0.00	0.00	23.80	0.00	62.04	98.37	184.22
55	0.00	0.00	23.80	0.00	62.04	78.93	164.77
50	0.00	0.00	23.80	0.00	62.04	59.52	145.36

Table 4 Cropping pattern through LP model in the middle reach for the varying percentage of water availability

Area in hectares

WA	Paddy	Sugarcane	Garden	Maize	Aerobic rice	Baby corn	Total
100	0.00	30.05	10.20	58.24	0.00	89.28	187.77
95	0.00	30.05	10.20	63.73	0.00	64.50	168.48
90	0.00	30.05	10.20	67.82	0.00	42.51	150.58
85	0.00	30.05	10.20	57.61	0.00	47.91	145.77
80	0.00	30.05	10.20	47.40	0.00	53.31	140.96
75	0.00	19.43	10.20	44.37	0.00	68.41	142.41
70	0.00	0.00	10.20	49.86	0.00	86.66	146.72
65	0.00	0.00	10.20	55.36	0.00	61.88	127.44
60	0.00	0.00	10.20	60.79	0.00	37.22	108.21
55	0.00	0.00	10.20	57.25	0.00	29.80	97.26
50	0.00	0.00	10.20	51.21	0.00	27.29	88.69

Table 5 Cropping pattern through LP model in the tail reach for the varying percentage of water availability

Area in hectares

WA	Paddy	Sugarcane	Garden	Maize	Aerobic rice	Baby corn	Total
100	0.00	60.11	0.00	68.03	0.00	181.21	309.34
95	0.00	60.10	0.00	62.54	0.00	169.50	292.14
90	0.00	58.21	0.00	58.45	0.00	159.36	276.02
85	0.00	35.25	0.00	68.66	0.00	168.23	272.14
80	0.00	12.29	0.00	78.87	0.00	177.10	268.26
75	0.00	0.00	0.00	81.90	0.00	176.27	258.17
70	0.00	0.00	0.00	76.41	0.00	164.57	240.97
65	0.00	0.00	0.00	70.91	0.00	152.86	223.77
60	0.00	0.00	0.00	65.48	0.00	141.03	206.51
55	0.00	0.00	0.00	69.02	0.00	112.04	181.06
50	0.00	0.00	0.00	75.06	0.00	78.16	153.22

A comparison of the area and economic benefit by adopting the new cropping pattern against the notified cropping pattern is presented in Fig. 4 and economic benefits are presented in Fig. 5.

The model predicts that an alternative to paddy crop, aerobic rice which requires less water is more beneficial in terms of yield and as well as economic returns. Also, adopting intermittent crops like Baby corn (a short

Table 6 Cropping pattern through LP model in the distributary for the varying percentage of water availability

Area in hectares

WA	Paddy	Sugarcane	Garden	Maize	Aerobic rice	Baby corn	Total
100	0.00	120.21	34.00	126.27	62.04	431.5	774.02
95	0.00	120.21	34.00	126.27	62.04	396.09	738.61
90	0.00	118.31	34.00	126.27	62.04	363.29	703.91
85	0.00	95.36	34.00	126.27	62.04	358.15	675.82
80	0.00	72.40	34.00	126.27	62.04	352.98	647.69
75	0.00	49.48	34.00	126.27	62.04	347.8	619.59
70	0.00	23.36	34.00	126.27	62.04	346.83	592.50
65	0.00	0.00	34.00	126.27	62.04	332.56	554.88
60	0.00	0.00	34.00	126.27	62.04	276.63	498.94
55	0.00	0.00	34.00	126.27	62.04	220.78	443.09
50	0.00	0.00	34.00	126.27	62.04	164.96	387.28

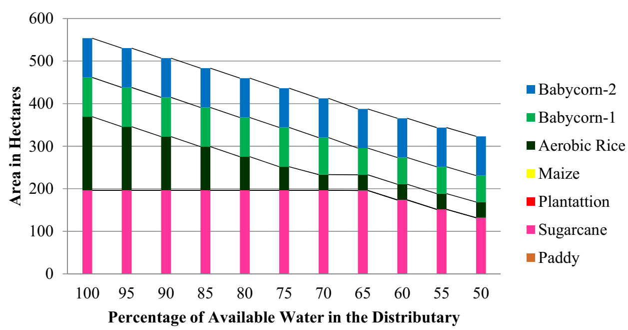

Fig. 2 Cropping pattern through LP model in the distributary for the varying percentage of water availability

duration crop) with left over water in the season enhanced the overall yield and economic returns. The increase in percentage cropping area against the notified cropping area by adopting the newer cropping pattern adopted in the model for varying discharge availability between 100 and 50% was 126.66 to 125.66%.

Adopting a new cropping pattern, the net revenue benefit was raised from 35.64 to 77.02 million Rs when 100% water available in the distributary and 22.52 million–35.08 million Rs when the water availability is reduced to 50%. If this model is put into use for few years, the water allocation will became familiar with the system of operation.

Conclusions

A sharp decline in the performance of the irrigation system was observed in a distributary of the Harihar branch canal of the Bhadra irrigation system over the decades. Hence, there was a need to address a solution to the problem through a newer cropping pattern. The deficit–surplus supply analysis of the distributary suggests that canal flow running under rotational supply cannot cater to the notified cropping pattern of the department except for two end rotations. Preliminary studies at the distributary level indicated that the canal water is also not reaching the tail end of the distributary.

Table 7 Estimated total yield for the cropping pattern through LP model in the distributary for the varying percentage of water availability

Yield in terms of 100 kg units

WA	Paddy	Sugarcane	Garden	Maize	Aerobic rice	Baby corn	Total
100	0.00	85,349.10	425.00	6313.70	3412.20	8198.4	103,698.39
95	0.00	85,349.10	425.00	6313.50	3412.20	7525.74	103,025.54
90	0.00	84,002.55	425.00	6313.50	3412.20	6902.43	101,055.68
85	0.00	67,703.17	425.00	6313.50	3412.20	6804.94	84,658.81
80	0.00	51,403.79	425.00	6313.50	3412.20	6706.56	68,261.05
75	0.00	35,129.49	425.00	6313.50	3412.20	6608.18	51,888.38
70	0.00	16,587.08	425.00	6313.50	3412.20	6589.7	33,327.48
65	0.00	0.00	425.00	6313.50	3412.20	6318.74	16,469.44
60	0.00	0.00	425.00	6313.50	3412.20	5255.99	15,406.70
55	0.00	0.00	425.00	6313.50	3412.20	4194.74	14,345.44
50	0.00	0.00	425.00	6313.50	3412.20	3134.36	13,285.06

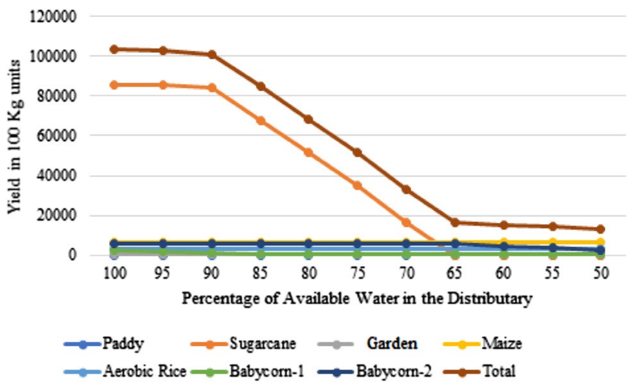

Fig. 3 Estimated total yield for the cropping pattern through LP model in the distributary for the varying percentage of water availability

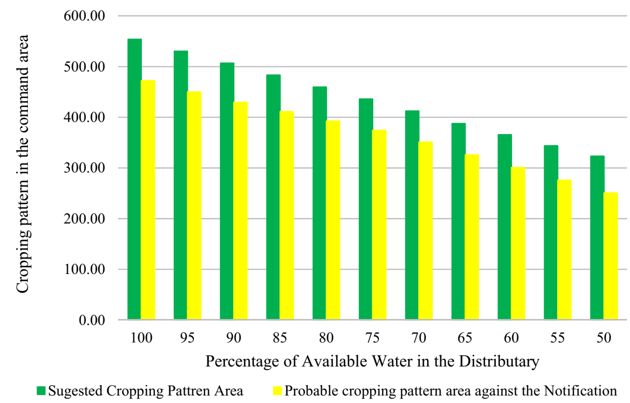

Fig. 4 Cropping pattern covered in the distributary command area by linear programming

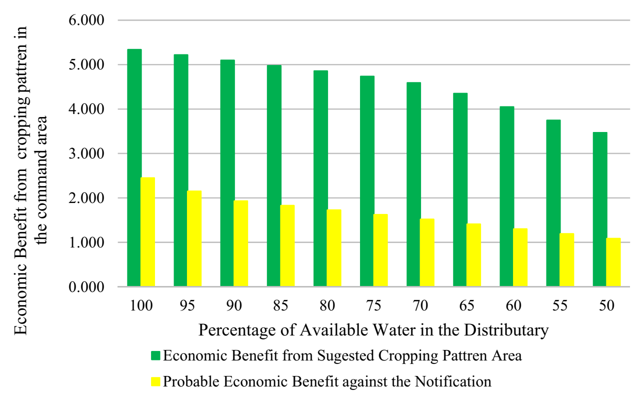

Fig. 5 Net returns from the cropping pattern covered in the distributary command area by linear programming

The number of days in the rotation period and the number of the rotations followed were not matching to the ideal cropping period during the water-deficit season. The computer model based on linear programming is useful to find the optimal cropping pattern and water release schedule at the minor level under a given scenario of mixed cropping and water availability. In the present model, the duration of water release is taken as the ideal crop period with a canal running at a lower capacity. The distributary command area is divided into head, middle, and tail reach considering the existing outlet's position. The discharge to these reaches was allocated following the area of these reaches. Since farmers prefer to grow the wet crop—Paddy in the command area against notified dry crops for their plot—a new variety of paddy "Aerobic rice" which requires less water is suggested in the command area. Intermittent crops like baby corn is suggested for surplus supplies in rotation periods. Constraints with regard to command area are suitably considered and a linear programming model is developed and run for

Table 8 Estimated net profit for the cropping pattern through LP model forth varying percentage of water availability

WA	Paddy	Sugarcane	Garden	Maize	Aerobic rice	Baby corn	Net returns in million rupees Total
100	0.00	16.45	10.65	5.47	3.18	41.27	77.02
95	0.00	16.45	10.65	5.47	3.18	37.88	73.63
90	0.00	16.19	10.65	5.47	3.18	34.74	70.23
85	0.00	13.05	10.65	5.47	3.18	34.25	66.60
80	0.00	9.91	10.65	5.47	3.18	33.76	62.97
75	0.00	6.77	10.65	5.47	3.18	33.26	59.33
70	0.00	3.20	10.65	5.47	3.18	33.17	55.67
65	0.00	0.00	10.65	5.47	3.18	31.81	51.11
60	0.00	0.00	10.65	5.47	3.18	26.46	45.76
55	0.00	0.00	10.65	5.47	3.18	21.12	40.42
50	0.00	0.00	10.65	5.47	3.18	15.78	35.08

the command area. The model results were very encouraging in terms of increment in area of irrigation and revenue for varied rotational supplies.

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Code availability Not applicable.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Informed consent For this type of study, formal consent is not required.

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