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Santosh S Mali
Indian Council of Agricultural Research

D.K. Singh
Indian Agricultural Research Institute

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Groundwater modeling for assessing the recharge potential and water table behaviour under varying levels of pumping and recharge

Santosh S. Mali[1,3] **and D.K. Singh**[2]

[1]*ICAR-Indian Agricultural Research Institute, New Delhi-110012;* [2]*Water Technology Centre, Indian Agricultural Research Institute, New Delhi-110012.*

[3]*E-mail: santosh.icar@gmail.com*

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ABSTRACT

Increased abstraction to meet the food demands of the burgeoning population has raised the concerns for groundwater sustainability in several parts of India. In order to develop an optimum management plan for such areas, impact of various management alternatives on water tables needs to be assessed. This study investigates the impact of different rates of groundwater withdrawal and artificial recharge on water tables in IARI farm located in alluvial tracts of Northern India. A three dimensional finite difference model MODFLOW was used to simulate the aquifer system of the study area. The model was calibrated and validated using observed data for the period 2007 to 2010. The results of calibration and validation showed agreement between observed and predicted water table elevation. The coefficient of determination (R^2) ranged between 0.80 to 0.91 for calibration and 0.81 to 0.94 for validation. The validated model was used to simulate the water table behaviour for the period of 2012 to 2018 under eight management scenarios. The modeling results showed that the prevailing pumping rate, groundwater level would go down at an average rate of 0.64 m yr^{-1}. If the pumping increases by 20%, the water table will decline at 0.91 m yr^{-1}. Recharging 60% of available surface runoff would reduce the rate of groundwater decline to 0.25 m yr^{-1} highlighting the fact that extensive recharging of groundwater is still not sufficient to check the declining water levels and there is need for demand management. The simulation results also showed that at prevailing pumping and recharge levels, the sustainability of groundwater resources cannot be ensured unless water availability at the IARI farms is increased.

Key words:
Artificial recharge,
Groundwater modelling,
MODFLOW

1. INTRODUCTION

Ground water plays a key role in meeting the water needs of various user-sectors across the world and it provides about one-third of the world's freshwater consumption (Moreaux and Reynaud, 2005). The worldwide groundwater use has showed rising trend over past decades and the abstraction of groundwater grew from a base level of 100 to 150 BCM in 1950 to 600 to 1100 BCM in 2000 (Zektser and Everett, 2004; Shah *et al.,* 2007; Doll, 2009; Qureshi *et al.,* 2010). In India, agriculture is the major consumer of fresh water and about 60% of the irrigated food grain production depends on irrigation from groundwater (Shah *et al.,* 2000). Indian agriculture consumes 90.41% of the total surface and ground water withdrawals (FAO, 2010). Out of total irrigated area of the country about 62.9% of area is equipped for irrigation from groundwater (Sibert *et al.,* 2010). In India, the over dependency on groundwater has led to decline of water table elevation in several regions. According to the Central Ground Water Board (CGWB) under Ministry of Water Resources India, out of 5723 assessed administrative units (Blocks/Taluks/Mandals/Districts) all over the country, 4078 units are 'Safe', 550 units are 'Semi-critical', 226 units are 'Critical', 839 units are 'Over-exploited' and 30 units are 'Saline' (CGWB, 2010).

The alluvial plains of Northern India, which have the most productive aquifers, are also under the threat of over exploitation. Implementation of groundwater management projects with 'artificial recharge' as its integral component can be a better option to manage the depleted aquifers to sustain groundwater use for both domestic and irrigation. Efficient utilization of rainwater through water harvesting and consequent recharge to aquifers is an important option to check falling water tables (Sharma and Dubey, 2013). Quantifying the response of aquifer systems to management strategies is essential for developing long-term water resource management plans. Understanding of the response of an aquifer system under changed recharge and withdrawal patterns would help to resolve potential water resources problems associated with excessive pumping. The most commonly used approach for studying the response of aquifers involves use of mathematical groundwater models. Mathematical models can simulate the complex and dynamic nature of aquifer systems and help in assessing the behaviour of ground water system to various operational schemes for developing sustainable management plan (Rai and Manglik, 1999). Many mathematical models are available to predict aquifer response of aquifer systems to different management scenarios (Anderson and Woessner,1992).

Simulation models have been used for conceptual understanding of the groundwater recharge and discharge processes, to analyse stream-surface water interaction, to assess the impact of management strategies on groundwater resources and to assess the impact of climate and land use changes on groundwater quality and quantity (Kong, 2010; Xu *et al.,* 2011; Rozemeijer, 2010; Barlow and Coupe, 2012; Calderhead, 2012; Manghi, 2012; Barthel, 2012). Manuel (2006) proposed a groundwater model for Tsinkanet Catchment using the finite difference groundwater flow simulator MODFLOW. He estimated the effect of a small reservoir located in the catchment on the groundwater recharge. Rai *et al.* (2006) provided an analytical solution of a two dimensional linearized Boussinesq equation to predict water level variation in a horizontal aquifer induced by time-varying recharge and/or withdrawal from any number of recharge basins, pumping wells and leakage sites of different dimensions. Rejani *et al.* (2008) simulated groundwater flow and transport under five pumping scenarios in Balasore coastal groundwater basin using the Visual MODFLOW package and suggested management strategy for groundwater use. Sayana *et al.* (2010) used Visual MODFLOW (ver 4.1) to assess the effectiveness of the recharge wells and a percolation pond in the St Peter's Engineering College campus in Avadi, near Chennai, India. Calderhead *et al.* (2012) examined groundwater management scenarios for the Toluca Valley, Mexico, with a three dimensional groundwater flow model coupled to with one dimensional compaction module. They suggested a management policy for minimizing land subsidence and also tested several scenarios by varying four main parameters: recharge, exports to other basins, local consumption, and relocating pumping centres.

IARI is an important aquifer which supports about 473 ha of agricultural land and meets the domestic needs. With increasing groundwater draft, the water tables are falling at very faster rate. Previous studies demonstrated the application of models to simulate the aquifer systems and assess the response of aquifers to changed stresses. Modelling is particularly helpful in assessing the impact that particular management strategy will have on the water tables dynamics. The main objective of the study is to work out the volume of the runoff that is needed to maintain the water table of the IARI aquifers in equilibrium. Impact of different varying levels of groundwater pumping and recharge was assessed to work out the better combination of recharge and withdrawal**.** In this study a three dimensional finite difference computer code MODFLOW (McDonald and Harbaugh, 1998) was used to simulate the IARI aquifer system. Study also investigates the potential of utilizing harvested rainwater for groundwater recharge.

2. MATERIALS AND METHODS

Study Area

The IARI farm is located in alluvial tracts of northern India (Fig.1) and lies between the latitudes of 28^{0}37'22” N and 38^{0}39' N and longitudes of 77^{0}8'45” E and 77^{0}10'24” E at

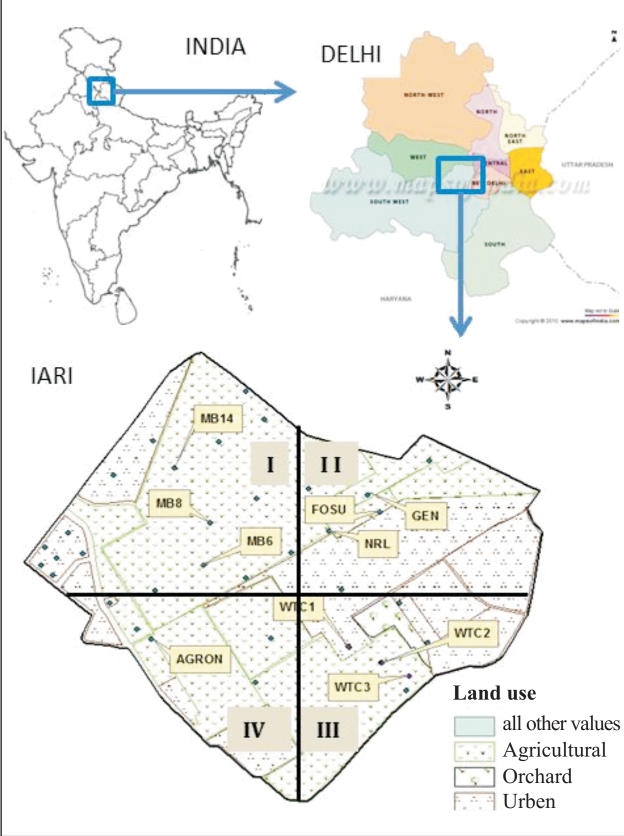


Fig. 1. Location of IARI farm and land use map of the study area

an average elevation of 230 m above msl. IARI farm has an area of 473 ha comprising mainly of farm area, residential complexes and office buildings. Agriculture and urban are two major land uses of the farm. Out of 473 ha, nearly 290 ha area is under Extensive agriculture. Major source of irrigation for this farm is groundwater. Irrigation and domestic water needs are met by pumping groundwater through tube wells which tap the unconfined aquifer. The normal annual rainfall is 710 mm of which, as much as 80% is received during monsoon season (June to September).

Long-term monitoring of water table elevation at the IARI farm revealed that groundwater situation at the IARI farm has been greatly varying in temporal scale. During 1963 to 1974 there were few pockets, which showed rising water level trend. After 1980's the import of canal water was reduced to 20 ha-m yr^{-1}. With the decrease in imported water, increase in agricultural area and expanding domestic and irrigation water needs, the water table elevation of the farm started declining at faster rate ever. At present, some places in IARI farm show the water level even at 15 m or more below ground level. Considering the water resource problems, availability of the hydrologic and land use data, IARI aquifer was selected for calibration and validation of model and to suggest suitable measures for groundwater development and management.

Aquifer Simulation Model

A cell-centered, saturated groundwater flow model MODFLOW developed by USGS (McDonald and Harbaugh, 1988) was selected for the simulation of the three-dimensional ground water flow of the IARI aquifer system. It is widely used and supported model for use in the public and private sectors (Liu *et al.,* 2010; *Xu et al.,* 2011). MODFLOW is a computer program that numerically solves the three-dimensional groundwater flow equation for a porous medium using a finite-difference method (McDonald and Harbaugh, 1988). MODFLOW is physically based model that combines Darcy's law and the mass balance for subsurface flow. MODFLOW offers the option of choosing from a variety of mixed-type boundary conditions. A variety of aquifers *viz.,* confined, unconfined or a combination of both can be simulated in MODFLOW. To load the input data into the model and to read the model results, a graphical user interface Processing MODFLOW for Windows (PMWIN) (Chiang and Kinzelbach, 2001) version 5.3 was used. The general sequence of activities and modelling procedure is presented in Fig. 2. The modelling steps followed are presented below:

Conceptual Model of the IARI Aquifer

Developing a modeling concept is the initial and most important part of every modeling effort. It requires a thorough understanding of hydrogeology, hydrology, and dynamics of ground water flow in and around the area of interest (Taheri and Zare, 2011). A detailed hydrologic and geologic characterization of the farm was done using the information of eight well logs and geophysical investigation (Fig. 3) carried out at two representative cross sections. Analysis of well logs showed that the greater part of IARI lies on alluvium but the small hills and ridges in and around IARI consist of Alwar quartzites of the Delhi system. Interpretation of well logs and geophysical surveys

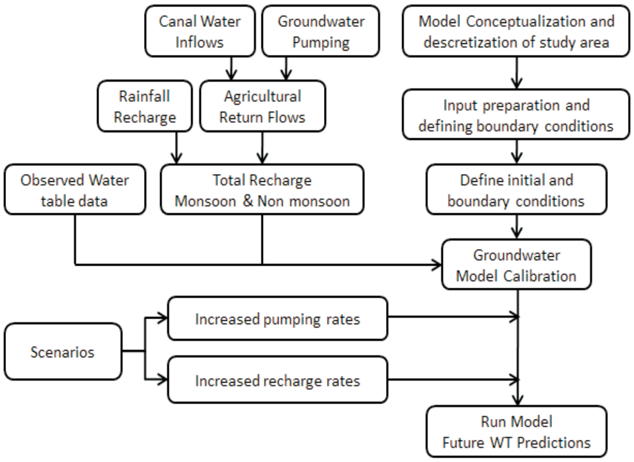
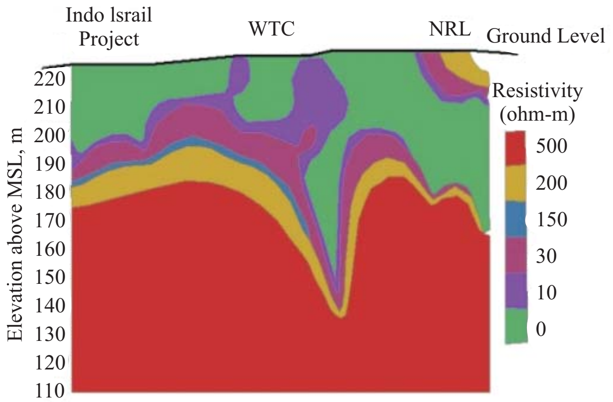
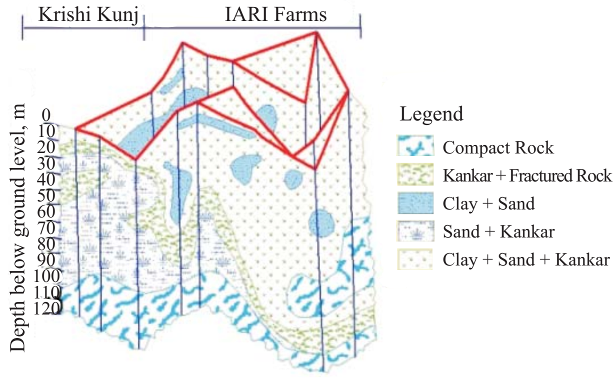


Fig. 2. Flow chart of modelling procedure



(a) Geo-electric section



(b) Fence diagram

Fig. 3. (a) Geo-electric section along the IIP-WTC-NRL (b) Fence diagram for Krishikunj and part of IARI farm (source: Chandrashekharan, 2001)

indicated that by and large aquifer in use is single layered unconfined aquifer. Rainfall and return flows from agriculture fields are the main sources of recharge.

Discretization of the Study Area

The study area was discretized into 30 rows and 30 columns with uniform cell size of 144.0 x 144.0 m (Fig.4). The grid cells were designated as 'inactive' outside the domain of the study area and as 'active' inside the model domain. Total numbers of active cells in study area were 505. Vertical section of the IARI aquifer was represented as single layer unconfined aquifer of varying thickness and bottom elevation. Time discretization in MODFLOW includes stress periods and time steps. In order to separate out monsoon and non-monsoon period, the time of a year was represented in the model by six transient stress periods. First stress period was from January to May (150 days) and was designated as 'non-monsoon' stress period. The next four stress periods were the four monsoon months (June to September) and were designated as 'monsoon' stress period (122 days with four monthly stress periods). The sixth stress period was from October to December which was again a 'non-monsoon' stress period (91 days). Under this kind of temporal set up, MODFLOW solved the flow equations for twelve monthly time steps in six stress periods of a year.

Initial and Boundary Conditions

The observed values of the hydraulic heads for the month of May 2007 were used as the initial values in the model. The observed water table elevation in May, 2007 were used to generate initial water level contours using Krigging module available in GIS and was imported in the MODFLOW. To account the subsurface inflows and outflows, the boundary conditions were specified as 'flow boundary'.

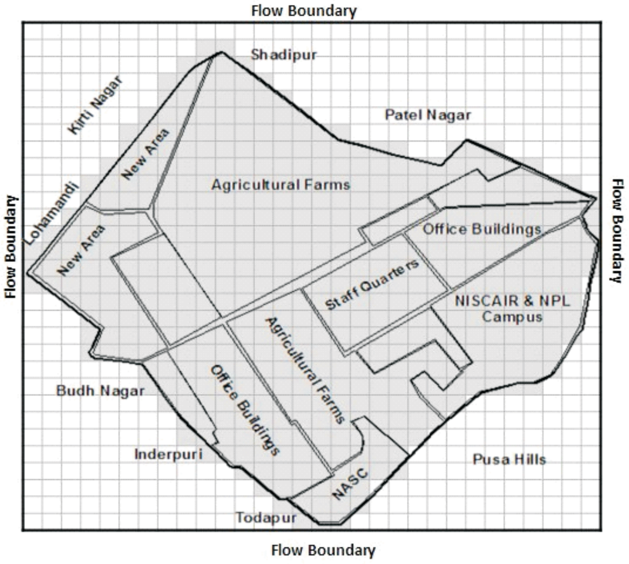


Fig. 4. Discretization of the study area and boundary conditions

Model Parameters

The hydraulic conductivity and specific yield of the aquifers were obtained from the pumping tests data available from past studies. The values of hydraulic conductivity of aquifers were available for seven locations in the farm (Sarkar, 1980) and the specific yield values were available for nine locations (Babu, 1978) spread over entire farm. The hydraulic conductivity and specific yield ranged between 0.32 to 1.74 m day^{-1} and 0.06 to 0.16, respectively.

In areas where ground water level monitoring is not adequate in space and time, rainfall infiltration method can be adopted to estimate the natural recharge during monsoon season (GEC, 2009). In the present study, the recharge in each of the four monsoon months was assumed to be a certain percentage of normal rainfall of that month (Table 1). However, it was ensured that the total recharge in the monsoon season as a whole does not exceed 26% of the normal monsoon rainfall as reported by Central Ground Water Board for this region (GEC, 2009). For projection of future water level under different scenarios (from 2012 onwards), recharge was calculated based on the 30-year normal rainfall of each month (Table 1). Deep percolation under paddy fields was taken as 3 mm day^{-1} for the paddy growing season.

Analysis of long term rainfall data revealed that the rainfall received during the non-monsoon months is only 20% of normal. The time span between successive rainfall events during non-monsoon period was large and also the quantity of rainfall received during individual events was very less and almost all the quantity of rainfall received during non-monsoon months gets stored in the upper soil profile in building soil moisture or lost through evaporation. Therefore, the rainfall recharge during non-monsoon period was not considered in the present study. The recharge due to return flows from irrigated fields to the aquifer system was taken as 25% of the total pumped water to the fields (GEC, 2009). There were 17 irrigation and 12 domestic tube wells in the study area which operates for about 8 hr and 4 hr a day with an average discharge rate of 33.27 m^3 hr^{-1}. There was import of 20 ha-m canal water yr^{-1} which is used for irrigation purpose. Taking into account the groundwater draft and recharge due to return flows, the net groundwater draft from agricultural areas was found to be 0.0012 m day^{-1} and that from urban area was 0.001 m day^{-1}. The

Table: 1
Groundwater recharge during monsoon months

Month	Normal Rainfall (mm)	% of rainfall as recharge	Monthly Recharge (mm)
June	71.97	15	10.79
July	208.43	25	72.90
August	223.47	35	55.90
September	118.62	20	23.70
Normal monsoon season recharge			154.40

evapotranspiration (ET) package simulate the effects of plant transpiration via capillary rise from the saturated zone. In IARI aquifers, the water table elevation is deep and the loss of groundwater by evapotranspiration was considered negligible in this study.

Model Calibration and Validation

The transient calibration was done by adjusting model parameters (Ting *et al.,* 1998) within the permissible limits obtained from pump test analysis. Model was calibrated for hydraulic conductivity and specific yield using the observed data of five tube wells for the years 2007-2008. The calibrated model was validated using the observed data of two tube wells for the period of 2008 to 2010. A mean error (ME), coefficient of determination (R^2) and root mean square error (RMSE) were used to measure the accuracy of model predictions and were estimated using following equations:

$$ME = \frac{1}{n}\sum_{i=1}^{n}(h_o - h_s) \qquad ...(1)$$

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}(h_o - h_s)\right]^{0.5} \qquad ...(2)$$

$$R^2 = \left\{\frac{\sum_{i=1}^{n}(h_{oi} - \bar{h}_o)(h_{si} - \bar{h}_s)}{\left[\sum_{i=1}^{n}(h_{oi} - \bar{h}_o)\right]^{0.5}\left[\sum_{i=1}^{n}(h_{si} - \bar{h}_s)^2\right]^{0.5}}\right\}^2 \qquad ...(3)$$

Where, h_o= observed head, h_s= simulated head, $\bar{h}_o$= mean observed head, $\bar{h}_s$ = mean simulated head, and n = the total number of observations.

Groundwater Management Scenarios

Eight management scenarios were considered under the present study. Each of the scenarios had different levels of groundwater pumping and recharge. In IARI, the demand for water will increase in future due to expansion of office and residential buildings. This may lead to further decline in water table. Previous studies showed that average quantity of runoff volume generated during monsoon season from 473 ha area of IARI farm was 559352 m^3 (Mali, 2004) which shows that there is scope for groundwater recharge. Artificial recharge can be a viable option to minimize the declining trend of water table. In present study, the impact of different levels of pumping and artificial recharge on IARI aquifer water level was evaluated for the period of six years. The scenarios considered for simulations included various levels of pumping and recharge as described in Table 2.

3. RESULTS AND DISCUSSION

Calibration and Validation

Comparison of observed and predicted water table elevations in five tube wells (Fig. 5 a-e) for calibration period showed that there was good match between observed and predicted water table elevation as the R^2 values were found to be in the range of 0.80 to 0.91 for five monitored wells (Table 3). The ME and RMSE for calibration period were within acceptable limits. The scatter plot between observed and predicted water table elevations plotted for pooled data of five tube wells is presented in Fig 5-f. The ME, RMSE and R^2 values for pooled data were -0.196, 0.33 and 0.99, respectively. The calibrated values of hydraulic conductivity and specific yield were 0.41 m day^{-1} and 0.21, respectively.

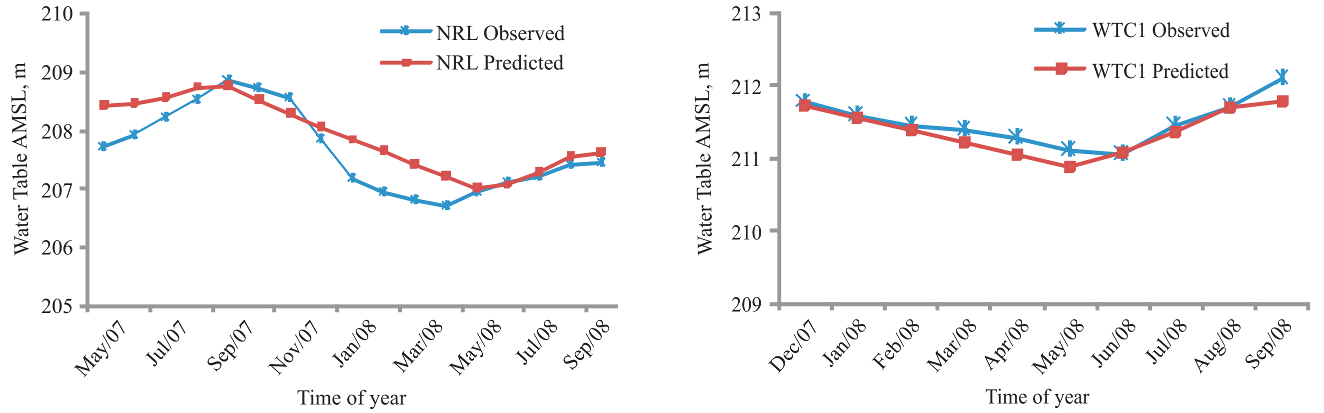
The model predicted water table elevations matched well with the observed data for validation period (Fig. 6 and Fig. 7). The R^2 for validation period was 0.80 and 0.94 for two monitored wells (Table 3). The validation period ME, RMSE and R^2 (Fig. 8) for pooled observed and predicted groundwater table elevations of two tube wells were 0.097, 0.312 and 0.98, respectively.

Simulating Impact of Groundwater Recharge and Pumping

In order to compare the predicted water table elevations within the various scenarios, the water table elevations at post monsoon season of 2011 were considered as reference levels. Under each scenario, water table elevation predicted at the end of sixth year (Post monsoon 2018) was compared with the reference water table elevation.

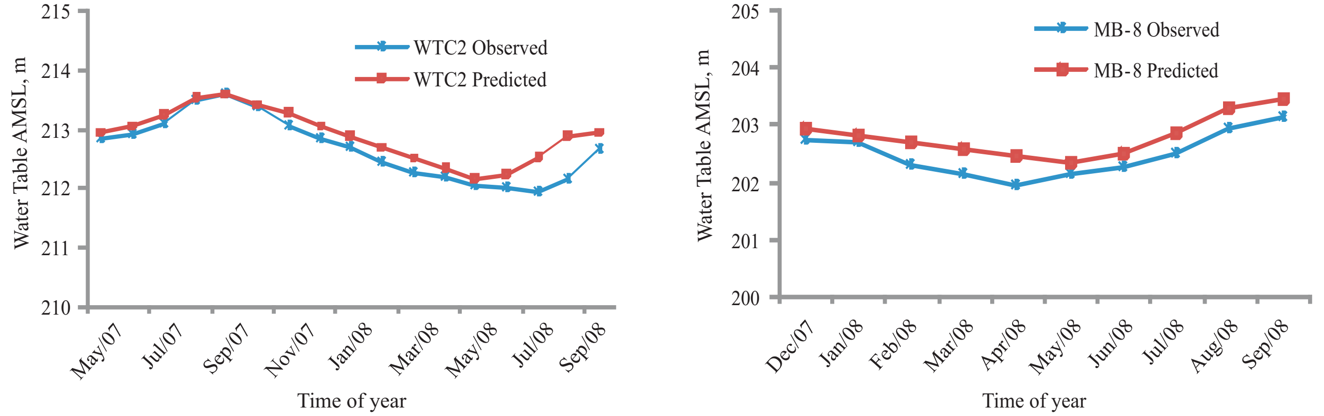
Table: 2
Description of modelling scenarios considered under study

Level of Pumping (P)	% of runoff as recharge (R)	Scenario	Description
Prevailing level of pumping (CP)	0 15 30 60	CPCR CP15R CP30R CP60R	These scenarios were planned to predict the water level situation in 2018 under various levels of groundwater recharge. Water level situation at prevailing levels of pumping (CP) and without any artificial recharge (CR) was predicted for 2018. The impact of recharging 15, 30 and 60% of the generated runoff volume was also evaluated.
20% increase in pumping (P)	0 15 30 60	20PCR 20P15R 20P30R 20P60R	This scenario assumes that the pumping will increase by 20% of prevailing pumping levels and simulates the impact of recharge with 15, 30 and 60% of available runoff Volume.



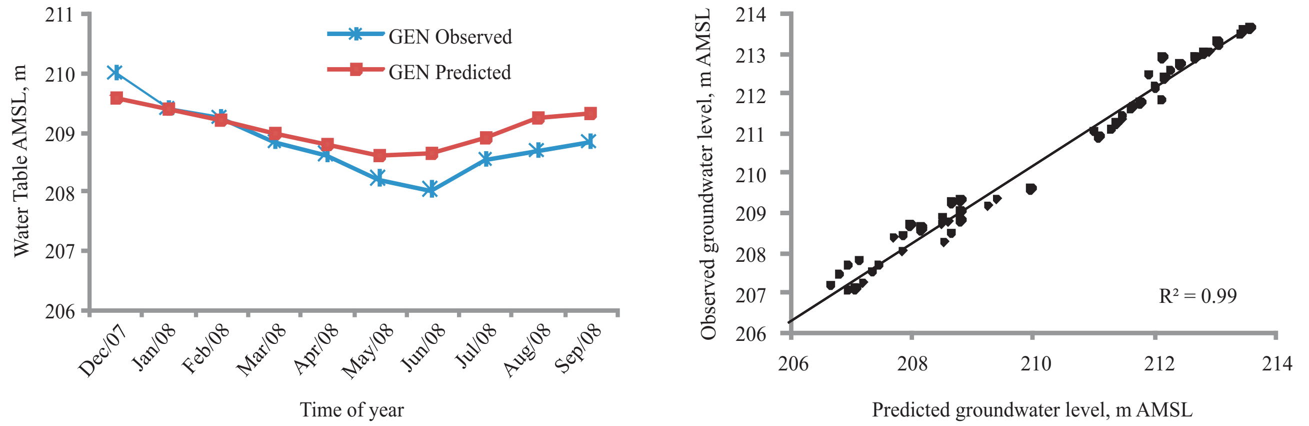
a. NRL

b. WTC1



c. WTC2

d. MB-8



e. GEN

f. Pooled data scatter plot

Fig. 5. Comparison between observed and predicted groundwater table elevation for the calibration period for five tube wells- (a) NRL (b) WTC1 (c) WTC2 (d) MB8 and (e) GEN and (f) scatter plot of pooled data on observed and predicted WT elevation of five tube wells.

Table: 3
Model performance statistics for calibration and validation period

Tube well	Calibration period (May 2007- Sep 2008)			Validation Period (Oct 2008 - Dec 2010)		
	ME	RMSE	R^2	ME	RMSE	R^2
NRL	-0.265	0.406	0.80	0.254	0.406	0.80
WTC2	-0.218	0.280	0.90	-0.061	0.172	0.94
WTC1	0.111	0.154	0.87			
GEN	-0.229	0.384	0.82			
MB-8	-0.312	0.334	0.91			

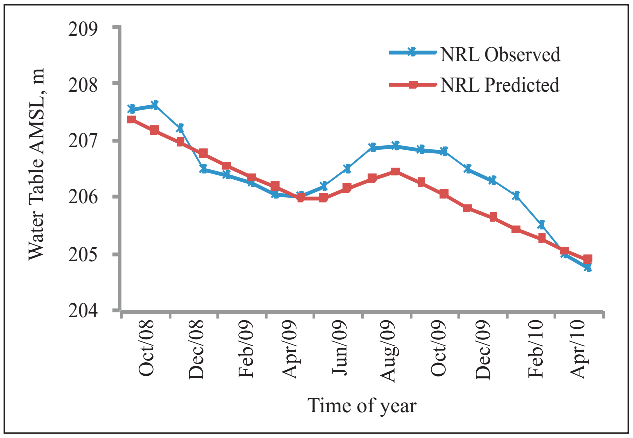


Fig. 6. Comparison predicted and observed groundwater table at NRL tube well

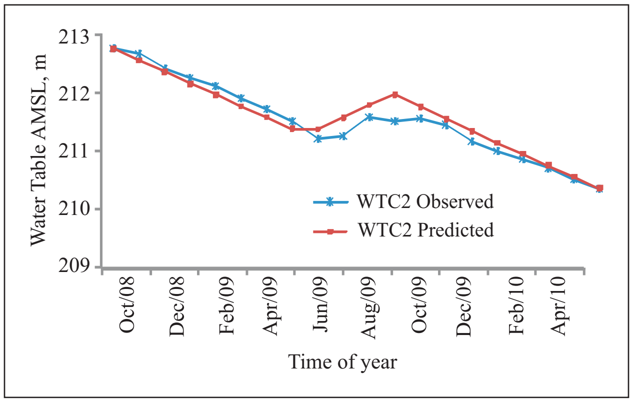


Fig. 7. Comparison predicted and observed groundwater table at WTC2 tube well

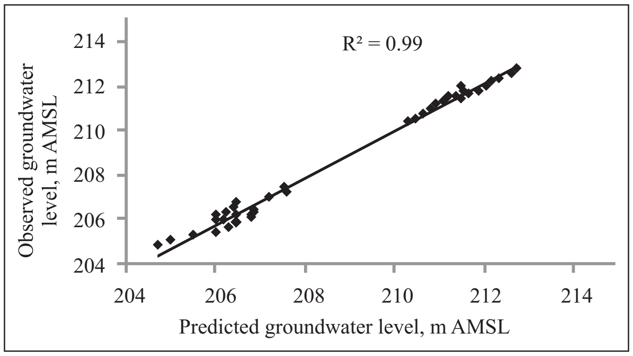


Fig. 8. Scatter plot of pooled data on observed and predicted water table

Prevailing pumping rate

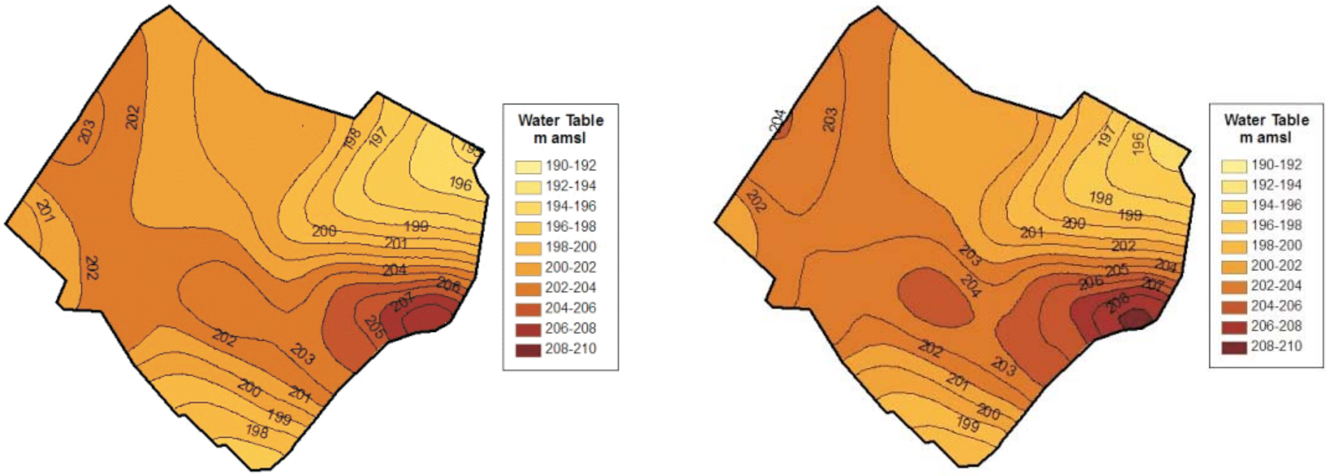
Simulation results (Table 4) showed that at prevailing levels of pumping and without any artificial recharge (scenario CPCR), water table will decline by 2.10 to 6.38 m in the study area. If present level of pumping continues, the average water table decline in the study area, calculated as average decline in all model cells, would be 4.48 m by the year 2018. This shows that under the prevailing pumping and recharge conditions ground water situation is going to be worse in future as water table would decline by 0.64 m yr^{-1}. The spatial distribution of water table elevation under CPCR (Fig. 9-a) showed that water table elevations in the study area would be in the range of 195 to 207 m above msl.

If 15% of available runoff is used for groundwater recharge (scenario CP15R), the water table decline will be slightly lesser than the water table situation under CPCR. Under this scenario, average water table decline in the study area would be 3.73 m by the year 2018. Although the decline was reduced, recharging 15% of available runoff will not be sufficient to reverse the declining water level trend. Distribution of water table elevations for scenario CP15R is presented in Fig. 9-b. In case, 30% of the available runoff volume is used for recharge (scenario CP30R), the average water table decline by the year 2018 will be 3.00 m. However, if 60% of available surface runoff is used for groundwater recharge then the water table decline by 2018 would be 1.75 m compared to reference scenario. Spatial distribution of water table elevation in the study area under the scenarios of CP30R and CP60R (Fig. 9-c and 9-d) showed that these would be in the range of 197.0 to 208.0 m above msl and 198.0 to 210.0 m above msl, respectively. The simulation results showed that even if 60% of the available surface runoff is used for groundwater recharge, declining water table trend in the study area cannot be reversed. Therefore, it is suggested that augmentation of water supply and demand side management can be considered as feasible alternatives to reduce pressure in groundwater resources in the study area.

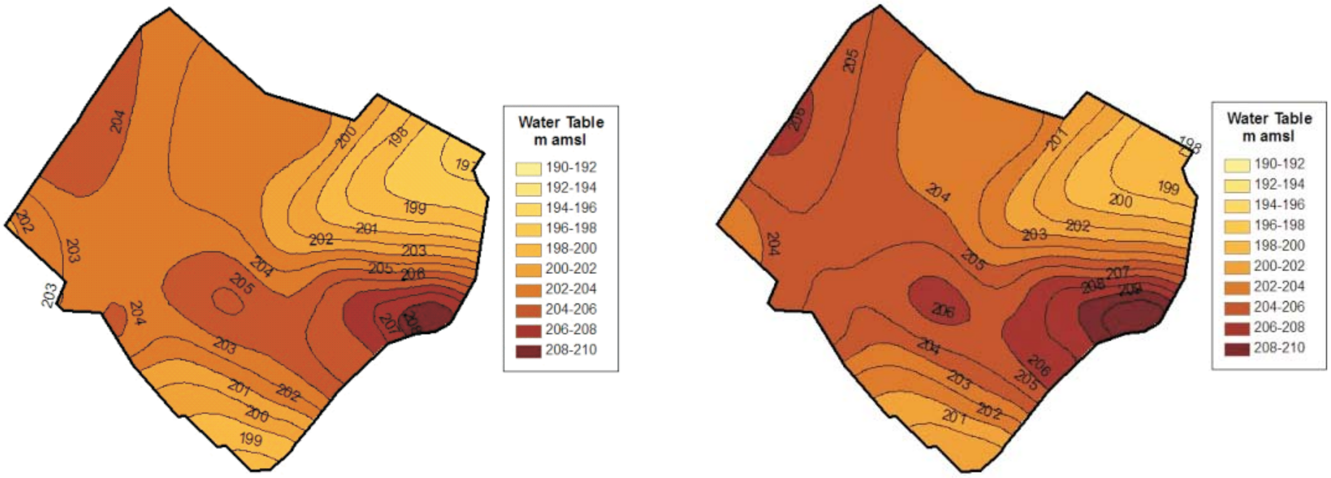
Table: 4
Predicted water table elevations and rise/fall of water table under different recharge scenarios for prevailing pumping level

Tube Well	Reference water table elevation, m amsl (2011 post monsoon)	Rise/fall in water tables compared to reference water table elevation, m			
		Scenario			
		CPCR†	CP15R	CP30R	CP60R
NRL	205.58	-4.98	-4.39	-3.78	-2.59
MB-8	204.00	-2.10	-1.55	-0.84	0.43
WTC-2	211.10	-6.38	-5.77	-5.13	-3.89
AGRON	205.60	-2.72	-2.04	-1.46	-0.20
Average water table rise/fall in IARI farms, m		-4.48	-3.73	-3.00	-1.75
Average annual rate of water table rise/fall, m yr^{-1}		-0.64	-0.53	-0.43	-0.25

†Current pumping-current recharge *Negative values indicates fall in water table



(a) CPCR (b) CP15R



(c) CP30R (d) CP60R

Fig. 9. Predicted water table elevation for 2018 (post monsoon) for prevailing pumping (CP) and under different recharge scenarios (a) without any artificial recharge and recharging (b) 15 % (c) 30 % and (d) 60 % of available runoff volume.

20% increase in prevailing pumping rate

The model predictions for the scenario with 20% increase in pumping and without any artificial recharge scheme (scenario 20PCR) showed that by 2018, average decline in water table there would be 6.37 m (Table 5). At prevailing levels of pumping and recharge, the rate of water table decline would be 0.64 m yr^{-1} which would increase to 0.91 m yr^{-1} if pumping increases by 20%. The spatial distribution of water table elevation under this scenario (Fig 10-a) showed that these would be in the range of 193.0 to 205.0 m above msl.

If the effect of 20% increase in pumping is partially compensated by recharging the aquifer with 15% of available surface runoff (20P15R), the rate of water table decline would be restricted to 0.82 m yr^{-1}. Similarly, under scenario 20P30R and 20P60R, the rate of decline would be 0.73 m yr^{-1} and 0.55 m yr^{-1}, respectively. This indicates that further increase in pumping would make groundwater use in the study area unsustainable. The spatial distrubution of water table elevations under scenarios of 20P15R, 20P30R and 20P60R (Fig 10) showed that water table elevation would be in the range of 193 to 206 m,194 to 207 m and 195 to 208 m amsl, respectively.

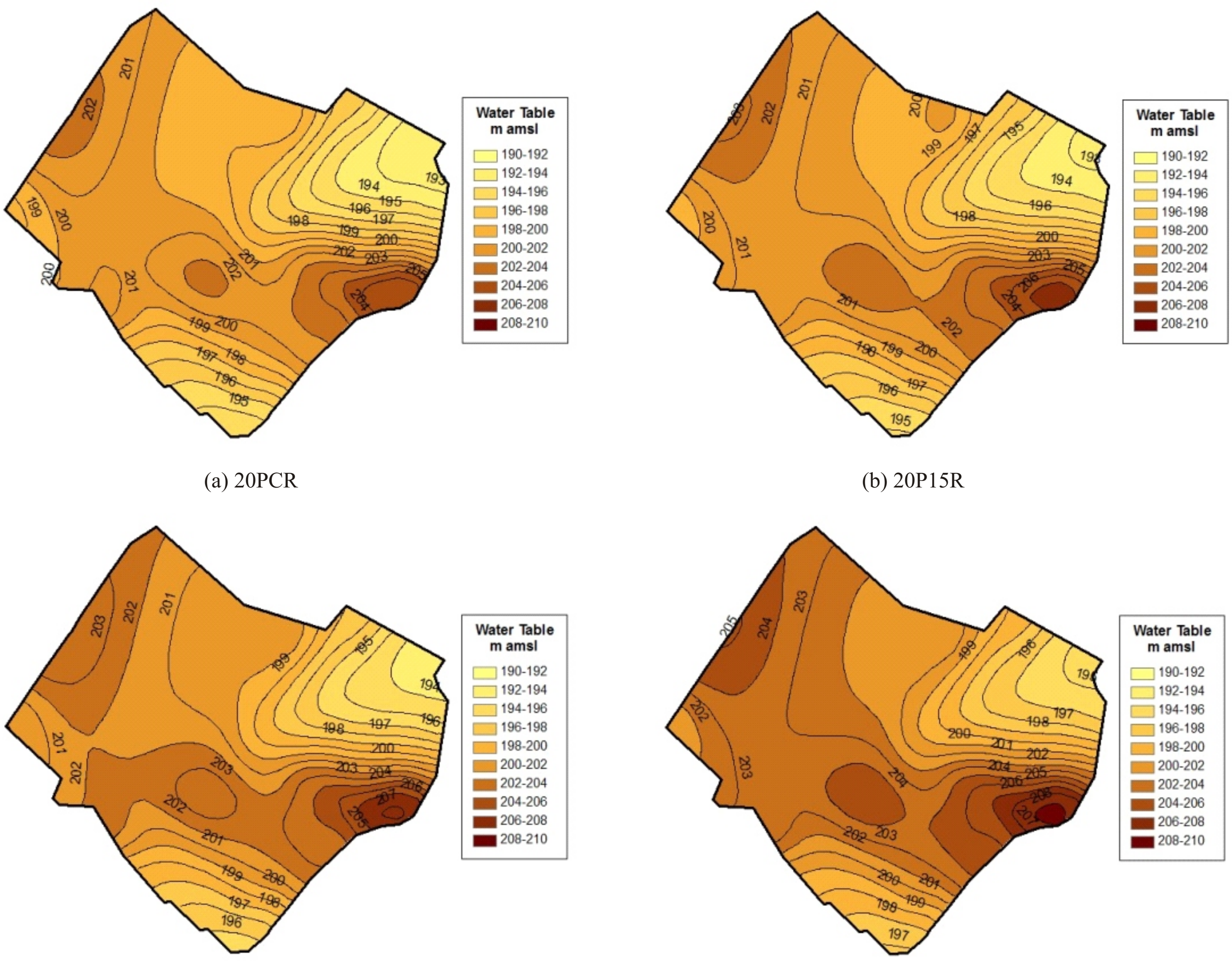
4. CONCLUSIONS

The groundwater table of IARI farm located in alluvial tracts of Northern India is declining at faster rate. A three dimensional groundwater model MODFLOW was calibrated and validated for simulating the water table behaviour under various pumping and recharge scenarios. The simulation results showed that the prevailing pumping and recharge conditions are not sustainable. Study demonstrated that at prevailing pumping levels, even if 60% of the available surface runoff is recharged, the declining water table trend cannot be reversed;

Table: 5
Predicted water table elevations and rise/ fall of water table under different recharge scenarios for 20% increase in pumping

Tube Well	Reference water table elevation, m amsl (2011 post monsoon)	Rise/fall in water tables compared to reference water table elevation, m			
		Scenario			
		CPCR	CP15R	CP30R	CP60R
NRL	205.58	-7.17	-6.58	-5.98	-4.79
MB-8	204.00	-3.85	-3.21	-2.58	-1.31
WTC-2	211.10	-8.40	-7.78	-7.16	-5.92
AGRON	205.60	-4.28	-3.65	-3.02	-1.77
Average water table rise/fall in IARI farms, m		-6.37	-5.74	-5.11	-3.86
Average annual rate of water table rise/fall, m yr^{-1}		-0.91	-0.82	-0.73	-0.55

*Negative values indicates fall in water table



(a) 20PCR

(b) 20P15R

(c) 20P30R

(d) 20P60R

Fig. 10. Predicted water table elevations for 2018 (post monsoon) for 20% increase in prevailing pumping (20P) and under different recharge scenarios (a) without any artificial recharge and pumping (b) 15% (c) 30% and (d) 60% of available runoff volume

however, the rate of decline can be reduced to 0.25 from 0.64 m yr^{-1}. This calls for implementation of water harvesting schemes with surface storage structures or aquifer recharge. In case the groundwater pumping increases in future, the water table situation will be more critical. The cost of pumping under such circumstances will be very high. Augmenting water supply from other surface sources and artificial recharge needs to be considered for ensuring the sustainability of groundwater resources in the study area.

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