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PLANNING FOR ALKALI LAND RECLAMATION UNDER RAINFALL UNCERTAINTY

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ABSTRACT

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A chance-constrained linear programming model with rainfall as stochastic input has been developed to plan optimal land and water use in alkali soils under reclamation. The model is based on the water balance of a typical alkali catchment in the command area of the Western Jamuna Canal in Haryana (India). The zero-order decision rule has been used to obtain the deterministic equivalent of chance constraint and optimal solutions have been obtained for four levels of rainfall probability. Available water supplies at low rainfall probabilities were found to be inadequate to sustain the high cost reclamation technology. Exploitation of the full potential of agricultural land calls for the augmentation of available water supplies.

INTRODUCTION

For the reclamation and utilization of alkali soils, which are characterized by high pH, high exchangeable sodium percentage, and low infiltration rate (Richards, 1968), for crop production, there is a highly water-dependent technology. The water requirements may sometimes exceed 200 cm/ha. In many areas of the world, and particularly those of the Indo-Ganges basin in India, where alkali soils occupy a very large area, a considerable part of the irrigation requirements is met by rainfall. Singh and Tyagi (1980) estimated that in years with a normal rainfall, as much as 42% of the water needs in the Karnal region of the Western Jamuna Canal command could be met by rainfall alone. However, like all other hydrological phenomena, rainfall is

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highly stochastic in nature and exhibits extreme variation in quantity and distribution. This probabilistic nature of rainfall has to be given due consideration in planning for optimal use of the land and water resources of alkali areas because of the high cost of reclamation.

Stochastic mathematical models can be used with advantage in such situations, as they permit explicit consideration of these factors in the systems analysis of the water resources. There are three major approaches for this under conditions of uncertainty. The first, due to Tintner (1955), derives a distribution function of the objective function, and is essentially based on empirical estimations. The second approach is stochastic programming with recourse, first used by Beale (1955) and Dantzig (1955). In this approach the problem is divided into two or more stages. Certain decision variables are selected in the first stage before the introduction of stochastic events. Possible violation of the constraints in the subsequent stages is taken care of by making new decisions in the second stage. The third approach is by chance-constrained programming (Charnes et al. 1958). Chance-constrained programming has the advantage that: (1) the explicit costs of constraint violation are not required, (2) optimization of several forms of the objective function is possible, and (3) procedures to compute deterministic equivalents are readily available. According to Smith (1970) chance-constrained programming is the most effective tool to analyse stochastic variability in irrigation planning. Extensive use of this technique, which has been adopted

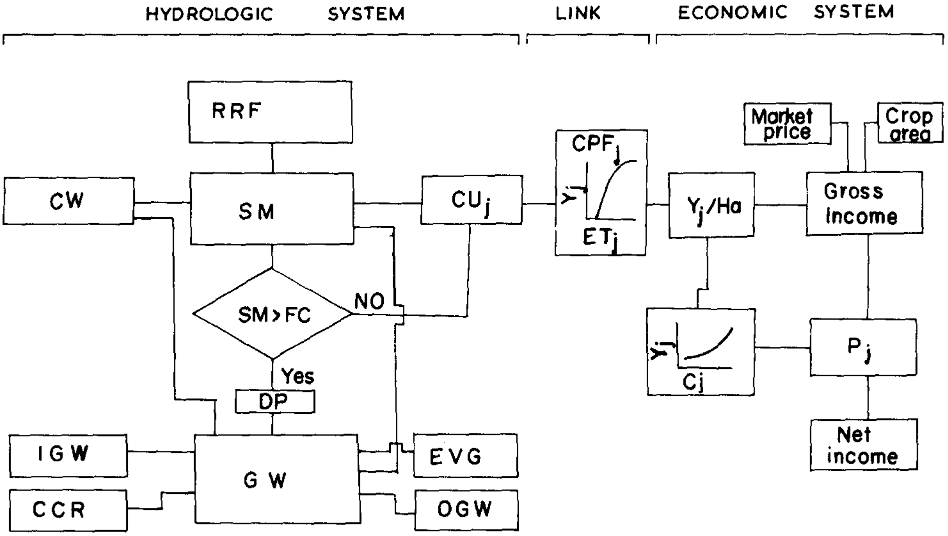

Fig. 1. Hydrologic–economic flow system showing production function as a link between the two systems.

for the present study, has been made for deriving optimal water use policies (Nieswand and Granstram, 1971; Eisel, 1972; and Smith, 1970).

WATER RESOURCES SYSTEM

The system under investigation is assumed to consist of two limited sources of water, viz., surface water from canals and ground water pumped within the area, and also of crop activities on normal and alkali soils. It is assumed that alkali soils that were hitherto uncultivated are being reclaimed by adding ammendments and by being put to crop production. This generates a demand for additional water. Part of the ground water is also pumped by deep tubewells and is used for augmenting the canal supplies for use elsewhere. Pumping by shallow and deep tubewells from the same ground water basin are considered two different activities because of the differences of technology in pumping, as well as the different uses to which the water so pumped is put. The main components of the water resources system under study are hydrologic and economic sub-systems, which are linked together by a crop-production function (Fig. 1). All the system inputs except the rainfall are assumed to be of a deterministic nature.

MATHEMATICAL MODEL

The mathematical model is composed of an objective function and a set of system constraints. It is assumed that the objective of the programme is to maximize the expected value of the total income from water use in irrigation of crops and the water export (augmentation supply). The objective function can be written as:

$$Z = \mathrm{Max}\left(\sum_{j=1}^{m} P_j A_j + \sum_{i=1}^{m} P^{DT} DT_i - \sum_{i=1}^{n} C^{CW} CW_i - \sum_{i=1}^{n} C^{ST} ST_i \right) \tag{1}$$

where Z = Maximized value of the objective function; Rupees (Rs). A_j = Area under crop j, ha. P_j = Income from crop j, Rs/ha. DT_i = Volume of water exported during period i. P^{DT} = Income from water export, Rs per 10^3 m^3. CW = Volume of canal water released during period i. C^{CW} = Sale price of canal water. ST_i = Volume of ground water pumped by shallow tubewell. C^{ST} = Sale price of ground water pumped by shallow tubewells. i = An index for time period having value 1, 2, 3,…n. j = An index for crop activity having value 1, 2, 3…m.

Since there is no stochastic variable in the objective function, the objective function remains unchanged on taking expectations.

SYSTEM CONSTRAINTS

The system is operated under a number of constraints which include: (1) Crop irrigation requirements, (2) Water availability from different sources, (3) Irrigation system capacity, (4) Available land areas in normal and alkali soils, (5) Area restriction on certain specific crops, and (6) Ground water mining.

Irrigation requirement: The assumption of rainfall as a stochastic input makes the irrigation requirement an uncertain quantity. It requires that the irrigation requirement during each decision period must be met at least in $10B$ years out of 10, with B being the level of risk. Such a probabilistic statement requires that the capacity of the irrigation system should be sufficient to supply total requirements of water with $100B\%$ reliability. This chance constraint can be written as:

$$Pr\left(\sum_{i=1}^{n} (CEC \cdot CW_i + CET \cdot ST_i) - \sum_{i=1}^{n} \sum_{j=1}^{m} \frac{IR_{ij} A_{ij}}{AE_j} \right) \geqslant B_i^W \tag{2}$$

where Pr = Probability operator. CEC = Conveyance efficiency of canal system. CET = Conveyance efficiency of shallow tubewell system. A_{ij} = Area under crop j during period i. IR_{ij} = Irrigation requirement of crop j during period i. AE_j = Field water application efficiency for crop j. B_i^W = Percentage probability.

Equation 2 states that irrigation requirements of crop j during period i must be met at least 100 $B_i^W\%$ of the time.

If $IR_{ij}(ERF_{ij})$ and $T_{ij}(IR_{ij})$ are the distribution functions of rainfall and irrigation requirement during period i then:

$$T_{ij}(IR_{ij}) = 1 - \frac{F_{ij}(CU_{ij} - ERF_{ij})}{AE_j} \tag{3}$$

where CU_{ij} = consumptive use of crop j during period i. Applying the zero-order decision rule, the probabilistic constraint becomes:

$$(CEC \cdot CW_i + CET \cdot ST_i) \geqslant T_{ij}^{-1}(B_i^W) \tag{4}$$

where $T_{ij}^{-1}(B_i^W)$ is the distribution function of

$$\sum_{i=1}^{n} \sum_{j=1}^{m} \frac{IR_{ij} A_{ij}}{AE_j}. \tag{5}$$

The percentage distribution of $T_{ij}^{-1}(B_i^W)$ can be determined from the distribution function of effective rainfall because:

$$T_{ij}^{-1}\left(B_i^W\right) = \frac{CU_{ij} - F^{-1}\left(1 - B_i^W\right)}{AE_j} \tag{6}$$

A typical distribution of the effective rainfall and irrigation requirement is shown in Fig. 2. It can be seen that as the percentage increases, the value of effective rainfall also increases and consequently the irrigation requirement decreases.

Irrigation system capacity : Water diversion into the canal, and the pumped ground water, cannot exceed their respective capacities:

$$CW_i \leqslant CCW \tag{7}$$

$$\frac{RPS \cdot ST_i}{CET} \leqslant CST \tag{8}$$

$$\frac{RPD \cdot DT_i}{CED} \leqslant CDT \tag{9}$$

where CCW, CST and CDT = Installed capacities of canals, shallow tube-

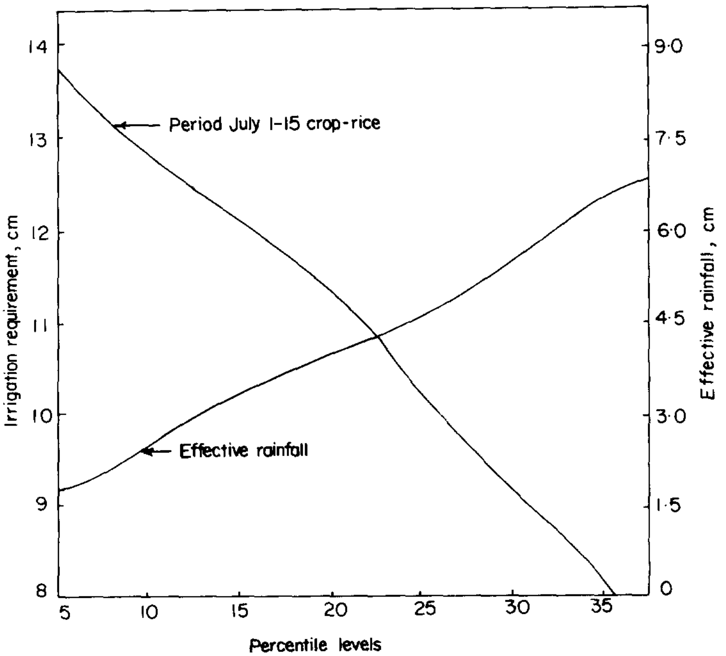

Fig. 2. Distribution of effective rainfall (ERF_i) and irrigation requirements (IR_{ij}) at different percentile levels.

wells and deep tubewells systems, respectively. RPS and RPD = Ratio of peak to average demand for shallow and deep tubewell waters, respectively. CED = Conveyance efficiency of deep tubewells system.

Water export constraint: A certain minimum amount of water has to be exported ($DT_{\min}$) to meet the demands of adjacent areas.

$$\sum_{i=1}^{n} DT_i \geqslant DT_{\min}$$

4. Land area constraint: The land area under normal and alkali soils cannot exceed the available land in each category.

$$\sum_{i=1}^{n} \sum_{j=1}^{\bar{m}} L_{ij} A_{ij} \leqslant NL \tag{10}$$

$$\sum_{i=1}^{n} \sum_{j=m+1}^{m} L_{ij} A_{ij} \leqslant AL \tag{11}$$

where L_{ij} = Land occupancy coefficient. $L_{ij} = 1$ if the land is occupied, otherwise it is zero. NL = Normal land. AL = Alkali land.

5. Ground water withdrawal constraint: It is stipulated that the ground water is being exploited with zero mining allowance, and that no annual rise or fall is permitted in the water table from year to year, though the water table may fluctuate within different periods of the year. Therefore, the expected change in ground water storage is zero. Mathematically:

$$\sum_{i=1}^{n} (ST_i + DT_i + OGW_i + EGW_i) - \sum_{i=1}^{n} \sum_{j=1}^{m} \mathrm{E}(CPR_{ij}) \\ - \sum_{i=1}^{n} (CWR_i + STR_i + CCR_i + IGW_i) \leqslant MGW \tag{12}$$

where IGW = Ground water inflow from adjacent areas. OGW = Ground water outflow to the adjacent areas. CWR = Recharge from canal conveyance system. STR = Recharge from tubewell conveyance system. CCR = Recharge from carrier canals and drains. $\mathrm{E}(CPR)$ = Expected recharge from cropland. Since recharge from cropland depends on rainfall, it becomes an uncertain quantity. MGW = Mining allowance.

6. Crop area constraint: There are restrictions on areas under certain crops to reflect the market demands and to ensure minimum production of essential foodgrains and fodder. These are given in Table I.

TABLE I

Constraints on area under different crops

Crop	Area constraint, ha	
	Minimum	Maximum
Rice in alkali soil	3000	–
Berseem in normal soil	1500	–
Berseem in alkali soil	–	1500
Wheat in alkali soil	3000	–
Sugarcane	–	3200
Potatoes	–	2000

SYSTEM'S DESCRIPTION

The study pertains to the command area of a canal distributory called Jundla, which gets its water from the Western Jamuna Canal, a run of the river project (Fig. 3). It is a compact block of 21,500 ha with a cultivated area of 16,000 ha. Nearly 30% of the culturable area (4800) is affected by alkalinity, which is characterised by high pH, dispersed soil structure and low infiltration rates. These soils are now being reclaimed by adopting a recently developed technology (Anonymous, 1980). A large number of shallow tubewells has been installed to meet the additional demand for water. The density of these tubewells is 1–4 per ha (Tyagi, 1980). The main sources of ground water are recharge from cropland, percolation of rain and irrigation water, and seepage from irrigation conveyance and drainage systems.

The average rainfall of the area as computed from rainfall data of three stations is 72 cm. The periodic rainfall distribution is skewed, with fortnightly rainfall data fitting to an incomplete gamma function (Fig. 4). The rainfall values at different percentages of occurrance are given in Table II.

MODEL INPUTS

The model input can be divided into three categories, viz. hydrologic, agricultural and economic. The hydrologic input data include rainfall, runoff, groundwater, inflow, outflow, and evaporation. Investigations were made to compute these factors; the detailed procedure of analysis is reported elsewhere (Tyagi and Narayana, 1982). The agricultural inputs included response of different crops to water applied, dates of planting, soil type, etc. Rice, wheat and berseem were the crops common to normal as well as alkali soils. Besides these crops, the programme included maize sorghum (fodder) and

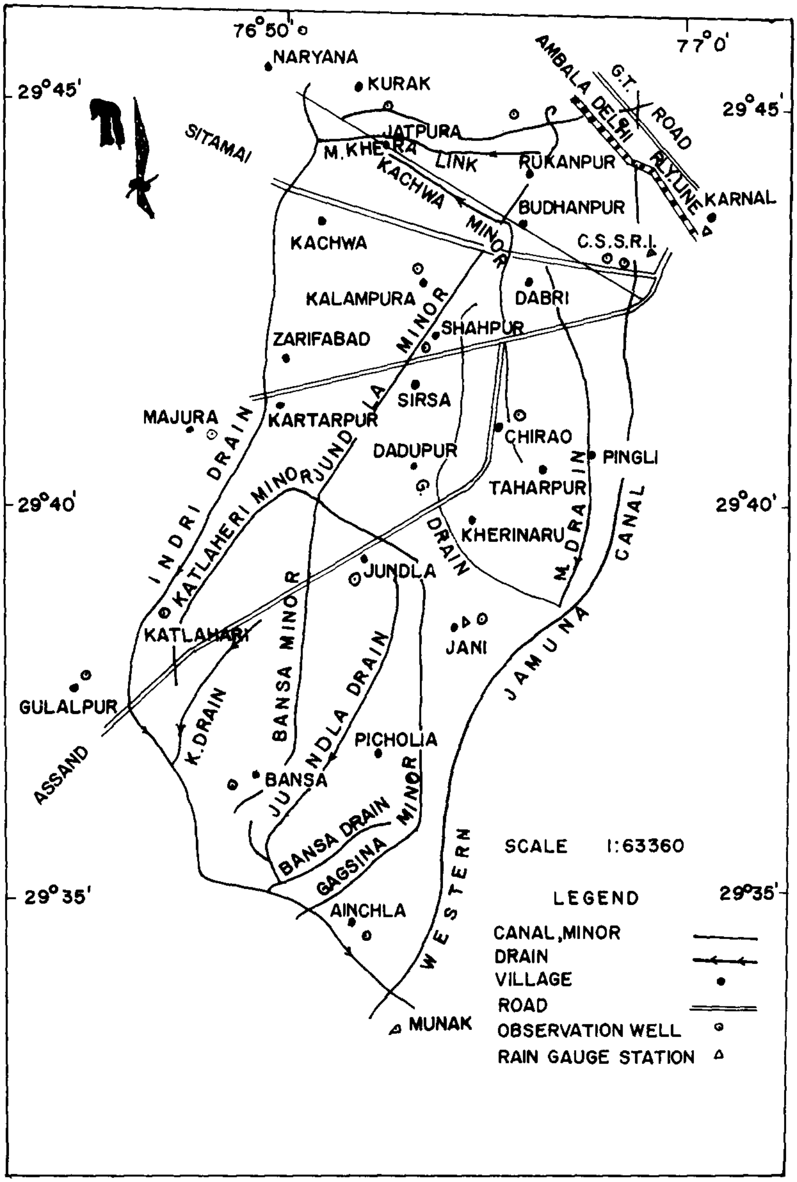

Fig. 3. Index map of Jundla command area.

sugarcane during the summer, gram and barley during the winter. Crop water production functions for these crops grown on normal as well as alkali soils were developed (Tyagi, 1980) and the values at discrete water use levels are given in Table III. Each crop that required different irrigation input, or was sown at a different date, was treated as a separate crop activity. In total, there were 42 crop activities considered.

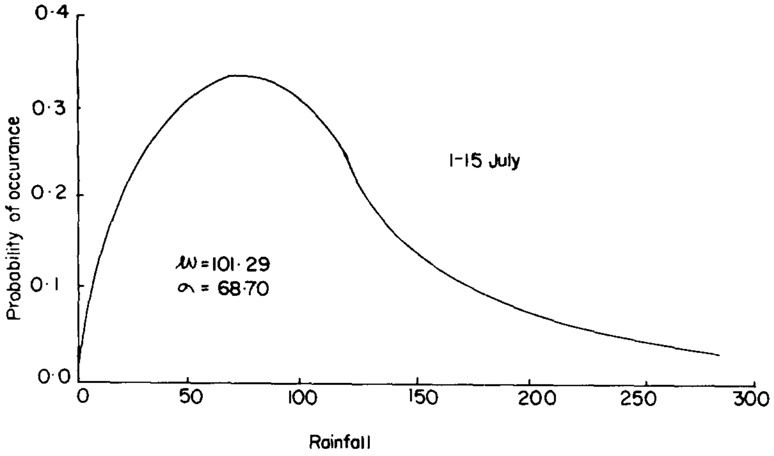

Fig. 4. Gamma distribution of 15 day period rainfall (1948–77).

TABLE II

Values of total rainfall, retained rainfall (rainfall–runoff) and percentile rainfall for the Jundla Command area

Period	Total rainfall (*RF*), cm	Retained * rainfall (*RRF*), cm	Rainfall at different percentile levels ** (*PRF*), cm				Remarks
			5	10	20	30	
1	1.28	1.28	0.01	0.03	0.08	0.17	
2	3.56	3.38	0.14	0.35	0.75	1.15	
3	10.00	8.42	1.80	2.70	4.10	5.60	
4	8.24	6.69	0.80	1.10	2.40	3.40	
5	12.80	9.99	4.60	5.60	6.20	7.80	
6	13.12	10.21	1.60	2.60	4.90	7.40	
7	5.03	4.20	0.60	0.78	0.90	1.25	
8	4.38	3.35	0.01	0.03	0.25	0.38	
9	1.70	1.06	0.02	0.04	0.12	0.15	
10	0.70	0.70	–	–	0.03	0.04	
11	0.20	0.20	–	–	–	–	
12	0.09	0.09	–	–	–	–	
13	0.29	0.29	–	–	–	0.01	
14	0.51	0.51	–	–	0.3	0.4	
15	0.87	0.87	0.02	0.03	0.07	0.03	
16	1.59	1.59	0.02	0.04	0.10	0.21	
17	0.95	0.95	0.00	0.01	0.03	0.05	
18	0.72	0.72	0.01	0.02	0.05	0.09	
19	0.76	0.76	–	0.01	0.22	0.04	
20	1.21	1.21	0.03	0.06	0.11	0.18	
21	0.43	0.43	–	0.01	0.02	0.04	
22	0.19	0.19	–	–	–	–	
23	0.60	0.60	–	–	0.1	0.03	
24	0.77	0.77	–	–	0.01	0.02	

* $RRF = RF - RU$. RU = Runoff. $RU_i(11-24) = 0$.

** Upto 30 percentile the rainfall values are very small, and therefore $PRF = RRF$.

TABLE III

Irrigation requirement (IR), ground water recharge contribution (CPR_j) crop yield (Y_j) and income from different crop activities

Crop Index j		Crop activity	Irrigation water (IR) (cm)	CPR_j (10^3/ha)	Yield Y_j (tonnes/ha)	Income Rs/ha
1	Rice	($NLE-A$)	125	7.114	6.03	5125
2	Rice	($NLE-B$)	106	6.158	5.37	4564
3	Rice	($NLE-C$)	93	5.194	3.79	3221
4	Rice	($NLM-A$)	120	6.950	6.03	5125
5	Rice	($NLM-B$)	96	5.008	5.37	4564
6	Rice	($NLM-C$)	73	5.109	3.79	3221
7	Rice	($NLL-A$)	88	5.233	4.60	3915
8	Rice	($ALE-A$)	75	4.011	4.90	4165
9	Rice	($ALE-B$)	60	3.588	3.75	3187
10	Rice	($ALE-C$)	45	3.002	3.20	2720
11	Rice	($ALM-A$)	70	3.783	4.90	4165
12	Rice	($ALM-B$)	58	3.492	3.75	3187
13	Rice	($ALM-C$)	49	3.165	3.20	2720
14	Rice	($ALL-A$)	54	3.002	4.10	3485
15	Maize	($NL-A$)	21	1.318	3.00	3000
16	Maize	($NL-B$)	10	1.114	2.35	3250
17	Jowar	($NL-A$)	70	1.700	32.00	3200
18	S. Cane	($NL-A$)	144	4.053	75.00	9375
19	S. Cane	($NL-B$)	108	3.331	60.00	7500
20	S. Cane	($NL-C$)	72	2.612	51.00	6375
21	Potato	($NL-A$)	44	0.462	24.60	6150
22	Potato	($NL-B$)	30	0.312	21.20	5300
23	Berseem	($NL-A$)	80	2.069	88.80	8800
24	Berseem	($NL-B$)	64	1.655	79.00	7900
25	Berseem	($NL-C$)	48	1.241	52.00	5200
26	Berseem	($AL-A$)	81	1.216	65.00	6500
27	Berseem	($AL-B$)	65	0.973	53.00	5300
28	Berseem	($AL-C$)	49	0.729	32.00	3200
29	Wheat	($NL-A$)	51	0.515	2.30	4550
30	Wheat	($NL-B$)	38	0.803	4.36	4905
31	Wheat	($NL-C$)	29	0.602	3.23	3634
32	Wheat	($AL-A$)	51	0.515	2.30	4550
33	Wheat	($AL-B$)	38	0.386	1.80	3710
34	Wheat	($AL-C$)	39	0.289	1.15	2240
35	Barley	($NL-A$)	20	0.190	2.50	2125
36	Barley	($NL-B$)	10	0.095	1.85	1572
37	Gram	($NL-A$)	14	0.130	1.60	3040
38	Gram	($NL-B$)	7	0.065	1.40	2660
39	Bajra	($NL-R$)	–	0.990	1.30	1105
40	Maize	($NL-R$)	–	0.951	2.00	2000
41	Other rainy season crops	($NL-A$)	88	0.998	32.00	3200
42	Other winter crops	($NL-A$)	50	2.069	1.50	4500

* Irrigation requirements reported in the table are at mean rainfall values.

NL = Normal land. AL = Alkali land. A = High irrigation. B = Medium irrigation. C = Low irrigation. E = Early planting. M = Middle planting. L = Late planting. R = Rainfed.

TABLE IV

Optimal cropping pattern (area in ha) at different percentile rainfall

Crop	Percentile rainfall				Mean rainfall
	5	10	20	30	
Rainy season					
Rice $(NL-C)$			219	254	4500
Rice $(ALE-C)$				4137	
Rice $(ALM-C)$	4500	4500	4401	362	4800
Rice $(ALL-A)$			81		
Total Rice	4500	4500	4701	4753	9300
Maize $(NL-B)$		1100	1100	1100	1100
Sugarcane $(NL-C)$		2	2	11	3200
Others $(NL-A)$	630	630	648	630	2400
Total cropped area	5130	6232	6451	6494	16000
Fallow land	10870	9768	9549	9506	–
Winter season					
Berseem $(NL-B)$	1500	1500	1500	1500	500
Berseem $(AL-B)$				560	1500
Total Berseem	1500	1500	1500	2060	2000
Wheat $(NL-A)$				7689	
Wheat $(NL-B)$		5527	6578		4332
Wheat $(NL-C)$		1070			
Wheat $(AL-C)$	3000	3000	3000	3000	3000
Total Wheat	3000	9597	9578	10689	7332
Potato $(NL-B)$	2000	2000	2000	2000	2000
Sugarcane $(NL-C)$		2	2	11	3200
Gram $(NL-B)$	1100	1100	1100		168
Others					1000
Total cropped area	7600	14199	14180	14760	15700
Fallow land	8400	1800	1820	1240	300
Cropping intensity (%)	80	128	129	132	198

NL = Normal land. AL = Alkali land. A = High irrigation. B = Medium irrigation. C = Low irrigation. E = Early (16–30 June), M = Middle (1–15 July), L = Late (16–31 July) planting.

The costs included sale price of different crops, income from water use for export (C^{DT}), costs of canal water (C^{CW}) and shallow tube-wells (C^{ST}). The prices of agricultural commodities for 1979–80 as fixed by the government (Table III) were used. The values of C^{DT}, C^{ST} and C^{CW} were taken as Rs. 120, 60 and 10 per 10^3 m^3, respectively.

RESULTS AND DISCUSSION

The chance-constrained linear programming model formulated in eqs. 1–12 was run on an IBM–1620 computer. In total, four probabilities of occurrence of rainfall were applied, viz. 5, 10, 20 and 30%. The computer output was analysed in terms of (1) area and water allocations to different crop activities, (2) income and shadow prices, and (3) ground water balance. Parametric programming was applied to see the change in income of the project area with respect to water export (DT) and canal water diversion (CW).

The analysis of the rainfall data over a period of 30 years (1948–77), as given in Table II, indicates that values of rainfall at low risk levels are quite small as compared to mean rainfall. The decrease in rainfall had a two-fold effect: it increased the irrigation requirement and decreased the ground water availability by means of a reduced ground water recharge. Consequently the total quantity of water available for allocation was reduced from 199.96×10^6 m^3/yr. at mean rainfall to 149.0×10^6 m^3/yr. at the five percentile level. The cropping patterns resulting from these allocations are given in Table IV. At all the four percentile levels that have been applied, the area under rice was less than 50% of the area at mean rainfall, while that under sugarcane became practically nil. However, crops like maize, sorghum (fodder) and gram, which require relatively less water, appeared in the solution at the maximum permissible levels. Almost no berseem appeared on alkali soils up to the 20 percentile rainfall level. But the area under berseem in normal soils increased from 500 to 1500 ha at all levels. Due to reduced water availability, the cropping intensity decreased from 198% at mean rainfall to only 132% at the 30 percentile. The land that remained uncultivated was in the alkali category because of relatively lower crop-water productivity. The effect of reduced cropping intensity and low crop yields

TABLE V

Income and shadow prices of water at different percentile rainfall levels

Risk level %	Income Rs. $\times 10^5$	Fall in income %	Shadow price Rs./10^3 m^3	
			Irrigation water	Export water
5	721.80	35.5	1334.5	−984.5
10	775.31	30.7	869.4	−719.4
20	795.03	29.0	706.3	−556.3
30	899.49	10.0	705.9	−555.9
Mean rainfall	1085.20	–	786.7	−636.7

which were associated with low levels of irrigation, was net reduction in income of the project area from Rs. 1085 × 10^5/yr. to only Rs. 722 × 10^5/yr. at the 5 percentile rainfall (Table V). This represents a 35.5% reduction in the total income as compared to income at mean rainfall (Table V). As expected, the gap in income decreased with increase in percentile level.

The analysis of shadow prices or marginal values of water indicated that at low percentile levels when water availability was low, the shadow prices of water were very high (Table V). For example, at the five percent level each additional 10^3 m^3 of irrigation water could generate an additional income of Rs. 1134.4, while its export cost the project area Rs. 984.5. The shadow price reduced to Rs. 705.9 at the 30 percentile level, which again is quite high. Under these circumstances, fixing of quota for water export (DT) becomes of crucial importance, as it influences the alkali land reclamation programme.

Ground water balance

Ground water balance being part of the internal structure of the model, the different components (eq. 12) are automatically computed in the output (Table VI). It is seen that the major change with respect to the percentile level of rainfall occurs only in recharge from crop land (CPR), which is drastically reduced from 70.6 × 10^6 m^3/yr. at mean rainfall to about 25.6 × 10^6 m^3/yr. at the 10 percentile level. This is equivalent to a reduction of

TABLE VI

Ground water balance

Item *	Rainfall percentile				
	5	10	20	30	Mean rainfall
Inflow					
CPR	23.75	26.60	29.11	32.51	70.60
CWR	10.49	10.49	10.49	10.49	10.12
CCR	64.70	64.70	64.70	64.70	66.24
STR	3.78	3.97	4.12	4.35	6.64
Total	102.72	105.76	108.42	112.05	153.60
Outflow					
ST	67.52	70.83	74.19	77.66	118.46
DT	35.00	35.00	35.00	35.00	35.00
Total	102.52	105.83	109.19	112.66	153.46
Balance					
	+0.20	−0.07	−0.77	−0.61	+0.14

* All values are in 10^6 cubic metres per year.

64%. Another component of water balance which undergoes change is the recharge from the conveyance system of shallow tubewells (*STR*). The remaining components of the water balance (eq. 12), not being functions of rainfall, remain unchanged at various percentile levels. The overall water supply at 10 percentile rainfall from all the sources combined together remained only 105.76×10^6 m^3/yr., thus causing a reduction of 31.3% from that at the mean rainfall level. At this level of availability, the water export (*DT*) which had been kept fixed at 35×10^6 m^3/yr. accounted for more than 33% of the total ground water available for pumping.

Parametric programming

Parametric programming is a procedure for generating new optimal solutions from an original optimal solution, while allowing one or more parameters (constraints or coefficient) to vary systematically over a specified range of values. In the present study the effect of change in water export (*DT*) and canal diversions (*CW*) on project income was investigated at the 30 percentile rainfall level.

The original value of *DT* on the basis of the past five years was 35×10^6 m^3/yr. Five additional values of *DT*, viz. 0, 10, 15, 25 and 45×10^6 m^3/yr. were used to generate optimal solutions. It can be readily seen (Fig. 5) that

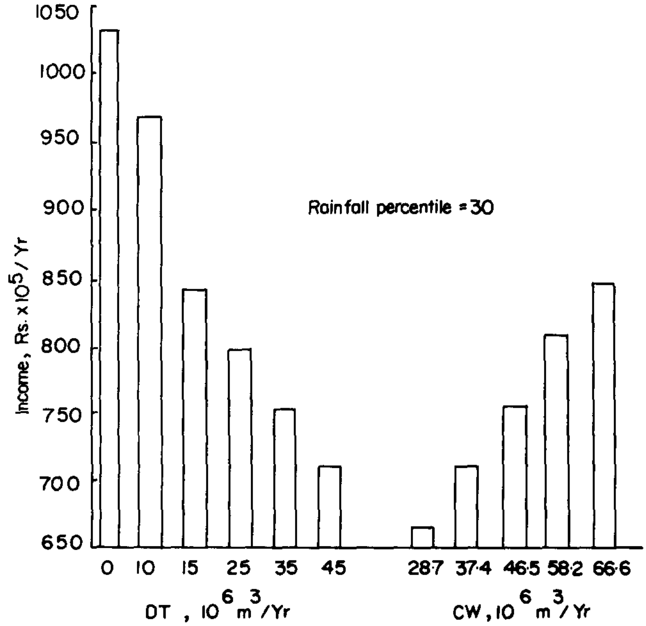

Fig. 5. Change in income of the project area with respect to water export (*DT*) and canal water supply (*CW*).

any decrease has the effect of increasing the available water supply for use within the project area. This results in higher allocations of water to crop at irrigation levels which are more productive (i.e. crop water production relationship is more favourable) resulting in an increased income from Rs. 780×10^5 to Rs. 1036×10^5 when DT was decreased from 45×10^6 m^3/yr. to 0.0×10^6 m^3/yr. This income is very close to the expected income of Rs. 1085×10^5 at mean rainfall level. It implies, therefore, that the quota of water export will have to be reduced in the years of deficit rainfall to stabilize the income of the project area, where large investments were made in high-cost reclamation technology.

In parametric analysis on canal diversion (CW), optimal solutions were obtained for four values representing 60, 80, 120 and 140% of the mean canal diversions (46.5×10^6 m^3/yr.). Since any increase in canal diversion permits higher allocation of water for crop production, the income shows an increase. For example, the annual income, which was only Rs. 666×10^5 at 0.60 CW increased to Rs. 846×10^5 when the canal diversions were increased to 1.4 CW (Fig. 5).

CONCLUSIONS

The chance-constrained linear programming model as applied in this paper can be used with advantage to predict optimal land and water use plans for alkali areas under reclamation. The application of the model to a typical alkali area of the Indo-Gangetic plains indicates that great risks are taken if reclamation programmes are undertaken on the basis of mean rainfall data. For sustaining higher-cost alkali land reclamation technology, it is essential that the stochastic nature of the rainfall input is taken into consideration and that land and water use plans are developed at a higher degree of security.

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REFERENCES

Anonymous, 1980. Principles and practices for reclamation of salt affected soils. Int. Symp. CSSRI, Karnal, India, Feb. 18–21, pp. 569.

Beale, E.M.L., 1955. On minimizing a convex function subject to linear inequalities. J. R. Stat. Soc., Series B, 17(2): 173–184.

Charnes, A., Cooper, W.W. and Symonds, G.H., 1958. Cost horizon to stochastic programming of heating of oil. Manage. Sci., 4(2): 235–263.

Dantzig, G.B., 1955. Linear programming under uncertainty. Manage. Sci., 1(3): 197–206.

Eisel, L.M., 1972. Chance constrained reservoir model. Water Resour. Res., 8(2): 339–347.

Nieswand, G.H. and Granstram, M.L., 1971. A chance constrained approach to conjunctive use of surface and ground waters. Water Resour. Res., 7(6): 1425–1436.

Richards, L.A. (Editor), 1968. Diagnosis and improvement of saline and alkali soils. U.S.D.A. Handbook No. 60, p. 160.

Singh, O.P. and Tyagi, N.K., 1980. Projections of irrigation demands for alkali area under reclamation programme. Proc. Int. Symp., Principles and practices for reclamation of salt affected soils, CSSRI, Karnal, Feb. 18–21, Vol. 1, pp. 549–554.

Smith, D.V., 1970. Stochastic irrigation planning models, East Pakistan land and water study. Centre for population studies, Harward University, Cambridge, MA., Report No. 39, p. 237.

Tintner, G., 1955. Stochastic linear programming with applications to agricultural economics. In: H.A. Antosiewics (Editor), 2nd World Symp. Linear Programming. Natl. Bur. Stand., Washington, D.C.

Tyagi, N.K., 1980. Crop planning and water resources management in salt affected soils—a systems approach. Unpublished Ph.D. thesis submitted to J.N. Tech. Univ. Hyderabad (India), p. 236.

Tyagi, N.K. and Narayana, V.V.D., 1982. Ground water recharge on alkali soils during reclamation. Agric. Water Manage., 5: 51–60.