Optimal Groundwater Pumping from Palla Well Fields to Augment Drinking Water Supply to Delhi

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Abstract: A real-life problem involving pumping of groundwater from a series of ninety existing wells along river Yamuna floodplain, northwest of Delhi (India) underlain with geologically occurring saline water is examined within a conceptual management model. Unplanned pumping often leads to upconing of saline water. Therefore it is required to determine optimal rates and their locations from an existing group of pre-selected candidate wells that minimize total salinity concentration in space and time. The nonlinear, non-convex problem is solved by embedding the calibrated groundwater model within a simulation-optimisation (S/O) framework. Optimisation is accomplished by using simulated annealing (SA)—a search algorithm. The computational burden is primarily managed by replacing the numerical model with a surrogate simulator—artificial neural network (ANN). The model is applied to the real system to determine optimal pumping schedule. The results of the operational model suggests that the skimming wells must be operated from optimal locations such that they are staggered in space and time to obtain least saline water.

INTRODUCTION

The practice of pumping fresh groundwater from flood plains along riverbanks is widely known. Under typical climate conditions in India the rainfall-runoff are mostly confined to a few months during the monsoon season. The floods during this period recharge the adjacent riverbanks in addition to the direct rainfall recharge in the alluvial flood plains in the vicinity of the river. Pumping from production wells along the banks from this naturally replenishing groundwater reservoir helps in meeting the ever increasing demand during both monsoon and non-monsoon season on a sustainable basis.

The problem of pumping groundwater from a stream-aquifer system becomes complex, when it is underlain with geologically occurring saline water. The amount of pumping in this case is mostly guided from water quality considerations rather than water quantity. This is because any excess pumping results in upconing of saline water leading to deterioration of water quality especially for drinking water needs. Therefore optimal pumping must ensure both quality and quantity. This is accomplished through regulated pumping in space and time from skimming wells (Saeed et al., 2003). Skimming wells seek to pump seasonally recharged freshwater (floodwaters) floating on more dense underlying saline water. Skimming wells also find wide application in coastal regions prone to seawater intrusion.

The present study was motivated from a field problem involving pumping from a series of existing 90 high capacity production wells installed along the bank of river Yamuna (see Fig. 1) to meet

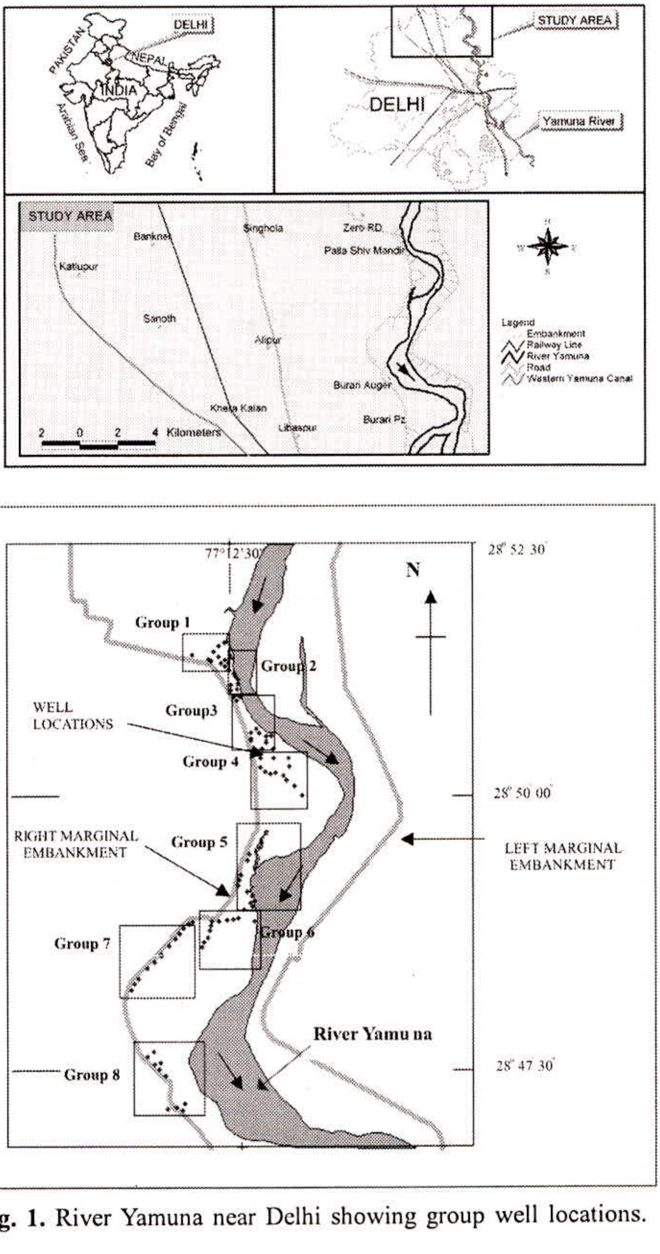

Fig. 1. River Yamuna near Delhi showing group well locations.

drinking water needs of Delhi (India). The river reach is recharged by floodwaters besides rainfall recharge during the monsoon season. The freshwater in the aquifer system is underlain with deposits of geologically occurring saline water. In the river Yamuna flood plain, north west of Delhi, a stream aquifer system with 90 wells is modelled within a conceptual framework. The conceptual aspects of this study are discussed in Rao et al. (2006). The nonlinear, non-convex problem involving discrete (pumping locations) and continuous (pumping rates) is solved within a simulation-optimization (S/O) framework. Gradient-based methods are not suitable for discrete variables and therefore simulated annealing (SA), a stochastic search technique, is used. Since all S/O problems involve high computational burden (Rao et al., 2004a), artificial neural network (ANN) is used as a surrogate simulator of a variable density driven flow and transport model.

MODEL FORMULATION AND BUILT-IN ASSUMPTIONS

The study primarily aims to develop an operational model for field implementation using a combined simulation–optimisation (S/O) approach which seeks to maximize pumpages from a series of existing production wells, while controlling the process of upconing from underlying saline water to desired levels. The model is formulated considering this objective function with respect to the study area (Fig. 1) as discussed in later sections. Since the production wells already exist, their location cannot become decision variable. However, when only part (subset) of the wells operate, location could become discrete decision variable in terms of on or off (i.e. zero or one) from a set of candidate wells. Further since all the wells have pumps with installed or fixed capacity the rate of pumping cannot be a decision variable. However since the duration of pumping in a day can be varied (say 12 to 20 hours per day), the rate of pumping could be considered as a continuous decision variable within a range. The optimal rate of pumping so determined by the model could be converted into equivalent fixed capacity installed pump via the duration of pumping per day. This involves an implied assumption that the aquifer simulation in terms of heads and concentrations for the two cases are the same. This assumption is considered to be a reasonable approximation of the reality.

The model seeks to determine maximum pumping in space and time over a range of pumping subject to a set of constraints assuming all wells are operated. Here pumping rates are continuous decision variables. The determined optimal rates are converted to installed fixed rates of pumps via duration of pumping as discussed in the previous paragraph. The model seeks to determine the maximum potential that can be developed for drinking water purposes over a planning horizon of one year. Mathematically the model may be formulated in general within S/O framework as follows.

$$\text{Max. J1} = \sum_{n=1}^{N}\sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{i=1}^{I} Q^{\mathrm{n}}_{\mathrm{s(i,j,k)}}$$

where $Q^{\mathrm{n}}_{\mathrm{s}}$ is the pumpage (decision variable) from production wells located at the node i, j, k (also a decision variable) at the end of the n^{th} time period.

The model is subject to the following constraints:

(a) Concentration ($c^{\mathrm{n}}_{\mathrm{i,j,k}}$) in production wells should be less than specified value c_s.

$c^{\mathrm{n}}_{\mathrm{i,j,k}} < c_{\mathrm{s}}$ ∀ All production wells at the end of the n^{th} time period

(b) Head ($h^{n}_{i,j,k}$) at nodes should not fall below a specified value h_s

$h^{n}_{i,j,k} < h_s$ ∀ All production wells at the end of the n^{th} time period

(c) Nonlinear flow and transport equations should be satisfied.

$f(h,c,q)^{n}_{i,j,k} = 0$ ∀ All i, j, k and n; h and q represent heads and source/sink terms

(d) Lower and upper bounds for pumpages.

$Q_{\min} < Q^{n}_{s(i,j,k)} < Q_{\max}$

In the above equations, i, j, k and n represent the number of rows, columns, layers and time periods relevant to the study area of interest (AOI). The decision variables are restricted to discrete values (within range) in respect of location and continuous values in respect of pumpages. The first constraint relates to groundwater quality, which ensures that salinity is within desired limits. The second constraint relates to quantity of water that is available on a sustainable basis by restraining the head or the drawdown. The third constraint relates to the physics of flow and is simply mass conservation and is accounted through the simulator. $Q_{\min}$ and $Q_{\max}$ correspond to lower and upper bounds for the pumpages.

Solution Methodology: Simulation Optimisation (S/O) Framework

The conceptual management models developed in this study use a modified S/O framework (Rao et al., 2004a, 2004b). The S/O framework in the present study has three important features. First, it interfaces the aquifer simulator (SEAWAT 2000 model) to account for the complex behaviour of groundwater flow in space and time. Second, the optimisation problem is nonlinear, non-convex and involves both continuous and discrete decision variables. Gradient-based optimisation methods do not work well in such situations. Therefore, simulated annealing (SA), a non-gradient based search algorithm is used. In this framework; handling nonlinearities in objective function and constraints is not a difficulty as they are external to the optimiser. The third relates to high computational burden that is inherent to all S/O based approaches. This is largely overcome by replacing the simulator with trained artificial neural network (ANN).

The general structure of S/O framework is shown in Fig. 2. It consists of a driver optimiser and an external simulator. The algorithm calls the simulator to verify the constraints and evaluates the objective function during each iteration. This procedure is repeated until either a near optimal solution or a preset termination criterion is met.

MODEL APPLICATION

The study area was briefly discussed earlier as shown in Fig. 1 indicating the area of interest (AOI). The river Yamuna receives much of its flows during the monsoon season (July to September). The study area is often flooded during this season. The palla flood plains within the embankments get significant recharge during this period. A battery of 90 tube wells were constructed in various stages since the year 2001 along the periphery of left embankment to augment drinking water supply from this induced recharge. The wells also draw groundwater from rainfall recharge from adjacent areas along the reach besides the river boundary. At present the wells are pumping 20–25 MGD (US Gallon)

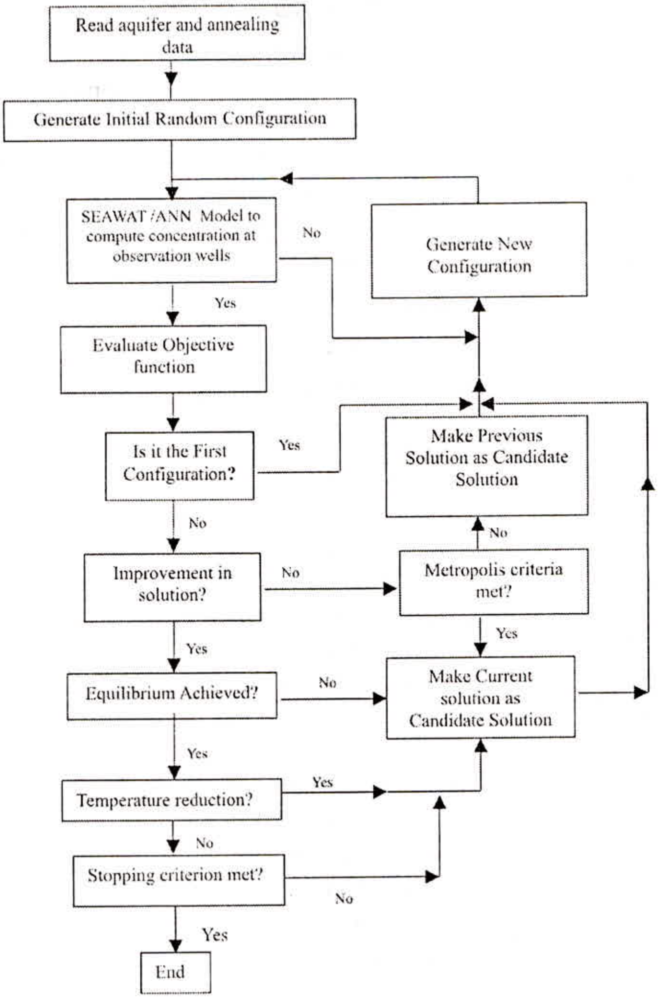

Fig. 2. General structure of S/O framework using simulated annealing.

of groundwater by operating these wells for 12–18 hours a day. This pumping schedule is arbitrary and not planned. The land use in and around the study area is mainly agriculture, involving cultivation of seasonal crops.

In general the study area is underlain with geologically occurring saline water everywhere at varying depths. The saline-freshwater interface is observed at a depth of 60–70 in the northern part of the study area. In the southern part it is rather shallow and is noticeable at 30–40 metres. The salinity is expected to increase with depth. The maximum salinity below the interface has been assumed to be at 2000 mg/l (constant) for the bottom-most layer. The depth of water table varies on an average 3–4 m below ground level. The water level fluctuation between pre- and post-monsoon on an average varies from 1.0 to 2.0 m. The groundwater quality from the production wells is good and is suitable for drinking purposes. The average EC (electrical conductivity) and pH values of the groundwater from production wells tapping aquifer up to a depth of 40-45 m has been measured as 300 μS/cm and 7.5 respectively (salinity concentration nearly zero).

In summary there is very little variation in sub-surface configuration of aquifer material along the stretch of Palla flood plain. In general finer material (clay) increases with depth in varied proportion of *kankars* or gravel. Therefore the hydraulic conductivity in the study area is expected to vary between 5–20 m/day, with higher values in the top layers. In the Z direction the values are expected to be one tenth of the above-mentioned values. The specific yield and specific storage values are expected around 0.2 and 0.0001 respectively. The above values in the present study including dispersivity, however, were arrived within practical range by trial and error and/or through a parameter estimation procedure.

Development and Calibration of Regional Aquifer Model (RAM)

The focus of present study is to develop an optimal pumping schedule in space and time for the group of 90 wells in the flood plain of river Yamuna (Fig. 1) near Palla Village bordering Haryana. The aquifer system pertaining to the AOI marked ABCD (Fig. 3) has to be modelled. To model the AOI, suitable boundary conditions are defined along the four sides and the bottom. In the absence of a hydrologic boundary, it is difficult to determine the western boundary condition along edge AB or to assess the amount of flux from this direction; therefore the areal extent of study area in this direction is extended until a well-defined hydrologic boundary condition is encountered. In the present case the western Yamuna canal along a ridge happens to be the boundary condition on the western side.

With the western Yamuna canal as boundary condition on one side and the river Yamuna on the other side, the study encompasses an area of about 240 km^2 (Fig. 3). Modelling this area helped in defining the boundary condition along AB. This approach is sometimes referred as *regional to local.* Generally a coarser grid is used for modelling at regional level and a finer grid at local level i.e. the AOI. In the present study regional model is first calibrated and then the AOI is removed using telescopic mesh refinement (TMR) approach, which is commonly in-built in most pre-processors (e.g. Rumbaugh et al., 2004). The TMR model with appropriate boundary conditions represents the actual AOI. The calibration is intended to simulate initial conditions in RAM in terms of groundwater heads and concentrations beginning monsoon season (or water year) when the system is assumed to be in steady-state or quasi-steady-state condition. The study area map was digitized for river boundary, floodplain embankments, well locations and western Yamuna canal alignment. A finite difference grid (250 x 250 m) with 53 rows, 99 columns and seven layers was constructed to represent the aquifer system. The ground elevations in the upper-most layer were made to conform to the topography in the region (Fig. 3). The upper-most layer shows variable thickness in space due to varying topography. As hard rock or impervious bed is not encountered for several hundreds of metres in depth and since the production wells tap up to a depth of 45 metres, a no-flow boundary was set at a depth of 80-100 metres. The remaining layers were assigned constant thickness as indicated in Fig. 4. Keeping in view the general groundwater flow direction on regional scale and based on the topography, which in general is falling from western Yamuna Canal (on the ridge line) towards the river Yamuna, the northern and southern edges are considered as no-flow boundaries. The groundwater table also follows this topography indicating general flow direction towards river Yamuna. The western Yamuna canal and the river Yamuna are considered as constant or specified head boundaries on the basis of available data. The bottom-most layer (7th layer) is assumed to be saline with a constant TDS of 2000 mg/l.

In the 6th and 5th layers the southern-most 10 and 5 rows were assigned the same constant TDS (2000 mg/l) respectively to represent rising saline-freshwater interface towards southern part of study area, as indicated by borehole logging data in terms of salinity. All remaining cells were set at an initial concentration of zero. The grid cells in all the layers, left of western Yamuna canal and right of river Yamuna were made inactive. Thus the model contains some 26,000 active cells.

The aquifer parameters adopted in the present study are listed in Table 1. These were based on available data of lithologs and limited pumping test data analysis. Recharge was assumed to vary in the range of 10–15 percent of annual rainfall. Additional recharge within the flood plain embankments from intermittent flood pondage during the monsoon season was estimated to vary from 0.3 m to 0.5 m. Initial parameter calibration in terms of observed and simulated heads was accomplished using a constant density model – MODFLOW (Harbaugh et al., 2000) and PEST (Daugherty et al., 1991) in arriving at reasonable value of equivalent hydraulic conductivity (K) in the X-Y directions for steady-state conditions. The K value was subsequently improved by trial and error with the variable density simulator SEAWAT-2000.

In the present study approximate calibration of the RAM is intended to arrive at initial conditions in terms of heads and concentrations in general and AOI in particular at the beginning of the water year (i.e. July) before onset of monsoon season wherein it is assumed that the aquifer system is in quasi-steady state conditions. To arrive at this initial condition the SEAWAT-2000 model was implemented with initial arbitrary heads/concentrations and the model was run for a long period such as 5000 days under average draft/recharge stresses. This approach is sometimes called as false-transient approach. At quasi-steady-state the simulated heads were in reasonable agreement with observed heads. This could be considered to be the beginning of a typical water year 2004. The observed and simulated heads are shown in Fig. 4.

Table 1. Regional aquifer model parameters used by SEAWAT—2000

Sl. No.	*Particulars*	*Values*
1.	Hydraulic conductivity in X, Y and Z directions (in the uppermost layer taken as 20 m/day)	9.8, 9.8 and 1.0 m/day
2.	Specific yield, Specific storage	0.2, 0.0001 (/m)
3.	Longitudinal and transverse dispersivity (α_l , α_t)	60 and 10 m
4.	Uniform rainfall recharge	0.10 m/monsoon season
5.	Grid in X and Y directions (Δx, Δy)	250 m
6.	Grid in Z direction (Δz)	10 – 25 (variable)
7.	Concentration of freshwater	0.0
8.	Max. Conc. of saline water (bottom-most layer)	2 kg/m^3
9.	Maximum density of saline water	1001.43 kg/m^3
10.	Density of freshwater	1000 kg/m^3
11.	Courant number, Coupling parameter DNSCRIT	$\leq$1, 0.01 kg/m^3
12.	Density—Concentration slope	0.71

Modelling Area of Interest—TMR model

The actual area of interest (AOI) as discussed earlier is the region close to the production wells defined by boundaries ABCD in Fig. 4. The TMR feature built in the pre-processor (Rumbaugh et al.,

2004) was used to isolate the AOI from the RAM. A finer grid with 125 x 125 m is used for the TMR model. The western boundary (i.e. edge AB of AOI in Fig. 4) within the TMR model is now represented as an equivalent constant head boundary. The TMR model with more that 36,000 active cells were separately run and were found to behave approximately similar to original model (RAM) in terms of aquifer responses i.e. heads and concentrations in all layers. The TMR aquifer model for the AOI is used for further transient analysis. Since the TMR model involves high computational burden it needs to be further replaced with ANN model as discussed in the next section.

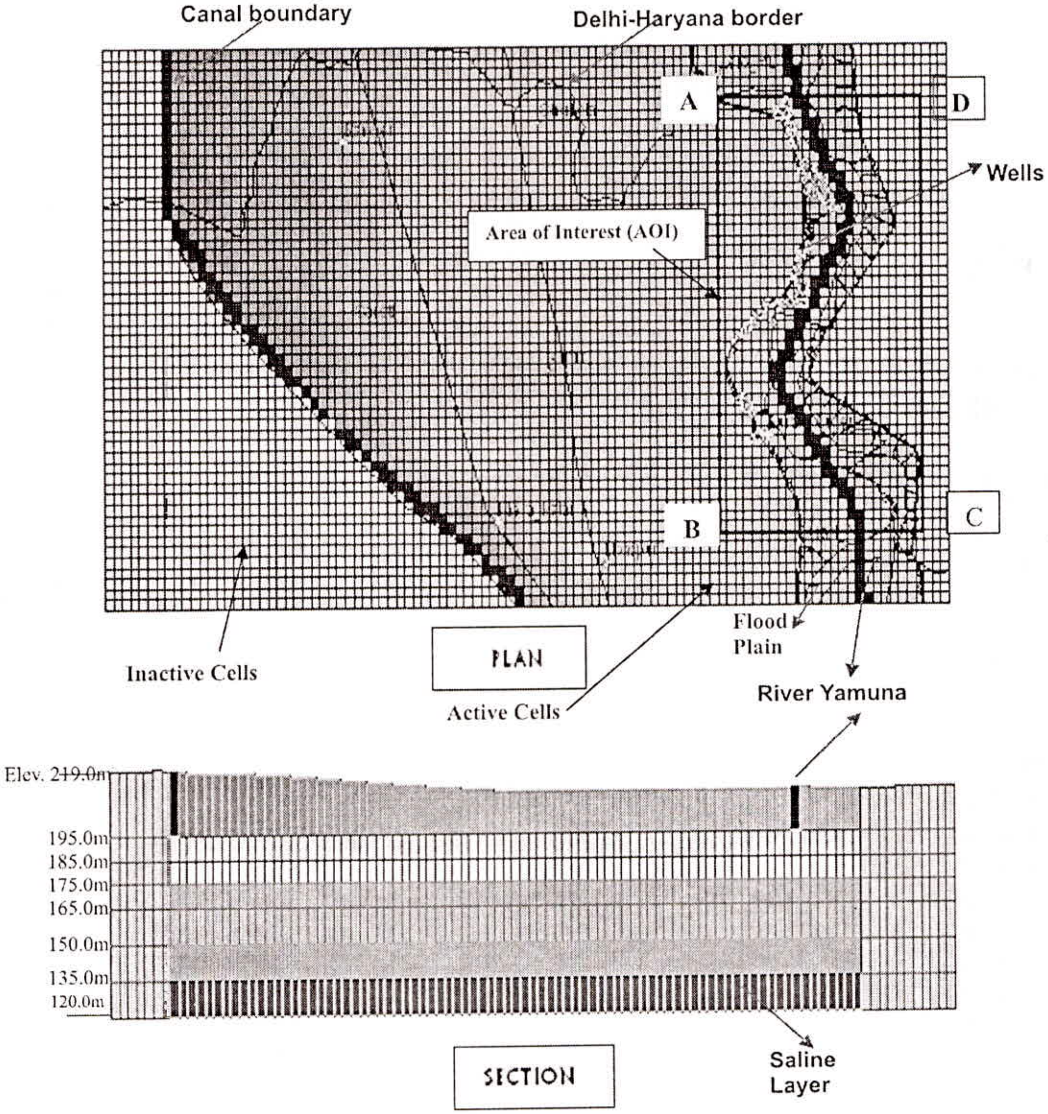

Fig. 3. Plan and cross-section of 7-layer Palla regional aquifer model (RAM) and area of interest (AOI).

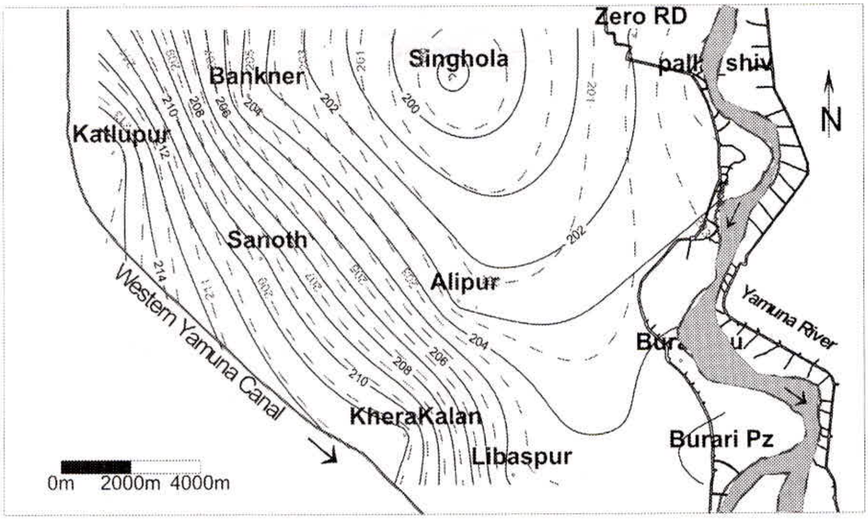

Fig. 4. Observed (continuous line) and simulated (dashed line) contours of groundwater levels—representing quasi-steady-state conditions beginning of water year 2004.

APPLICATION OF MODEL TO PALLA WELL FIELDS FOR MAXIMUM GROUNDWATER DEVELOPMENT

Data Generation, ANN Training and Optimal Solution

Model-1 seeks to maximize pumpages from production wells in space and time subject to a set of constraints. In the Palla well field there are 90 production wells (see Fig. 1). Assuming 10 percent of the wells need maintenance and repair at any time, it is proposed to operate only 80 wells at any given time. The number of decision variables need to be restricted; otherwise the computational burden will become unmanageable even with ANN as the surrogate simulator on a desktop PC. Therefore the 80 wells were grouped into eight subgroups with each group containing 10 wells (see Fig. 1). This implies eight decision variables during each time step or season. In all there are 16 decision variables corresponding to monsoon and non-monsoon seasons.

The range of pumping for each group was restricted between 200 and 2000 m^3/d with respect to the installed pumping capacities of the real system. Within each group same rate of pumping is assumed. Thus random pumpages were generated within the above range and were assigned to the eight groups during each of the two stress periods corresponding to monsoon and non-monsoon season. Uniform rainfall recharge (10 percent of rainfall) and additional flood recharge within the embankment (0.5 m) was assumed for monsoon season. No recharge was assumed during the non-monsoon season. The SEAWAT–2000 was repeatedly executed with TMR aquifer model discussed earlier for generating data sets for ANN training. No constraints were imposed for generating data sets for ANN training. Each transient run was found to take nearly 20 minutes (Pentium IV PC, 2.4 GHz processor) involving two stress periods of 180 days each corresponding to the two seasons. During each stress period the eight pumpages and their corresponding concentrations were recorded in an output file at typical well screen grid locations representative of the subgroup of ten wells. This meant during each run 16 pumpages and their corresponding concentrations. Heads are not recorded as it is presumed that water quality and not quantity is a limiting constraint. Some 250 data sets were generated and appended in stages involving nearly 83 hours of total computer execution time. A 3-layer feed forward network was trained using MATLAB (2000) as discussed previously to obtain optimal weights and biases for each group of wells and at the end of monsoon and nonmonsoon seasons.

The S/O model (Fig. 2) was implemented with ANN as surrogate simulator. The annealing parameters for SA were arrived through trial and error (Dougherty et al., 1991; Cunha, 1999; Rao et al., 2004b). The initial temperature (set at 0.5) was arrived such that more than 80% of the feasible configurations are accepted in the beginning. The chain length (equilibrium criterion) was set in the range of 80–90 times the number of decision variables) and the cooling factor (rate of reducing the temperature) was varied in the range of 0.3 to 0.5. The SA procedure was terminated when four successive temperature reductions did not yield improvement in solution. The SA procedure with ANN as the surrogate simulator takes few minutes for computation.

The model-1 seeks to determine maximum pumpage subject to water quality constraint to meet drinking water requirements. The total dissolved solids of water should not exceed 1 kg/m^3 (1000 mg/l) as per drinking water standards in India. The optimal solution wherein the average salinity of the eight groups (in grid cells at well screen locations in fourth layer) during each stress period is restricted to 720 mg/l corresponding to pumping of 24 MGD is presented in Table 2. The evolution of optimal solution using SA procedure is shown in Fig. 5. Clearly if the salinity level is relaxed a higher objective function can be realized. This leads to a tradeoff curve as shown in Fig. 6. The tradeoff curve prioritizes the amount of groundwater pumpage with respect to acceptable levels of salinity.

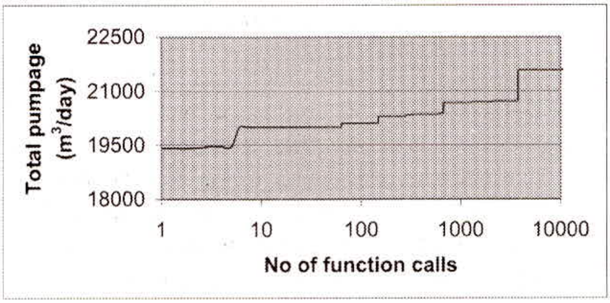

Fig. 5. Evolution of model solution.

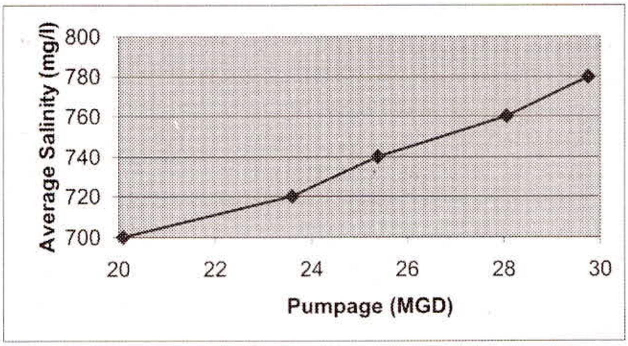

Fig. 6. Tradeoff curve between total pumpage and salinity.

Mass Balance and Effect of Induced Flood Recharge

The optimal solution (Table 2) when implemented using the actual simulator SEAWAT – 2000 gives the picture of total flux mass balance (kgs) on an annual basis (360 days) as under. The mass balance (Table 3) with and without optimal pumpages from Palla well field helps in understanding the aquifer flow dynamics. While the amount of recharge on a seasonal basis is the same for the two cases above, the aquifer storage, river leakage, flux from western boundary and the draft (pumpage) are different. The flux from western boundary is not significant (relative to total inflow/outflow). This indicates that a no-flow boundary could as well be used as an approximation in place of a constant head boundary condition arrived using TMR model along the western side of study area (AOI).

From the mass balance table (Table 3), the Palla wells pump about 57 billion kg of groundwater to meet demand from agricultural (18 billion kg) and drinking water (39 billion kg corresponding to 24 MGD) on an annual basis. This pumping comes from rainfall and induced flood recharge (40%), river boundary (38%) and aquifer storage (22%).

Table 2. Optimal pumping schedule from a group of 80 wells with average salinity of all groups constrained at 720 mg/l to pump 24 MGD

	Group 1	*Group 2*	*Group 3*	*Group 4*	*Group 5*	*Group 6*	*Group 7*	*Group 8*
Installed capacities of production wells (m^3/day) running at full capacity for duration indicated below	2993	1922	2267	2611	1196	2700	1250	2000
	2938	3000	2500	2500	1310	1950	2779	2146
	2500	2410	2500	2500	2339	2104	1639	2267
	2500	3250	2500	2500	1950	2400	1739	2074
	2543	2550	2500	2500	2600	1922	3243	850
	2267	900	2500	2500	2260	1922	2939	1660
	2267	3150	2907	1971	2500	1922	1310	1979
	2543	2679	3000	2104	2100	2188	1488	2074
	2267	2543	2500	2500	2407	2675	1628	1979
	2814	2407	2500	2819	2100	2747	2000	1475
Optimal pumpage per day (m^3/day)								
Monsoon	18738	19661	8212	18763	6439	8382	17226	14739
Non-monsoon	17593	18637	6038	14151	9448	7831	12465	17484
Duration of pumping per day (hours)								
Monsoon	17.5	19.0	7.7	18.4	7.4	8.9	20.7	19.1
Non-monsoon	16.5	18.0	5.6	13.9	10.9	8.3	14.9	22.7

The aquifer storage is depleted due to Palla well fields pumping. It is important to note the values of flow into and out of aquifer storage for the two cases. For the first case with Palla well pumping a net storage space of approximately 13 billion kg (i.e. approximately 17–4) is created due to a modest draft of 2 to 3 metres at the end of a year. On the other hand without Palla well pumping a negative or excess storage of about one billion kg (i.e. approximately 7–8) joins the river (constant head) boundary. Therefore Palla well pumping helps in utilizing groundwater recharge, which would otherwise join the river boundary.

It is important to note that recharge in the present study was estimated on the assumption that 10% of the annual rainfall (700 mm) reaches the groundwater table. Further an additional flood recharge of 500 mm during the monsoon season is estimated to occur in the flood plain. These values were verified through approximate calibration of the regional model (RAM) in terms of observed groundwater levels (Fig. 4). However this value needs to be experimentally determined for reliable estimation by installing a network of peizometers in the floodplain. This will help assess flood recharge for each flood event during the monsoon season to arrive at a dependable recharge on a seasonal basis. This assessment could be highly variable for a flood year when compared to a drought year. The maximum flood level approximately reaches 210.0 metres (high flood level) at least 2 or 3 times near the well fields at Palla on an average during the monsoon season. The alluvial sandy soils in the top layer with high hydraulic conductivity and storage properties can easily recharge the draft space of 2 to 3 metres discussed in the previous paragraph during a normal flood during the monsoon season. The river leakage or conductance depends mainly on hydraulic conductivity (of bed material and its thickness) and the head difference between river stage and the groundwater level in the well field. A significant amount of water comes directly in the well field due to proximity of the river boundary. It is important to note that river is a constant head source of water supply in the model and is a reasonable approximation of reality given the fact that the river Yamuna is perennial.

Table 3. Overall mass balance (kgs.) on an annual basis

Sl. No		*With Palla well pumping*	*Without Palla pumping*
Mass Inflow			
1.	Storage	17210954422.7	7394235191.2
2.	Constant head (flux on western side)	349135740.7	95267435.1
3.	Wells	0.0	0.0
4.	River leakage	25870685059.5	4341989678.0
5.	Recharge	22185506250.0	22185506250.0
6.	Correction for Vol.	6311470.4	
7.	Total inflow		
Mass Outflow			
1.	Storage	4110891021.9	8245771662.6
2.	Constant head (flux on western side)	1094317742.4	1957334680.1
3.	Wells	57455247430.0	18582724402.5
4.	River leakage	2898353462.0	5177833471.3
5.	Recharge	0.0	0.0
6.	Correction for Vol.	63790004.2	56763850.4
7.	Total Outflow	65622599660.8	34020428067.2
	Inflow—Outflow	-6717.3	-6613.3
	Per cent error (not significant at first decimal)	0.0	0.0

CONCLUSIONS AND SCOPE FOR FURTHER WORK

Following conclusions may be drawn from this study:

1. The guiding philosophy of skimming wells prone to upconing in general must be based on optimal spacing and operating the wells by staggering both in space and time. The proposed optimum pumping schedule (Table 2) could be useful for field implementation based on existing locations and installed pump capacities at Palla well field.

2. The existing well locations, their adjacent spacing (of 90 wells) i.e. the group of wells (especially northern side) are closely spaced. Close spacing of wells results in well interference i.e. upconing phenomena below the pumping screen locations. This interference enhances the advective velocities of solute (salt water) towards the grid cells, containing the well screens, leading to increased concentration or salinity. Therefore care must be taken while deciding the location of future wells in the study area or similar study areas.
3. The flood recharge during the monsoon season in the upper alluvial sandy layer is expected to be abundant. The aquifer properties (specific yield and hydraulic conductivity) are conducive for causing significant recharge during floods even if they are of short duration. Nearly 25–30 MGD of water can be drawn safely during both monsoon and non-monsoon seasons to meet drinking water standards (i.e. salinity less than 1000 mg/l). The tradeoff curve prioritizes groundwater development in the study area. Palla well fields help in utilizing the induced flood recharge, which would otherwise join river boundary.
4. In the present study each group of well contained 10 wells. This was done to minimise the number of decision variables and constraints to minimum. The ultimate goal was to keep computational burdens that could be managed on a desktop PC. However more improved solutions could be obtained for smaller group of wells (say five wells per group) with more number of decision variables. This may be achieved through parallel processors.
5. Considering the limitations of model calibration and data availability the results from this study are suggestive and subjective.

The results of a combined simulation-optimisation model largely depend on the extent of calibration of an aquifer model to field conditions. There is further scope in transient model calibration (especially salinity concentration) to realistic field conditions through improved data collection and understanding of the aquifer system under study. The data collection could include:

(a) A network of peizometers within the flood plain to make a realistic assessment of flood recharge during the monsoon season.
(b) Water quality data (salinity) in shallow and deeper layer aquifers in the study area.
(c) Isotope data to verify groundwater contribution to river Yamuna at specific locations

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