Simulation Modeling and Optimization Studies for the Groundwater Basins of Northwest India: Case Studies and Policy Implications

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Abstract

There has been spectacular enhancement in agricultural production in northwest India during the last few decades. This could be possible due to adoption of high yielding crop varieties and fertilizer use coupled with indiscriminate exploitation of groundwater resources which has led to problems of declining water table, deterioration of groundwater quality, water logging and soil salinity in many parts of northwest India. This scenario of falling/ rising water table is threatening the sustainability of agriculture in this food bowl of India. In order to study various strategies and frame policies for the management of water resources, it is necessary to assess the impact of human interventions on groundwater system through water balance studies and various models. In this paper application of simulation and optimization modeling has been discussed for ground water basins of northwest India. Case studies covering irrigated areas of Punjab and Haryana have been presented to demonstrate the usefulness of these models for developing strategies for sustainable agriculture. The studies indicate that if the present trend of excessive pumping of groundwater through installation of various structures continue, it will not be possible to pump groundwater by centrifugal pumping system because of declining water table at a very fast rate. The farmers will have to install submersible pumps at a very high cost in order to irrigate the field crops. In case of rising water table situations, the adoption of consumptive use practice of surface and poor quality groundwater coupled with efficient irrigation application system can help in sustaining the agricultural production in these regions. Policies for management of ground water resource on sustainable basis have also been discussed.

Introduction

In India, significant emphasis is being laid to increase the agricultural production in order to meet the food and fiber needs for the increasing population of the country. In order to meet the enhanced demand, the agricultural technology is being updated by adopting high yielding crop varieties and increasing fertilizer use, coupled with indiscriminate exploitation of groundwater resource which has led to problems of declining water table, deterioration of groundwater quality,

water logging and soil salinity in many parts of the country especially northwest India. This scenario of falling/rising water table is threatening the sustainability of agriculture and is creating unsavory situation for the planning and administrative authorities. Current scenario warrants that a greater emphasis is laid on using the available water resources most scientifically and efficiently so that the country is saved from a very difficult situation and ensure food security for all.

In order to study various strategies and frame policies for efficient management of water resources, it is necessary to assess the impact of human interventions on groundwater systems through water balance and various modeling studies.

Case Study of Southwest Punjab

Water table has been progressively rising in almost all the districts of southwest Punjab due to inadequate drainage system, excessive application of water through canal irrigation and under-exploitation of groundwater resource due to its poor quality. To improve and sustain the agricultural production of the area afflicted by water logging and soil salinity, it is necessary to prevent further deterioration and reclaim the area already rendered waterlogged and saline by proper groundwater development in conjunction with canal water.

The joint use of simulation and optimization techniques to determine the optimal development and operation of ground water system is becoming an important and powerful tool (Gorelick, 1983; Yeh, 1992; Ahlfeld and Manoucherhr, 1994; Aggarwal et al, 2004). One such method to couple simulation model of particular groundwater system with an optimization model is the embedding technique, in which finite difference or finite element approximations of governing groundwater flow equations are introduced in linear programming model having a set of constraints. The groundwater variables are included as decision variables in the linear programming formulation. Conjunctive water use and management policies in southwest Punjab to control the rising water table using simulation-optimization approach have been developed.

Study Area

The study area is part of the Indo-Gangetic basin. The area lies between latitude 29°55′34″N and 31°09′47″N and longitude 73°50′31″E and 74°58′38″E and located in Ferozepur, Muktsar and Faridkot districts covering an area of about 6, 51,079 hectare. The region is bounded on western side by Sutlej river; toward south area is surrounded by Rajasthan boundary and toward east by Sirhind feeder (Fig.1) canal. The normal annual rainfall is 300 mm and almost 80 per cent of rainfall takes place in *kharif* season. The soils of the area are formed through alluvial deposits. In Muktsar and Ferozepur districts the soil is sandy. In Faridkot district, the soils vary from sandy loam to loamy sand. The major crops grown in area are rice, cotton and wheat. Irrigation is done by both canal and groundwater. The groundwater cell of the Department of Agriculture, Punjab and Water Resources Directorate of the Department of Irrigation, Punjab have installed about 60 observation wells in the study area to monitor the depth of water table below

ground surface. The observations are taken twice a year; the pre-monsoon water table is recorded in the month of June and post monsoon in the month of October.

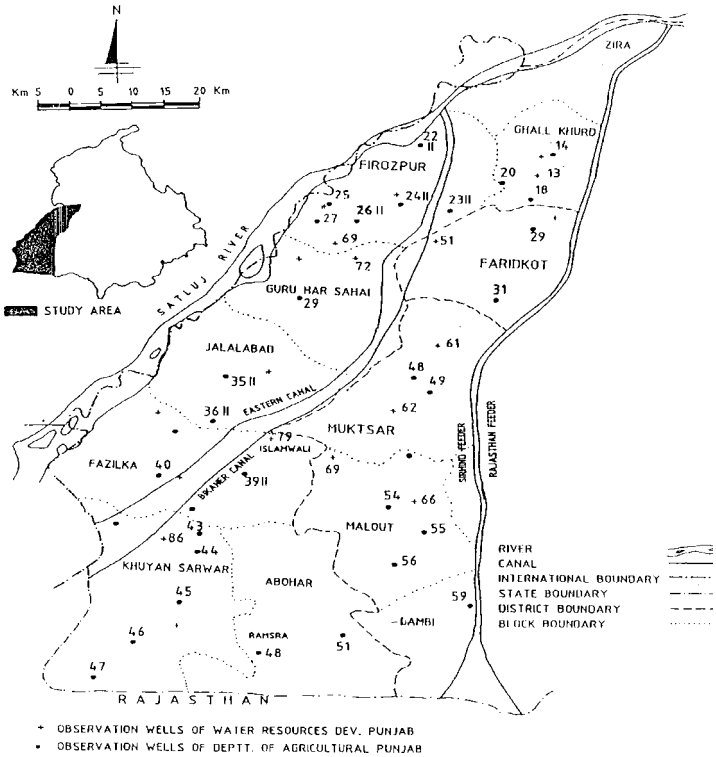

Figure 1. Location map of Southwest Punjab

Groundwater Simulation Model Inputs

A grid map having consistent grid spacing of 10 km x 10 km is superimposed over the map of southwest Punjab to discretize the area into cells (Fig.2). The boundary of the aquifer is approximated in a linear stepwise fashion. Based on the June/October water level data the water level contour maps are drawn. The grid map is superimposed on these maps to incorporate the values of hydraulic head at the center of each cell lying inside the study area. Same procedure is used to estimate the values of hydraulic conductivity and specific yield and bottom elevation of aquifer for each cell. For computing the source/sink terms, the recharge and draft values were distributed to various cells. The block wise groundwater draft and recharge was distributed to each cell falling in the block according to the area of that cell in the block.

Water Resources Allocation Model Inputs

The inputs to the water resources allocation model include variables such as net irrigation water requirement of crops, canal and tube well water availability, and quality of groundwater. These are discussed as follows:

Net Irrigation Water Requirement of Crops

The net irrigation requirement of crops is the depth of irrigation water, exclusive of effective rainfall, carry-over soil moisture or ground water contribution. Since the rainfall is stochastic in nature, the effective rainfall and ultimately the irrigation requirements of crops also become stochastic. The rainfall data from 1986-87 to 1997-98 is used for fitting Gamma probability distribution and the value of rainfall at 95, 85 and 75 per cent probabilities has been determined. The effective rainfall at different probabilities is estimated using USDA Soil Conservation Service Method (Smith, 1992). Net irrigation water requirement of crops at 5, 15 and 25 per cent risk level has been determined by taking the difference of potential evapo-transpiration and effective rainfall.

Actual Irrigation Requirement of Crops

After computing net irrigation requirement, gross irrigation requirement was computed by dividing it with irrigation efficiency. Since quality of irrigation water is poor, so leaching requirement is also added to gross irrigation requirement (Rhoades, 1974).

Groundwater Pumpage

Groundwater pumpage depends upon the actual irrigation requirement, quality of groundwater and canal water availability.

Quality of Groundwater

Groundwater quality of study area has been divided in three categories viz. < 2.0, 2.0-4.0 and > 4.0 dS/m (Brar and Singh, 1993). For present study groundwater is divided into five categories namely < 2.0, 3.0, 4.0, 5.0 and 6.0 dS/m. The groundwater was used by mixing with canal water in such a proportion that the resultant EC is acceptable for the range of crops to be grown in the study area.

Water Allocation Model

A water allocation model is developed to maximize ground water pumpage considering the groundwater quality, actual irrigation requirement, canal water availability and hydraulic head. The decision variables of the model are groundwater hydraulic head and tube well discharges. The linear programming package is used for this purpose. The model is combined with simulation model.

Objective Function

The objective function is to maximize tube well discharge at all the active nodes. The maximum discharge is given by equation:

$$\text{Max } Z = \sum_{i=1}^{14} \sum_{j=1}^{11} Q_{i,j} \tag{1}$$

where,

Z = Total discharge at all the nodes, $Q_{i,j}$ = Tubewell discharge at *i*th row and *j*th column

i = Number of row and j = Number of column

Constraints

To achieve the above objective the following constraints have been considered.

(i) *Groundwater flow equations*: For unconfined homogeneous aquifer two dimensional transient flow equation can be written as

$$\frac{h_{i+1,j} + h_{i,j+1} - 4h_{i,j} + h_{i-1,j} + h_{i,,j-1}}{(\Delta x)^2} = \frac{s_{i,j}}{T_{i,j}}\left(\frac{h_{i,j} - h_{i,j,t=0}}{\Delta t}\right) + \frac{Q_{i,j} - r_{i,j}}{T_{i,j}} \quad (2)$$

where,

h = hydraulic head (m), w = sink/source term (m/day), T = transmissivity (m^2/day)

r = recharge (m/day), Q= pumpage (m/day) and t = time, (day)

The system of algebraic linear equations at every grid point becomes a set of constraints and they insure that the groundwater variables are directly incorporated as decision variables in management model.

(ii) *Groundwater pumpage*: Groundwater used in each season must be less than or equal to the maximum groundwater potential available in that season (which depend upon the quality of groundwater, actual irrigation requirement and canal water availability)

$$MQ_{i,j} = AIR_{i,j} * (EC_{mw} - EC_{cw}) / (B_{i,j} * EC_{twi,j} - EC_{cw} + A_{i,j}\ EC_{mw}) \quad (3)$$

$$Q_{i,j} \pounds MQ_{i,j} \quad (4)$$

MQ = Maximum potential of groundwater at ith row and jth column.

AIR = Actual irrigation requirement (mm),

A = Fraction of safe tube well water

B = Fraction of unsafe tube well water

EC_{mw} = Electrical conductivity of mix water, dS/m

E_{Ccw} = Electrical conductivity of canal water, dS/m

$EC_{t/w}$ = Electrical conductivity of tube well water, dS/m

(iii) *Hydraulic head constraints:* Hydraulic head constraints at any/all nodes can be added in the model so that water level should not rise/fall under specified limit.

$$h_{i,j} <= Ri,j - X \quad (5)$$

$$h_{i,j} >= Ri,j - Y \quad (6)$$

X = upper limit of water table depth (m)

Y = lower limit of water table depth (m)

Ri, j = reduced level (m)

(iv) *Evapo-transpiration(ET) constraints:* Actual irrigation requirement was found at 90 percent level of ET at upper limit of pumpage was changed as the difference between the actual irrigation requirement and canal water availability at that node.

$$Q_{i,j} \pounds AIR_{ET\%i,j} - CW_{i,j} \quad (7)$$

where,

$AIR_{ET\%i,}$ = Actual irrigation requirement

$CW_{i,j}$ = Canal water availability

For developing optimal pumping strategies for controlling the rise in water

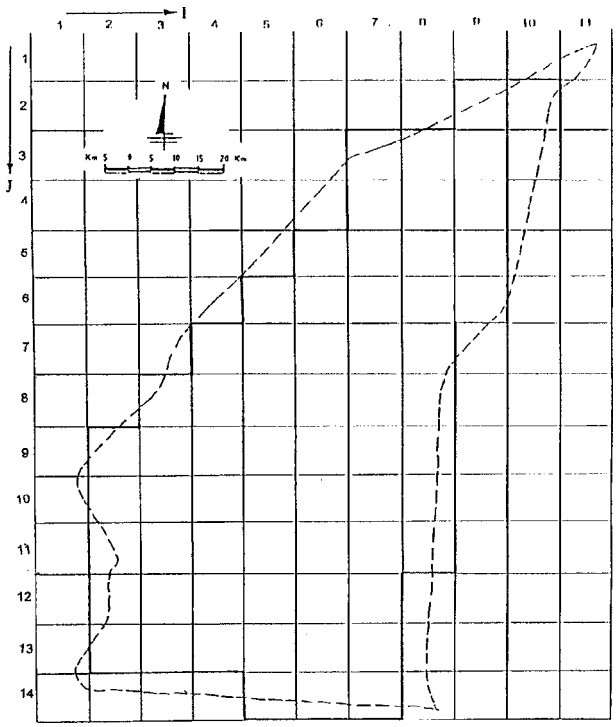

Figure 2. Discretization of aquifer of Southwest Punjab

table a number of simulation runs were carried out using the simulation-optimization model in which objective function was to maximize the pumping with a view to arrest rise in water table. The impact of management alternatives on water table depth was evaluated with reference to simulated groundwater conditions in southwest Punjab for June,1998. The following simulation runs were performed.

- *Simulation-optimization run one:* 100 per cent ET demand, maximum safe pumpage depending upon groundwater quality and actual irrigation requirement with no constraint on hydraulic head.
- *Simulation-optimization run two:* 100 per cent ET demand, maximum safe pumpage depending upon groundwater quality and actual irrigation requirement with hydraulic head constraint 3 to 10 meter below ground surface.
- *Simulation-optimization run three:* 90 per cent of ET demand, maximum canal water use, upper limit constraint on pumpage, no constraint on hydraulic head and 30 per cent of canal water available in Malout block distributed equally in Khuian Sarwar, Fazilka and Jallalabad blocks.

The impacts of different simulation optimization runs on groundwater regime are discussed below:

- *Simulation-optimization run one:* The model was run to predict the water levels in *rabi* and *kharif* seasons during next five years. A perusal of Table 1 and 2 reveal that the proposed management plan will require 134,743 ha-m of

groundwater and 29,968 ha-m of canal water in *kharif* season. In *rabi* season this plan will require 201,277 ha-m of groundwater and 38,878 ha-m canal water to meet 100 per cent ET demand. These data also reveal that under this management plan the groundwater pumpage will increase to 134,743 ha-m from 60,413 ha-m (June 1998) during *kharif* and from 60,413 ha-m to 201,277 ha-m during *rabi* season. However, the canal water will remain under utilized to the extent of 57.8 per cent during *kharif* and 60.5 per cent during *rabi* season. Table 1 and 2 reveals that the proposed plan will result in sharp decline in water table over the entire southwest Punjab.

- *Simulation-optimization run two:* A perusal of data under Table 1 and 2 reveals that total groundwater pumpage decreased gradually from 129,104 ha-m to 96,652 ha-m for *kharif* season and from 187,105 ha-m to 92,405 ha-m for *rabi* season. The canal water requirement increases gradually from 35,607 ha-m to 68,059 ha-m during *kharif* seasons and 53,050 ha-m to 147,750 ha-m during *rabi* seasons. Under this management plan water table depth remains generally between 3 to 10 m below ground surface. Table 1 also reveals that during *kharif* the canal water supplies are sufficient to meet the ET demand. However, during *rabi* the canal water supplies fall short by 33,740; 47,211 and 49,167 ha-m in third, fourth and fifth year, respectively (Table 2). It will not be possible to meet the deficit during the *rabi* season even if the surplus canal water available during *kharif* is transferred to *rabi* season.
- *Simulation-optimization run three:* In this simulation run upper limit on groundwater draft was decided as the difference between the irrigation requirement and canal water supply at each node except for the nodes (9,5), (10,6), (10,7) (11,6) and (11.7). The nodes (10,6), (10,7), (11,6) and (11,7) fall in Malout block whereas node (9,5) falls in part of Muktsar, Fazilka and Jalalabad blocks. For these nodes the upper limit on groundwater draft was decided depending upon actual irrigation requirements and safe groundwater quality. After running the model for one year it was observed that there is a sharp rise in water table at nodes (6,6), (7,6) and (8,4) which falls under Guruharsahai and Jalalabad blocks. So upper limit of groundwater draft on these nodes were decided during *rabi* season on the basis of irrigation requirement at 90 per cent ET and available groundwater quality. Maximum pumpage was done on these nodes to arrest rise in water table for the next four *rabi* seasons by changing upper limit of groundwater draft.

A perusal of data under Table 1 and 2 reveal that the groundwater draft requirement remains 72,745 ha-m during all five *kharif* seasons and for *rabi* season it is 138,233 ha-m for the first rabi season and 140,518 ha-m for the next four *rabi* seasons whereas existing groundwater draft for the *rabi* season (ending June 98) is 60,413 ha-m. Data further reveal that canal water supplies are sufficient in both the seasons for all the five years. These data also reveal that water- logged area first increases from existing 94,470 ha to 165,961 ha during the first *kharif* season and then it reduces sharply to 17,873 ha during the first *rabi* season. During second *kharif* season it increases to 102,130 ha but during next four *rabi* seasons it remain zero and it reduces gradually to 91,917 ha, 63,831 ha and 35,746 ha in third, fourth and fifth *kharif* season. Table 1 reveals that area under water table depth greater than 10 meter was zero for first three years of simulation run but increased to

Table 1. Results of different management strategies for monsoon season

Year	Management strategies	Monsoon						
		CW[1] available (ha-m)	Pumpage (ha-m)	CW req. (ha-m)	Area under water table depth (ha)			
					<2m	2 to 3m	3 to 10	>10m
	JUNE, 98	98583	60413	71110	94470	168515	370221	17873
1st	SOR1*	71110	134743	29968	20426	114896	497884	0
	SOR2*	71110	129104	35607	5107	86810	559162	0
	SOR3*	71110	72745	71110	165961	76598	408520	0
2nd	SOR1	71110	134743	29968	0	0	385541	265538
	SOR2	71110	123468	41243	0	0	651079	0
	SOR3	71110	72745	71110	102130	61278	487671	0
3rd	SOR1	71110	134743	29968	0	0	117450	533629
	SOR2	71110	104432	60279	0	0	651079	0
	SOR3	71110	72745	71110	91917	30639	528523	0
4th	SOR1	71110	134743	29968	0	0	651079	638313
	SOR2	71110	98040	66671	0	0	651079	0
	SOR3	71110	72145	71110	63831	20426	520863	45959
5th	SOR1	71110	134743	29968	0	0	2583	648526
	SOR2	71110	96652	68059	0	0	651079	0
	SOR3	71110	72745	71110	71100	35746	477457	112343

*See footnote under Table 2, [1]CW = Canal water

Table 2. Results of different management strategies for winter season

Year	Management strategies	Monsoon						
		CW available (ha-m)	Pumpage (ha-m)	CW req. (ha-m)	Area under water table depth (ha)			
					<2m	2 to 3m	3 to 10	>10m
	JUNE,98	98583	60413	71110	94470	168515	388094	0
1st	SOR1*	98583	201277	38878	0	0	651079	0
	SOR2*	98583	187105	53050	0	0	651079	0
	SOR3*	98583	138233	77903	0	84257	548949	0
2nd	SOR1	98583	201277	38878	0	0	74044	577035
	SOR2	98583	146597	93558	0	0	651079	0
	SOR3	98583	140518	75619	0	74044	577035	0
3rd	SOR1	98583	201277	38878	0	0	20426	630653
	SOR2	98583	107832	132323	0	0	651079	0
	SOR3	98583	140518	75619	0	15320	651079	0
4th	SOR1	98583	201277	38878	0	0	2553	648526
	SOR2	98583	145794	145794	0	0	651079	0
	SOR3	98583	140518	75619	0	5107	536182	109790
5th	SOR1	98583	201277	38878	0	0	2553	648526
	SOR2	98583	92405	147750	0	0	651079	0
	SOR3	98583	140518	75619	0	0	485118	165961

*SOR1= Maximum pumpage, no constraint on head, 100% ET; *SOR2= Maximum pumpage, head 3 to 10m, 100% ET; *SOR3= Maximum pumpage and canal water use, no constraint on head, 90% ET

45,959 ha and 112,343 ha in fourth and fifth *kharif* season. During *rabi* season it increases to 109,790 ha and 165,961 ha in fourth and fifth season (Table 2).

The simulation optimization run results in area under water table depth < 2 m in Guruharsahai, parts of Jalalabad and Muktsar blocks where as declining water table trend was observed in Fazilka, Khuian Sarwar and Abohar blocks. The problem of area having water table depth < 2 m can be solved by increasing the pumping limit to maximum possible discharge limit.The declining water table area can be controlled by reducing the pumping in that area and meeting the remaining irrigation demand by transfer of canal water from rising water table area to declining water table area. Another alternative could be to decrease the pumping in declining water table area by shifting the cropping pattern so that irrigation requirements are reduced as compared to existing one. This can be achieved by decreasing the area under paddy in Fazilka, Khuian Sarwar and Abohar blocks.

Case Study of Sirhind Canal Tract

The Sirhind canal tract of Punjab comprises of four districts: Ludhiana, Patiala, Sangrur and parts of Ropar. Water table has been declining in most of the blocks in this tract for the last three decades. Out of the total irrigated area, seventy five percent is now irrigated by groundwater through tube wells, against 55% three decades ago. Because of excessive extraction of groundwater the water table is declining at the rate of 17 cm to more than 1 m per year. This has resulted in lowering of existing centrifugal pump sets deeper into the pits to meet their suction requirement or have been replaced by costly submersible pump sets. In order to develop various strategies for management of water resources in this tract a management model was developed and combined with simulation model using response matrix approach.

Groundwater Simulation Model

The two-dimensional groundwater flow equation was used to simulate groundwater flow in non-homogeneous, anisotropic aquifer. The Galerkin's finite element method with linear quadrilateral elements was used to discretize the groundwater flow equation in space. The region was sub-divided into 49 quadrilaterals having 73 nodes. Eigen-value solution of the resulting ordinary differential equation was obtained continuous in time (Kaushal and Khepar, 1988). The model was used to compute hydraulic head at nodal points and at the water level observation points being monitored by the Central Groundwater Board, State Water Resources Directorate and State Department of Agriculture (Fig. 3) The value of transmissivity varied from 700-2500 m^2/day and storage coefficient was 0.2. The expected value of recharge for part of the Sirhind canal tract (Fig. 3) was 74,692 ha-m, whereas the withdrawal for the year 1987-88 was 100,896 ha-m. There was a decline of water level at the rate of 0.18 to1.4 m/ year, the higher value of decline occurred in the central part of the tract.

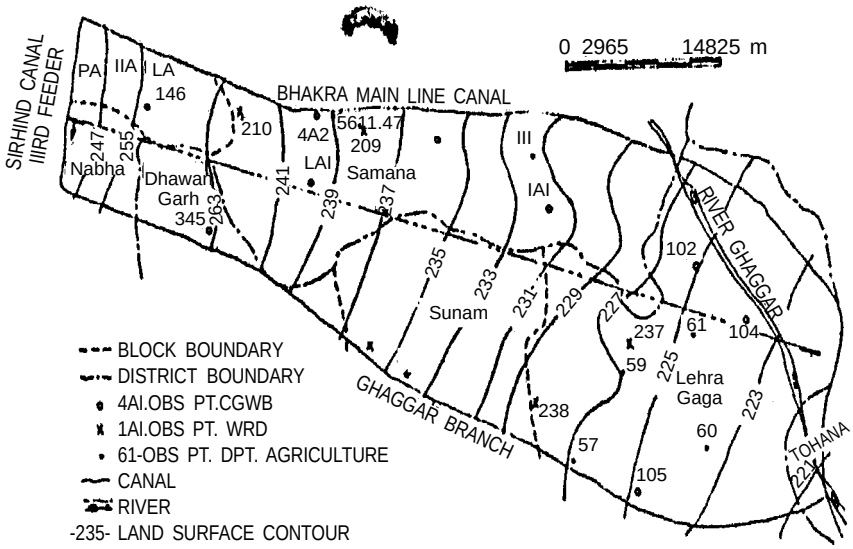

Figure 3. Study area showing land surface contours (m) and water table observation points

Management Model

A chance constrained linear programming model was developed (Kaushal & Khepar, 1992).

Objective function: The objective was to maximize annual net returns. The maximum net return (Max Z) is given by the equation:

$$\text{Max } Z = \sum_{S=1}^{2} \sum_{w=1}^{W} \sum_{k=1}^{K} NRswk \;\; Xswk - \sum_{S=1}^{2} CSs \;\; SWs$$

$$- \sum_{S=1}^{2} \sum_{n=1}^{N} CTsn \; TWsn - \sum_{n=1}^{N} PCTWn \; (NSLn + DHn - hn) \qquad (8)$$

where,

S = growing season (S=1 for winter season and S=2 for monsoon season);

W = level of water application, W=1,2,.. W; k = crop index, k=1,2...K; n = finite element, n=1, 2..

N; NRswk = net returns; Rupees/ha, above all variable production cost, excluding the cost of irrigation water, from crop k with level of irrigation water W in season S;

Z =total net returns, in Rupees over variable costs;

Xswk =area in ha allocated to crop k, grown with level of irrigation water W in season S;

CSsn = cost in Rupees for applying 1 ha-m of canal water in season S;

SWs = canal water in ha-m allocated at head of the field in season S;

CTsn = cost in Rupees for applying 1 ha-m of groundwater at node n in season S;

TWsn= groundwater in ha-m allocated from element n in season S;

NSLn = natural surface elevation (RL) in metres at node n;

DHn = dynamic head in meters at node n;
hn = hydraulic head elevation (RL) in metres at node n and
PCTWn = penalty cost weighting factor, Rupees/m of head, because of water level lowering at node n.

Constraints

(i) In applying the model, following constraints have been taken into consideration. Water allocation: Irrigation water requirements of crops must be met from canal and groundwater supply in season at a probability of b

$$P\left\{\sum_{k=1}^{K}\sum_{w=1}^{W} NIRswk\ Xswk \le SWs + \sum_{n=1}^{N}\theta ct\ \ TWsn\right\} \ge \beta \text{ for all s} \qquad (9)$$

where,

NIRswk = irrigation water required in ha-m for crop k with irrigation level W in season S;
q = tubewell water conveyance efficiency;
P = probability operator;
b = probability level, 0 < bs £ 1
The deterministic equivalent to the probabilistic constraint when formulated in terms of chance constrained is:

$$\sum_{k=1}^{K} S^{-1}swk\ (\beta s)\ Xswk \le SWs + \sum_{n=1}^{N}\theta ct\ TWsn \text{ for all s} \qquad (10)$$

$^{-1}$swk (βs) is inversse distribution function of NIRswk for βs level of assurance.

(ii) Land area: The total area under various crops in each season cannot exceed the total available area for irrigation

$$\sum_{k=1}^{K}\sum_{w=1}^{W} ALFAs\ Xswk \le Tas \text{ for all s} \qquad (11)$$

where
ALFAs = land area occupying coefficient for crop activity (ALFAs = 1, if the crop is grown in the season S, otherwise it is zero), and
Tas = crop land in ha available in season S

(iii) Canal water: Canal water allocated in season S cannot exceed canal water available in season S after allowing for all losses.

$$SWs \le ASWs \qquad \text{For all S} \qquad (12)$$

where,
ASWs = canal water in ha-m available in season S after allowing for all losses.

(iv) Tubewell water: Tubewell water allocated from element n cannot exceed tubewell water available in season

$$TWsn \le ATWsn \qquad \text{for all s,n} \qquad (13)$$

where,
ATWsn = tubewell water in ha-m available in season S.

(v) Minimum area:

$$\sum_{w=1}^{W} Xswk \geq MIARsk \text{ for all s and } k = 3,10,11,13 \quad (14)$$

where,
MIARsk = minimum area in ha required for crop k grown in season S.

(vi) Maximum allowable area:

$$\sum_{w=1}^{W} Xswk \leq MAALsk \qquad \text{For } s = 1;\ k = 5 \quad (15)$$

where,
MAALsk = maximum area in ha allowable to crop k grown in season S.

(vii) Hydraulic head : The hydraulic head in an element cannot exceed the hydraulic head elevation simulated by the groundwater model at node n

$$hn \leq hsmm \qquad \text{for all } n \quad (16)$$

where,
hsmn = hydraulic head elevation (EL) in meters simulated by groundwater model at node n.

(viii) Non-negativity :

$$Xswk \geq 0;\ Sws \geq 0;\ TWsn \geq 0;\ hn \geq 0 \quad (17)$$

Methodology

A tract in Sirhind Canal (Fig. 3) bounded by the Bhakra Main Line Canal, Ghaggar Branch, Sirhind Canal Third Feeder and River Ghaggar was used for application of the models (Figure 3). The tract lies between latitude 29° 38' 27" N to 30° 24' 7"N and longitude 75° 51' 15" E to 76° 15′E. The climatic conditions in the tract are, severely cold winters particularly in the month of December and January, and intense hot summers in April, May and June. Mean monthly air temperature during winter is 5° C whereas mean monthly air temperature in the summer reaches 40° C.

The groundwater simulation model was calibrated and validated for prediction of groundwater table by using observations for the period 1975 to 1987. The simulation model was used to determine the effect of unit responses in terms of groundwater withdrawal on hydraulic head. An assemblage of unit responses was included in the management model. Other inputs to the management model were net irrigation water requirement of crops at 5% and 25% risk levels (expected values of ET was taken as average of 30 years, rainfall was considered probabilistic, and, a two parameter gamma distribution was fitted to the monthly rainfall data), water resources availability, cost of irrigation water and net returns excluding the cost of irrigation water. Net irrigation requirements of crops were computed by diminishing effective rainfall (using USDA, SCS method) at 5% and 25% risk level, from the expected value of ET. Water application was considered at levels 1, 2, 3

and 4, which corresponds to water production functions at 25, 50, 70 and 100% of the net irrigation water requirement. Crop water production functions were developed based on experimental observations (Rajput, 1985). Four type of functions were used (Eqs. 18 to 21) namely Cobb-Douglas, quadratic, square root and Modified Mitscherlich-Spillman functions for wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), raya (*Brassica juncea*), gram (*Cicer ratinum),* potato (*Solanum tubersom),* berseem fodder (*Trifolium alexandrinum*), rice (*oryza sativa),* cotton (*Gossypium arborium*), maize (*Zea mays*), sugarcane (*Saccharum offinarum*), groundnut (*Arachis hypoge*), green gram (*Phaseolus radiata*) and sorghum fodder (*Sorghum vulgare*)

Cobb-Douglas function

$$Y = a\ W^{b} \tag{18}$$

Quadratic function:

$$Y = a + bW + CW^{2} \tag{19}$$

Sqare-root function

$$Y = a + bW + cW^{0.5} \tag{20}$$

Modified Mitscherlich-Spillman functions

$$Y = a\ (1\text{-}e^{-b(w+c)}) \tag{21}$$

where,
Y = crop yield, q/ha; (1quintal=100 kg)
W = depth of water applied, cm and
a, b, c = constants

The crop yield is influenced by crop variety and soil fertility. However, these factors were fixed and only water applied was considered a variable. The soils were sandy loam. The available nutrients such as organic matter, P_2O_5 and K_2O varied from 0.162 – 0.308%, 1.8 – 13.2 and 51 – 113 kg/ha,respectively.

The model outputs are in terms of cropping pattern, canal water and groundwater allocation and hydraulic heads at nodes for maximized net returns. The depth of pumping cost of water, rain, price of crop and availability of land and water influence maximized net returns. In this study the hydraulic heads at nodal points were made a constraint in the management model. The cost of canal water and groundwater was Rs 240 and Rs 927 per ha-m of water, respectively. The annual rainfall was 38 cm at 75% probability level. Prices of crops prevailing in Punjab during the year 1988 were used. Total land resources of the study area were 115,803 ha. The annual canal water and groundwater resources available were 39,170 ha-m and 100,896 ha-m, respectively.

Water Production Functions

The best-fit water production functions based on statistical analysis are given in Table 3. The quadratic functions were selected for wheat, barley, raya, gram, rice, sugarcane, moong and sorghum fodder; square root functions for cotton, maize and berseem fodder; Modified Mitscherlich-Spillman functions for potato and groundnut crops.

Table 3. Crop water production functions

Sl.No.	Crop	Coefficients			R^2	F-value
		a	b	c		
Quadratic						
1.	Wheat	16.31263	1.034402 (5.65*)	-0.012068 (-2.6) NS	0.985	67.12*
2.	Barley	9.586905	0.654469 (2.55) NS	-0.009018 (-1.09) NS	0.972	17.58*NS*
3.	Raya	9.0495	0.212845 (1.83) *NS*	0.002534 (-.67)*NS*	0.957	11.11*NS*
4.	Gram	8.65822	0.2777529 (1.41) *NS*	-0.003947 (-0.62) *NS*	0.914	5.32*NS*
5.	Rice	-1.632408	0.357109 (2.78) *NS*	-0.000431 (-1.33)*NS*	0.998	294.40*
6.	Sugarcane	- 37.435425	9.717468 (7.27*)	-0.024837 (-5.18)*NS*	0.996	153.45*
7.	Green gram	- 2.08542	0.914279 (2.02) *NS*	-0.020513 (-1.74) *NS*	0.890	4.07*NS*
8.	Sorghum fodder	161.66644	7.125275 (2.16) *NS*	-0.055064 (-1.81)*NS*	0.947	9.08*NS*
Square root						
9.	Cotton	- 29.346767	-0.730293 (-1.32)*NS*	12.418518 (1.79)*NS*	0.974	18.89*
10.	Maize	- 32.315575	-1.256317 (-48)*NS*	18.086426 (0.71)*NS*	0.945	8.67*NS*
11.	Berseem fodder	20.887573	-10.78100 (-3.0)*NS*	182.26563 (3.47*)	0.979	23.92*
Modified Mitscherlich-Spillman functions						
12.	Groundnut	21.2	0.084569 (3.54*)	4.6319	0.862	12.54*NS*
13.	Potato	205.0	(0.082384) (1.84) *NS*	-28.3002	0.630	3.41*NS*

Note: ** The values in parentheses are t-values for the coefficients significant at 1% level of significance
* Significant at 5% level of significance
NS: Not significant at 5% level of significance

Optimization of Net Benefits

The results of management model combined with simulation model using response matrix approach were obtained at risk levels of 5% and 25% (95% and 75% probability of rainfall). The cropping pattern is given in Table 4. As the risk level increased from 5% to 25% the area under wheat and cotton at water application level 3 increased from 59,853 ha to 68,778 ha and 100,749 ha, respectively. Maize shifts to water application level 4. Rice and sugarcane that have a higher water requirement are deleted from cropping pattern. Canal water and groundwater were fully utilized. The hydraulic head remained at the levels predicted by the groundwater simulation model. As the risk level increased from 5 to 25% the annual net returns increased. The reason for this is, that with an increase in risk

level, the irrigation water requirements of crops decreased. The model adjusts the allocation of land and water resources in such a way that more area is allocated to crops under higher levels of water application, thereby increasing annual net returns. The study did not consider labour as a constraint. However the results may be influenced if high value, labour intensive crops are included in crop planning.

Table 4. Land and water allocation at 5 and 25% risk level

Crop	Risk level					
	5%			25%		
	Water application index	Irrigation (cm)	Area (ha)	Water application index	Irrigation (cm)	Area (ha)
Winter wheat	(2)	29.1	46844	(2)	28.3	37919
Wheat	(3)	43.6	59853	(3)	42.4	68778
Mustard	(3)	33.3	2316	(3)	32.0	2316
Berseem fodder	(2)	50.9	6790	(3)	49.7	6790
Monsoon cotton	(3)	48.6	64175	(3)	59.1	100749
Cotton	(3)	72.8	36574	—	—	—
Maize	(3)	35.8	2316	(4)	35.7	2316
Green gram	(2)	25.6	1158	(2)	18.3	1158
Sorghum fodder	(3)	37.5	11580	(2)	17.8	4876
Sorghum fodder	—	—	—	(3)	26.8	6704
Annual net returns (M INR)		1271.5			1304.5	

Case Study of Southwest Haryana

The main hindrance for agricultural development in southwest Haryana is the scarcity of water resources to irrigate farmer's fields. In order to find solutions for optimum water management for this region a regional water management analysis has been carried out using an integrated model for Sirsa Irrigation Circle. (Aggarwal and Roest, 1996)

Description of Sirsa Irrigation Circle

Sirsa Irrigation Circle, with an area of about 0.42 million hectare (ha), represents arid climatic conditions with annual average rainfall varying from 300 to 550 mm, less than 25 rainy days and an annual potential evapo-transpiration from 1500 to 1650 mm. The topography of the area consists of gently sloping terrain with some isolated steep contours in the vicinity of the Ghaggar River. The general direction of the landscape slope is from east to west and towards the Ghaggar river. The different geomorphological units found in Sirsa Irrigation Circle are the recent alluvial plains and aeolian plains with sand and sand dunes. The soil texture varies from loamy sand to sandy loam with some sandy soils occurring in patches.

Canal water supply to Sirsa Irrigation Circle is provided through three canals: Bhakhra Main Line in the north serving about 34,4000 ha; Sukhchain Distributary

in the central part serving about 29,500 ha and Fatehbad Distributary in the south serving 18,200 ha. The Ghaggar river is only carrying water during some months in the monsoon season and its water is partly used for irrigation during these months through Ottu feeder. A part of the feeder, infiltrates in the riverbed, resulting in recharging of the groundwater aquifer. Total annual canal water supply was about 5 * $10^9 m^3$. The canal water supply triggered rising water tables in the northwest and southeast where groundwater is poor. Due to deficiencies in the canal water supply, over-exploitation of groundwater in the belt along the Ghaggar river, where groundwater quality is good, caused a decline in the water tables. The maximum annual rise in water table in the northwest and southeast during the period between 1976 and 1991 was over 1 m and the maximum decline in the central part of the area was 0.4 m annually. The scenarios presented here are based on an extensive set of data and gives a more detailed view of the problem for Sirsa district compared to the trends presented on state level.

The groundwater quality on both sides of the Ghaggar river is generally good, resulting in the installation of numerous tube wells in its vicinity during the past several years. Groundwater quality in the western side in Dabwali block is quite poor from varying 7 to 10 dS m^{-1}, restricting its use for irrigation. During the last five years, however, relatively good quality water developed along canals, overlying the saline groundwater, prompting farmers to go for shallow tubewells. General movement of groundwater is from Ghaggar river towards the northwest and southeast. During 1992 water table depths ranged from 1.5 – 25 m in the area with the shallowest groundwater table are found in the Phaggu-Rori area in the east and the deepest in Sikanderpur in the southeast. Serious water logging and salinity problems have emerged in the Phaggu, Desu and Rohan villages of Rori area, leading to the loss of large tracts of agricultural lands.

Major crops in Sirsa Irrigation Circle are wheat, cotton and gram. 17% of potential cultivable land is kept fallow, while about 45% of the remaining area was irrigated in winter and 57% during summer.

Model Calibration and Validation

Study area was subdivided into 46 calculation units for simulation study. The canal water command system was followed in classifying these units. Within the boundaries of calculation units, homogeneity was assumed with respect to soils, cropping pattern, climatic conditions, groundwater salinity and depth of groundwater table depth.

Model calibration on observed historical groundwater levels was performed for the observation period from 1977 to 1988. Calibration was achieved by adjusting number of spatially distributed input parameters such as, storage coefficient, transmissivity and soil physical parameters. After calibration of input parameters for the period from 1977 to 1981, the model was validated for the period from 1982 to 1990. The validation results were satisfactory for the complete study area with predictive value of 75% and higher. In about 52% of study area the predicted values were matching even above 90%.

Description of Integrated Model

Integrated model consists of SIWARE for canal and on –farm water management and SGMP for regional groundwater flow (Smit et al., 1996 and Boonstra et al., 1996). The integrated model comprises of a number of sub-models DESIGN, FRAME, WDUTY and REUSE required for pre-processing of data and computation of water distribution, canal seepage and spatially distributed crop water requirements.

Water Management Analysis

The analysis of water management in Sirsa irrigation circle, using the integrated model, provides observations on: water supply and crop coater requirement and recharge of groundwater.

i) *Water supply and crop water requirement*: The water requirements of irrigated crops were computed by the model that are to be met by canal water supply, rainwater and groundwater exploitation. The water supply from canal and rainfall exceeded the crop demands with about 15% during the first four months from January till April and with about 90% in December. The water supply was deficient by about 30% during the months of May and June and 40-50% during the months of September till November. During the months of July and August the supply covered the demands almost completely. During the period from 1977 to 1990 the average annual shortage of water supply was 210 mm for the water deficiency periods. The average annual excess in water supply was 50 mm with a minimum of 25 and a maximum of 125 mm. The irregular and erratic rainfall caused significant deviation from these average values both in time and space.

ii*) Recharge of groundwater*: Because of the absence of drainage systems, water available through rainfall, groundwater pumpage and canal water in excess of the water holding capacity of soil, percolates to the aquifer system. Recharge causes groundwater table to rise. For a number of reasons the total quantity of water received by Sirsa Irrigation Circle was not fully utilized, and resulted in water table rise. The following recharge components were recognized:

- Excess rainfall on non- agricultural areas
- Seepage losses from canals
- On-farm water losses
- Aquifer recharge by Ghaggar river during the monsoon period.

The seepage losses from canals were about 25% of the total losses and 10% of the canal water supply. On farm water losses were caused by seepage losses from the field irrigation channels, percolation and leaching losses due to rainfall events, especially if they occurred just after field irrigation of crops. Percolation losses during field irrigation were generally not caused by excessive canal water supply, but due to the uneven field water distribution. The border and furrow irrigation methods applied by farmers caused relatively more infiltration at the heads of the fields compared to the tail ends. Also imperfect land leveling and non-ideal sloping fields promoted inhomogeneous water distribution within agricultural fields. The on-farm water losses accounted for about 60% of the total aquifer recharge and 25%of the canal water supply.

Conveyance losses from the canals showed only moderate fluctuations during the period between 1997 and 1990, while the other losses varied from about 175mm ha^{-1} to as much 400 mm ha^{-1}. Defining the overall project efficiency as the ratio of crop evapo-transpiration and total water-supply (including rainfall and groundwater use), the system can be classified as highly efficient with values varying between 68 and 79% for the different years. However, large spatial differences in aquifer recharge occurred in the area, during this period.

The analysis of water management in Sirsa Irrigation Circle revealed that irrigation performance was quite good resulting in a high overall project efficiency ranging from 68% to 79%. The average annual canal water supply was sufficient to meet the water requirements of irrigated crops during winter and early spring, for the winter irrigation intensity of 45%. During the summer and monsoon season the high water requirements for irrigated crops with irrigation intensity of 57% was met through canal irrigation and rainfall for 50 to 60%.

The combined effect of irregular rainfall, canal seepage; water-holding capacity of soils, and irrigation methods used by farmers resulted in percolation losses to the aquifer with a high spatial variability. In about 20% of the area, total annual percolation losses varied from 450 to 625 mm ha^{-1}, in 60% of the area from 150 to 450 mm ha^{-1} and in the remaining 20% from 75 to 150 mm ha^{-1}. The annual canal seepage varied from 85 to 125 mm. The percolation losses together with canal seepage and conveyance losses from the Ghaggar river, caused in major parts of Sirsa Irrigation Circle a groundwater table rise during the period 1977-1990 from 0 to 16 m. In the belt along the Ghaggar river, groundwater tables declined due to significant groundwater abstraction rates. Here the decline varied from 2 to 6 m. The effective porosity in the aquifer system varies from 8-16%, so a change of 1m in water table depth changes the groundwater reservoir with 80 to 160mm.

Alternative Water Management Strategies

Future regional water management strategies for Sirsa Irrigation Circle should solve the problem of rising water tables in the northern and southern part of the area and problem of declining water tables in the central part of the study area. Although, a complete solution cannot be achieved without a drainage outlet to remove the salts imported with the irrigation water, the question remains whether an adapted regional water management could delay the rise of water tables in the endangered zones. This means that alternatives have to be found to reduce the aquifer recharge in the rising water-table areas, increased groundwater use in these areas and/or increased recharge in the areas with falling water tables of reduced groundwater use in these areas.

Increased groundwater use in areas with rising water tables and poor groundwater quality is an issue, which should be solved at the level of on-farm water management. Implementation of such strategies has to be pursued through extension services to farmers in order to convince the profitability to extend their irrigated area using supplemental irrigation and manage the deficient canal water supply.

Out of the four components of aquifer recharge, the regional water manager does not control two. These are the recharge due to rainfall in the non-agricultural areas and the recharge from the Ghaggar river during monsoon. The later takes

place in the zone of declining water table and is rather beneficial. Two recharge components are under control of the regional water manager. These are the canal seepage losses and the on-farm water management losses. The canal seepage losses were estimated at about 10% of the canal water supply. Further reduction of these losses of this highly efficient system will be very difficult to achieve.

Two water management strategies addressing the reduction of on-farm water losses to the aquifer were evaluated and discussed as follows. Both strategies were applied for the period between 1971 and 1990, to enable comparison with the historical water table development.

Water Pricing

The analysis of on-farm water management resulted in recommendations to increase the irrigated area using the same amount of canal water. Reduced irrigation water application, as proposed, can be implemented by changing the method of recovering the cost of irrigation water from farmers. Presently, farmers are charged on the basis of irrigated area. Although water charges are quite low, farmers are not encouraged by this system to irrigate more land with the same amount of water.

In the water pricing alternative strategy, it was assumed that payment for water would be based on the amounts of water delivered to farmers, giving farmers freedom to optimize their on-farm water management operations without additional charges. Given the present *Warabandi* water-supply system, which is based on equity, such a change in water pricing methodology does not involve expensive and laborious monitoring of volumes delivered. Simple changes in the basis of pricing from irrigated area from 50% to about 85% was assumed in the simulations by converting the rainfed crops to irrigated crops.

As a result of this strategy, the crop evapo-transpiration increased at the expense of water losses to the aquifer. The annual rise in water table in the utmost northwestern and southeastern part of Sirsa district reduced by about 15%. By adopting this strategy water logging problems cannot be avoided, but can be postponed by 5 to 10 years. At the same time total crop production in the area appeared to increase as well. However, through this strategy, declining water table in the central part of the area was not arrested.

Water Supply According to Demand

Adjusting the temporal and spatial canal water supply to the actual crop water requirements of the irrigated crops can obtain additional water use efficiency improvements. Presently, canal supply exceeds requirement by about 55 mm during the winter period and the late summer shortage in supply is about 210 mm. The present canal water distribution is based on cultivable area rather than on water requirements of the irrigated cropping pattern. This could be improved by discarding the *Warabandi* system and by distributing canal water based on the spatially distributed crop water requirements. During the monsoon period, irrigation water requirements depend to a large extent on rainfall. Solutions for technical and managerial provisions to adjust canal water supply to the erratic and spatially distributed rainfall conditions were considered beyond the scope of study. Although

application of regional models as predictive tools, can play prominent role in future water management accounting for rainfall, at this stage, long-term average rainfall has been assumed as input for matching the water distribution with the spatial and temporal distributed water requirements.

The effects of this regional water management strategy were expressed in the number of years elapsed until water logging occurred. In the reference situation with unchanged water management, in about 10% of the Sirsa Circle, water logging problems will occur within a time period of 15 to 45 years. With water distribution matching the temporally and spatially distributed water requirements, these percentages are considerably reduced. In about 5% of the area water logging is expected within 5 years, in about 15% of the area within 5 to 15 years and in about 25% water logging problems will occur within a time period of 15 to 45 years. An additional benefit from this alternative is that in the central part of Sirsa district with declining water table, a status quo or a reversed situation was achieved.

Evaluation of Alternatives

Compared to the present canal water management system in Sirsa Irrigation Circle, both, alternative strategies have the advantage that rising water tables were delayed in the saline groundwater areas in the north and south of Sirsa district. Water distribution according to demand was slightly more effective in these areas. In the central part of Sirsa district water distribution according to demand led to slightly rising water tables. This could easily be corrected by reducing canal water supply to these areas or by compensating the increased recharge with more groundwater use.

The strategy of changing water pricing has the obvious advantage that no investments are required and operation of the canal system can be maintained at the present mode. The strategy with distribution according to demand requires a differentiated allocation and distribution of canal water and the present system of distribution based on equity has to be abandoned. For the strategy with distribution according to demand a number of practical constraints have to be solved: water scheduling and control requires more labour and additional investments to adapt water control structures. Such a system will be more susceptible to sabotage and bribery by influential farmers trying to receive more canal water. Also social and political constraints must be solved before implementing such a strategy. Farmers in the advantageous situation with access to good quality groundwater will receive more canal water than their colleagues in the poor quality groundwater zones.

Policy Implications

The lessons drawn from three case studies –Southwest Punjab and Srihand Canal Tract in Punjab and Sirsa Irrigation Canal in southwest Haryana provide evidence for policy issues pertaining to management of groundwater. The policy implications that can be drawn are:

Groundwater Legislation

There is need to enact proper groundwater legislation to prevent indiscriminate exploitation of groundwater resource. In addition, inheritance of property law also needs to be modified to prevent progressive fragmentation of land holdings. The task of water distribution becomes very simple and easy for a big size holding from an outlet in comparison to different sizes of holdings scattered all over the command area.

State Water Authority

India's National Water Policy (Ministry of Water Resources, 2002) clearly recognizes that exploitation of groundwater resources should be regulated so that it does not exceed recharging possibilities, and also ensures social equity. The detrimental environmental consequences of over-exploitation of groundwater need to be effectively prevented by the central and state governments. Water being the state subject, the State Water Authority should be set up with an aim to regulate and control groundwater development and management on sustainable basis.

Agricultural Power Supply and Pricing Structure

The use of flat rate for electricity, combined with unreliable electricity supply provides no incentives for efficient use of groundwater. The subsidized electricity tariff also results in heavy financial losses to State Electricity Boards. Thus there is an urgent need to revamp agricultural power supply and tariff structure. Specific policy issues aiming at sustainable use of groundwater will need supporting initiatives which ensure fair prices for alternate crops to growers through state mediated system.

Restructuring Subsidies

There is a need to restructure subsidies to encourage farmers to adopt efficient irrigation methods and improve water management with a view to improve groundwater use efficiency.

Stakeholder Participation

Participation of farmers, NGOs and scientists in defining and pursuing the strategies for sustainable resource use should be encouraged.

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