OPTIMIZATION OF IRRIGATION WATER MANAGEMENT: A CASE STUDY OF SECONDARY CANAL, SINDH, PAKISTAN

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ABSTRACT

Irrigated agriculture in Pakistan is in a quiet crisis. Despite undeniable past successes in contributing to food production, irrigation expansion has lost momentum from last three decades due to a considerable slowdown in new investment, losses of irrigated areas due to water logging and salinization resulted in poverty and unsustainable livelihood of agriculture community. However, irrigated agriculture still remains essential for future food security.

In order to optimize irrigation water a pilot study was carried out in the command area of secondary canal (Jamal Shah distributary) off-taking from main Rohri Canal of Sindh Province of Pakistan. The relevant data such as discharge, cropping pattern, cropping intensity, input cost, net return, were collected for one canal year and the installed capacity daily and operational factor of the tubewell water. Analyzing the data it was found that the fresh water (canal) was fluctuating with crop season. In summer it was short of 26% of crop water requirement and in winter it was in surplus of about 20%. However, the actual net income was about Rs 288.71 million from cropping intensity of 116%.

Using optimization “Linear Interactive Discrete Optimizer” (LINDO) model, four scenarios were studied for different cropping pattern with fresh canal water availability and optimal use of tubewell water keeping minimum country requirement of staple crops: (1) By applying 78% of canal water and cropping intensity (C.I) of 37%, the net benefit obtained is about Rs 222 million; (2) by applying 55% fresh water and C.I of 40%, the net benefit obtained is Rs 851 million; and (3) using 65% fresh water and C.I of 41%, the outcome is Rs 526 million and (4) applying 76% fresh water and cropping intensity of 65.5%, the net income is Rs 1,072 million.

Thus, study concludes that the scenario 4 is the optional solution having a maximum net benefit of Rs.1,072 million, which gives more consideration to vegetables and maximum utilization of tubewell water during hot days when the crop water requirement is high and shortfall of canal water. It is also concluded that

Scenario-IV balances the crop pattern by reducing to cultivating area of high delta crops such as cotton and sugarcane and giving more emphasis on cultivating vegetables.

It has been observed that in winter season there is surplus water which is not being used; therefore, it is suggested that the planning of conservation of this surplus water can be made by constructing a small storage reservoir at the head of the canal command area which can be used during the shortage of canal water in the summer season.

Keywords: Optimization, Irrigation Water Management, LINDO Model, Cropping Pattern

1. INTRODUCTION

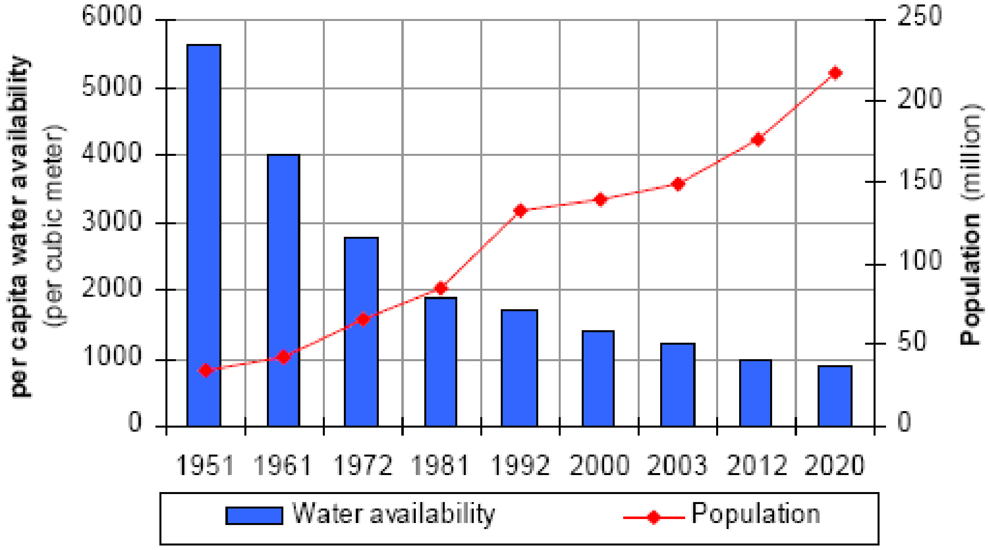
Water indeed a precious commodity; it needs to be quantified by drops. Water saving can add the prosperity to life. It can style mentally as well as physically. With the developing world, it is needed to plan for the optimum use of water and ensure its supply on the basis of demand.

Management of irrigation systems requires consideration of the various resources available to an area including water, land and people. But it has been observed that both land and people are far in excess of available water resources. Therefore, it has become imperative to re-constitute over water requirement to get more out of this scarce resource to meet food and fiber requirements.

As the inevitable expansion of irrigated lands for increased food production comes into conflict with accelerating economic competition for water and rising environmental concerns, this fundamental precept of irrigation management will probably be abandoned. The new operational rule that replaces it will be based on maximizing total benefits rather than yields (English et al. [1]).

An economically optimal irrigation allocation may not necessarily result in a maximum yield due to diminishing marginal returns of production inputs (Martin and Heerman [2]; Qureshi et al. [3]). An economically efficient cropping pattern defines the optimal crop area and water allocation for seasonal, annual and perennial crops, subject to constraints on land and water availability (Mujumdar, [4]; Young, [5]). However, pressures on water resources are increasing with the expanding scale of global development (Falkenmark and Rockström [6])

The quantity of fresh water in Pakistan is limited; its per capita availability is going to be declined because of growing population. It has been declined low from 5650 cubic meters in 1950-51 to 1200 cubic meters in 2003 (see Figure 1). This implies that the country’s per capita water availability is only marginally above the threshold level of water scarcity i.e. 1,000 cubic meters (i.e. in 2012). The most significant element in this worsening trend was the relatively poor focus on both water management and population growth (Majeed et al. [7]).



Source: (Majeed et al. [7])

Fig. 1 Per Capita Water Availability and Population

Although Pakistan owns one of the largest integrated surface irrigation systems in the world yet the water is insufficient not only for industrial and domestic needs but to meet the crop water requirement, leaching of salt affected lands and to bring new lands under crop cultivation. It is estimated that one cusec of water is provided for 310 acres which is hardly sufficient to meet the water requirement of crops including leaching requirements for 100 acres of irrigated land. In spite of good quality irrigation water and favorable soil and climatic conditions, agricultural production in the country is far away from potential, which is due to inadequate water and inefficient use of available water by farmers. Thus water shortage and mismanagement are becoming major constraints in the country for low crop yields.

The need is to device such a tool to accrue maximum net-benefits out of available resources either, by rescheduling the cropping pattern or to manage the available water resources at hand. The aim is to estimate the forthcoming benefits through different scenarios of crop water use and the cropping pattern, ascertaining the minimum standard requirement of each crop for food and fiber and for other social uses.

The objectives of the study are two-fold: 1) to develop a computer model for the optimization of water resources, and 2) to run the optimization model using the collected data of irrigation, agronomy and economics.

2. THE STUDY AREA

The study area is Jamal Shah distributary which off-takes on right side from Rohri Main canal at R.D 578 and is located in district Nawabshah. It has a designed full supply discharge of 99 cusec having its length of 14 miles and 62 watercourses. It has a GCA of 30,886 acres and a CCA of 28,043 acres. The command area is shown in Figure 2. Its maximum actual discharge observed is cusecs,

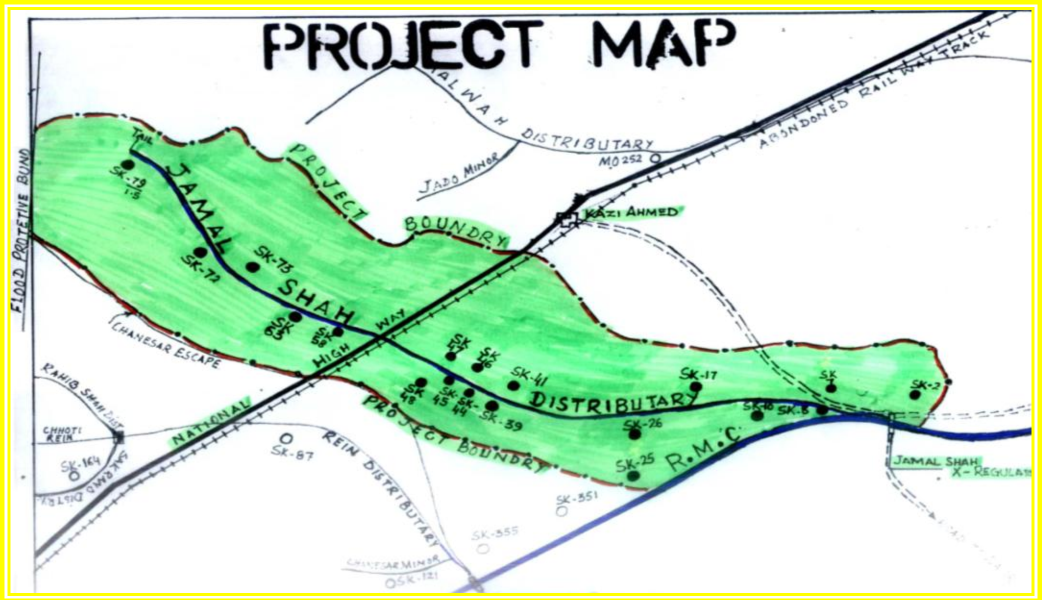


Fig. 2 Map showing command area of Jamal Shah distributary

3. DEVELOPMENT OF MODEL

The history of operational research is not a long one although its origins can be traced back to the industrial revolutions (Cohen [8]). In the last decade, optimization techniques have widely been used in the field of integrated water resources management. Medellín-Azuara et al. [9] applied an economic-engineering optimization model to explore and integrate water management alternatives such as water markets, reuse and seawater desalination in Ensenada, Mexico. Han et al. [10] presented a multi-objective linear programming model to allocate various water resources among multi-users and applied it to obtain reasonable allocation of water supply and demand in Dalian, China.

The developed model in this project is a linear optimization model using Linear Interactive Discrete Optimizer (LINDO). Therefore, the objective function is a linear in parameter function that is subject to a number of linear constraint equations. The outcome/Objective Function of the study is determination of optimum cropping pattern for available monthly canal water discharges and tube well pumpages in the area to achieve maximum net benefits (for detail refers Khero [11]).

Maximizing:

O. F. = **G**ross **V**alue of **C**rop **P**roduce **–** **E**xpenses (*which includes cost of Production i.e. Seed, Fertilizer, Land Preparation, Harvesting, Labor, Weeding, Hoeing, Look after*) **–** **C**ost of **C**anal **I**rrigation **S**upplies **–** **C**ost of **T**ubewell **P**umpages (1)

Gross Value of Crop Produce

$$\sum Y_I * SP_I * A_I \qquad (2)$$

Where Y_I = Yield of crop, SP_I = Sale Price of crop, A_I = Area of crop and subscript I stands for the crop.

Cost of Production

$$\sum CP_I * A_I \qquad (3)$$

Where, additionally CP_I is a cost of production of each crop.

Cost of Canal Irrigation Supplies (per acre-ft)

Q_{CJ} = Volume of Canal Water in J^{th} month in Acre-ft

Q_{CJ} ≤ Canal Capacity * Canal operation factor * No of days in J^{th} month x 1.98347

= 145 x 0.85 x N x 1.98347 = 244.5 x N

Where N is number of days in a month

However, gauge records were observed at 2 hourly bases; hence, the actual water available at the head of Jamal Shah distributary was different for different months. Therefore, on the basis of the actual available supplies, the upper limit/ceiling of the discharge or volume of the water in acre-ft for all 12 months has been used in the model.

Net Water Requirements for Crop Water Use Constraint

Net Water Requirement (in acre-ft) for all Crops in j^{th} Month

$= NW_{C,J} \times A_C + NW_{m,J} \times A_m + NW_{KF,J} \times A_{KF} + NW_{KV,J} \times A_{KV} + NW_{r,J} \times A_r + NW_{S,J} \times A_S + NW_{W,J} \times A_W + NW_{O,J} \times A_O + NW_{RF,J} \times A_{RF} + NW_{RV,J} \times A_{RV} \leq E_C \times Q_{CJ} + E_T \times Q_{TJ}$

The above statement describes that the volume of net water required to all crops at the root zone in J^{th} month must be less than the available supplies of water from canal and tubewell water after deducting conveyance and field application losses. Net Water Requirement (in acre-ft) of i^{th} Crop in j^{th} Month will be as follows:

$$\sum NW_{I,J} * A_I \leq E_C \times Q_{CJ} + E_T \times Q_{TJ} \qquad (4)$$

Where subscript C = canal water and subscript T = Tubewell water

Effective Rainfall Constraint

Effective Rainfall in J^{th} month = NR_J

$$NR_J = R_J - RO_J - DP_J \qquad (5)$$

J = Counter for months (i.e. from Jan. to Dec.), R_J = Total Rainfall in Jth month
RO_J = Runoff in Jth month and DP_J = Deep Percolation in Jth month

4 RESULTS AND DISCUSSIONS

4.1 Canal Water Availability and Crop Water Requirement

Management of irrigation water begins by knowing the quantity of water available in the system. Therefore, the basic data required to accomplish the job was the collection and analysis of data on the water supply and demand in the Jamal Shah distributary of main Rohri canal.

Based on 10 – daily discharge measurements at head of Jamal Shah distributary, the canal water availability for the Kharif 2003 and Rabi 2003-04 seasons has been computed. The crop water requirement (CWR = K_C x ET_O) was also calculated using the actual cropped area and considering 80% farm efficiency and 90% water course efficiency (USDA-SCS [12], IPD [13] and WAPDA [14]. Comparison of the water availability with crop water requirement is given in Figures 3 and 4.

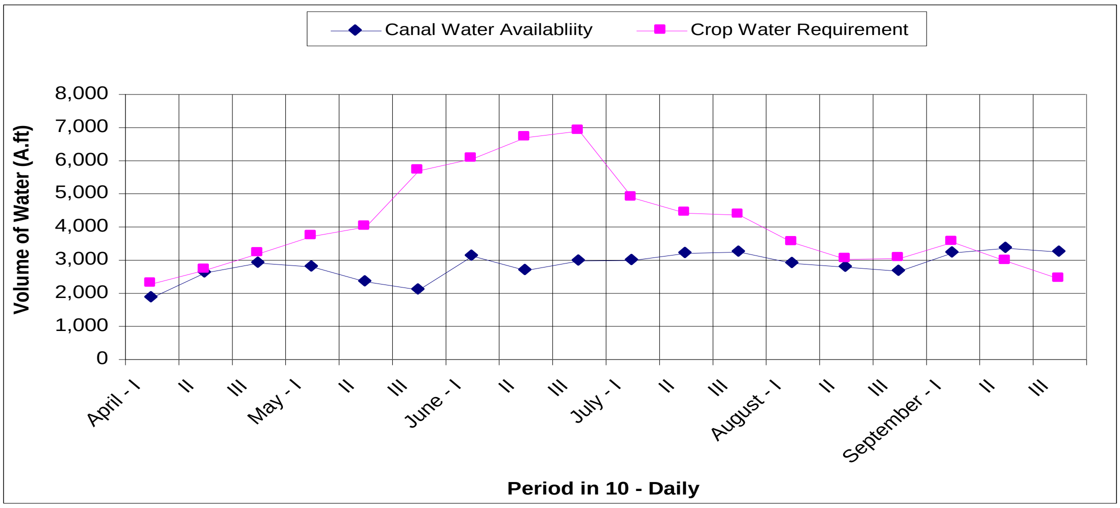


Fig. 3 Canal water availability and crop water requirement for Kharif 2003

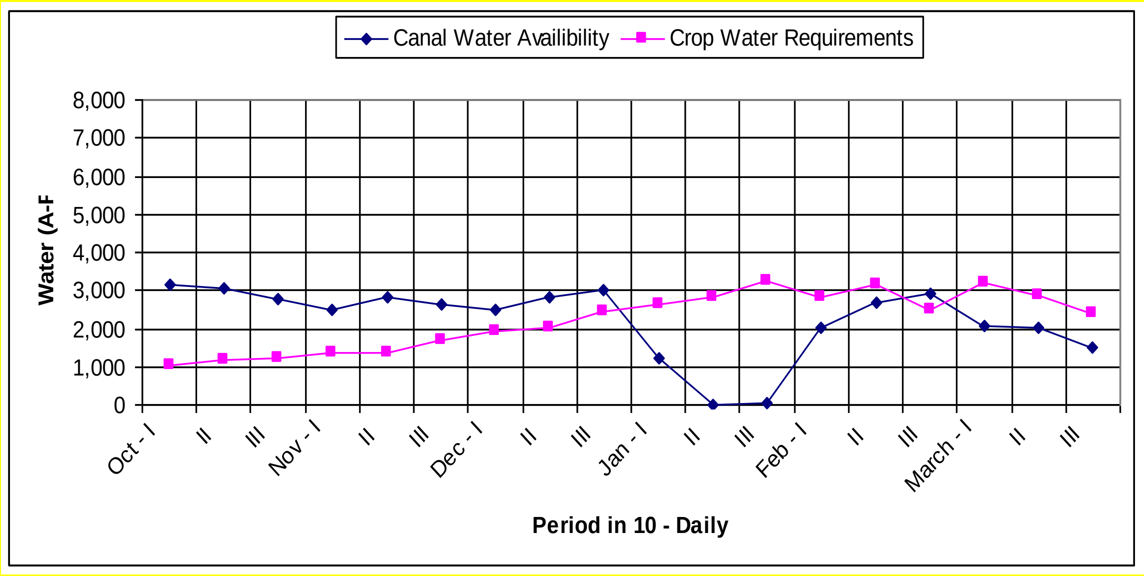


Fig. 4 Canal Water Availability and Crop Water Requirement for Rabi 2003-04

The observed data show that total water availability in Kharif 2003 and in Rabi 2003-04 was 54612 acre-ft and 49782 acre-ft respectively. Crop water requirement (CWR) values show that during Kharif 2003 season the CWR was 73415 acre-ft and Rabi 2003-04 season was 39948 acre-ft. It concludes that the distributary was short of 26% of crop water requirement in Kharif season and it was in surplus of about 20% in Rabi season.

Further results indicate that the deficiency in canal water availability was observed throughout both seasons except September to December, which are winter season months that requires less water. The maximum surplus is about 5582 acre-ft in the month of October, which is considered as a transition period of crop cultivation which does not require irrigation water. The major deficiency was observed 10856 acre-ft in the month of June, which is the hottest month of the year, which can be managed using groundwater. The private tubewells are already installed in the command area.

4.2 Constraints for Actual Canal Supplies and Use of Tubewell Water

For optimizing the canal and tubewell water, following constraints are being considered in the model.

Constraints for Canal Water Supplies used in the model

Total crop water requirements in Kharif for 6 months [i.e. May (Q_{C5}) to October (Q_{C10})] should not exceed the available water supplies of 52,652 acre-ft. Thus, Canal water constraint for Kharif was:

$$Q_{C4} + Q_{C5} + Q_{C6} + Q_{C7} + Q_{C8} + Q_{C9} <= 52652 \quad (6)$$

Similarly, total crop water requirements in Rabi for 6 months [i.e. Nov (Q_{C11}) to April (Q_{C4})] should not exceed the available water supplies of 43,142 acre-ft, so that canal water constraint for Rabi:

$$Q_{C10} + Q_{C11} + Q_{C12} + Q_{C1} + Q_{C2} + Q_{C3} <= 43142 \quad (7)$$

Constraints for Tube well Pumpage used in the model Cost of

Tubewell pumpage in all 12 months should not exceed the recharge to ground water from canal, tubewell and rain water. Tubewell water has been used when there is a short supply in the canal water. The average tubewell water is 3300 acre; however, it can be extracted up to 6600 acre-ft. Both are used in the model for testing of scenarios.
Q_{TJ} = Volume of Tubewell Water in J^{th} month in Acre-ft

$$Q_{TI} <= 3300 \quad (8)$$

Where subscript I = 1, 2, 3,………12.

$$Q_{TI} <= 6600 \quad (8')$$

4.2 Model Implementation and Scenario Simulation

4.2.1 Model Implementation

Using the actual cultivated cropped area (in local language called Partal), its yield, computed cost of production (expenditure) and sales price or cost of produce (revenue) (see Table 1 and 2), the input cost, output and the net-benefits for Kharif 2003 and Rabi 2003-04 seasons have been computed by the developed model. The net-benefit for the year 2003-04 was about Rs. 288.74 million from 32,598 acres of cropped area.

Table 1 Net-Benefits accrued in Jamal Shah distributary command area

Season	Input Cost (Million Rs.)	Input Cost (Million Rs.)	Input Cost (Million Rs.)
2003-04	171.67	491.30	288.71

The above calculations have been made using the developed linear optimized model described in equation 1 for the Objective Function and equations 2 to 9 for the constraints (detailed calculations are available in Khero [11]).

Table 2 Yield, cost of production, sale price and cost of produce of various crops in the command area of Jamal Shah distributary for year 2003-04

Description		Area (acres)	Yield		Expenditure (Rs) Per Acre	Sale price (Rs)	
Kharif crops 2003	Cotton	8291	18	Maund Acre	7,500	800	Per Maund
	Sugar cane	3533	800	Maund Acre	13200	41	Per Maund
	Rice	280	35		4700	300	
	Garden	194	30000	Per acre	5000	50000	Per acre
	Banana	464	500	Maund/acre	20000	250	Per Maund
	Kharif fodder	3325	300		1500	20	
	K. Vegetable	5	300		5000	800	
	K. Pluses	0	20		2000	550	
Rabi crops 2003-04	Wheat	13746	30		3000	350	
	Rabi Fodder	1652	300		2000	20	
	Rabi oil seeds	1089	15		1500	600	
	Garden	102	30000	Per acre	5000	50000	Per acre
	Banana	374	500		20000	250	Per Maund
	Rabi vegetable	19	17	Maund/acre	5000	600	
	Rabi Pulses	0	20		14000	700	

4.2.2 Scenario Simulation

Four scenarios have been developed. The description of the each scenario is as under:

Scenario – I: Net benefit calculated with minimum area fixed under each crop which is described in Table 3 with allocation of tubewell water up to3300 acre-ft per month

Scenario – II: Net benefit calculated with fixing minimum of 12.5% of actual cropped area and with allocation of tubewell water up to 3300 acre-ft per month

Scenario – III: Net benefit calculated with fixing minimum of 25% of actual cropped area and with allocation of tubewell water up to 3300 acre-ft per month

Scenario – IV: Net benefit calculated with fixing minimum of 25% of each cropped area and with allocation of tubewell water up to 6600 acre-ft per month

Constraint for Minimum Cropped Area

Area allocated to all crops should be greater or equal to the minimum designated/decided area for each crop.

$$A_I \geq Min_I \tag{9}$$

Table 3 Minimum standard requirement of each crop for the country

CROP	Cotton	Banana	K.F	K.V	Rice	S.cane	Wheat	O.seeds	R.F	R.V	Garden
Minimum Country Requirement (%)	3	15	2	1	2	1	15	0.5	2	1.5	10

Source: WAPDA [14]

The cropping pattern predicted using above four scenarios for the selected distributary command area is described in Table 4 along with the actual cropped area of cropped year 2003-04. From Table it is observed that the main crops of the command area are cotton (having cultivated land of 8291 acres) and wheat (having 13746 acres) followed by sugarcane and Kharif fodder cultivated on 3533 and 3325 acres respectively

Table 4 Cropping pattern calculated based on different scenarios for Jamal Shah distributary command area

Crops	Actual Cropped Area (acres)	Scenario-I Minimum Country Requirement (acres)	Scenario-II Minimum 12.5% A.P Area (acres)	Scenario-III Min: 25% A.P Area (acres)	Scenario-IV Min: 25% A.P Area with maximum utilization of tubewell water (acres)
1	**2**	**4**	**5**	**6**	**7**
Cotton	8291	725	1036	2073	2073
Banana	464	464	58	116	116
Kharif Fodder	3325	67	416	831.25	831
Kharif Vegetable	5	5	3207	1702	3829
Rice	280	6	35	70	70
Sugarcane	3533	3533	442	883	883
Wheat	13746	5294	5497	5112	9833
Oil seeds	1089	5.445	136.13	272	272
Rabi Fodder	1652	33	207	413	413
Rabi vegetable	19	0.3	2	5	5
Garden	194	194	24	49	49

Table 4 describes the actual cropped area cultivated in command area of the distributary as Col. 2, Col. 3 describes the minimum area required to be cultivated for each crop in the country (Scenario-I) and Col. 4 – 6 are the areas which model suggests for optimizing the net benefits (for Scenario-II to IV) to be accrued from the distributary command area (see Figure 5).

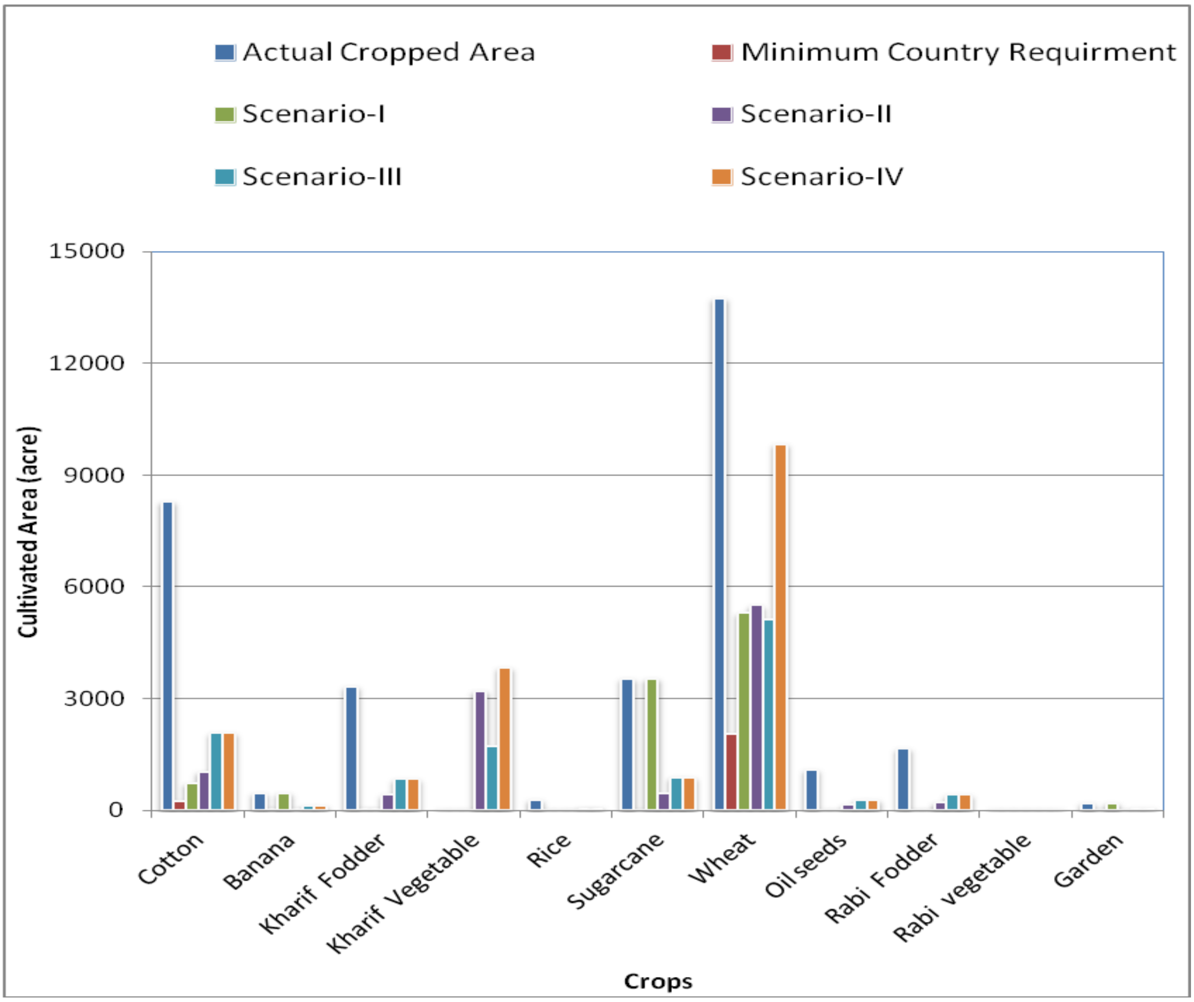


Fig. 5 Cultivated crops' area (Actual and Simulated for various scenarios)

Scenario–I gives about 39,933 acre-ft surplus water, Scenario–II shows surplus water about 34,312 acre-ft, Scenario–III gives surplus water about 24,737 acre-ft and Scenario–IV has surplus water about 23,128 acre-ft. However, surplus water is not constant throughout the year; therefore, the planning for conservation of water can be made by constructing small storage reservoirs in the command area of the distributary, that can be used in the case of shortage of water.

The net-benefits to be achieved using different options of cropping pattern are described in Table 5 and shown in Figure 6.

Table 5 Summary of canal water availability and its use

Scenario	Cropped Area (Acres)	Available Canal Water	Canal Water Used	% Use of Available Canal Water	Use of Tubewell Water	Net Benefit (10^6.Rupees)
Actual Cultivated	32598	95794.48	95794.48	100	8600	288.71
Scenario-I	10326.6	95794.48	75055.13	78.35	14276	222.2
Scenario-II	11059.9	95794.48	52333.39	54.63	9149	850.65
Scenario-III	11525.5	95794.48	61748.24	64.46	9310	525.99
Scenario-IV	18374.0	95794.48	72666.61	76.00	24156	1072.92

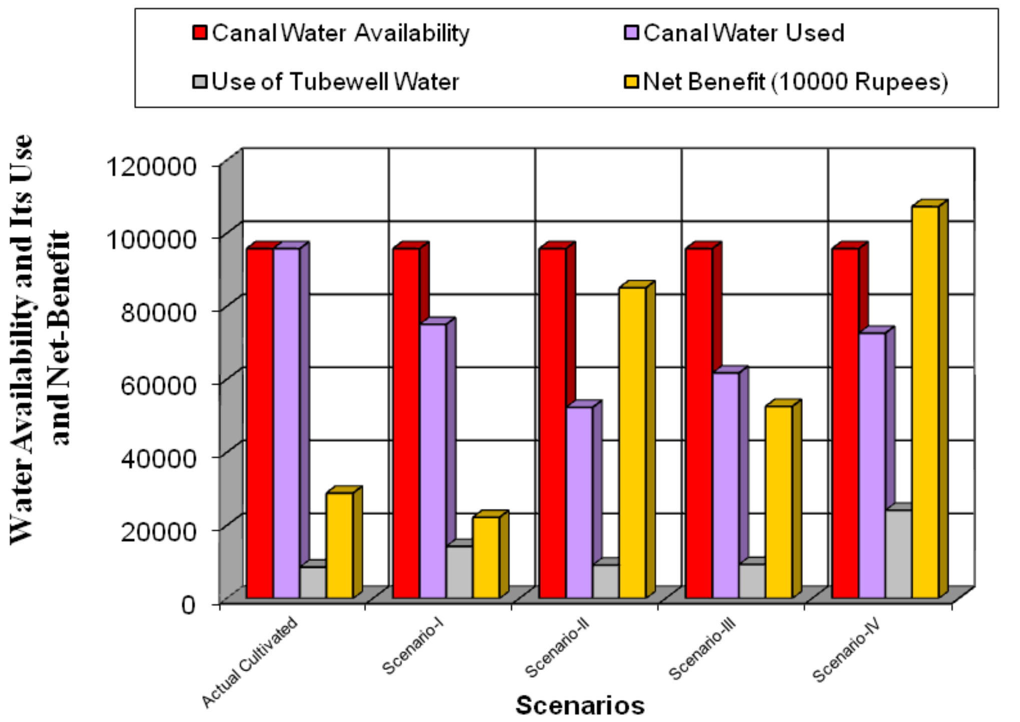


Fig. 6 Canal water availability and its use with calculated net-benefit with different scenarios

The model has estimated net-benefits and proper use of canal water. Results indicate that in existing conditions and when all canal water was used the net benefit was Rs. 288.7 millions and the cropping intensity was about 116 percent. However, using different options of cropping pattern as mentioned in various scenarios the outcome has: developed. In scenario-I, the use of canal water was 78% and net-benefit is Rs 222 millions against cropping intensity of 37%. In scenario–II, the use of canal water was 55% and net-benefit is Rs. 851 millions against cropping intensity of 40%. In scenario–III, the use of canal water was 65% and net-benefit is Rs. 526 millions against cropping intensity of 41%. In scenario–IV, the use of canal water was 76% and net-benefit is Rs.1073 millions against cropping intensity of 65.5%.

From Figure 7 (Scenario-IV), it is clear that there is no usage of tubewell water from July to December; because during this period the canal water availability is greater than the crop water requirement. However, the tubewell water used in the months of May and June is maximum i.e. more than 6000 acre-ft. It is also apparent from table 5 that in spite of utilizing more tubewell water, Scenario-IV gives an optimal solution, which balances the crop pattern by reducing to cultivating area of high delta crops such as cotton and sugarcane and giving more emphasis on cultivating vegetables.

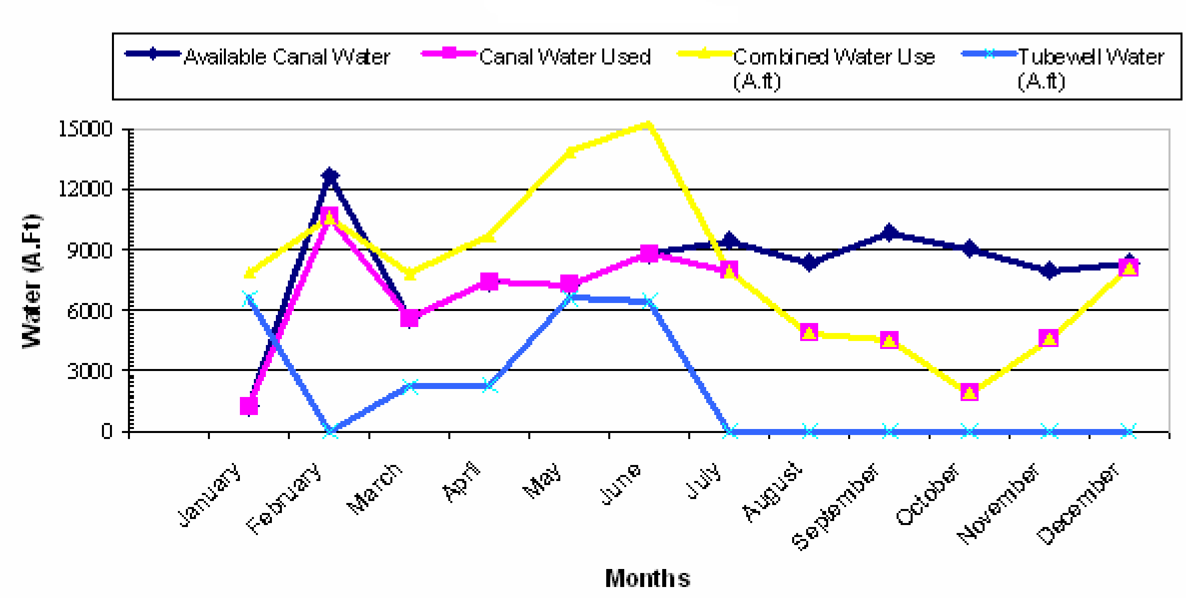


Fig. 7 Availability and use of canal and tubewell waters for Scenario-IV

5 CONCLUSIONS

Following conclusions are made from the study;

The actual net income was calculated is Rs 288.7 million from 32,598 acres of cropped area with cropping intensity of 116%. The main crops are cotton having cultivated land of 8291 acres and wheat 13746 acres followed by sugarcane and Kharif fodder cultivated on 3533 and 3325 acres respectively.

The observed data show that total water availability in Kharif 2003 and in Rabi 2003-04 was 54612 acre-ft and 49782 acre-ft respectively. However, crop water requirement (CWR) values show that during Kharif 2003 season the CWR was 73415 acre-ft and in Rabi 2003-04 was 39948 acre-ft. It is also observed that canal water was fluctuating with crop season: In summer it was short of 26% of crop water requirement and in winter it was in surplus of about 20%. Hence, it is suggested that the water conservation can be made by constructing small storage reservoirs at the head of the command area of the distributary which can be used in the case of shortage of water.

Using developed optimizing model, four scenarios were studied using different cropping patterns with maximum utilization of available canal water and optimal usage of tubewell water show that : (1) By applying 78% of canal water and cropping intensity (C.I) of 37%, the net benefit obtained is only about Rs 222 million; (2) by applying 55% fresh water and C.I of 40%, the net benefit obtained is Rs 851 million; and (3) using 65% fresh water and C.I of 65%, the outcome is Rs 526 million and (4) applying 76% fresh water and cropping intensity of 65.5%, the net income is Rs 1,072 million. Thus, it is concluded that the scenario 4 is the optional solution having a maximum net benefit of Rs.1,072 million, which gives more consideration to vegetables and maximum utilization of tubewell water during hot days when the available canal water is insufficient to meet the crop water requirement.

It is also concluded that Scenario-IV balances the crop pattern by reducing to cultivating area of high delta crops such as cotton and sugarcane and giving more emphasis on cultivating vegetables.

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