Optimizing Groundwater Yield through Enhanced Stream-Aquifer Interaction: A Case Study of Lower Ghaggar Basin in India

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Abstract:

A steady state hydraulic optimization model based on linear programming algorithm, with the objective of maximizing sustainable pumping yield in Lower Ghaggar Basin (LGB) extending over the three Indian states – Punjab, Haryana and Rajasthan, was set up. The model outputs included: optimum pumping rates (OPR), resulting potentiometric surfaces (PS) and the stream aquifer interaction (SAI) etc. The inter-cell variation in OPR was of the of 34 times, the values particularly in river cells being several times higher as compared to the existing pumping rates. OPR induced about 60 % additional flow from stream to the aquifer. The increased groundwater supply, if used in conjunction with canal water, will impact the agricultural productivity positively and interstate tensions arising due to water scarcity may be reduced

Introduction

The Lower Ghaggar Basin (part of Indus system) extends over three Indian states-Punjab, Haryana and Rajasthan, having predominantly an agrarian economy. The overall water supply being deficient, it often leads to interstate tensions. As the competition for limited water supply grows, the need to augment available water supply and use it more efficiently, is increasing. Amongst the various options to achieve the objectives of supply augmentation and improvement in water use productivity, enhanced groundwater recharge from monsoon flows in rivers, development of saline groundwater and its use in conjunction with canal water supplies and on-farm harvested rain-water appear to be quite promising (Tyagi et al,1995, Tyagi,1988). Mathematical models that help simulate the system response to the hydrologic stimuli and the management actions are often used for planning the development of groundwater. These models are essentially simulation models used for determining the feasibility of groundwater operations and aim at managing groundwater stresses such as pumping and recharge and treat the stress and hydraulic heads directly as decision variables (Peralta et al, 1985). This study explores the possibility of augmenting ground water supply by inducing recharge from the river along its length in LGB.

Description of Groundwater Basin

The LGB is a part of the large Indo-Gangetic quaternary basin in the northern part of India (Fig 1). The climate is semi-arid with rainfall varying from 150 to 600 millimeters (mm), but in the upper reaches of the river the rainfall exceeds 1000 mm. The basin has received the benefit of canal irrigation through the famous Bhakra system by way of inters- basin water transfer. Even though the water supplies are inadequate, the canal network is extensive and has caused water logging and salinity in some parts. The upper reaches being hilly, the river flows are quite high during monsoon months from July to September.

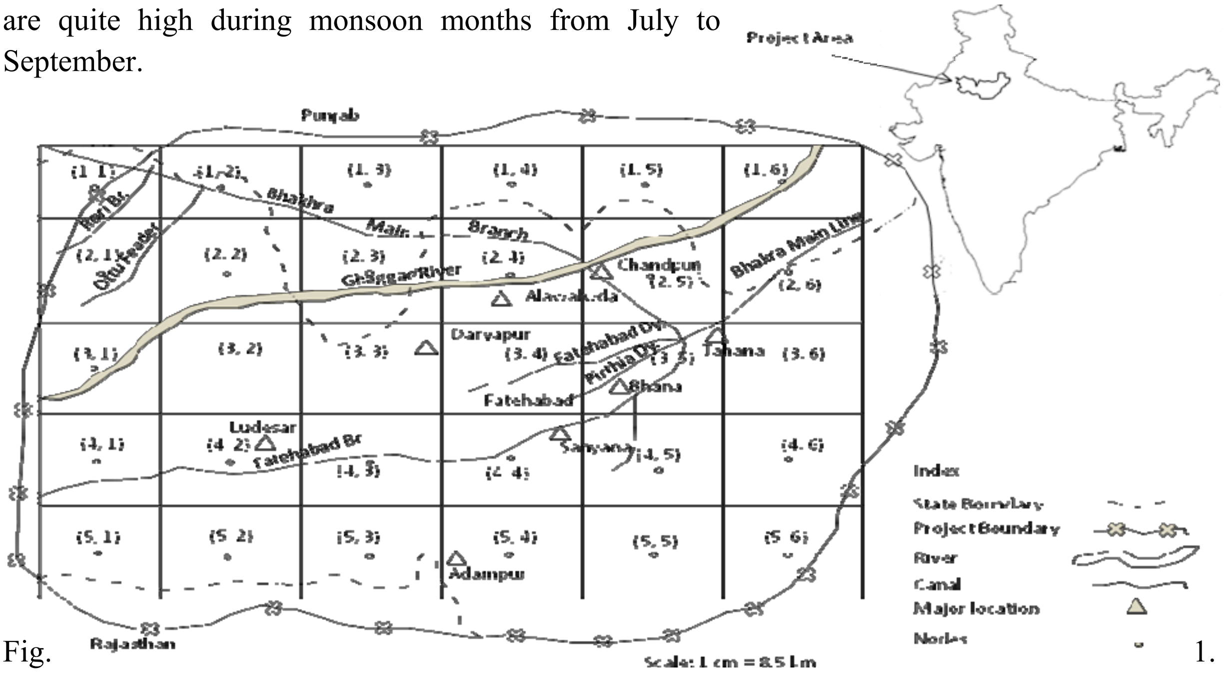

Fig. 1. Location map of the area discretized into finite difference cells

Detailed hydro- geological investigations of exploratory boreholes indicate that the basin has alluvial deposits of varying grades up to depths ranging from 200-300 meters (m) with basement rocks situated at a depth of 200-300 m on the western side and 270-330 m on northeast to southwest sides (HSMITC, 1983). Though there is only one aquifer complex in the area, but it is possible to differentiate locally shallow unconfined and deeper confined layers with thickness ranging from 20-50 m in a depth of 200 m. The hydraulic conductivity of river cells was in the range of 11.5 -19.4 m/day whereas aquifer specific yield varies from 12.5-15.5 %. The transmissibility showed vide variation, the range being 50-1200 m^2 per day. The groundwater quality along the river is fresh, but shallow aquifer layer away from the river have marginal quality waters.

Steady –State Flow Optimization Model

The steady state hydraulic optimization model with the objective of maximizing sustainable pumping yield under well identified constraints was set up (Table 1). The steady state excitation rates are values of pumping and recharge which, when applied to the system continuously, maintain constant potentiometric surface (PS) elevations. For a set of PS elevations, there exists a corresponding set of steady state pumping rates.

Table 1 Brief description of the model

Objective function: Set to maximize the groundwater pumping from variable head cells

Constraints: The following are the important constraints

1. Acceptable draw down- Limits imposed to prevent extreme rise or fall in groundwater table.
2. Hydraulic head- Upper and lower limits were placed to avoid water logging on one end and preventing the aquifer running dry on the other end.
3. Stream-aquifer flows- Limits the stream aquifer interaction and maintain certain base flow in the river.
4. Pumping rates- The minimum limit is current rate and maximum is a certain multiple of the current rate. The upper limit can be raised or decreased to suit lower and upper hydraulic head limits.

The whole area was divided into a nodal network (Fig 2). The size, number and distribution of nodal area and the location of the natural and arbitrary boundaries of the study area were decided on the basis transmissivity, specific yield and groundwater levels. Keeping in view the constraints of quality and availability of data, the area was discredited into 30 nodes, of which 15 were internal and the remaining 15 as external nodes. The internal nodes were variable head cells, used in the study to evaluate the pumping strategies. As the ideal boundary conditions seldom exist, the setting of boundaries was based on preliminary estimation of water table fluctuation arrived at in an earlier groundwater simulation study (HSMITC, 1983). The western boundary of the study area, where the condition of low recharge/low pumping existed with little variation in water table throughout the year, was considered as zero flow boundaries. On the three other sides the boundary behaved more or less as flow controlled. The reach conductance for river cells was estimated on the basis of hydraulic conductivity, the reach length, river width and thickness of river bed. The difference between river stage and river bottom elevations (water depth) was varying in the range of 1.5 3.0 m. Due to space limitations ,only range of values of different parameters has been mentioned as it would help in appreciating the type aquifers studied .

The hydraulic optimization model with linear programming algorithm was translated into GAMS and run with model inputs generated for the study area. The results obtained are presented in the next section.

Results and Discussions

The model outputs include: maximum pumping rates, resulting potentiometric surfaces and the stream aquifer interaction. The total sustainable pumping is the sum of the optimal pumping in different cells.

Pumping rates:

The pumping for different cells (Table 2) shows quite large variation in optimal rates with values ranging from 0.25 m^3s^{-1} to 8.48 m^3s^{-1}. The pumping values, particularly in river cells, are several times higher as compared to the existing pumping rates. The optimal pumping rates depend largely on the type of aquifer formation and the recharge opportunity, with cells along the river having higher opportunity for recharge as compared to cells located away from river/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 –river cells 3,2; 3,3; 3,5; 4,1 and 4,2.

Table: 2. Values of model outputs

Internal nodes	Drawdown (m)	Saturated thickness (m)	Optimal head (m)	Optimal pumping (m^3s^{-1})
2,1	1.26	106.7	195.5	2.59
2,2	-8.00	108.5	200.6	7.93
2,3	1.33	102.3	202.6	8.48
2,4	0.67	93.6	210.6	8.10
2,5	1.00	118.8	214.0	2.39
3,1	8.00	112.2	176.6	2.42
3,2	-3.16	100.8	184.3	2.02
3,3	4.27	94.1	195.4	0.85
3,4	7.00	99.6	195.3	1.32
3,5	6.00	109.9	200.5	1.65
4,1	-2.80	135.2	185.8	1.90
4,2	-3.29	127.4	201.3	0.25
4,3	3.77	112.9	192.9	1.50
4,4	1.56	107.7	193.9	1.34
4,5	-0.35	118.2	197.8	1.39

Potentiometric surfaces (PS):

The optimal PSs obtained fall in the range of 184 to 214 m above mean sea level giving a depth to water table of 4 to 22 m from ground surface (Fig. 2). The maximum difference between the initial and steady state water table is 8 m in cell 3,1 whereas the minimum difference is of 1 m in cell 2,4.The cells 2,2;2,3;2,4 and 2,5 are river cells with continuous recharge. In few locations the difference between existing and desired pumping rates was responsible for rise in water table.

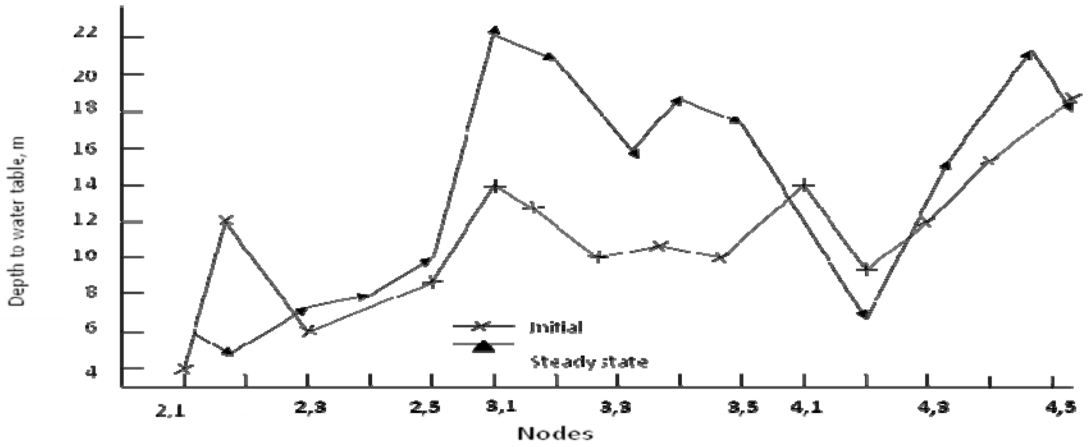

Fig. 2 Depth to water table under maximized pumping scheme

The maximum draw down did not exceed 50 % of the saturated thickness of the aquifer in all cases. The PSs elevations have several implications for groundwater management. Should the PS be high, it would lead to water logging resulting in direct evaporation from soil surface and would cause salinity. A very low PS elevation would increase the cost of pumping. As seen from fig. 2, in optimized pumping scheme, both these conditions have been avoided.

Stream –Aquifer Interaction (SAI)

The SAI may involve flow from aquifer to stream and vice-versa. The magnitude of SAI is determined by the hydraulic head differences between the water bodies and aquifer and the conductance of transmitting medium. The estimated SAI for different cells is shown in Table 2.

Table: 3. Stream –aquifer interaction, boundary flow and current interflow in each river cells and boundary cell under maximized steady–state scheme.

Nodes	SAI interflow (m^3s^{-1})	Boundary flow (m^3s^{-1})	Current interflow (m^3s^{-1})
2,1	1.73	0.095	1.73
2,2	6.97	0.095	4.77
2,3	6.97	0.095	4.75
2,4	7.08	0.095	5.26
2,5	1.38	0.015	1.38
3,1	0.45	-	0.40
3,2	-	0.070	-
3,3	-	0.080	-
3,4	-	0.090	-
3,5	0.11	0.090	0.12
4,1	0.45	0.140	0.45
4,2	0.30	0.090	0.31
4,3	0.34	0.090	0.34
4,4	0.15	0.090	0.15
4,5	0.17	-	0.17

It is seen that the total SAI is of the order of 26.10 m^3s^{-1} as compared to the existing SAI of 16.2 m^3s^{-1}. The model generated total maximized pumping is 44.1 m^3s^{-1}. The optimized pumping induced about 60 % additional flow from stream to the aquifer. The increase in SAI with maximized pumping rates indicates the feasibility of generating more water resource from river flow which goes waste and creates water logging at the tail end of the river in Rajasthan. To achieve the goal of enhanced SAI, establishing optimized PSs is a pre-requisite which could be accomplished by increasing the number of tube well units. These additional tube wells would be needed in all the cells, but more of them in river cells. Based on the aquifer properties and the size of the strata, the number of tube well units can be estimated.

Conclusions

It is inferred from this study that there is need as well scope for augmenting the water supply through induced groundwater recharge from river flow, particularly during monsoon period when the river flows are high. In river cells the induced stream-aquifer interaction will substantially increase groundwater availability in the basin. To accomplish this objective, groundwater withdrawal in the area would have to be increased to establish desired hydraulic head differences between river flow stage and the groundwater table. It would be desirable to increase pumping in river as well as in non river cells by increasing the number of pumping units. In non river cells which have marginal quality groundwater in some areas, higher pumping will eliminate the possibility of water-logging and salinity by lowering groundwater table. The increased groundwater supply in the both situations (river as well as non river cells), when used in conjunction with canal water, will have a positive impact on agricultural productivity and will reduce interstate tensions arising due to water scarcity.

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