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Modifying the Canal Delivery Schedule during the Periods of Limited Water Availability

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ABSTRACT: An alternative canal delivery schedule during the dry season to improve the water regime in the canal command is suggested through model study. A distributary of Puri main canal system (a run-of-the-river scheme) in the state of Orissa was chosen for simulation study. The design discharge of the distributary is 6.045 m^3/sec at its head regulator. Historical daily flow data of the distributary was analyzed to study the feature of the prevailing delivery schedule which is observed to be Continuous with variable flow rate. The modeling approach adopts a procedure of daily water balance/moisture balance simulation in the root zone of paddy and other dry season crops. In addition to Continuous schedule, five alternative rotational (variable discharge, constant duration and constant frequency) schedules were considered. The major crops considered are winter rice, groundnut, potato, tomato, cabbage, cauliflower, brinjal, green gram and black gram. Two tentative dates of canal water supply for the dry season i.e., 1st and 15th of December were considered. Daily water balance simulation was performed for the dry season (145 days from the beginning date of canal water supply) for 15 years period. The results reveal that during the dry season canal closure of more than seven days will have moisture stress on crop fields. Considering both paddy and non-paddy crops to be grown in the command during dry season, 7 days canal operation followed by 7 days canal closure rotational schedule was found to be the best alternative amongst the schedules considered.

Keywords: Canal Delivery Schedule, Evapotranspiration, Irrigation Efficiency, Irrigation Water Supply, Crop Water Demand.

INTRODUCTION

In India, rapid expansion of irrigation facilities has raised the irrigation potential from 22.6 M ha since 1951 to 95.40 M ha (provisional) by the end of ninth five-year plan, 1997–2002 (Anonymous, 2003). This has resulted substantial increase in overall agricultural production and productivity of the area brought under irrigation. In spite of these gains, there is a growing concern that the returns from these projects have not been satisfactory as was envisaged at the time of their commissioning. Most of the surface irrigation projects in India and Southeast Asia operate at a poor overall efficiency of about 30% to 35% (Sanmugnathan and Bolton, 1988). Poor distribution and management of irrigation water is a major factor responsible for this situation. Mostly, at the lower level of water conveyance system, the control structures are either permanently damaged or partially defunct. This leads to a situation of wastage of irrigation water in the head and middle reach and scarcity in the tail reach, when there is a flow in the canal system. Thus, there is a need to improve the performance of these large irrigation systems so as to make them efficient and productive.

Performance of the canal irrigation system can be improved either through structural improvement or through operational modifications. Creation of new sources of irrigation is becoming difficult day by day due to many limiting factors such as non-availability of favourable sites, increasing cost of construction, lack of fund and human resettlement costs. To meet the increasing demand of irrigation water within the domain of these constraints, enhancing the efficiency of existing systems looks to be a viable alternative over creation of new sources of irrigation water. Further, due to financial resource crunch, efficient operation and management of the system also sounds to be a suitable alternative over infrastructural development. Improved operation and management of the canal system through a better delivery schedule can enhance the overall system's performance and productivity of the command (Mishra *et al.*, 2002; Haque *et al.*, 2004).

Irrigation system managers typically rely on experience and rules-of-thumb to determine the canal operation schedule for known or anticipated water demands. Their control strategies and operational

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schedules are inadequate for good water management practices. The mismatch between irrigation water supply and crop water demand not only reduces the productivity level of the command but also encourages the irrigation induced secondary problems such as salinization and water logging. Bridging the gap between the irrigation water supply and crop water demand will not only make the system more efficient and productive but also sustainable. This is of utmost importance during the dry season when the availability of irrigation water is limited. Therefore, in this study, an attempt has been made in understanding the prevailing delivery schedule of a canal system and developing an alternative delivery schedule for the dry season taking into account the prevailing cropping pattern, soil characteristics, climatic variation and canal capacity constraints etc. The objective was to improve upon the water regime of the command within the existing supply level.

STUDY CANAL SYSTEM

The Phulnakhara distributary of Puri Main Canal System (a run-of-the-river scheme) located in the state of Orissa, India was selected for study purpose. The designed Cultivable Command Area (CCA) of the distributary is 5424.78 ha and verified CCA is 3864.14 ha. The length of the distributary is 21.528 km. About 7 minors and 35 sub-minors are off taking from this distributary. The distributary has a design discharge of 6.045 m^3/sec at its head regulator. During the year, the irrigation water flows continuously in the canal system in two spells i.e., the first spell in rainy season (July to November) and the second spell in dry season (January to May). During the rainy season, the canal runs continuously for a period of about 3.5 months, beginning on last week of July and ceasing on 2nd week of November. The predominant crop during rainy season is rice. Similarly, during dry season the canal begins to operate during last week of January and continues up to 1st week of May. The major crops grown during dry season are green gram, black gram, vegetables, groundnut, potato etc. In both the spells the canal runs continuously with a variable flow rate. Thus, the prevailing canal delivery schedule is continuous with varying flow rate. This continuous flow is provided to each distributary, each minor, each sub-minor and each farmer. The flow changes in the distributary are supposed to be distributed proportionately. However, due to lack of adequate control structures the flow changes are not translated proportionately as a result of which the tail-end farmers suffer maximum. Further, in the dry season, the irrigation water availability is limited; hence there is an acute need to improve the delivery schedule for a better water regime in the command.

The command area of the study distributary is dominated by clay loam soil at its head reach and sandy clay loam soil at its middle reach and tail reach. Soil samples in the head, middle and tail reach of the study distributary were collected and analysed for determining their physical properties. The soils of head reach are relatively heavier than middle and tail reach. The soils of middle reach are highly porous. Sandy clay loam is the predominant soil type of the command. Bulk density of soil ranged between 1.42 to 1.64 gm/cm^3. Saturated vertical hydraulic conductivity ranged between 0.253 to 1.024 cm/hr and horizontal hydraulic conductivity between 0.133 to 0.896 cm/hr. The average annual rainfall of the study area is 1573 mm.

To compute the irrigation water requirement, the cropping pattern data of the command during dry season was collected for 12 years period (1988 to 2000) from the office of the Deputy Director of Agriculture, Cuttack, Government of Orissa. Analysis revealed that about 90% of the command is covered by various crops during dry season. On an average, Pulses such as green gram and black gram; Vegetables such as potato, tomato, cauli flower, cabbages and brinjal; Cereals such as winter paddy; Oil seeds such as groundnut and sunflower have been grown in about 31%, 29%, 15% and 15% of the command area, respectively.

MODEL DEVELOPMENT

A model for modifying the delivery schedule during dry season was formulated as suggested by Tyagi *et al.* (1995). The model is based on the soil moisture balance simulation approach in the crop root zone of the command area. This model is used for simulating the moisture content in the root zone depth for crops other than paddy. The equation governing the daily soil moisture balance in crop root zone depth is as follows,

$$\theta_i = \theta_{i-1} + IR_i + ERF_i - ET_{ai} \quad \text{... (1)}$$

For, $\theta_{i-1} < SMS$

$$ERF_i = RF_i \text{ if } RF_i < SMS - \theta_{i-1} \quad \text{... (2)}$$

$$ERF_i = SMS - \theta_{i-1} \text{ if } RF_i \geq SMS - \theta_{i-1} \quad \text{... (3)}$$

where, θ_i = soil moisture content in the crop root zone on i^{th} day, mm; RF_i = total rainfall on the i^{th} day, mm; ERF_i = effective rainfall on the i^{th} day, mm; IR_i = net irrigation water applied on the i^{th} day, mm; ET_{ai} = actual evapotranspiration on the i^{th} day, mm; SMS = soil moisture content at saturation, mm; and i = an index for days since crop growth 1, 2, 3, ..., n.

Since the above basic governing equation is concerned with the daily soil moisture balance in the crop root zone, a linear root growth module is considered for determining the depth of root zone at any particular day. The equation considered is as follows,

$$RD_i = DS + (DM - DS)\frac{i}{m} \qquad \ldots (4)$$

where, RD_i = depth of root zone on i^{th} day, mm; DM = maximum root zone depth, mm; DS = depth at which seed is sown, *mm*; and m = days after seeding when the maximum root zone depth is reached.

Further, the actual evapotranspiration for non paddy crops is computed from the reference evapotranspiration,

$$ET_{ai} = ET_{oi} \cdot K_{Si} . K_c \qquad \ldots (5)$$

$$K_{Si} = 1, \quad \text{if} \quad \frac{AWR}{AW} \geq 0.75 \qquad \ldots (6)$$

$$K_{Si} = \frac{AWR}{0.75AW}, \quad \text{if} \quad \frac{AWR}{AW} < 0.75 \qquad \ldots (7)$$

where, K_c = crop coefficients which depends on crop growth stages; K_{Si} = crop stress factor on the i^{th} day, which is a function of relative available soil moisture content in the field; ET_{oi} = reference crop evapotranspiration on i^{th} day; AWR = remaining available soil moisture; and AW = available soil moisture (field capacity-wilting point).

Here, while calculating the crop stress factor, it is considered that up to depletion of 25% of the available soil moisture, the actual evapotranspiration is equal to potential evapotranspiration and thus, there is no stress on the crop. The crop stress factor is considered to increase linearly when depletion level of available soil moisture increases above 25%. Irrigation is applied to crops when both the following conditions are satisfied *i.e.*, the available soil moisture reached a stage of 25% depletion level and the canal is in operation. The depth of application of irrigation is kept as the highest value between (field capacity – θ_i) and 6 cm.

For paddy, simple water balance approach of the rice field in the command (input-output = change in storage) is followed, which can be mathematically written as,

$$W_i = W_{i-1} + RF_i - ET_{ai} - DP_i + IR_i \qquad \ldots (8)$$

where, W_i = water level in a paddy field/irrigation unit on the i^{th} day in mm; RF_i = rainfall in the i^{th} day in mm; and DP_i = deep percolation and seepage from paddy field on the i^{th} day in mm.

The actual evapotranspiration for paddy is computed from the reference evapotranspiration as follows,

$$ET_{ai} = ET_{oi} \cdot K_c \;\; \text{if } SMC_i \geq FC \qquad \ldots (9)$$

$$ET_{ai} = ET_{oi} \cdot K_c \cdot K_{Si} \;\; \text{if } SMC_i < FC \qquad \ldots (10)$$

where, SMC_i = soil moisture content for i^{th} day; and FC = moisture content at field capacity. The crop stress factor K_{Si} is estimated as follows,

$$K_{Si} = \frac{\log\left[1 + 100\left(\dfrac{SMC_{i-1}}{AWC_i}\right)\right]}{\log(101)} \qquad \ldots (11)$$

where, AWC_i = total available soil moisture storage capacity for i^{th} day.

Deep percolation loss from the paddy field is computed using Darcy's law (Paulo *et al.*, 1995) as given below,

$$V_i = -K_v(\Delta H_i / \Delta Z) \qquad \ldots (12)$$

where, V_i = vertical flow velocity on i^{th} day (m/day); K_v = saturated vertical hydraulic conductivity (m/day); ΔH_i = difference in hydraulic head between two points in the vertical direction on i^{th} day (m), and ΔZ = vertical distance between the two points (m).

Assuming no spatial variability inside the paddy field, the vertical seepage can be computed as,

$$Q_{vi} = -K_v \cdot A \cdot (\Delta H_i / \Delta Z) \qquad \ldots (13)$$

where, Q_{vi} = vertical seepage from the paddy field on i^{th} day, m^3/day; and A = area of the paddy field, m^2.

The horizontal seepage from the paddy field is computed through Dupuit's approach (Walker and Rushton, 1984) as given below,

$$Q_{hi} = \lambda(K_h / 2L)[(W_i + D_d)^2 - h_1^2] \qquad \ldots (14)$$

where, Q_{hi} = total horizontal seepage flow along the bund (m^3/day) on i^{th} day; λ = length of the bund (m); K_h = horizontal saturated hydraulic conductivity (m/day); L = width of the bund (m); h_l = hydraulic head downstream (m), (the depth of the water in the drainage ditch); and D_d = depth of the drainage ditch (m)

In an irrigation supply day if water level of the paddy field (W_i) falls below the minimum water level (W_{min}), then irrigation (IR_i) is applied ($IR_i = W_{opt} - W_i$) where W_{opt} is the optimum water level in the field. Here, the value of W_{opt} and W_{min} are assumed as 12 cm and 3 cm, respectively for simulation purpose. A computer program was developed based on the above model and the flow chart of the program is shown in the Figure 1.

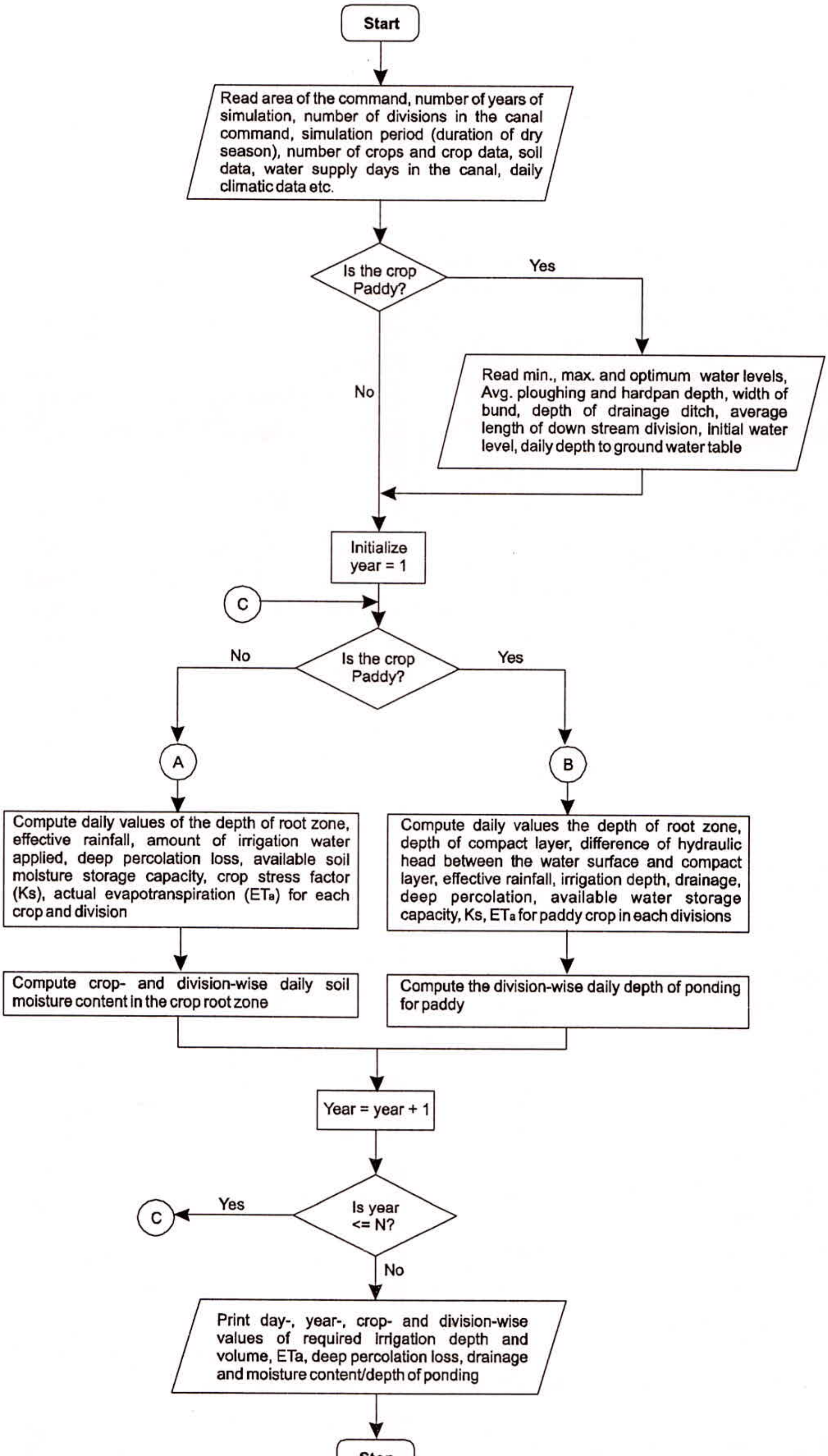

Fig. 1: Flow chart of the computer program based on the model for modifying the canal delivery schedule

INPUT DATA AND SIMULATION

Based on the analysis of crop coverage data for past 12 years, the percentage of area to be covered under various crops in the command of the Phulnakhara distributary was decided. The major crops considered for simulation and the percentage of command area covered are winter rice (15%), groundnut (20%), potato (15%), tomato (5%), cabbage (5%), cauliflower (5%), brinjal (5%), green gram and black gram (30%). Considering that green gram and black gram can be grown with the residual soil moisture after harvest of paddy crop of rainy season or with a pre-sowing irrigation, the remaining seven crops covering 70% of the command area were taken into consideration for model simulation which will be requiring irrigation water. Different parameters of crops which are considered as model input parameters are given in Table 1. Monthly crop coefficients values were extracted from the crop coefficients values of crops based on their phenological stages and used as input data set. For the purpose of simulation, two dates for beginning canal water supply was considered i.e., 1st and 15th of December. Simulation duration of 145 days was considered from the canal operation dates. Simulation was performed for 15 years (1985–1986 to 1999–2000) period. For the simulation period, daily climatic parameters such as rainfall, pan evaporation, depth to ground water table; hydro-physical properties of soil such as saturated vertical and horizontal hydraulic conductivity, initial soil moisture content, moisture content at saturation, field capacity and wilting point; and crop parameters were used as input data sets for the model. The entire command of the distributary was divided into three divisions for simulation purpose i.e., head, middle and tail. Each division has cultivated area of 1288 ha.

Simulation was performed for the prevailing continuous schedule and five alternative rotational schedules. The alternatives considered are: (i) 7 days canal operation followed by 7 days canal closure (7_7), 10 days canal operation followed by 10 days canal closure (10_10), 15 days canal operation followed by 15 days canal closure (15_15), 10 days canal operation followed by 7 days canal closure (10_7) and 15 days canal operation followed by 7 days canal closure (15_7). The output from the model includes crop wise daily actual evapotranspiration, irrigation requirement, daily depth of ponding in paddy field, daily soil moisture content in the root zone depth for other non-paddy crops etc.

RESULTS AND DISCUSSION

Computed Actual Evapotranspiration

Actual evapotranspiraton (ETa) during the entire season is an indicator of crop growth and yield. Table 2&3 presents the model computed seasonal actual evapotranspiration (15 years average) of winter crops grown under different delivery schedules for the canal supply beginning on 1st and 15th December respectively. The last column of the tables shows the area weighted average of the actual evapotranspiration. On comparison of last column of both the tables, a negligible higher ETa is seen for supply date beginning on 1st December. This is because, the crops occupying almost half of the command i.e., rice, ground nut and potato sowing date is 15th of December (Table 1). Further, some time is also required for canal routine maintenance after monsoon supply. Therefore, it is suggested to begin the canal supply for dry season on or after 15th of December. In case of a good shower during the 1st half of December, the canal opening may be further delayed depending on the moisture content of the command area. Hereafter, the simulation data considering beginning of canal supply on 15th of December is considered for further analysis.

Table 1*:* Input Parameters for Different Crops

Sl. No.	*Crop Name*	*Percentage of Command Area Covered (%)*	*Start Date*	*Crop Duration (Days)*	*Maximum Root Zone Depth (mm)*	*Depth at Which Seed is Sown (mm)*	*Days on Which Maximum Root Zone is Attended*
1.	Paddy	15	15th December	130	1000	50	90
2.	Groundnut	20	15th December	125	1000	70	82
3.	Potato	15	15th December	110	600	70	90
4.	Tomato	5	1st December	120	1500	50	115
5.	Cabbage	5	1st December	135	800	50	125
6.	Cauliflower	5	1st December	120	700	50	105
7.	Brinjal	5	1st December	130	1200	50	90
8.	Greengram and Blackgram	30	1st December	90	1000	50	65

Table 2: Model Computed Seasonal Actual Evapotranspiration under Different Delivery Schedules for Canal Supply Beginning on 1st December

Delivery Schedule	*Seasonal Actual Evapotranspiration (mm)*							
	Paddy	*Ground-Nut*	*Potato*	*Tomato*	*Cabbage*	*Cauli-Flower*	*Brinjal*	*Weighted Average*
C	494.20	322.29	304.23	298.11	363.61	302.09	389.18	359.82
7_7	492.08	319.82	295.43	293.60	353.11	293.07	380.53	354.44
10_10	488.99	311.78	283.49	289.32	342.61	289.13	370.99	346.90
15_15	483.44	313.24	275.37	285.21	332.82	273.91	368.62	342.14
10_7	491.06	316.50	291.47	294.18	350.59	291.52	383.00	352.35
15_7	492.31	319.45	295.95	293.88	353.18	293.59	384.82	354.86

Table 3: Model Computed Seasonal Actual Evapotranspiration under Different Delivery Schedules for Canal Supply Beginning on 15th December

Delivery Schedule	*Seasonal Actual Evapotranspiration (mm)*							
	Paddy	*Ground-Nut*	*Potato*	*Tomato*	*Cabbage*	*Cauli-Flower*	*Brinjal*	*Weighted Average*
C	494.20	321.90	303.87	288.67	353.55	292.30	368.85	356.09
7_7	491.42	319.43	294.33	285.82	344.45	284.06	363.18	350.89
10_10	489.05	315.91	287.61	283.67	333.93	275.76	360.74	346.26
15_15	484.41	310.14	278.95	276.82	319.19	266.33	353.99	339.07
10_7	492.11	319.05	293.62	284.69	341.77	282.88	364.67	350.53
15_7	492.70	319.82	296.68	286.65	344.83	285.34	365.04	352.09

Perusal of Table 3 reveals that highest seasonal ETa was observed under continuous schedule. Among the alternatives considered, schedule 7_7, 10_7 and 15_7 computed almost same seasonal ETa. There is about 17 mm reduction in seasonal ETa (area weighted average of all crops) in 15_15 schedule than that of continuous schedule. Similarly, there is about 10 mm reduction in average seasonal ETa in 10_10 schedule than that of continuous schedule. Thus, a reduction of 17 mm (about 5% of total seasonal ETa) in case of 15_15 schedule and 10 mm (about 3% of total seasonal ETa) in case of 10_10 schedule narrows down the prospects of these two rotational canal delivery schedules from the list of alternatives considered.

Depth of Ponding and Soil Moisture Content

Table 4 presents the average depth of ponding in winter rice fields and the average moisture content for other crops during the crop growth period for different delivery schedules. Schedule 15_15 and 10_10 registers a very low level of depth of ponding in rice

Table 4: Model Computed Average Water Level (in paddy) and Moisture Content (in Other Crops) under Different Delivery Schedules for Supply Beginning on 15th December

Delivery Schedule	*Average Water Level (mm)*	*Average Moisture Content (cm³/cm³)*					
	Paddy	*Ground-Nut*	*Potato*	*Tomato*	*Cabbage*	*Cauli-Flower*	*Brinjal*
C	46.96	0.23	0.23	0.23	0.23	0.23	0.23
7_7	28.13	0.23	0.23	0.23	0.23	0.23	0.22
10_10	18.98	0.23	0.23	0.22	0.22	0.22	0.22
15_15	9.28	0.23	0.23	0.22	0.22	0.22	0.22
10_7	30.46	0.23	0.23	0.22	0.22	0.22	0.22
15_7	34.24	0.23	0.23	0.23	0.23	0.23	0.22

field and therefore these two schedules seems to be not suitable for winter rice. The average moisture content of the command at field capacity and wilting point is determined as 0.262 and 0.133 respectively. Thus, at 25% depletion level of available soil moisture the moisture content works out to be 0.229. Perusal of Table 4 indicates that for all the crops, schedules Continuous, 7_7 and 15_7 have average moisture content > 0.229 for almost all crops. Schedule 10_7, 10_10 and 15_15 have average moisture content value less than 0.229. Hence, there will be stress to crops if these three schedules (10_7, 10_10 and 15_15) are practiced. In other words, during dry season, canal closure of more than 7 days will create moisture stress on crops.

Comparison of Actual Irrigation Water Supplies and Crop Water Demands

The actual canal water supplied during the dry season and the model computed canal water required for irrigation under different delivery schedules at the head regulator of the distributary are presented in Table 5. The average values are taken considering only the years when there was supply during the dry season. Thus, while calculating the average values of supply and model computed demand, the values for the years 1991, 1993, 1995, 1996 and 1998 were taken into account.

In case of prevailing continuous schedule, the irrigation water requirement is more than the actual water supplied. In case of rotational alternative schedules considered, the model computed water requirements were found to be less than the actual water supplied. Among the two options of rotational delivery schedules i.e., 7_7 and 15_7, schedule 7_7 requires lesser amount of water. Adopting this schedule will save on an average about 10.58% of irrigation water when compared with the actual irrigation water supplied. Thus, 7 days on followed by 7 days off rotational schedule will save considerable amount of irrigation water without bringing any moisture stress on the crops. In addition to the advantages of rotational schedule, adoption of this schedule will motivate farmers to upkeep and maintain the field channels, which were constructed by Command Area Development Authority. This schedule will discourage field to field irrigation. Therefore, 7_7 rotational schedule can be safely applied to study system during dry season as an alternative to the prevailing continuous schedule.

Table 5: Irrigation Water Supply and Crop Water Demand in the Dry Season at the Head Regulator of Phulnakhara Distributary

	Actual Irrigation Water Supplied, Mm^3	*Model Computed Crop Water Demand under Different Delivery Schedules, Mm^3*					
		C	*7_7*	*10_10*	*15_10*	*10_7*	*15_7*
1985	26.26	30.71	24.73	24.54	24.38	26.14	26.43
1986	24.48	28.39	22.18	22.45	22.11	23.63	24.14
1987	37.06	31.78	25.53	25.32	25.03	26.78	27.55
1988	42.04	33.38	27.19	27.27	27.01	28.89	29.07
1989	34.22	26.58	20.74	21.07	20.75	22.08	22.84
1990	25.26	29.70	23.65	23.54	23.00	25.10	25.84
1991	0.00	31.90	26.31	26.13	25.37	27.03	27.74
1992	0.98	29.07	22.94	22.83	22.45	24.20	24.75
1993	0.00	24.49	18.69	18.57	18.79	20.33	20.29
1994	15.16	30.82	25.28	24.77	24.36	26.05	26.70
1995	0.00	29.82	24.16	24.01	24.01	24.74	25.96
1996	0.00	30.71	24.73	24.54	24.38	26.14	26.43
1997	29.14	28.39	22.18	22.45	22.11	23.63	24.14
1998	0.00	31.78	25.53	25.32	25.03	26.78	27.55
1999	19.18	33.38	27.19	27.27	27.01	28.89	29.07
2000	38.47	26.58	20.74	21.07	20.75	22.08	22.84
Average	26.57	29.69	23.76	23.68	23.39	25.00	25.57

CONCLUSIONS

A model for modifying the canal delivery schedule during dry season was formulated. Model simulation study over 15 years period during the dry season revealed that 7 days rotational schedule is the best alternate over the continuous schedule. The alternate schedule registers a better crop evapotranspiration. In addition to creating a favourable water regime for paddy and non-paddy crops, this schedule also saves about 10.58% of irrigation water over the prevailing continuous delivery schedule. An added advantage of this schedule is the reliability of water supply. Practicing this schedule will encourage farmers to invest more on other inputs and dissuade them to go for field to field irrigation. All these advantages together will result in enhanced crop yield and water use efficiency in the canal command.

REFERENCES

Anonymous (2003). *Annual report, 2002–2003.* Ministry of Water Resources, Government of India, pp. 180.

Haque, M.A., Najim, M.M.M. and Lee, T.S. (2004). "Modelling irrigation water delivery schedule for rice cultivation in east coast Malaysia". *Tropical Agricultural Research.* 16, 204–213.

Mishra, A., Singh, R. and Raghuwanshi, N.S. (2002). "Alternative delivery scheduling for improved canal system performance". *Journal of Irrigation and Drainage Engineering* (ASCE), 128(4), 244–248.

Paulo, A.M., Pereira, L.A., Teixeira, J.L. and Pereira, L.S. (1995). "Modelling paddy rice irrigation". *Crop-Water-Simulation Models in Practice*, Pereira, L.S., van den Broek, B.J., Kabat, P., Allen, R.G., (Eds.*), Proc. of the 2nd workshop on Crop-Water-Models at the 15th Congress of the International Commission on Irrigation and Drainage* at the Hague, The Netherlands in 1993, 287–302.

Sanmugnathan, K. and Bolton, P. (1988). *Water management in third world irrigation schemes—Lesson from the field*, ODU Bull., 11, Hydraulic Research, London, UK.

Tyagi, N.K., Bhirud, S., Kaushal, R.K., Ambast, S. and Mishra, A. (1995). *Improving Canal Water Delivery Performance—Some Approaches.* Central Board of Irrigation and Power, New Delhi. Publication No. 246, 69 pp.

Walker, S.H. and Rushton, K.R. (1984). "Verification of lateral percolation losses from irrigated rice fields by a numerical model". *Journal of Hydrology.* 71 (3–4), 335–351.