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Optimizing Approach of Water Allocation to Off-Takes During Reduced Flows

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Abstract
Multi-objective optimization models with an index were developed based on farmers' preferences, local requirements, supplies available at the head of the canal, system losses, crop demand about different growth stages, and field soil moisture balance. The models were applied using linear programming. The Model 1 determines the cropping pattern by maximizing net economic benefits using a monthly basis lumped volume available at the head of the canal and is set to the minimum and maximum area constraints along with the constraint of minimum main crop area. The areas for different crops given by the first model form input for the Model 2. The other inputs of Model 2 included periodic supply available at the head of the primary canal (7-day period in this study), root growth depth, demand, and soil moisture constants. The Model 2 optimizes the sum of relative yields of all the crops and provide the irrigation levels of various crops for specified periods. Finally, the distributed area and irrigation levels determined by Model 2 are used in conjunction with the losses to decide flow rates of off takes. The complete program was implemented in the West branch irrigated area of Mirpurkhas subdivision. The results showed that the resources were allocated to off-takes in a competitive and conflict-free manner.

Keywords Agricultural water management; Irrigation water allocation · Linear programming · Optimization · Preference index

1 Introduction

The participatory irrigation management approach devolved the decision-making authority to the lower level. This empowers the officials and users (such as Farmers organization) responsible for canal command to make decisions for canal operation. The canal operation, in turn, is governed by many subtle considerations, for instance: the available supplies at the head, crop nature, timing of irrigation, crop growth stages, competition for land and

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water recourses among different crops and commands, knowledge of system losses and the effect of reduced supply on the crop yield. Besides that, farmers at the individual level want to cultivate more crop areas whereas a government official plan would be to have a maximum production from overall command. Thus, a farmer's interest sometimes leads to conflicts during policymaking regarding the primary canal and its off-takes operations during reduced flows. As a result, decision-makers have to resort to distributing the water on the rotation basis despite the fact that every off-take from the primary canal has its command area which may have the same water demand at the same time.

Against above-stated facts, the problem faced by decision-maker during the reduced supply in the canal system can comprise three stages: (1) formulating crop-mix to achieve maximum profit taking into account local and market demands; (2) allocating limited water resources among the crops to achieve maximum returns, meaning deciding irrigation levels for different crops in accordance with the crop demand, growth stages, sensitivity to water stress and water losses; and (3) distributing resources among competing command areas. Thus, a single decision-making mechanism or program is needed for the efficient use of water at the field. The decision should explicitly indicate how much water should be in the canal system in the given period along with allocation to the multiple crops and allocation to the off-taking commands (Bozorgi et al. 2021).

Optimization of the cropping area provides solutions for the large command areas considering available resources of that area, especially during reduced flows in the primary canal (Al-Maktoumi et al. 2021). In the present study, linear programming technique was used. Developed a linear model to optimize the cropping area by setting to groundwater balance and crop area constraints (Singh 2014). Homayounfar et al. (2014) developed an optimization model to derive an optimal cropping pattern during deficit irrigation conditions. Ahlfeld and Baro-Montes (2008) invoked successive linear programming algorithm to solve water supply problem in Antelope Valley, (Galoie et al. 2021; Rheinheimer et al. 2015) proposed an optimization model for optimal planning and management of irrigated area under uncertainty using production function given by Jensen et al. (1990) and Zhang and Huang (2011). They applied the model to the Yangchuan irrigation district in Wuwei, China, and obtained good results that were deemed as useful for water managers of that area. (Rheinheimer et al. 2015; Al-Maktoumi et al. 2021) developed an optimization model and implemented using linear programming (LP) to allocate reservoir releases.

Previously, the optimal solutions were found to achieve maximum monetary returns and conflict-free spatial distribution (Pinarlik et al. 2021; Shiau 2021; Shaikh et al. 2015a). Whereas water managers must allocate supplies to the off takes rather than allocating only the area under different crops (Luo et al. 2021). To address the prevailing problem, this study was embarked upon. Thus, two optimization models were formulated. The results of Model 1 were used in Model 2 as input. Finally, the results of Model 2 in conjunction with Preference index results were utilized to allocate supplies for competing channels in a conflict-free manner. This study provides a tool to policymakers for preparing a conflict-free water supply schedule of off-takes during reduced flows.

2 Materials and Methods

2.1 Description of Study Area

This study was carried out for West Branch irrigated Mirpurkhas subdivision which is located between latitude 25^0 25′14.22″ to 25^0 44′ 08.96″ North and between longitude 68^0 53′11.58″ to 69^0 09′34.79″ East and 19.5 m above the mean sea level in the southern climatic zone of Sindh province, Pakistan. The climate of subdivision is characterized as very dry with an annual mean rainfall of less than 50 mm. Dominant textures are silty clay, silty loam, and clay loam. The maximum temperature in summer could go as high as 48 °C and a minimum of 1 °C can occur in winter. The maximum daily mean temperature of 40 °C occurs in May and a minimum daily mean temperature of 9 °C occurs in January. The average relative humidity varies from 61 to 77% in summer and 54 to 65% in winter.

In the study area, there are two cropping seasons, namely, Summer (April to September) and Winter (October to March) which are locally known as Kharif and Rabi respectively. The groundwater is saline and deep and thus not used. Crops grown in the research region include cotton, sugarcane, fodder, rice, onion, tomato, lentil, banana, chilies, wheat, oilseeds, and maize.

2.2 Models Description

Model 1 Purpose The Model 1 is intended to prepare the cropping pattern during low flow situations. The cropping pattern is prepared to obtain maximum financial benefits while giving the priorities to the farmer's desires. The decision variable is the cropping area under each crop.

Mathematical Formulation The Deterministic LP model has the following form to maximize economic net returns for preparing optimum crop mix.

$$R = max\left[\sum_{p=1}^{n} B_p P_p A_p - \sum_{p=1}^{n} \sum_{k=1}^{m} C_{pk} A_p\right] \tag{1}$$

where, R is the cumulative monetary benefit from all grown crops in Rupees (Rs.); p represents crop index (1, 2,…n); k is the index for inputs (1,2,3,…m); B_p is the financial return from p^{th} crop in Rs; P_p is the crop production of p^{th} crop per unit area in $t\ ha^{-1}$; A_p is the area under p^{th} crop in hectares; C_{pk} is the expenditure incurred on the k^{th} input (Rs).

The objective function is subjected to the following linear constraints.

2.2.1 Available Water Constraint

This constraint ensures that the monthly water release is in accordance with the irrigation requirement.

$$\frac{W_t}{I_{pt} A_p} \geq 1.0 \quad \forall p, t \tag{2}$$

where W_t is the available quantum of water for month t at the head of the canal in ha-mm. I_{pt} is the net irrigation requirement of the p^{th} crop for month t in mm.

2.2.2 Maximum Area Limit

This limit was imposed considering the current cultivation practices of the study area.

$$\sum A_p \leq A_{CS} \quad \forall\ p \tag{3}$$

where A_{CS} represents available culturable area in different seasons. $CS = 1$ for rabi season and $CS = 2$ for the Kharif season.

2.2.3 Minimum Irrigable Area limit

The following lower limit of the area under each crop was levied during reduced flows.

$$\sum A_p \geq \mu A_{CS}, \quad \forall p \tag{4}$$

where μ depicts the percentage of p^{th} crop given as the fraction of the total area.

2.2.4 Main Crop Constraint for the Area

A constraint, shown below, was set to ensure the staple food requirement (Wheat) of the study area.

$$\sum P_w A_w \geq F_R \tag{5}$$

where w subscript represents wheat crop, F_R is the total food requirement of the area (t).

Model 2 Purpose The Model 2 allocates the available water among the multiple crops by maximizing the relative yields. The model considers the soil moisture balance model (shown in Fig. 1) and allocate the supply to replenish the soil reservoir up to the field capacity.

Mathematical Formulation The mathematics formulation of the Model 1 can be written as follows.

$$z = max \sum_{p=1}^{n} \left[1 - \sum_{s=1}^{S} Ky_s^p \left(1 - \frac{\sum_{t \in s} ET_a}{\sum_{t \in s} ET_{max}} \right)_s \right] \tag{6}$$

where, z is the maximized sum of relative yields; p is the crop index (1,2,…n); s is the index for growth stages (1,2,3,…S); t is the period in particular growth stage; Ky is a yield response factor of the crop c for growth stages (Ky relates the relative yield reduction to the ET_{max} reduction caused by soil water shortage); ET_a is the actual evapotranspiration in mm for period t; ET_{max} is the maximum or potential evapotranspiration in mm for period t.

The model was subjected to the following constraints.

2.2.5 Soil Moisture Balance Constraint

Can be expressed as

$$ML_p^{t+1} RZD_p^{t+1} = ML_p^t RZD_p^t + EP^t + IRA_p^t + CR_p^t - ETa_p^t + ML_i \left(RZD_p^{t+1} - RZD_p^t \right) - DP_p^t \quad \forall p, t \tag{7}$$

$$IRA = \left(\frac{Q}{A} \right) \times 10^5, \tag{8}$$

where, ML is soil moisture level in mm cm^{-1}in period t for crop p; RZD is the root zone depth in cm in period t for crop p; EP is effective rainfall in period t in mm; IRA (mm)is the

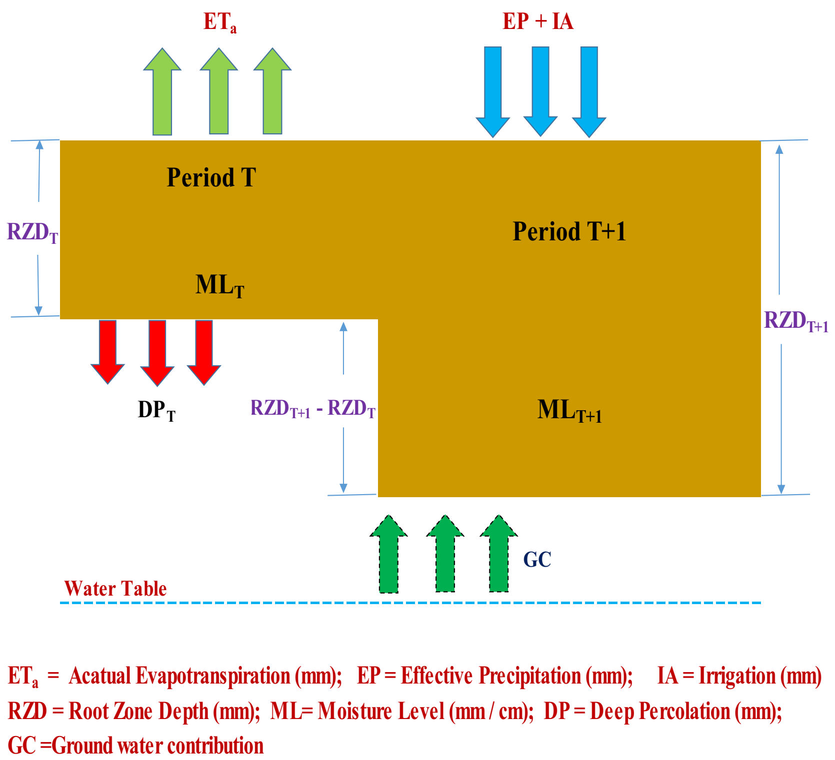

Fig. 1 Soil Moisture Balance Model

irrigation amount allocated in period t to crop p; Q is the volume of water in Mm^3; A is the area in hectares; CR is the capillary rise in period t for crop p; i subscript represents initial soil moisture; DP is the deep percolation in mm.

2.2.6 Upper and Lower Bounds on Soil Moisture

$$ML_p^{t+1} \leq ML_f \quad \forall p, t \tag{9}$$

$$ML_p^{t+1} \geq (1 - MAD) \times \left(ML_f - ML_w\right), \quad \forall p, t \tag{10}$$

where, MAD is the management allowable deficit and f and w subscripts represent field capacity and permanent wilting point respectively. An integer α is used which can take value of 1 or 0 to ensure that the deep percolation occurring is greater than zero only when the soil moisture is at field capacity which is written as

$$ML_p^{t+1} \geq ML_f \times \propto_p^t. \quad \forall p, t \tag{11}$$

Similarly, to compensate deep percolation term to ensure for soil moisture to reach field capacity, an arbitrary large number B is introduced as follows.

$$DP_p^{t+1} \leq B \times \propto_p^t \quad \forall p \tag{12}$$

The conditions imposed in the form of relations (9), (11), and (12) ensure that the moister level in $t+1$ period for crop c will not exceed field capacity.

2.2.7 Bounds on Actual Evapotranspiration

In the present study, a linear relationship between ET_a and ET_{max} is considered since when ET_a is at permanent wilting point, the soil moisture is zero, and ET_a is equal to the ET_{max} when soil moisture is at field capacity which is the maximum soil moisture. Thus, in order to keep constraint linear, ET_a is restricted to be less than ET_{max} and given as follows.

$$ET_{a_p}^{\ t} \leq \left(ML_p^t \times RD_p^t + IA_p^t + EP^t + CR_p^t - ML_w \times RD_p^t\right) \times \frac{ET_{max_p}^{\ t}}{\left(ML_f - ML_w\right)RD_p^t} \forall p, t \tag{13}$$

$$ET_{a_p}^{\ t} \leq ET_{max_c}^{\ t}. \quad \forall p, t \tag{14}$$

2.2.8 Bound on Allocation of Irrigation Amount in Relation to Water Available

A constraint is set to the allocation of irrigation supplies to a crop in a certain period such that it should not exceed the total available volume of water for that period and can be written as

$$\sum_p IA_p^t \times A_p \leq VW^t, \quad \forall t \tag{15}$$

where, additionally, A_p is area obtained from the first model for a particular crop based on monthly lumped available water volume; VW is the volume of water available for t period in as growth stage of the crop (In this study, the period is of 7 days considering irrigation turn period in the study area).

2.2.9 Models Assumptions

For the models, it was assumed to have uniform command area resources (land, labor, capital, and other agricultural inputs); uniform management practices throughout the region; same sowing and crop duration every year; rainfall is uniformly distributed with no spatial variation; uniform irrigation efficiency. At the commencement of the crop season, soil moisture was assumed to be known i.e., soil moisture is at 75% of field capacity (maximum soil moisture content, soil can hold). For arid and large irrigation schemes, such assumptions are made. For instance, such assumptions were made by (Sethi et al. 2006).

2.2.10 Models Solutions and Inputs

Models were solved using the LP technique since the objective functions and all constraints in the models were linear. The models were implemented using the LINGO software version.13.0.

2.3 Data Collection

Some data pertinent to models and index inputs were collected through personal interview surveys from sample farmers at the head, middle, and tail sections of the channel. The data included land area availability and utilization, cropping pattern, cropping intensities, production cost (seed, labor, machinery, chemicals, fertilizers, and others), returns per acre, and yield per acre for different crops. Similar data was also procured from the Revenue and Irrigation Department. The flow rate data at the head were obtained from the Sindh Irrigation, Drainage Authority for the West branch. The flow rate data were converted to volumetric units using time elapsed. In Model 1, monthly basis volume was used while in Model 2, the volume available on a weekly basis was used. The available water for crop use was computed by deducting losses (distribution + application) from the supply at the head of the canal. The losses values were taken from the research work of (Shaikh et al. 2015b; Shaikh and Lee 2016). Twenty-two years of weather data obtained from the Pakistan Meteorological Department were utilized for the study area to compute irrigation requirements of different crops.

2.4 Irrigation Requirement

The irrigation requirement of each crop cultivated in the study area was computed as follows, following the volume balance approach:

$$IR = ET_{max} + LR - (ML \times RD + EP + CR) \tag{16}$$

where IR is the irrigation requirement (mm). The irrigation is applied to the crop when the soil moisture in the root zone is below the allowable depletion level (*MAD*—which is in depth units written as $(1 - MAD) \times (ML_f - ML_p) \times RD$ to replenish the root zone up to maximum capacity (ML_f) by Eq. (16) or else IR is equal to zero and is expressed as IR = 0, when

$$(ML \times RD + EP + CR) \geq (1 - MAD)\text{x}(ML_f - ML_w) \times RD \tag{17}$$

ET_{max} is the maximum crop requirement (mm) which was computed as $ET_{crop} = ET_o \times K_c$. In some cases, its uncertainty is considered for computing actual demand. Here ET was treated as a deterministic component. ET_o is the reference evapotranspiration (mm) which was calculated by the Penman–Monteith method using twenty-two years of climatic data (Shaikh et al. 2018).

K_c is the crop coefficient and *LR*, the leaching requirement to flush out excess salts from the root zone, was determined using the (Rhoades 1974) equation expressed as follows:

$$LR = \frac{EC_w}{5\left(EC_e\right) - EC_w}, \tag{18}$$

where, LR (in fractions) is the leaching requirement to restrict salts within tolerance limits of crop, EC_w is the salinity of the applied irrigation water in dS m^{-1}. The average value of EC_w = 1.53 dS m^{-1} as determined by the Irrigation Department and was used in the computation. EC_e is the average soil salinity tolerated by the crop. The EC_e values used by the research department for different crops at 10% yield reduction were used. The computed LR was in the range of 5 to 8%, which is less than the application losses (23%) in the study area. Hence, it was ignored. In Model 2, due to restriction on deep percolation, the leaching term

Table 1 Salient features of the irrigation network of the study area

Main Canal	Off-taking Channel	Global Position		Off-taking RD	Branches of Off-take Channels
		Northing	Easting		
West Branch	Lakhaki Distributary	25^0 38′ 22.06”	68^0 54′ 38.18”	37.22	Mithrao Minor
	Bitharo Minor	25^0 33′ 06.90”	68^0 53′ 36.90”	66	…….
	Sangro Distributary	25^0 30′ 09.16”	68^0 54′ 11.71”	88	Jarwar Minor
					Chahu Minor
	Daulatpur Minor	25^0 26′ 33.49”	68^0 56′ 48.18”	115	…….
	Belharo Minor	25^0 21′ 40.42”	68^0 56′ 48.18”	146.52	Khumbri Minor
	Direct Outlets	…….			…….

was not included. If LR were more than the application losses it would have been included in the final calculations. ML is the stored soil water level (mm) which was assumed to be the same before and after the cultivation of crops for Model 1 (Singh et al. 2001). EP (mm), the effective precipitation was calculated by the U.S. Department of Agriculture's Soil Conservation Service method (Clark et al. 1998) using the following equations:

$$EP = \frac{P \times (125 - 0.2 \times P)}{125} \quad for\ P \leq 250mm \tag{19}$$

$$EP = 125 + (0.1 \times P) \quad for\ P > 250mm \tag{20}$$

where, P is precipitation in mm. CR is the groundwater contribution through capillary rise (mm).

$$CR = exp\left(\frac{ln(z) - b}{a}\right) \tag{21}$$

where CR is the expected groundwater contribution (mm d^{-1}), z is the depth (m) of the water table below the soil surface and "a" and "b" parameters specific for the soil type and its hydraulic characteristics (Table 1). The "a" and "b" parameters of the equation varies with the textural class and can be computed by empirical relations given by (Janssens 2006). The relations are tabulated as follows (Table 2).

2.5 Root Zone Depth

The linear root growth model (shown in Fig. 2). For water balance calculations, 20 to 30 cm of minimum rooting depth is considered at the time of planting (Raes et al. 2009) and (Fu and Guo 2014). In the present study, 15 cm depth was initially considered for the first week.

Table 2 Empirical relations for parameters "a" and "b"

Soil Texture	K_{sat} (mm d^{-1})	Relation for a	Relation for b
Sandy soils	200–2000	$-0.3112 - 10^{-5}\ K_{sat}$	$-1.4936 + 0.2416\ \ln(K_{sat})$
Loamy soils	100–750	$-0.4986 + 9\ (10^{-5})\ K_{sat}$	$-2.1320 + 0.4778\ \ln(K_{sat})$
Sandy clayey	5–150	$-0.5677 - 4\ (10^{-5})\ K_{sat}$	$-3.7189 + 0.5922\ \ln(K_{sat})$
Silty clayey	1–150	$-0.6366 + 8\ (10^{-4})\ K_{sat}$	$-1.9165 + 0.7063\ \ln(K_{sat})$

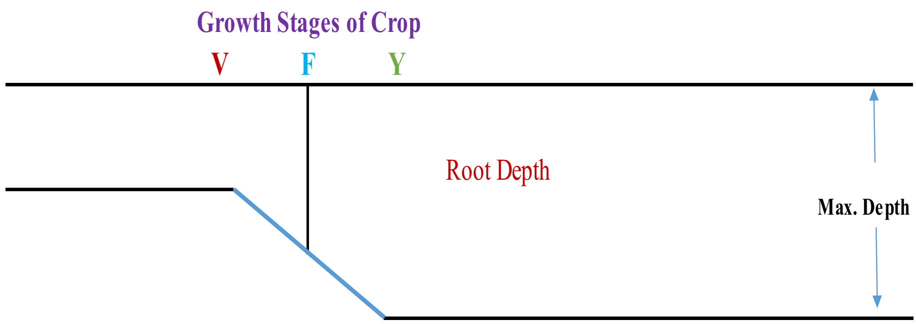

Fig. 2 Linear Root Growth Model

2.6 Yield Response Factor (Ky)

The values of Ky were obtained from Drainage Research center for various crops for four above-mentioned growth stages. For two crops (Banana and Chilies) values for Ky were adopted from (Doorenbos and Kassam 1979).

2.7 Management Allowable Deficit (MAD) and Moisture Constants

MAD values for different crops were adopted from the literature on Sindh areas and values for some crops were also obtained from research departments. MAD of 60% for cotton and 55% for wheat (Laghari et al. 2008) was used. For maize, oilseeds, vegetables, lentil, banana, and sugar cane MAD of 55, 50, 50, 50, 40, and 60% respectively were used. For the study area, the depletion for rice of less than 20% of saturation is considered. Hence, a 15% MAD value was used for rice. The dominant soil textures of the study areas are silty clay, silty clay loam, and silty loam. Thus, field capacity values and wilting point values were adopted as 3.38, 3.32, 2.95 and 1.78, 1.62, and 1.45-mm cm^{-1} respectively.

2.8 Preference Index (PI)

The index developed by (Shaikh et al. 2015a, b) was used to distribute cropping areas among off takes. In this index, the yield per unit area was used as a weighting factor and an index named as Preference Index (PI) was formulated as follows.

$$PreferenceIndex(PI) = \frac{Y_c \times A_E}{Y_{c1} \times A_{E1} + Y_{c2} \times A_{E2} + Y_{c3} \times A_{E3} + \ldots \ldots \ldots . + Y_{cn} \times A_{En}} \tag{22}$$

where, A_E represents existing area under the certain crop in hectares for the channel command to which optimized area to be allocated; the Y indicates crop yield per unit area in; subscript 1, 2, 3…n depicts parameters of c^{th} crop for competing channels off-taking from the same primary canal. The PI varies from 0 to 1 and is unitless.

Following relation was invoked to allocate area to crop for each off-taking channel.

$$AA_{co} = OA_c \times \frac{Y_c \times A_E}{Y_{c1} \times A_{E1} + Y_{c2} \times A_{E2} + Y_{c3} \times A_{E3} + \ldots\ldots\ldots. + Y_{cn} \times A_{En}} \quad (23)$$

where, AA_{co} is the allocated area for the c^{th} crop to the o^{th} off-take channel; OA_c optimized area for c^{th} crop.

2.9 Models and Index Implementation for Various Scenarios

The models and PI were implemented to develop land and water management scenarios. The implementation steps are shown in Fig. 3.

For West Branch, optimization was done at 100%, 80%, and 70% of the existing supply considering concurrence with previous water availabilities levels for the study area. The scenarios were designed for net benefits by fixing the minimum area under each crop, and different availability water levels stated above.

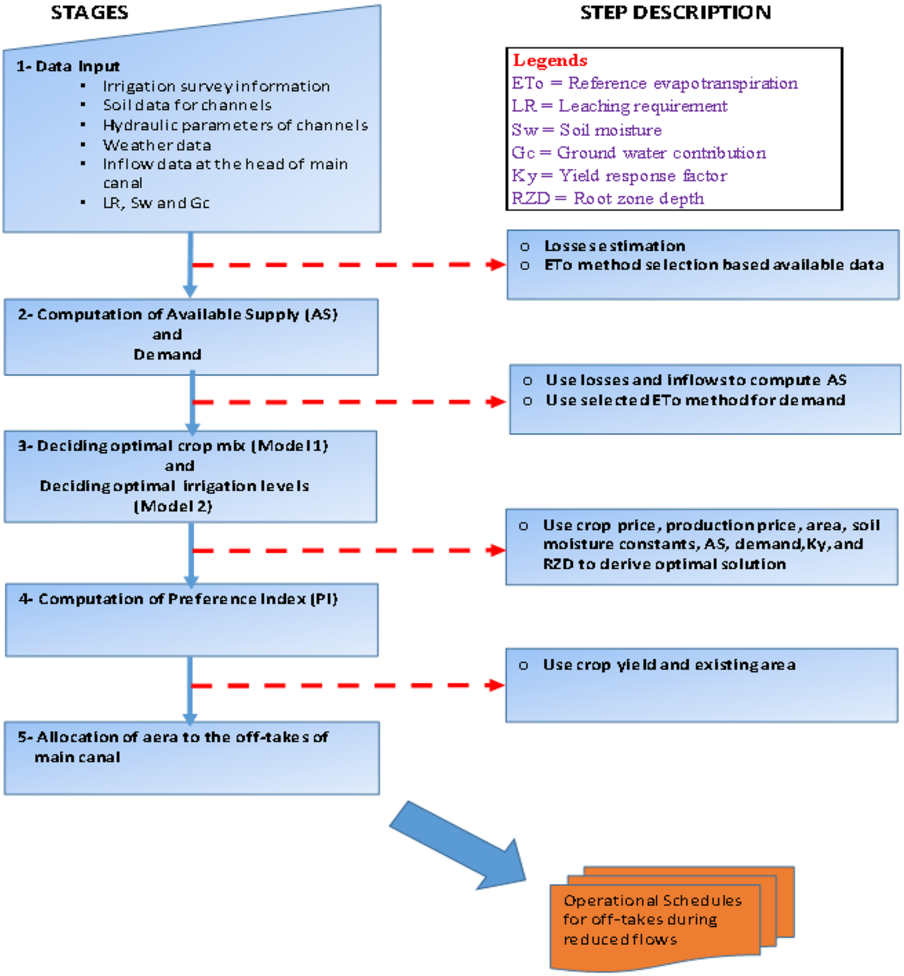

Fig. 3 Flow Chart Showing Implementation Steps

2.10 Flow Rate in Off-Taking Channel

After optimization to decide cropping pattern and irrigation levels by two models and aerial distribution through preference index among competing channels, periodic flow rates of off-taking channels were computed as follows.

$$Flow\ rate(Q)in\ m^3s^{-1} = \left[\left[\frac{\sum_c^T \left(IA_c^k \times AA_{co}\right)}{Time}\right] \div 3600\right] + Losses\ in\ m^3s^{-1} \quad (24)$$

where, IA_c is the irrigation depth (m) allocated to the crop for a particular period; AA_{co} (m^2) is the allocated area through PI; Time is in hours.

3 Results and Discussions

In the present study, monthly lumped net available supplies (after deducting losses) were used in the Model 1 and periodic supplies (7-days) were used in the Model 2. The month-wise available supplies at the head of the West branch are presented in Table 3 and periodic supplies divided into the two cropping seasons are portrayed in Table 4. The total available annual quantum of water (Table 3) is 312,735,427 ha mm (313 Mm^3). Glancing at Table 3, it can be noted that the maximum volume is available in June i.e., 12.5% of the total volume available. The minimum volume of water is available in November (5% of total volume). The 26 periods of Kharif represent the periodic supplies from April to September and 24 periods of Rabi season presents available volume from October to March. Figure 4 depicts the existing cropping pattern of the area irrigated by the West branch. The main crops of the region are Wheat, cotton, and sugarcane which are cultivated on 27, 24, and 13 percent area, respectively. The remaining area is occupied by the Kharif and Rabi pastures, tomato, onion, orchard, lentil, chilies, rice, and oilseeds.

Table 3 Monthly net available volume at the head of West Branch (brackets values are in Mm^3)

No.	Month	Volume Available (ha mm)
1	Jan	1,906,209 (19.0)
2	Feb	2,013,284 (20.1)
3	Mar	2,360,571 (23.6)
4	Apr	3,108,086 (31.1)
5	May	3,658,886 (36.6)
6	Jun	3,934,286 (39.3)
7	Jul	3,698,229 (36.9)
8	Aug	3,029,400 (30.2)
9	Sept	19,671,429 (19.7)
10	Oct	19,278,000 (19.3)
11	Nov	14,845,162 (14.8)
12	Dec	21,851,338 (21.9)
Total		312,735,427 (313)

Table 4 Periodic net available volume for Kharif and Rabi seasons

Period	Available Volume (Mm^3)	
	Kharif	Rabi
1	7.21	4.55
2	7.23	4.49
3	7.21	4.53
4	7.25	4.56
5	8.34	3.93
6	8.56	3.46
7	8.53	3.47
8	8.54	3.39
9	8.83	3.94
10	9.23	5.09
11	9.16	5.11
12	9.18	5.10
13	9.10	5.11
14	8.64	4.49
15	8.62	4.45
16	8.62	4.44
17	8.61	4.37
18	7.50	4.57
19	7.05	4.70
20	7.07	4.70
21	7.07	4.67
22	6.35	5.09
23	4.60	5.50
24	4.59	5.51
25	4.57	—-
26	4.59	—-

3.1 Preference Index

The Preference indices computed from yield per unit area and existing cropping area for competing channels for the crops of the study region are summarized in Table 5 reveals that a maximum yield of cotton, sugarcane, Kharif pasture, rice, and chilies is obtained in the cultivation area of DOs, Bitharo, DOs, Belharo, and Khumbri respectively. The minimum yield of cotton, sugarcane, Kharif pasture, rice, and chilies were observed in the command areas of Chahu, Khumbri, Daulatpur, Sanghro, and Bitharo respectively. Similarly, the maximum production of onion, tomato, Rabi pasture, wheat, and oilseeds were found in the respective areas commanded by the DOs, Lakhaki, Jarwar, Lakhaki, and Lakhani. The maximum yield of the orchard was observed as 28-ton ha^{-1} for Lakhaki, Jarwar, and Sangro. Likewise, the maximum output of the lentil crop (0.85-ton ha^{-1}) was in the Lakhaki and Jarwar irrigated areas. The minimum yield per unit area contribution for onion, lentil, orchard, Rabi pasture, and oilseeds were observed in the jurisdiction of Daulatpur whereas tomato (10-ton ha^{-1}) and wheat (2 ton ha^{-1}) minimum yield areas were in the commands of Jarwar and Sangro respectively.

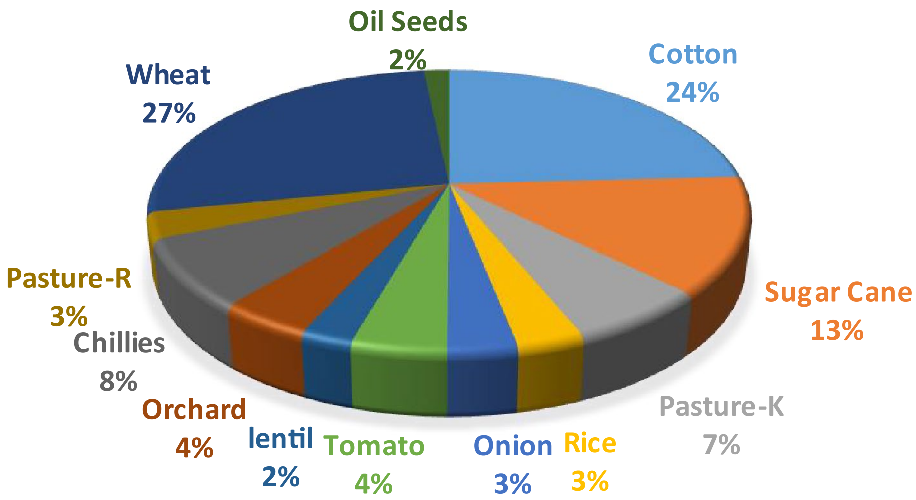

Fig. 4 Existing Cropping Pattern of the West Branch Command Area

The computed values of Preference Indices in Table 5 for DOs of the West branch varied from 0.38 to 0.41 for the study area crops which shows that 38 to 41 percent optimized area will be allocated to the DOs. The Lakhaki and Mithrao preference indices ranged from the 0.105 to 0.148 and 0 to 0.033 respectively, indicating 10.5 to 14.8% and 0 to 3% allocation of different crop areas. According to the PI, the Jarwar, Bitharo, and Sangro will occupy about 3 to 7%, 2 to 3%, and 7 to 13% of the crop areas, respectively. The rest of the channels, Daulatpur, Belharo, Chahu, and Khumbri will take and irrigate the cropping area in the range of 17 to 32%. It is noteworthy from Table 6 that the Preference index kept the distribution competitive and conflict-free.

3.2 Evaluated Scenarios for West Branch

Three scenarios as already stated were evaluated for the West branch irrigated area. At first, the Model 1 was run to determine an optimized area to obtain maximum financial benefits taking into account farmers' preferences. The aerial output of the Model 1 was used as one of the input parameters in the Model 2 to distribute available water resources among multiple crops based on their periodic requirements which governed by the crop growth stages. The results pertaining to evaluated scenarios are discussed in the following paragraphs.

3.2.1 Scenario 1: Supply at Existing Level

The Model 1 was applied to obtain optimal cropping pattern for maximized net financial returns for existing resources. The results are portrayed in Table 6. It can be seen from the results that the area under each crop is unchanged after optimization which indicates the current cropping pattern in the West branch command is already well set and giving maximum benefits to the farmers' i.e., 2,797 million rupees. Besides that, it is also noteworthy that the crops which are grown in the study region are receiving sufficient water. Hence, the

Table 5 Preference index of West Branch competing channels

Parameters	Channels									
	WB1	WB2	WB3	WB4	WB5	WB6	WB7	WB8	WB9	WB10
	Cotton									
Yield per unit area (t ha^{-1})	0.780	0.757	0.727	0.690	0.650	0.755	0.680	0.672	0.630	0.705
Existing area (ha)	3832	1149	259	549	278	987	801	1104	757	203
Preference index	0.412	0.120	0.026	0.052	0.025	0.103	0.075	0.102	0.066	0.020
	Sugarcane									
Yield per unit area (t ha^{-1})	49.0	49.0	49.9	48.0	52.0	55.0	53.0	50.8	45.9	43.0
Existing area (ha)	2119	635	134	303	153	549	447	609	418	100
Preference index	0.381	0.114	0.024	0.053	0.029	0.111	0.087	0.114	0.070	0.016
	Pasture-Kharif									
Yield per unit area (t ha^{-1})	46.0	42.0	41.0	40.0	35.0	41.0	33.0	43.0	44.0	39.0
Existing area (ha)	1020.0	305.9	64.3	145.8	73.7	264.5	215.1	293.3	201.1	47.9
Preference index	0.419	0.115	0.024	0.052	0.023	0.097	0.063	0.113	0.079	0.017
	Rice									
Yield per unit area (t ha^{-1})	2.89	3.00	2.84	2.95	2.97	2.45	2.80	3.20	2.50	0.00
Existing area (ha)	486	146	42	70	35	137	103	140	96	0
Preference index	0.392	0.122	0.033	0.057	0.029	0.094	0.080	0.125	0.067	0.000
	Orchard									
Yield per unit area (t ha^{-1})	26.0	28.0	23.0	28.0	27.0	28.0	19.0	22.0	22.0	0.0
Existing area (ha)	674	217	43	98	49	175	157	194	133	0
Preference index	0.401	0.139	0.022	0.063	0.030	0.112	0.068	0.098	0.067	0.000
	Chilies									
Yield per unit area (t ha^{-1})	1.90	2.00	2.00	1.70	1.50	1.70	2.00	2.00	1.60	2.20
Existing area (ha)	1240	372	78	177	90	321	261	356	244	58
Preference index	0.393	0.124	0.026	0.050	0.022	0.091	0.087	0.119	0.065	0.021
	Onion									
Yield per unit area (t ha^{-1})	14.0	12.0	12.0	13.0	9.2	9.5	9.0	13.0	12.6	11.0
Existing area (ha)	504	150	32	72	36	130	106	144	99	24
Preference index	0.439	0.112	0.024	0.058	0.021	0.077	0.059	0.117	0.078	0.016
	Tomato									
Yield per unit area (t ha^{-1})	25.0	26.0	25.0	10.0	12.0	27.0	10.1	15.0	15.0	25.0
Existing area (ha)	690	207	44	99	50	179	146	199	136	32
Preference index	0.461	0.144	0.029	0.026	0.016	0.129	0.039	0.080	0.055	0.022
	Lentil									
Yield per unit area (t ha^{-1})	0.80	0.85	0.82	0.85	0.76	0.76	0.72	0.73	0.81	0.78
Existing area (ha)	379	114	24	54	27	99	80	109	75	18
Preference index	0.391	0.125	0.025	0.060	0.027	0.097	0.075	0.103	0.078	0.018
	Pasture-Rabi									
Yield per unit area (t ha^{-1})	70.8	67.51	77.5	77.6	77.3	69.15	65.1	70	77	71
Existing area (ha)	478	144	30	68	35	124	101	138	94	23
Preference index	0.386	0.105	0.029	0.066	0.033	0.096	0.068	0.109	0.089	0.018
	Wheat									
Yield per unit area (t ha^{-1})	3.00	3.20	2.50	2.70	2.80	2.00	2.50	2.30	3.00	2.90
Existing area (ha)	4207	1251	266	603	305	1092	890	1213	832	230

Table 5 (continued)

Parameters	Channels									
	WB1	WB2	WB3	WB4	WB5	WB6	WB7	WB8	WB9	WB10
Preference index	0.419	0.133	0.022	0.054	0.028	0.073	0.074	0.093	0.083	0.022
	Oil seeds									
Yield per unit area (t ha^{-1})	1.25	1.38	0.00	1.00	0.92	1.06	1.00	1.24	1.24	1.10
Existing area (ha)	269	87	0	38	19	68	55	75	52	12
Preference index	0.415	0.148	0.000	0.046	0.022	0.089	0.068	0.116	0.079	0.017

WB1 DOs-West Branch, *WB2* Lakhaki Distributary, *WB3* Mithrao Minor, *WB4* Jarwar Minor, *WB5* Bhittaro Distributary, *WB6* Sangro Distributary, *WB7* Daulatpur Minor, *WB8* Belharo Distributary, *WB9* Chahu Minor, *WB10* Khumbri Minor

current cropping pattern is recommended to continue when the supplies are at the existing level in the West branch irrigated area.

3.2.2 Scenario II: 80% of Existing Level

Model 1 was run when the water availability is reduced by 20%. The model results are summarized in Table 6. The model results suggest a reduction in the cropping area of Kharif and Rabi pastures, rice and wheat by 56, 75, 75 and 11% of existing area whereas area under cotton, sugarcane, banana, onion, tomato, oilseeds, chilies, lentil remained at their existing levels for maximum financial benefits. It is noteworthy that the areas of rice and Rabi pasture were reduced up to the lower limit set for them. The most likely reasons for the reduction in the areas of the Kharif and Rabi pastures, rice, and wheat are either their high-water demand or low financial benefits as compared to the other crops. However, the allocated area to all crops is above the levied minimum limits. The maximum net benefits that can be achieved for the

Table 6 Optimal cropping pattern for evaluated scenarios

No.	Crop	Optimized Area (ha)		
		100% of existing supply	80% of existing supply	70% of existing supply
1	Cotton	9919(100%)	9919(100%)	7063(71%)
2	Sugar Cane	5466(100%)	5466(100%)	5466(100%)
3	Pasture-K	2632(100%)	906(34%)	658(25%)
4	Rice	1255(100%)	314(25%)	314(25%)
5	Banana	1741(100%)	1741(100%)	1741(100%)
6	Chilies	3198(100%)	3198(100%)	3198(100%)
7	Onion	1296(100%)	1296(100%)	1296(100%)
8	Tomato	1789(100%)	1789(100%)	1789(100%)
9	Lentil	980(100%)	980(100%)	980(100%)
10	Pasture-R	1235(100%)	309(25%)	309(25%)
11	Wheat	10,890(100%)	9789(90%)	7346(67%)
12	Oil Seeds	676(100%)	676(100%)	676(100%)
Net Returns (million Rs.)		2797	2622	2405

set constraints and available resources are 2,622 million rupees which are 6% lesser than the benefits obtainable at the existing supply.

Having obtained optimal cropping pattern to give maximum returns, the optimized cropping areas of the crops were used in the Model 2 to determine volumetric water allocation to individual crops by integrating field soil moisture conditions with available supplies. The results obtained for the crops after running the Model 2 are presented in Table 7 for Kharif and Rabi periods.

The optimal allocation of available water among multiple crops during 20% reduced flows given by Model 2 shows that the water has been allocated in accordance with field soil moisture balance conditions to keep the soil moisture at the field capacity or above the set depletion level. No water was allocated to the crop when the soil moisture content is within the prescribed limits (e.g., Period 3 for cotton and Period 15 for sugarcane). It is also noteworthy from the results (Table 7) that the moisture level remained near the field capacity which may be due to the cropping area that is based on the available water. The moisture content for the first period for all crops was set at 75% of the field capacity considering the real scenario. The cotton crop was allocated maximum water in the period 17 (4.69 Mm^3) and minimum in the period 24 (0.62 Mm^3) based on the field conditions, area,

Table 7 Irrigation water volume (Mm^3) allocation and moisture level ($mm\ cm^{-1}$) at the beginning for various crops

S.#	Crop	Season	At 80% availability		At 70% availability	
			IA	MC	IA	MC
1	Cotton	Kharif	0.62–4.69	2.5–3.32	0.44–4.28	2.5–3.32
		Rabi	0.79–2.58	3.13–3.24	0.36–2.03	3.13–3.27
2	Sugar Cane	Kharif	0.35–4.16	2.37–3.32	0.46–5.52	2.35–3.32
		Rabi	0.25–2.99	2.5–3.32	0.05–2.55	2.5–3.32
2	Pasture-K	Kharif	0.09–0.4	2.21–2.95	0.02–0.29	2.21–2.95
		Rabi	0.00–0.00	0.00–0.00	0.00–0.00	0.00–0.00
4	Rice	Kharif	0.01–0.18	3.04–3.38	0.01–0.18	3.04–3.38
		Rabi	0.07–0.15	3.04–3.38	0.09–0.15	3.04–3.38
5	Banana	Kharif	0.2–0.62	2.5–2.93	0.2–0.82	2.5–3.32
		Rabi	0.21–0.99	2.5–3.32	0.09–0.99	2.5–3.32
6	Chilies	Kharif	0.35–1.39	2.5–3.32	0.02–1.39	2.5–3.32
		Rabi	0.00–0.00	0.00–0.00	0.00–0.00	0.00–0.00
7	Onion	Kharif	0.43–0.43	2.21–2.21	0.43–0.43	2.21–2.21
		Rabi	0.17–0.36	2.21–2.95	0.17–0.36	2.21–2.95
8	Tomato	Kharif	0.00–0.00	0.00–0.00	0.00–0.00	0.00–0.00
		Rabi	0.22–0.71	2.34–3.32	0.21–0.71	2.34–3.32
9	Lentil	Kharif	0.00–0.00	0.00–0.00	0.00–0.00	0.00–0.00
		Rabi	0.09–0.3	2.5–3.32	0.09–0.3	2.5–3.32
10	Pasture-R	Kharif	0.00–0.00	0.00–0.00	0.00–0.00	0.00–0.00
		Rabi	0.04–0.1	2.5–3.32	0.04–0.1	2.5–3.32
11	Wheat	Kharif	1.26–1.28	2.03–3.32	0.95–0.96	2.03–3.32
		Rabi	0.54–3.17	2.5–3.32	0.53–2.23	2.5–3.32
12	Oil Seeds	Kharif	0.00–0.00	0.00–0.00	0.00–0.00	0.00–0.00
		Rabi	0.01–0.22	2.5–3.32	0.01–0.22	2.5–3.32

consumptive requirements, availability, and sensitivity to deficit. Similarly, Kharif pasture, rice, chilies, and banana were apportioned maximum supplies of 0.4, 0.18, 1.39 and 0.99 Mm^3 respectively. The respective maximum supplies allocated to the sugarcane, tomato, onion, lentil, Rabi pasture, wheat, and oilseeds are 4.16, 0.43, 0.71, 0.30, 0.10, 2.79 and 0.22 Mm^3. It can be seen that the moisture content for rice remained at field capacity (3.38 mm cm^{-1}) or above 90% of the field capacity and thus, each period gets water allocation. The value of objective function (relative yield) was one for most of the crops except cotton, sugarcane, pasture Rabi and wheat (shown in Table 8) at the 20% reduction of supply relative to the existing supply.

The optimal allocation of irrigations to the crops followed preference index based aerial distribution among off-taking channels for various crops and is summarized in Table 9.

Similar distribution can be seen from the comparison of Tables 5 and 9 for sugarcane, tomato, onion, lentil, banana, chilies, and oilseeds crops. It can also be noted that reduction in the area of Kharif and Rabi pasture, rice and wheat crops have been suggested by the Model 1 to get maximum returns during reduced flows.

The area allocated to the competing channels and the allocated depths of irrigation water to the multiple crops were used to determine the flow rate by Eq. (24). Therefore, the flow rate of them shown in Figs. 5 and 6 is below all other channels flow rate.

3.2.3 Scenario III: 70% of existing level

The optimization models cum preference index were applied to evaluate the situation when the water availability is at 70% of the existing supply. The optimal cropping pattern (Table 6) for this situation obtained from Model 1 suggests a decrease in the cultivation area of cotton, Kharif and Rabi pastures, rice, and wheat crops. The reduction for these crops is in the order of 2856, 1974, 926, 941, and 3544 ha for achieving maximum financial returns. The rest of the crops namely sugarcane, tomato, onion, lentil, chilies, banana, and oilseeds occupy the same area. The reasons for such a pattern are the same as already mentioned in the scenario-II. The maximum achievable returns for this situation are 2405

Table 8 Relative yield ratio for different crops

Crops	Relative Yield Ratio	
	At 80% availability	At 70% availability
Cotton (C)	0.999	1
Sugar Cane (SC)	0.923	0.98
Pasture-K (PK)	1	1
Rice (R)	1	1
Onion (O)	1	1
Tomato (T)	1	1
Lentil (L)	1	1
Banana (B)	1	1
Chilies (CH)	1	1
Pasture-R (PR)	0.954	0.977
Wheat (W)	0.978	0.98
Oil Seeds (OS)	1	1

Table 9 Preference index based aerial distribution among competing channels (Scenario-II)

Channel Name	Distributed Area (ha)											
	C	SC	PK	R	B	Ch	O	T	L	PR	W	OS
WB1	4085	2084	379	123	698	1257	569	825	384	119	4100	280
WB2	1189	625	104	38	242	397	145	257	123	33	1300	100
WB3	257	134	21	10	39	83	31	52	25	9	216	0
WB4	518	292	47	18	109	161	75	47	59	20	529	31
WB5	247	160	21	9	52	72	27	29	26	10	277	15
WB6	1018	606	88	29	195	292	100	231	95	30	710	60
WB7	745	475	57	25	119	279	77	70	73	21	723	46
WB8	1014	620	102	39	170	380	151	142	101	34	907	78
WB9	652	384	71	21	116	209	100	98	77	28	811	54
WB10	196	86	15	0	0	68	21	39	18	6	217	11
Optimized	9919	5466	906	314	1741	3198	1296	1789	980	309	9789	676
Actual	9919	5466	2632	1255	1741	3199	1296	1789	980	1235	10,890	676
Change	0	0	1726	941	0	0	0	0	0	927	1102	0

million rupees which are 14% and 10% lesser than the amount achievable for existing supply and 80% of existing supply respectively.

Like scenario II, aerial optimization to obtain maximum financial benefits followed available water quantum distribution among various crops of the study area by Model 2.

The optimal allocation of available water among multiple crops during 30% reduced flows given by the Model 2 show the similar pattern as described for scenario II that the water has been allocated in accordance with field soil moisture balance conditions to keep the soil moisture at the field capacity or above the set depletion level. No water was allocated to the crop when the soil moisture content is within the prescribed limits (e.g., Period 5 for cotton and Period 17 for sugarcane). However, it is also noted that the periodic allocation pattern in scenario III is different from scenario II such as no water was allocated in period 3 for cotton crop while for scenario III, cotton crop received an allocation of 0.77 Mm^3. This is due to a decrease in the area of the cotton crop which changed the moisture

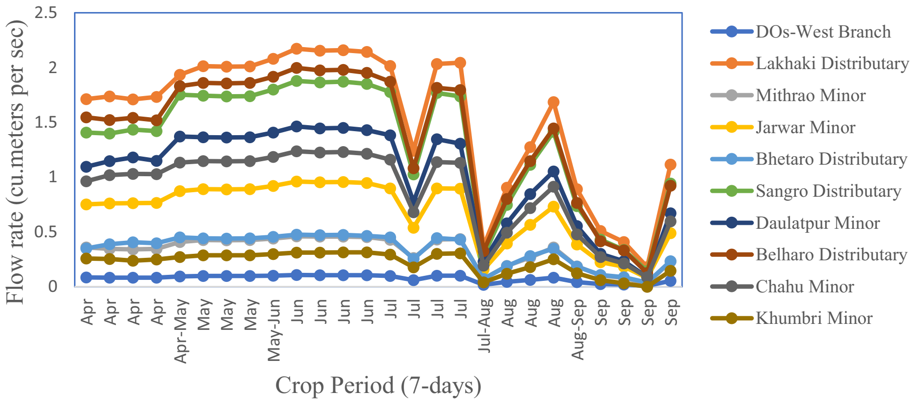

Fig. 5 Allocated Flow Rates to the Competing Channels When the Supplies are at 80% of the Existing Level for Kharif Season

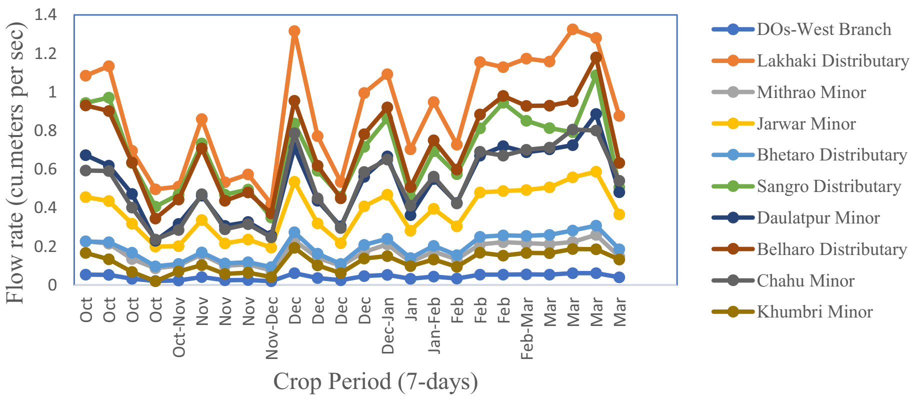

Fig. 6 Allocated Flow Rates to the Competing Channels When the Supplies are at 80% Of the Existing Level for Rabi Season

distribution for all periods of the crop while the initial moisture level was the same for both scenarios (i.e.,2.50 mm cm^{-1}).

The same pattern is visible for the crops which received reduced areas upon optimization (Table 7). For this scenario, the moisture content for the first period for all crops was also set at 75% of the field capacity considering the real conditions. The cotton crop was allocated maximum water in the period 15 in evaluated scenario (4.28 Mm^3) and minimum in the period 25 (0.44 Mm^3) based on the field conditions, area, consumptive requirements, availability, and sensitivity to the deficit. Similarly, Kharif pasture, rice, chilies, and banana were apportioned respective maximum supplies of 0.29, 0.18, 1.39, and 0.99 Mm^3. The maximum supplies allocated to the sugarcane, tomato, onion, lentil, Rabi pasture, wheat, and oilseeds are 5.52, 0.43, 0.71, 0.30, 0.10, 2.23, and 0.22 Mm^3 respectively. It can be seen that the moisture content for rice remained at field capacity (3.38 mm cm^{-1}) or above 90% of the field capacity and thus, each period gets water allocation. The value of the objective function (relative yield) was one for most of the crops except sugarcane, pasture rabi, and wheat (shown in Table 8) at the 30% reduction of supply relative to the existing supply.

The aerial allocation among the competing channel for scenario III was also made by invoking preference index. The results are tabulated in Table 10. The results revealed that the allocation among channels remained appropriate and of the same pattern as already elaborated for scenario II.

Similarly, as for scenario II, steps were taken to determine the total flow rate of the competing channels by Eq. (24). The results are shown in Figs. 7 and 8. The figures trends are identical to that of scenario II. However, the stream size (flow rate) is different. At 30% reduction, the flow rate is less than the scenario II.

The developed models and index provide the optimum solution after carrying out some finite number of mathematical steps. Several studies have been carried out to allocate resources among competitors (e.g., Singh 2014; Shaikh et al. 2015a, b). However, not a single study has been reported which distribute the primary canal supplies to off-takes in this fashion.

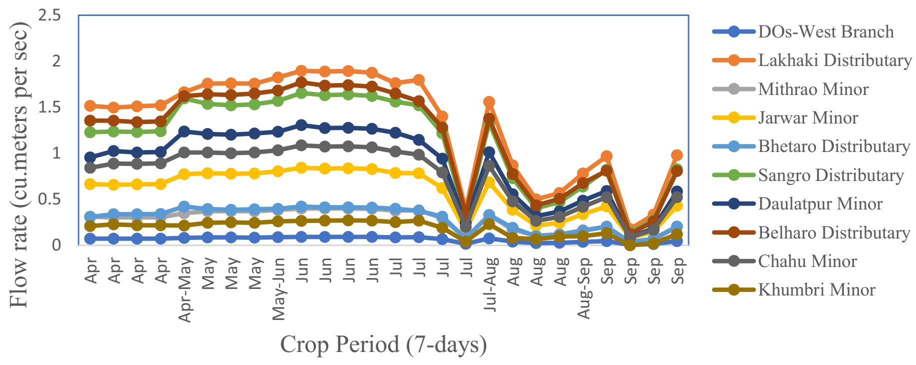

Fig. 7 Allocated Flow Rates to the Competing Channels When the Supplies are at 70% of the Existing Level for Kharif Season

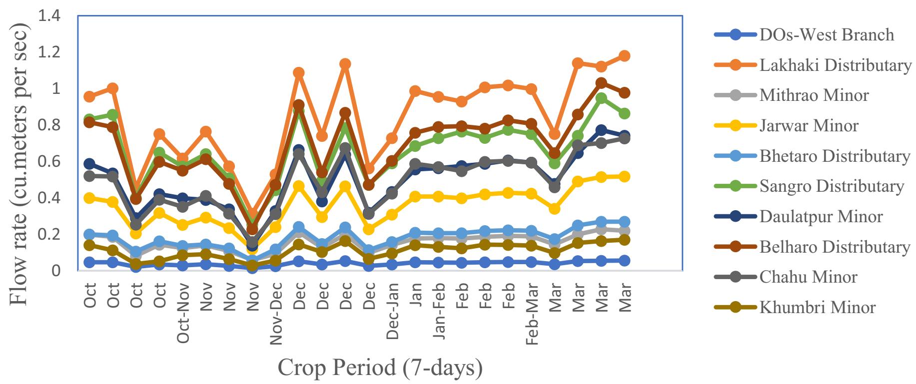

Fig. 8 Allocated Flow Rates to the Competing Channels When the Supplies are at 70% of the Existing Level for Rabi Season

Table 10 Preference index based aerial distribution among competing channels (Scenario-III)

Channel Name	Distributed Area (ha)										
	C	SC	PK	R	B	Ch	O	T	L	PR	W	OS
WB1	2909	2084	275	123	698	1257	569	825	384	119	3077	280
WB2	847	625	75	38	242	397	145	257	123	33	976	100
WB3	183	134	15	10	39	83	31	52	25	9	162	0
WB4	369	292	34	18	109	161	75	47	59	20	397	31
WB5	176	160	15	9	52	72	27	29	26	10	208	15
WB6	725	606	64	29	195	292	100	231	95	30	533	60
WB7	530	475	42	25	119	279	77	70	73	21	542	46
WB8	722	620	74	39	170	380	151	142	101	34	680	78
WB9	464	384	52	21	116	209	100	98	77	28	608	54
WB10	139	86	11	0	0	68	21	39	18	6	163	11
Optimized	7063	5466	658	314	1741	3198	1296	1789	980	309	7346	676
Actual	9919	5466	2632	1255	1741	3199	1296	1789	980	1235	10,890	676
Change	**2855**	**0**	**1974**	**941**	**0**	**0**	**0**	**0**	**0**	**927**	**3544**	**0**

4 Conclusions

The models (Model 1 and Model 2) with PI were implemented in the West branch irrigated area for the low flow's situations. Three scenarios were evaluated for the West branch command area. For all evaluated scenarios, the emphasis was given to grow chilies, onion, tomato, banana, lentil, and oilseeds crop to get maximum financial returns. The maximum attainable returns for existing conditions are Rs. 2797 million whereas it gets reduced by 6 and 14% when the water availability is at 80 and 70% of existing supply, respectively. The optimal allocation of available water among multiple crops during 20% and 30% reduced flows given by the Model 2 show that the water has been allocated in accordance with field soil moisture balance conditions when the soil moisture remained at the field capacity or above the set depletion level. The crops are allocated water almost for all periods based on the field conditions, area, consumptive requirements, availability, and sensitivity to the deficit. Most of the assumptions are met as the irrigated areas are governed by the irrigation and agriculture departments. The exception is the rainfall uniformity which is a random variable. Thus, for arid and large irrigation schemes, it is assumed to be uniform.

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Availability of Data and Materials All data that support the findings are available from the corresponding author upon reasonable request.

Declarations

Consent to Participate The authors declare their consent to participate in this work.

Consent to Publish The authors declare their consent to publication of this manuscript by "Water Resources Management" journal.

Competing Interest The authors declare that they have no conflicts of interest to report regarding the present study.

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