Conceptualization of community-based integrated farming system model design with multi-objective optimization management

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Effective utilization of land and water resources is attempted in the present study through an integrated farming system and multi-objective optimization management framework model using goal programming algorithm in a coastal waterlogged paddy area in Odisha, India. A methodology is developed to identify the water harvesting structure locations in the study area using spatial science tool. Due to the uncertainty of parameters and control variables, development of management framework was considered with 85% and 75% probability of rainfall occurrence and runoff generation. To incorporate the uncertainties, a multi-objective linear goal programming optimization model is developed considering the objective of maximizing the net annual return and production subject to optimal allocation of land. While evaluating the model for different water resources scenarios, the net annual return is found to be Rs 4,343,474 and maximum production is 10,424 q from scenario I, whereas maximum production of 10,980 q is obtained in scenario II. Tomato and rice cultivation area increased from 11.47 to 21.43 ha and 8.82 to 10.48 ha respectively in scenario II. The developed methodology shows the potential applicability in similar farming situations in other areas.

Keywords: Integrated farming system, land and water resources management, linear goal programming, multi-objective optimization.

INTEGRATION of farming system (integrating crop–livestock) as a resource management strategy is essential to meet diverse requirements of farm households and to protect their livelihood. The basic aim of the integrated farming system (IFS) approach is to derive a set of resource development and utilization practices, which leads to substantial and sustained increase in agricultural production[1]. Thus, the farming system aims for enhanced productivity, profitability, sustainability and ultimately standard of living of farming community.

The Indian population is projected to become 1.53 and 1.69 billion respectively, in 2030 and 2050 from the present population of 1.27 billion[2]. The challenges on natural resources conservation need to be addressed judiciously due to decline in per capita availability of land from 0.5 ha in 1950–51 to less than 0.1 ha by 2020. Agricultural production will have to increase by at least 70% for the developed countries and 100% in the developing countries to cope with a 40% increase in the world population[3]. On an average, about 2035 farmers in our country are losing 'main cultivator' status per day for the last 20 years[4]. In India, 14.29 m ha is under coastal waterlogged area with Odisha's share of about 6671 ha[5]. In this adverse condition, it is imperative to develop strategies and agricultural technologies to enable adequate employment, income generation and especially to develop interest of the small and marginal farmers.

Multi-criteria or multi-objective decision-making is becoming increasingly popular as a decision tool for managing natural resources at the microscale. There exist two key components, namely the biophysical 'production system' comprising crops, pastures, animals, soil and climate, together with certain physical inputs and outputs, and the 'management system', made up of people, values, goals, knowledge, resources, monitoring opportunities and decision-making to characterize a farming system[6,7]. Diagnostic experiments based on IFS models, including various affiliated and region-specific farm enterprises have been demonstrated successfully in Indian conditions[8–11]. In addition to field-scale experiments, application of mathematical optimization models[12–14] offers flexibility of appropriating the available resources such as land and water[15–17] within the limits of the IFS system in the best possible way to attain certain preferred goals while fulfilling certain other goals of alternative agricultural Best Management Practices (BMPs), making the IFS system more sustainable[18]. However, very few studies have been reported on the application of the IFS model, including livestock component in problematic waterlogged and salt-affected crop-land situations. Therefore, the present study focuses on the development of an approach for identifying the suitable water harvesting structure locations

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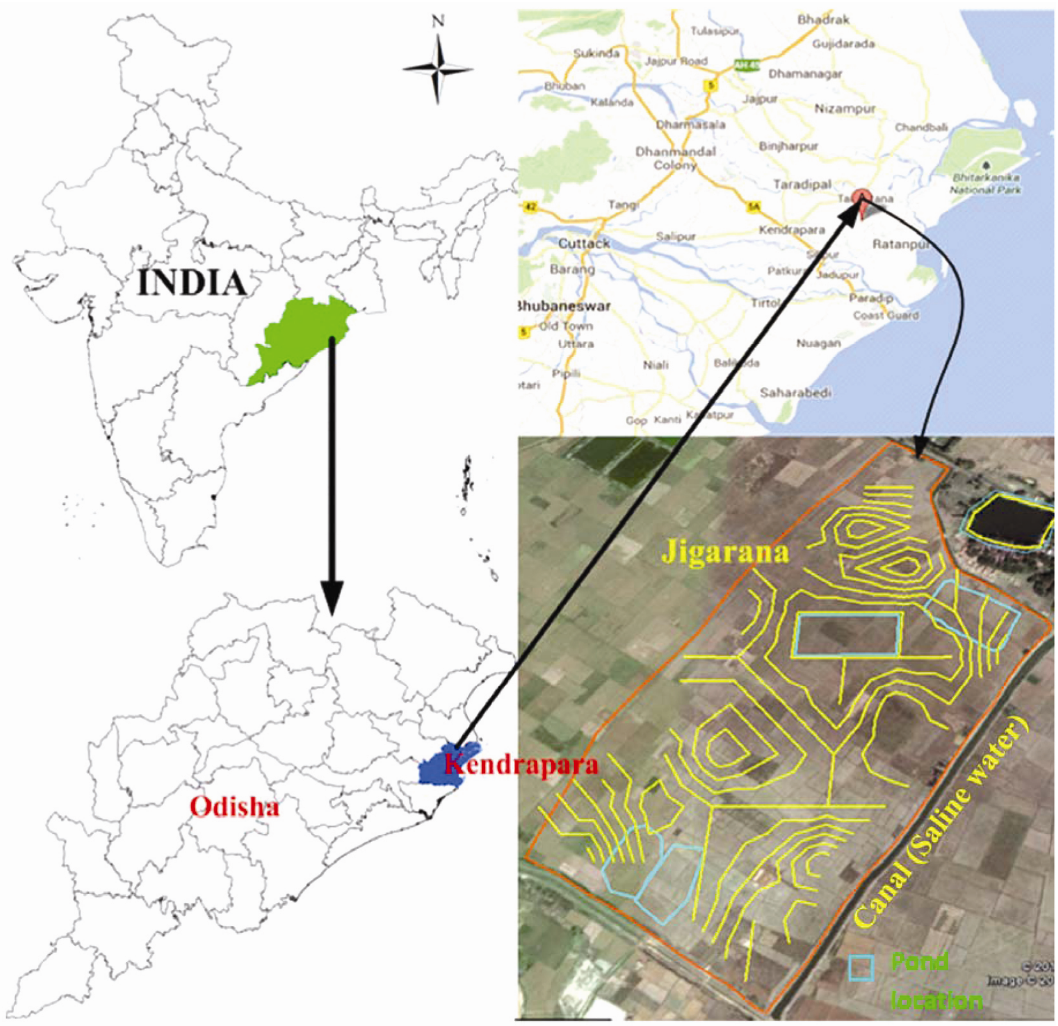

Figure 1. Location of the study area (Jigarana, Pattamundai, Kendrapara district, Odisha, India).

to facilitate the development of an IFS model with multi-objective optimization algorithm for a 41.4 ha coastal waterlogged paddy area in Odisha. The objective of the optimization model is maximizing net annual return and production maximization subject to optimal allocation of land and water resources.

Materials and methodology

Study area

The study area (Figure 1), a coastal waterlogged paddy area comprising 41.40 ha, lies between 86°58′–86°59′E and 20°51′–20°52′N in Odisha. Maximum elevation varies from 1 to 6 m amsl. Pattamundai main canal and Gobari extension canal pass in close proximity to the study area. Field drains executed on the east side of the study area by the Command Area Development, Department of Water Resources, Government of Odisha, adequately help in modulating the waterlogged paddy crop fields. Analysis of soil shows that it is acidic in nature (pH 6.0), and electrical conductivity (EC) varies from 0.4 to 0.5 dS/m. Soil contains average nitrogen of 240.8 kg/ha and K_2O of 190.60 kg/ha. The study area receives rainfall during the southwest monsoon from June to October. The average annual rainfall (1997–2008) of this area is found to be 1815 mm; temperature rises to a maximum of 43°C in May and falls to a minimum of 12.8°C in January, with an average maximum and minimum temperature of 29.8°C and 23.50°C respectively. Total number of rainy days is 149 and the number of effective rainfall (as run-off) days is 79 per year. The relative humidity is found to be maximum (93%) during September and minimum (28%) during May.

Integrated farming system model

In the present IFS model, livestock (fishery and poultry), horticultural and agricultural crops are introduced. For promotion of pisciculture, four water harvesting structures have been proposed with 9.6 ha land and bund area, covering 15% of the pond area. Composite fish culture practice having ratio 30 : 30 : 40 (surface : column : bottom layers for catla (*Catla catla*), rohu (*Labeo rohita*), and mrigal (*Cirrhinus cirrhosus*) respectively, @ 5000 fingerlings/ha) is proposed. On bund area of the proposed water harvesting structures (1.2 ha), banana (*Musa acuminata*) and papaya (*Carica papaya*) plantation with poultry farming are proposed in 0.50 ha. Rest of the land (30.1 ha) is proposed for use in agricultural activity during monsoon and winter seasons.

Identification of water harvesting structure locations

Run-off estimation is made using USDA SCS–CN method[19]. The rainfall data were taken from NASA POWER, Climatology Resource for Agro-climatology[20]. Total water resources has been estimated for the area and size of the water harvesting structures is decided based on run-off generation. Water harvesting structure helps store the excess surface run-off, which otherwise causes water-logging. Using satellite image SRTM DEM and ArcGIS software, contour, flow direction, flow accumulation, and slope map have been created to locate the suitable water harvesting structures.

Optimization model formulation

Charnes and Cooper[21] developed the goal programming technique to obtain solutions for a linear model. The technique involves formulation of specific goals corresponding to the criteria (objective functions) in a prioritized or weighted order. The goal objectives are assigned target levels and a relative priority for achievement of the desired goal. Optimum solution will be achieved when its value comes as close as possible to the targets. The linear goal programming (LGP) allows the multiple objective functions under common constraints. An LGP model can be written as

$$\text{Minimize } Z = \sum_{i=1}^{m} (W_i^+ d_i^+ + W_i^- d_i^-), \tag{1}$$

$$\text{Subject to } \sum a_{ij} x_j + d_i^- - d_i^+ = b_i; \forall\, i, \tag{2}$$

$$\text{Variables, } x_j, d_i^+, d_i^- \geq 0; \forall\, i \,\&\, j, \tag{3}$$

where m is the number of constraints. Equation (1) represents the objective function of goal programming, which minimizes the weighted sum of deviational variables, Equation (2) shows the goal constraint related to decision variables x_j and b_i. Equation (3) represents the basic hypothesis of the linear programming; all variables and deviational variables should not be negative. The optimization model was formulated consisting of two objective functions and a set of system constraints.

Objective function

The objective function maximizes the annual net return (G_1) and production (G_2) from the developed IFS model subjected to resources constraints.

Maximize net return (G_1)

$$= \sum_{i=1}^{n} \sum_{j=1}^{2} [(NR)_{ij} * A_{ij}];\ i = 1, 2, \ldots, n, \tag{4}$$

$$\text{Maximize production } (G_2) = \sum_{i=1}^{n} \sum_{j=1}^{2} (Y_{ij} * A_{ij}), \tag{5}$$

$$\text{where } (\mathrm{NR})_{ij} = (\mathrm{MR})_{ij} - (\mathrm{CC})_{ij}, \tag{6}$$

where i is the index for crop i, $i = 1, 2, \ldots, n$ (number of crops); j the index for season, $j = 1$ for monsoon (*kharif*) and $j = 2$ for winter (*rabi*) season; NR_{ij} the net return for crop i in season j (Rs/ha); A_{ij} the area allocation to crop i in season j (ha); Y_{ij} the yield of crop i in season j (q/ha); MR_{ij} is market return from crop i in season j (Rs/ha), and CC_{ij} is cultivation cost for crop i in season j (Rs/ha).

System constraints

The following constraints are involved in the optimization model:

(a) Land area constraints

$$\sum_{i=1}^{n} A_{ij} \leq \mathrm{TA};\ \forall\, j, \tag{7}$$

where TA is total area (ha) available for the season j.

(b) Water availability constraints: The irrigation water requirement for all proposed crops needs to be fulfilled from the available surface water resources. Water demand for poultry and minimum depth in the pond for fishery need to be provided to maintain normal growth. Surface water is the only available water resource for the proposed IFS model. Net irrigation requirement is computed considering different K_c values at different stages of individual crop

$$\sum_{k=1}^{12} \sum_{i=1}^{n} [(\mathrm{NIR})_{ik} * A_{ik}] + \sum_{k=1}^{12} [(\mathrm{PWR})_k * A_{\mathrm{poultry}}] \leq (\mathrm{TSWA})_k, \tag{8}$$

where

$(\mathrm{NIR})_{ik} = (\mathrm{ET}_c)_{ik} - (\mathrm{ER})_k$; $\forall$ ith crop and kth month,

$$(\mathrm{ER})_k = R_k - Q_k,$$

$$\mathrm{TSWA} = [(h_{\max} - h_{\min})*A_p];\ \forall\ k,$$

where K is the index for month, $K = 1, 2, \ldots, 12$; 1 for January, and so on; $(\mathrm{NIR})_{ik}$ the net irrigation requirement (mm) of crop i in month k; $(\mathrm{PWR})_k$ the poultry water requirement (mm) in month k; $(\mathrm{TSWA})_k$ the total surface water availability (ha-mm) in month k; $(A)_{\mathrm{poultry}}$ the area proposed for poultry cultivation; $(\mathrm{ET}_c)_{ik}$ the crop evapotranspiration (mm) for crop i in month k; $(\mathrm{ER})_k$ the effective rainfall (mm) in month k; R_k the rainfall (mm) in month k; Q_k the run-off (mm) in month k; $h_{\max}$ the maximum water storage height in pond (3.5 m); and $h_{\min}$ is the minimum water storage height in pond (1.2–1.5 m) depending on availability and demand.

(c) Fertilizer availability constraints

$$\sum_{i=1}^{5}(N_{ij}*A_{ij}) \le (\mathrm{TAN})_j;\ \forall\ j, \tag{9}$$

$$\sum_{i=1}^{5}(P_{ij}*A_{ij}) \le (\mathrm{TAP})_j;\ \forall\ j, \tag{10}$$

$$\sum_{i=1}^{5}(K_{ij}*A_{ij}) \le (\mathrm{TAK})_j;\ \forall\ j, \tag{11}$$

where N_{ij}, P_{ij} and K_{ij} are nitrogen, phosphorus and potassium needed for crop i and season j respectively; while TAN, TAP and TAK are total nitrogen, total phosphorus, and total potassium available for crop i and season j respectively.

Minimum/maximum allowable area

(a) For maximum area

$$A_{ij} \le \mu_{ij}^{\max}\mathrm{TA}. \tag{12}$$

(b) For minimum area

$$A_{ij} \ge \mu_{ij}^{\min}\mathrm{TA}, \tag{13}$$

where $\mu_{ij}^{\max}$ and $\mu_{ij}^{\min}$ are the factors by which the existing area of crop i can be increased or decreased respectively, in season j.

Non-negativity

$$A_i \ge 0; (\mathrm{TSWA})_{ij} \ge 0; \text{and } N_i, P_i, K_i \ge 0;\ \forall\ i, j. \tag{14}$$

USDA SCS curve number method

The basic hypothesis of SCS–CN technique for a simple storm is that a relationship exists between the runoff and the rainfall, which occurs simultaneously beyond a threshold rainfall that does not produce any runoff. An empirical relationship among rainfall (P), run-off (Q) and maximum potential retention (S) was developed

$$Q = \frac{(P-0.2S)^2}{(P+0.8S)},\ \text{when } P > 0.2S, \tag{15}$$

$$Q = 0,\ \text{when } P \le 0.2S.$$

In practice, the relation between curve number (CN) and S is as follows

$$S = \frac{25,400}{\mathrm{CN}} - 254, \text{when S is in millimetres}, \tag{16}$$

where CN is a dimension less value that ranges from 0 to 100. The CN value is determined from land cover and management, and from the hydrologic soil group using standard table from the SCS handbook. This CN value corresponds to average soil moisture and is adjusted based on five-day prior rainfall depth that depends on whether the crop is in the dormant or growing season. Further modifications have been made by converting the event-based USDA SCS–CN method to total rainfall in 24 h period. A reduction of antecedent moisture content (AMC) (II) curve number by 5 gave the closest agreement between the total run-off estimated from the individual event in 24 h period and that estimated from rainfall in a 24 h period as reported earlier[22].

Effective rainfall

Only the water retained in the root zone after rainfall that can be utilized by the plants is called the effective rainfall from agronomic point of view. Effective rainfall is calculated in relation to monthly rainfall using the following equations[23], which are applicable in areas with a maximum slope of 4–5%

$$\mathrm{ER} = 0.8 * R - 25; \text{if } R > 75 \text{ mm/month}, \tag{17}$$

$$\mathrm{ER} = 0.6 * R - 10; \text{if } R < 75 \text{ mm/month}, \tag{18}$$

where R is the rainfall or precipitation (mm/month) and ER is the effective rainfall or effective precipitation (mm/month); $\mathrm{ER} \ge 0$.

Net irrigation requirement

The net irrigation requirement is the amount of irrigation water required for optimum crop growth and production. Due to insufficient meteorological data availability, the Hargreaves and Samani[24] method was used in the present study to find the daily reference evapotranspiration (ET), which requires extraterrestrial solar radiation and mean daily maximum and minimum temperature data.

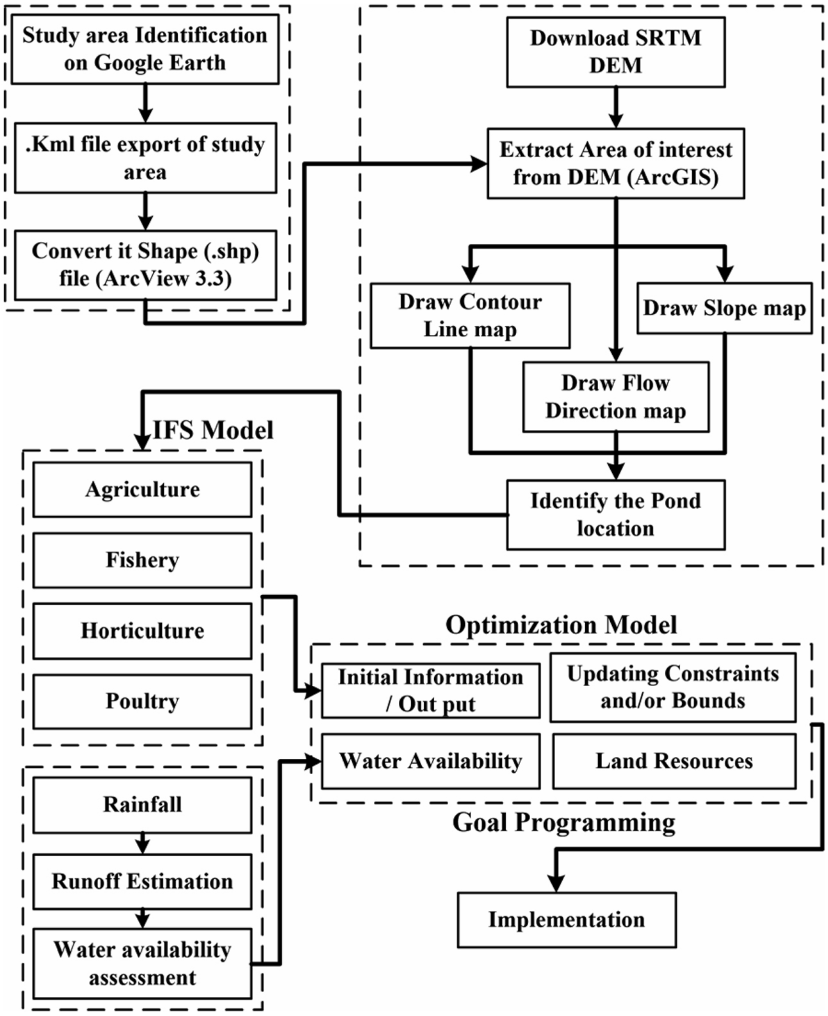

Figure 2. Schematic diagram of an integrated farming system and management framework model using goal programming algorithm.

$$ET_0 = 0.0023R_a\,(T_{mean} + 17.8)(T_{max} - T_{min})^{0.5}, \quad (19)$$

where ET_0 is reference evapotranspiration (mm day^{-1}); R_a the extraterrestrial solar radiation (MJ m^{-2} day^{-1}); T_{max}, T_{min} and T_{mean} are the daily maximum, minimum and mean air temperatures (°C) respectively. The crop coefficient (K_c) values for each crop were taken from Allen *et al.*[25] to calculate crop evapotranspiration (ET_c) at different crop growing stages. ET_c (mm day^{-1}) was calculated by multiplying the reference crop evapotranspiration (ET_0) and crop coefficient (K_c)

$$ET_c = K_c * ET_0. \quad (20)$$

So, net irrigation requirement (NIR) of crop that needs to be applied to meet the crop demand can be estimated from the equation

$$NIR = ET_c - ER. \quad (21)$$

Integrated management model

Figure 2 presents the overall methodology. With initial information about the different system parameters, optimization algorithm is utilized to obtain a possible policy. The management framework interlinks the IFS model and optimization model iteratively to give meaningful land and water resources management strategy.

Model application

Identification of suitable water harvesting structure locations: To identify the suitable water harvesting structure locations for gravity flow within the study area, SRTM DEM is used. The study area is identified from satellite imagery, and is marked and exported in .kml file. Extraction of the study area from DEM is done in ArcGIS environment using Arc toolbox (spatial analyst tool).

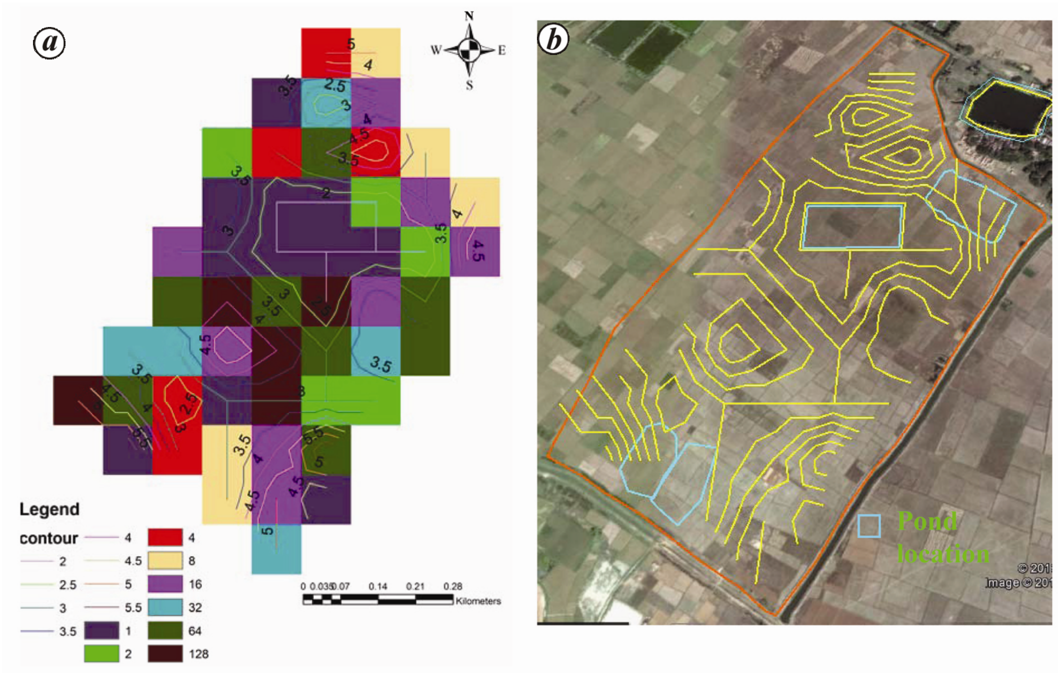

Figure 3. ***a***, Contour and flow direction map; ***b***, Contour map with probable pond location.

Table 1. Annual run-off (1997–2008) of the study area by soil conservation service curve number method

Year	Rainfall (mm)	Run-off (mm)	Run-off coefficient
1997	1841.1	1249.08	0.68
1998	1801.0	1217.78	0.68
1999	1951.5	1467.42	0.75
2000	1412.1	968.43	0.69
2001	1948.5	1355.51	0.70
2002	1469.6	982.75	0.67
2003	1967.8	1403.74	0.71
2004	1664.8	1218.46	0.73
2005	1957.0	1436.93	0.73
2006	1820.9	1330.26	0.73
2007	1966.6	1467.72	0.75
2008	1984.3	1475.04	0.74
Average	1815.43	1297.76	0.71

Figure 3 *a* shows the contour and flow direction map of the study area. Based on contour, flow direction and slope map, the water harvesting structure locations are marked (Figure 3 *b*). Model result is verified by field visit and Google Earth.

Estimation of run-off: Daily rainfall data of 12 years (1997–2008) were used to estimate daily run-off and were aggregated annually to find out annual run-off coefficient (Table 1), which was calculated as 0.71. Figure 4 shows temporal variation of rainfall and runoff value. These annual rainfall and run-off pairs were then ranked individually to find the run-off at 75% and 85% probability. While doing so, it was assumed that the same annual probability of rainfall would produce the same probability of run-off[26]. The Weibull discrete probability technique was used to determine the rank probability in either of the cases. In this method, at a dependable rainfall of 75% (1700 mm) and 85% (1460 mm), the run-off was determined as 763 mm and 660 mm respectively.

Estimation of reference crop evapotranspiration: The daily reference crop evapotranspiration (ET_0) was computed using the Hargreaves and Samani method based on 16 years (1997–2012) daily data (Figure 5). Figure 5 shows the average monthly variation of maximum and minimum temperature. The minimum and maximum ET_0 values of 90 and 212 mm/month were observed during August and March respectively. Average daily, monthly and yearly average ET_0 values were 4.52, 137.33 and 1648 mm respectively.

Estimation of effective rainfall: Figure 6 represents 12-years monthly average variation of rainfall and effective rainfall at 85% and 75% dependable rainfall. Average rainfall and effective rainfall were 1815.5 and 1229.50 mm/year respectively.

Results and discussion

The LGP optimization model has been developed and solved in WINQSB[27] for two different scenarios. Conceptualization of the IFS model was made and optimization model was run for finding the optimum solution of the IFS model. The lower and upper limits of the existing cropping pattern and the newly proposed four crops (i.e.

Table 2. Existing input parameter for both seasons of the study area

	Kharif paddy¥	*Rabi* paddy€	Tomato	Brinjal	Miscellaneous (papaya + banana)	Fishery	Poultry
NIR (mm)	106	587	256	622	1103	**	720
Unit profit (Rs, */ha)	25	24	80.5	86	207	110	500
Yield (q/ha)	35	30	200	150	480	36.5	8000
Nitrogen (kg/ha)	62	62	90	60	121	–	–
Phosphorus (kg/ha)	30	15	25	30	40	–	–
Potassium (kg/ha)	30	15	25	20	363	–	–

*Rupees in thousand units; **Water depth in pond maintained at minimum (1.2–1.5 m) for normal growth. ¥*Kharif* means monsoon season, €*Rabi* means winter season. NIR, Net irrigation requirement.

Table 3. Optimal crop area allocation for scenario I

Crop/decision variable	Area allocation (ha)	Unit profit (Rs/ha)	Total contribution (Rs)
Kharif paddy	8.82	25,000	220,622
Rabi paddy	0	24,000	0
Tomato	11.47	80,500	923,277
Brinjal	18.53	86,100	1,595,495
Miscellaneous	1.44	207,000	298,080
Fishery	9.6	110,000	1,056,000
Poultry	0.5	500,000	250,000

*Goal 1, maximum profit = Rs 4,343,474.00. **Goal 2, maximum production = 10,424 q.

Table 4. Optimal crop area allocation for scenario II

Crop/decision variable	Area allocation (ha)	Unit profit (Rs/ha)	Total contribution (Rs)
Kharif paddy	10.48	25,000	262,117
Rabi paddy	0	24,000	0
Tomato	21.43	80,500	1,724,965
Brinjal	8.57	86,100	738,038
Miscellaneous	1.44	207,000	298,080
Fishery	9.6	110,000	1,056,000
Poultry	0.5	500,000	250,000

*Goal 1, maximum profit = Rs 4,329,200.00. **Goal 2, maximum production = 10,980 q.

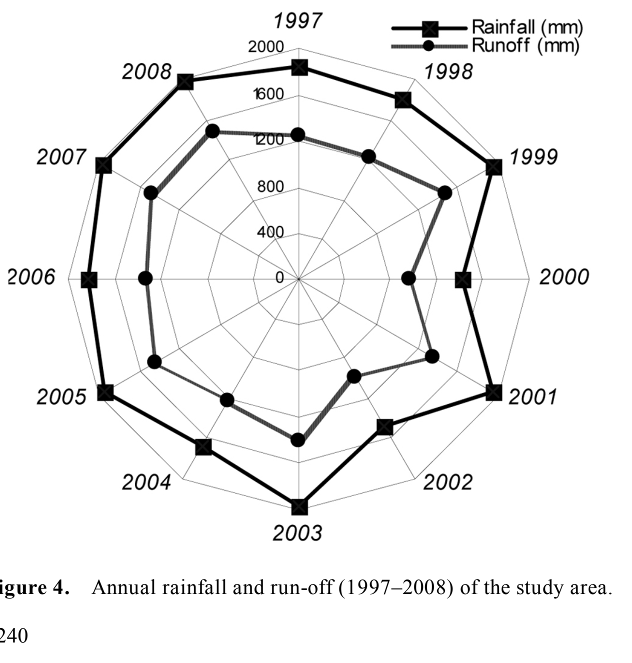

Figure 4. Annual rainfall and run-off (1997–2008) of the study area.

tomato, brinjal, papaya and banana) based on the farmers' preferences and available water resources have been considered in the IFS model. Basic existing crop information like availability of fertilizer use and net return for the preferential crops collected from the local District Agriculture Office, Government of Odisha (Table 2) was used. Pisciculture in the water harvesting structures and horticultural crops like papaya and banana on the bunds of the proposed structures were considered in the model. A total of 0.5 ha area was considered for rearing poultry cultivation. In total, in scenario I, based on water availability considered as estimated run-off from the 75% dependable rainfall is 763 mm. The net annual return and maximum production were computed as Rs 4,343,474 and 10,424 q respectively, from the proposed IFS model (Table 3).

Scenario II is similar to scenario I, except for water availability. Run-off estimated from the 85% dependable rainfall is 660 mm. Table 4 shows the optimum allocation

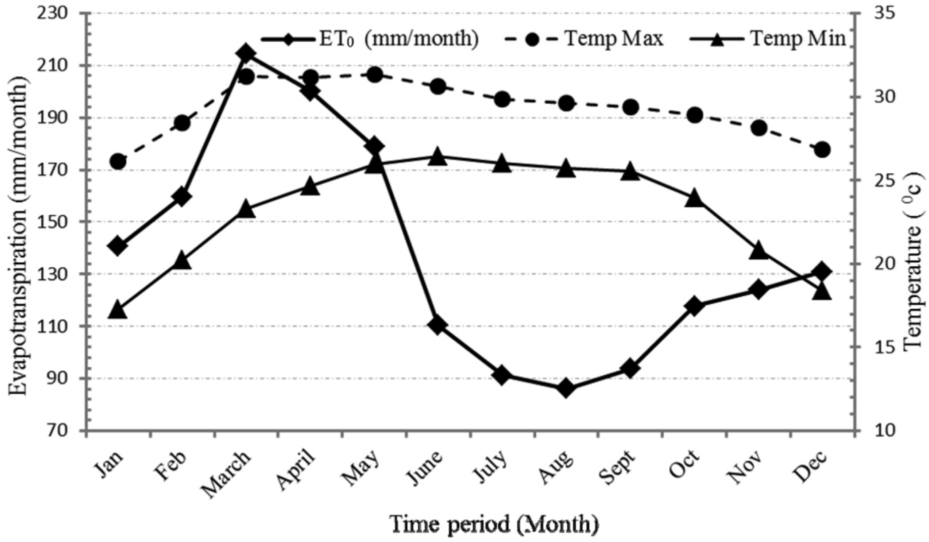

Figure 5. Monthly average (1997–2012) reference crop evapotranspiration (ET_0) and temperature variation of the study area.

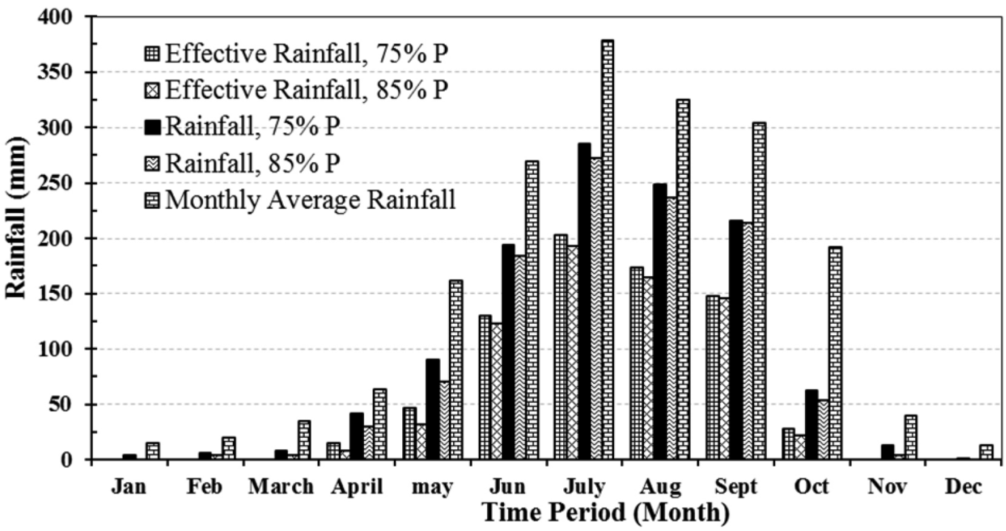

Figure 6. Monthly average rainfall, effective rainfall of 12 years (1997–2008) at different probabilities.

of the IFS model. In scenario II, it is deduced that the allocated area for monsoon season paddy cultivation increases in comparison to scenario I. It is also observed that tomato crop significantly increased compared to other crops in scenario II, and the net annual return decreased by Rs 14,274; however, productivity increased by 556 q. Tomato and paddy cultivation area increased from 11.47 to 21.43 ha and 8.82 to 10.48 ha respectively. No significant difference was observed between the two scenarios for net annual profit and production. However, the study inferred considering 85% probability level of run-off for minimizing the initial investment and successful implementation of the proposed framework. It also indicated that community-based IFS in coastal waterlogged crop lands has significant impact on local farmers.

Conclusion

A community-based IFS model with multi-objective optimization model has been developed to calculate the effectiveness of the IFS model, maximum net benefit, maximize production and optimum crop area allocation under uncertain hydrological events like rainfall. Two different scenarios (run-off estimated at 75% and 85% of dependable rainfall) were considered. A methodology has been developed to identify the suitable water harvesting structure locations for the gravity flow in saucer-shaped waterlogged crop field, situation using spatial science tool. Crop area allocated for monsoon season paddy cultivation increased in scenario II with decrease in profit. However, due to less utilization of available water resources in scenario II, tomato and monsoon season paddy cultivated area showed an increase. For more realistic and sustainable development of the methodology, scenario II is considered for implementation. The developed IFS model linked with the multi-objective optimization model are effective tools for socio-economic development of the coastal waterlogged areas and can be applied to any region with variation in resource constraints. The proposed model does not consider any physical process involvement. However, the limits (upper/lower bounds) are defined based on field conditions and availability of resources generation.

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