Optimal Cropping Pattern by Multi Objective Optimization using Genetic Algorithm

By

Centre for Ganga River Basin Management & Studies (cGanga)

Lead Persons

1. Vinod Tare, IIT Kanpur
2. Shivanuj Shukla, IIT Kanpur

1. Introduction

Agriculture is the largest consumer of fresh water resources and responsible for about 70 percent of fresh water withdrawals from rivers, lakes and aquifers (FAO, 2014). Water shortage or water scarcity is a global issue for which one of the solutions is to make efficient use of water in agriculture. Irrigation projects often operate with low efficiency because of poor management practices, non-use and misuse of water, and focus only on economic returns without accounting for the direct subsidies as well as subsidies that are hidden (e.g. on water supplied for irrigation).

It is imperative that the focus of irrigation planning is not restricted to economic returns to individual farmers but also to ensure food security in terms of energy capture in agricultural produce. This research is a small step to reach this goal.

The objective of the study is to allocate the available land resource to multi-crop system in such a manner that maximum return in economic terms can be achieved along with producing maximum number of calories of food energy that is obtained from the cultivation of several crops using the canal water as a source of irrigation water.

The study area chosen for this purpose lies in the western part of Uttar Pradesh and irrigated by the Upper Ganga Canal (UGC) system. UGC system, being the first major irrigation system of the country, takes off from the Bhimgoda Barrage at Haridwar, Uttarakhand. The UGC system was constructed during the period 1842-1854 and commissioned in 1854. The increase in population led to an increase in agricultural production and eventually led to an increased demand of water for irrigation; hence the UGC system kept on expanding and presently irrigates an estimated command area of around 10.08 lakh hectares as per Irrigation Department of Uttar Pradesh. An attempt has been made to analyze the impact of deficit irrigation on food energy and net economic benefit, if the abstraction of canal water is to be reduced by some percentage to meet the requirement of Environmental Flows (E-Flows) downstream of Bhimgoda barrage in the national river Ganga.

2. Literature Review

Indian population is increasing rapidly and it is expected to touch 1.7 billion mark by 2050 (United Nations, 2015) and to achieve food security for escalating population growth, importance of irrigation cannot be overlooked. Since, agriculture is the single largest consumer of water and hence in the past, several attempts have been made to optimize its usage in the agriculture. This chapter briefly reviews application of optimization techniques in agriculture.

Lakshminarayana & Rajagopalan (1977) used Linear Programming approach for the optimization (maximization) of net benefit from agriculture in an alluvial tract between two rivers in Northern India. Maji and heady (1978) developed an optimal cropping pattern for the Mayurakshi irrigation project (India) using two chance-constrained linear programming models and concluded that for maximization of net return from the project area, a change in the existing cropping is desirable. Sarker *et al*., 1997 developed a linear programming model based on the constraints of food demand, land, capital, contingency to develop an optimal cropping pattern for the maximizing the overall agricultural production. Sethi *et al*. (2002) determined the optimal cropping pattern for a coastal river basin in Orissa, India using the linear programming optimization model and the corresponding optimization results were obtained for various scenarios of river flow and groundwater availability. Prasad *et al*. (2006) employed deterministic dynamic programming method for maximizing the net annual benefit from the project located at Nagarjuna Sagar Right Canal command in the semiarid region of South India. Singh and Panda (2012) developed linear programming model in order to maximize the net annual income from the irrigation area in the State of Haryana, India for the optimal allocation of land and water resources.

Kuo *et al*. (2000) employed a simple genetic algorithm optimization model for optimization of economic profit. An important point stated by the authors is that "traditional optimization methods have limitations in finding global optimization results and are difficult to apply to a complex irrigation planning problem since they search from point to point for the optimization. On the other hand, the genetic algorithm method searches the entire population instead of moving from one point to the next and can, therefore, overcome the limitations of the traditional methods." Md. Azamathulla *et al*. (2008) making a comparison between Genetic Algorithm and Linear Programming while determining optimum cropping pattern for a basin in Madhya Pradesh, India found that GA model is superior to LP Model because it is robust and can be run with different types of objective functions. Much of the works described above used linear programming technique for optimization of a single objective i.e. maximizing the net annual income or return from an agricultural area. A few multi-objective optimization studies have also been reported where alternative to maximizing the increase in the net income has been considered. Mainuddin *et al.* (1997) worked with **t**wo objectives, i.e. maximization of net economic benefit and maximization of irrigated area in the Sukhothai Groundwater Development Project in Thailand. Reddy and Kumar (2006) used Multi-objective Genetic Algorithm (MOGA) for a multipurpose reservoir system to obtain a Pareto front between water usage for irrigation and hydropower generation. They propounded that MOGA approach helps in finding many Pareto optimal solutions which supports the decision maker to take appropriate decisions at different levels.

Though, the studies reported in literature, reveal application of multi-objective optimization but maximization of net calories has not been taken care of. In the present study, therefore, an attempt has been made to optimize the net income taking into consideration the maximization of calories (energy) to be obtained from agriculture.

3. Methodology

The work presented in this thesis is carried out in 8 steps shown as a flowchart in Figure 3.1.

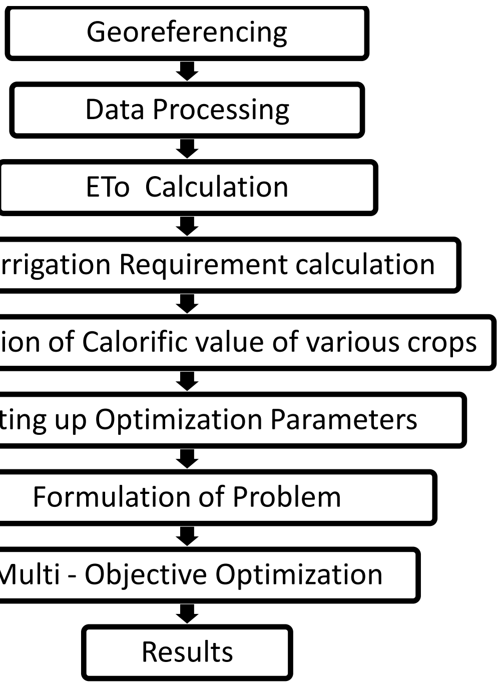

Figure 3.1: Schematic Representation of the Steps Involved

Geo-referencing of index map of Upper Ganga Canal (UGC) is done to identify the area in which canal system is operating. The canal command area is divided into particular grids to utilize the gridded data of temperature and precipitation to calculate the Net Irrigation Requirement (NIR) of various crops in the particular grids. The average value of the NIR is used for a particular crop in the canal command area.

Another optimization parameter, Cost and net benefit obtained from various crops is taken from the Directorate of Economics and Statistics. Calories obtained per hectare of various crops were used as the second objective function in multi-objective optimization. The optimization is then run to find the results for Rabi and Kharif Season.

3.1 Geo-referencing and Formation of Grids

Since, temperature and precipitation data is available in gridded form, geo-referencing of index map of UGC is done to find out the grids whose data is required. The coordinates are plotted and grids are shown in the geo-referenced map in Figure 3.2.

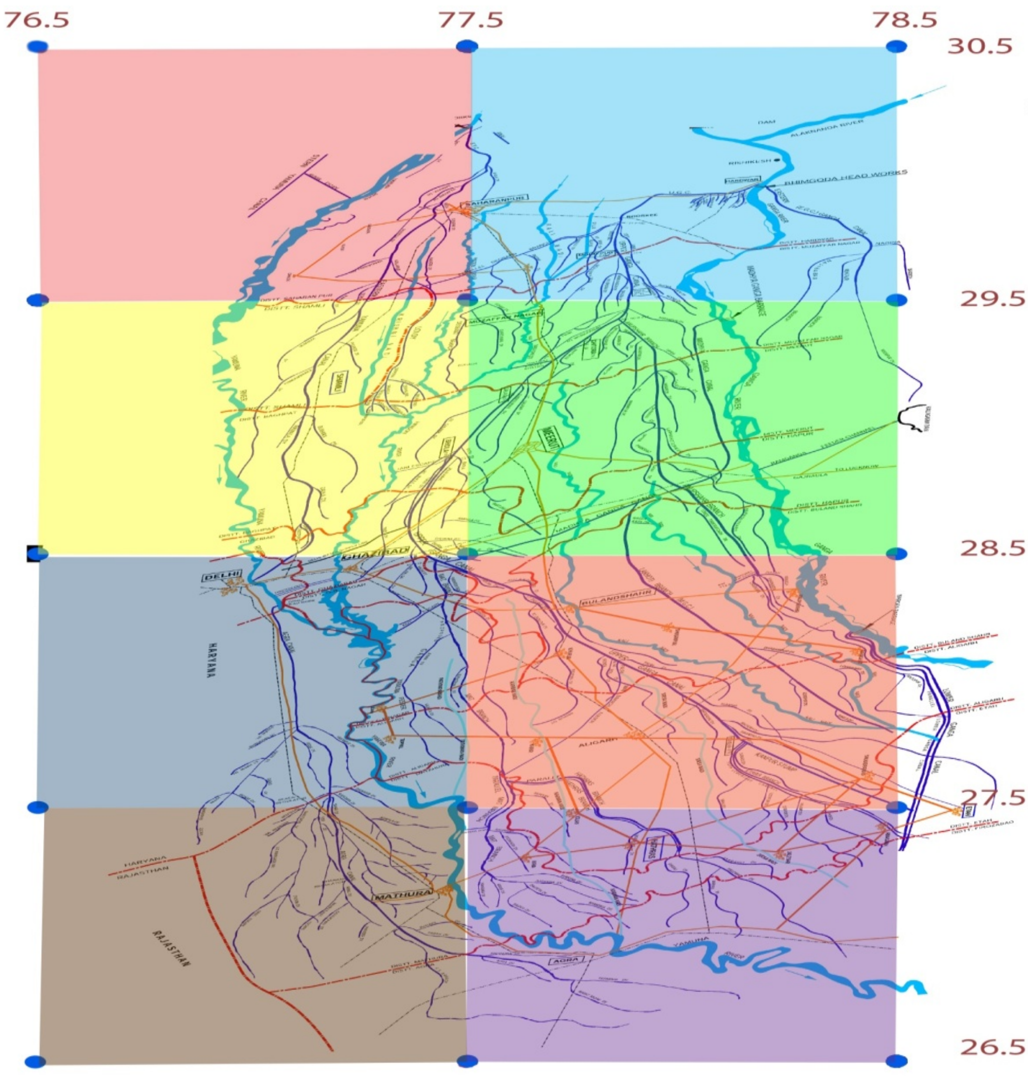

Figure 3.2: Geo-referencing of Index Map of Upper Ganga Canal

It can be seen that the canal command area of UGC lies in the following five grids and thus these particular grids are taken as the area under which the cultivation of crop is done.

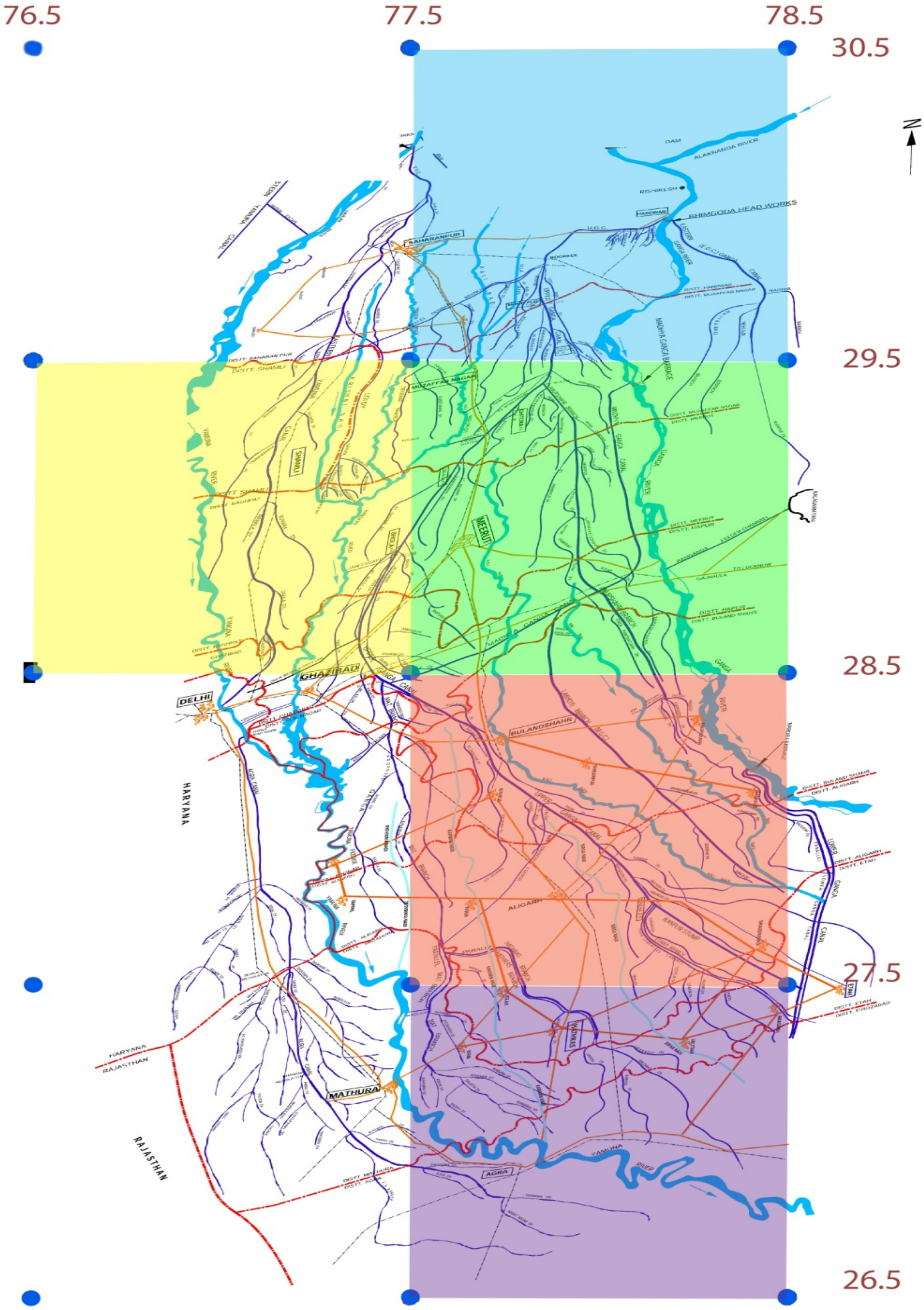

Figure 3.3: Grids Under the UGC System

The geospatial coordinates of the extent of the grids are presented in Table 3.1.

Table 3.1: Geospatial Coordinates of Grids

Grids	From		To	
	Northing	Easting	Northing	Easting
Grid 1	29.5	77.5	30.5	78.5
Grid 2	28.5	77.5	29.5	78.5
Grid 3	27.5	77.5	28.5	78.5
Grid 4	26.5	77.5	27.5	78.5
Grid 5	28.5	76.5	29.5	77.5

3.2 Data Processing

The data provided by Indian Meteorological Department (IMD) is in ASCII format and contain gridded data in following resolution:
Temperature data: Latitude 67.5 – 97.5, Longitude 7.5 -37.5, resolution of 1 degree
Precipitation data: Latitude 66.5 – 97.5, Longitude 6.5 -38.5, resolution of 0.25 degree
Since resolution of both the climatic data was different, Thiessen polygon method is used to determine the precipitation at 1 degree resolution. Hence, the resolution of both the climatic data were now obtained at resolution of 1 degree.

Since, the raw gridded data were of very large size and data of only selected grids were required, hence the data is filtered by writing a suitable code in MATLAB. The ASCII file is imported in MATLAB and by running the code; the required data is filtered out from the raw data set. After, the gridded data of required grids are obtained, it is manually fed in the CROPWAT 8.0 software to obtain the ".pem" and ".crm" files of the particular grids. Once, the ".pem" (temperature) and ".crm" (rainfall) files of a particular grid is created and saved, then it can be recalled at any time for future use. These temperature and rainfall data files are used along with that data of crop characteristics to get the Net Irrigation Requirement of different crops. So, it is suggested to create and save ".pem" &".crm" files of each location. The process of data processing can be summarized as follows.

1. Filtering required gridded data from raw data.
2. Feeding filtered data into CROPWAT 8.0

Process flow of data processing is shown in Figure 3.3 as follows.

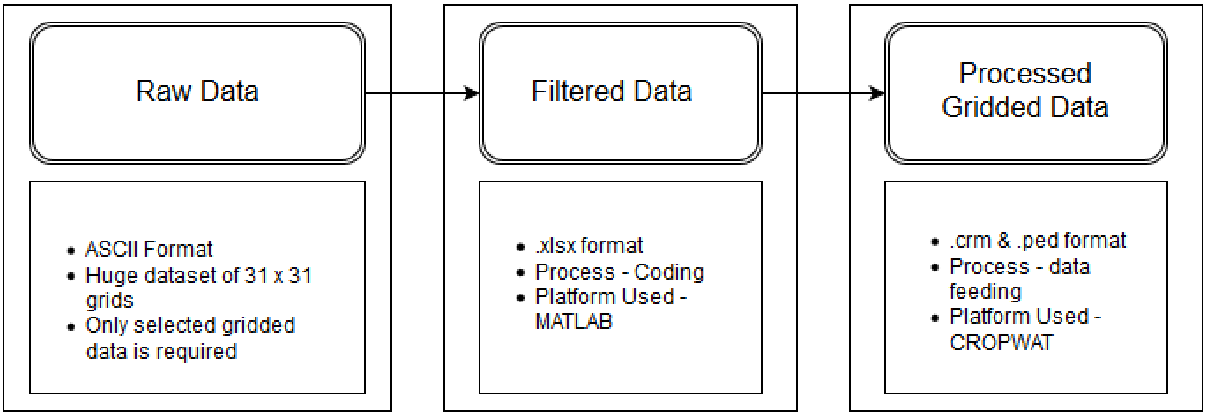

Figure 3.4: Process of conversion of Raw Data to Gridded data

3.3 Reference Evapotranspiration (ETo) and NIR

There are several methods used to calculate reference Evapotranspiration, namely Penman- Monteith equation, FAO Penman Monteith Method (Allen *et al*., 1998), Pan evaporation method and reference evapotranspiration estimation with inaccurate data conditions (Droogers and Allen, 2002). However, FAO has developed a software suite for calculation of Evapotranspiration and NIR. This software suite is extensively used by researchers around the world – Surendran *et al*., 2015, Cavero *et al.* (1999), Zhiming *et al.* (2007), Singh *et al.* (2002). In this thesis work also, CROPWAT 8.0 is used for calculation of Evapotranspiration and NIR. For calculation of reference crop evapotranspiration, CROPWAT 8.0 uses the FAO Penman-Monteith method.

3.3.1 Calculation of Net Irrigation Requirement (NIR)

In order to calculate NIR, following data is required.

- Rainfall
- Soil Data
- Crop Coefficient

After feeding the following data, the software (CROPWAT 8.0) calculates the NIR.

Rainfall: When rainfall data is entered, CROPWAT 8.0 allows users to choose effective rainfall from the following options - Fixed percentage, Dependable rain, Empirical formula, USDA Soil Conservation Service. Since more detailed information is not available for local conditions, hence “Fixed percentage” criterion is chosen and 80% is taken as effective rainfall.

Soil Data: Total Available Water (TAW), maximum infiltration rate, maximum rooting depth and initial soil moisture depletion are the required input. These data are generally collected from field. Since, primary data is not available hence suitable values are assumed based on the literature (Naresh *et al*., 2014; Pathak, 2001).

Crop Characteristics: The crop characteristic required for the calculation of ET_o are as follows.

1. Length of individual growth stages
2. Crop factors, relating crop evapotranspiration to reference evapotranspiration
3. Rooting depth
4. Allowable depletion levels
5. Yield response factor

All the above information of several crops is provided by FAO and are available in the CROPWAT 8.0 software. The characteristics mustard and wheat were not available with the software, so these values are taken from the literature (Raut *et al.*, 2010). After feeding the rainfall, soil and crop characteristics, NIR for every crop in every grid is calculated. After calculating the crop NIR in every grid, the average of the NIR values is taken as NIR as the NIR of that particular crop in the whole canal command area.

3.3.2 Calculation of calories obtained by various crops

The food energy (calories) produced from various crops is another objective of our optimization which we want to maximize. The data of calories per 100 gram of food crop are used to calculate the calories obtained per hectare for particular crops.

Formula Used:

Calories per hectare = (Calories per 100 gram) x (Yield per hectare (kg/hectare)) x 10

Calories per 100 gram and Yield per hectare of various crops is taken from the secondary data. Yield data is taken from Directorate of Economics & Statistics and presented in Appendix II.

Table 3.2: Calorie Values of Various Food Crops

S No	Crop	Calories (per 100 gm)
1	Lentil	116
2	Barley	354
3	Maize	365
4	Potato	77
5	Wheat	339
6	Rice	130
7	Millet	378
8	Mustard	66

Source: USDA

3.4 Setting up Optimization Parameters

The optimization parameters required for multi-objective objective optimizations are as follows.

1. Net Benefit from various crops – The cost of cultivation and value of main product and by-products are obtained by the department of economics and statistics. The difference between value of main product and byproduct and cost of cultivation is taken as net benefit obtained from the particular crop. Complete data is presented in Appendix I
2. Net Irrigation Requirement of various crops – NIR values as calculated from the software, CROPWAT 8.0, is taken as it is to be used as a coefficient in the constraint for optimization
3. Calories obtained per hectare of various crops – calories obtained per hectare is obtained by the formula used in the previous section and is used as a coefficient of the objective function later in the formulation of the problem. An adjustment is done while setting up the optimization coefficients for mustard. Mustard is an oilseed and contributes more to the economic return and its contribution to food energy is very less i.e. it gives least amount of calories compared to other crops. Also, it has a highest ratio of economic return per unit water consumption, so it is already superior in giving economic return and when its calories contribution is taken into consideration then in optimization results, it became the most dominating crop in rabi Season and covered a large portion of area. Since, only one crop cannot be allowed to dominate over the entire region because other crops are also required for consumption and mustard's contribution to contribute calories is very less, hence the calorie contribution for mustard is ignored so that the dominance of mustard crops can be reduced.
4. Total canal water available for rabi season – The flow of canal water is available in Cusecs. It is converted to hectare-mm by multiplying with suitable factors. The total water taken up by the canal has several losses such as evaporation in canal, runoff, return flow etc. Hence, the available canal water flow is not totally used by the crops. According to a report of Planning Commission, the canal water use efficiency is between 33-38 %. Hence, the total water, which is available for irrigation, is multiplied by 0.33 and the value, thus obtained, is taken as the total water which is available for crop water requirement.

3.5 Formulation of the Problem

The formulation of problem is done according to the following criteria.

- Maximizing the net benefit from cultivation of crops.
- Maximizing the total calories obtained from cultivation of crops.
- Total water available for irrigation is taken as a constraint.

In Rabi Season, the major crops cultivated are Lentil, Barley, Wheat, Mustard and Potato. Hence, our aim is to allocate the available area to respective crops subject to following objective function and constraints.

Objective Function

$$\text{Maximize} \sum_{i=1}^{5} NB_i A_i$$

$$\text{Maximize } \sum_{i=1}^{5} CF_i A_i$$

Constraint

$$\sum_{i=1}^{5} NIR_i A_i \leq TWR$$

Where, NB is the net benefit obtained after cultivation of i^{th} crop; CF is the total calories obtained after cultivation of i^{th} crop; A is the area in hectares allocated to i^{th} crop; NIR is the net irrigation requirement of i^{th} crop; TWR is the total water availability.

For Rabi season, optimization is run for two times under two different conditions of canal water availability: (a)100% canal water availability, and (b) 75% canal water availability

3.6 Multi Objective Optimization Using Genetic Algorithm

In our optimization problem, two objectives are competing for the same resource i.e. canal water. Hence, it is suggested to find the Pareto optimal solution for the multi-objective optimization problems. Pareto Optimality or Pareto efficiency is a condition in multi objective optimization when the resources are allocated to two or more competing objectives in the most efficient way possible and it is not possible to make one objective better off without making the other objective worse off.

Genetic algorithms (GAs) are a heuristic search and optimization algorithm (McCall, 2004) inspired by Darwin's principle of natural selection. It was first proposed by John Holland (Holland, 1975) and has been used to solve optimization problems in a wide variety of disciplines such as Computer Science (Raghvan and Agarwal, 1987), physical sciences (Shaffer, 1985) and engineering and operations research (Goldberg and Smith, 1987).

To find the Pareto optimal solutions, Genetic algorithm is used for optimization. The Genetic algorithm is a probabilistic stochastic search algorithm. Even when all the parameters are the same, the results obtained after the optimization are not the same for each run of algorithm. Since the result is not the same but every result is near to each other, hence, under normal circumstances, the average of all the optimization results are taken for reporting final result.

In our optimization method, the optimization is run for 5 times for the rabi season and the average of the 5 runs is calculated to report the final result.

A software suite MATLAB R2013a is used for the computer implementation of genetic algorithm. While running the optimization using genetic algorithm, initial population is generated randomly and then subsequent population is generated as per the following Criteria – Probability of crossover – 0.80, Probability of mutation – 0.05. The optimization is run for 1000 generations and final population after 1000 generations is taken as the final result of optimization for that particular run. The results obtained after each run are Fitness value (total net benefit & total calories) and fittest chromosome (value of the area allocated to various crops) and it is reported in the 'Results and Discussion' section of this thesis.

A set of Pareto optimal points corresponding to the fitness values are obtained after each run. Pareto front gives a set of non-dominated points which are used to make the curve but practically, we have to select one solution out of several points from the Pareto set. These Pareto optimal points are reported in the Results & Discussion section of the thesis. However, for reporting final result, average of these Pareto Optimal points is taken.

4. Results & Discussion

4.1 Net Irrigation Requirement of Rabi Crops

NIR for various crops of rabi season is calculated as described in Section 3.3.1. Typical results for wheat are presented in Tables 4.1 through 4.5. NIR for wheat ranges from 163.4 to 263.1.2 mm (Figure 4.1). Average NIR of wheat in canal command area is 255.22 mm.

Table 4.1: Net Irrigation Requirement of Wheat in Grid 1

Month	Decade*	Stage	Kc	ETc mm/day	ETc mm/dec	Effective Rainfall mm/dec	Irrigation Requirement mm/dec
Nov	1	Init	0.3	1.08	10.8	0.4	10.4
Nov	2	Init	0.3	0.97	9.7	0.6	9.1
Nov	3	Deve	0.38	1.1	11	1.8	9.2
Dec	1	Deve	0.52	1.35	13.5	1.6	11.9
Dec	2	Deve	0.66	1.5	15	1.9	13.1
Dec	3	Deve	0.81	1.77	19.4	9	10.4
Jan	1	Deve	0.96	1.94	19.4	16.9	2.6
Jan	2	Mid	1.1	2.1	21	23.3	0
Jan	3	Mid	1.15	2.55	28.1	29.6	0
Feb	1	Late	1.15	2.94	29.4	41.4	0
Feb	2	Late	1.08	3.08	30.8	50.5	0
Feb	3	Late	1	3.35	26.8	34.8	0
Mar	1	Late	0.92	3.54	35.4	10	25.4
Mar	2	Late	0.83	3.61	36.1	0	36.1
Mar	3	Late	0.74	3.55	35.5	0.2	35.2
Total					341.8	222	163.4

*10 day period (1st to 10th; 11th to 20th; & 21st to 30th)

Table 4.2: Net Irrigation Requirement of Wheat in Grid 2

Month	Decade*	Stage	Kc	ETc mm/day	ETc mm/dec	Effective Rainfall mm/dec	Irrigation Requirement mm/dec
Nov	1	Init	0.3	1.11	11.1	0.2	10.9
Nov	2	Init	0.3	0.99	9.9	0.1	9.8
Nov	3	Deve	0.38	1.14	11.4	0.9	10.5
Dec	1	Deve	0.52	1.42	14.2	2	12.2
Dec	2	Deve	0.66	1.62	16.2	2.8	13.4
Dec	3	Deve	0.81	1.89	20.8	2.2	18.6
Jan	1	Deve	0.96	2.12	21.2	0.3	20.9
Jan	2	Mid	1.1	2.3	23	0	23

Jan	3	Mid	1.15	2.59	28.5	2.8	25.7
Feb	1	Late	1.15	2.69	26.9	22.1	4.8
Feb	2	Late	1.08	2.67	26.7	32.7	0
Feb	3	Late	1	3.12	25	22.9	2.1
Mar	1	Late	0.92	3.5	35	9.1	25.9
Mar	2	Late	0.83	3.66	36.6	0.7	36
Mar	3	Late	0.74	3.52	35.2	0.5	34.6
Total					341.5	99.2	248.2

*10 day period (1st to 10th; 11th to 20th; & 21st to 30th)

Table 4.3 Net Irrigation Requirement of Wheat in Grid 3

Month	Decade*	Stage	Kc	ETc mm/day	ETc mm/dec	Effective Rainfall mm/dec	Irrigation Requirement mm/dec
Nov	1	Init	0.3	1.08	10.8	0.1	10.7
Nov	2	Init	0.3	0.93	9.3	0	9.3
Nov	3	Deve	0.38	1.06	10.6	0	10.6
Dec	1	Deve	0.52	1.32	13.2	0	13.2
Dec	2	Deve	0.66	1.5	15	0	15
Dec	3	Deve	0.81	1.75	19.3	0.7	18.6
Jan	1	Deve	0.96	1.91	19.1	2.7	16.3
Jan	2	Mid	1.1	2.03	20.3	4	16.3
Jan	3	Mid	1.15	2.38	26.2	7.1	19.2
Feb	1	Late	1.15	2.6	26	12.3	13.7
Feb	2	Late	1.08	2.63	26.3	16.2	10.1
Feb	3	Late	1	3.14	25.1	11	14.1
Mar	1	Late	0.92	3.56	35.6	1.7	34
Mar	2	Late	0.83	3.77	37.7	0	37.7
Mar	3	Late	0.74	3.67	36.7	0.1	36.5
Total					331.3	55.9	275.4

*10 day period (1st to 10th; 11th to 20th; & 21st to 30th)

Table 4.4: Net Irrigation requirement of Wheat in Grid 4

Month	Decade*	Stage	Kc	ETc mm/day	ETc mm/dec	Effective Rainfall mm/dec	Irrigation Requirement mm/dec
Nov	1	Init	0.3	1.23	12.3	0.1	12.3
Nov	2	Init	0.3	1.12	11.2	0	11.2
Nov	3	Deve	0.38	1.29	12.9	0.1	12.8
Dec	1	Deve	0.52	1.61	16.1	0	16.1
Dec	2	Deve	0.66	1.85	18.5	0	18.5
Dec	3	Deve	0.81	2.21	24.3	0.7	23.6
Jan	1	Deve	0.96	2.55	25.5	1.6	23.9

Jan	2	Mid	1.1	2.85	28.5	2.3	26.1
Jan	3	Mid	1.15	3.02	33.2	4.9	28.3
Feb	1	Late	1.15	2.89	28.9	9.3	19.6
Feb	2	Late	1.08	2.69	26.9	12.6	14.4
Feb	3	Late	1	3.26	26.1	8.5	17.6
Mar	1	Late	0.92	3.83	38.3	1.1	37.2
Mar	2	Late	0.83	4.07	40.7	0	40.7
Mar	3	Late	0.74	3.88	38.8	0	38.8
Total					382.2	41.2	341

*10 day period (1st to 10th; 11th to 20th; & 21st to 30th)

Table 4.5: Net Irrigation Requirement of Wheat in Grid 5

Month	Decade*	Stage	Kc	ETc mm/day	ETc mm/dec	Effective Rainfall mm/dec	Irrigation Requirement mm/dec
Nov	1	Init	0.3	1.08	10.8	0	10.8
Nov	2	Init	0.3	0.95	9.5	0	9.5
Nov	3	Deve	0.38	1.1	11	0.1	10.9
Dec	1	Deve	0.52	1.38	13.8	2	11.8
Dec	2	Deve	0.66	1.59	15.9	3	12.9
Dec	3	Deve	0.81	1.89	20.8	3.1	17.8
Jan	1	Deve	0.96	2.18	21.8	1.8	20.1
Jan	2	Mid	1.1	2.43	24.3	1.3	23
Jan	3	Mid	1.15	2.61	28.7	6.6	22.1
Feb	1	Late	1.15	2.51	25.1	15.5	9.7
Feb	2	Late	1.08	2.36	23.6	21.6	2
Feb	3	Late	1	2.89	23.1	14.5	8.7
Mar	1	Late	0.92	3.37	33.7	0.5	33.2
Mar	2	Late	0.83	3.58	35.8	0	35.8
Mar	3	Late	0.74	3.51	35.1	0	35
Total					333.2	70	263.1

*10 day period (1st to 10th; 11th to 20th; & 21st to 30th)

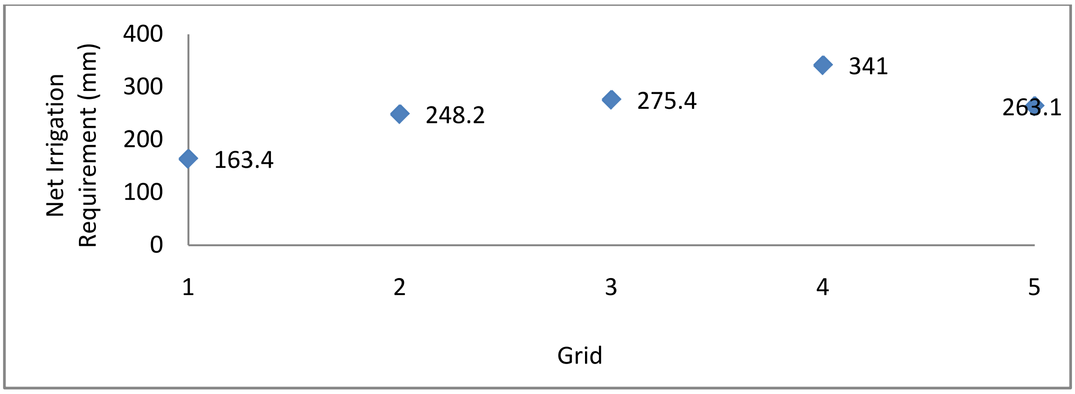

Figure 4.1: NIR of Wheat in Grid 1-5

A summary of results obtained on NIR of crops cultivated in rabi season is presented in Table 4. 6. Column 3 in the table shows the range of NIR in different grids while column 4 shows the average values.

Table 4.6: Net Irrigation Requirement of Crops in Rabi Season

S No	Crop	NIR (mm)	Average NIR (mm)
1	Lentil	105.9 – 236.7	178.04
2	Barley	112.5 - 252.4	187.4
3	Mustard	123.9 – 279	258.22
4	Wheat	163.4 – 341	205.44
5	Potato	130.4 – 310	224.46

4.2 Results of Optimization

Optimization is done using the multi objective genetic algorithm and a set of pareto optimal points are generated.

4.2.1 Results of optimization for rabi crops (75% Canal Water Availability)

The optimal areas allocated to the various crops (Lentil, Barley, Mustard, Wheat and Potato) for each run are presented in Tables 4.7 to 4.11. The corresponding values of net benefit obtained after cultivation of these crops and the food energy in calories are presented in Table 4.12. **Table 4.7: Run 1. Area in Hectare Obtained Under 75 % Canal Water Availability**

S No	Lentil	Barley	Mustard	Wheat	Potato
1	1.3635709	0.00089	279048.5	0.003248	0.017362
2	37916.334	17804.3	72853.72	107190.8	19654.16
3	8291.4174	3125.503	231885.9	24822.8	4678.894
4	13186.127	4028.444	206365.4	39131.24	6780.308
5	22215.084	8928.63	156173.7	63872.13	13086.84
6	11577.62	5370.719	221726.3	27564.28	6220.119
7	6617.0205	2188.821	259467.7	4088.936	5194.772
8	36960.313	17116.95	77758.65	104603.9	19439.99
9	39505.582	19080.67	51501.26	110370.9	22717.74
10	15306.652	6169.385	194146.6	44416.64	8748.872
11	22736.675	4543.229	161408.5	64465.22	11196.93

12	31101.295	5663.003	120509	87226.8	15101.48
13	1.3635709	0.00089	279048.5	0.003248	0.017362
14	26709.642	7940.861	135448.9	77732.98	13207.21
15	1.3616178	0.00089	279048.5	0.004045	0.01764
16	24196.906	6817.204	152185.3	67771.61	11980.26
17	3179.6137	1546.695	260284.1	9112.749	2002.482
18	34130.026	15928.23	93179.34	96663.49	17740.19
19	21828.174	9963.865	162536.2	54431.93	17665.14
20	15298.374	2883.662	199498.4	44226.38	7182.687
21	17303.342	8013.137	184816.6	48969.32	9100.656
22	39944.474	19409.53	22782.9	111212.7	32856.47
23	24972.555	5813.382	146485.6	73740.71	10960.23
24	29213.608	8597.791	112123.3	91428.23	16657.69
25	39728.659	19246.51	27092.57	110544.9	31755.97
26	33039.544	9627.381	90203.5	103454.1	18928.74
27	11559.353	3279.767	217270.2	33819.84	5015.328
Average	20982.314	7892.137	162772.2	59291.21	12143.45

Table 4.8: Run 2. Area in Hectare Obtained Under 75 % Canal Water Availability

S No	Lentil	Barley	Mustard	Wheat	Potato
1	0.222146	0.000356	279049.5	0.000588	0.036703
2	0.002048	0.142102	0.00011	222012	0.000471
3	0.026507	0.127069	33154.28	195619.2	0.00532
4	0.109301	0.073029	135980.7	113825.6	0.018127
5	0.05069	0.104001	40135.75	186791.1	0.01632
6	0.222146	0.000356	279049.5	0.000588	0.036703
7	0.198338	0.015835	249515.6	23466.26	0.033666
8	0.009655	0.199503	10694.57	213502.8	0.002183
9	0.161571	0.059141	173535.9	83847.99	0.03544
10	0.089116	0.087962	108412.8	135506.5	0.015945
11	0.14699	0.068699	157117.2	96729.89	0.036503
12	0.05413	0.185466	51403.32	180121.4	0.058687

13	0.167239	0.08953	147311.2	104599	0.041037
14	0.168024	0.094046	162964.5	92075.06	0.046483
15	0.214545	0.008969	266130.4	10253.98	0.042905
16	0.18638	0.048295	201065.4	61774.34	0.057949
17	0.113679	0.088455	120642.8	125788.9	0.023834
18	0.007484	0.138761	7367.987	216146.7	0.001548
19	0.187362	0.022724	235121.3	34949.24	0.031053
20	0.162613	0.06234	180886.5	75843.97	0.048867
21	0.226181	0.039703	211890.3	51756.75	0.050546
22	0.06921	0.115905	83933	155045.6	0.012497
23	0.056621	0.115435	73451.14	161198.2	0.01152
24	0.201519	0.048114	193050.4	68037.33	0.035559
25	0.089577	0.096514	98045.92	143853	0.021643
26	0.063712	0.142274	62939.28	171902.8	0.059755
27	0.229393	0.033585	257941	16652.1	0.052799
Average	0.127266	0.081784	141510.7	108937	0.030891

Table 4.9: Run 3. Area in Hectare Obtained Under 75 % Canal Water Availability

S No	Lentil	Barley	Mustard	Wheat	Potato
1	164796.8	149311.7	0.578025	0.426452	0.069488
2	106791.9	203897.8	0.469883	0.697751	0.067249
3	36742.88	266984.5	0.782514	0.789848	0.089214
4	14546.36	292015.7	0.064452	0.828208	0.010025
5	193176	122241.9	0.957566	0.61114	0.115558
6	208077.2	108019.3	0.749036	0.35968	0.093734
7	265093	51726.83	1.102859	0.233084	0.130452
8	118794.9	192602.2	0.492261	0.641611	0.067712
9	299590.7	20772.48	1.085264	0.136074	0.135095
10	175519.5	139127.5	0.613876	0.398048	0.072736
11	0.002523	305911.2	0.000446	0.8489	0.001471
12	288721.9	26612.81	0.778779	0.344901	0.0906
13	181504	133418.7	0.636613	0.385412	0.075744

14	284689.9	34959.99	1.035019	0.176134	0.129104
15	276185.3	43419.36	0.968472	0.145943	0.117364
16	133360.6	177299.1	0.698315	0.670802	0.102437
17	245421.9	71127.64	1.308155	0.411828	0.14924
18	308631.2	12389.8	1.094065	0.08184	0.133772
19	145082.3	167934	0.535496	0.518548	0.067071
20	93313.31	215731.5	0.74454	0.83815	0.048499
21	232300.3	84463.92	1.020624	0.179376	0.115482
22	61056.92	243390.4	0.524232	0.957881	0.044195
23	256420.9	60705.19	1.207201	0.267034	0.141736
24	2890.42	303156.7	0.013974	0.845133	0.003192
25	50514.71	256869.2	0.816929	0.998431	0.078789
26	156550.9	155659.5	0.376399	0.625632	0.083521
27	321993.5	0.000237	1.107073	0.00168	0.131815
Average	171176.6	142212.9	0.731928	0.497019	0.087604

Table 4.10: Run 4. Area in Hectare Obtained Under 75 % Canal Water Availability

S No	Lentil	Barley	Mustard	Wheat	Potato
1	1.023959	0.002292	279048.8	0.003496	0.001306
2	10737.42	88838.08	160758.8	18165.22	4322.518
3	6550.538	54807.64	205876.3	11420.34	2664.074
4	17741.06	133526.4	104563.3	23558.02	6562.806
5	25280.94	180921.5	45636.86	28496.99	9180.55
6	16624.77	123645.7	118255.2	21085.79	6027.958
7	22044.99	157697.2	76406.83	24156.34	7796.751
8	24121.48	150135.5	80497.55	24916.92	8324.004
9	3214.297	23386	248598.3	3917.363	1158.818
10	267.5366	2206.295	276111.1	451.1454	107.3495
11	18630.25	139115.8	97614.01	24140.49	6871.521
12	14211.2	116615.5	126681.2	21094.66	5980.332
13	24557.04	176192.1	52348	27273.16	8705.094
14	26348.44	188482	36847.24	28872.71	9319.154

15	8257.9	64371.85	193382.3	12722.14	3118.047
16	1.023959	0.002292	279048.8	0.003496	0.001306
17	3772.036	27211.53	243667.9	4501.788	1347.553
18	6298.137	45343.58	220129.6	7394.19	2217.321
19	20178.64	144857.6	92068.21	22875.87	7141.42
20	7114.218	50928.84	213496.8	7888.72	2515.107
21	18030.74	132321.3	107861.5	21540.29	6523.151
22	12045.04	65707.49	182753.8	15877.59	4243.979
23	1677.521	12253.2	263024.6	2078.01	591.5938
24	23912.21	170583.4	59396.65	26193.11	8438.342
25	10704.94	85000.29	166942.3	15776.03	3823.551
26	23640.56	169253.6	61197.7	26216.87	8358.668
27	2154.813	15639.41	258570.2	2704.139	768.1183
Average	12893.29	93297.85	157436.4	15678.44	4670.659

Table 4.11: Run 5. Area in Hectare Obtained Under 75 % Canal Water Availability

S No	Lentil	Barley	Mustard	Wheat	Potato
1	0.009432	2.353062	0.004187	222010.4	0.002072
2	3.754654	0.048753	279046.4	0.000706	0.019772
3	1.379497	1.051537	162336.1	92833.05	0.046888
4	1.958824	1.14954	145662.6	105979.9	0.044144
5	2.697956	0.782823	196278.6	65768.14	0.032375
6	2.345587	1.07706	219955.1	45729.23	0.209228
7	1.903738	0.913858	188387.1	72005.97	0.174832
8	3.222324	0.566095	239682.1	31310.41	0.267664
9	0.009432	2.353062	0.004187	222010.4	0.002072
10	0.870562	2.125282	60383.01	173654.3	0.36136
11	0.940775	1.781803	70752	165583.5	0.01197
12	0.298278	2.416103	22067.59	203211.5	0.155588
13	0.683166	2.174861	47244.35	184176	0.283183
14	1.003935	1.499751	106013.7	137541	0.031035
15	4.167929	0.174911	266354.2	10028.91	0.335389

16	3.754654	0.048753	279046.4	0.000706	0.019772
17	0.148943	2.193173	10548.27	213563.2	0.021163
18	3.435763	0.252554	255020.2	19018.4	0.043856
19	2.173692	1.046031	164192.3	91034.61	0.04853
20	1.069532	1.944582	86067.52	153401.9	0.251003
21	0.601032	1.723754	75092.05	162258.2	0.118673
22	4.685875	0.139328	273607.2	2897.668	0.025933
23	3.841364	0.632432	210236.6	54467.84	0.088748
24	2.37432	0.901346	173221.6	84175.28	0.271044
25	0.428343	2.163396	31491.08	196910.7	0.134376
26	4.581374	1.300823	253686.9	20039.16	1.150877
27	1.732132	0.316794	128632.5	119572.6	1.043026
Average	2.002708	1.227091	146111.3	105525.3	0.192392

Table 4.12: Pareto Optimal Sets Obtained After Optimization for 75% Canal Water Availability

S No	Run 1		Run 2		Run 3		Run 4		Run 5	
	Revenues	Calories	Revenues	Calories	Revenues	Calories	Revenues	Calories	Revenues	Calories
1	3927914682	1.60193	3.93E+09	0.269568	2803618719	1248944	3927914780	1.223398	2337338866	2342908
2	2938757270	1304742	2.34E+09	2342910	2407422460	1570426	3123640981	835858.6	3927913911	4.647612
3	3697221991	294526.2	2.53E+09	2064384	1913343079	1938529	3430309705	517841.9	3262419166	979682.8
4	3577127979	457932.2	3.11E+09	1201211	1784558691	2090978	2746242861	1218645	3166139044	1118424
5	3340723475	765354.1	2.53E+09	1971220	2995466333	1089081	2351426381	1616555	3455269679	694064.4
6	3653057649	343455.3	3.93E+09	0.269568	3096140978	1005073	2838776041	1120990	3577570743	482594.1
7	3847954306	67251.83	3.76E+09	247641.5	3471050368	670341.9	2555674570	1401811	3409853278	759892.8
8	2962769647	1271427	2.4E+09	2253111	2489408105	1503901	2610729892	1358596	3703456251	330428.7
9	2733812105	1349770	3.33E+09	884854.3	3715006678	489872.1	3721681653	211357.7	2337338866	2342908
10	3521196483	531716.5	2.95E+09	1430010	2876344649	1188852	3907939786	20759.68	2678212417	1832602
11	3380540073	740696.2	3.23E+09	1020798	1686338233	2173064	2699681380	1265571	2739192442	1747428

S No	Run 1		Run 2		Run 3		Run 4		Run 5	
	Revenues	Calories	Revenues	Calories	Revenues	Calories	Revenues	Calories	Revenues	Calories
12	3197048508	999158.1	2.62E+09	1900836	3616578441	518942.7	2889153898	1068377	2450054111	2144523
13	3927914682	1.60193	3.17E+09	1103841	2916797159	1155137	2392651215	1569126	2604042218	1943639
14	3244911762	909770.4	3.26E+09	971675.4	3614137531	573628.6	2287794173	1675473	2940306423	1451492
15	3927914676	1.608164	3.85E+09	108211.3	3558560154	624002.5	3346725001	601557.2	3854851583	105841.8
16	3324812466	793560	3.48E+09	651909.5	2580103369	1411838	3927914780	1.223398	3927913911	4.647612
17	3829976553	111169.9	3.02E+09	1327460	3341595114	785682.2	3688442390	245373.4	2396885284	2253763
18	3035695302	1175628	2.38E+09	2281012	3777446734	440654.5	3528099234	407751.5	3789943997	200708.2
19	3385746998	673516.9	3.68E+09	368822.1	2669345722	1358704	2661736317	1294834	3269622167	960704.5
20	3557911186	506059.9	3.34E+09	800387.4	2310674536	1639088	3484037921	453634.8	2826532028	1618877
21	3476091257	595207.1	3.53E+09	546193.1	3257408770	865422	2767797987	1189114	2765270680	1712335
22	2464651042	1363427	2.81E+09	1636208	2075484648	1798710	3296443777	648886.9	3881870298	30585.64

23	3299228638	850113.1	2.73E+09	1701137	3416324370	724211.8	3818879444	111000.3	3532786290	574811.8
24	3135020725	1062484	3.43E+09	718003.2	1705891323	2156800	2438695874	1517099	3324508054	888316.8
25	2501860928	1354765	2.89E+09	1518091	2023094829	1882412	3158117923	783251	2516364706	2078029
26	3031425613	1201513	2.7E+09	1814103	2739511909	1284617	2452766328	1507578	3781954375	211489.4
27	3630289690	394366.6	3.81E+09	175731.3	3869734646	367909.8	3927914780	1.223398	3069531393	1261863

The Pareto Optimal Sets as presented in Table 4.12 for various Run Numbers 1 to 5 are presented in graphical form in Figures 4.2 to 4.6 respectively. A summary of the outcome of optimal results are presented in Figure 4.7, Figure 4.8 and Table 4.13.

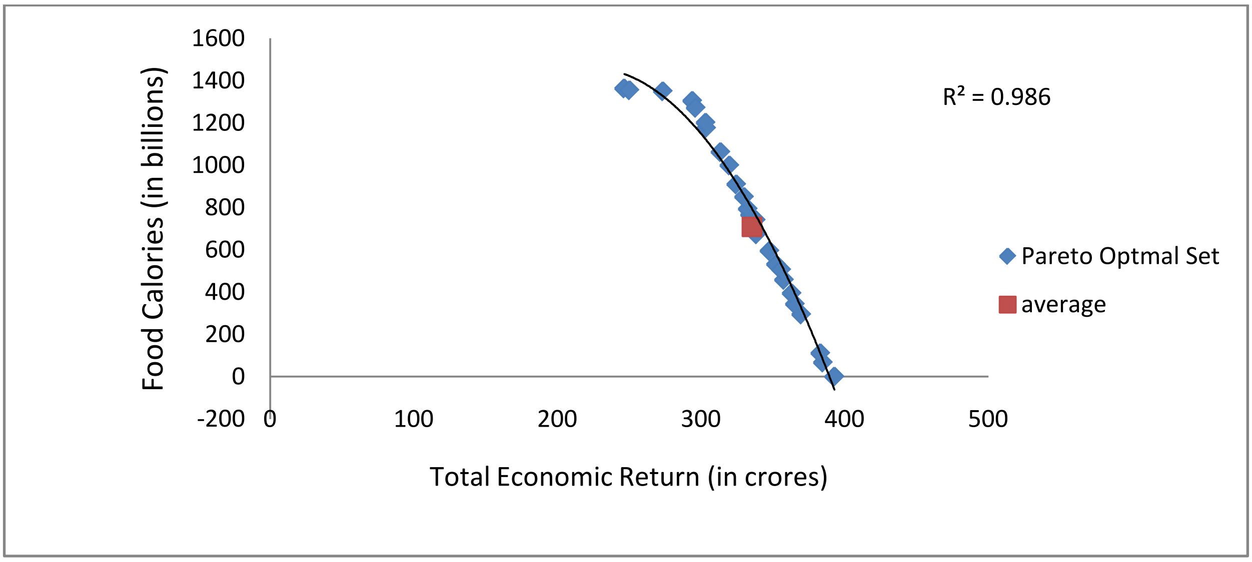

Figure 4.2: Pareto Optimal Set – Run 1 (75% Canal Water Availability)

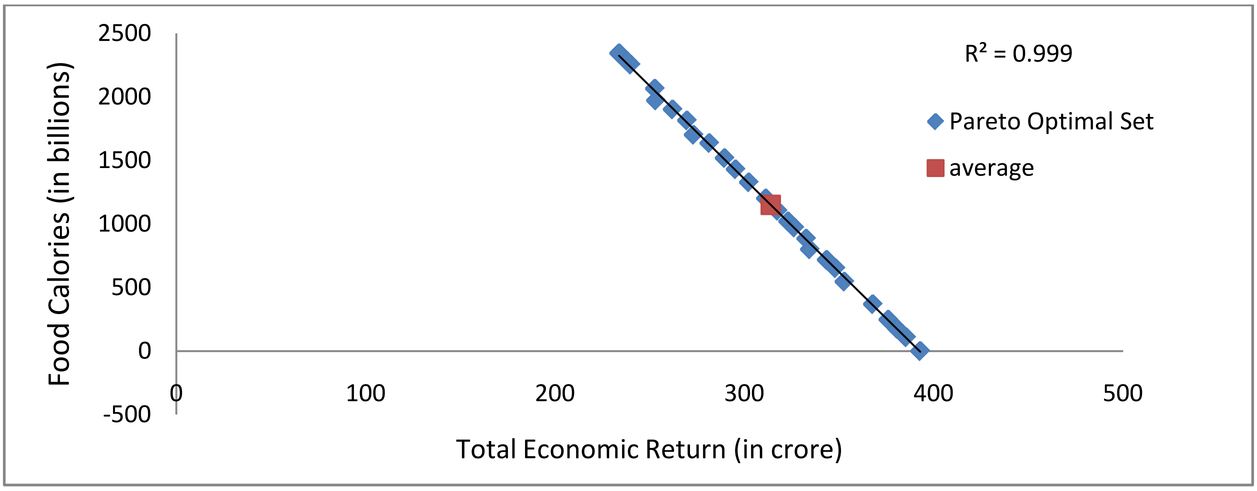

Figure 4.3:5 Pareto Optimal Set – Run 2 (75% Canal Water Availability)

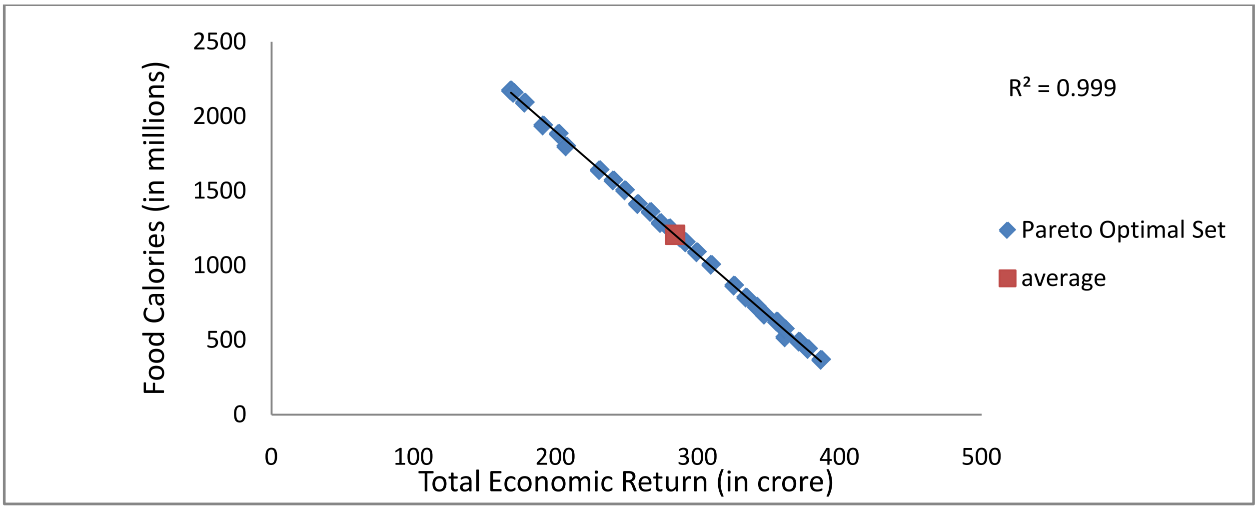

Figure 4.4: Pareto Optimal Set – Run 3 (75% Canal Water Availability)

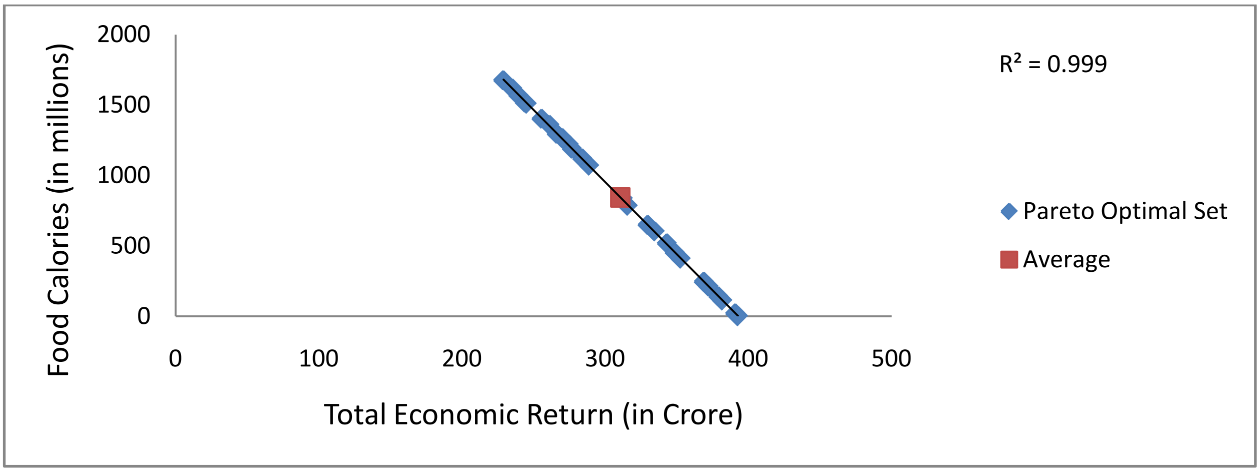

Figure 4.5: Pareto Optimal Set – Run 4 (75% Canal Water Availability)

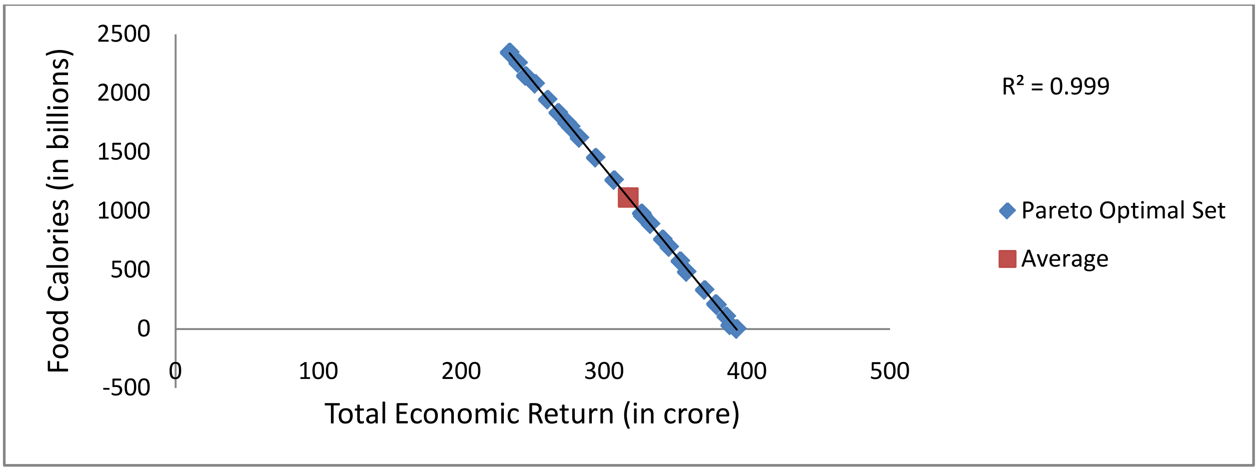

Figure 4.6: Pareto Optimal Set – Run 5 (75% Canal Water Availability)

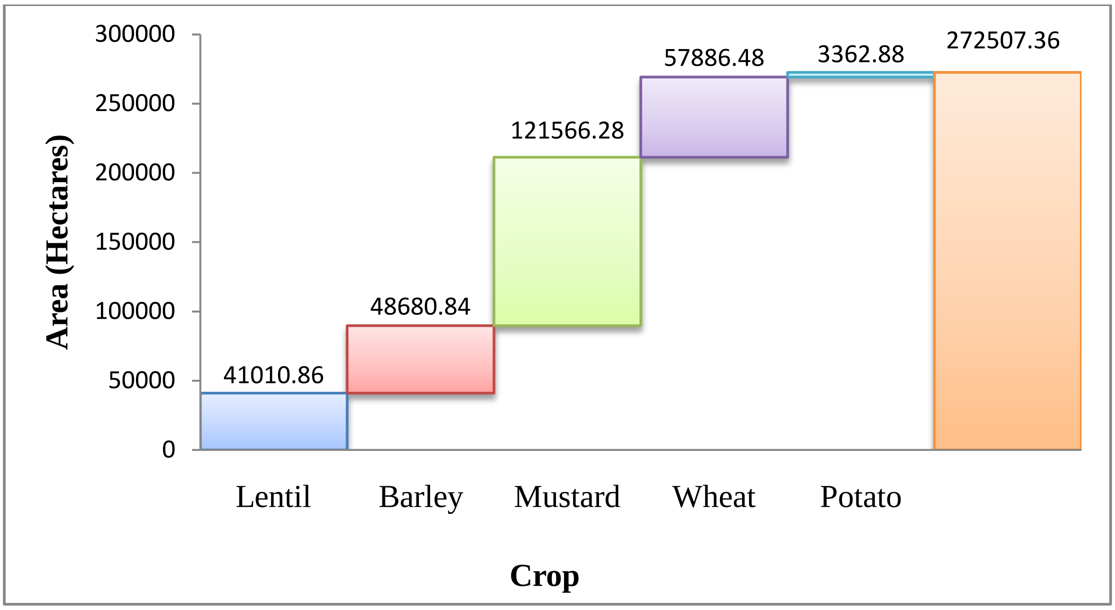

Figure 4.7: Area Allocation to Crops Under 75% Canal Water Availability

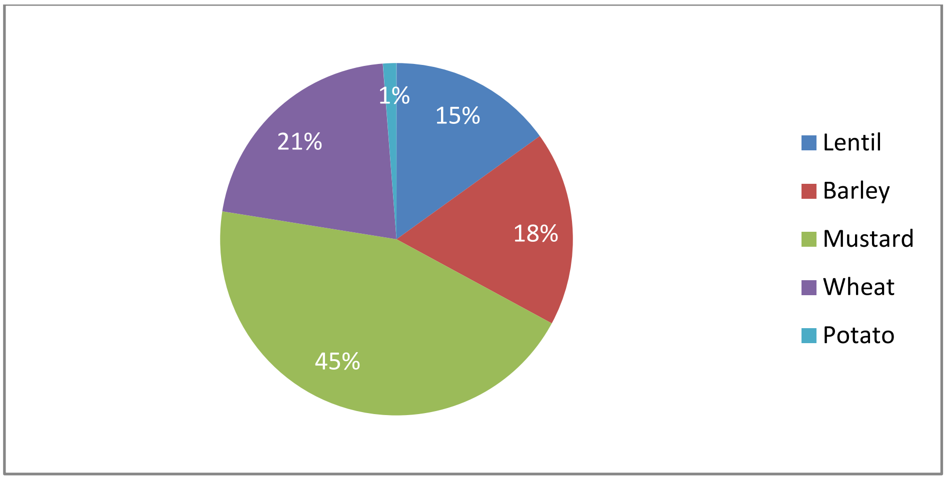

Figure 4.8: Percentage-wise Shares of Various Crops Under 75% Canal Water Availability

Table 4.13: Area, Net Benefit and Food Energy Obtained Under 75% Canal Water Availability

	Lentil	Barley	Mustard	Wheat	Potatoes	Total
Area	41010	48680	121566	57886	3362	272504
Net Benefit (INR in Crores)	49.28	26.83	171.12	60.94	3.95	312.13
Energy (in million Calories)	46,858	3,45,800	-	6,10,875	642	10,04,176

4.2.2 Results of optimization for rabi crops (100% Canal Water Availability)

For 100% canal water availability, the area allocated to the crops - Lentil, Barley, Mustard, Wheat and Potato for each run are presented in Table 4.14 to 4.18. The corresponding values of net benefit obtained after cultivation of these crops and the food energy in calories are presented in Table 4.19.

Table 4.14: Run 1- Area in Hectare Obtained Under 100% Canal Water Availability

S No	Lentil	Barley	Mustard	Wheat	Potato
1	1.586492	8.10E-07	372064.9	1.12E-06	9.70E-07
2	0.892405	0.999712	0.040626	296014.7	0.015284
3	122.1454	2.707459	153588.9	169305	0.534783
4	37.88367	2.118702	322842	39083.19	0.133454
5	36.29632	1.651046	231375.3	111303	0.272531
6	8.682325	0.143166	361999.6	3581.875	0.011643
7	38.01139	1.550869	307575.2	49005.35	0.64811
8	14.20165	0.441301	344406.1	19913.2	0.293981
9	0.892405	0.999712	0.040626	296014.7	0.015284
10	32.14372	1.982342	145340.1	178714.7	0.409537
11	51.87104	3.955575	72074.35	238071.1	1.101401
12	56.29294	2.507929	63919.42	244904.1	0.206897
13	61.04043	4.179239	85985.74	226852.1	0.377764
14	15.15289	1.40E+00	13558.08	2.85E+05	0.106097
15	26.9882	0.775888	240869.9	98987.66	0.151367
16	1.390225	0.894773	42304.96	262249	0.015056
17	65.28841	4.139441	80061.82	230410.8	0.384454
18	83.30203	2.462166	179468	151707.4	0.444346
19	15.98401	1.510375	20560.56	275824.9	0.343128
20	1.586492	8.10E-07	372064.9	1.12E-06	9.70E-07
21	26.66637	1.935494	111353.9	207114.2	0.262945
22	17.38842	0.839766	121732.8	199125.2	0.078325
23	23.01302	1.185528	98100.3	213298.9	0.233633
24	12.12614	0.286247	352063.6	15712.93	0.053485
25	48.53516	2.780829	272655.5	76927.68	0.258566
26	53.89493	1.434917	221641.6	119549.5	0.511627
27	137.01	3.213741	134349	188711.7	1.954971
Average	36.67654	1.707296	174887.3	155462.5	0.326617

Table 4.15: Run 2- Area in Hectare Obtained Under 100% Canal Water Availability

S No	Lentil	Barley	Mustard	Wheat	Potato
1	0.000324	407881	3.19E-05	1.547954	0.000281
2	43846.83	363986.5	0.212519	1.378105	0.028709
3	165088.7	250264.7	0.636902	0.878098	0.096989
4	429324.6	0.002504	1.506426	0.012282	0.115411
5	357169.6	68386.51	1.265813	0.240988	0.140384
6	206151.5	205714.3	0.769282	0.822104	0.116107
7	194644.1	221309.8	0.725026	0.820968	0.086971
8	279558.5	139545.3	1.081061	0.448917	0.106274
9	118488.2	294692.2	0.620308	0.789921	0.120316
10	149668.7	264971.4	0.520144	0.907611	0.087986
11	365293.9	59786.6	1.294075	0.234202	0.137608
12	59720.25	350333.7	0.264645	1.279003	0.080414
13	92285.6	318247.9	0.294671	1.186754	0.057513
14	415465.5	13166.9	1.46048	0.050086	0.156889
15	136883.6	273803.8	0.590673	0.935082	0.082355
16	429324.6	0.002504	1.506426	0.012282	0.115411
17	325301.5	96592.78	1.157017	0.242441	0.117958
18	104396.4	307774.5	0.566919	0.865567	0.10468
19	263402.7	155375.4	0.793022	0.364732	0.096248
20	388744.3	34112.97	1.172785	0.161691	0.11706
21	343072.1	80091.51	1.225662	0.187515	0.132245
22	79230.61	330797.4	0.299892	1.187921	0.048636
23	217322.9	196309.9	1.38049	0.210986	0.108638
24	379323.5	46910.79	1.297475	0.193424	0.191811
25	28527.26	380754	0.116425	1.47181	0.088793
26	294899.5	125077.2	0.861796	0.252243	0.032766
27	403264.9	22035.86	1.403566	0.185729	0.275415
Average	232237	185478.6	0.852723	0.624756	0.105329

Table 4.16: Run 3- Area in Hectare Obtained Under 100% Canal Water Availability

S No	Lentil	Barley	Mustard	Wheat	Potato
1	0.42166	1.35098	128992.5	192632.9	0.059023
2	0.271627	1.587177	86509.45	227103	0.037791
3	0.358924	1.431641	114441	204823.5	0.048036
4	0.002152	2.064135	0.000158	296014.7	0.000316
5	0.101634	1.886824	32539.72	270040.5	0.017295
6	1.168891	0.000375	372065.1	0.000682	0.145685
7	0.670949	0.886702	213176.4	126170.1	0.093662
8	0.257267	1.51859	95716.85	218157.9	0.037377
9	0.897827	0.486927	285094.8	69061.29	0.117588
10	0.974423	0.307369	315643.3	43489.38	0.124682
11	0.507337	1.115993	166188.1	163538.8	0.07408
12	0.324845	1.475801	105979.9	211302.4	0.044426
13	0.057749	1.946148	20701.04	279176.3	0.008331
14	1.061319	0.19185	337740	27256.81	0.134446
15	0.82507	0.598635	262088.3	87031.58	0.104518
16	0.625175	1.03931	180311.9	147039.1	0.070874
17	0.778818	0.679861	247537.9	98613.74	0.09872
18	0.916571	0.44926	291712.4	63806.38	0.11979
19	0.257483	1.61483	81397.22	231104.6	0.036085
20	1.122642	0.082337	357330.5	11700.18	0.140267
21	0.952462	0.376433	302957.3	54689.36	0.120127
22	0.026561	2.02264	7505.617	289999.3	0.003732
23	0.441718	1.277514	139192.3	184657.4	0.058205
24	0.470816	1.238277	149676.8	176745.2	0.066817
25	0.740166	0.760862	235917.8	107850.6	0.100274
26	0.622462	1.011068	197371	136953.5	0.07735
27	0.22526	1.672057	71102.15	239307.7	0.031559
Average	0.558585	1.0768	177736.6	154009.9	0.073002

Table 4.17: Run 4- Area in Hectare Obtained Under 100% Canal Water Availability

S No	Lentil	Barley	Mustard	Wheat	Potato
1	0.002005	1.521074	0.000513	296015.1	0.000595
2	429325.7	0.002499	0.753829	0.001398	0.00398
3	390024.1	0.174742	0.707612	26707.72	0.016182
4	320082.5	0.456927	0.740199	74913.86	0.13978
5	424011.9	0.021486	0.744678	3663.644	0.004278
6	127630.5	0.984839	0.352781	205616.8	0.05488
7	91160.69	1.250115	0.143817	233126.1	0.123882
8	341036.8	0.604811	0.635459	57491.55	0.254526
9	295950.2	0.649547	0.55798	91608.26	0.177791
10	429325.7	0.002499	0.753829	0.001398	0.00398
11	329125.9	0.408788	0.600502	68990.32	0.041416
12	178388.1	0.845549	0.324979	170382.8	0.025744
13	152179.8	1.066441	0.321629	190938.3	0.110177
14	284519.8	0.69934	0.523011	97688.43	0.162793
15	133754.9	1.284561	0.211114	203553.7	0.156821
16	225765.6	0.76656	0.418878	138636.7	0.087019
17	33033.85	1.52747	0.131085	272299.2	0.153869
18	103257.4	1.422472	0.608479	224794.5	0.376006
19	261875.1	0.748355	0.501962	115150.6	0.161766
20	379694.7	0.25351	0.642698	34155.9	0.065748
21	162602.8	1.215073	0.61674	183844.2	0.348836
22	42831.62	1.794992	0.628419	266452.9	0.569948
23	0.002005	1.521074	0.000513	296015.1	0.000595
24	358939.4	0.472214	0.634545	46699.63	0.489128
25	68126.25	1.467089	0.326117	248696.1	0.138927
26	206259.7	1.055111	0.278269	153577.8	0.281739
27	83055.39	2.167459	0.797122	237149.1	1.157967
Average	216739.2	0.903133	0.47988	145858.1	0.189199

Table 4.18: Run 5- Area in Hectare Obtained Under 100% Canal Water Availability

S No	Lentil	Barley	Mustard	Wheat	Potato
1	0.011353	171530.2	0.008233	171530.3	0.002828
2	0.38301	139406.5	49295.66	155191.5	0.324731
3	0.582589	22851.31	288977.6	49142.99	0.309133
4	0.522326	96165.86	143467	111655.5	0.371275
5	0.391961	127631.6	75839.57	141236.2	0.135363
6	0.710346	7960.954	354389.7	8276.531	0.34584
7	1.165397	32508.5	229280.7	89036.93	0.336777
8	0.357178	47787.68	171720.3	122771.6	0.200841
9	0.754535	0.000232	372065.3	0.043008	0.295755
10	0.839416	27100.08	260253	63877.14	0.363605
11	0.770951	25254.9	272200	60565.6	0.334986
12	0.547718	79469.89	183583.6	91958.91	0.351476
13	0.304467	145973.1	21908.81	170566.7	0.157461
14	0.959937	12863.76	332667.5	20697.41	0.492935
15	0.725918	42440.27	251205.5	64895.66	0.31431
16	0.130862	146444.9	46943.23	151553.7	0.066912
17	0.814009	4387.308	358628.3	7059.033	0.388761
18	0.011353	171530.2	0.008233	171530.3	0.002828
19	0.404126	38289.15	190660.6	114531	0.212852
20	0.877953	16159.49	315181.2	31274.19	0.412728
21	0.318296	136107	61943.46	147632.2	0.237031
22	0.948196	12128.5	334919.4	19514.4	0.481664
23	0.097144	164602.5	10630.94	168006.7	0.051459
24	0.624121	97627.43	121883.6	127677.4	0.23474
25	0.581804	108705.3	103242.7	134426.7	0.33881
26	0.105634	126847.1	82591.97	135985.9	0.175858
27	0.845216	18700.1	298702.7	44266.16	0.384335
Average	0.547623	74832.36	182673.4	95365.21	0.271307

Table 4.19: Pareto Optimal Set Obtained After Optimization for 100% Canal Water Availability

S No	Run 1		Run 2		Run 3		Run 4		Run 5	
	Revenues	Calories	Revenues	Calories	Revenues	Calories	Revenues	Calories	Revenues	Calories
1	5.24E+09	1.812744	2.25E+09	2897419	3.84E+09	2032879	3.12E+09	3123879	2.75E+09	3028644
2	3.12E+09	3123872	2.53E+09	2635711	3.61E+09	2396646	5.16E+09	490547.5	3.1E+09	2628029
3	3.95E+09	1786847	3.36E+09	1966408	3.77E+09	2161528	4.97E+09	727491.2	4.71E+09	680935.6
4	4.96E+09	412506	5.16E+09	490546.5	3.12E+09	3123878	4.64E+09	1156301	3.73E+09	1861428
5	4.43E+09	1174642	4.67E+09	893891.6	3.3E+09	2849770	5.13E+09	523138.9	3.26E+09	2397113
6	5.13E+09	37810.72	3.61E+09	1696859	5.24E+09	1.373254	3.7E+09	2315726	5.12E+09	143894.7
7	4.85E+09	517211.4	3.56E+09	1794494	4.33E+09	1331489	3.55E+09	2564366	4.34E+09	1170540
8	5.06E+09	210164.8	4.13E+09	1310695	3.64E+09	2302247	4.7E+09	996385.4	3.97E+09	1635080
9	3.12E+09	3123872	3.05E+09	2228754	4.74E+09	728813.1	4.52E+09	1304906	5.24E+09	1.374128
10	3.93E+09	1886039	3.26E+09	2053258	4.9E+09	458949.8	5.16E+09	490547.5	4.49E+09	866607.8
11	3.52E+09	2512469	4.72E+09	842084.5	4.06E+09	1725845	4.68E+09	1104122	4.61E+09	818553.4
12	3.48E+09	2584573	2.65E+09	2556863	3.72E+09	2229900	3.94E+09	2001894	3.99E+09	1534968
13	3.6E+09	2394085	2.86E+09	2366148	3.23E+09	2946181	3.84E+09	2188874	2.91E+09	2836930
14	3.19E+09	3008752	5.07E+09	568243.2	5.04E+09	287645.6	4.45E+09	1356010	4.97E+09	309800.8
15	4.43E+09	1044660	3.15E+09	2101392	4.61E+09	918455.6	3.75E+09	2300954	4.45E+09	986325.9
16	3.36E+09	2767540	5.16E+09	490546.5	4.09E+09	1551722	4.17E+09	1721008	3.06E+09	2639636

S No	Run 1		Run 2		Run 3		Run 4		Run 5	
	Revenues	Calories	Revenues	Calories	Revenues	Calories	Revenues	Calories	Revenues	Calories
17	3.55E+09	2431645	4.44E+09	1057844	4.52E+09	1040683	3.26E+09	2911348	5.15E+09	105660.9
18	4.12E+09	1601092	2.95E+09	2305584	4.78E+09	673357.4	3.61E+09	2490264	2.75E+09	3028644
19	3.19E+09	2910828	4.02E+09	1404685	3.58E+09	2438875	4.36E+09	1514416	4.1E+09	1480643
20	5.24E+09	1.812744	4.86E+09	686504.1	5.15E+09	123474.7	4.92E+09	794290.6	4.85E+09	444829.6
21	3.75E+09	2185735	4.56E+09	960930.2	4.84E+09	577144.4	3.89E+09	2125920	3.18E+09	2524817
22	3.81E+09	2101408	2.78E+09	2440378	3.16E+09	3060397	3.32E+09	2860848	4.99E+09	292093.4
23	3.63E+09	2250993	3.69E+09	1642812	3.9E+09	1948712	3.12E+09	3123879	2.83E+09	2942249
24	5.12E+09	165835.5	4.82E+09	766650.3	3.97E+09	1865213	4.81E+09	902952.1	3.6E+09	2040891
25	4.65E+09	811898.5	2.44E+09	2737316	4.46E+09	1138162	3.44E+09	2702359	3.47E+09	2190809
26	4.38E+09	1261686	4.23E+09	1225447	4.22E+09	1445288	4.1E+09	1856397	3.29E+09	2336134
27	3.88E+09	1991667	4.97E+09	617305.3	3.52E+09	2525443	3.49E+09	2597566	4.77E+09	599982

The Pareto Optimal Sets as presented in Table 4.19 for various Run Numbers 1 to 5 are presented in graphical form in Figures 4.9 to 4.13 respectively. A summary of the outcome of optimal results are presented in Figure 4.14 and Table 4.20.

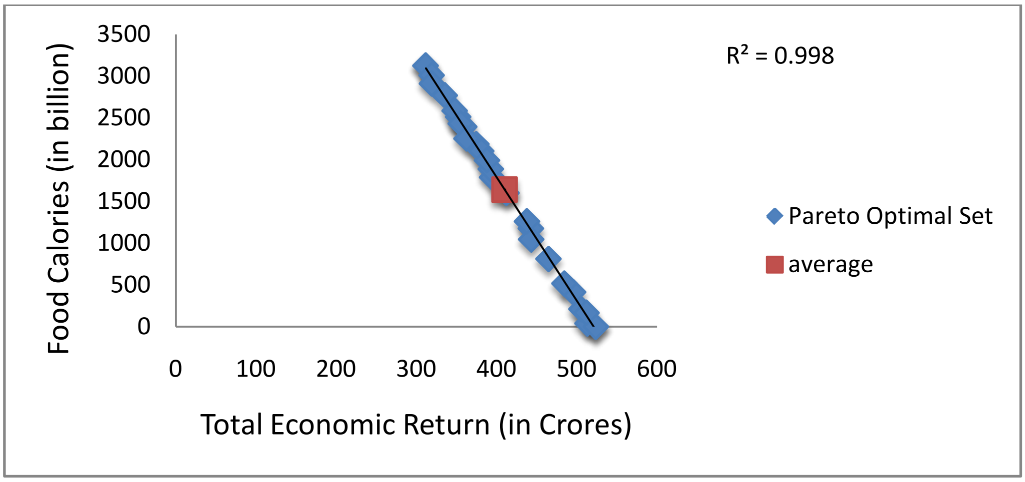

Figure 4.9: Pareto Optimal Set – Run 1 (100% Canal Water Availability)

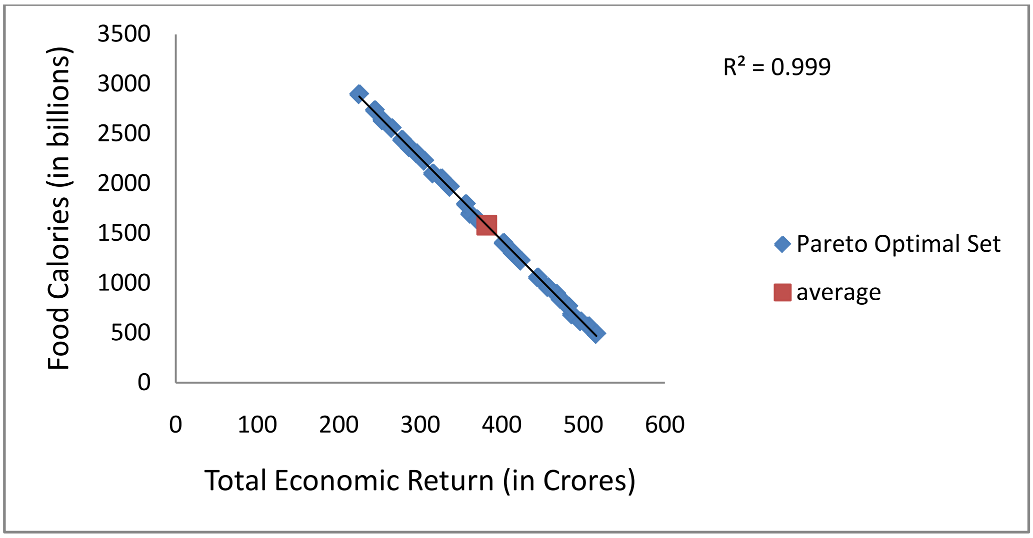

Figure 4.10: Optimal Set – Run 2 (100% Canal Water Availability)

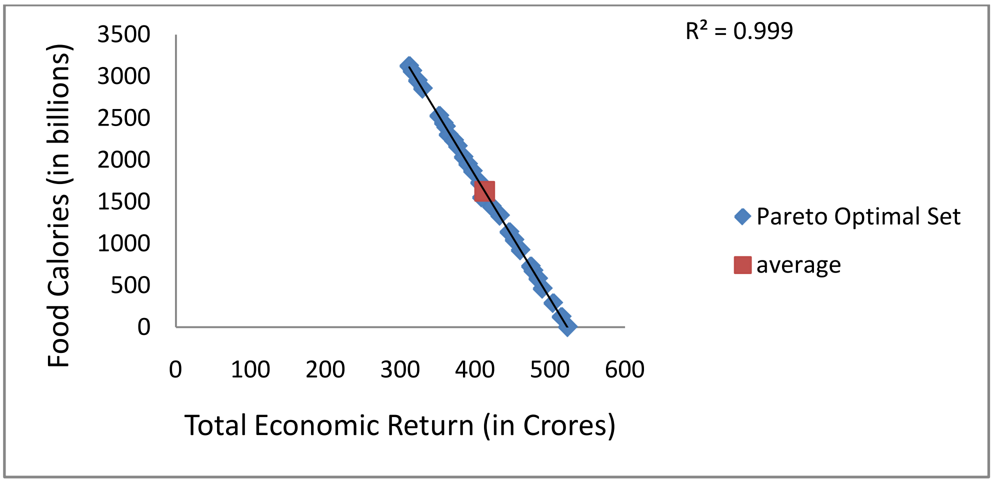

Figure 4.11: Optimal Set – Run 3 (100% Canal Water Availability)

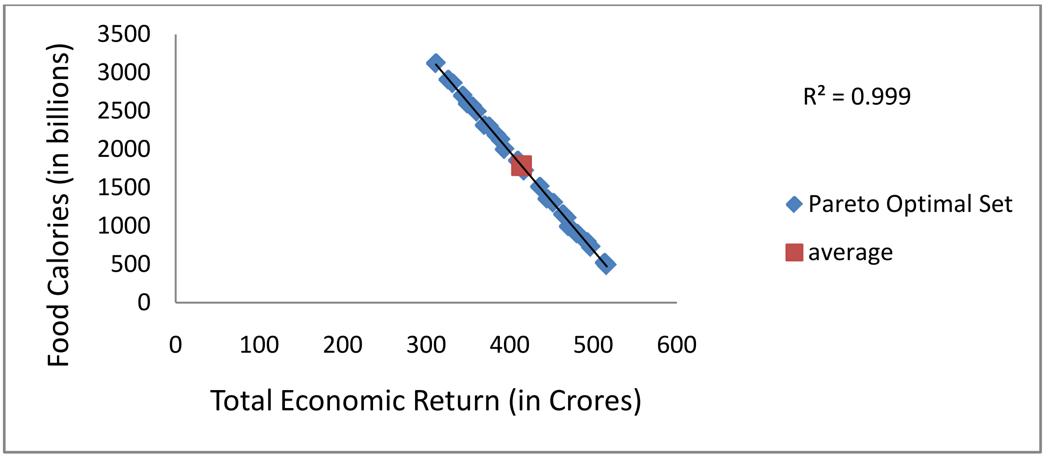

Figure 4.12: Optimal Set – Run 4 (100% Canal Water Availability)

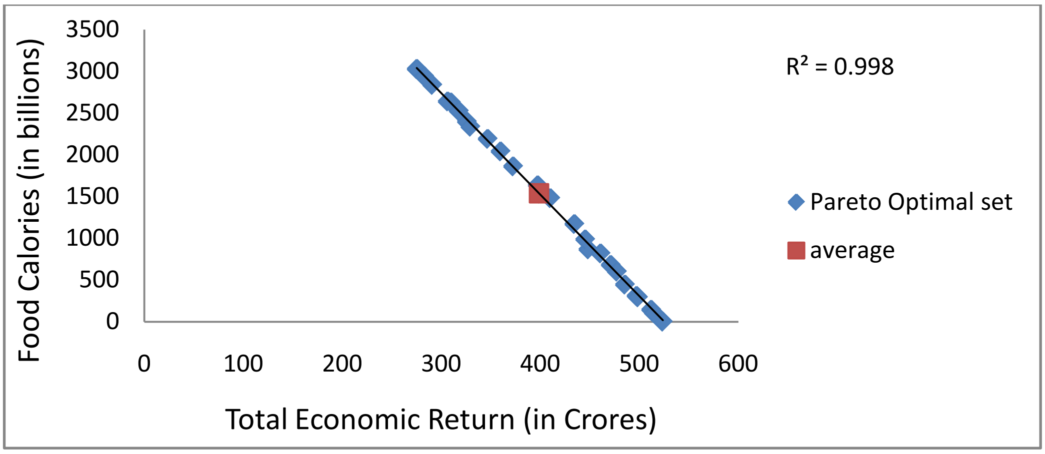

Figure 4.13: Optimal Set – Run 5 (100% Canal Water Availability)

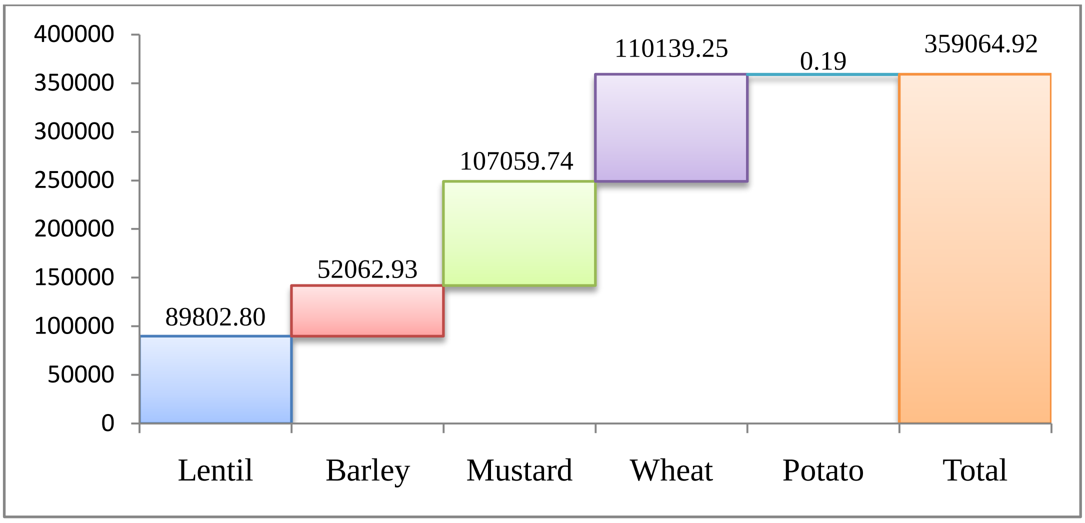

Figure 4.14: Area Allocation to Crops Under 100% Canal Water Availability

Table 4.19: Area, Net Benefit and Food energy obtained under 100% canal water availability

	Lentil	Barley	Mustard	Wheat	Potatoes	Total
Area	89802	52062	107059	110139	0.19	359062
Net Benefit (INR in Crores)	107.92	28.70	150.70	115.95	0.000223	403.27
Energy (in million Calories)	102608	369825	-	1162305	0.036282	1634737

4.3 Discussion

The area allocated to mustard in 100% canal water availability is 1,07,059 hectares and for 75% canal water availability, area allocation to mustard is 1,21,566 hectares. For both the cases i.e 100% canal water availability and 75% canal water availability, mustard is the most dominating crop followed by wheat. Wheat holds the second largest share in area allocation in both the cases but its magnitude is decreased considerably and nearly halved (1,10,139 hectares in 100% canal water availability and 57,886 hectares in 75% canal water availability), when in deficit irrigation.

The area allocation to Lentil is 89,802 hectare in 100% canal water availability and 41,010 hectare in 75% canal water availability. Like wheat, the area allocation to lentils is also reduced considerably and hence it can be contemplated that Lentil and Wheat are the most sensitive to deficit in irrigation. Potato in both cases has got least share in area allocation because of the lower yield per hectare and hence lowest calorie contribution per hectare. The area allocation to barley is 52,062 hectares in 100% canal water availability and 48,680 hectares in canal water availability.

There is very small decrease in the area allocation when in deficit irrigation so it can be contemplated that barley is the least sensitive to deficit in irrigation or decrease in water availability. The results obtained by the optimization under two different conditions of irrigation are presented in Table 4.20.

Table 4.20: Comparison of Net Benefit and food energy under different conditions of Irrigation

	Rabi (75% Canal Water Availability)	Rabi (100% Canal Water Availability)
Net Benefit (in Rs)	312,13,02,675	403,27,43,561
Calories Obtained (in million calories)	1004176	1634737
Reduction in net benefit in economic terms	22.60 %	
Net Reduction in Food Energy	38.57 %	

It can be seen from the results that the decrease in 25% canal water availability results in 22.6 % decrease in Net benefit in economic terms and 38.57 % decrease in total calories obtained by the agriculture. Hence in case of deficit irrigation, the production of food energy is reduced considerably as compared to net economic return.

5. Summary & Conclusion

An attempt is made to allocate the available land resource to a multi-crop system in such a manner that maximum return in economic terms can be achieved along with producing maximum number of calories of food energy that is obtained from the cultivation of several crops using the canal water as a source of irrigation.

Firstly, reference Evapotranspiration is calculated by FAO Penman Monteith method using climatic data and then in combination with the soil and crop characteristics data, net irrigation requirement (NIR) of various crops in the multi crop system is determined. Other important parameters such as costs and calories of food energy obtained from cultivation of various crops are determined using secondary data. After studying several optimization techniques, Genetic Algorithm is selected for the multi objective optimization. MATLAB 2013a is used for optimization and computer implementation of Genetic Algorithm. A set of Pareto optimal set is obtained which is later used to determine the optimal cropping pattern.
From the multi objective optimization done for a multi crop system in rabi season under two different conditions of canal water availability, following conclusions can be made.

1. The crops, Wheat and Lentil, are most sensitive to a change in water availability.
2. Barley is the least sensitive crop to a change in water availability.
3. For a reduction in canal water availability, food energy and the net benefit also suffers reduction. However, the percentage reduction in food energy is very high as compared to the net economic return.

References

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration: Guidelines for computing crop requirements. Irrig. Drain. Pap. No. 56, FAO 300. doi:10.1016/j.eja.2010.12.001
Cavero Jose, Inma Farre, Philippe Debaeke and Jose M. Facib, Simulation of Maize Yield under Water Stress with the EPICphase and CROPWAT Models. Agronomy Journal, Vol. 92 No. 4, p. 679-690

Droogers, P., Allen, R.G., 2002. Estimating reference evapotranspiration under. Irrig. Drain. Syst. 16, 33–45. doi:10.1023/A:1015508322413

FAO, 2014. The Water-Energy-Food Nexus - A new approach in support of food security and sustainable agriculture. Food Agric. Organ. United Na 1–11. doi:10.1039/C4EW90001D

Zhiming Feng, Liu Dengwei , Zhang Yuehong. Water requirements and irrigation scheduling of spring maize using GIS and CropWat model in Beijing-Tianjin-Hebei region. Chinese Geographical Science, March 2007, Volume 17, Issue 1, pp 56–63

Holland J., 1975. Adaption in Natural and Artificial Systems, University of Michigan Press, Ann Arbor, MI,.

Kuo, S.-F., Merkley, G.P., Liu, C.-W., 2000. Decision Support for Irrigation Project Planning Using a Genetic Algorithm. Agric. Water Manag. 45, 243–266. doi:10.1016/S0378-3774(00)00081-0

Mainuddin, M., Das Gupta, A., Onta, P.R., 1997. Optimal crop planning model for an existing groundwater irrigation project in Thailand. Agric. Water Manag. 33, 43–62. doi:10.1016/S0378-3774(96)01278-4

Md. Azamathulla, H., Wu, F.-C., Ghani, A.A., Narulkar, S.M., Zakaria, N.A., Chang, C.K., 2008. Comparison between genetic algorithm and linear programming approach for real time operation. J. Hydro-environment Res. 2, 172–181. doi:10.1016/j.jher.2008.10.001

Pathak M. D., 1991. Rice Production In Uttar Pradesh, Wiley Eastern Limited,.

Naresh, R. K., Dhaliwal, S. S., Kumar, D., Tomar, S. S., Misra, A. K., Singh, S. P., Kumar, P., Kumar, V. and Gupta, R. K., 2014. Tillage and rice-wheat cropping systems influences on soil physical properties: Water balance and wheat yield under irrigated conditions, Vol.9 (32), pp. 2463-2474

Prasad, A.S., Umamahesh, N. V., Viswanath, G.K., 2006. Optimal Irrigation Planning under Water Scarcity. J. Irrig. Drain. Eng. 132, 228–237. doi:10.1061/(ASCE)0733-9437(2006)132:3(228)

Raghavan V.V., and Agarwal, B., 1987. Optimal Determination of User Oriented Cluster:

An application for the reproduction plan, Genetic Algorithms and its applications, Proc. 2nd Intl. conf. on genetic algorithm, 246-241

Reddy, M.J., Kumar, D.N., 2006. Optimal reservoir operation using multi-objective evolutionary algorithm. Water Resour. Manag. 20, 861–878. doi:10.1007/s11269-005-9011-1

Sarker, R.A., Talukdar, S., Haque, A.F.M.A., 1997. Determination of optimum crop mix for crop cultivation in Bangladesh. Appl. Math. Model. 21, 621–632. doi:10.1016/S0307-904X(97)00083-8

Sethi, L.N., Kumar, D.N., Panda, S.N., Mal, B.C., 2002. Optimal crop planning and conjunctive use of water resources in a coastal river basin. Water Resour. Manag. 16, 145–169. doi:10.1023/A:1016137726131

Singh, A., Panda, S.N., 2012. Development and application of an optimization model for the maximization of net agricultural return. Agric. Water Manag. 115, 267–275. doi:10.1016/j.agwat.2012.09.014

Surendran, U., Sushanth, C.M., Mammen, G., Joseph, E.J., 2015. Modelling the Crop Water Requirement Using FAO-CROPWAT and Assessment of Water Resources for Sustainable Water Resource Management: A Case Study in Palakkad District of Humid Tropical Kerala, India. Aquat. Procedia 4, 1211–1219. doi:10.1016/j.aqpro.2015.02.154