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Irrigation Planning using Genetic Algorithms

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Abstract. The present study deals with the application of Genetic Algorithms (GA) for irrigation planning. The GA technique is used to evolve efficient cropping pattern for maximizing benefits for an irrigation project in India. Constraints include continuity equation, land and water requirements, crop diversification and restrictions on storage. Penalty function approach is used to convert constrained problem into an unconstrained one. For fixing GA parameters the model is run for various values of population, generations, cross over and mutation probabilities. It is found that the appropriate parameters for number of generations, population size, crossover probability, and mutation probability are 200, 50, 0.6 and 0.01 respectively for the present study. Results obtained by GA are compared with Linear Programming solution and found to be reasonably close. GA is found to be an effective optimization tool for irrigation planning and the results obtained can be utilized for efficient planning of any irrigation system.

Key words: cropping pattern, genetic algorithms, irrigation planning, linear programming

1. Introduction

Need for an efficient integrated management tool for an irrigation system is keenly felt due to growing demand for agricultural products, escalating cost of supplying water for the fields and stochastic nature of water resources. Due to dwindling supply of water for irrigation, the profit conscious irrigators like to allocate the available water among the competing crops to maximize the benefits. The allocation of water is required to be optimized over time, among the crops and also among the competing units of the same crop simultaneously. To meet these requirements, mathematical models and newer irrigation management methodologies are required for optimum irrigated area planning.

Genetic Algorithms (GA) possess several characteristics that answer the above planning problems and make them preferable to classical optimization methods. Genetic Algorithms are search procedures based on the natural genetics and natural selection. They combine the concept of the survival of fittest with genetic operators extracted from nature to form a robust search mechanism. Goldberg (1989) identified the following differences between GAs and the traditional optimization methods:

- GAs work with coding of the parameter set but not with the parameters themselves.
- GAs search from a population of points, not a single point.
- GAs use objective function information, not derivatives or other auxiliary knowledge.
- GAs use probabilistic transitions rules, not deterministic rules.

Any nonlinear optimization problem without constraints is solved using genetic algorithms involving basically three tasks, namely, coding, fitness evaluation and genetic operation. The decision variables for the given optimization problem are first identified. These variables are then coded using binary coding into string like structures called chromosome. The length of the chromosome depends on the desired accuracy of the solution. The decision variables need not necessarily have the same sub string length (Deb, 1995). Corresponding fitness function is next derived from the objective function and is used in successive genetic operations. If the problem is for maximization, fitness function is taken as directly proportional to the objective function. The fitness function value of a string is known as the string's fitness. Once the fitness of each string is evaluated, the population is operated by three operators, reproduction, crossover and mutation for creating new population of points. In reproduction, good strings are selected to form a mating pool. In the present study Roulette wheel simulation is used for selection of good strings. The newly created population is further evaluated and tested for termination to decide the maximum number of generations. If the termination criterion is not met, the population is iteratively operated further by the above three operators and evaluated. One cycle of these operations and its subsequent evaluation is known as a generation. This process is continued until termination criterion of preset maximum number of generations is met. If the problem is constrained, it is converted into an unconstrained problem by using penalty function method. In this process, the solution falling outside the restricted solution region is considered at a high penalty. This penalty forces the solution to adjust itself in such a way that after some generations it will fall into the restricted solution space. In penalty function method, a penalty term, corresponding to the constraint violation, is added to the objective function. Bracket operator penalty term is generally used.

$$F_i = f(x) + \in \sum_{j=1}^{k} \delta_j (\phi_j)^2 \tag{1}$$

where F_i is fitness value, $f(x)$ is objective function value, k is total number of constraints, $\in$ is –1 for maximization and +1 for minimization, δ_j is penalty coefficient and ϕ_j is amount of violation. Once the problem is converted into an unconstrained problem, rest of the procedure remains the same. A detailed description of genetic algorithms is given by Deb (1999).

In the present study, genetic algorithms and irrigation planning are integrated for evolving optimum cropping pattern and reservoir operation policies for the case study of Sri Ram Sagar Project, Andhra Pradesh, India. The results are compared with those obtained using Linear Programming (LP) method, to assess the relative validity of both the models for a real world planning problem.

2. Literature Review

Tang and Mays (1998) applied genetic algorithms to optimal operation of soil aquifer treatment (SAT) systems for finding optimal water application time and drying time to maximize infiltration for a predetermined starting influent rate of waste water. They concluded that GA-SAT model performs better compared to the successive approximation linear quadratic regulator algorithm. Chang and Chen (1998) applied two types of genetic algorithms, namely, real-coded and binary-coded and applied to the optimization of a flood control reservoir model. It is observed that both the genetic algorithms are more efficient and robust than the random search method. They however observed that the real-coded GA was performing better in terms of efficiency and precision compared to the binary-coded GA. Wardlaw and Sharif (1999) evaluated several formulations of a genetic algorithm for four-reservoir, deterministic, finite-horizon problem. They also considered a nonlinear four-reservoir problem, one with extended time horizons and a complex ten-reservoir problem. They concluded that genetic algorithm approach is more robust. Hilton and Culver (2000) compared two methods – additive penalty method (APM) and multiplicative penalty method (MPM) – for constraint handling within the genetic algorithm framework. They concluded that MPM is a more robust method. Sharif and Wardlaw (2000) presented genetic algorithm approach for optimization of multireservoir systems for a case study in Indonesia and its results were compared with those of discrete differential dynamic programming. They concluded that genetic algorithm results are closer to the optimum. Wu and Simpson (2001) applied messy genetic algorithm for optimal design and rehabilitation of a water distribution system by examining two benchmark problems. They found that number of design trials required for the messy genetic algorithm are fewer than for the other genetic algorithms. Gentry *et al.* (2001) applied genetic algorithm in combination with a numerical modeling technique to determine both the spatial distribution and the flux represented by the accretion component of the groundwater flow equation. Yoon and Shoemaker (2001) applied a real-coded genetic algorithm (RGA) coupled with two newly developed operators: directive recombination and screened replacement for an in-situ bioremediation of ground water. They concluded that RGA performs better than the binary-coded GA. Nicklow *et al.* (2003) developed an optimal control methodology for minimizing sediment aggradation and degradation. The simulation model, HEC-6 is used to solve the governing hydraulic and sediment constraints, while the genetic algorithm is used to solve the overall control problem. The methodology is validated with a hypothetical and a real case study proving the practical utility of the methodology as a decision-making tool for sedimentation control. Similar studies were reported by Mohan (1997) for estimating the parameters of two nonlinear Muskingum routing models and by Reddy (1996) for land grading design for irregular fields.

Lakshminarayana and Rajagopalan (1977) used Linear Programming model for maximizing the irrigation benefits for Bari Doab basin in North India. Maji and Heady (1980) developed an optimal cropping pattern and reservoir operation policy for Mayurakshi irrigation project, India, to maximize the net benefits by considering the average inflows and chance constrained inflows by assuming gamma distribution. Castillo *et al.* (1997) proposed a methodology consisting of combination of linear programming (LP) for maximization of net returns of the farmers and simulation model to study the performance of the system. This methodology was applied to the case study of Fuerte-Carrizo irrigation system in northwest Mexico. They concluded that the methodology proved to be a useful tool for operation of the irrigation system. Loucks *et al.* (1981) discussed the micro level irrigation planning with a detailed example. Paudyal and Gupta (1990) solved a complex problem of irrigation management in Tinao river basin, Nepal, by multilevel LP models. The problem consisted of determining the optimal cropping pattern in various sub areas of the river basin, optimal design capacities of irrigation facilities including surface and ground water resources, and the optimal water allocation policies for conjunctive use to obtain a high level efficiency. Surface water diversion, ground water withdrawal and recharge and alternative operational scenarios were analyzed. Carvallo *et al.* (1998), developed an optimization model for determination of optimum cropping pattern in irrigated agriculture. Decision variables were the cultivated areas in each soil type of the farm. The objective function was based on the crop production, irrigation technology used and value of the products. Sensitivity analysis of the optimal solution of land, labour and water resources was conducted. They concluded that water availability affects distribution and area of crops. Garg and Ali (1998) developed two level optimization (LP) model for a case study of Dadu canal command of the lower Indus basin. The results showed an overall increase of 40% in the crop intensity and 38% in benefits over the existing ones. Kumar *et al.* (1998) presented an optimization model for a case study of minor irrigation scheme. They concluded that a 50% increase in the cropped area is possible compared to the intensive irrigation approach. Similar studies were also reported in Vedula and Nagesh Kumar (1996) and Mohammadi (1998). Sethi *et al.* (2002) developed groundwater balance model and linear programming based management model to determine optimum cropping pattern and groundwater allocation from private and government tube wells according to different soil types (saline and non-saline), type of agriculture (rainfed and irrigated) and seasons (monsoon and winter). The methodology was applied to a case study of a coastal river basin in Orissa State, India, and was found satisfactory. Kuo *et al.* (2000) used genetic algorithm based model for irrigation project planning for a case study of Delta, Utah, for maximization of economic benefits for a command area. They

Table I. Salient features of Sri Ram Sagar project

Type of Dam	Gravity
Length of Earth Dam	13.640 Km
Length of Masonry Dam	0.958 Km
Maximum height of Masonry Dam	42.67 m
Gross Storage Capacity	3173 Mm^3
Live Storage Capacity	2300 Mm^3
Full Reservoir Level (FRL)	332.5 m
Water Spread Area at FRL	434.8 Mm^2
Designed flood Discharge	45300 m^3/s
Culturable Command Area (stage 1)	178100 ha

compared solution of genetic algorithms with that of Simulated Annealing and iterative improvement techniques.

The present study differs from earlier studies in that Genetic Algorithms are used for irrigation planning integrating reservoir operation and canal scheduling and a comparison made of solutions obtained from GA and LP models.

3. Irrigation System and Mathematical Modeling

Sri Ram Sagar Project (SRSP) is on river Godavari in Andhra Pradesh, India. Its headworks are located in Pochampadu village in Nizamabad district of Andhra Pradesh at 18°58′ N latitude and 70°20′ E longitude. Salient features of the project are presented in Table I. Location map of SRSP is presented in Figure 1. The climate of the area is subtropical and semi-arid. There is an extreme variation in temperature with average maximum and minimum values of 42.2 and 28.6 °C. The average relative humidity for the period from July to September remains above 80% whereas for April to June it is 65%. The evaporation loss varies from 124.3 mm in October to 386.3 mm in April. The average annual rainfall of the study area is 944 mm out of which 800 mm falls during June to October. The culturable command area (CCA) of the project (stage 1) is 178100 ha. Crops grown in the command area are Paddy (rice), Sorghum, Maize, Groundnut, Chillies and Sugarcane in both summer (Kharif) and winter (Rabi) seasons. The objective function and the corresponding constraints are explained below.

The net benefits (BE) under different crops from command area of SRSP are to be maximized. The net benefit is obtained by deducting the cost of production from the total income obtained from the crop on unit area basis. For this purpose, cost of labour, fertilizer, water, yield and value of crops are obtained from secondary

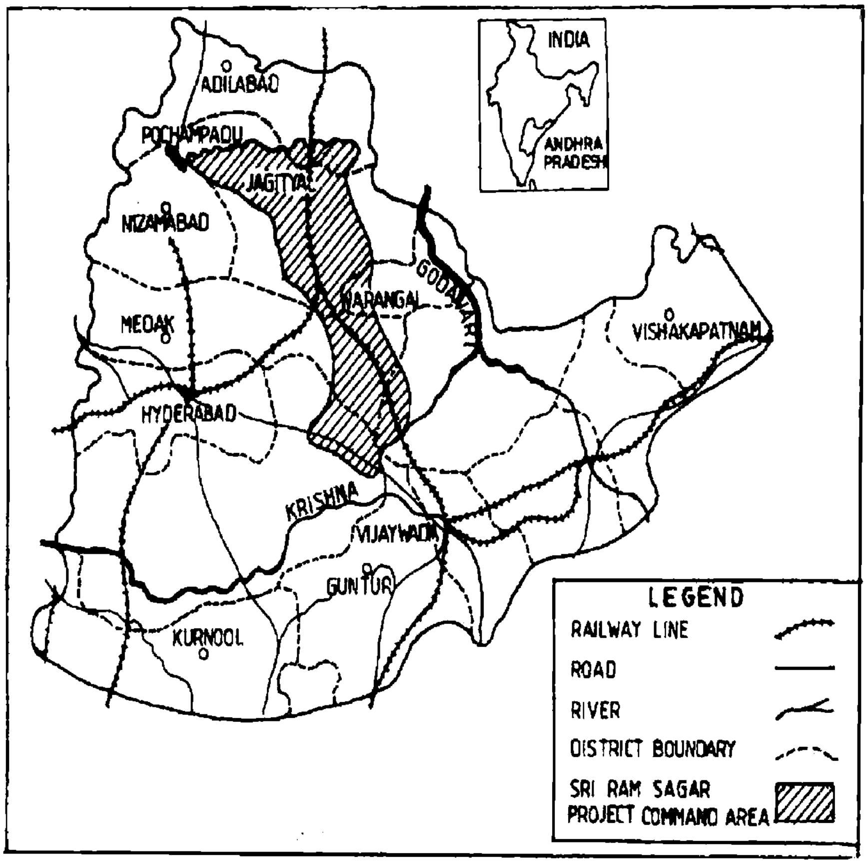

Figure 1. Location map of Sri Ram Sagar project.

sources as on 1993–94. Net benefits from these crops are computed individually irrespective of the period of its crop season.

$$BE = \sum_{i=1}^{10} B_i A_i \tag{2}$$

Where i = Crop index [1 = Paddy (S), 2 = Maize (S), 3 = Sorghum (S), 4 = Groundnut (S), 5 = Paddy (W), 6 = Maize (W), 7 = Sorghum (W), 8 = Groundnut (W), 9 = Chilies (TS), 10 = Sugarcane (P)]. S = Summer, W = Winter, TS = Two season, P = Perennial, t = Time index (1 = January, ... 12 = December). BE = Net benefits from the whole planning region (Indian Rupees); B_i = The net benefit from cultivation of different crops (including costs of water, fertilizers, labour employment etc) in Indian Rupees per hectare; A_i = Area of crop i grown in the command area (ha).

The model is subject to the following constraints.

3.1. CONTINUITY EQUATION

The continuity equation for reservoir operation includes inflows, storage, release and spillage. Water transfer activities consist of transport of water from the reservoir to the cropped areas through canal networks to meet the irrigation requirements. The continuity equation for reservoir operation can be expressed as

$$S_{t+1} = S_t + I_t - R_t - O_t \qquad t = 1, 2, ...12 \tag{3}$$

where S_{t+1} = Reservoir storage in the reservoir at the end of month t (Mm^3); I_t = Inflows into the reservoir during the month t, at 90% dependable level (Mm^3); R_t = Releases from the reservoir during the month t (Mm^3); O_t = Spillage from the reservoir during the month t (Mm^3). Evaporation and seepage losses from the reservoir are considered negligible. The monthly inflows into the Sri Ram Sagar reservoir are assumed to follow the log-normal distribution. Twenty three years of historical inflow data is used to obtain the various dependability levels of inflows. In the present study inflows at 90% dependability level are considered. These are 132.10, 372.88, 798.50, 812.70, 352.02, 56.9, 36.00 Mm^3 respectively during the months June to December. The inflows of other months are not significant and so are neglected.

3.2. CROP AREA RESTRICTIONS

The cropped area allocated for different crops in the command area in a particular season should be less than or equal to the Culturable Command Area (*CCA*).

$$\sum_i A_i \leq CCA \qquad \text{i = 1, 2, 3, 4, 9, 10 for Summer season} \tag{4}$$

$$\sum_i A_i \leq CCA \qquad \text{i = 5, 6, 7, 8, 9, 10 for Winter season} \tag{5}$$

where *CCA* = Culturable Command Area (178100 Ha). Crops of two seasons, namely, Chillies and Sugarcane (indices 9 and 10) are included in both the equations because they occupy the land in both the seasons.

3.3. CROP WATER REQUIREMENTS

Crop water requirements (EvapoTranspiration, ET) are computed based on the product of monthly pan evaporation and consumptive use coefficient. These can be fully or partly met from effective rainfall. In the present study, 80% dependable rainfall is considered to be the effective rainfall. The irrigation requirements (CWR_{it}) are based on the difference between monthly ET and the effective rainfall and considering the overall efficiency. During the absence of any crop activity,

CWR_{it} is taken as zero. Total water releases from Sri Ram Sagar reservoir should meet the irrigation demands of the cropped area.

$$\sum_{t=1}^{12}\sum_{i=1}^{10} CWR_{it}A_i \leq R_t \tag{6}$$

where CWR_{it} = Crop water requirements for crop i in month t (meters)

3.4. CANAL CAPACITY RESTRICTIONS

The total releases from reservoir cannot exceed the canal capacity

$$R_t \leq CC \qquad t = 1, 2, ...12 \tag{7}$$

Discharging capacity of canal can be expressed as $m^3\ s^{-1}$. In the present study, it is converted into volumetric units, Million cubic meters (Mm^3), to be compatible with releases.

3.5. LIVE STORAGE RESTRICTIONS

Reservoir storage volume S_t in any month t should be less than or equal to the maximum live storage capacity of the reservoir.

$$S_t \leq \text{LSP} \qquad \text{t} = 1,2, ...,12 \tag{8}$$

Where *LSP* = Maximum live storage capacity of the reservoir (2300 Mm^3)

3.6. CROPPING PATTERN CONSTRAINTS

Since the command area lies in a region, which predominantly depends on agricultural economy, the planners have to ensure production of certain cash crops in addition to food crops. Minimum and maximum area restrictions are based on food requirements of the population in the command area (Gopalan *et al.*, 1984). Information in this regard is based on existing cropping pattern, reports, discussion with the officials of irrigation and agricultural department, Command Area Development Authority, Sri Ram Sagar Project, Directorate of economics and statistics (1992), Government of Andhra Pradesh; and secondary sources such as marketing societies etc.

$$A_i \geq A_{i.\min} \qquad i = 1, 2, ...10 \tag{9}$$

$$A_i \leq A_{i.\max} \qquad i = 1, 2, ...10 \tag{10}$$

Where $A_{i.\min}$ and $A_{i.\max}$ are minimum and maximum limits of the cropped area.

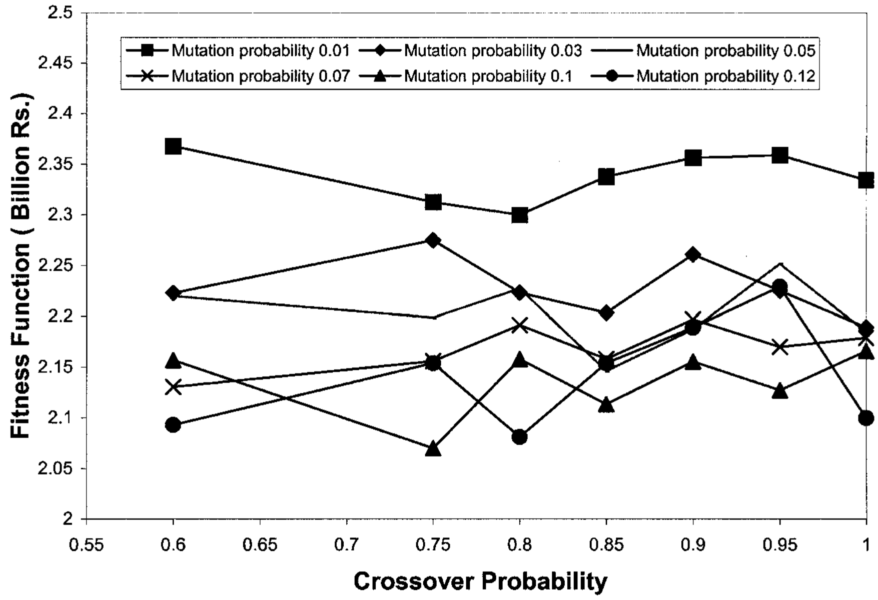

Figure 2. Comparison of fitness function values for various crossover and mutation probabilities.

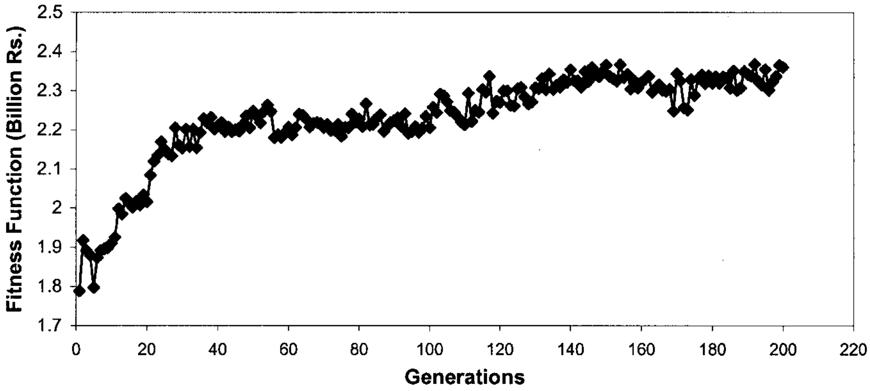

Figure 3. Comparison of fitness function values for various generations.

4. Results and Discussion

Irrigation planning problem is solved using both Genetic Algorithms (GA) and Linear Programming (LP). Since the objective function is of maximization in nature (net benefits), value is –1 (as per Equation 1). In this case value of fitness function is equal to objective function. Penalty function approach is used to convert the constrained problem into an unconstrained problem with a reasonable penalty function. Since GA is dependent on various parameters such as population, gen-

Table II. Crop pattern obtained by two models

No	Crops with seasons		Crop area in '000 ha		Percentage deviation
			GA	LP	
1.	Paddy	(s)	29.43	30.00	1.90
2.	Maize	(s)	29.37	30.00	2.10
3.	Sorghum	(s)	49.71	50.00	0.58
4.	Groundnut	(s)	8.95	9.00	0.55
5.	Paddy	(w)	21.71	22.00	1.32
6.	Maize	(w)	27.38	30.00	8.73
7.	Sorghum	(w)	42.11	50.00	15.78
8.	Groundnut	(w)	9.83	10.00	1.70
9.	Chillies	(ts)	6.13	6.20	1.13
10.	Sugarcane	(ts)	8.14	8.20	0.73
Total irrigated area			232.76	245.40	5.15
Net Benefits in billion Rs.			2.3903	2.4893	3.97

s = Summer; w = Winter; ts = Two season.

erations, cross over and mutation probabilities various combinations are tried. To conserve space, only a selected set of results is presented. Seven values of crossover probability viz., 0.6, 0.75, 0.8, 0.85, 0.9, 0.95, 1.0 and six values of mutation probabilities viz., 0.01, 0.03, 0.05, 0.07, 0.1, 0.12 are chosen with a population size of 50 and maximum number of generations of 200. The maximum fitness function values are obtained for the above mutation and crossover probabilities. The results obtained are presented in terms of total fitness function values in Figure 2 and number of generations in Figure 3. It is observed from Figure 2 that for mutation probability value of 0.01 and for various crossover probabilities, each solution maintains its identity being different from other sets of solutions. Among these, the maximum fitness function value of 2.3678 Billion Rupees is achieved for crossover probability of 0.6 and mutation probability of 0.01 and this combination is used for further analysis. Termination criterion is set to perform 200 generations of GA simulation i.e., program will terminate with 200th generation. Even before reaching 200 generations, maximum fitness function value was reached at 192nd generation, which is taken as solution for the present study.

Efforts are also made to compare the solution of Genetic Algorithm (GA) with Linear Programming (LP) algorithm. Cropping patterns obtained by both the methods are presented in Table II. Considerable deviations between the two methods are observed such as 15.78% for Sorghum (w) and 8.73% for Maize (w). Maximum benefits obtained by LP solution are 2.4893 Billion Rupees and 2.3903 Billion Rupees by GA. Irrigated area and net benefits obtained from GA have deviated

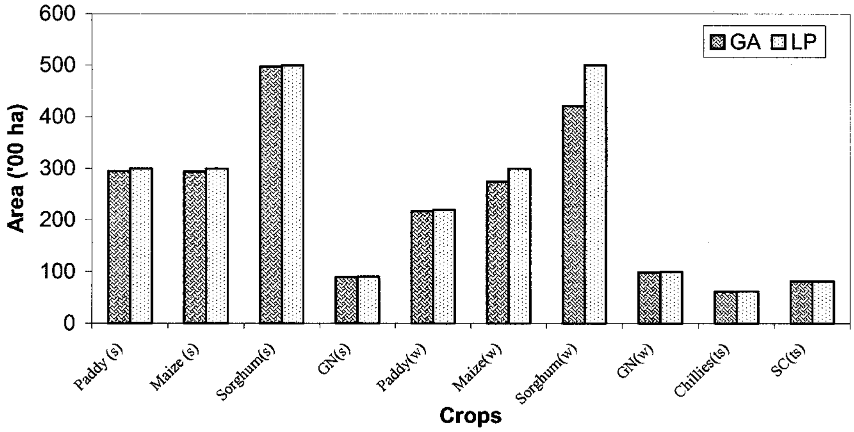

Figure 4. Comparison of cropping pattern (GN-Groundnut, SC-Sugarcane).

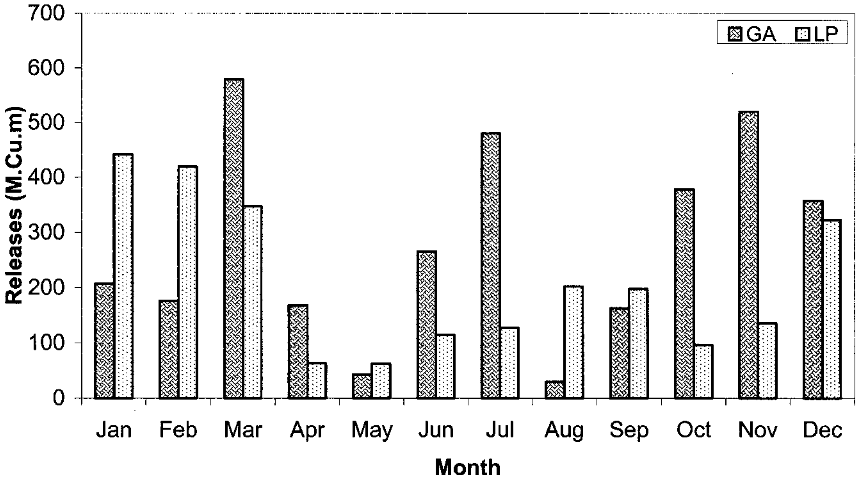

Figure 5. Comparison of monthly releases.

from LP by 5.15 and 3.97%. In Figure 4 cropping patterns obtained from both the methods are presented.

Monthly release policies obtained by both the methods are presented in Figure 5. It is observed that LP solution suggests more releases in the months of January, February, May, August and September. Monthly storage policies obtained by both the methods are presented in Figure 6.

It is observed from the results that solutions obtained by both GA and LP are reasonably close proving that GA can be used for irrigation planning problems with more confidence and it can be extended for larger problems. However, the solution obtained by GA for irrigation planning can be further refined for a number

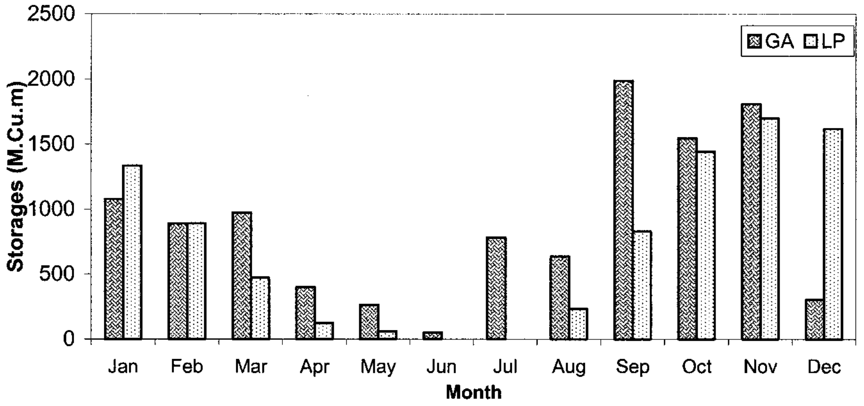

Figure 6. Comparison of monthly storages.

of factors such as penalty function values, mutation and crossover probabilities, generation and population.

5. Conclusions

In the present study, a GA based model is developed for evolving an optimum cropping pattern for Sri Ram Sagar Project, Andhra Pradesh, India. The objective is to maximize net benefits with the constraints such as continuity equation, land and water requirements, canal capacity, reservoir storage restrictions and cropping pattern considerations. The results obtained from the GA model are compared with those obtained from Linear Programming model. The observations from the study are as follows.

1. Maximum benefits obtained by LP solution is 2.4893 Billion Rupees where as these are 2.3903 Billion Rupees by GA.
2. It is observed that solutions obtained by both GA and LP are reasonably close. Irrigated area and net benefits obtained by GA have deviated by 5.15 and 3.97% as compared to LP solution.
3. Appropriate GA parameters identified from this study are: Number of generations = 200, Population size = 50, Crossover probability = 0.6 and Mutation Probability = 0.01. These parameters were also found to hold good in similar other analyses by the authors.
4. Genetic Algorithms is found to be an effective optimization tool for irrigation planning and can be used for more complex systems involving non-linear optimization.

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