Systems Analysis of Tank Irrigation: I. Crop Staggering

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Abstract: The irrigation potential of a tank system, thousands of which are found in South India, depends upon a number of factors other than water availability. These factors are mainly influenced by the agricultural technology adopted, food practices of people and livestock, the interdependence of land-human-livestock components of life, and socioeconomic practices prevailing in rural areas. The system needs to pertain not only to grain yield but also to fodder production. In semiarid regions of India, uneven distribution and insufficient rainfall during the initial crop season develops water stress in plants. Relatively higher irrigation efficiency, which is possible to attain in tank systems, leads to an increase in the energy resources required for various agricultural operations. An attempt is made in this paper to investigate the effect of these factors on the optimal use of irrigation potential of a minor irrigation tank system. The method involves developing a linear programming (LP) model to optimize the net profit from the system and to determine the optimal cropping pattern under the influence of various parameters, e.g., animal power, labor, fodder production, the resources of farmers, and the nutritional energy requirement of the system, in addition to water availability. The crucial nature of these factors as well as the irrigation efficiency is analyzed. The solution reveals the effectiveness of prevailing agricultural practices consistent with the availability of water resources in the initial crop season.

Introduction

In the southern states in semiarid tropical India, small irrigation systems have existed since Vedic times (Von Oppen and Subba Rao 1980). Small reservoirs formed by building earthen bunds across local streams receiving runoff from small watersheds are extensively found in peninsular India. These reservoirs are generally known as tanks (Prasad 1983). It is not uncommon to find a series of tanks interconnected and also interdependent in their use. Normally, tanks are surrounded by agricultural land and situated near one or more villages. Some domestic and most agricultural water needs of such villages are met by these tanks. The operation, maintenance, and use of tanks often differ from those of conventional reservoirs due to a number of reasons. The geographical location, larger watershed area, higher capacity, smaller free-water surface area compared to the command area, larger length of canals, and multiple uses of stored water are the main factors, which need consideration in the analysis for optimal benefit from big reservoirs. On the other hand, comparatively smaller watershed and low-inflow, smaller storage, larger free-water surface area compared to the command area, and shorter length of the canals, as well as the socioeconomic practices prevailing in the adjoining villages, constitute a different basis of analysis for the optimal use

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of tanks. Compared to the multiple uses of conventional reservoirs, tanks are mainly irrigation-oriented.

Tanks are in general shallow, with the maximum depth of water in most of them around four meters. The storage capacity of tanks varies widely. The average storage per tank in Karnataka, a state in South India, is about 350,000 m^3. The free-water surface area bears on the average a ratio of about 0.75 to the area irrigated. The ratio is lower for new tanks but increases with age due to progressive sedimentation. Since tanks are in the midst of agricultural land, the submergence of land by the tanks represents a loss of cultivable land. The large free-water surface area in relation to the storage in the tanks results in large evaporation rates. This contributes the major portion to the loss of storage. At the end of summer or just before the monsoon, most of the tanks are almost dry. The loss of storage due to seepage through the tank bed and sides are small compared to the evaporation loss. Even though in the initial years of the life of a tank the seepage loss is considerable, subsequently, due to silting, this loss becomes negligible. Since the irrigable land is almost immediately downstream of the tank, the length of irrigation canals are short, and thereby the loss of water from canals due to evaporation and seepage is also small compared to the evaporation from the tank free-water surface area.

About 40% of the irrigated area in Karnataka is supplied by water from tanks (Fig. 1). The region of the state considered here normally receives most of its rainfall in the months of September, October, and November. However, the normal crop season starts during the second and third week of July in order for the crop to get the benefit of warm weather during the flowering and yield formation stages of crop development. In this paper, a typical tank irrigation system is analyzed with due consideration to the prevailing agricultural practices consistent with the socioeconomic conditions of the village.

Numerous mathematical models have been developed for single-purpose, single-reservoir systems, multiple-purpose, single-reservoir systems, and multiple-purpose, multiple-reservoir systems. These models decide the operation policy, optimum storage, or optimum cropping pattern considering either deterministic or stochastic inflows.

The treatment of the subject in these works is in the socioeconomic context prevailing in developed countries. The situation is less developed countries (LDC) is quite different, and constraints not even mentioned in the existing literature become important in LDCs. In any case, not much work has been done on the kind of tank irrigation system described here, which forms one of the major sources of irrigation in many parts of India.

Description of Typical Tank Irrigation System

The source of irrigation water, the prevailing agricultural technology, the food practices of people and livestock, and the interdependence of the land-human-livestock components of life principally necessitate the consideration of the tank irrigation system as part of an agricultural system. The agricultural technology of Indian villages is mainly human-labor oriented. The various operations involved can further be bifurcated into male- and female-labor oriented. For example, plowing is done by men and transplanting by women. The technology is also extensively dependent upon draft-animal power

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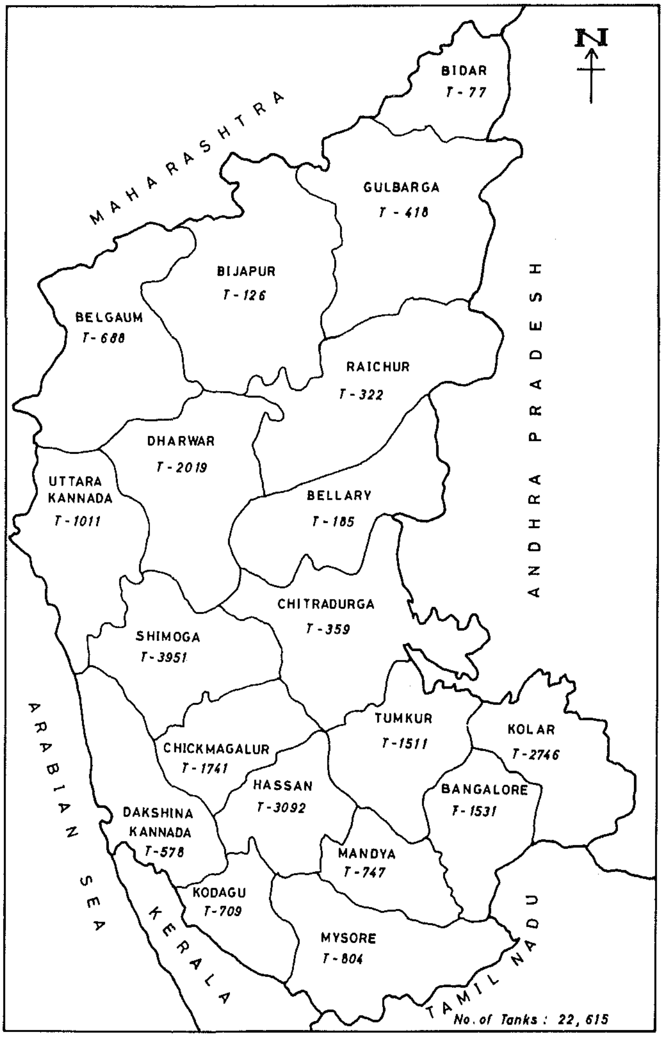

FIG. 1. Distribution of Tanks in Karnataka by District

for its energy requirements, e.g., plowing. The availability of draft animals further depends upon the fodder produce. Since crop straw is the major fodder variety, it is insufficient for the optimal cropping pattern to be aimed solely toward higher grain production. Due consideration must be given to fodder production as well.

The village agricultural ecosystem is highly dependent on the external world for several necessary items, including food articles. Change of cropping pattern and replacement of one crop by another of higher carrying capacity (caloric value per unit area of land) is not uncommon. The food components not available locally are imported from outside the system, which is compensated by the exporting of local produce out of the system. This import and export of food grains out of and into the ecosystem to meet the basic nutritional requirements in the system affects the economy of the system. In addition, the resources input in the agricultural ecosystem, primarily for fertilizers, seedlings, irrigation, human labor, and animal power, is highly limited because of small holdings, which at times has considerable influence on the cropping pattern.

The present paper treats a single-purpose, single-tank system. The objective is to determine an optimal cropping pattern in a tank-irrigated ecosystem that will provide maximum return consistent with the techniques of agricultural operations used and the needs of the village.

Data

In the present study, a typical village agricultural ecosystem existing in the state of Karnataka is considered. The village Ungra is located at a distance of 113 km from Bangalore, the capital of Karnataka.

The tank under consideration has a catchment area of 17.8 km^2, a gross storage of 90 ha-m, a live storage of 81 ha-m, and a waterspread of 182.8 ha. Mean annual rainfall in the catchment is 76.7 cm. Weekly normal rainfall and the inflows to the tank are given in Table 1, which shows nearly 80% of the inflow takes place during the months of September, October, and November (Ramana and Havanagi 1979).

A detailed survey of various facets of the ecosystem of the village was conducted during the year 1980–81 by the Centre for Application of Science and Technology to Rural Areas (ASTRA), an interdisciplinary, interdepartmental program of the Indian Institute of Science (Ravindranath 1981). The data used in the following analysis were collected during that survey. In the analysis, eight crops, rice, ragi (finger millets), maize, wheat, sorghum, oilseeds, and pulses, produced in the region and surroundings are considered.

Formulation of Model

A deterministic LP model is first formulated to represent the existing situation associated with a tank irrigation system. The objective function is formulated to maximize the net return from the crops.

$$\sum_{i=1}^{N} P_i X_i \qquad (1)$$

in which P_i = net profit per hectare of the ith crop; X_i = cropped land area of the ith crop; and N = number of crops (eight in this analysis).

The net profit for different crops is the difference between the selling price at the farmer's end and the cost of production that includes cost of labor, fertilizers, irrigation, and seedlings (Table 2).

The constraints concerned with tank irrigation can be grouped into three major classes; land area, water, and resources input.

Land Constraint

The total land area of all the crops should not be greater than the available

TABLE 1. Normal Weekly Rainfall and Inflows (Catchment Area 17.8 km²)

Week (1)	Date (2)	Mean weekly rainfall (mm) (3)	Mean weekly inflow (ha-m) (4)
13	3/29–4/1	3	—
14	4/2–8	5	—
15	4/9–15	9	—
16	4/16–22	13	—
17	4/23–29	13	—
18	4/30–5/6	21	0.18
19	5/7–13	21	0.18
20	5/14–20	29	0.54
21	5/21–27	31	1.43
22	5/28–6/3	26	1.78
23	6/4–10	21	1.96
24	6/11–17	13	1.25
25	6/18–24	14	1.42
26	6/25–7/1	13	1.78
27	7/2–8	14	2.14
28	7/9–15	15	2.49
29	7/16–22	17	2.85
30	7/23–29	19	3.92
31	7/30–8/5	21	4.99
32	8/6–12	20	5.52
33	8/13–19	21	6.05
34	8/20–26	28	8.90
35	8/27–9/2	29	10.15
36	9/3–9	27	11.04
37	9/10–16	20	8.54
38	9/17–23	46	23.14
39	9/24–30	44	20.11
40	10/1–7	55	31.15
41	10/8–14	48	30.79
42	10/15–21	32	21.89
43	10/22–28	24	16.91
44	10/29–11/4	19	14.24
45	11/5–11	14	11.04
46	11/12–18	14	10.15
47	11/19–25	9	7.30
48	11/26–12/2	4	3.38
49	12/3–9	6	3.74
50	12/10–16	6	4.27
51	12/17–23	4	3.81
52	12/24–30	—	0.89

land in the system:

$$\sum_{i=1}^{N} X_i \leq TL \qquad (2)$$

in which TL = total available irrigable land, in this case 243.7 ha.

TABLE 2. Net Profit from Various Crops

Crop (1)	Grain yield (Rs/kg) (2)	Selling price (Rs/kg) (3)	Value of produce (Rs/ha) (4)	Total input (Rs/ha) (5)	Net profit (Rs/ha) (6)
Rice (kharif)	3,930	3.00	11,790	3,486	8,304
Ragi	2,527	1.65	4,170	2,475	1,695
Maize	2,527	1.55	3,917	3,214	703
Wheat	1,685	2.80	4,718	3,664	1,054
Sorghum	2,527	1.50	3,790	2,772	1,018
Sunflower	1,011	5.15	5,207	2,626	2,581
Groundnut	1,235	5.00	6,175	2,942	3,233
Pulses	741	2.50	1,852	1,552	300

Water Constraints

Water Availability

As there is no carry-over storage available in small tanks of the type considered, the irrigation application depends primarily upon seasonal rainfall and the inflows. The total quantity of water applied to various crops in any irrigation should not be greater than the water storage available during the time period under consideration:

$$\sum_{i=1}^{N} W_{ti}X_i \leq S_{t-1} + I_t - E_t, \qquad t = 1, \ldots, N_t \quad (3)$$

Continuity equation:

$$S_t = S_{t-1} + I_t - E_t - \sum_{i=1}^{N} W_{ti}X_i - Q_t, \qquad t = 1, \ldots, N_t \quad (4)$$

Canal capacity constraint:

$$\sum_{i=1}^{N} W_{ti}X_i \leq C, \qquad t = 1, \ldots, N_t \quad (5)$$

Storage constraints:

$$S_t \leq S_{\max}, \qquad t = 1, \ldots, N_t \quad (6)$$

The crop-water requirement for optimal crop yield is computed by the method developed by Doorenbos and Pruitt (1977). A reference evapotranspiration is first calculated from the weather data with a modified Penman formula, and then an empirical multiplier crop coefficient (Doorenbos and Kassam 1979), whose value depends on the crop growth stage, is used to obtain the maximum evapotranspiration and, in turn, W_{ti}. Table 3 gives the weekly evapotranspiration calculated this way for different crops. Dastane (1977) developed a relationship between mean monthly effective rainfall, mean monthly rainfall, and mean monthly crop evapotranspiration that is used in the present analysis to arrive at the effective rainfall. The difference between the evapotranspiration ET and effective rainfall is then divided by the irrigation efficiency η to give the canal releases:

TABLE 3. Weekly Evapotranspiration for Different Crops (mm)

Week (1)	Crop						
	Rice (2)	Ragi and maize (3)	Wheat (4)	Sorghum (5)	Sunflower (6)	Groundnut (7)	Pulses (8)
1	41	15	13	13	13	17	17
2	40	14	13	13	13	16	16
3	38	13	25	26	25	25	26
4	45	31	30	31	30	30	31
5	37	26	25	26	25	25	26
6	51	35	34	35	34	34	35
7	51	35	34	49	51	51	51
8	61	42	61	58	61	61	61
9	51	51	51	49	51	51	49
10	40	40	40	28	40	40	38
11	42	33	26	29	28	42	40
12	45	35	28	31	30	32	41
13	47	34	28	31	30	32	41
14	42	31	24	27	14	28	—
15	36	31	8	21	14	28	—
16	31	27	7	18	—	18	—
17	27	15	—	—	—	15	—
18	31	18	—	—	—	—	—
19	37	—	—	—	—	—	—
20	37	—	—	—	—	—	—
21	33	—	—	—	—	—	—
22	34	—	—	—	—	—	—
23	35	—	—	—	—	—	—
24	31	—	—	—	—	—	—
25	30	—	—	—	—	—	—

$$W_{ti} = (ET_{ti} - \text{effective rainfall}) \frac{1}{\eta} \quad (7)$$

The evaporation loss E_t from storage on a given day is proportional to the tank waterspread. It is assumed here that the waterspread is proportional to the square of the depth of storage and the storage volume to the cube of the depth. Evaporation can then be reflected to the volume of water stored by the equation

$$E_t = KS_{ta}^{2/3}E_d \quad (8)$$

in which K = proportionality constant; S_{ta} = average volume of storage during the week (in ha-m); and E_d = depth of evaporation during the week.

K is determined on the basis of the waterspread area at the full tank level. In view of the simplifications introduced, it is not worthwhile solving a nonlinear equation due to the storage term in Eq. 8. In the range of interest, the expression $0.18S_{ta} + 4$ adequately represents $S_{ta}^{2/3}$ (Fig. 2). Depth of evaporation during the week is considered on the basis of the seasonal mean evaporation in the region as estimated by the India Meteorological Department. The mean depth of evaporation for winter (November–February) is

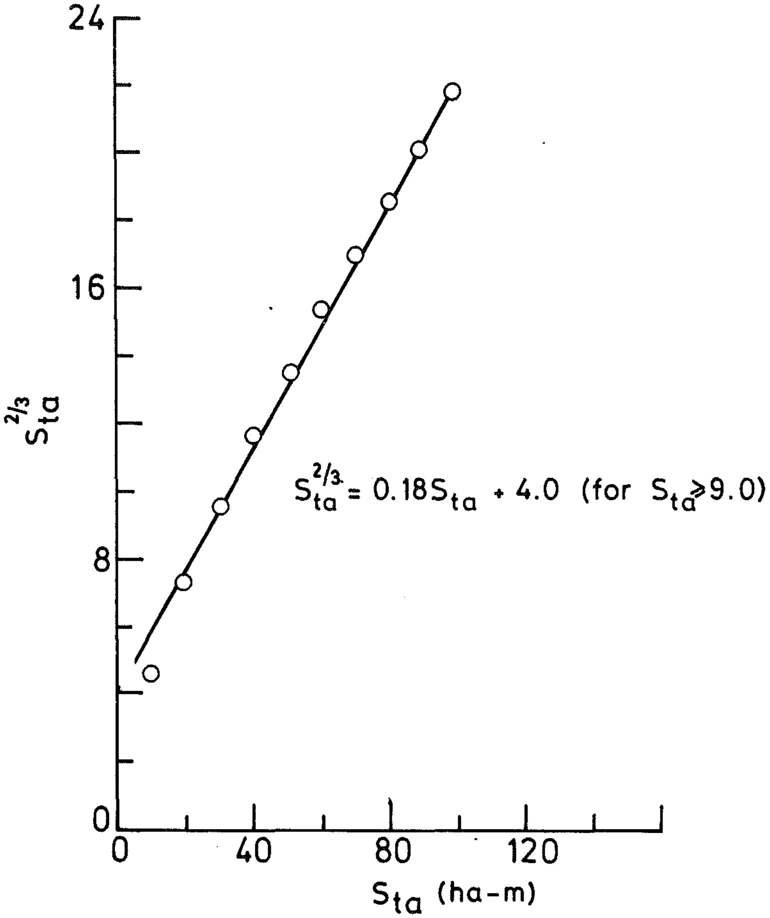

FIG. 2. Relationship between S_{ta} **and** $S_{ta}^{2/3}$

75 mm/mo; for summer (March–June), 250 mm/mo; and monsoon (July–October), 125 mm/mo. To represent the average storage S_{ta}, a function of initial and final storages, S_{t-1} and S_t in any given week, the weekly volumetric evaporation losses from the tank waterspread are represented by the following:

Winter:

$$E_t = 0.0144(S_{t-1} + S_t) + 0.896 \qquad (9a)$$

Monsoon:

$$E_t = 0.0239(S_{t-1} + S_t) + 1.492 \qquad (9b)$$

The summer period is irrelevant here as there is no crop. The normal crop season in the region starts from the second week of July. Rice has the largest duration (20 weeks), and thus there will be 20 weekly irrigation applications.

Thus Eqs. 3 and 4 can be represented as follows:

Water availability:

$$\sum_{i=1}^{N} W_{ti}X_i - 0.9761S_{t-1} + 0.0239S_t \leq I_t - 1.492, \qquad t = 1, \ldots, 15 \quad \ldots\ldots (10)$$

$$\sum_{i=1}^{N} W_{ti}X_i - 0.9856S_{t-1} + 0.0144S_t \leq I_t - 0.896, \qquad t = 16, \ldots, 20 \quad \ldots\ldots (11)$$

Continuity equation:

$$\sum_{i=1}^{N} W_{ti}X_i + 1.0239S_t - 0.9761S_{t-1} + Q_t = I_t - 1.492, \quad t = 1, \ldots, 15 \ldots\ldots (12)$$

$$\sum_{i1}^{N} W_{ti}X_i + 1.0144S_t - 0.9856S_{t-1} + Q_t = I_t - 0.896, \quad t = 16, \ldots, 20 \qquad (13)$$

Irrigation efficiencies in many irrigation projects in developing countries are as low as 25–40% (Hargreaves et al. 1985). With an overall efficiency of 30% (water application efficiency 60%; conveyance efficiency 50%), the irrigation water release W_{ti}, considering the effective rainfall, is

$$W_{ti} = \frac{(ET_{ti} - \text{effective rainfall})}{0.3} \quad \ldots\ldots (14)$$

Constraints Based on Resources Input

Draft Animal Pair (DAP) Requirement

The crucial importance of DAP in a traditional agricultural ecosystem is primarily due to its major contribution to the energy input. Plowing followed by harrowing are the major agricultural operations involving DAP. Normally, plowing is spread over the first two weeks, followed during the third week by harrowing, after which the fields are ready for transplanting. Thus, the DAP is used in the first three weeks of the crop season. The requirement of DAP during any week should not be greater than the available DAP in the ecosystem. The DAP constraint is given by

$$\sum_{i=1}^{N} \text{DAP}_{ti}X_i \leq \text{DAP}_{\max}, \qquad t = 1, 2, 3 \quad \ldots\ldots (15)$$

in which DAP_{ti} = DAP hours required for any agricultural operations per hectare of the ith crop during the week; and $\text{DAP}_{\max}$ = maximum hours of DAP available.

Male Labor Requirement

Male labor in agricultural operations is required for land preparation, consisting of plowing and harrowing and for transplanting during the initial period of crop season. Later, during harvest, male labor is used for harvesting, bundling, and transportation, and for post-harvest operations of threshing, winnowing, and rolling. Male labor is also used for irrigation, manuring,

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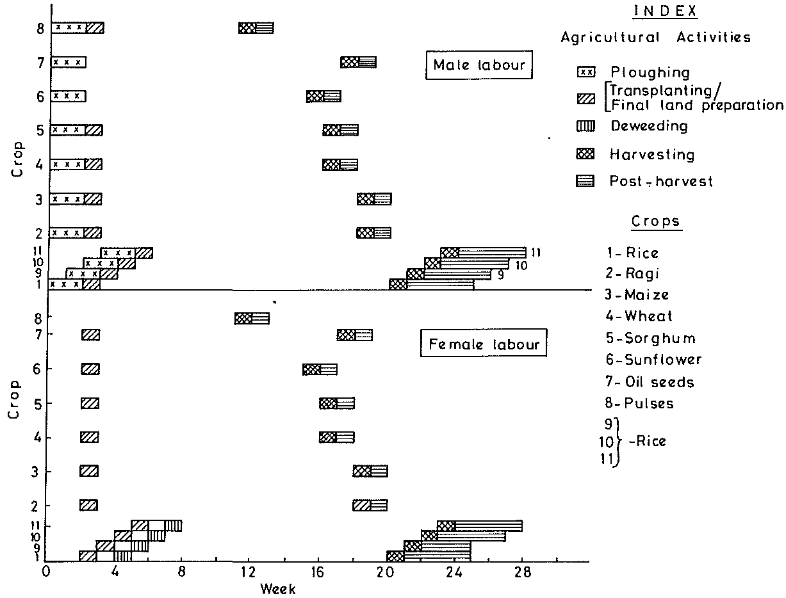

FIG. 3. Labor Requirements for Different Agricultural Activities

and spraying pesticides. However, the requirement for these operations is negligible and is therefore not considered here. During land preparation male labor is required in conjunction with DAP, and thus there are three constraints on male labor. Harvesting, bundling, and produce transport during harvesting and post-harvest operations like threshing, winnowing, and rolling are two separate simultaneous operations. These operations for rice take place from week 21 to week 25, while for other crops, they start as early as the week 13 and end in week 20, depending upon the crop period, with a gap in week 15. Fig. 3 shows the weekly requirement of male labor for different agricultural operations for various crops. Thus, there will be a total of 15 constraints on male labor:

$$\sum_{i=1}^{N} M_{ti}X_i \leq M_{\max} \qquad t = 1, 2, 3, 13, 14, 16, \ldots, 25 \qquad (16)$$

in which M_{ti} = male labor hours required for any agricultural operation per hectare of the ith crop during the week; and $M_{\max}$ = total male labor hours available locally.

Female Labor Requirement

The agricultural operations involving female labor can be grouped as: (1) Transplanting and weeding; (2) harvesting, bundling, and transporting; and (3) threshing and winnowing. Transplanting is traditionally female-labor oriented. Since no female labor is involved in plowing, constraints on it are applicable from week 3 onward when transplanting begins. It is followed by weeding after a gap of one week. Thus, there are two constraints due to

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transplanting and weeding. Female labor is used simultaneously with male labor for harvesting and post-harvest operations. The number of constraints on female labor due to these operations is 12. The total number of constraints is therefore 14:

$$\sum_{i=1}^{N} F_{ti}X_i \leq F_{\max} \qquad t = 3, 5, 13, 14, 16, \ldots, 25 \qquad (17)$$

in which F_{ti} = female labor hours required per hectare of the ith crop during tth week; and $F_{\max}$ = total female labor hours available.

The requirement of DAP, male, and female labor hours as given in Table 4 are based on the data collected by ASTRA (Ravindranath 1981). The available DAP, male, and female labor hours in the system are 4,984, 10,808, 7,672, respectively.

Capital Input Constraint

This constraint involves monetary resources available in the ecosystem. Most of the farmers have land holdings of less than two hectares. The resources input capacity of these farmers is normally very low, thus imposing a limit on the available total resources input in the system. This constraint can be represented by

$$\sum_{i=1}^{N} R_iX_i \leq R_{\max} \qquad (18)$$

in which R_i = resources input required per hectare of the ith crop in rupees; and $R_{\max}$ = total resources available in the system in rupees. The monetary expenditure involved is mainly toward labor, fertilizers, irrigation, and seedlings. The labor changes vary for different agricultural operations and for male and female labor. The labor charges prevailing in the region are given in Table 5. The cost of fertilizers and seedlings are considered on the basis of the recommended values for different crops in this region (Puttarudraiah 1983). The irrigation water charges used in the analysis are the actual charges prevailing in the region per hectare of cropland. Table 6 gives the capital resources input required for the system. The available capital resources are estimated at Rs (rupees) 1,025,000.

Fodder Requirement

The heavy dependency of the ecosystem on animal energy makes the fodder constraint important. Since crop straw is the major form of fodder used, the ecosystem must produce enough fodder for its livestock. The fodder produced by the crop should therefore at least be equal to the fodder requirement:

$$\sum_{i=1}^{N} FR_iX_i \geq FR_{\min} \qquad (19)$$

in which FR_i = fodder produced per hectare of the ith crop; and $FR_{\min}$ = total fodder requirement of the system. Rice, ragi, wheat, maize, and sorghum are the main crops producing straw. The fodder consumption per day is of the order of 2.58 tons/day (Ravindranath 1981). It has been observed that

TABLE 4. DAP and Human Labor Requirements for Various Agricultural Activities for Different Crops (hr/ha)

Agricultural activity (1)	Rice			Wheat, Ragi, Maize			Sorghum			Groundnut, Sunflower			Pulses		
	DAP (2)	Male labor (3)	Female labor (4)	DAP (5)	Male labor (6)	Female labor (7)	DAP (8)	Male labor (9)	Female labor (10)	DAP (11)	Male labor (12)	Female labor (13)	DAP (14)	Male labor (15)	Female labor (16)
Nursery growing	—	11	2	—	20	—	—	18	—	—	—	—	—	—	—
Plowing; manure transport	105	110	—	80	80	—	66	66	—	83	83	—	66	66	—
Puddling; harrowing; bunding	30	171	—	16	16	—	16	16	—	16	16	—	—	—	—
Transplanting; dibbling; sowing	—	11	170	—	85	118	—	40	158	—	65	—	—	34	—
Weeding	—	—	60	—	—	—	—	—	—	—	—	70	—	—	—
Fertilizer application; irrigation; manuring	—	20	20	45	65	20	—	36	—	—	36	—	—	—	—
Harvesting; bundling; product transport	23	122	205	10	18	162	10	18	162	3	65	107	3	65	107
Threshing winnowing; rolling	4	184	64	—	24	73	—	60	60	—	58	34	—	57	34
Total	162	629	521	151	308	373	92	254	380	102	258	276	69	222	141

TABLE 5. Labor Charges for Various Agricultural Operations (Rs/hr)

Agricultural operations (1)	Male Labor (Average Value) hr/day (2)	Daily wages (Rs) (3)	Wages (Rs/hr) (4)	Female Labor (Average Value) hr/day (5)	Daily wages (Rs) (6)	Wages (Rs/hr) (7)
Plowing	6	5.20	0.86	—	—	—
Harrowing	7	12.07	1.73	—	—	—
Transplanting	—	—	—	10	10.35	1.04
Weeding	—	—	—	6	3.45	0.58
Bunding	10	10.35	1.04	—	—	—
Harvesting	8	8.63	1.08	10	6.33	0.63
Bundling	8	12.08	1.51	10	6.33	0.63
Threshing	10	13.80	1.38	—	—	—
Winnowing	—	—	—	10	6.90	0.69
Average	—	—	1.27	—	—	0.71

only 60% of the fodder required is met by the crop straw; the rest is provided by grass. Considering the total population of the livestock and the portion of the annual fodder requirement supplied by crops, the lower limit on fodder is fixed at 565 tons.

Nutritional Energy (NE) Requirement

The system must be self-sufficient in its food needs for both humans and livestock since there is virtually no industry in the area. It is common practice in rural areas to import the food varieties locally not available in exchange for locally produced surplus food. The total nutritional energy of the crops produced should not be less than the requirement of the system:

$$\sum_{i=1}^{N} E_i X_i \geq E_{\min} \quad (20)$$

in which E_i = NE value per hectare of the ith crop (in kcal); and $E_{\min}$ = minimum NE requirement of the system (in kcal). The NE requirement of the population is 827,000 kcal (Reddy 1981). The crop straw and NE value

TABLE 6. Input for Various Crops in Rs/ha of Irrigated Land Area

Crop (1)	Labor charges (2)	Cost of fertilizers (3)	Irrigation water charges (4)	Cost of seeds (5)	Total rupees (6)
Rice (kharif)	1,170.30	1,745.20	74.00	496.00	3,486
Ragi	655.47	1,745.20	44.00	30.00	2,475
Maize	655.57	2,424.40	44.00	90.00	3,214
Wheat	655.57	2,165.20	44.00	799.00	3,664
Sorghum	593.52	2,106.40	44.00	28.00	2,772
Sunflower	523,62	1,981.20	44.00	77.00	2,626
Groundnut	523.62	1,620.40	44.00	754.00	2,942
Pulses	382.05	1,035.60	44.00	90.00	1,552

TABLE 7. Grain and Fodder Yield from Crops

Crop (1)	Seed or grain yield (kg/ha) (2)	Straw yield (kg/ha) (3)	Nutritional Energy Value	
			Per kg kcal (4)	Per ha 10^3 kcal (5)
Rice	3,930	6,227	3,552	13,960
Ragi	2,527	5,286	3,723	9,408
Maize	2,527	3,173	4,541	11,475
Wheat	1,685	2,594	4,397	7,409
Sorghum	2,527	2,722	3,735	9,435
Sunflower	1,011	—	6,859	6,935
Groundnut	1,235	—	6,859	8,470
Pulses	741	—	3,108	2,303

of the crops considered are given in Table 7.

In the present formulation of the LP model, the area under each crop X_i, the end of period tank storage S_t, and the spill during each time period Q_t are considered to be the decision variables. They must satisfy the following nonnegativity constraints:

$$X_i \geq 0 \quad \text{(21a)}$$

$$S_t \geq 0 \quad \text{(21b)}$$

$$Q_t \geq 0 \quad \text{(21c)}$$

Thus there are a total of 48 decision variables and 116 constraints. The LP model is solved by the revised simplex method.

Initial Analysis

In the first phase of the analysis, it was found that there is no feasible solution for the LP model formulated as given. The constraint on fodder requirement was found to be violated since the land area necessary to produce the minimum fodder requirement could not be brought under cultivation. Of the various crops considered, rice is the most popular due to the obvious reason that the return per hectare of rice is relatively higher. The contribution of rice straw toward fodder requirement is also substantially greater. If rice is the only crop grown, it is necessary that at least 91 ha of land be planted with rice. During the third week of crop season, harrowing and transplanting take place simultaneously. Table 4 shows that the male and female labor required during this week are 181 hr and 120 hr, respectively. Thus, to transplant 91 ha of land, 16,470 hr and 15,470 hr of male and female labor, respectively, are required, which are much more than the available quantity during any week of the crop season. In addition, the female labor availability becomes critical during harvesting, when 205 hr/ha are needed (Table 4).

Modified Formulation

In reality, the area planted with rice is much more than 91 ha, and the fodder produced is enough to meet the requirement in a normal year. Otherwise, the actual number of livestock in the system could not be supported. How is this paradox resolved? A study of the local agricultural practices revealed that the land preparation and transplanting in the area earmarked for rice do not take place simultaneously everywhere. The sowing of rice is spread over a period of about one month. This has the affect of staggering the agricultural operations for rice in different areas. Seedbed preparation for different rice fields takes place during different weeks, and, as a consequence, transplanting and subsequent agricultural operations also take place in different weeks. This releases the pressure on labor and energy resources, and a large area can be planted with rice. In accordance with this real-life situation, a second attempt at a solution was made, dividing the total rice area into four regions. Agricultural operations start during successive weeks in each region, not simultaneously. The rice crop in each region is treated as a separate crop. Thus the number of crops N, though technically eight, would, for analysis, be eleven.

This modification requires an increase in the duration of irrigation water application of three weeks. The modified crop calendar is also shown in Fig. 3. Since the optimal time of transplanting rice for maximum yield in this region is before July 15, a reduction in benefit is inescapable with staggered operations. The grain yield will decrease by 200 kg/ha for every week of delayed transplanting (Puttarudraiah 1983). Accordingly, the coefficients in the objective function are modified. In the modified formulation, the constraints on water availability, the continuity equation, canal capacity, and tank capacity will each increase by three.

It is assumed that plowing for rice in the first region (rice I) starts along with other crops, while for the remaining three regions, rice II, rice III, and rice IV, it is delayed successively by a week. This increases the constraints on DAP from three to six. As the male labor for plowing and transplanting operations is required in conjunction with DAP, there will be six constraints on male labor for these operations. Harvest and post-harvest operations for rice start from week 21 and are spread over eight weeks due to the successive operations in three additional rice regions. Thus, the total number of constraints on male labor now will be 21. Female labor for transplanting and weeding starts from week 3 and ends in week 8, spread over six weeks due to successive agricultural operations in three regions of rice crop. For the rest of the operations during harvest and post-harvest, female labor is required simultaneously with male labor. Thus the number of constraints on female labor is also 21. Fig. 3 also shows the modified use of DAP, male, and female labor hours. Constraints involving fodder, resources input, nutritional energy requirements, and nonnegativity requirements remain the same. The modified formulation has a total of 57 decision variables and 144 constraints and was solved by the revised simplex method. The results are presented in the following.

Results

Fig. 4 shows the hydrographs and mass curves of inflows, evaporation loss, irrigation release, and storage in the tank. Out of the total inflow of 264 ha-m during the crop season, 62 ha-m (23.5%) is lost as evaporation, 120 ha-m (45.5%) is the consumptive use, 29 ha-m (11%) spill, and the balance of 53 ha-m (20%) appears as the storage in the tank at the end of

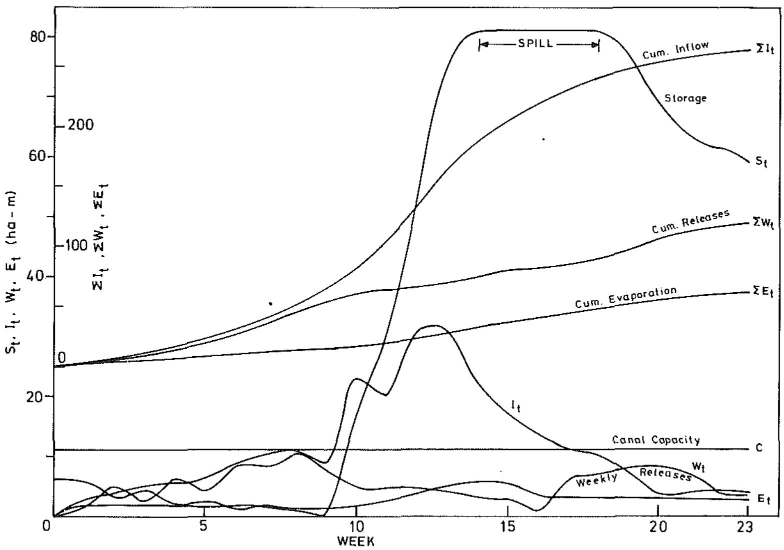

FIG. 4. Hydrographs and Mass Curves (Irrigation Efficiency 30%, No Minimum on Ragi Crop)

the crop season. This storage is not sufficient to support the post-monsoon "Rabi" crop because of high evapotranspiration loss. Even without a Rabi crop, the storage evaporates completely in just ten weeks, which is less than the minimum growth period of the crops considered. The residual storage thus will not even be available to provide minimal irrigation during the initial weeks of low inflow during the coming crop season. It therefore appears that the storage capacity provided is too high, at least for mean hydrologic conditions. The difference between the maximum live storage (81 ha-m) and the end storage (53 ha-m) with an additional capacity for dead storage (i.e., a gross storage of about 30 ha-m) would have been sufficient. The tank would then have interrupted an inflow volume about four times its capacity.

Table 8 gives the crop areas, net benefit, and the surplus fodder produced. Only two crops, rice and ragi, result from the LP solution, with a total crop area of 92.4 ha. Rice occurs in only three areas totaling 81.4 ha, with a minimum of 12.7 ha in rice I and a maximum of 36.4 ha in rice II. No rice

TABLE 8. Crop Areas, Net Benefit, and Surplus Fodder

Condition (1)	Irrigation efficiency (%) (2)	Rice in Different Regions (ha) I (3)	II (4)	III (5)	IV (6)	Total rice (ha) (7)	Ragi (ha) (8)	Groundnut (ha) (9)	Total crop area (ha) (10)	Net benefit Rs × 10^3 (11)	Surplus fodder, *t* (12)
No minimum on ragi	30	12.7	36.4	—	32.3	81.4	11.0	—	92.4	614.2	—
With a minimum on ragi	30	—	36.9	—	32.1	69.02	36.0	—	105.0	553.9	55.0
	50	13.9	36.3	33.3	30.9	114.6	36.0	16.3	166.9	945.0	339.1

TABLE 9. DAP, Male, and Female Labor Use (Irrigation Efficiency 30%; No Minimum on Ragi Crop)

	DAP Hours		Male Labor Hours		Female Labor Hours	
Week (1)	Utilization (2)	Availability (%) (3)	Utilization (4)	Availability (%) (5)	Utilization (6)	Availability (%) (7)
1	1,113	22.3	1,138	10.5	—	—
2	3,044	61.1	3,142	29.1	—	—
3	2,488	49.9	5,411	50.1	3,455	45.0
4	2,804	56.2	8,370	77.4	6,195	80.7
5	1,711	34.3	1,775	16.4	760	9.9
6	969	19.4	5,841	54.0	7,622	100.0
8	—	—	—	—	1,937	25.2
19	—	—	199	1.8	1,788	23.3
20	—	—	265	2.5	806	10.5
21	—	—	1,545	14.3	2,596	33.8
22	—	—	5,028	46.5	7,672	100.0
23	—	—	2,259	20.9	786	10.2
24	—	—	6,196	57.3	7,401	96.5
25	—	—	3,743	34.6	1,302	16.9
26	—	—	3,161	29.2	1,100	14.3
27	—	—	1,485	13.7	517	6.7
28	—	—	1,485	13.7	517	6.7

is planted in rice III. This result comes about primarily because of the inflow pattern into the tank. Until week 9, inflows are small, and at the end of week 9, the tank storage is depleted to zero (Fig. 4). If there is any crop in rice III, there would not be enough water to last till week 9 without reducing other crop areas, which will result in a nonoptimal solution. However, there are 32.3 ha of crop in rice IV since the inflow is just sufficient to meet the water requirement of the cropped area until the ninth week. The water availability during the initial weeks thus restricts the area that can be irrigated.

Table 9 gives the DAP, male, and female labor use during the crop season. Of the available 4,984 hr of DAP, a maximum of only 61% is used (during week 2 of the crop season), mainly for plowing in rice I and II. Even though no area is planted in rice III, the DAP used in this week is for harrowing in rice I and for plowing in rice II. During week 4, a portion of DAP is used for harrowing in rice II and the rest of DAP use during weeks 4–6 are only for rice IV. Utilization of male labor during land preparation and transplanting primarily follows the utilization of DAP hours, as men have to drive the animals. However, a maximum of only 77.4% of available male labor is used. This occurs during week 4 due to combined operations of harrowing in rice II and plowing in rice IV. Female labor is used mainly for transplanting and, after a gap of one week, for weeding during the initial crop season. Female labor utilization is 100% in week 6, partly for weeding in rice II and the balance for transplanting in rice IV. During the week 4, female labor is used only for transplanting in rice II. As only 36.4 ha of land is transplanted in rice II utilizing 80.7% of available female labor, 19.3% is left untapped, enough for transplanting another 8.7 ha of rice. Thus, with the available female labor, a maximum of 45.1 ha can be transplanted with rice in a week, providing the female labor is used exclusively for transplanting rice.

DAP for harvesting is not considered, as only a small quantity is required for produce transport. During rice harvesting, there is a heavy demand for labor (Fig. 3) since harvesting in each rice region is to be completed within a week's time. The subsequent post-harvest operations connected with rice are normally spread over more than a month, and thus the labor demand is low. The highest demand on male labor during this period is in week 24, when the harvesting in rice IV and the post-harvest operations for rice I and II are grouped together. Female labor for harvesting closely follows the male labor usage, as both are required simultaneously. The demand would be high during weeks 22–24.

The solution provides no surplus fodder, showing that the fodder constraint is also active. The net benefit is Rs 614,200, nearly twice the resources. Thus it appears that female labor, water supply in the initial period, and the fodder requirement of the ecosystem are critical, restricting the crop area.

Effect of Imposing Minimum Ragi Production

It has been observed (Reddy 1981) that cropping pattern in this ecosystem is gradually changing over from ragi to rice as the return per hectare of rice is relatively higher. This trend is noticeable in other irrigated areas as well. Ragi is, however, the second major foodgrain consumed in the system.

It is therefore desirable to meet the ragi requirements of the ecosystem by producing enough of it locally. In the present case, ragi is consumed on the order of 90 tons/annum (Ravindranath 1981) and, with the assumed yield, the minimum ragi area to achieve self-sufficiency is 36 ha. The LP problem was reformulated in order to study the effect of imposing a minimum area in ragi as an additional constraint. Table 8 gives the crop areas for this case. The results show that the ragi area remains at the minimum prescribed value, namely 36 ha, with an increase of 13.6% in the total crop area. However, the rice area is reduced simultaneously by 15%, with no rice in the first region. This may be attributed to insufficient water during the initial period, as the storage at the end of week 9 of the crop season decreases to zero. It is also seen that imposing a minimum ragi crop affects the distribution of rice in different regions. Though there is an increase in the total crop area, the net profit has decreased, due to the partial replacement of rice crop by ragi and the lower return on ragi. However, there is an increase in fodder production, as ragi is one of the major fodder crops. The results also show that there is no substantial change in energy utilization except for a slight redistribution due to the redistributing of crop areas.

Impact of Irrigation Efficiency and Sensitivity Analysis

The actual irrigated rice area of 131 ha, the most popular crop in this region, is much more than that obtained in the results reported. One reason for this discrepancy might be the low irrigation efficiency (30%) assumed in the analysis, which is primarily applicable for conventional large irrigation projects in developing countries. Tank systems are generally much smaller

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both in the size of command area and storage volume. The canal length is shorter, as the irrigated area is adjacent to the tank. Further tank irrigation occurs only during the monsoon season when the soil moisture is high. A large reservoir, on the other hand, provides irrigation during the post-monsoon season as well, when soil moisture is low and seepage loss is high, bringing down the average conveyance efficiency. It is reasonable to expect that a higher irrigation efficiency may prevail in tank irrigation, although no measurements are available.

The task committee on water quality problems resulting from increasing irrigation efficiency (1985) concluded that from a water-quality viewpoint, there is no reason to avoid increasing irrigation efficiency, but any such progress should be analyzed thoroughly in advance to determine whether local circumstances warrant the improvements. Willardson (1985) discussed the basinwide effects of increasing irrigation efficiency and concluded that irrigation efficiency should be raised to the highest practical level in any river basin to ensure that the maximum volume of high quality water is available for all conjunctive uses. Hargreaves et al. (1985) observed that an overall efficiency of 60% can be achieved with surface irrigation, if the lands are smoothed and properly prepared. Low crop yields are associated with low irrigation efficiency, resulting from leaching of fertility and lack of adequate soil moisture.

Thus, an overall irrigation efficiency of 50% is assumed to be attainable as well as desirable. A sensitivity analysis was made by solving the problem with this improved efficiency. All the constraints, including the minimum area imposed on ragi, remain the same. However, the values of W_{ti} change.

Table 8 gives the crop areas, net benefit, and surplus fodder production with the increase irrigation efficiency. There is a substantial increase (60%) in the total rice area and in the total crop area (59%) compared to the area irrigated with an irrigation efficiency of 30%. The ragi area in both cases is at the minimum of 36 ha. However, an additional crop of groundnut in 16.3 ha is added in the present case, as the return per hectare of this crop is second only to rice. The increase in the net benefit is of the order of 71%, while the surplus fodder produced is almost six times that when the efficiency is 30%.

The results also indicated that there is no change in the total quantity of irrigation release when the irrigation release efficiency is assumed to be 50%, despite an increase in total crop area. The increased efficiency, particularly during the initial nine weeks of the crop season, helps in bringing a larger area under cultivation, as this period is crucial for raising crops considering the water availability. As a result, rice is planted in all four regions unlike the lower efficiency model.

The results indicated that there is a more uniform use of energy components for agricultural operations. DAP is used nearly fully for three weeks due to simultaneous operations of harrowing and plowing for all the crops together. Usage of male labor during the initial period is mainly associated with DAP use and the area to be transplanted, and thus it is at a maximum when the DAP use is maximum and transplanting is intensive. The use of female labor during the initial crop season is primarily for transplanting and weeding. During the first week of transplanting, female labor is fully utilized

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for transplanting alone. In the remaining weeks of transplanting, use of female labor is at a maximum only when there is overlapping of transplanting and weeding operations. On an average, the utilization of these energy forms, particularly male and female labor, is high for about four weeks, during which the major part of the initial agricultural operations of plowing and transplanting would be completed.

For harvesting and post-harvest operations, both male and female labor are used over 11 weeks from week 18 to week 28 of the crop season. However, male labor usage is maximum at 70% only once during this period. Female labor, however, is fully used for three weeks due to simultaneous operations of harvesting and post-harvest operations of rice. Thus it is apparent that the cropped area and cropping pattern with a higher irrigation efficiency are influenced by the availability of female labor, especially during the harvesting, although DAP and male labor use reach their limits early in the season.

Summary and Conclusions

Tank irrigation systems supplying water for about 40% of the total irrigated land in Karnataka in South India have been analyzed as an independent village agricultural ecosystem. The factors involved, though apparently simple, are different from those involved in a conventional reservoir systems and exert a significant influence on the optimum cropping pattern. The low rainfall and inflows during the initial crop season together with the interdependence of land-human-livestock components on the agricultural technology play a major role in evolving the optimum cropping pattern and crop areas. The amount of water available in the first nine weeks play a major role in limiting the total area that can be irrigated. The fodder requirement of the ecosystem can be met only by staggering the planting of rice in different areas, which simultaneously improves the crop production and net profit. On the basis of optimum profit, only two crops in the irrigated area, rice and ragi, are indicated by the analysis, which conforms to the actual practice, although other crops are also grown in the surrounding rain-fed land. If a minimum production of ragi, the second major stable food, is enforced, the net profit decreases, and an adjustment of the staggered pattern of rice planting is required. An irrigation efficiency of 30% leads to a cropping pattern in which the animal and male labor potentials are considerably underutilized. A higher irrigation efficiency of 50%, which looks probable, not only gives a higher profit, but leads to a fuller utilization of animal power and human labor. In all three analyses, the crucial importance of female labor availability in the ecosystem appears, leading to the conclusion that the area irrigated cannot be significantly increased without increasing the supply of female labor and improving the water supply during the initial period.

The LP model, discussed herein with reference to a particular system, is capable of being implemented for other tank systems as well. While some parameters, e.g., storage capacity, command area, labor, and animal power availability, will be site-specific, others, e.g., unit labor utilization, DAP requirement, unit costs and profits, and fodder requirement, do not vary significantly.

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Appendix II. Notation

The following symbols are used in this paper:

C = canal capacity (ha-m);
DAP_{ti} = draft animal pair hours required in tth week for ith crop;
DAP_{max} = maximum available draft animal pair hrs;
E_d = depth of evaporation (mm);

E_i = nutritional energy value per hectare of ith crop (kcal);
E_{min} = minimum requirement of nutritional energy value (kcal);
E_t = evaporational loss in tth week (ha-m);
ET_{ti} = maximum evapotranspiration tth week of ith crop (mm);
F_{max} = maximum available female labor hours;
F_{ti} = female labor hours required in tth week for ith crop;
FR_i = fodder produced per hectare of ith crop (t);
FR_{min} = minimum fodder requirement of system (t);
I_t = inflow to tank in tth week (ha-m);
K = constant;
M_{ti} = male labor hours required in tth week for ith crop;
M_{max} = maximum available male labor hours;
N = total number of crops;
P_i = net profit per hectare of ith crop (rupees);
Q_t = spill in tth week (ha-m);
R_i = resources input required for ith crop (rupees);
R_{max} = maximum available capital resources in system (rupees);
S_{max} = maximum storage volume of tank (ha-m);
S_t = tank storage at end of tth week (ha-m);
S_{ta} = average volume of storage in tth week (ha-m);
t = time period in weeks;
TL = total available irrigable land (ha);
W_{ti} = irrigation water release in tth week for ith crop (ha-m);
X_i = crop land area of ith crop (ha); and
η = efficiency.

Subscripts

d = depth;
i = crop; and
t = time.