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Modeling of Groundwater Flow in Part of Western Yamuna Canal Command, Haryana

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ABSTRACT: A mathematical model has been developed to simulate the hydrogeological conditions and groundwater flow in part of the Western Yamuna Canal (WYC) command area in the state of Haryana, India. An area of 7508 sq km out of the total 13543 sq km area of WYC command was selected for modeling. The model area includes 32 blocks (some full and some partial) of Yamuna Nagar, Karnal, Panipat, Sonipat, Rohtak, Jhajjar, Kurukshetra and Jind districts. The 3-D Modular Finite Difference Groundwater Flow Package MODFLOW with Visual MODFLOW as an interface is used for model development. Conceptualization of the area was done based on the hydrogeological, bore hole lithology, fence diagram and water level fluctuations as reported in Upper Yamuna Basin (UYB) reports of Central Ground Water Board (CGWB). The area was discretized into 1 km × 1 km grids. The eastern and south-western side of the model area was represented by river boundary, western side as no flow boundary and north and southern sides as flux boundaries. Major canals and drains were simulated in the model as rivers to account for their recharge/discharge to groundwater system. The simulation was carried out for three years from June 2002 to May 2005. The calibrated model was run further for a period of ten years (2005–2015) to see the impact of continuing with the present day groundwater withdrawal on the groundwater conditions in the year 2015. The results indicate that the present rate of groundwater pumping may lead to further deterioration in the ground water situation. The results of the study will be useful to predict the sustainability of the groundwater resources of the study area and to evaluate possible management actions.

INTRODUCTION

Increasing demand for groundwater due to ever increasing population has necessitated the need for effective management of available groundwater resources. Groundwater modeling is a powerful management tool to study the behaviour of aquifer system and to predict its response to external stresses.

The Western Yamuna Canal (WYC), the oldest canal in the State of Haryana, takes off from the Yamuna River at the Hathnikund barrage and supplies water for irrigation, drinking and industrial use. The WYC command area is part of the well known Indo-Gangetic alluvial area and is rich in groundwater potential. This area has witnessed phenomenal increase in the development of groundwater over the years by private and state government agencies (CGWB, 1985). The area experiences the problem of declining water table in some parts and rising water table in other parts. Long-term behaviour of water table (May1985–May 2004) reveals that in central, north and all along river Yamuna, water level has gone down by 10 to 16 m. In the south and south-western part, water level has risen by 5 to 10 m. Due to intense irrigation, water table in certain area has become much shallow creating waterlogging conditions.

The objective of the present study is to develop a mathematical model to simulate the hydrogeological conditions and groundwater flow in part of the WYC command area and to investigate the impact of further development of groundwater.

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STUDY AREA

WYC Command, with a geographical area of 13,543 Sq. km, covers part of Upper Yamuna Basin (UYB) and inland alluvial basin, and is located between the north latitudes 28°20′ and 30°28′ and east longitudes 75°48′ and 77°35′ in the state of Haryana (Figure 1). The area is predominantly an agricultural tract, with more than 70% area under cultivation. The average annual rainfall of the WYC Command is 608 mm.

The WYC Command area has a flat and monotonous topography with a regional slope from north-east to south-west direction. The surface elevation varies from 210 to 310 m amsl. The River Yamuna behaves as an influent at places (mostly in the northern part of the command area) and effluent at other places (mainly in southern part). The phreatic surface is a subdued replica of surface topography. Prominent groundwater ridge was found along WYC. The master slope of water table is from north to south with lateral slopes away from the ground water ridges. The depth to water level varies from less than 2 m to more than 20 m bgl.

The CGWB, Chandigarh has estimated the groundwater resources of the command (CGWB, 2005; Bhatia *et al.*, 2005). It has been observed that out of 49 blocks falling in WYC Command area, 19 blocks fall in safe category, 1 block in semi-critical, 2 in critical and 27 in over-exploited category. The selected model area of 7508 sq km includes 32 blocks, 13 fully and 19 partially, out of total 49 blocks of WYC command area (Figure 1).

HYDROGEOLOGY

The WYC Command plain tract lying south of the Siwalik zone forms a part of Indo-Gangetic alluvial plains of recent origin. The alluvial plains are underlain by loose unconsolidated river borne sediments and form very good repository of groundwater. The aquifer system lying closest to the land surface holds water in unconfined condition. At deeper levels, particularly below regionally or sub-regionally extensive poorly permeable layers, the groundwater occurs in semi-confined to confined conditions.

SUB-SURFACE GEOLOGY

Exploratory drilling has revealed existence of three aquifer systems down to 450 m depth (CGWB, 1977, Bhatnagar *et al.*, 1982a). Aquifer-I extends from the ground surface downwards to different depths to a maximum of 167 m below ground level (m.b.g.l.). This is composed of relatively coarser sediments. It is underlain by a clayey horizon, 10 to 15 m thick, which appears to be more to less regionally extensive except in the foothill region. The group is unconfined and semi-confined. The transmissivity varies from 800–5210 m^2/day, lateral hydraulic conductivity (K) from 8.75 to 47.1 m/day and Specific yield from 2.1 to 24%.

Aquifer-II consists of numerous sand and clay lenses occurring at variable depth ranging from 65 m to 283 m.b.g.l. The sediments of this group are less coarser and are occasionally mixed with kankar. The groundwater occurs under confined to semi-confined conditions. This aquifer is underlain by another clayey horizon which is considerably thick at places and appears to be regionally extensive. The transmissivity varies from 350–1050 m^2/day, lateral hydraulic conductivity (K) from 3.95 to 10.70 m/day, Storativity from 5.6×10^{-4} to 1.7×10^{-3} and vertical conductivity of the upper confining clay layer (K) from 5.35×10^{-4} to $2.7 \times$ to 10^{-3} m/day.

Aquifer-III comprises thin sand layers alternating with thicker clay layers occurring at variable depths ranging from 197 to 346 m.b.g.l. The granular material of this group is generally finer in texture. Kankar occurs in the southern parts of the area. In this aquifer group, the groundwater normally occurs under confined condition. The transmissivity varies from 345–830 m^2/day, lateral hydraulic conductivity (K) from 3.50 to 10.70 m/day, Storativity from 6.6×10^{-4} to 2.4×10^{-4}.

MODEL DEVELOPMENT

Model Description

The 3-D Modular Finite Difference Groundwater Flow Package MODFLOW (McDonald and Harbaugh, 1988) was used. Visual MODFLOW (Waterloo Hydrogeologic, 2002) was used as an interface to the MODFLOW model. MODFLOW solves the following partial differential equation describing the three-dimensional movement of groundwater of constant density through porous material,

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t} \quad \ldots (1)$$

where, K_{xx}, K_{yy}, K_{zz} are values of hydraulic conductivity along the x, y, and z coordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity (L/T); h is the potentiometric

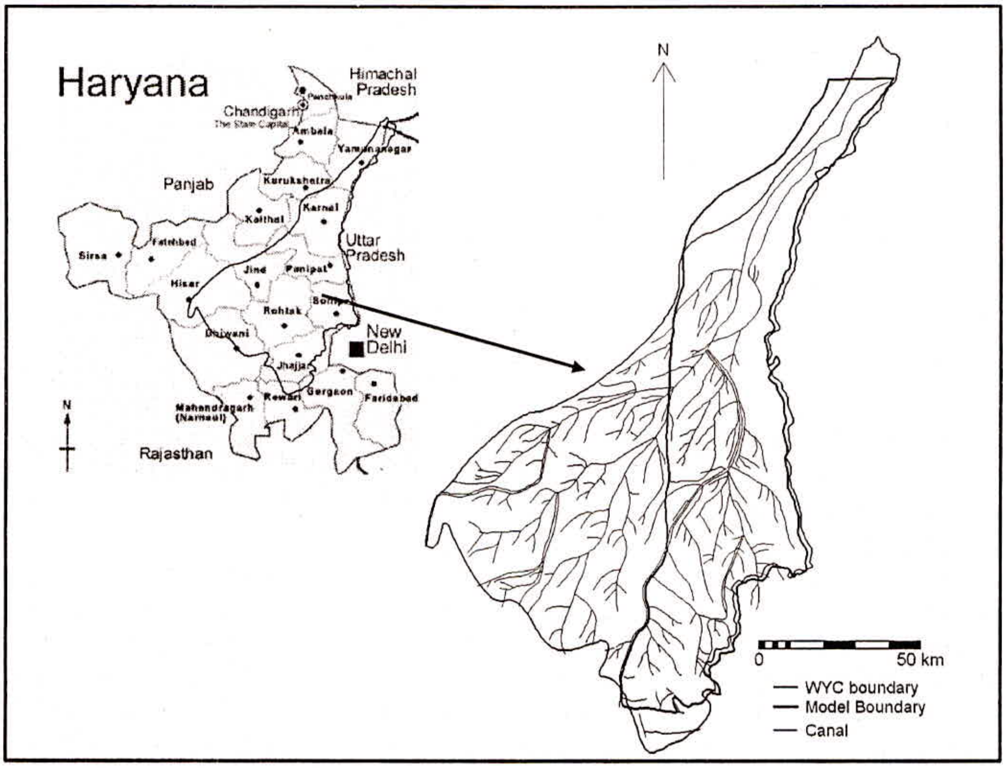

Fig. 1: Study area

head (L); W is a volumetric flux per unit volume and represents sources and/or sinks of water (T^{-1}); S_s is the specific storage of the porous material (L^{-1}); and t is time (T).

S_s, K_{xx}, K_{yy}, and K_{zz} may be functions of space and W may be a function of space and time. This equation, combined with specification of boundary and initial conditions, is a mathematical expression of a ground-water flow system. MODFLOW uses the finite difference method to obtain an approximate solution to this equation.

Conceptual Model of the Area

The conceptual model of the hydrogeologic system was based on detailed study of the hydrogeological and subsurface geological data available in various reports of UYB of CGWB (Bhatnagar *et al.*, 1982a&b; CGWB, 1977, 1985), drilling details, fence diagram, geophysical surveys, field visits and especially based on discussions with the Scientists who have earlier worked in the area. Three distinct groups of permeable granular zones separated by two different poorly permeable/impermeable horizons exist in the area as reported above. As little data was available about the various parameters and the ground water behaviour for the lowest aquifer, only three layers (two aquifers separated by an aquitard) were considered during the development of the model. The upper unconfined aquifer was considered to be occurring all over the study area. The area around Yamuna Nagar, where phreatic aquifer is connected with the confined aquifer below (as per the Upper Yamuna Report) was simulated accordingly.

Spatial and Temporal Discretization of the Area

The model area was digitized in GIS environment and was imported in the Visual MODFLOW. Horizontally the model area was discritized in a square grid of 1 km×1 km, resulting in 7653 active grid cells. Vertically, the hydrogeologic units are modeled by three Modflow layers. The unconfined aquifer is modeled as an unconfined Modflow layer. The clay aquitard and second aquifer are modeled as a convertible confined/unconfined Modflow layers.

The map of surface elevation (top of layer 1) is created in GIS environment. This is exported to an ASCII file and subsequently imported in to the Visual MODFLOW. The bottom of the first layer (i.e. top of the second confining layer) and similarly top and bottom of the third layer (Aquifer II) are created in MODFLOW based on the available drilling data, geophysical survey data and fence diagram.

The simulation was carried out for three years from June 2002 to May 2005. Data like recharge and discharge (pumping data) were available on monsoon and non-monsoon basis and accordingly assigned on monsoon and non-monsoon basis. River gauge (boundary) data was available and assigned on monthly basis in the model. Visual MODFLOW automatically merge all of the different time period data defined for each pumping well and boundary condition into the stress period required by MODFLOW. Accordingly, the Visual MODFLOW has divided the three year period into 36 stress period, each stress period of one month.

Boundary Conditions

The eastern part of the study area is bounded by the Yamuna river which was taken as river boundary. The western boundary of the study area is the watershed boundary of the Upper Yamuna basin. The flow across this boundary is negligible and hence it was considered as no-flow boundary. The south western portion of the study area does not coincide with the watershed boundary and instead a canal is running along this portion. This portion of the boundary was considered as river boundary. The river boundary was assigned based on the gauge data (collected from the field), various L sections and ground elevation data. Northern and southern sides of the study area do not have any conventional hydraulic boundaries. These two sides were hence considered as flux boundaries. Flux computation was carried out based on Darcy's equation $Q = KIA$, where Q is flow rate, K is hydraulic conductivity, I is hydraulic gradient and A is cross-sectional area.

Initial Conditions

To start the computations in the model, the initial ground water heads for various layers throughout the model area is to be known. The initial groundwater heads in the Aquifer I were derived from the groundwater observations well measurements taken in May, 2002. The initial heads for the confining layer and the confined aquifer is assigned similar to that of the first layer.

Model Inputs

The model inputs include hydrogeological parameters, recharge, and groundwater abstractions.

Hydrogeological Parameters

Transmissivity and specific yield/storativity for aquifer I (14 locations) and II (8 locations) (Bhatnagar *et al.*, 1982b) was used in assigning the hydraulic parameters to different layers. The vertical hydraulic conductivity of aquifer I was taken as 0.15 m/day, whereas for aquifer II, it was taken as 1/10 times of the horizontal hydraulic conductivity of that aquifer. The hydraulic conductivity (both horizontal and vertical) of second layer was taken as 0.0002 m/day.

Recharge Data

Recharge to groundwater in the study area is taking place from rainfall, canals, irrigation, water conservation structures, lakes and ponds. The Rainfall Infiltration Factor (R.I.F.) of 22% (CGWB, 2005) is used to compute monsoon and non-monsoon rain fall recharge for each block. Recharge from other sources such as canals, surface water irrigation, groundwater irrigation, water conservation structures, lakes and ponds were also compiled monsoon and non-monsoon wise from the CGWB (2005).

Major canals and drains were simulated in the model to account for their recharge/discharge to the ground water system. The WYC canal, the augmentation canal, Delhi parallel/Delhi branch (up to Delhi) and part of the Jawaharlal Nehru feeder was simulated in the model using the river boundary option. The required data were assigned based on the gauge data (collected from the field), various L sections and ground elevation data available.

Groundwater Abstraction Data

Based on the data on the number of groundwater abstraction structures and their pumping rate for each block (CGWB, 2005), the groundwater draft from each block for monsoon and non-monsoon period considering 33% of total annual draft in monsoon and 67% in non-monsoon for domestic purposes and 45% in monsoon and 55% in non-monsoon for agriculture requirement was estimated. Water withdrawn from each block was divided uniformly among the grids falling in that block.

RESULTS AND DISCUSSION

Model Calibration

The model was calibrated using initial input data under steady and transient state. A total of 29 observation (20 in aquifer I and 9 in aquifer II) wells were selected for calibration of the model. The first stress period was run under steady condition considering average values of recharge and pumping. The transient simulation was run with first stress period under steady state condition and as such the transient simulation started from stress period 2 and completed after 37 stress period. The calibration was carried out using a trial and error procedure.

The model was run initially several times under steady state condition to rectify the errors in assigned data. The calibration of heads in Layer-I and Layer-III was attempted using the calculated Vs observed head plot. The observation points where greater error was noticed were analyzed. The reasons explored and several runs were carried out trying with some minor changes around the area. Initially, some modifications were made in the assigned values of hydraulic conductivity in some parts of the model area. Then modifications were made in recharge and pumping rates. The resultant scatter plots of the goodness of fit between observed and simulated heads are presented in Figure 2 for aquifer I and II. The simulated and the observed groundwater heads for steady state condition is given in Figure 3. The mean error between simulated and observed heads, ideally zero for all the aquifers, was found to be close to zero. The absolute mean error and root mean square error was low, which indicates that the model was well calibrated (Table 1).

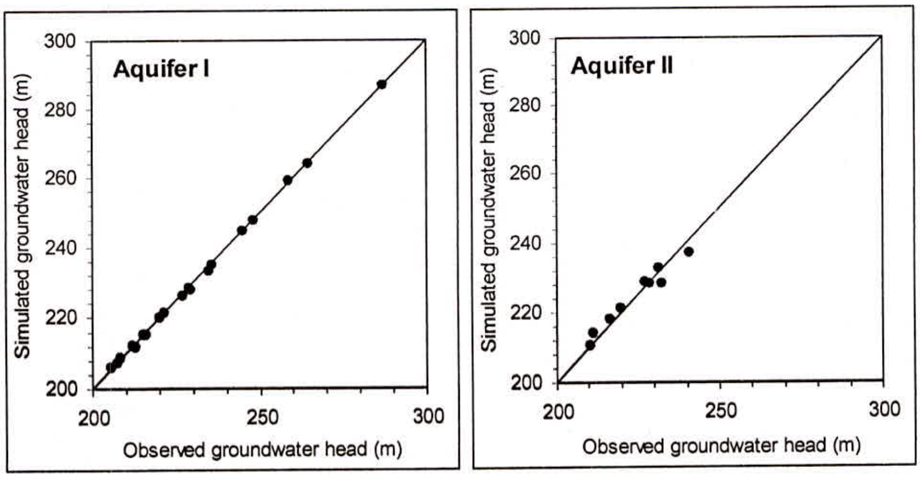

Fig. 2: Scatter plot of simulated and observed groundwater levels for steady state

Table 1: Summary of Calibration Error*

Time	*Error (m)*				*SEE (m)*	*RMSE (m)*	*NRMSE (%)*
	Max	*Min*	*Mean*	*Abs. Mean*			
			Aquifer I				
Steady State	–1.26	0.02	–0.10	0.45	0.13	0.57	0.71
Augus 02	1.84	–0.02	0.37	0.54	0.14	0.71	0.86
May 03	1.53	–0.02	0.10	0.32	0.10	0.47	0.57
August 03	–1.00	–0.03	–0.07	0.41	0.11	0.49	0.60
May 04	1.12	–0.01	0.02	0.34	0.10	0.46	0.57
August 04	1.14	0.03	0.16	0.33	0.10	0.46	0.57
May 05	–1.91	–0.03	–0.36	0.66	0.17	0.82	1.02
			Aquifer II				
Steady State	–4.26	0.12	0.30	1.99	0.83	2.36	7.78
August 02	6.06	0.01	2.89	3.57	0.92	3.90	12.58
May 03	–4.12	1.7	1.22	2.53	0.82	2.63	8.68
August 03	7.57	2.2	2.32	4.29	1.37	4.52	11.88
May 04	–4.31	1.16	1.09	2.88	0.99	3.02	9.35
August 04	5.36	2.6	2.10	3.6	1.08	3.73	10.62
May 05	–4.3	0.85	0.57	2.45	0.93	2.69	8.77

*SEE: Standard error of the estimate;
*RMSE: Root mean squared error
*NRMSE: Normalized root mean squared error

Fig. 3: Simulated and observed heads for aquifer I for steady state

Figures 4 and 5 shows the observed and simulated groundwater level hydrographs at all observation wells in aquifer I and II, respectively. The quantitative results of comparison of observed and simulated results are provided in Table 1. As seen the quality of calibration varies from one observation well to another. Figure 4 and Table 1 indicates good calibration for aquifer I. Figure 5 indicates that the simulated heads are higher than the observed heads at some points and are lower than the observed heads at other points. As seen from Figure 5 and Table 1, the calibration is not as good as required for aquifer II. But in the absence of sufficient data for aquifer II, the results were considered good. The simulated groundwater levels does not show the fluctuations as seen in observed heads but it simulates the falling trend in groundwater levels over a period of three years. In the developed model, it was considered (as no data was available) that there was no pumping from aquifer II, but from the groundwater hydrograph it looks that some pumping is also taking place from this aquifer.

GROUNDWATER BALANCE

The groundwater budget of the entire study area for steady state (stress period 1) and end of calibration period (May 2005, stress period 37) obtained from the groundwater flow model is presented in Table 2. The steady state total water budget over the entire aquifer shows a balance between inflows and outflows of water, which is consistent with the steady state modelling hypothesis.

The steady state groundwater balance shows that the groundwater inflow from the recharge (rainfall and other sources like irrigation, lakes, ponds etc) supplies the model area with most of its water (62% of the total input to the aquifer). A second important source of water is the river leakage (37%). There is small amount of recharge (0.08 MCM, about 1%) through flux boundaries. The main outputs of water from the aquifer are groundwater abstraction by pumping wells (97%). Output of water through river leakage and evapo-transpiration is rather small compared to the abstraction by wells, i.e. on average only 0.26 MCM, or 3% of the total outflow.

Table 2: Groundwater Budget Achieved from the Groundwater Flow Model

Water Balance Term		*Steady State (Stress Period 1)*	*End of Calibration (Stress Period 37)*
Model Inflow (MCM)	Storage	0.0	1475.52
	Wells (Flux)	0.08	81.66
	River leakage	2.97	3155.96
	Recharge	4.94	5810.61
	Total	7.99	10523.75
Model Outflow (MCM)	Storage	0.00	882.35
	Wells	7.73	9299.65
	River leakage	0.11	161.95
	ET	0.15	179.81
	Total	7.99	10523.76
Inflow-outflow (MCM)		0.0 (0 %)	–0.01 (0 %)

Model Forecast

The calibrated model was run further for a period of ten years (2005–2015) to see the impact of continuing with the present day groundwater withdrawal on the groundwater conditions in the year 2015. The model results indicated deterioration in ground water regime in the study area. The groundwater table declined

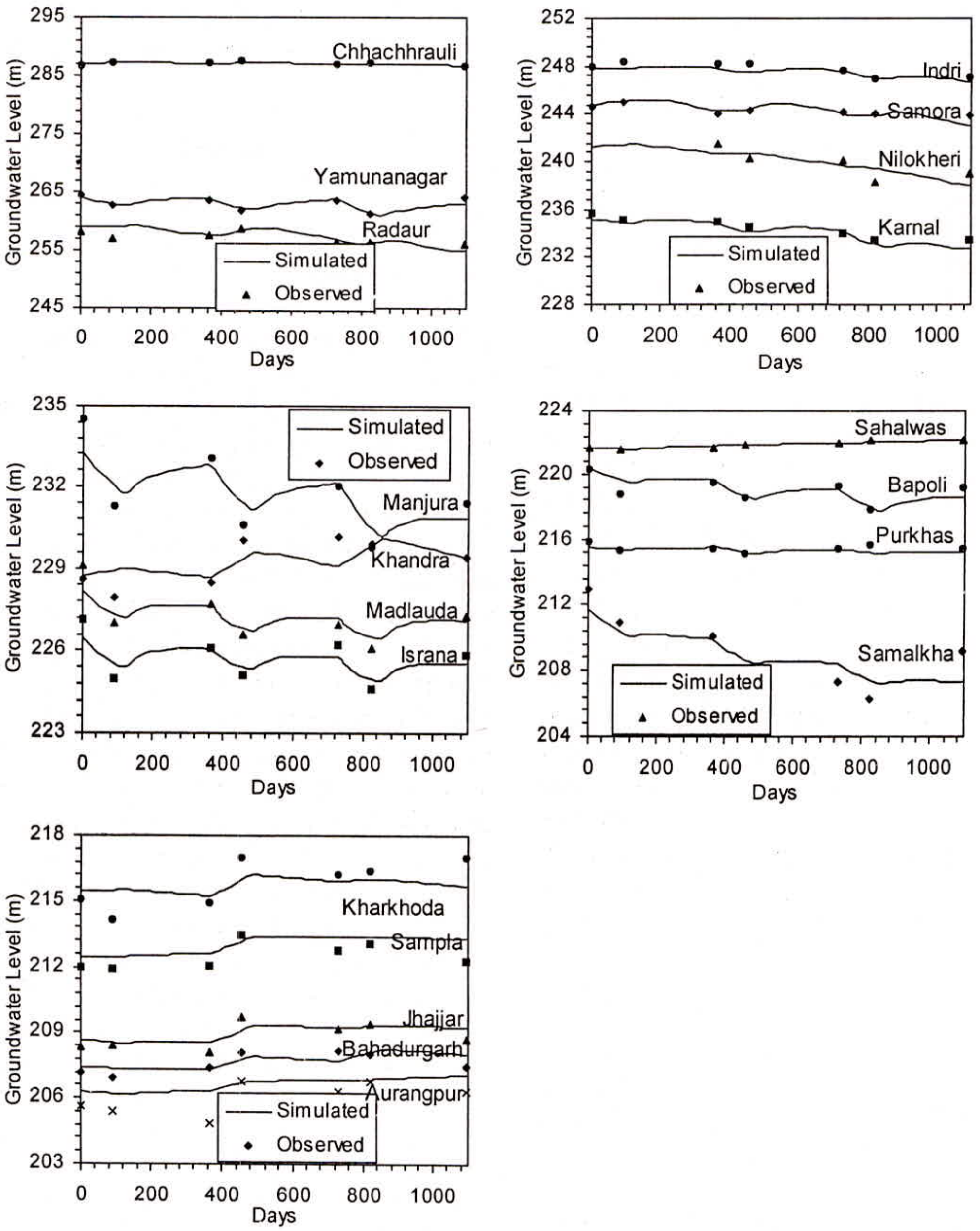

Fig. 4: Observed and simulated groundwater level hydrographs for Aquifer I

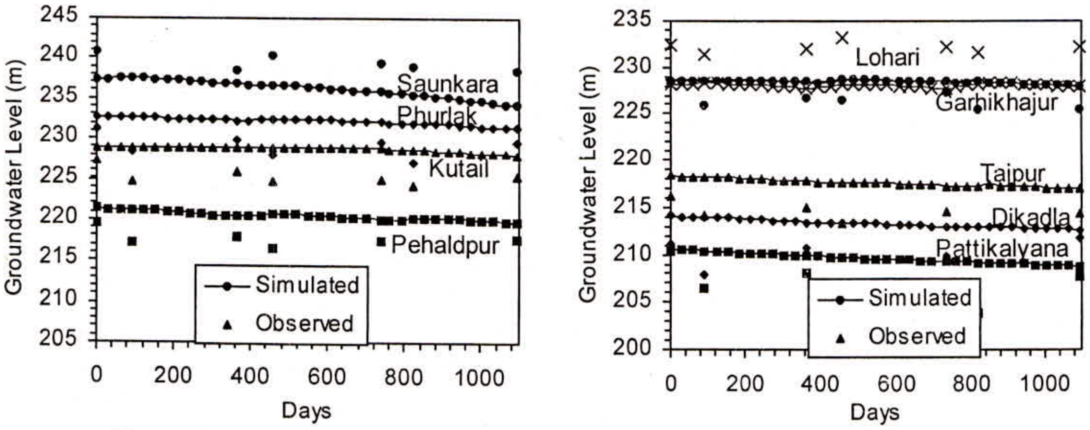

Fig. 5: Observed and simulated groundwater level hydrographs for Aquifer II

further in the already declining water level area. The area falling in different depth below ground level (in percentage) for year 2005 and 2015 (Table 3) indicates that there is not much change in the waterlogged/prone to waterlogging area but the area falling under <10 m depth has reduced from 61% to 44%. Similar decrease was noticed for other depths also. The maximum depth of groundwater in the study area which was about 25 m in year 2005 has gone upto 37 m. Thus, there is overall deterioration in the ground water scenario in the whole area.

Table 3: Area (%) Falling Under Different Groundwater Depths

Groundwater Depth below Ground Level	*Year 2005*	*Year 2015*
2 m	12.8	12.8
3 m	18.2	17.6
5 m	28.6	25.9
10 m	61.1	43.7
15 m	87.0	65.6
20 m	98.5	82.2
25 m	100.0	90.2
30 m		95.5
35 m		99.0
40 m		100.0

CONCLUSIONS

A mathematical model has been set-up to simulate the hydrogeological conditions and groundwater flow in part of the WYC command area. The model has been calibrated to the extent possible, but the calibration results for second aquifer were not so good. The area simulated is comparatively large (more than 7500 sq. km.) with the limitation in data availability in space and time, particularly for the semi-confined aquifer. For this aquifer, the aquifer parameters were known at only 8 points out of which only four points were inside the model area. These four points are located in the central part of the study area and no data was available in the northern and southern part of the study area. Further, limited data on recharge/discharge to/from this layer was used in the model development. Keeping this in view, the results of this modelling are only indicative and are to be used with caution. The results of modelling study indicate that continuing with the present rate of groundwater pumping may lead to further deterioration in the ground water situation in future.

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