Application of Hydraulic and Economic Optimization for Planning Conjunctive Use of Surface and Saline Ground Water: A Case Study

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Abstract

Conjunctive use of water from different sources is considered to be a valuable tool to overcome the constraint of the surface and groundwater systems, if operated independently. The conjunctive use planning requires establishment of firm water supplies and their distribution, effect of water development and use on groundwater behaviour, allocation of water to different users based on economic returns and tolerance to salinity,and effect of saline water use on surface and groundwater salinities. Decisions regarding the development and allocation of water are complicated processes and are best attempted through modeling. This paper deals with formulation and application of groundwater hydraulic optimization and allocation models for planning the development and use of surface and groundwater in Lower Ghaggar Basin of Haryana,India.

The problem of conjunctive water development and utilization planning has been dealt as a two-stage process. The first stage, deals with determination of optimal groundwater development, while the second stage, deals with water allocation to crops in a conjunctive use milieu. For hydraulic optimization, a steady state flow optimization model has been formulated to develop optimal groundwater pumping strategies. The model predicts the optimal pumping volumes and the resulting groundwater potentiometric surfaces. In association with a groundwater simulation model, it also makes possible to forecast the time frame in which groundwater table in different sub areas in a region, would attain steady state condition. The special features of the model are the inclusion of functions for stream-aquifer interaction and direct evaporation from the ground watertable. For water allocation and economic optimization, a non-linear conjunctive water use-planning model is formulated. The model maximizes net benefits from water use of varying salinities through allocations to different crops and determines the optimal groundwater pumping for irrigation and drainage water disposal.

Results of the application of the hydraulic optimization model show that there is considerable scope for augmenting the groundwater supply in areas adjoining the River Ghaggar by increasing stream-aquifer interaction. The present stream aquifer interaction in river cells is of the order of 16 m^3s^{-1}*, which can be increased to 26* m^3s^{-1} *with optimal pumping. The optimal potentiometric surfaces fall in the range of 184 to 214 m above MSL giving a water table depth of 4 to 22 m, thus ensuring against waterlogging and salinity development.*

A non-linear conjunctive water use optimization model decides the water allocation to different crops and mapping of the resultant groundwater quality scenarios. A GAMS version of the model is prepared for analysis with GAMS/ MINOS software. The allocation essentially centres on crop-water-salinity production functions, which are non-linear in nature. The required production functions have been developed with basic data on crop-water-production and applied water-salinity-yield functions. The two functions for which the experimental data were available from different sources are synthesized into a single water-quality-quantity production function. The required costs and benefits estimates for different activities were developed using standard techniques of estimating and costing. The estimates of groundwater in different quality zones are based on water quality information from shallow tubewells, which was subjected to analysis by statistical software called GEOEAS.

It appears from the results of economic optimization that cash crops such as cotton and mustard, which are otherwise, also salt tolerant, will find favour with increased saline water use, if risk associated with pest and disease is minimized. Increase in cost of water is not likely to make any difference in water allocation due to large differences between return from water use and the present cost of irrigation water. Conjunctive use of saline groundwater with canal water on sustained basis will require disposal of some part of saline water through evaporation ponds and regional drains. Volume of groundwater to be disposed is governed by quantity and quality of canal water supply and the quality of groundwater. This minimum quantity of disposable water in the lower Ghaggar Basin is 14 percent of the annual recharge.

Introduction

The survival of mankind depends upon its ability to produce enough food and provide enough water for public health and industrial purposes. As the competition for water grows, the need to use the available resource efficiently without impairing its quality increases. This can be achieved by proper planning and management of water resources. For surface water, the stream flows with high temporal and spatial variability, are to be converted into a set of comparatively regular flows. For groundwater, the pumping rates are to be adjusted to suit the aquifer properties and the sustainable recharge. Optimal development of water resource is generally the outcome of the conjunctive use of water from various sources (Hall, 1986). Conjunctive use of water resources can be defined as the management of multiple water resources in a coordinated operation such that the water yield of the system over a period of time exceeds the sum of water yields of the individual components of the system resulting from uncoordinated operation. Normally conjunctive use is planned and practiced with the objectives of mitigating the effect of shortages in canal water supplies, increasing the dependability of the existing water supplies, alleviating the problem of high water table and salinity, facilitating the use of high salinity groundwater and mitigating the damages due to drought (Abrol et al., 1988).

In the canal irrigated area, introduction of huge quantities of water from outside areas, results in disturbance of existing hydrologic equilibrium of the groundwater basin. Increased groundwater accessions induce positive net recharge, forcing a rise in water table very close to the surface and creating significant waterlogging and salinity. In areas, where groundwater quality is good and aquifer formations favorable, increased recharge adds to the water resources of the area in a dependable manner. This is because such water can be developed and used according to crop requirements. However, in many places, irrigated areas are underlain by aquifers of poor quality and in normal course; there is very little groundwater development in such areas. In the absence of commensurate ground water withdrawal, rise in water table beyond permissible limit is inevitable. Such a situation exists in a major part of the southwestern part of Haryana, Punjab and north and eastern parts of Rajasthan. States of Gujarat, Maharashtra, Karnataka and Tamil Nadu also face similar situations.

Under the given surface water supply conditions, the development and use of water resources in the saline ground water basin involves four distinct processes. The first process, is concerned with planning the development of resources. Mathematical models, that can simulate and predict the system response to the management and hydrologic simulation, are often used for planning the development. Outputs from simulation model do not answer the whole range of questions and a different set of the models called optimization models are required (Lefkoff and Gorelick, 1990). The second process, is concerned with simulating the effect of saline water use on crop production. This is, essentially an agronomic component and has to do with establishing crop-water-salinity production function. The response of crops and stages of growth to water and salinity stress differs. The effect is also amenable to change with water application technologies and cultural practices (Zeng et al., 2001). The third process, deals with hydrologic system in saturated and unsaturated zones. Development and utilization of water resources disturbs the hydrologic equilibrium. The system remains in transient stage till the new equilibrium is reached. The direction of change may be both positive (beneficial to the environment) and negative (harmful to the environment), but extremes in either direction are unfavorable to the environment. In physical terms, the process includes changes in the hydro-salinity regimes of the ground water basin. The fourth and final process is economic in nature and deals with profitability of investments.

A number of conjunctive use planning models have been developed to determine pumping rates for a sustainable potentiometric surface (Tyagi et al., 1995), allocation of water to areas under different crops and optimal hydro-salinity regimes in a basin (Tyagi, 1987). The economic aspects of water allocations have received greater attention and both linear (Khepar and Chaturvedi, 1982; Tyagi et al., 1993) and dynamic programming models (Knapp and Wichelns, 1990) have been used in such studies. Groundwater simulations have also received greater attention, and analytical as well as numerical approaches have found use (Helweg and Labadie, 1976; Lefkoff and Gorelick, 1990), but the models that develop a quantitative understanding of economic, agronomic and hydrologic processes that occur in a saline irrigated system have been rather limited.

This paper deals with formulation and application of ground water hydraulic and economic optimization models for planning the development and use of surface and ground waters in Lower Ghaggar Basin (LGB) of Haryana,India. In this paper the problem of conjunctive water development and use planning has been addressed as a three-stage process. The first stage deals with the determination of optimal ground water pumping. The second stage is concerned with the development of crop-water-salinity production function. The third stage, relates to hydro-economic optimization of water use and is performed to maximize benefits from conjunctive use in a sustained manner. Measures that would facilitate development of groundwater on extensive scale in the poor water quality zones are briefly discussed.

Study Area

The study area extends over 51,300 ha in the Ghaggar River Basin in Sirsa and Hisar districts of Haryana in India (Figure. 1). The area has the possibility of exploiting groundwater through shallow tubewells. Analysis of water samples collected from observation wells of shallow depths from various parts of the study area indicate that maximum value of electrical conductivity (EC) is 16.8 dS/m and the minimum 1.3 dS/m. The sodium adsorption ratio varies from 0.1 to 17.1.

In few locations, the waters are sodic in nature with (RSC) of more than 2.5 me/l. From consideration of salinity (EC), fresh water aquifers occupy 12% area (EC < 2 dS/m), marginal water (EC 2-6 dS/m) 53% and saline water (EC >6 dS/m) 47%. 73% of the groundwater has RSC of less than 0.2 me/l. The sodium adsorption ratio (SAR) varies from 0.2 to 1.7, and 86% of the water have SAR less than 10. There is limited canal water supply (Bhakra Canal System) to supplement the precipitation and groundwater. Due to the absence of adequate groundwater development and continuous utilization of canal water supplies, the groundwater levels and salinity are increasing. At the same time the total water supply is not sufficient to achieve high irrigation intensity.

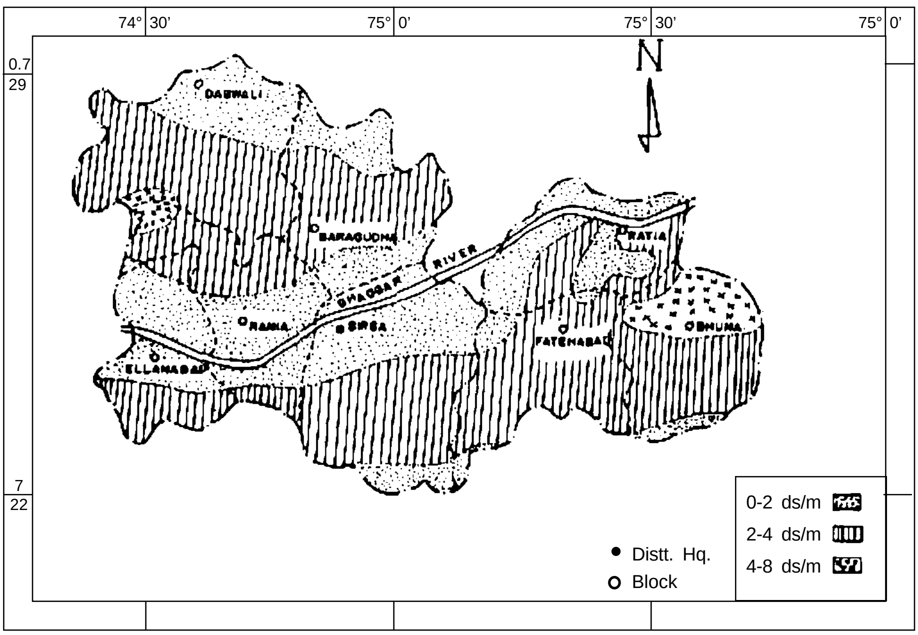

Figure 1. Location and ground water quality in lower Ghaggar basin

There is also a need to dispose off part of the pumped ground water to maintain the salt balance in the groundwater system, thereby preventing groundwater quality deterioration. The irrigated system lies in land locked area with little scope for disposal of saline water outside the system. At present evaporation ponds are the only possibility to dispose extra saline water for maintaining a favourable salt balance in the aquifers. There may be some adverse environmental impacts but considering the socio-economic conditions in the area, the benefits far exceed the possible environmental damage.

Hydraulic Optimization and Water Allocation Models

A schematic diagram of the linkages in the optimization and water allocation models is shown in Figure 2. A steady state optimization model to evolve groundwater development strategies and a water allocation and economic optimization model are formulated to aid in development of management strategies.

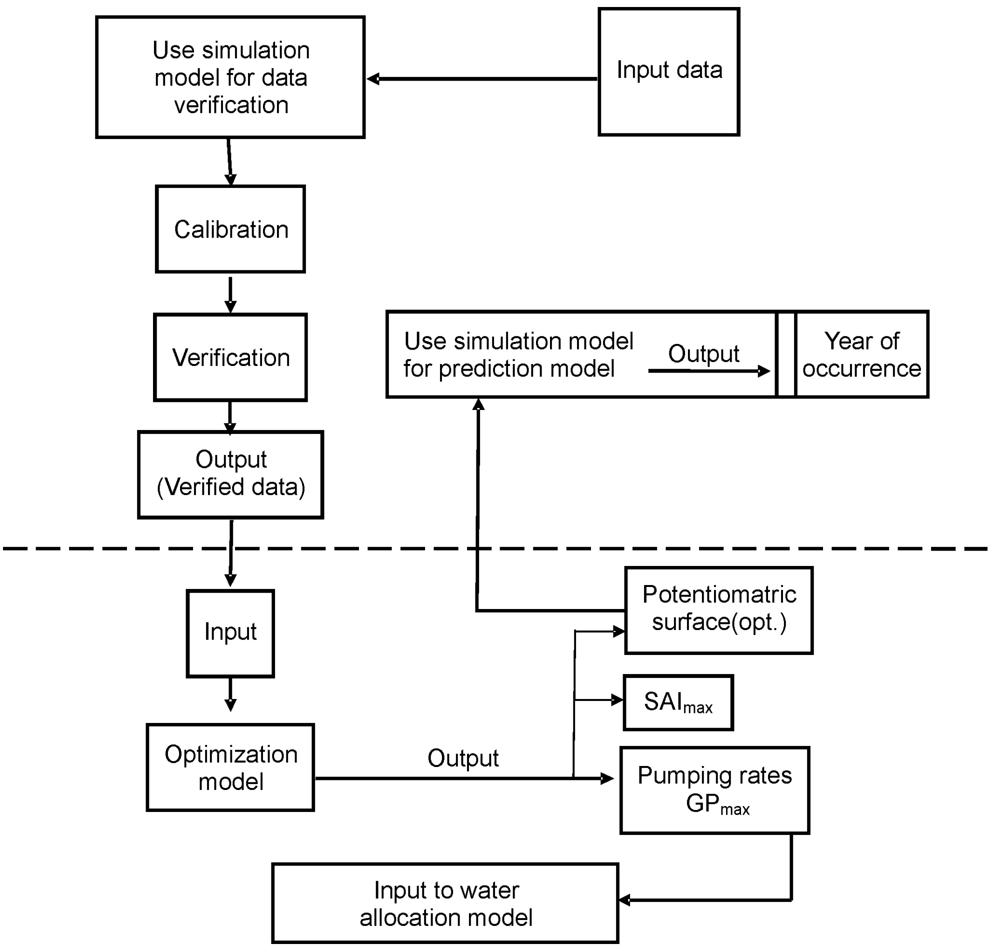

Figure 2. Linkage between simulation and optimization model

Steady-state Flow Optimization Model

The model consists of an objective function and a number of constraints. The objective function gives the maximum sustainable pumping yield for the entire area under well-defined constraints and bounds. The total sustainable pumping is the sum of individual sustainable pumping of each sub area, which has its local bounds and limits.

The size, number and distribution of the nodal areas and the location of the natural and arbitrary boundaries of the study area have been decided on the basis of transmissivity, storativity and groundwater levels. Keeping in view the constraints of quality and availability of basic data, the area was discretized into 30 nodes, of which 15 were internal nodes and the remaining 15 are external nodes (Figure 3). The 15 internal nodes are variable head cells, where the study is being made to evaluate the pumping strategies. The 15 external nodes are primarily required to construct the network near the boundaries.

Ideal boundary conditions described do not exist there. A groundwater simulation study had been conducted in part of the LGB with a view to have preliminary estimation of the water level fluctuations and behavior (HSMITC, 1983). The existing nodal network has been superimposed on the nodal network used in that study and the boundary conditions have been interpolated. The western boundary of the study area, where a condition of low recharge and low pumping exists and water levels do not vary throughout the year, is considered as zero flow boundary. On the other three sides, the boundary is assumed to be flow controlled.

The steady-state excitation rates are those values of pumping and recharge which, when applied to the system, continuously maintain constant potentiometric surface elevations. For a given set of potentiometric surface elevations, there exists a corresponding set of steady-state pumping values*.

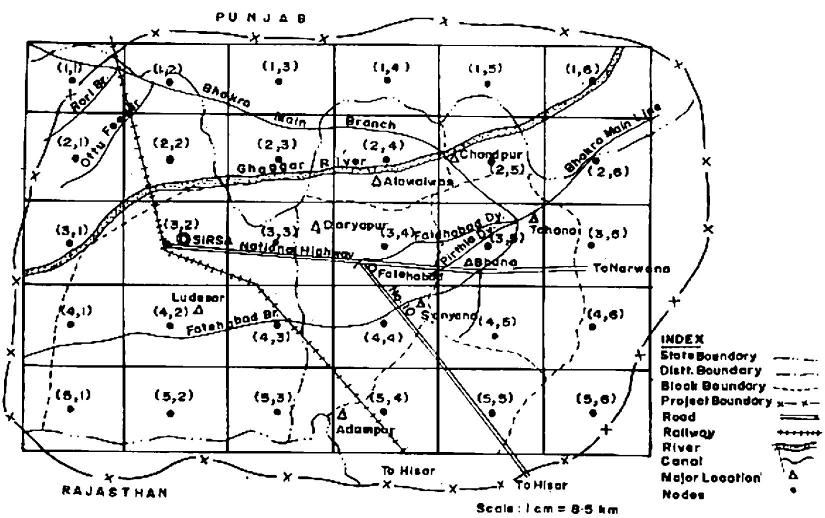

Figure 3. Study area discretized into finite difference cells

*See Tyagi, et al. 1995 for the Mathematical form of model.

The Water Allocation and Economic Optimization Models

The groundwater optimization model described in previous section can be used to determine the optimal levels of groundwater development. Formulation of a canal and groundwater conjunctive use model is attempted to assist in planning strategies for water allocation to crop activities. Disposal of saline ground water to maintain salt and water balance in the crop root zone as well as in aquifer, is an integral part of the model. The problem is treated as non-linear optimization, and a conjunctive use management model is developed.

The model allocates water to a number of crops according to their sensitivity to saline water to maximize net returns. The income is generated from disposal of crop produce while the cost is incurred in purchase of canal and tubewell water. The non-water production inputs are treated as fixed costs. To keep the groundwater salinity at original level, part of the groundwater pumped is disposed through evaporation ponds and has a cost. The detailed mathematical formulation can be found in Srinivasulu et al. (1997).

Crop-Water-Salinity Production Function

Crop-water-salinity production functions are essentially the mathematical relationships between yield of crop and the amount of applied water and its salinity. The model requires empirical relations that can be used to study the effect of water quality, quantity and their interaction. The approach used is based on combining the crop-water-quantity and the crop-water salinity production functions, first proposed by Letey et al. (1985). The crop-water-salinity functions for important crops used in this model were developed by Srinivaslu and Tyagi (2001) and are given in Table 1.

Table 1. Crop-water-salinity production functions

	$RY = a+b(AW/Ep)+c(AW/Ep)^2+d(S_j)+e(S_j)^2+f(AW/Ep)(Sj)$					
Crop	a	b	c	d	e	f
Wheat	-0.1668	1.4465	-0.2947	-0.0071	0.0005	-0.0302
Mustard	-0.2718	1.6733	-0.4662	-0.0065	0.0002	-0.0282
Berseem	-0.1150	1.2603	-0.1027	-0.0189	0.0024	-0.0958
Cotton	-0.2431	2.5401	-1.0751	-0.0087	0.0003	-0.0345
Pearl millet	-0.8671	2.9815	-1.0102	-0.0066	-0.0012	-0.0534
Maize	-0.4692	2.5843	-0.9030	-0.0142	0.0018	-0.0661

Source: Srinivasulu & Tyagi, 2001

Optimal Ground Water Pumping and Water Allocation Scenarios

The groundwater hydraulic optimization and the conjunctive use management models mentioned in the preceding sections were applied to develop optimal plans for groundwater development and its use in conjunction with canals for the LGB. In case of groundwater optimization model the data were first prepared for the groundwater simulation model set for the same area. Tyson and Weber model

(1964) as modified by Goodwill (1989) was used. The data screened in the process of calibration of the simulation model were subsequently used in the optimization model. The procedure employed is explained in Figure 2. Possibilities of augmenting groundwater supplies have been explored through increased stream-aquifer interaction. Issues concerning sustainability of saline water use have also been explored.

Hydraulic Optimization

The model was run for steady state condition using Linear Programming (LP) algorithm written in GAMS. The output from the model include: optimum pumping rates, resulting potentiometric surfaces and stream-aquifer interaction.

Pumping Rates

The pumping rates for different cells are given in Table 2. It is seen that there is wide variation in optimal discharge among different cells. The values range from 0.25 cumecs to 8.48 cumecs. The pumpable quantities of groundwater depend largely on recharge opportunity and the type of aquifer. Areas falling along the course of rivers and perennial canals have higher opportunity for recharge as compared to cells or sub areas located away from the river and perennial canals. For example, the river cells 2,2; 2,3; 2,4; 2,5 and 3,1 have pumping rates 4 to 20 times of non-stream cells 3,2; 3,3 and 4,1.

Table 2. Values of model outputs

Internal nodes	Draw down (m)	Saturated thickness (m)	Optimal head (m)	Optimal pumping (cumecs)
2,1	1.26	106.66	195.54	2.59
2,2	-8.00	108.53	200.61	7.93
2,3	1.33	102.32	202.62	8.48
2,4	0.67	93.55	210.58	8.10
2,5	1.00	118.76	213.97	2.39
3,1	8.00	112.17	176.56	2.42
3,2	-3.16	100.82	184.32	2.02
3,3	4.27	94.11	195.43	0.85
3,4	7.00	99.64	195.27	1.32
3,5	6.00	109.85	200.53	1.65
4,1	-2.80	135.21	185.81	1.90
4,2	-3.29	127.35	201.25	0.25
4,3	3.77	112.89	192.94	1.50
4,4	1.56	107.72	193.91	1.34
4,5	-0.35	118.19	197.78	1.39

The optimal pumping rates were compared with existing (1985) pumping rates. It was observed that in the river as well as in the non-river cells, the existing pumping rates are much lower than optimal pumping rates. As expected, the river cells have higher current pumping rates. The magnitude of the difference between optimal and current pumping rate varies from less than 0.5 cumecs to more than 8 cumecs. This difference in potential and current pumping rates is responsible for rise in water table.

Potentiometric Surface

Potentiometric surfaces have several implications for ground water management. If the surfaces will be high, it will lead to waterlogging resulting in direct evapotranspiration from soil surface and cause salinity. If the potentiometric surfaces are very low, the pumping cost may be high for economic exploitation of groundwater. Further, in areas where groundwater quality problem occurs, the quality deteriorates with depth (in most cases). Therefore, decisions about desired potentiometric surfaces have to be chosen with care. The existing potentiometric surfaces have values between 185 m to 216 m above mean sea level (MSL) and the corresponding depth to water table is within 4 to 17 m (Figure 4). In areas where the average depth to water table is within 4 to 5 m, such as those represented by cell 2,1; 2,3, part of the area suffers from high water table and salinity. The results from groundwater simulation model (Tyagi et al., 1996) indicated that the water table had a rising trend with rates varying 0.22 to 0.60 m/year. It means, though at present the water table is below the critical levels, in the absence of groundwater development, it may become critical at some future date.

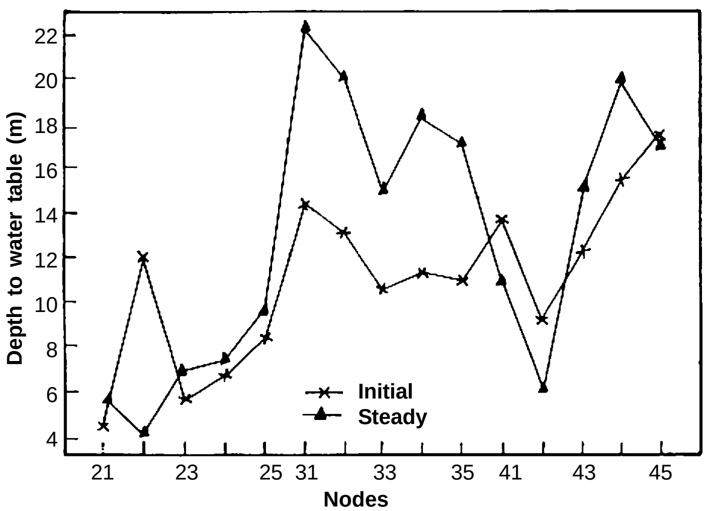

Figure 4. Depth to water table in maximization scheme

The optimal potentiometric surfaces, that have been obtained with the application of model fall in the range of 184 to 214 m above MSL giving a depth of water table 4 to 22 m. It is observed from the depth to water table graph (Figure 4) that under the steady-state situation the water table would fall below the existing level by 2 to 7 m, except in case of cell 2,2; 3,2; 4,1; 4,2 and 4,5 where the water table would come up. The maximum difference in initial and steady-state water table is 8 m in cell-3,1 whereas the minimum difference is 1 m in case of cell-2,4. The cells-2,2; 2,3; 2,4 and 2,5 are river cells with high pumping rates. In spite of higher pumping rates the draw down are low because of continuous recharge from the river and perennial canals. However, in case of cell 3,1, which is also river cell, the draw down is maximum (8 m) though the steady-state pumping rate for the cell is only one-third of the other river cells such as cell- 2,2; 2,3 and 2,4. This cell lies in area where there is an abrupt fall in the riverbed elevation. Since the surface water body in the form of left and right Ghaggar canals are at higher elevation, the water table around this area is higher than river bed and contributes to sub-surface flow into the river. The saturated thickness of the aquifer in the whole region is in the range of 93.50 m to 135.20 m. In the model, a constraint has been put on the maximum draw down (lowering of water table from initial level), which would not allow the water table to fall more than 50 percent of saturated thickness of the aquifer.

Stream-Aquifer Interaction

Stream-aquifer interaction (SAI), which may involve flow from aquifer to stream or vice-versa is an integral part of the model. As has been indicated earlier, the possibility of SAI exists in areas, having large or perennial flowing surface water bodies such as river, canal and ponds. The magnitude of SAI is determined by the hydraulic head difference between water bodies and aquifer, and the conductance of the transmitting medium. On the basis of the available water table elevations and the elevation of surface water body, and the conductance, the current SAI i.e. flow to and from the water body were determined. As the pumping increases the head differential between surface water bodies and groundwater table level also increases, facilitating higher SAI. In case of maximized scheme, the total SAI is 26.08 cumecs as compared to current interaction of 20.81 cumecs (Table 3). In case of minimized pumping scheme, which maintains water table 3 m in the entire area, the SAI reduces to 21.92 cumecs. The increase of about 25% in SAI at maximized pumping rates indicates the feasibility of generating more water resources from river flow, which at present goes waste and creates waterlogging problem at tail end of the Ghaggar depressions in Rajasthan.

Pumping Scheme

Meeting the maximized pumping rate would require a large number of tubewell units. In this area, shallow tubewells and pump sets are frequently used. At present, the number of tubewell units is few and they are sparsely spaced. In order to obtain the optimized potentiometric surfaces, the differences between current pumping units and the optimally required pumping units must be reduced. The average pumping rates of shallow tubewells vary from 4 lps to 8 lps (HSMITC, 1983). The operation time of shallow tubewells in the area is 10 hours a day for about 100 days in a year (HSMITC, 1984). In case of maximized pumping scheme the number of pumping units is around 8 times of units existing in 1985. Recent estimates show that the number of pumping units has more than doubled: from 37,262 in 1985 to 82,682. The pumping units have to be increased in all the cells, though larger increase is required in river or canal cells. It should be understood that for all tubewell discharges (4-8 lps), the number of tubewells per unit area is

Table 3. Maximized interflow, boundary flow and current interflow in each river cell and boundary cell under maximized steady-state scheme

Nodes (Variable head)	Maximum interflow (cumecs)	Nodes (boundary)	Boundary flow (cumecs)	Current interflow* (cumecs) (1985 Data)
2,1	-1.73	1,1	-0.095	-1.73
2,2	-6.97	1,2	-0.095	-4.77
2,3	-6.97	1,3	-0.095	-4.75
2,4	-7.08	1,4	-0.095	-5.26
2,5	-1.38	1,5	-0.015	-1.38
3,1	-0.45	1,6	-	-0.40
3,2	-	2,6	-0.070	-
3,3	-	3,6	-0.080	-
3,4	-	4,6	-0.090	-
3,5	-0.11	5,1	-0.090	-0.12
4,1	-0.45	5,2	-0.140	-0.45
4,2	-0.30	5,3	-0.090	-0.31
4,3	-0.34	5,4	-0.090	-0.34
4,4	-0.15	5,5	-0.070	-0.15
4,5	-0.17	5,6	-	-0.17
Total	26.08		1.145	20.81

* 1985

not the same. One would require more number of tubewells to extract a given volume of water per year with low discharge tubewells. The average density for maximized pumping tubewell scheme works out to be 12.5/100 ha.

Conjunctive Water Use Management Plan

The results from application of water allocation model are discussed in terms of cropping patterns, groundwater disposal policies, total benefits and benefits per unit area/applied water.

Cropping Pattern

Two crop seasons (*kharif* and *rabi*) with three irrigated crops in each season were considered. There could be crop areas under rain fed farming, but these were not part of the present decision process. Of the total irrigated area of 15,391 ha in *kharif*, 80.1% is occupied by cotton and 11.3% by pearl millet. The remaining 8.6% area is allocated to maize. The irrigation intensity during *kharif* season works out to be 36.6%, and the value of irrigation intensity during *rabi* is 47.7%. Thus, the annual irrigation intensity is 84.3%. The area under irrigated farming during *rabi* is higher by 30% as compared to *kharif*. This may be due to higher profitability of the *rabi* season crops. The total benefit resulting from optimal water allocation is Rs. 165.92 million. The benefit per unit of water use is Rs. 108.6/ha-cm during *kharif* and Rs. 120.8/ha-cm during *rabi.*

Water Allocation

Of the total water supply from canal and groundwater, 588,000 ha-cm is used during *kharif* and 959,345 ha-cm during *rabi*. During *kharif*, cotton is allocated 83.1% of the total water and the remaining is shared almost equally between pearl millet and maize. During *rabi*, major share of saline groundwater goes to mustard (50.3%), followed by wheat (41.4%) and berseem (8.2%). In the existing allocation, wheat receives more than 60% of water supply.

Ground Water Disposal

The sustainability of irrigated agriculture depends on keeping groundwater table and its quality within the permissible range. Whereas it is possible to keep water table within acceptable limits by groundwater development and its use within the basin, it is not so with ground water quality. The groundwater quality can be maintained at the existing level only if salt input and output are kept fully balanced. Along with water allocation to crops, the model also computes the ground water to be pumped and the volume of groundwater to be disposed in different quality zones. As per the constraints imposed in the model, 625,345 ha-cm ground water is pumped annually. This is, 15% more than the average annual recharge. Of the total ground water pumped, 86,000 ha-cm is disposed through evaporation ponds. This is about 13.8% of the total ground water pumped.

All the water of 0-4 dS/m range is used for irrigation and the waters of 4-6 dS/m and >6 dS/m range are disposed through evaporation ponds. The fraction of the groundwater disposed through the evaporation ponds increases with increase in ground water salinity. This has got two implications: (i) better water quality is more beneficial for irrigation, and (ii) disposal of higher salinity water through evaporation permits maintaining salt balance in the basin with relatively lower disposal volumes. It should, however be understood that in this analysis the entire ground water basin has been treated as one. If it is disaggregated, then one will have to determine groundwater evacuation and disposal from individual cell.

Table 4. Net benefit per unit water use and water disposal as affected by ground water salinity (SG)

Item	At existing	$2\ SG_o$	$3\ SG_o$	$4\ SG_o$ Salinity (SG_o)
Net benefit (10^6 Rs.)	179.94	166.75	163.86	159.27
Water used (10^3 ha-cm)	1547.35	1575.42	1591.58	1602.05
Net benefit per unit water use (Rs./ha-cm)	116.16	111.76	107.18	102.55
Ground water disposal (10^3 ha-cm)	58856.00	39649.00	28589.00	21441.00

Sustainability of Saline Ground Water Use

It is possible to maintain water table at the prescribed level without groundwater disposal by adjusting groundwater pumping. However, it is not a practice that can be sustained on long-term basis. In the absence of disposal, the salt load in the groundwater reservoir will continue to increase and after sometime the negative effects of rise in groundwater salinity will start appearing in the form of reduced yields and lower net benefits. In order to evaluate the level of groundwater salinity, at which the cost of disposal and benefits from increased availability of ground water without disposal will balance yield and income reductions, the model was run at various groundwater salinity levels. The resulting benefits from water use without disposal were compared with benefits occurring with ground water disposal at various salinity levels (Figure 5).

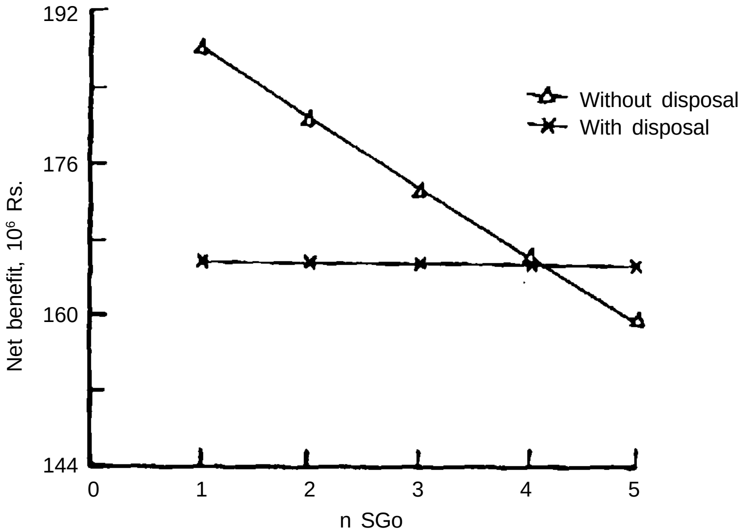

Figure 5. Net benefit with and without disposal at various levels of ground water salinity (SG)

It may be seen that the benefits from optimization scheme without disposal were higher than benefits with disposal upto a salinity level nearly 4.1 times that of original salinity. It has got the following implications from the viewpoint of operation and management of saline ground water in conjunction with canal water:

(1) Investment on disposal in the form of evaporation ponds can be deferred till such a time, that the yield losses from increased groundwater salinity nearly balance the cost of disposal. The duration for which, investment can be deferred will depend upon the original salinity of the ground water, rainfall amount, and its distribution, canal water quality and quantity.
(2) The level of investment in groundwater disposal through evaporation pond should be less than or equal to the annual reduction in net benefits.
(3) Whereas lowering of water table and keeping it below critical levels is a necessary condition for sustainable conjunctive use of fresh and saline waters, it is not a sufficient condition. The sufficiency is provided by salt disposal only.

Concluding Remarks

The application of groundwater simulation and optimization models in this paper is based on data, which was available at a large irregular grids.The availability of hydro- geologic data on micro-scale is desirable not only for better prediction but also for development of saline ground water aquifers, which exhibit large spatial variability. The development and use of ground water in the study area, part of which is saline in nature, in conjunction with canal water is providing opportunity of increasing production and minimizing risk of water logging. There has been more than 230% increase in groundwater development since the study was first undertaken in the late eighties, but the full advantage that would occur from inducing recharge in Ghaggar River bed, has not been taken. The development of higher salinity water continues to be low due to several technological and economic constraints. Efforts would be needed both at farmers' level, as well as, at government level to realize the potential gains of conjunctive water management. Maybe, introduction of brackish aquaculture could promote higher salinity ground water development.

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