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Fuzzy Multiobjective and Linear Programming Based Management Models for Optimal Land-Water-Crop System Planning

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Abstract. In this article, linear programming and fuzzy optimization models are developed for planning and management of available land-water-crop system of Mahanadi-Kathajodi delta in eastern India. The models are used to optimize the economic return, production and labour utilization, and to search the related cropping patterns and intensities with specified land, water, fertilizer and labour availability, and water use pattern constraints. Due to extreme backwardness of the study area, it has been decided to keep all the three objectives of the linear programming models at the same priority level to obtain the compromised solution in a fuzzy environment that incorporates the imprecision in fuzzy goals and fuzzy constraints. These non-structural models facilitate the conjunctive use of available surface water and groundwater resources. A comparative evaluation along with the benefit-cost ratios of the existing and proposed farming systems is also presented.

Key words: benefit-cost ratio, conjunctive use, fuzzy optimization, linear programming, Mahanadi-Kathajodi delta, optimal planning

Introduction

The development of agriculture-based economy, which is prevalent in most of the underdeveloped and developing countries, requires an integrated planning of its land and water resources to get the maximum economic returns. The immediate objective in both dry as well as irrigation farmings should be to enhance the existing productivity levels to deal with the increasing level of population growth accounting for the uncertainties, inherent in climatic variables. The main input for increasing productivity in irrigated areas is to ensure timely supply of water to crops from the available surface water resources along with the proper utilization of groundwater potential. With a view to economising on use of water and increasing the productivity of irrigated crops, conjunctive use of surface and groundwater should be permissible in all the command areas. It is necessary that the new techniques for economical use of water be used without any inhibitions.

Cropping and irrigation water management is characterized by uncertainty due to randomness of hydrologic variables such as rainfall, evapotranspiration, groundwater availability and the imprecision in their management goals, socio-economic constraints, and crop response. Further, the variations in availability of irrigation water quantity and quality, coupled with the indiscriminate nature of irrigation water supply and demand, create an imbalance in agricultural production in semi-arid regions (Panda *et al.*, 1996). Currently, most irrigation water management models only consider crop water requirements (Lohani *et al.*, 2004), yet in many cases it is also necessary to consider economic factors (Kuol and Liu, 2003). Furthermore, conflicts may exist among decision-makers and varied interest groups. For a given goal, many alternative measures may exist with different levels of satisfaction for the related decision makers and stakeholders. It is, thus, difficult to clearly identify the 'best' among them (e.g., Fontane *et al.*, 1997; Yin *et al.*, 1999).

To handle the multiple criteria decision systems, in general, there are various tools available viz. the utility theory, the goal programming, the vector-maximum methods, the interactive methods, and the fuzzy programming. The recent tool of fuzzy optimisation can deal with the uncertainties due to vagueness in various components of the management problem (Majumdar, 2002). The fuzzy logic approach may provide a promising alternative to the existing management methods and allows incorporation of expert opinions (Panigrahi and Mujumdar, 2000). In this paper an attempt has been made to optimally allocate land and water resources in a stochastic regime under a multi-crop environment for three complementary goals, viz. maximization of production, maximization of net annual return and minimization of labour cost for a deltaic command area using fuzzy optimisation programming (FOP) and linear programming (LP) models.

Study Area and Data Used

The site selected for the present study is Vayalish Mouza in the Mahanadi-Kathajodi delta of Orissa in eastern India, comprising a cultivable command area of 842 ha (Figure 1). It is situated at the latitude of 20°38′N and longitude of 86°12′E having a mean sea level of 23.1 m. The climate of the study area is sub-tropical monsoon with mean annual rainfall of about 1548 mm (thirty one years average starting from 1968–1998). About 80% of its annual rainfall is contributed by the southwest monsoon during the month of June to September. The meteorological data like daily rainfall, evaporation, temperature, solar radiation, daily sunshine hours, humidity, wind velocity and albedo were collected from the Central Rice Research Institute, Cuttack, which is about 5 km away from the study area. The soil of the study area is generally derived from river transported alluvial soil, whereas it is sandy along the rivers and sandy clay loam in lower areas. The soil is moderately fertile and is slightly acidic.

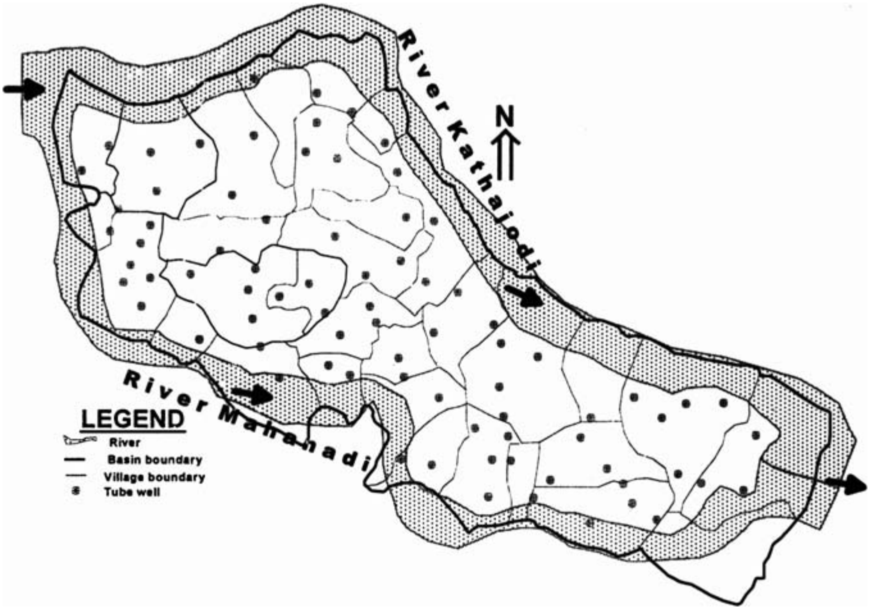

Figure 1. Index map of the Vayalish Mouza delta.

The sub-tropical monsoon climate of the study area has made two distinct cropping seasons viz. monsoon or *kharif* (June–September) and winter or *rabi* (October–February). The crop rotation during *kharif* and *rabi* seasons are: *kharif* paddy, sugarcane (perennial); and *rabi* paddy, wheat, potato, mustard, chilly, vegetables, arum, green gram, fodder and onion, respectively. Paddy is the predominant crop in the study area covering about 80% during *kharif* season and 20% during *rabi* season. Pulses cover about 15 to 30% of the command area during *rabi* season. The average groundwater table of the study area is about 2.45 m, which ranges from about 2 to 4 m during the post-monsoon period and from about 1 to 3 m during the monsoon period. The rivers Mahanadi and Kathajodi make the aquifer of the study area heavily recharged which has a replenishable groundwater resources of 85.57 million m^3 (MCM) and a utilizable irrigation potential of 165.21 MCM (Mohapatra, 1994). The level of groundwater development of the study area is mere a 14.76%, which can further effectively be utilized for the development of the deltaic command area.

Although the agro-climatic and soil condition are quite favourable for sound agricultural practices, there is poor crop production because of the uncertainty in rainfall, unreliability in canal supply and improper management practices. As per the local survey, the annual income of a labourer is Rs. 3000 and that of a farmer is Rs. 5500 (1 US \$ = Rs. 48). Hence, for better management practices the socio-economic conditions of the people cannot be ignored.

Model Development

THE FOP MODEL

Conventionally, the fuzzy optimization problem is defined as the simultaneous satisfaction of the constraints and goals. No additional distinction is assumed to exist amongst the constraints and goals. Firstly, the multi-objective decision problem with independent objectives is stated, and then, the model is adjusted to reality by introducing interdependences among the objectives. Interdependences among the objectives exist whenever the computed value of an objective function is not equal to its observed value. In lexicographic ordering, objectives are first ordered by importance. Then, the first objective is solved: $Z_1 = \max\{f_1(X)\text{: given constraints}\}$. Then, for each $i > 1$, $Z_i = \max\{f_i(X)\text{: } f_k(X) = Z_k(X) \text{ for } k = 1, \ldots, i - l\}$; where Z_i and f_i are the objective functions and constraints, respectively. This method would be quite useful if there exist more than one X for Z_1(X) and if there is a predetermined ranking of importance for objectives. However, in this paper all the incompatible objective functions are kept under equal priority level considering dealing with the extreme backwardness of the region under consideration.

The fuzzy optimization programming takes into account three fuzzy objective functions to deal with the problem of proper management of land and water resources of the deltaic study area under consideration. The conflicting goals in the fuzzy decision-making process are given below.

$$\text{Maximize } Z_p = f_1(X_1, X_2, \ldots, X_{12}) \tag{1}$$

$$\text{Maximize } Z_{\text{NR}} = f_2(X_1, X_2, \ldots, X_{12}) \tag{2}$$

$$\text{Minimize } Z_{\text{LC}} = f_3(X_1, X_2, \ldots, X_{12}) \tag{3}$$

where Z_P, Z_{NR} and Z_{LC} are the fuzzy goals of crop production, net returns and labour cost, respectively. $X_1, X_2, \ldots, X_{12}$ are the crop variables where $X_1 \equiv$ paddy cultivated during June-September (*kharif* paddy), $X_2 \equiv$ paddy cultivated during October-February (*rabi* paddy), $X_3 \equiv$ chilly, $X_4 \equiv$ potato, $X_5 \equiv$ vegetables, $X_6 \equiv$ sugarcane, $X_7 \equiv$ wheat, $X_8 \equiv$ mustard, $X_9 \equiv$ arum, $X_{10} \equiv$ green gram, $X_{11} \equiv$ fodder, and $X_{12} \equiv$ onion. The fuzzy goal $f(X_1, X_2, \ldots, X_{12}) \geq k$ which is called as fuzzy set f defined over the set of feasible solutions, are shown with the membership functions μ_1, μ_2 and μ_3, defined linearly as follows:

$$\mu_1 = \begin{cases} 1, & f_1(X_1, X_2, \ldots, X_{12}) > Z_P \\ \dfrac{f_1(X_1, X_2, \ldots, X_{12}) - P_{\text{LC}}}{Z_P - P_{\text{LC}}}, & P_{\text{LC}} \leq f_1(X_1, X_2, \ldots, X_{12}) \leq Z_P \\ 0, & f_2(X_1, X_2, \ldots, X_{12}) < P_{\text{LC}} \end{cases} \tag{4}$$

$$\mu_2 = \begin{cases} 1, & f_2(X_1, X_2, \ldots, X_{12}) > Z_{NR} \\ \dfrac{f_2(X_1, X_2, \ldots, X_{12}) - B_{\mathrm{LC}}}{Z_{NR} - B_{\mathrm{LC}}}, & B_{\mathrm{LC}} \leq f_2(X_1, X_2, \ldots, X_{12}) \leq Z_{\mathrm{NR}} \\ 0, & f_2(X_1, X_2, \ldots, X_{12}) < B_{\mathrm{LC}} \end{cases} \tag{5}$$

$$\mu_3 = \begin{cases} 1, & f_3(X_1, X_2, \ldots, X_{12}) < Z_{\mathrm{LC}} \\ \dfrac{f_3(X_1, X_2, \ldots, X_{12}) - L_P}{Z_{\mathrm{LC}} - L_P}, & L_P \leq f_3(X_1, X_2, \ldots, X_{12}) \leq Z_{\mathrm{LC}} \\ 0, & f_3(X_1, X_2, \ldots, X_{12}) < L_P \end{cases} \tag{6}$$

where P_{LC} = value of production corresponding to feasible solution of minimization of labour requirement; B_{LC} = value of benefit corresponding to feasible solution of minimization of labour requirement; and L_P = value of labour requirement corresponding to feasible solution of production maximization.

The membership functions μ_1, μ_2 and μ_3 of the fuzzy sets characterizing the objective function vary linearly in [0, 1] at the highest achievable value of Z_P, Z_{NR} and Z_{LC}, respectively. The boundary conditions of the membership function reflect two extreme scenarios of the system, i.e., μ_i $(i = 1, 2, 3) = 1$ indicates the complete satisfaction of all the fuzzy goals, and μ_i $(i = 1, 2, 3) = 0$ indicates a total-conflict scenario having at least one goal of zero satisfaction.

Then the fuzzy decision Z can be defined as

$$Z = Z_p \cap Z_{\mathrm{NR}} \cap Z_{\mathrm{LC}} \cap \mu_1 \cap \mu_2 \cap \mu_3 \tag{7}$$

Then the fuzzy optimization model can be formulated as:
Maximize Z
Subject to:
$Z \leq \mu_i (i = 1, 2, 3)$; and other constraints as defined by Equations (11)–(24) in the next section.

THE LP MODELS

An optimal plan of the command should satisfy both the farmers' interest to maximize the profit with less investment and the national objective to maximize the production. In view of this, three alternate planning systems were considered for the study area, to make out each by three independent LP models as follows.

(i) Maximizing Production (LPP Model)

Objective Function

$$\text{Max. } Z_P(X) = \sum_{j=1}^{cl} Y_j^{K*} A_j^K + \sum_{j=1}^{c2} Y_j^{K*} A_j^R \tag{8}$$

where $Z_P(X)$ = production function; Y_j^k = yield per unit area from the jth crop in the *kharif* season (kg/ha); A_j^K = area allocated for the jth crop in the *kharif* season (ha); Y_j^K = yield per unit area from the jth crop in the *rabi* season (kg/ha); A_j^R = area allocated for the jth crop in the *rabi* season (ha); c1 = total no. of *kharif* crops; and c2 = total no. of *rabi* crops.

(ii) Maximizing Net Return (LPNR Model)

Objective Function

$$\begin{aligned}\text{Max.}Z_{\text{NR}}(X) = {} & \sum_{j=1}^{cl} \left[\left(P_j Y_j^K + PB_j{}^* YB_j^K - C_j^{P,K} \right) A_j^K \right. \\ & \left. - (c^{SW} SW^K + (cp^{GW} + cg^{GW}) GW^K) \right] \\ & + \sum_{j=1}^{c2} \left[\left(P_j Y_j^R + PB_j{}^* YB_j^R - C_j^{P,R} \right) A_j^R \right. \\ & \left. - (c^{SW} SW^R + (cp^{GW} + cg^{GW}) GW^R) \right] \end{aligned} \tag{9a}$$

where

$$\begin{aligned} C_j^{P,K} &= LC * M_j^K + FC_j^K + IF_j^K; \quad \text{and} \\ C_j^{P,R} &= LC * M_j^R + FC_j^R + IF_j^R \end{aligned} \tag{9b–c}$$

P_j = current market price of jth crop (Rs./kg); PB_j = current market price of the byproducts of jth crop (Rs./kg); YB_j^K, YB_j^K = yield of byproducts of crop j in *kharif* and *rabi* seasons, respectively (kg/ha); $C_j^{P,K}$, $C_j^{P,R}$ = unit cost of production of crop j in *kharif* and *rabi* seasons, respectively (Rs./kg); C^{SW} = unit cost of the surface water (Rs./m^3); SW^K, SW^R = volume of surface water utilized during *kharif rabi* seasons, respectively (m^3); cp^{GW} = pumping cost of groundwater from shallow private tube wells (Rs./m^3); cg^{GW} = pumping cost of groundwater from government deep tube wells (Rs./m^3); LC = labour cost per man day; M_j^K, M_j^R = no. of man days for crop j in *kharif* and *rabi* seasons, respectively; FC_j^K, FC_j^R = fertilizer cost for crop j in *kharif* and *rabi* seasons, respectively (Rs.); and IF_j^K, IF_j^R = investment on farming for crop j in *kharif* and *rabi* seasons, respectively (Rs.).

(iii) Minimizing Labour Requirement (LPL Model)

Objective Function

$$\text{Min. } Z_{\text{LC}}(X) = \sum_{j=1}^{c1} M_j^K + \sum_{j=1}^{c2} M_j^R \tag{10}$$

The objective functions are subjected to the following constraints.

Area Constraints

The area constraints for different crops for the study area are defined to account for total area available for cultivation during *kharif* and *rabi* seasons, the crop rotation, the soil texture, the topography and the affinity of the farmers to a specific crop. The area constraints are given by:

$$\sum_{j=1}^{c1} A_j^K - CA \leq 0 \quad \text{(for } \textit{kharif} \text{ season)} \tag{11}$$

and

$$\sum_{j=1}^{c2} A_j^R - CA + \sum_{j=1}^{p} A_j^K \leq 0 \quad \text{(for } \textit{rabi} \text{ season)} \tag{12}$$

where CA = total cultivable area; and $p =$ total no. of perennial crops.

Water Requirement Constraints

The expected irrigation water requirements of all the crops must be fully satisfied during all the seasons from the available surface water and groundwater resources in addition to rainfall. The water requirement constraint should be such that the 14-daily crop water requirements in the command area should be less than equal to the 14-daily cumulative water availability. The water requirement constraints for both the seasons are given by:

$$\sum_{i=1}^{sl} \sum_{j=1}^{c1} IWR_{ij}\, A_i^K - \sum_{i}^{s1} \left(\eta_i{}^* SW_i^K + \eta_a{}^* GW_i^K\right) \leq 0 \quad \text{(for } \textit{kharif} \text{ season)} \tag{13}$$

and

$$\sum_{i=1}^{s2} \sum_{j=1}^{c2} IWR_{ij} A_j^R - \sum_{i}^{s1} \left(\eta_i\, {}^* SW_i^R + \eta_a\, {}^* GW_i^R\right) \leq 0 \quad \text{(for } \textit{rabi} \text{ season)} \tag{14}$$

where IWR_{ij} = net irrigation water requirement of *j*th crop during *i*th 14-daily period; $s1, s2$ = number of calculation intervals in 14-daily basis over the base period of crops in *kharif* and *rabi* seasons, respectively; η_i = irrigation efficiency of surface water; η_a = field water application efficiency of groundwater; SW_i^K, SW_i^R = surface water availability for *i*th interval in *kharif* and *rabi* seasons, respectively; and GW_i^K, GW_i^R = groundwater availability (from tube wells) for *i*th interval in *kharif* and *rabi* seasons, respectively.

The crop evapotranspiration, crop coefficient, percolation loss and effective rainfall govern the net irrigation water requirement of a crop; and this can be estimated as:

$$IWR_{ij} = KC_{ij} * ETo_i + P_{ij} - \mathrm{Re}_i \tag{15}$$

where KC_{ij} = crop coefficient of the *j*th crop in the *i*th interval; ETo_i = potential evapotranspiration in the *i*th interval; P_{ij}= percolation loss for the *j*th crop in the *i*th interval; and Re_i = effective rainfall during the *i*th interval.

While considering the total water availability of the command area, it is required to emphasize that the groundwater table shall not fall below the critical level, accounting for the conjunctive use of surface water and groundwater. The critical level of groundwater table can be maintained by restricting the pumping of groundwater up to the permissible mining allowance of the aquifer. Thus, a hydrological mass balance constraint of the groundwater system should be satisfied for both the cropping seasons as given below.

$$\eta_a * GW_j^K - (1 - \eta_i) SW_j^K - \theta_p \, E(R_j) A_T + E_j^{GW,K} + DWU_j \leq PMA_j \quad \text{(for } kharif \text{ season)} \tag{16}$$

$$\eta_a * GW_j^R - (1 - \eta_i) SW_j^R - \theta_p E(R_j) A_T + E_j^{GW,R} + DWU_j \leq PMA_j \quad \text{(for } rabi \text{ season)} \tag{17}$$

where θ_p = fraction of rainfall as percolation loss; $E(R_j)$ = expected rainfall during *j*th interval; A_T = gross command area; $E_j^{GW,K}$, $E_j^{GW,R}$, = evaporation loss from groundwater in *j*th interval for *kharif* and *rabi* seasons, respectively; DWU_j = groundwater consumption in domestic, industrial and other sectors during *j*th interval; and PMA_j = permissible mining allowance during *j*th interval.

Affinity Constraints

There is a tendency of the farmers of the region to grow paddy crops during *kharif* season and pulses during *rabi* season ensuring storage of their basic food requirement. To safeguard the interest of farmers, the lower limit of area under paddy cultivation is kept as 70% of total irrigated area.

$$A_1^K \geq 0.7 \sum_{j=1}^{c1} A_j^k \tag{18}$$

where A_1^K = area under paddy cultivation.

Similarly, for *rabi* season the minimum area under pulse cultivation is kept as 20% of total irrigated area.

$$A_8^R + A_{10}^R \geq 0.2 \sum_{j=1}^{c2} A_j^R \tag{19}$$

where A_8^R = area under mustard and A_{10}^R = area under green gram.

Cropping Pattern Constraints

Keeping in view the cropping pattern of area, constraints of cropping pattern for different crops has been fixed putting area as the limiting condition.

Labour Requirement Constraints

The labour requirement in 14-days basis should not exceed the labour availability during that interval to deal with the uncertainty of migrated labour force of the region. The constraint is given by:

$$\sum_{j=1}^{c1} M_j^K + \sum_{j=1}^{c2} M_j^R < \sum_{j=1}^{s1+s2} LA_j \tag{20}$$

where LA_j = total labour availability during the jth interval.

Fertilizer Constraints

The major nutrients supplied to the crops through fertilizer are nitrogen (N), phosphorus (P) and potassium (K). The total fertilizer requirement by all the crops in *kharif* and *rabi* seasons should be less than or equal to the fertilizer availability in the area.

$$\sum_{j=1}^{c1} FN_j^K + \sum_{j=1}^{c2} FN_j^R \leq TN \tag{21}$$

where FN_j^K, FN_j^R = nitrogen requirement by jth crop during *kharif* and *rabi* seasons, respectively; and TN = total nitrogen availability in the area.

$$\sum_{j=1}^{c1} FP_j^K + \sum_{j=1}^{c2} FP_j^R \leq TP \tag{22}$$

where FP_j^K, FP_j^R = phosphorus requirement by jth crop during *kharif* and *rabi* seasons, respectively; and TP = total phosphorus availability in the area.

$$\sum_{j=1}^{c1} FK_j^K + \sum_{j=1}^{c2} FK_j^R \leq TK \tag{23}$$

where FK_j^K, FK_j^R = potassium requirement by jth crop during *kharif* and *rabi* seasons, respectively; and TK = total potassium availability in the area.

Non-Negativity Constraints

$$\begin{aligned} &A_j^K, A_j^R, Y_j^K, Y_j^K, YB_j^K, YB_j^K, SW^K, SW^R, FN_j^K, FN_j^R, FP_j^K, \\ &FP_j^R, FK_j^K, FK_j^R, M_j^K, M_j^R \geq 0 \; \forall \, i, j \end{aligned} \tag{24}$$

Assumptions

For the development of the FOP and LP models, the following assumptions are made in the framework of the optimization theory concept.

(i) All the relationships within the models are based on the framework of linearity.
(ii) All the available resources are divisible and transportable.
(iii) The soil of the study area is homogeneous in nature.
(iv) Each land unit under consideration receives the same management practice for a particular crop activity, and hence, the yield and net return under a particular cropactivity is constant.
(v) All the activity levels of various crops are independent of each other within their finite limits that satisfy the non-negativity constraint.
(vi) The timings and duration of the cropping activity are constant and do not vary over years. The cropping year is distinctly divided into two seasons (viz. *kharif* and *rabi*) without any overlapping. However, in certain overlapping situations, care is taken by suitable constraints.

Model Inputs

The management models, described in the above sections require the following data base as model inputs: basin data (cultivable area, gross command area, soil type, and topography), crop data (cropping pattern, planting date, crop base period, crop coefficients at different growth stages and nutrient requirement by each crop), hydrometeorological data (rainfall, evaporation and deep percolation losses, infiltration loss from rainfall, discharge rate from tube wells, reference evapotranspiration which is a function of temperature, humidity, radiation, daily sunshine hours, wind velocity, and crop resistances), and management practice data (irrigation system efficiency, field water application efficiency, fertilizer and labour availability, and current market price of the crop produce).

For calculating the crop water requirement for each crop a reference evapotranspiration ($ET_{\circ}$) at 14-daily basis was first computed from the weather data with the FAO Penman-Monteith equation (Allen *et al.*, 1998). Then, the crop coefficient (K_c) curves for each crop were drawn (Doorenbos and Kassam, 1979) to calculate the potential crop evapotranspiration ($ET_c = K_{c^*}ET_{\circ}$) (Doorenbos and Pruitt, 1977). The effective rainfall was estimated using the USDA-SCS curve number method (USDA-SCS, 1972).

The daily rainfall data, collected over 31 years (1968–1998), and daily evaporation data, collected over 20 years from (1979–1998), were fitted into the best probability distribution functions (pdf) considering the Weibull's distribution as the reference. These best-fit pdfs were used to calculate the 75% dependable rainfall (Figure 2) and 50% dependable evaporation of the study area on 14-daily basis (in the present case normal distribution is the best-fit pdf). These values of probability level are considered for safe system planning accounting for any extremity of rain-

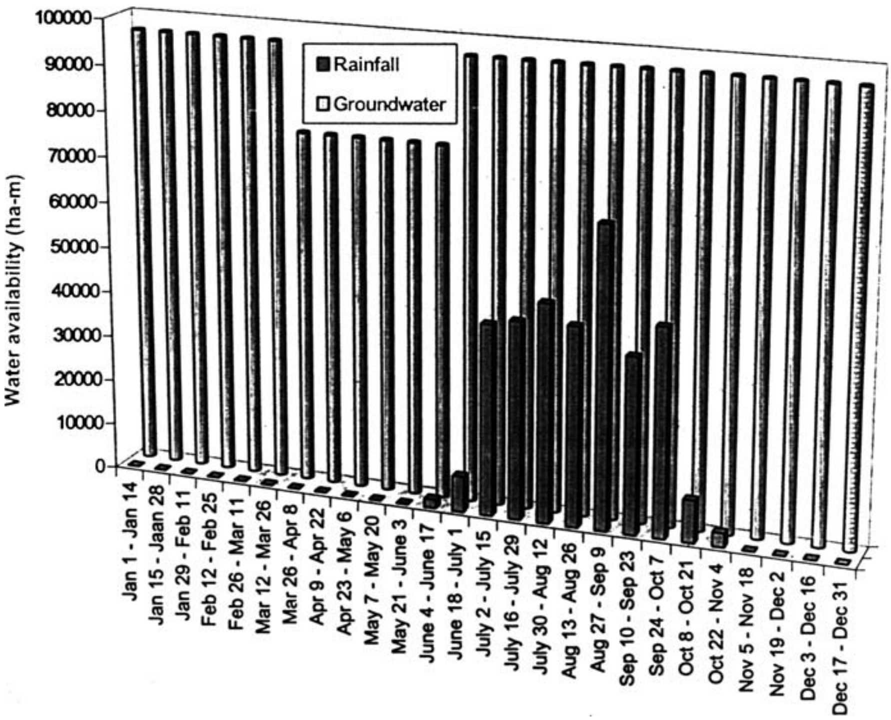

Figure 2. Water availability at 75% dependability in the study area.

fall, may be due to global climate change. It is observed that at 75% probability level, there is no rainfall from October 22 to May 20; and less than 10 mm of rainfall from May 21 to June 17, and October 8 to October 21. Similarly, the 50% dependable reference evapotranspiration goes on increasing from January 1 to May 20 and attains the maximum value during May 7 to May 20, and minimum during December 3 to December 16.

The expected effective rainfall and the canal water release forms the basis of availability of surface water resources. Depending upon the major soil type of the catchment the deep percolation loss for the command area is fixed at 3 mm/day. The irrigation efficiency of surface water and the field water application efficiency of groundwater have been fixed at 70 and 90%, respectively. The average discharge rates of 70 tube wells, installed throughout the study area, were collected to estimate the total groundwater potential of the command area. It is assumed that tube wells are operating 6 h/day during the *kharif* season and 10 h/day during the *rabi* season. The evaporation loss from groundwater is assumed as 0.5 mm/day during *kharif* season and 0.4 mm/day during *rabi* season. The permissible mining allowance of the aquifer and the water consumption by various sectors except irrigation during the calculation interval of the cropping seasons have been fixed at 75% and 20% of the groundwater availability during that interval, respectively. Figure 2 depicts

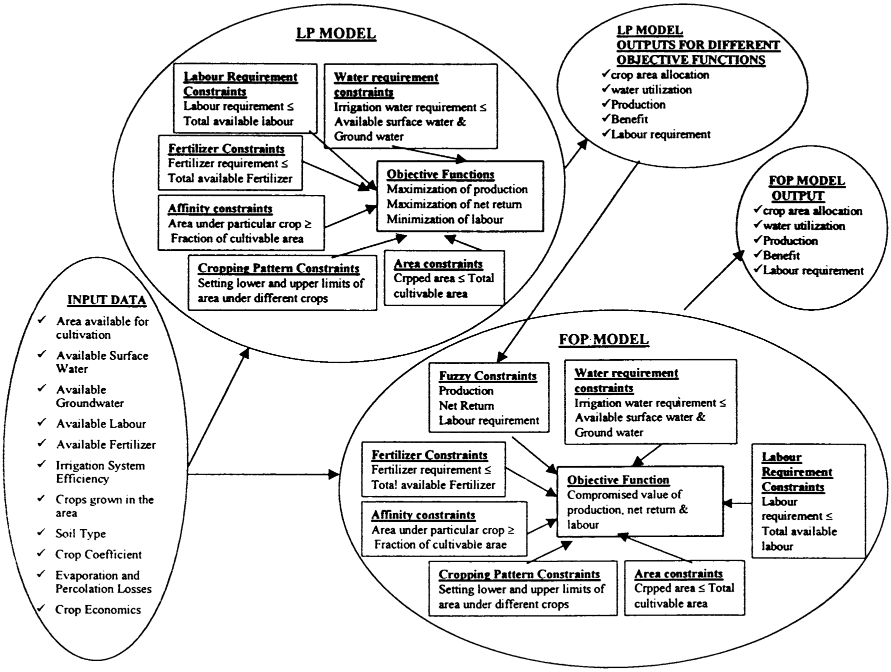

Figure 3. Schematic representation of the fuzzy optimization model showing linkages with linear programming model.

the grondwater availability at 75 % permissible mining allowance. The paddy crop needs some excess water for puddling, which is assumed as 150 mm. Further, an excess 30 mm of water is allocated for land preparation for each crop. The groundwater quality test showed that it is very much suitable to use for domestic, industrial and irrigation purposes. Hence, no water quality constraint was used to improve the quality of groundwater by proper blending of surface and groundwater (e.g., Panda *et al.*, 1996).

The discrete labour force requirement per unit area for different crops and their availability, the optimum amount of fertilizer requirement by different crops and their availability were obtained from the Agriculture Guide Book (DAFP, 1997). Assuming that the change in availability of labour forces for agricultural production is not significant in subsequent years with rapid mechanization in the agricultural sector, the labour availability is treated as an upper limit of the labour constraints.

Results and Discussion

The conceptualized fuzzy multiobjective and linear programming based management models illustrating the computational requirements of different constraints and their linkages to the objective function is depicted in Figure 3. It is clearly evident (Figure 3) that in order to achieve the compromised solution of the objective function in a fuzzy environment a maximum of three-tier computational hierarchy for the fuzzy constraints such as production, net return and labour requirement guide the solution. However, the other constraints are guided by single-tier computations.

The objective functions (Equations (8) to (10)) of the linear optimization model are to maximize crop production, net return and to minimize labour requirement in the Mahanadi-Kathajodi delta of Orissa, India. The present problem is solved using LINDO software developed by LINDO Systems Inc., Chicago, USA. The formulated linear programming problems constitute a total of 160 constraints. However, the FOP model constitutes a total of 163 constraints.

The intended target is to allocate available land and water resources in such a manner to achieve maximum production and net return by utilizing minimum labour. Such allocations of land and water resources are also based on the availability of fertilizer, affinity of farmers to any crop and crop water requirement. All the three linear programming models allocate the land and water resources in such a manner so as to achieve the maximum value of the target objective function. Allocations under one objective function need not necessarily provide the maximum targeted values for other objective function. Therefore, a compromised solution is required so as to achieve a solution that provides values of production, net return and labour requirement closer to targeted optimum solution. In order to achieve a compromised solution fuzzy optimization model (Figure 3) utilizes the output of linear programming model for formulating fuzzy constraints.

Results of the nonlinear optimization model corresponding to the prescribed input values (Figure 2) and the limiting conditions are given in Table I, which suggest the optimized area allocated under different crops. Table I also provide the cropping intensities and the optimal management functions at four model simulations. While the existing cropping intensity of the study area is 124.87%, the LPP model provides a highest cropping intensity, followed by the LPNR, FOP and LPL models. The percent deviation of the four-optimization model outputs from their optimum values is presented in Figure 4. It reveals that the LPP model shows the least deviation from the optimized values of production and benefit as compared to the other models, followed by the LPNR model. These two models exhibit more percentage of deviation of minimization of labour requirement from the optimum value. The LPL model shows the maximum deviation for maximizing production and benefit. At the same time, the FOP model seems to satisfy all the chosen goals. Fixing the criterion that the best management model should have the capability to tend to satisfy all the other goals simultaneously, while satisfying its intended goal built into the model, the LPP model can be considered as the best management model in the present context. Similarly, the LPNR and the FOP models can be put in the second best category. However, while choosing all the goals at the same priority level, the FOP model can be considered as the best option.

Table I. Optimum cropping pattern at different model simulations

Model	Optimal area allocated to the crop variables (ha)												Cropping intensity (%)	Optimal solution
	Kharif paddy	Rabi paddy	Chilly	Potato	Vegetables	Sugarcane	Wheat	Mustard	Arum	Green gram	Fodder	Onion		
LPP	379.28	42.10	42.10	84.20	252.60	79.25	42.10	42.10	25.26	84.20	8.42	84.20	147.87	20130630 kg
LPNR	380.50	42.10	42.10	84.20	256.74	75.11	42.10	42.10	25.26	84.2	8.42	84.20	147.52	RS. 24380840 P*
LPL	378.90	42.10	42.10	84.20	252.60	67.36	42.10	42.10	25.26	84.20	8.42	84.20	145.00	255210.2 man-days
FOP	378.90	42.10	42.10	84.20	253.23	72.79	42.10	42.10	25.26	84.20	10.04	84.20	146.55	0.541854

*1 US $ ≈ Rs. 48.

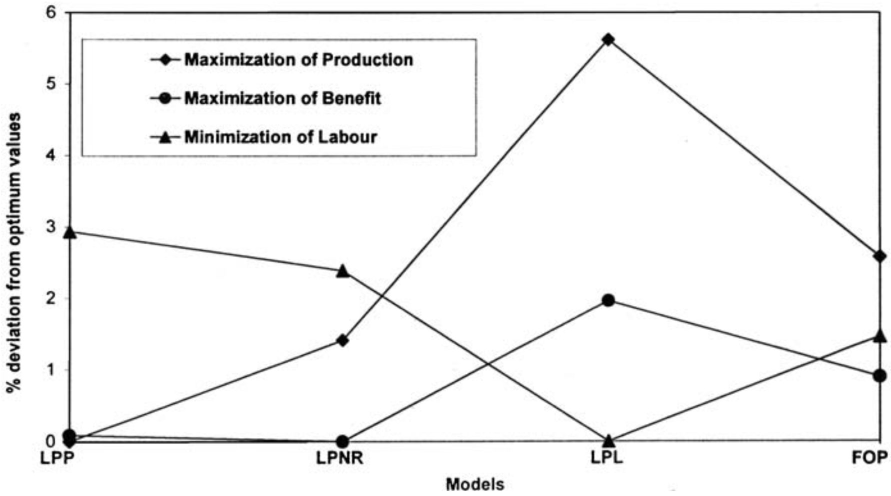

Figure 4. Deviation of objective functions from their optimum values for different management models.

From the resource utilization pattern of the study area (Table II and Figure 5), it can be revealed that the LPP model utilizes the highest land, fertilizer and labour resources of the study area for maximizing production, while the FOP model utilizes the maximum water resources. However, on an average, the LPNR model takes its second place for maximum utilisation of all the resources of the command area for maximizing the benefit. Since, the labour requirement in case of the LPP and the LPNR models is much higher than that of the FOP model, the later one may be the best option subject to the shortage of agricultural labour in peak periods and their possible city-ward migration in future. Further, with the increased agricultural mechanization in near future, the LPL model may be obsolete. Furthermore, the LPP model gives the highest benefit-cost ratio, followed by the LPNR, FOP and LPL models (Figure 6) over the benefit-cost ratio of the existing cropping system plan (Table III and Figure 5). However, the fuzzy based model (FOP), which gives

Table II. Resource utilization pattern of the command area at different model simulations

Model	Land (ha)	Water (MCM)*	Labour (man days)	Fertilizer (kg)
LPP	1245.06 (73.93%)	9366.5861 (31.81%)	262025 (33.04%)	217606.49 (88.54%)
LPNR	1242.31 (73.77%)	9274.7077 (31.50%)	260639 (32.87%)	217231.00 (88.38%)
LPL	1220.90 (72.50%)	9015.1600 (30.62%)	254536.6 (32.10%)	214120.6 (87.12%)
FOP	1234.01 (73.27%)	10597.9823 (35.996%)	258272 (32.57%)	216243.614 (87.98%)

*MCM= million cubic metre.

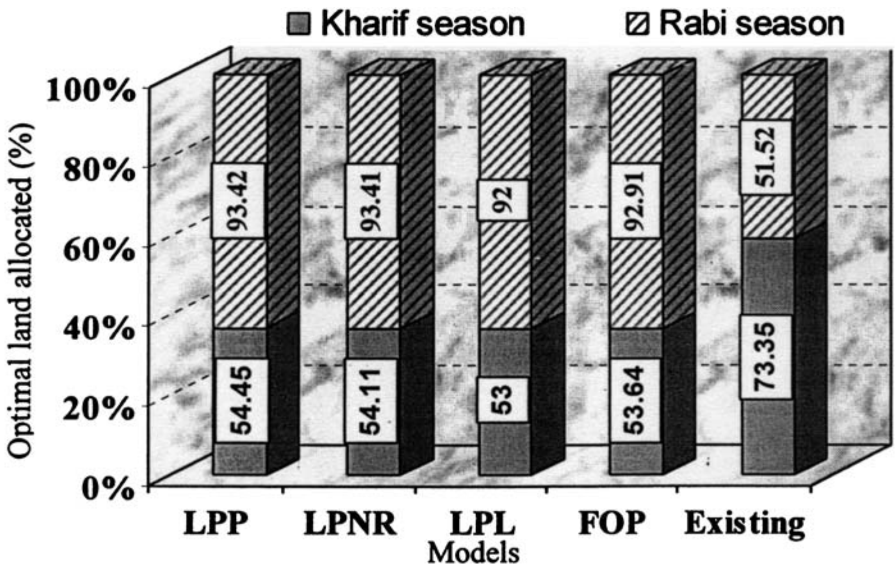

Figure 5. Comparison of cropping season-wise optimum land resources utilization pattern at four different management models with those of the existing for the deltaic basin.

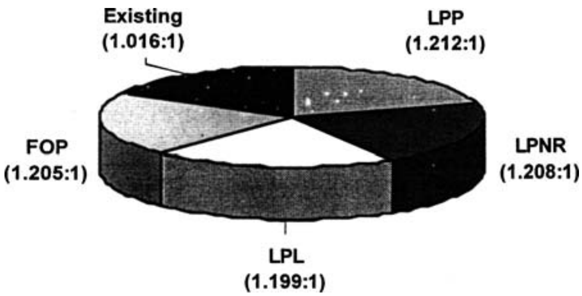

Figure 6. The benefit-cost ratios of the land-water-crop system planning at four different management models and that of the existing for the deltaic basin.

a compromised solution of 0.5418, is best suited for the delta with conflicting objectives between the decision makers and stakeholders.

Conclusions

The land-water-crop system planning of a deltaic basin has been carried out with three independent linear programming based objective functions and one fuzzy optimization based multi-criteria decision function. The LPP model utilizes the maximum resources of the study area and achieves the highest benefit-cost ratio, followed by the LPNR, FOP and LPL models. Hence, the models like LPP, LPNR

Table III. Benefit-cost ratios under different management plans

Management Model	Investment on farming system (Rs.)*	Net agricultural returns (Rs.)*	Total cultivated area(%)	
			Kharif season	Rabi season
LPP	20116507	24378470	54.45	93.42
LPNR	20180389	24380840	54.11	93.41
LPL	19934350	23902275	53.00	92.00
FOP	20045327.53	24161928.01	53.64	92.91
Existing	13827675	14046938	73.35	51.52

*1 US $ ≈ Rs. 48.

and FOP are best suited for the study area, depending upon the objectives of the decision makers and the farmers. In the present crop planning, the conventional crops have been selected keeping in view the interest of the farmers. However, some high yielding cash crops could be selected for the study area to increase the benefit-cost ratio of the farming system. Since, the delta is abundant with resources, the unutilised resources may be abstracted for the development of nearby resource-deficient commands. However, conjunctive use of water is advisable to restrict further depletion of groundwater table, which may happen in future years with the increase in water demand by the stakeholders. Further, the result of the study could be affected with the variation in the market price of the crop produce, cost of crop production, unit labour cost, unit fertilizer cost, groundwater pumping volume and unit water price. The study shows that the linear programming based management models have the capability for optimal land-water-crop system planning in case of single criteria decision systems, while the fuzzy rule based management models can still be used to deal with multiple criteria management decision systems.

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