Planning for the Subernarekha river system in Eastern India

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Abstract. The study describes the systems studies carried out to plan a river basin in order to determine the nature and size of water storage facilities and releases for irrigation and industrial uses, and the associated cropping pattern. The model has been formulated in the framework of a linear programming model for a specific target year. This model is developed in the context of planning the Subernarekha river basin. The results are discussed and these provide information and insight suggesting the need for more disaggregated analysis of interaction between irrigation and related agro-economic parameters.

Keywords. River basin planning; LP model; storages; Subernarekha river system; agro-economic parameters.

1. Introduction

The Subernarekha is an inter-state river flowing through Bihar, West Bengal and Orissa. It rises in the Chhotanagpur plateau of Bihar and flows into the Bay of Bengal. The upper part of the Subernarekha and its tributaries run through the fertile land of Bihar, but the farming in this region is mainly dependent on the inadequate and untimely rains, and the water resources of the Subernarekha river system remain largely untapped. The upper basin, besides containing fertile land, also contains large reserves of minerals. A number of important industries have therefore grown along the banks of the river.

For integrated development of this basin the construction of dams, one on the Subernarekha at Chandil and the other on its tributary Karkai and two barrages, one on the Karkai at Bhua and the other on the Subernarekha at Galudih, is proposed. The gross irrigated area envisaged under this programme is about 2,30,000 ha in Bihar.

This study aims at an economic appraisal of the scheme in a coordinated manner to determine the nature and size of the water storage facilities and the releases for irrigation and industrial uses as well as the associated cropping patterns such that the water potential in this region is exploited optimally.

Detailed systems analysis studies are required for this purpose which incorporate the interactions of hydrological, agronomic and economic considerations in an integrated manner. Initially the model was formulated in the framework of a linear programming (LP) model for a specific target year which would take into account some of the chief interrelated factors affecting the optimum utilization of the water potential in this area. Since the projects mainly benefit the agricultural sector, both the cropping pattern and

A list of symbols & indices is given at the end of the paper.

the capacities of the dams and barrages with their associated canals were considered as choice variables in the model. The idea was to provide a logical framework so that the initial results could provide some useful information and insights for subsequent systems studies with detailed (multiperiod) programming models or simulation models which may be useful for obtaining the capacities and operational schedule of the system.

2. An overview of the model

The target year LP model for 1980 as outlined above is disaggregated over space and considers temporal differentiation (in terms of the 12 months) over a year. A schematic diagram of the Subarnarekha river system is presented in figure 1. The objective of our model is to maximise the annual additional benefits considering returns from the crop, the supply of industrial water, net project costs, farm costs and benefits foregone. All such benefits and costs have been computed from society's point of view.

2.1 Decision variables

The LP problem determines the following investment decision variables:

- (i) Capacities of the reservoirs to be built at each of the two sites,
- (ii) Delivery capacity of the associated canal system.

The associated operating decision variables evaluated by the model are the following:

- (i) For each crop, the area sown, where production activities are differentiated by site,
- (ii) The amount of industrial water to be supplied from each site during each month.

Figure 1. Schematic outline of the Subarnarekha river basin

- (iii) The downstream flows from each of the dams and barrages during each month.
- (iv) The diversion for irrigation purposes from each site in each month.
- (v) Volume of water to be stored by the end of each month for the subsequent periods.

2.2 Constraints

The levels of both the investment decision variables and operating decision variables are simultaneously determined in the model such that the total additional benefit to society, less the project costs, is maximized subject to the following constraints of continuity, capacity, agronomy and land area.

- (i) The flow continuity constraint for the dams for each period states that the inflows should equal the outflows plus the water that is stored for the next period. The water that is stored for the next period should not go below a minimum level (*i.e.* the dead storage level). Since there are no storage facilities in barrages, the flow continuity constraints simply require that the inflows should equal the outflows from such modes.
- (ii) The capacity constraints for dams require that the volume of water to be stored in each decision period should not exceed the capacity of the dam to be built at that site. Similarly, the amount of water for irrigation purposes in each period should not exceed the delivery capacity of the canal.
- (iii) The irrigation flow constraints state that the amount of water diverted for irrigation purposes each month should be at least as large as the water requirements of perennial and non-perennial crops.
- (iv) The land area constraint requires that the total planting in each season should be restricted to the culturable command area less the acreage required for fodder crops and the area left fallow in a particular season.
- (v) Certain limits have also been imposed on the production of certain crops (for example, vegetables) as commodity demand functions have not been included in our model. Certain constraints have also been introduced on the acreage under paddy to reflect consumer preference for rice.

Detailed sensitivity analyses have also been carried out on different assumptions with respect to the river flow data and detailed parametric programming has also been performed on the coefficients of the objective functions (especially with respect to changes in the relative price of wheat to that of other crops) for mapping out the different patterns of irrigation development with respect to changes in the above parameters.

3 The algebraic formulation of the model

The mathematical model is described by (A1)–(A14) (appendix A). There are four sites considered in the model which are differentiated by the subscript i (see list of symbols & indices).

Fourteen crops have been considered indexed by t . Irrigated crops with different levels of irrigation have been designated as different crops. The figures in brackets denote water supplied corresponding to which appropriate yields are adopted.

The activities or choice variables, of which the two land use activities are measured in thousand hectares and all the remaining which are hydrologic activities, are measured in million cubic metres.

4. Data base

The main data inputs for the model are: benefit and cost coefficients in the objective function, water requirements of various crops for each month, hydrological inputs for different months at various sites, downstream flow requirements at the Subernarekha barrage for downstream use, coefficients of return flows from irrigation and industrial water supplies and coefficients of reservoir losses in each month.

In the objective function, the coefficients required are: value of each crop net of variable farm costs, fixed farm costs, unit revenue from the sale of industrial water, the annualized investment costs of reservoirs and canals and annual maintenance costs of reservoirs and canals. Gross value of each crop has been estimated as the sum of the value of grain output and the value of fodder. The assumptions regarding yield rates, prices and value of output have been given in table 1. The yield rates are based on the data obtained from the Agriculture Department (Ministry of Agriculture 1971) and from the Project Report (Ministry of Irrigation and Power 1972). The yield of paddy is assumed to decline by 10% when the total water requirements (at canal head) are reduced from 75 to 67.5 cm. Similarly, the yield of wheat is assumed to be 10% lower when the total water input is reduced from 70 to 57.5 cm. The accounting (or shadow) prices used to estimate benefits from major crops are expected to reflect the social value of these agricultural commodities since these prices take into account (i) economic cost of production of additional foodgrains in a surplus region of the country plus (ii) the economic cost of transportation (including cost of distribution and storage) of these commodities to the project region. We have used prices of foodgrains fixed by the Agricultural Prices Commission in the nearest surplus region plus the average cost of transporting these commodities to the project region (Sinha & Bhatia 1976). Valuation of agricultural output on this basis is expected to reflect the need for increasing agricultural output in regions away from the granaries of the country. The net value of each crop has been estimated by deducting the cost of seeds, fertilizers and manures, pesticides and human labour. To reflect the relatively higher levels of unemployment of unskilled agricultural labour in the region, we have used shadow wage rates which are lower than the market wages. We have assumed the ratio of shadow wages to market wages to be 0.25. The estimated values for various elements of variable costs and net benefit for each crop are given in tables 2 and 3. The fixed farm costs are assumed to include the following elements: (i) annualized costs of additional bullocks and implements required in irrigated agriculture, (ii) annual costs of maintenance of bullocks, command area development costs such as those of land levelling and shaping, field channels, field drains, improvement in facilities for storage, marketing, transport and communication. These costs have been estimated to be Rs 136 per acre and are relevant for the culturable command area at different sites (Sinha & Bhatia 1976).

The social cost of investment for the dams and canals has been calculated by giving due consideration to the foreign exchange component, wage component due to unskilled labour and the construction period of the project. The social investment cost per unit has been calculated by applying the following formula.

$$I = \sum_{t=1}^{\theta} \sum_i P_i J_i(t) (1+r)^{\theta-t} \quad (1)$$

Table 1. Yields, prices and benefits for different crops (at social prices)

Crops	Yield (Q/hectare)	Shadow price (Rs/Q)	Value of grain output (Rs)	Fodder (Q/hec.)	Shadow price of fodder (Rs/Q)	Value of fodder (Rs)	Value of output (per hectare) (Rs)
Paddy (75 cm)	29.6	95	2812	29.6	3	88.8	2900
Paddy (67.5 cm)	26.7	95	2536	26.7	3	80.0	2616
Maize (K)	19.8	90	1782	12.3	2	24.6	1806
Maize (R)	19.8	90	1782	12.3	2	24.6	1806
Wheat (70 cm)	24.7	135	3335	24.7	15	370.5	3705
Wheat (57.5 cm)	22.2	135	2997	22.2	15	333.0	3330
Pulses and oilseeds	12.4	130	1612	6.2	3	18.6	1630
Vegetables (potatoes)	296.0	30	8880	—	—	—	8880
Vegetables (S)	247	40	9880	—	—	—	9880
Paddy (S)	24.7	110	2717	24.7	3	74.0	2791
Sugarcane	500	12	6000	50.0	5	250.0	6250
Paddy (unirrigated)	10	95	950	10.0	3	30.0	980
Maize (unirrigated)	7	90	630	4.3	2	8.6	638
Pulses and oilseeds (unirrigated)	7	130	910	3.5	3	10.5	920

Q = quintal (100 kg); K = kharif; R = rabi; S = summer (this is so for all the tables)

Table 2. Input costs of different crops (variable farm costs) (Rs/hectare) (at social prices)

Crops	Seeds	Human labour	Fertilizers and pesticides	Total
Paddy (75 cm)	74	149	1093	1316
Paddy (67.5 cm)	74	149	1093	1316
Maize (K)	52	104	765	921
Maize (R)	52	104	765	921
Wheat (70 cm)	346	119	1201	1666
Wheat (57.5 cm)	346	119	1201	1666
Pulses & oilseeds	242	83	841	1166
Vegetables (R)	1853	141	2298	4292
Vegetables (S)	1853	141	2298	4292
Paddy (S)	74	149	1093	1316
Sugarcane	642	206	3632	4480
Paddy (unirrigated)	45	129	62	236
Maize (unirrigated)	31	90	43	164
Pulses and oilseeds (unirrigated)	111	60	86	257

Table 3. Net benefits (at social prices) for different crops (Rs/hectare)

Crops	Benefits	Cost	Net benefits
Paddy	2900.8	1316.5	1584.3
Paddy (67.5 cm)	2616.0	1316.5	1299.5
Maize (K)	1806.6	921.9	884.7
Maize (R)	1806.6	921.9	884.7
Wheat (70 cm)	3705.5	1666.3	2039.2
Wheat (57.5 cm)	3330.0	1666.3	1663.7
Pulses & oilseeds	1630.6	1166.2	464.4
Vegetables (potatoes)	8880.0	4292.0	4588.0
Vegetables (S)	9880.0	4292.0	5588.0
Paddy (S)	2791.0	1316.5	1474.5
Sugarcane	6250.0	4480.0	1770.0
Paddy (unirrigated)	980.0	236.8	744.2
Maize (unirrigated)	638.6	164.3	474.3
Pulses & oilseeds (unirrigated)	920.5	258.0	662.5

A construction period of 7 years has been assumed for the Kharkai and the Subernarekha dams. The investment cost has been annualised by assuming a capital recovery factor of 10.01 % *i.e.* 10 % social rate of discount and a 50-year life for the dams. We have also added the annualised maintenance and operating cost with the annualised investment cost of dams. The annualised maintenance and operating cost has been taken to be 2 % of the investment cost. This includes labour, maintenance and overhead costs. The resulting estimates for annual costs are Rs 32.05 and Rs. 22.52 per thousand cu m for the Kharkai and the Subernarekha dams respectively. The capital costs of canals have also been annualized using the capital recovery factor mentioned above. These costs also include the cost of the Subernarekha and Kharkai barrages.

The revenue from the sale of industrial water has been taken to be Rs. 61.32 per thousand cu m.

The yield series for water for the two dams and the two barrages have been developed on the basis of rainfall series computed at each site separately. The rainfall runoff correlations which have been used for computing the yield series have been developed for Mango Weir (Jamshedpur site) at which runoff data were available for the period June 1961 to October 1973, assuming that the same will hold good at these dam and barrage sites. Since the Subernarekha waters have been allocated to the three cobasin states on the basis of an estimated 75% dependable annual water yield, the hydrological input in this model for the year in which the annual yield corresponded to 75% dependability is different for different control points. Therefore the adoption of different years for different sites in a static linear programming model could neither be considered appropriate nor consistent with the principle underlying the sharing of waters among the States on the basis of water yield as estimated at Kokpara at 75% dependability. Accordingly, the year corresponding to 75% dependability at the terminal structure, that is, the Subernarekha barrage site, was first found out in the 32-year series and the computed month wise yield in this year separately at each site has been utilized for this study. This procedure has also facilitated earmarking or reserving water for utilization from above the control points by excluding catchment areas in proportion to the 75% dependable water yield.

In this study for 75% dependability, the monthly runoffs net of project/protected utilization on the upstream of each site, corresponding to the year 1957–58 have been considered. An alternative solution considers the yield series for 1946–47 which corresponds to 50% dependability at the terminal structure *i.e.* at Subernarekha barrage.

The economic and hydrologic data are given in tables 1 to 9.

5. Results

The results obtained from the model have been presented in the form of a Reference Solution (RS) as well as in terms of sensitivity analysis. The RS is based on the following assumptions: (i) 75% dependability factor for water availability (ii) no bounds on area under major irrigated crops such as paddy, wheat and maize, except for vegetables in rabi and summer (5% of culturable command area (CCA) in each case); (iii) no upper bounds on capacities of dams and canals; (iv) minimum flow required at Subernarekha barrage for downstream use; (v) bounds have been imposed on industrial water supply using exogeneously given estimates; (vi) upper bounds have been imposed on the following unirrigated crops: paddy (25% of CCA), maize (15% of CCA) and pulses and oilseeds (5% of CCA). The sensitivity analysis is presented mainly in terms of changes in relative prices of crops and area under different crops.

The results of the RS have been analyzed with respect to the following: (i) optimum cropping pattern suggesting area allocated to different crops in various seasons (*i.e.* in kharif, rabi and summer); (ii) the optimum capacities of the two reservoirs and the associated releases for irrigation, industrial water supply and downstream uses; and (iii) the associated diversions from the two barrages for the above-mentioned uses.

Table 5 presents the optimum cropping pattern in the RS and tables 6–9 give the corresponding water balances at each of the 4 sites. It may be seen that irrigation intensity (gross area irrigated as a ratio of culturable command area) for the two dams

Table 4. Monthly requirements of water for different crops (in cm)

Crops	July	August	September	October	November	December	January	February	March	April	May	June	Total
Paddy (75 cm)	20	15	15	22.5								2.5	75
Paddy (67.5 cm)	20	11.25	11.25	22.5								2.5	67.5
Maize (K)	8.8	5	9.8	6.1	0.3								29.6
Maize (R)							15	15	15				45
Wheat (70 cm)					12.5	17.5	17.5	12.5	10				70
Wheat (57.5 cm)					5	12.5	17.5	12.5	10				57.5
Pulses & oilseeds						10	12.5	10					32.5
Vegetables (potatoes)					15	15	15	15					60
Vegetables (S)										25.0	12.5	7.5	45
Paddy (S)	10.0									45	35	30	120
Sugarcane	15.3	15.3	7.9	17.7	14	8.3	5.8	6.2	9.5	19.8	40.6	34.6	195

varies from 108 % for the Kharkai dam and 129 % for the Subernarekha dam. The irrigation intensity for the Kharkai barrage is 136 % while it is 179 % for the Subernarekha barrage. The crops in the kharif (monsoon) season are irrigated maize, unirrigated maize and unirrigated paddy for the Kharkai and Subernarekha dams.

Table 5. Optimum cropping pattern in the reference solution (75 % dependability factor) (in thousand hectares)

	Kharkai dam	Kharkai barrage	Subernarekha dam	Subernarekha barrage
<i>Kharif</i>				
Unirrigated paddy	16.2	0	19.5	2.4
Irrigated paddy (75 cm)	0	8.5	0	7.3
Irrigated paddy (67.5 cm)	0	0	0	0
Unirrigated maize	9.7	0	11.3	0
Irrigated maize	28.3	0	34.8	0
<i>Rabi</i>				
Irrigated wheat (70 cm)	35.2	0	58.3	0
Irrigated vegetables	2.8	0.4	3.3	0.4
Unirrigated pulses & oil seeds	3.3	0.4	4	0.4
Wheat (57.5 cm)	0	3.6	0	9
<i>Summer</i>				
Irrigated vegetables	2.8	0.4	3.3	0.4
Irrigated paddy	0	0.4	0	3.3
Gross cropped area (A)	98.4	13.8	134.4	23
Gross irrigated area (B)	69.2	13.4	100	20.2
Culturable command area (C)	64	10	77	11.3
Intensity of cropping (A/C) (%)	154	136	175	204
Intensity of irrigation (B/C) (%)	108	132	129	179

Table 6. Inflow and outflow balances for the Kharkai dam in the reference solution (m cu m)

Month	Inflow	Diversion to			Storage at the end of the month
		Irrigation	Kharkai barrage	Reservoir losses	
July	393.5	26	0	—	361.4
August	130.0	14.8	0	2.5	467.5
September	278.8	28.4	0	3.7	708.0
October	5.0	17.3	140	3.7	546.5
November	3.7	49.3	0	6.15	488.5
December	1.23	66.6	2.5	6.15	408.3
January	2.5	66.6	2.5	3.7	331.8
February	18.5	48.0	0	5	291.0
March	3.7	48.0	1.23	3.7	248.0
April	2.5	7.4	0	3.7	233.0
May	0	3.7	0	6.15	217.0
June	0	2.5	0	5	203.5

Diversion to industrial water supply during all the months has been taken as 6.15 m cu m.

Table 7. Inflow and outflow balances for the Kharkai barrage in the reference solution (m cu m)

Month	Hydrological input	Inflow from Kharkai dam	Return flow from irrigation by Kharkai dam	Total Inflow	Diversions to		Total diversion
					Irrigation	Flow for downstream use at Subernarekha barrage	
July	50.6	0	1.23	56.8	19.7	33.4	56.8
August	146.8	0	0	151.8	19.7	128.4	151.8
September	251.6	0	1.23	257.8	19.7	234.4	257.8
October	5	125.8	0	135.8	19.7	122.1	145.5
November	0	0	1.23	6.23	2.5	0	6.2
December	0	2.5	2.5	10	5	0	8.7
January	2.5	2.5	2.5	12.5	7.5	1.23	12.5
February	2.5	0	1.23	8.7	5	0	8.7
March	1.23	1.23	1.23	8.7	3.7	0	7.4
April	1.23	0	0	6.23	2.5	0	6.2
May	1.23	0	0	6.23	2.5	0	6.2
June	2.5	0	0	7.5	3.7	0	7.4

Return flow from industrial water supply by Kharkai dam during all the months is 5 m cu m. The diversion to industrial water supply is 3.7 m cu m in all cases.

Table 8. Inflow and outflow balances for Subernarekha dam in the reference solution (m cu m)

Month	Inflow	Diversions to			Storage at the end of the month
		Irrigation	Subernarekha barrage	Reservoir losses	
July	680.6	30.8	0	1.23	606.6
August	177.6	17.3	0	6.2	718.8
September	617.7	34.5	0	6.2	1254
October	50.6	21	21	10	1211
November	12.33	80	16	13.6	1071.5
December	3.7	108.5	25	15	885.3
January	5.0	108.5	28.4	13.6	698
February	34.5	39.5	0	11.1	640
March	2.5	59.2	0	10	531.4
April	0	8.6	0	11.1	470
May	0	3.7	0	15	409.4
June	0	2.5	0	13.6	351.4

Diversion to industrial water supply is 42 m cu m in all cases.

Irrigated paddy is the main crop for the two barrages. For rabi (winter) season, the major crop is irrigated wheat (around 60–70 % of CCA) along with some area under pulses and oil seeds and vegetables. The crops for the summer are irrigated paddy at the Subernarekha barrage and vegetables at the other sites. Crops with higher water

Table 9. Inflow and outflow balances for Subernarekha barrage in the reference solution (75% DF) m cu m

Month	Hydro- logi- cal input	Inflow from Subernarekha dam	Inflow from Kharkai barrage	Return flow from irrigation from Subernarekha dam	Total inflow	Diversion to			Desired flow at Subernarekha barrage
						Irrigation	Flow for downstream use at Subernarekha Barrage	Total Diver- sions	
July	301	0	30	1.23	367.0	17.3	341.6	366.4	161.8
August	175	0	116	0	326.8	11.1	310.6	329.3	107.9
September	330.5	0	210.8	1.23	578.3	17.3	561	585.8	107.5
October	17.3	18.5	109.7	1.23	182.5	17.3	161.5	186.3	161.8
November	3.7	15	0	2.5	57.0	5	38.2	50.7	38.5
December	2.5	22.2	0	3.7	64.2	12.5	38.2	58.2	38.5
January	2.5	26	1.23	3.7	69.2	16	38.2	61.7	38.5
February	12.5	0	0	1.23	49.5	12.5	26	46	23.1
March	1.23	0	0	1.23	38.2	17.3	10	34.8	0
April	0	0	0	0	35.8	17.3	7.5	32.3	0
May	0	0	0	0	35.8	17.3	7.5	32.3	0
June	0	0	0	0	35.8	12.5	12.5	32.5	12.3

The return flow from industrial water supply (iws) by Kharkai barrage is nil, from Subernarekha 29.6 m cu m, from iws by Kharkai barrage 2.5 m cu m and iws by Kharkai dam 3.7 m cu m

requirements had a substantially greater yield than crops with lower water requirement although the fixed costs were the same. For this reason the former crops have been preferred to the latter.

The solution suggests that the optimum economic use of water would be to use it mainly on maize in the kharif season (around 45 % of CCA) and wheat in the rabi season. It is economic to add adequate storage capacities in the two reservoirs such that available water yield in the monsoon period is carried over to the next season for use in the rabi crops. This is because the net social value of wheat per hectare is Rs 2040 compared with Rs 1584.30 per hectare of paddy, although the total water requirement for wheat (70 cm) is less than that for paddy (75 cm). Even within kharif crops, irrigated maize is preferred over irrigated paddy on account of lower water requirements although the yield (and the benefit) for maize is lower than that for paddy.

These results have to be analyzed further by changing the assumptions regarding (i) net benefit from wheat to net benefit from other crops (ii) preference of consumers for rice *vis-a-vis* wheat or maize. In table 10 we have presented the results of changes in optimum cropping pattern when the net benefit from wheat is parametrically decreased up to 40 % of the estimated value in the rs. There is no significant change in the cropping pattern until the net benefit from wheat is decreased to 60 % of its level in the rs. When the wheat benefit is reduced by 40 %, substantial area is allocated to irrigated paddy in the kharif and irrigated maize in the rabi seasons. In the rabi season, the entire area under wheat gets shifted to irrigated maize and in the kharif, area under maize gets reallocated to paddy. The area under irrigated paddy during the kharif also increases mainly on account of the total available area in the rabi season going to irrigated maize. If additional crop area was available, the model may have preferred to store more water in the kharif to be used later in the rabi season.

Table 11 shows the optimal cropping pattern when at least 65 % of the land is assumed to be under paddy cultivation to reflect the consumer preference for rice. When comparing this table with table 5 we see that: (i) the irrigated maize has been almost totally replaced by irrigated paddy in both dams and (ii) the irrigated wheat (70 cm) cultivated has been decreased by half in the Kharkai Dam and by about a third in the Subernarekha dam, while the unirrigated crops have not been affected.

Although the benefit from irrigated maize is about two times that from unirrigated maize, it is substantially lower than that of irrigated wheat. So the cropping pattern is in favour of using the kharif land for unirrigated maize and saving the water for wheat in the rabi season. Since the requirement of water for paddy is about twice that for irrigated maize, the increase in paddy cultivation increased the diversion of water from the dams for irrigation. Thus the water yield in the kharif season carried over to the rabi season is less than before. This in turn reduces the irrigated area under wheat as reflected in the results.

The capacities of the two reservoirs do not change significantly until the net benefit from wheat decreases by 35 to 40 %. In the rs the optimum storage capacity of the Kharkai dam is 707.8 m cu m (table 6). This is lower than the capacity planned at present, which also takes into account the carryover storage from year to year besides carryover from season to season. The optimum storage capacity for the Subernarekha dam is 1254 m cu m (table 8). This is only marginally less than the 1470 m cu m planned. The optimum capacities in the solution with lower net benefit (60 % of that in the rs) are 616.5 m cu m and 1233 m cu m (table 10).

Table 10. Sensitivity analysis of cropping pattern to relative price of wheat (Class I) (in thousand hectares)

	$P = 1.0, 0.95, 0.90, 0.85$					$P = 0.80, 0.75, 0.70, 0.65$					$P = 0.60$				
	KD	KB	SD	SB		KD	KB	SD	SB		KD	KB	SD	SB	
<i>Kharif</i>															
U Paddy	16.2	0	19.5	2.4		16.2	0	19.5	0		16.2	0	19.5	0	
I Paddy (75 cm)	0	8.5	0	7.3		0	8.5	0	9.7		32	8.5	8.5	9.7	
U Maize	9.7	0	11.3	0		9.7	0	11.3	0		6.5	0	11.3	0	
I Maize	28.3	0	34.8	0		28.3	0	34.8	0		0*	0	26.3	0	
<i>Rabi</i>															
I Wheat (70 cm)	35.2	0	58.3	0		48.4	0	45.3	0		0*	0*	0	0	
I Vegetables	2.8	0.4	3.3	0.4		2.8	0.4	3.3	0.4		2.8	0.4	3.3	0.4	
U Pulses & oilseeds	3.3	0.4	4	0.4		3.3	0.4	4	0.4		3.3	0.4	4	0.4	
I Wheat (57.5 cm)	0	3.6	0	9		0	4	0	0		0	0	0	0	
I Maize	0	0	0	0		0	0	0	9		48.6	3.6	58.3	9	
<i>Summer</i>															
I Vegetables	2.8	0.4	3.3	0.4		2.8	0.4	3.3	0.4		2.8	0.4	3.3	0.4	
I Paddy	0	0.4	0	3.3		0	0.4	0	4.4		0	0.4	0	—	
Capacity of dam (live storage)	707.8		1254			707.8		1254			615.3		1232		
m cu m															

KD-Karkai Dam, KB-Karkai Barrage, SD-Subernarekha Dam, SB-Subernarekha Barrage, I-Irrigated, U-Unirrigated.

Table 11. Optimum cropping pattern in Reference Solution with lower bounds on paddy (in thousand hectares)

	Kharkai dam	Kharkai barrage	Suberna rekha dam	Suberna rekha barrage
<i>Kharif</i>				
Unirrigated paddy	16.2	0	19.5	2
Irrigated paddy (75 cm)	25.5	8.5	30.8	7.7
Irrigated paddy (67.5 cm)	0	0	0	0
Unirrigated maize	9.7	0	11.3	0
Irrigated maize	2.8	0	4	0
<i>Rabi</i>				
Irrigated wheat (70 cm)	18	0	38	0
Irrigated wheat (57.5 cm)	0	3.3	0	8.9
Unirrigated pulses and oil seeds	3.3	0.4	4	0.4
Irrigated Vegetables	2.8	0.4	3.3	0.4
<i>Summer</i>				
Irrigated vegetables	2.8	0.4	3.3	0.4
Irrigated paddy (75 cm)	0	0.4	0	3.7
Gross cropped area (A)	80.3	13.4	114.2	23.5
Gross irrigated area (B)	52.2	13	79.3	21
Culturable command area (C)	64	10	77	11.3
Intensity of cropping (A/C) (%)	127	132	148	207
Intensity of irrigation (B/C) (%)	82	128	103	186

To summarize, the tentative results do indicate the importance of analyzing the possible choices available in utilization of water for different crops. It seems more economical to increase the storage capacities mainly for use in the rabi season when rainfall is relatively lower than in the kharif season. Since optimum cropping pattern depends on many other agro-economic variables besides water supply, such as size and ownership of land, availability of inputs, farmer's attitude to risk, home-consumption requirements and consumer's preferences, there is need for more disaggregated analysis of interaction between irrigation planning and related agro-economic variables.

Appendix A. The model.

Objective function

$$\begin{aligned} \text{Maximize} \quad & \sum_{i,j} a_{ij} C_{ij} & - \sum_i b_i k_i & + \sum_{i,j} f_{ij} I_{ij} & - \sum_i c_i \\ & (\text{Net value of crops} & (\text{Annualized cost of} & (\text{Net value of indus-} & (\text{Fixed farm costs}) \\ & \text{net of variable farm} & \text{irrigation canals}) & \text{trial water supply}) & \end{aligned} \quad (\text{A1})$$

The constraints

1. Flow continuity constraints:

$$\begin{aligned} \text{Kharkai dam} \quad & V_{i1} = \bar{Q}_{i,1} & + \bar{V}_{i0} & - X_{i1} & - I_{i1} & - Q_{i1,1} & J=1(\text{1st period}) & (\text{A2}) \\ \text{Subarnarekha dam} \quad & V_{ij} = \bar{Q}_{i,j} & + \beta_{ij} V_{i,j-1} & - X_{ij} & - I_{ij} & - Q_{i,j} & j=2, \dots, 12, & (\text{A3}) \\ (\text{Storage at site } i \text{ at the} & (\text{inflow at site } i & (\text{storage at site } i & (\text{diversion for ir-} & (\text{diversion for} & (\text{release from } i\text{th site to} \\ \text{end of the } j\text{th period}) & \text{during the } j\text{th} & \text{at the beginning} & \text{rigation at } i\text{th} & \text{industrial supply} & \text{kth site during } j\text{th period.} \\ & \text{period}) & \text{of the } j\text{th} & \text{site for the } j\text{th} & \text{during the } j\text{th} & \\ & & \text{period, net of} & \text{period}) & \text{period}) & \\ & & \text{evaporation} & & & \\ & & \text{losses}) & & & \end{aligned}$$

for $i = 2$ and 3 .

Capacity-constraints for dams

$$\begin{aligned} V_{ij} & - K_i & \leq 0 & (\text{A4}) \\ V_{ij} & & \geq \bar{D}_i & (\text{A5}) \\ & & (\text{dead storage level of} & \\ & & \text{the reservoir}) & \end{aligned}$$

Continuity constraint for Kharkai barrage

$$\begin{aligned}
 & \bar{H}_{2,j} + \rho_{12} X_{1,j} + \gamma_{12} Q_{12,j} + \phi_{12,j} I_{1,j} \\
 & \text{(Hydrological input at 2nd site in } j\text{th period)} \quad \text{(Regeneration from } i\text{th site/} j\text{th period)} \quad \text{(Inflow from 1st site to 2nd site in } j\text{th period)} \quad \text{(Return flow from industrial water from } i\text{th site in } j\text{th period)} \\
 & = X_{2,j} + Q_{24,j} + I_{2,j} \\
 & \text{(diversion for irrigation from 2nd site in } j\text{th period)} \quad \text{(outflow from 2nd site to 4th site during } j\text{th period)} \quad \text{(diversion for industrial water supply from 2nd site in } j\text{th period)}
 \end{aligned} \tag{A6}$$

Continuity constraint for Subernarekha barrage

$$\begin{aligned}
 & \bar{H}_{4,j} + \rho_{14} X_{1,j} + \rho_{24} X_{2,j} + \rho_{34} X_{3,j} + \gamma_{24,j} Q_{24,j} + \gamma_{34,j} Q_{34,j} \\
 & \text{(Hydrological input at 4th site in } j\text{th period)} \quad \text{(regeneration from irrigation use diverted from 1st site in } j\text{th period)} \quad \text{(regeneration from irrigation use from 2nd site in } j\text{th period)} \quad \text{(regeneration from irrigation use from 3rd site in } j\text{th period)} \quad \text{(inflow of water from 2nd site to 4th site in } j\text{th period)} \quad \text{(inflow of water from 3rd site to 4th site)} \\
 & + \phi_{14,j} I_{1,j} + \phi_{24,j} I_{2,j} + \phi_{34,j} I_{3,j} = X_{4,j} + E_j + I_{4,j} \\
 & \text{(return flow from industrial sites 1, 2 and 3 to site 4 during } j\text{th period)} \quad \text{(diversion for irrigation from 4th site)} \quad \text{(flow for downstream use at 4th site)} \quad \text{(diversion for industrial supply of water from 4th site)}
 \end{aligned} \tag{A7}$$

2. Irrigation Flow Constraint

$$\begin{aligned}
 & X_{ij} \geq \Sigma_{uij}^{\delta} C_{ui} + \Sigma \lambda_{uij} P_i \\
 & \text{(Diversion for irrigation from } i\text{th site in } j\text{th period)} \quad \text{(Water requirement for non-perennial crops)} \quad \text{(Water requirement for perennial crop/sugarcane)}
 \end{aligned} \tag{A8}$$

3. Canal capacity constraint

$$\begin{aligned} X_{ij} - X_i &\leq 0 \\ X_i &\leq \bar{X}_i \end{aligned} \quad (A9)$$

4. Constraints on culturable command area

$$\begin{aligned} \text{Kharif} \quad & \sum_{i=1}^5 C_{ii} + P_i \leq \bar{C}_{Ki} \quad \text{for } i=1 \text{ to } 4 \quad (A10) \\ & \text{(land used by crops at site } i) \quad \text{(land used by sugarcane at site } i) \quad \text{(total available land during the Kharif season)} \end{aligned}$$

$$\begin{aligned} \text{Rabi} \quad & \sum_{i=6}^{11} C_{ii} + P_i \leq \bar{C}_{Ri} \quad \text{for } i=1 \text{ to } 4. \quad (A11) \\ & \text{(land used by Rabi crops at site } i) \quad \text{(land used by sugarcane at site } i) \quad \text{(total available land during the rabi season)} \end{aligned}$$

$$\begin{aligned} \text{Summer} \quad & \sum_{i=12}^{13} C_{ii} + P_i \leq \bar{C}_{Hi} \quad \text{For } i=1 \text{ to } 4. \quad (A12) \\ & \text{(land used by summer crops)} \quad \text{(total available land during the summer season)} \end{aligned}$$

$$\begin{aligned} & A_i \quad \text{for } i=1 \text{ to } 4 \\ & \text{(land prepared for sowing at site } i) \\ & \sum_{i=1}^3 C_{ii} \quad \text{for } i=1 \text{ to } 4 \\ & \text{(land used by Paddy)} \end{aligned}$$

$$\geq 0.6 \bar{C}_{Ki}, \quad \text{for } i=1 \text{ to } 4 \quad (A13)$$

5. Industrial water supply constraints

$$I_{ij} \leq \bar{I}_{ij} \quad (A14)$$

List of indices and symbols

Indices

- $i = 1$ Kharkai reservoir at Icha
 2 Kharkai barrage at Bhua
 3 Subernarekha reservoir at Chandil
 4 Subernarekha barrage at Galudih

 $t = 1$ kharif unirrigated paddy.
 2 kharif irrigated paddy (75 cm).
 3 kharif irrigated paddy (67.5 cm).
 4 kharif unirrigated maize.
 5 kharif irrigated maize.
 6 rabi irrigated wheat (70 cm)
 7 rabi irrigated wheat (57.5 cm)
 8 rabi irrigated pulses and oilseeds,
 9 rabi unirrigated pulses and oilseeds,
 10 rabi irrigated maize
 11 rabi irrigated vegetables,
 12 summer irrigated vegetables
 13 summer irrigated paddy
 14 perennial sugarcane

(The figures in brackets denote water supplied corresponding to which appropriate yields are adopted)

Symbols

- a_{ti} —net value of crop t at site i (Rs million per thousand hectares)
 b_i —annualised cost of reservoir i (Rs million per m cu m) for $i = 1, 3$
 C_{ti} —land used by crop t ($t = 1$ to 10) at site i ($i = 1$ to 4)
 c_i —coefficient of fixed cost at site i
 d_i —annualised cost of canals, including cost of barrage at sites 2 and 4, at site i (Rs million per m cu m)
 E_j —flow for downstream use at Subernarekha Barrage during the j th period
 f_{ij} —unit value of industrial water supply at site i during the j th period (Rs million per m cu m)
 I_i —investment per thousand cu m
 I_{ij} —Industrial water supply from site i during period j ($j = 1$ to 12)
 $I_i(t)$ —investment cost due to the i th element in the t th period
 K_i —capacity of the i th reservoir
 P_i —land used by the perennial crop (sugarcane) at site i (in (A1)–(A14); the appropriate shadow price of the i th element in investment cost (in (1)).
 $Q_{ik,j}$ —flow of water from site i to site k during the j th period

r	—the rate of interest
t	—the running time variable
V_{ij}	—storage of water at site i at the end of the j th period
X_i	—capacity of irrigation canal at site i
X_{ij}	—flow of irrigation water from site i during period j
β_{ij}	—reservoir losses at the i th site during the j th period
$\gamma_{ik,j}$	—efficiency coefficient for flow from site i to site k during the j th period
$\delta_{it,j}$	—water required by crop t at site i during the j th period (cm)
$\phi_{ik,j}$	—coefficient of return flow from industrial water supply from the i th site to the k th site/ j th period
$\lambda_{it,j}$	—water required by sugarcane during the j th period (cm)
$\rho_{ik,j}$	—coefficient of return flow from the i th site to the k th site during the j th period
θ	—the total number of years for the construction of the project

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