SYSTEMS ANALYSIS OF TANK IRRIGATION: II. DELAYED START AND WATER DEFICIT

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ABSTRACT: Tank irrigation systems in the semiarid regions of India are discussed in this paper. To optimize the grain yield of rice, it is essential to start the agricultural operations in the second week of July so that favorable climatic conditions will prevail during flowering and yield formation stages. Because of low inflow during the initial few weeks of the crop season, often farmers are forced to delay planting until sufficient sowing rain and inflow have occurred or to adopt deficit irrigation during this period. The delayed start affects the grain yield, but will lead to an improved irrigation efficiency. A delayed start of agricultural operations with increased irrigation efficiency leads to the energy resources becoming critical during the peak requirement week, particularly those of female labor and animal power. This necessitates augmenting these resources during weeks of their peak use, either by reorganizing the traditional methods of cultivation or by importing from outside the system.

INTRODUCTION

Tanks, which are small reservoirs formed by earthern embankments across small streams, are found extensively in the semiarid region of Karnataka in India and elsewhere in the world. They generally have small storage capacity. The rainfall being scanty during the initial crop season which starts in July, the inflow is also low in this period. The free-water surface area of tanks is large compared to the command area, resulting in high evaporation loss. The tanks primarily supply water for irrigation. Since the agricultural land is close to the tanks, a higher irrigation efficiency can be achieved than with large reservoir systems (Mayya and Prasad 1989). Due to the prevailing favorable climatic conditions, rice is the most widely grown crop. Only one crop is possible during the Kharif season (July–November), as further plantings would result in insufficient water availability for the entire crop season of the subsequent "R abi" season. A small difference between day and night temperature during flowering and yield formation is essential for a good yield. The agricultural operations for the Kharif crop normally begin in July so that necessary climatic conditions will prevail during flowering and yield formation stages. Further delay in the crop season causes these important growth stages to fall in the winter, which reduces the grain yield. It is recommended that in the region under consideration the latest sowing or transplanting date should be July 15 for maximum rice yield. On the average, for every week of delay in the transplanting date, there will be a reduction in grain yield by 8–10% (Puttarudraiah 1983).

At the same time, the commencement of agricultural operations depends upon the sowing rain, which is normally expected in the months of June and

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July in this region. However, good rainfall and runoff generally take place only towards September, thus affecting the initial agricultural operations considerably. Though the initial rainfall can be used advantageously for crops other than rice that require less water, the farmers in the region have gradually opted for rice since it has the highest net return among all the crops. A lack of sufficient water at the beginning of the crop season compels some of the farmers to delay the start of the agricultural operations, particularly for rice, until there is enough moisture in the soil and water in the canals. It is not uncommon to observe rice transplanting starting as late as the end of August.

When water supply is not sufficient to fully meet crop water requirements, actual consumptive use will fall below the maximum. The effect of reduced consumptive use on growth and yield depends on the crop variety and the magnitude and time of occurrence of the water deficit. Many crops are relatively more sensitive to water deficit at particular growth stages. Large differences in yield can occur with the same water deficit due to differences in the sequencing of water stress (Doorenbos and Kassam 1979). A deficit during a critical growth period, usually the flowering, fruit setting, or grain formation stage, has a significantly larger influence on yield than a deficit during other growth periods. Hagen and Stewart (1972) presented water production functions relating yield reductions to water deficits for principal crops, developing a preseason irrigation programming technique based on crop, soil, and weather factors. They also compiled available data on allowable soil-water depletion for various crops. Stewart and Hagen (1973) developed water-production functions useful in quantitatively estimating yields for principal irrigated crops under water deficit conditions. Hargreaves and Samani (1984) presented mathematical yield models relating crop evapotranspiration and total water available to relative yields. Israelsen and Hansen (1962) indicated that mildly stressing a crop in its flowering stage may be economically advantageous, even though this is a sensitive period with respect to the effect of stress on yield.

The present work discusses two possibilities, namely: (1) Delayed rice crop; and (2) deficit irrigation during the initial crop season. In the first case, crops that require less water than rice are assumed to start at the normal time. The staggering of the rice crop (Mayya and Prasad 1989) in four regions is considered. The agricultural operations in the first region is delayed by two weeks and, for the other three regions, successively by a further week each. A delayed start of the crop season has an additional advantage in that it achieves a higher irrigation efficiency since sufficient rainfall will have increased the soil moisture, leading to a reduction in the water losses during conveyance and application of irrigation water. An irrigation efficiency of 50% is therefore assumed as more realistic. Higher efficiencies can be achieved with an effective supply system (Merriam and Davids 1986). The feasibility of augmenting the energy resources is also studied.

In the second case, irrigation deficits are planned for the first nine weeks, after which the inflow into the tank improves. In this case, an efficiency of 30% is assumed, as soil moisture levels are low in the initial period. If more area is irrigated at the cost of water deficit in the initial period, it might be possible to fully meet irrigation requirements in the subsequent growth stages. A higher profit can conceivably he realized with this strategy, rather than permitting no deficit during any growth stage. The deficit imposed is 20%

of the evapotranspiration during each of the first nine weeks, after which rice will get its full requirement as well. The 20-week growing season for rice can be divided into four stages (Doorenbos and Kassam 1979): establishment (five weeks), vegetative (seven weeks), flowering (two weeks), and yield formation and ripening (six weeks). The first nine weeks of deficit therefore span the establishment and earlier part of the vegetative stages, when water deficit will not have a large effect on ultimate yield. The reduced yield is considered in formulating the objective function on the basis of the relationship between deficit in evapotranspiration and the corresponding yield reduction developed by Doorenbos and Kassam (1979).

MATHEMATICAL MODEL

Delayed Start

The deterministic LP model developed by Mayya and Prasad (1989) is used in the present analysis. The objective function, the net return from the system, considering eight crops common in the region is

$$\sum_{i=1}^{11} P_i X_i \quad \text{(1)}$$

in which P_1, P_9, P_{10}, and P_{11} = the net return per hectare of rice in rupees (Rs) in the four regions; P_2–P_8 = those of ragi (finger millets), maize, wheat, sorghum, sunflower, oilseeds, and pulses, respectively; and X_i = the area planted with the ith crop. Crops other than rice start on schedule; rice in each of the four regions starts two weeks later than the normal start. As a consequence, the net profit from rice is reduced. For every week's delay, the reduction is taken to be Rs 200/ha (Puttarudraiah 1983). Table 1 gives the modified net profit from rice planted during different weeks, which are also the respective coefficients in the objective function for delayed start. P_2–P_8 retain their earlier values (Mayya and Prasad 1989).

The constraints involving land area, water, and the resource input are given as follows:

Land area:

$$\sum_{i=1}^{N} X_c \le TL \quad \text{(2)}$$

TABLE 1. Net Profit from Rice Planted during Different Weeks

Week of commencement of agricultural operations (1)	Beginning date (2)	Grain yield (kg/ha) (3)	Value of produce (Rs/ha) (4)	Total input (Rs/ha) (5)	Net profit (Rs/ha) (6)
3	July 29	3,530	10,590	3,486	7,104
4	August 5	3,330	9,990	3,486	6,504
5	August 12	3,130	9,390	3,486	5,904
6	August 19	2,930	9,790	3,486	5,304

Note: Week 1 starts from July 15 of the year.

Water availability:

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

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:

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

Storage constraints:

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

Draft animal power requirement:

$$\sum_{i=1}^{N} \mathrm{DAP}_{ti}X_i \leq \mathrm{DAP}_{max} \qquad t = 1, \ldots, 8 \quad (7)$$

Male labor requirement:

$$\sum_{i=1}^{N} M_{ti}X_i \leq M_{max} \qquad t = 1, \ldots, 8, 13, 14, 16, \ldots, 30 \quad (8)$$

Female labor requirement:

$$\sum_{i=1}^{N} F_{ti}X_i \leq F_{max} \qquad t = 3, \ldots, 10, 13, 14, 16, \ldots, 30 \quad (9)$$

Capital input constraint:

$$\sum_{i=1}^{N} R_iX_i \leq R_{max} \quad (10)$$

Fodder requirement:

$$\sum_{i=1}^{N} FR_iX_i \geq FR_{min} \quad (11)$$

Nutritional energy requirement:

$$\sum_{i=1}^{N} E_iX_i \geq E_{min} \quad (12)$$

Nonnegativity constraints:

$$X_i \geq 0 \quad (13a)$$

$$S_t \geq 0 \quad (13b)$$

$$Q_t \geq 0 \quad (13c)$$

in which TL = total available irrigable land; W_{ti} = irrigation water release in tth week for ith crop; S_t = tank storage at the end of the tth week; I_t = inflow to tank in tth week; E_t = evaporation loss in tth week; Q_t = spill in tth week; C = canal capacity; S_{max} = maximum storage volume of tank; DAP_{ti} = draft animal pair hours required in tth week for ith copy; DAP_{max} = maximum available draft animal pair hours; M_{ti} = male labor hours required in tth week for ith crop; M_{max} = maximum available male labor hours; F_{ti} = female labor hours required in tth week of ith crop; F_{max} = maximum available female labor hours; R_i = resources input required for ith crop; R_{max} = maximum available capital resources in the system; FR_i = fodder produced per hectare of ith crop; FR_{min} = minimum fodder requirement of the system; E_i = nutritional energy value per hectare of ith crop; and E_{min} = maximum requirement of nutritional energy value. The constraints are discussed in greater detail by Mayya and Prasad (1989).

The delay of two weeks in planting rice in region IV necessitates two additional irrigation applications toward the end of the crop season, and thus the total number of irrigation applications for the entire season will be 25 instead of 23 for normal start. This will result in two additional constraints each of water availability, continuity equation, canal capacity, and tank storage. Further, two additional weeks of water applications will introduce two decision variables of storage S_t, and two more of supluses Q_t.

There will also be two additional constraints on draft animal power (DAP) utilization, which in turn will impose two more constraints on male labor use since DAP requires male labor. Harvesting and post-harvest operations for crops other than rice considered in the present analysis will start from week 13 of the crop season and end in week 20. However, these operations for rice will be delayed until week 23 and end in week 30. Thus, there will be no change in the male labor use during harvesting and post-harvest agricultural operations, resulting in an overall increase of only two constraints on male labor for the entire crop season. Female labor utilization will start from week 3 of the crop season for transplanting crops other than rice. Transplanting of rice starts only at week 5 and ends in week 10 of the crop season. No female labor is required in week 4 as no transplanting is done. Thus, only one additional constraint on female labor for transplanting is needed compared to normal start. Female labor for harvesting and post-harvest operations are simultaneous with male labor and thus the number of constraints on female labor for these agricultural operations is the same as that on male labor. The constraints on land use, fodder production, capital resources input, and nutritional energy requirements remain the same. Thus, the present formulation of the LP model for delayed start of rice crop will have 157 constraints and 61 decision variables.

Deficit Irrigation

The LP model described is used in this case as well. However, it needs a slight modification in the number of constraints since it is assumed that the agricultural operations for all the crops start simultaneously with the normal commencement of the season. Further, the water constraints involving consumptive use have different coefficients as a result of deficit irrigation.

The new values of irrigation release W_{ti} are computed on the basis of 80% of normal maximum evapotranspiration ET_t for $t = 1, \ldots, 9$. Thus, W_{ti} is given by the equation

$$W_{ti} = (0.8ET_{ti} - \text{effective rainfall})\frac{1}{0.3} \quad \text{(14)}$$

The deficit would impose moisture stress on crops other than rice. Since normal rice irrigation ensures submergence, a deficit in the case of rice might lead to the disappearance of ponded water on the field for part of the time. Since the deficit is only 20%, the disappearance of submergence would last only a few hours per day. Effective weed control would still be possible since the field would be submerged for a large part of the time.

RESULTS

Delayed Start

Table 2 gives the crop, net profit, and the surplus fodder quantities obtained by the solution of the problem formulated as described. The ragi area amounts to 46 ha, even without a minimum imposed as a constraint. Table 2 also gives the results for the case when the agricultural operations for rice are started at the beginning of the crop season with the other crops (Mayya and Prasad 1989), and no lower limit is imposed on ragi. The results show that there is a significant increase in the total irrigated area where rice is delayed. However, the increase in rice area is only marginal at five hectares. This is primarily due to the combined effects of the amount of available water and the female labor constraint during harvest, which curb any increase in rice area. In both these cases, the rice area in any region (i.e., transplanted in any week) is not more than 37 ha, indicating that the female labor requirement at harvest controls the rice area planted in any week.

Though a delayed rice crop helps in increasing the total irrigated area, there is a reduction in the net profit from the system as a result of reduced rice yield. At the same time, increase in rice and ragi areas results in higher surplus fodder production, as there is a substantial contribution of crop straw from these crops.

Fig. 1 shows the results from the solution of the model. Compared to the case of normal start (Mayya and Prasad 1989), the seasonal irrigation water release is 17% higher, and the end of season storage is consequently lower. There is also a reduction in the total spill during the crop season. Thus there

TABLE 2. Crop Areas and Net Profit for Normal and Delayed Rice Crop

Description (1)	Rice in Different Regions (ha) I (2)	II (3)	III (4)	IV (5)	Total rice (ha) (6)	Ragi (ha) (7)	Groundnut (ha) (8)	Pulses (ha) (9)	Total crop area (ha) (10)	Net profit Rs × 10^3 (11)	Surplus fodder, t (12)
Normal start	37	35	26	30	128	4	14	3	149	1,005	249
Delayed rice crop	37	35	32	29	133	46	—	—	179	911	506

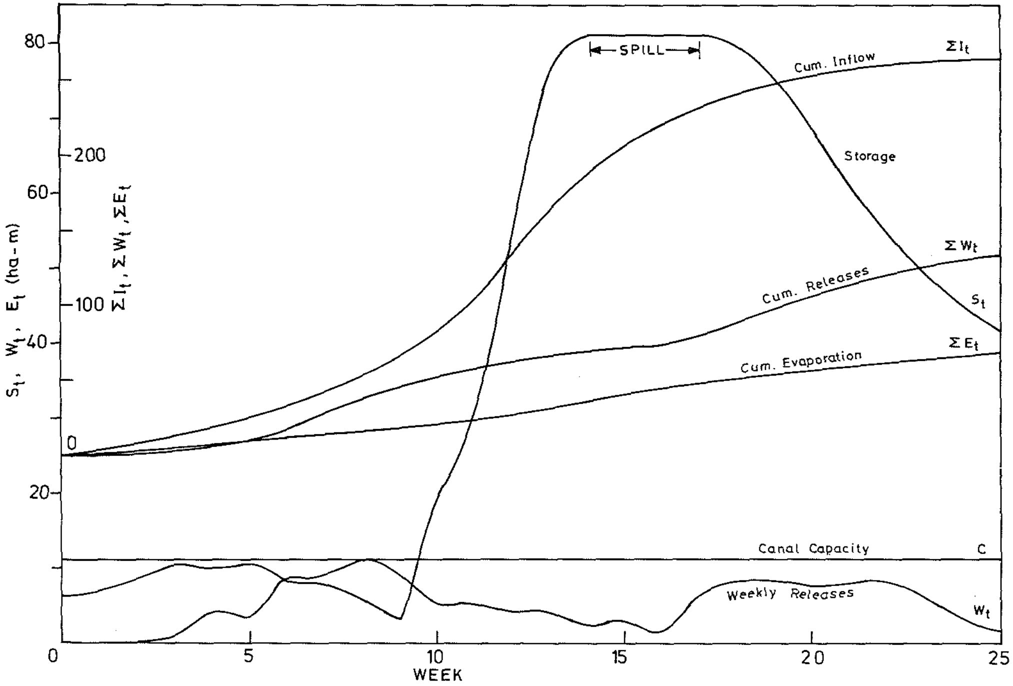

FIG. 1. Hydrographs and Mass Curves (Irrigation Efficiency 50%, Delayed Start, No Minimum on Ragi Crop)

TABLE 3. Energy Use (Delayed Start)

	DAP Hours		Male Labor Hours		Female Labor Hours	
Week (1)	Utilization (2)	Availability (%) (3)	Utilization (4)	Availability (%) (5)	Utilization (6)	Availability (%) (7)
1	1,837	36.9	1,837	17.0	—	—
2	1,837	36.9	1,837	17.0	—	—
3	2,719	54.6	6,696	61.2	5,419	70.6
4	3,813	76.5	3,957	36.7	—	—
5	4,638	93.1	10,422	96.4	6,363	82.9
6	4,276	85.8	9,608	88.9	5,866	76.5
7	2,509	50.3	7,371	68.2	7,654	99.8
8	880	17.7	5,309	49.1	7,056	92.8
9	—	—	—	—	1,909	24.9
10	—	—	—	—	1,760	23.0
19	—	—	827	7.7	7,439	97.0
20	—	—	1,102	10.2	3,352	43.7
23	—	—	4,566	42.2	7,672	100.0
24	—	—	5,931	54.9	7,672	100.0
25	—	—	7,190	66.5	7,672	100.0
26	—	—	8,350	77.3	7,672	100.0
27	—	—	6,122	56.6	2,130	27.8
28	—	—	4,400	40.7	1,531	20.0
29	—	—	2,813	26.0	979	12.8
30	—	—	1,350	12.5	470	6.1

will be a better utilization of the available water resources, especially in the latter parts of the crop season. Delaying the rice crop does not reduce the storage to zero during the crop season, as in the case of normal start, indicating that water availability is not the critical constraint limiting any further increase in the irrigated area. On the other hand, the existing canal capacity and energy resources do act as limiting values in the present case.

Impact of Energy Resources

Table 3 gives the DAP, male, and female labor usage for the case of delayed rice crop. DAP is used during all the eight weeks, with a maximum utilization of 93% of the availability in week 5. As a result, male labor is also used during all the eight weeks, with a maximum of 96% of the available male labor in the system during the fifth week. Female labor for transplanting is used nearly fully in week 7 and at a rate greater than 90% during week 8. However, the energy constraints for the initial agricultural operations are not critical, as available energy is not fully utilized during any of the first ten weeks of the crop season, by the end of which transplanting will be completed.

For harvesting and post-harvest operations female labor is utilized fully for four weeks starting in week 23 and continuing through week 26 as seen from Table 3. This demonstrates the crucial role played by female labor in tank irrigation systems. At the same time, locally available male labor is underused even during harvesting. The net profit can be improved by supplementing female labor, which can be achieved by the following two ways:

TABLE 4. Crop Areas and Net Profit Utilizing Surplus Male Labor

Rice in Different Areas (ha)				Total rice (ha)	Ragi (ha)	Total crop area (ha)	Net profit (Rs)	Surplus fodder produced, *t*
I (1)	II (2)	III (3)	IV (4)	(5)	(6)	(7)	(8)	(9)
38	38	34	36	146	21	167	944,000	454

1. Importing female labor from outside the system during peak weeks.
2. Utilizing locally available excess male labor for female labor-oriented agricultural operations.

Another option, extending the harvest period by a few days, was not explored since its effect on yield is not known.

Importing female labor during the peak weeks is a feasible alternative since the system considered is surrounded by a dryland area in which surplus female labor is normally available. However, this increases costs; imported labor involves transport costs as well. The alternative of using locally available excess male labor for female labor-oriented agricultural operations in addition to the locally available female labor is therefore considered in the following analysis. To facilitate comparison, a delayed start of rice operations is imposed in this case as well.

In the LP model formulated, the constraint on female labor is modified to provide for use of surplus male labor to compensate for the shortfall in female labor as follows:

$$\sum_{i=1}^{N} F_{ti}X_i \leq F_{max} + M_{max} - \sum_{i=1}^{N} M_{ti}X_i,$$

$$t = 3, \ldots, 10, 13, 14, 16, \ldots, 20, 23, \ldots, 30 \qquad (15)$$

The objective function and the remainder of the constraints remain unaltered. Table 4 presents crop area net profits and the surplus fodder produced by solving the reformulated LP problem.

It can be seen from Table 4 that the new strategy leads to an increase (compare Table 2) in the rice area by 13 ha (10%), with an even distribution of rice in all the four regions considered. However, the total crop area is reduced by 12 ha (7%), due to a reduction in the ragi area by 25 ha (54%). Thus, using surplus male labor for female labor-oriented works contributes to bringing more area under rice, as the return per hectare is relatively higher. As a result, there is an increase in the net profit of Rs 32,000 (4%). However, the decrease in total crop land reduces the surplus fodder produced. In addition, due to the small increase in rice area and the substantial decrease in ragi area, there is not much change in the total water utilization. The tank storage is again not depleted to zero during the season. This indicates that the water availability has not reached the critical stage. Table 5 shows energy usage during different weeks of the crop season. DAP utilization is seen to be a little more intensive as compared with Table 3, resulting in full utilization of male labor in weeks 5 and 6 and its more intensive use in the other weeks as well. However, surplus male labor available during these two weeks

TABLE 5. Energy Use (Male Labor for Female Labor Oriented Works)

Week (1)	DAP Hours		Male Labor Hours		Female Labor Hours		Male Labor for Female Labor Works	
	Utilization (2)	Availability (%) (3)	Utilization (4)	Availability (%) (5)	Utilization (6)	Availability (%) (7)	Utilization (8)	Percentage of male labor (9)
1	835	16.8	835	7.7	—	—	—	—
2	835	16.8	835	7.7	—	—	—	—
3	2,327	46.7	4,176	38.6	6,638	86.5	—	—
4	4,033	80.9	4,186	38.7	—	—	—	—
5	4,984	100.0	10,808	100.0	6,394	83.3	—	—
6	4,857	97.5	10,808	100.0	6,543	85.3	—	—
7	2,915	53.5	8,160	75.5	7,672	100.0	409	3.8
8	1,068	21.4	6,442	59.6	7,672	100.0	688	6.4
9	—	—	—	—	2,056	26.8	26.8	—
10	—	—	—	—	2,136	27.8	—	—
19	—	—	376	3.5	2,756	49.0	—	—
20	—	—	501	4.6	2,024	26.4	—	—
23	—	—	4,588	42.5	7,672	100.0	38	0.3
24	—	—	6,426	59.5	7,672	100.0	819	7.6
25	—	—	7,681	71.1	7,672	100.0	570	5.2
26	—	—	9,419	87.1	7,672	100.0	1,589	12.9
27	—	—	6,714	62.1	2,335	30.4	—	—
28	—	—	4,984	46.1	1,734	22.6	—	—
29	—	—	3,214	29.7	1,118	14.6	—	—
30	—	—	1,638	15.1	569	7.4	—	—

TABLE 6. Crop Areas, Net Profit, and Surplus Fodder

Condition (1)	Irrigation status (2)	Rice (ha)					Ragi (ha) (8)	Groundnut (ha) (9)	Total crop area (ha) (10)	Net profit (Rs) (11)	Surplus fodder, *t* (12)
		I (3)	II (4)	III (5)	IV (6)	Total (7)					
With minimum on ragi	20% deficit	14	36	34	28	112	36	16	164	691,000	324
Without minimum on ragi	20% deficit	33	35	21	23	112	—	31	143	704,000	133
	Full	13	37	—	32	81	11	—	92	614,000	—

is not completely utilized, due to a shortage of DAP and male labor in weeks 5 and 6, thus indicating the critical nature of DAP and male labor in the system during the initial crop season. Table 5 also shows that during harvesting and post-harvest operations, surplus male labor is available even after utilizing male labor for female labor-oriented work from weeks 23–26, when available female labor is used fully. Thus, the results indicate that the DAP and male labor during land preparation and transplanting limit the optimal solution, in conjunction with the existing canal capacity, as opposed to the water availability. This demonstrates the importance of DAP and human labor in agriculture in tank systems.

Deficit Irrigation

Table 6 gives the crop areas, the net profit, and the surplus fodder produced for the two cases considered for the analysis. The results for full irrigation (Mayya and Prasad 1989) are also given for comparison. In both cases of deficit irrigation, rice occupies an area of 112 ha, distributed through all four regions. This contrasts with the corresponding cases for full irrigation where one or two regions are fallow. An additional point of contrast is that a groundnut crop is also present. Both are due to the availability of water saved by planning water deficit. The net profit is also substantially higher than in the full irrigation case. This is due to the increased rice area, which more than compensates for the yield reduction due to water deficit. When no minimum is imposed on ragi, the total area irrigated decreases (although the net profit increases), and it is interesting to note that the ragi area disappears, making way for an increased groundnut area, with some redistribution in the rice regions. The increase in rice I and the groundnut areas is primarily due to a higher return on these crops as compared to ragi. The redistribution leaves more or less unaltered the total area planted in the first week (rice I + ragi + groundnut). Since groundnut does not produce fodder, an increase in groundnut area at the expense of ragi results in reducing the total surplus fodder produced.

Table 6 shows that if there is no minimum on ragi crop, 11 ha of ragi crop are planted under full irrigation, but none when water deficit is planned. This result is due to the fodder constraint. A minimum of about 91 ha of fodder-producing crop is necessary to satisfy this constraint. With full irrigation and no minimum on ragi, the rice area would be less than 91 ha due to water constraint. Consequently, the result is the balance ragi area, with a total area of 92 ha. This is just enough to produce the required fodder. There is no surplus fodder. Under the water deficit system, however, there

TABLE 7. DAP Male and Female Labor Use (with Minimum on Ragi) (Deficit Irrigation)

	DAP Hours		Male Labor Hours		Female Labor Hours	
Week (1)	Utilization (2)	Availability (%) (3)	Utilization (4)	Availability (%) (5)	Utilization (6)	Availability (%) (7)
1	2,881	57.8	2,909	27.0	—	—
2	4,806	96.4	4,907	45.4	—	—
3	4,951	99.3	10,284	95.1	7,672	100.0
4	4,359	87.5	9,967	92.2	6,175	80.5
5	2,499	50.1	7,612	70.4	7,642	99.6
6	846	17.0	5,103	49.2	6,972	90.9
7	—	—	—	—	2,010	26.2
8	—	—	—	—	1,692	22.1
18	—	—	1,023	9.5	1,684	22.0
19	—	—	1,561	14.4	6,367	83.0
21	—	—	1,723	15.9	2,895	37.7
22	—	—	5,081	47.0	7,672	100.0
23	—	—	6,406	59.3	7,672	100.0
24	—	—	7,300	67.5	7,122	92.8
25	—	—	5,158	47.7	1,794	23.4
26	—	—	4,508	41.7	1,568	20.4
27	—	—	2,837	26.2	987	12.9
28	—	—	1,297	12.0	451	5.9

is more rice area and surplus fodder is produced. Constraints other than fodder dictate what other crop can be grown. Groundnut, which produces no fodder but yields a higher return, therefore edges ragi out.

The results of this analysis clearly show the influence of water availability in the initial period of crop season, particularly during the first week when all the farmers would like to start the agricultural operations simultaneously. Allowing water deficit in the initial stages certainly permits a larger crop area, thereby compensating for the reduction in yield. It is justified by the increase in the net profit by Rs 14,000 (28%) and in fodder production by 268 tonnes. Improvement can therefore be achieved in the overall economy of the system by planning water supply deficit during the initial period.

The results (not given here) show that the overall water utilization increases by 35 ha-m (30%) by adopting deficit irrigation. It is interesting to note that the deficit irrigation does not deplete the storage to zero during the crop season as is the case with full irrigation (Mayya and Prasad 1989), indicating that some constraint other than water availability limits the optimal solution during the first few weeks. An examination of the values of the decision variables showed that the canal capacity constraint had become effective. The results also show that the storage at the end of the crop season is 44 ha-m in the case of deficit irrigation, as compared to 62 ha-m when full irrigation is adopted. The spill is also reduced by 50% without any significant change in the evaporation loss. Thus it can be established that more efficiennt use of the inflow in the latter part of the crop season can be achieved by adopting deficit irrigation during the initial crop season when the inflow is low.

Table 7 presents the utilization of energy resources for the deficit irrigation case with a lower limit on ragi area. DAP is used primarily for land preparation (plowing + harrowing), which must be completed in the first six weeks of the crop season. Deficit irrigation in the initial stages permits the utilization of nearly 100% of available DAP during weeks 2 and 3, nearly 90% during week 4, and more than 50% during weeks 1 and 5, showing a better use of the available animal energy in the system than for the no-deficit case. This comes about because the available water is distributed to a larger area. Male labor again closely follows the utilization of DAP, and more than 90% of available male labor is used during weeks 3 and 4 of the crop season. Female labor for transplanting is utilized fully during weeks 3 and 5 at a rate greater than 80% during weeks 4 and 6. There is therefore nearly full utilization of female labor during four of the six weeks of transplanting. During harvesting there is a more uniform use of male labor because of the spread of rice crop in all four regions. However, female labor for harvesting is more critical, at least for three weeks, which affects the solution.

Given these factors, it appears that increasing the irrigation efficiency or the canal capacity further will increase the irrigated area only marginally, as then the energy constraints, especially DAP and female labor, become critical. Any further increase in irrigated area will certainly necessitate the importation of DAP and female labor.

SUMMARY AND CONCLUSION

Insufficient inflow to the tanks in the initial period of the crop season causes delays in the agricultural operations in the command area, especially for rice. A delayed start facilitates bringing more area under irrigation, resulting in more efficient use of available water resources. However, a delayed start extends the total crop season which affects the grain yield due to unfavorable climatic conditions during flowering and yield formation stages. The reduced grain yield decreases the net profit from the system. The energy resources, particularly female labor, become critical during some given week, regardless of the model.

There is a strong case for supplementing the available female labor during peak weeks of agricultural operations. Utilization of surplus male labor for female labor-oriented agricultural operations leads to full utilization of the available DAP and male labor in the system during the peak weeks. Any further increase in the irrigated area requires augmentation of the energy resources, particularly DAP. A delayed start makes more uniform use of these energy resources.

The shortage of female labor during peak weeks indicates the need for changing the traditional use of male and female labor for particular agricultural operations, especially for transplanting and harvesting. This reduces the underutilization of male labor, thereby reducing the unemployment that is one of the major problems faced by these systems.

It is advantageous to adopt deficit irrigation in the initial period of the crop season as a matter of policy. This will not affect the grain yield per hectare appreciably, and the overall net profit of the system can still be increased. Since every farmer in the command of the tank expects to get irrigation water from the first week of the season, practicing deficit irrigation during the initial period is an attractive alternative. It not only helps achieve more efficient use of the inflow in the latter part of the crop season, but also permits a better and more uniform utilization of the available energy resources.

APPENDIX I. REFERENCES

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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 *t*th week for *i*th crop;
DAP_{max} = maximum available draft animal pair hrs;
E_i = nutritional energy value per hectare of *i*th crop (K cal);
E_{min} = minimum requirement of nutritional energy value (K cal);
E_t = evaporational loss in *t*th week (ha-m);
ET_{ti} = maximum evapotranspiration in *t*th week of *i*th crop (mm);
F_{max} = maximum available female labor hr;
F_{ti} = female labor hours required in *t*th week for *i*th crop;
FR_i = fodder produced per hectare of *i*th crop (t);
FR_{min} = minimum fodder requirement of system (t);
I_t = inflow to tank in *t*th week (ha-m);
M_{ti} = male labor hour required in *t*th week for *i*th crop;
M_{max} = maximum available male labor hour;
N = total number of crops;
P_i = net profit per hectare of *i*th crop (rupees);
Q_t = spill in *t*th week (ha-m);
R_i = resources input required for *i*th 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 *t*th week (ha-m);
t = time period (weeks);
TL = total available irrigable land (ha);

W_{ti} = irrigation water release in tth week for ith crop (ha-m); and
X_i = crop land area of ith crop (ha).

Subscripts

i = crop; and
t = time.