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Groundwater flow modelling in a canal command of Haryana State, India

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Abstract Groundwater flow in part of the Western Yamuna Canal (WYC) command area in the Haryana state (India) has been simulated. An area of 7508 km^2 of the total 13 543 km^2 area of WYC command was selected for modelling. The groundwater in the selected area is under high stress. The block-wise groundwater development in the model area varies from 56% to 190% with 24 blocks (out of 32 blocks falling in the study area) having a groundwater development of more than 100%. 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 hydrogeology, bore hole lithology, the fence diagram and water level fluctuation in wells, as reported in the literature. The area is modelled as a three layer system with layer 1 representing upper phreatic aquifer, layer 2 representing confining layer and layer 3 representing confined/semi-confined aquifer. The area was discretized into 1 × 1 km grids. The eastern and southwestern side of the model area was represented by the river boundary, western side as no flow boundary and north and southern sides as flux boundaries. Major canals and drains were also simulated in the model as rivers, to account for their recharge/discharge to the groundwater system. The various model inputs, like hydrogeological parameters, areal recharge and groundwater abstraction, were assigned to the model based on the data available in literature. A total of 29 observation wells (20 in aquifer I and 9 in aquifer II) were used for model calibration. The model was run for three years (June 2002 to May 2005) consisting of 37 stress periods, with the first stress period under steady state conditions. Very good calibration is achieved for aquifer I (layer 1). But due to very limited data availability, mainly recharge and discharge, the calibration results achieved for the third layer (aquifer II) are not as good as those of layer I. The calibrated model was run further, for a period of 10 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 groundwater 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.

Key words groundwater; visual modflow; western Yamuna canal; India

INTRODUCTION

The Western Yamuna Canal (WYC) is the oldest canal in the State of Haryana, India. It supplies water for irrigation, drinking and industrial use. The WYC command covers parts of the Upper Yamuna Basin and the inland alluvial basin in the State of Haryana, and is rich in groundwater potential. This area has witnessed a phenomenal increase in the development of groundwater over the years by private and state government agencies (CGWB, 1985). To augment deficient surface water availability, schemes for large-scale development of groundwater in the command have been planned and executed. A large number of augmentation wells were constructed along WYC in order to augment canal supplies and prevent water logging in the adjacent tract. Further, in order to prevent seepage losses from WYC and to further augment its supply, a lined augmentation canal, taking off from Yamuna Nagar and falling out in WYC at Munak (69 km in length), was constructed in 1971. Heavy duty wells constructed along this canal were used to direct about 14–15 cumecs of groundwater to the surface water canal system. The augmentation wells have become defunct since 2002 due to mechanical problems/non-maintenance of these tube wells. Since then, the augmentation canal has been used as a conduit to supply canal water as seepage loss will be less in the lined canal compared to the unlined one.

The tube well density in the command area varies between 10 tube well/km^2 to more than 25 tube well/km^2. Block-wise groundwater resource potentials reveal that most of the blocks are over developed and so there is no scope for further development in general. It has been observed that out of 49 blocks falling in WYC Command area, 27 blocks fall into the over-exploited category.

There is a need to check the development of groundwater in these blocks. Long-term behaviour of the water table (May 1985–May 2004) reveals that in central area, north and all along the River Yamuna the water level has gone down by 10–16 m. Due to intense irrigation, the water table in a certain area has become much shallower, creating waterlogging conditions. In the south and southwestern part, the water level has risen by 5–10 m. As such, the area experiences the problem of declining water table in some parts and rising water table in other parts.

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.

STUDY AREA

WYC takes off from the Yamuna River at Hathni kund Barrage (3 km upstream of Tajewala, the old head works). At Hathni kund the water from Yamuna is diverted into two canal systems, namely the Eastern Yamuna Canal, serving parts of Uttar Pradesh, and the Western Yamuna Canal, serving Haryana. The water from WYC is also diverted to NCT Delhi for water supply. WYC Command, with a geographical area of 13 543 km^2, 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 (Fig. 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 southwest monsoon rainfall sets in the last week of June, withdraws at the end of September, and contributes 82% of the average annual rainfall.

The WYC Command area has a flat and monotonous topography, with a regional slope from northeast to a southwest direction. The surface elevation varies from 210 to 310 m a.m.s.l. The

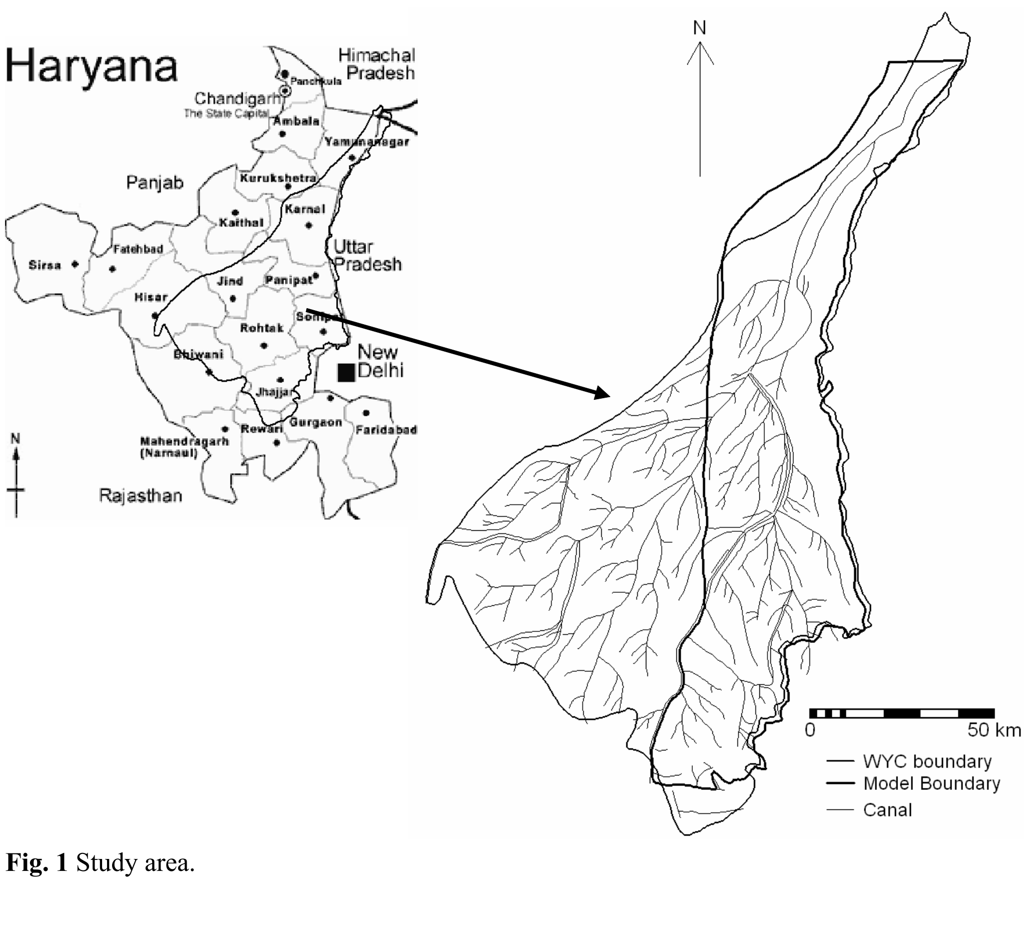

Fig. 1 Study area.

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 main slope of the water table is from north to south with lateral slopes away from the groundwater 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 (Bhatia *et al.*., 2005; CGWB, 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 km^2 includes 32 blocks, 13 fully and 19 partially, out of a total of 49 blocks of WYC command area (Fig. 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 a very good repository of groundwater. The aquifer system lying closest to the land surface holds water in an 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, 10–15 m thick, which appears to be more or 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 coarse 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 thicker in 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× 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 conditions. The transmissivity varies from 345 to 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 & 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 3-D movement of groundwater of constant density through porous material:

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

where, K_{xx}, K_{yy}, and 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 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 groundwater 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 hydrogeological system was based on detailed study of the hydrogeological and subsurface geological data available in various reports of UYB of CGWB (CGWB, 1977, 1985; Bhatnagar *et al.*, 1982a,b), 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 groundwater 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 occur all over the study area. The area around Yamuna Nagar, where the 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 a GIS environment and was imported into Visual MODFLOW. Horizontally the model area was discretized in a square grid of 1 × 1 km, resulting in 7653 active grid cells. Vertically, the hydrogeologic units are modelled by three Modflow layers. The unconfined aquifer is modelled as an unconfined Modflow layer. The clay aquitard and second aquifer are modelled as a convertible confined/unconfined Modflow layers.

The map of surface elevation (top of layer 1) is created in a GIS environment. This is exported to an ASCII file and subsequently imported into 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 a monsoon and non-monsoon basis and accordingly assigned on a monsoon and non-monsoon basis. River gauge (boundary) data was available and assigned on monthly basis in the model. Visual MODFLOW automatically merges all of the different time period data defined for each pumping well and boundary condition into the stress period required by MODFLOW. Accordingly, Visual MODFLOW has divided the three year period into 36 stress periods, each of one month.

Boundary conditions

The eastern part of the study area is bounded by the Yamuna River, which was taken as the 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 a no-flow boundary. The southwestern portion of the study area does not coincide with the watershed boundary; instead a canal runs along this portion. This portion of the boundary was considered as a 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 groundwater heads for various layers throughout the model area need 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 are 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) were 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 takes place from rainfall, canals, irrigation, water conservation structures, lakes and ponds. The Rainfall Infiltration Factor (RIF) of 22% (CGWB, 2005) is used to compute monsoon and non-monsoon rainfall 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 groundwater system. The WYC canal, the augmentation canal, Delhi parallel/Delhi branch (up to Delhi) and part of the Jawaharlal Nehru feeder were 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 the 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 a steady and transient state. A total of 29 observation wells (20 in aquifer I and 9 in aquifer II) were selected for calibration of the model. The first stress period was run under steady conditions considering average values of recharge and pumping. The transient simulation was run with the first stress period under steady state conditions, and as such the transient simulation started from stress period 2 and completed after 37 stress periods. The calibration was carried out using a trial and error procedure.

The model was initially run several times under steady state conditions to rectify the errors in the 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 analysed. The reasons were explored, and several runs were carried out, testing 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 Fig. 2 for aquifer I and II. The simulated and the observed groundwater heads for steady state conditions are given in Fig. 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).

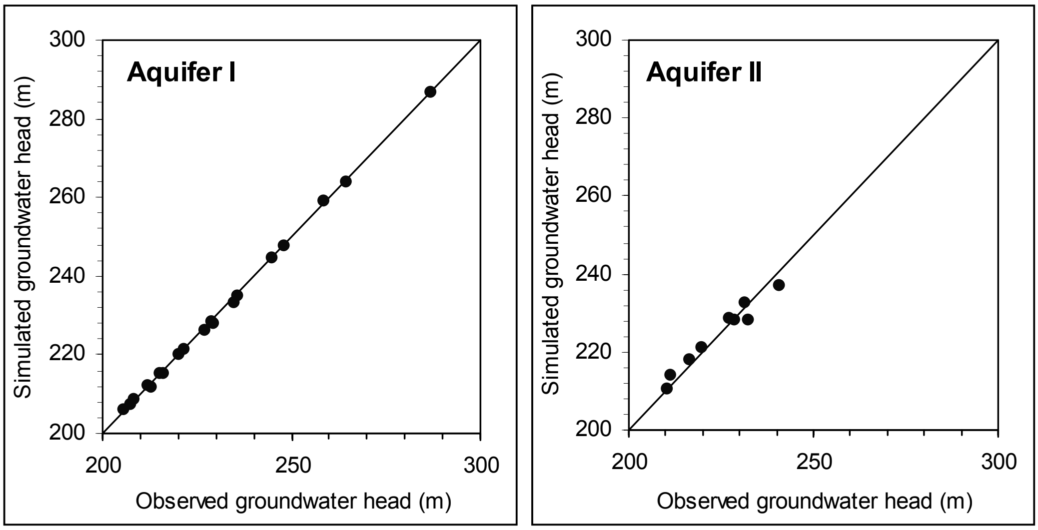

Fig. 2 Scatter plot of simulated and observed groundwater levels for steady state.

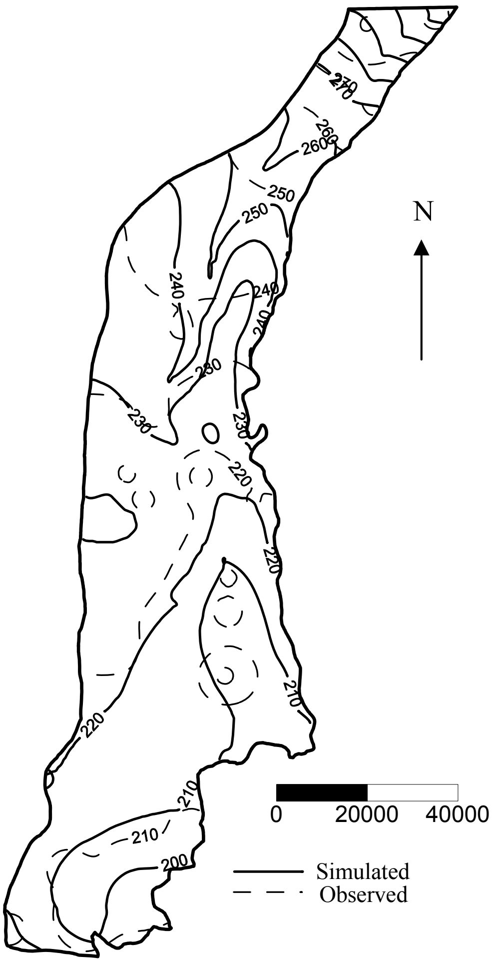

Fig. 3 Simulated and observed heads for Aquifer I for steady state.

Table 1 Summary of calibration error.

Time	Error (m) Max	Min	Mean	Abs. mean	SEE (m)	RMSE (m)	NRMSE (%)
Aquifer I							
Steady State	–1.26	0.02	–0.10	0.45	0.13	0.57	0.71
August02	1.84	–0.02	0.37	0.54	0.14	0.71	0.86
May03	1.53	–0.02	0.10	0.32	0.10	0.47	0.57
August03	–1.00	–0.03	–0.07	0.41	0.11	0.49	0.60
May04	1.12	–0.01	0.02	0.34	0.10	0.46	0.57
August04	1.14	0.03	0.16	0.33	0.10	0.46	0.57
May05	–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
August02	6.06	0.01	2.89	3.57	0.92	3.90	12.58
May03	–4.12	1.7	1.22	2.53	0.82	2.63	8.68
August03	7.57	2.2	2.32	4.29	1.37	4.52	11.88
May04	–4.31	1.16	1.09	2.88	0.99	3.02	9.35
August04	5.36	2.6	2.10	3.6	1.08	3.73	10.62
May05	–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.

Figures 4 and 5 show 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 indicate 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 Fig. 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 like 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 evapotranspiration is rather small compared to the abstraction by wells, i.e. on average only 0.26 MCM, or 3% of the total outflow.

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

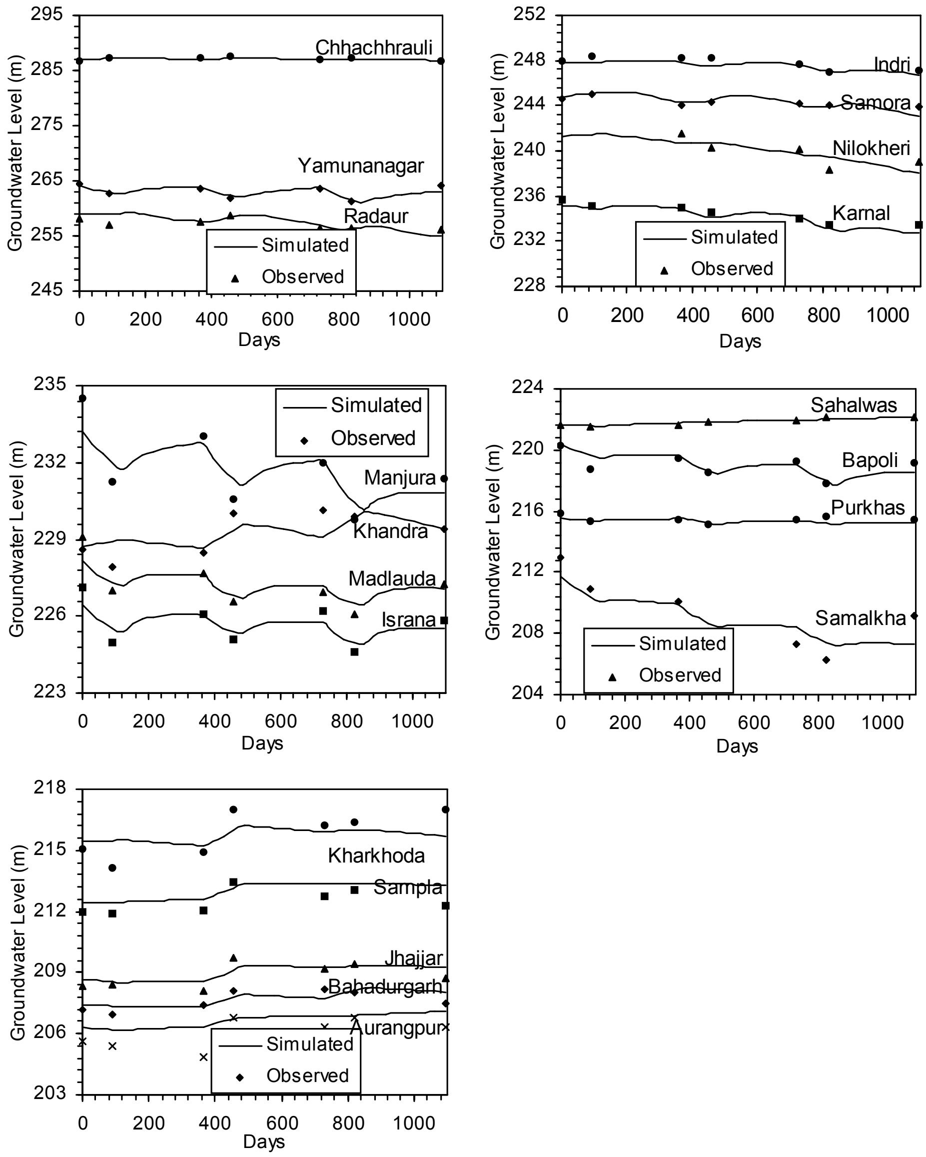

Fig. 4 Observed and simulated groundwater level hydrographs for Aquifer I.

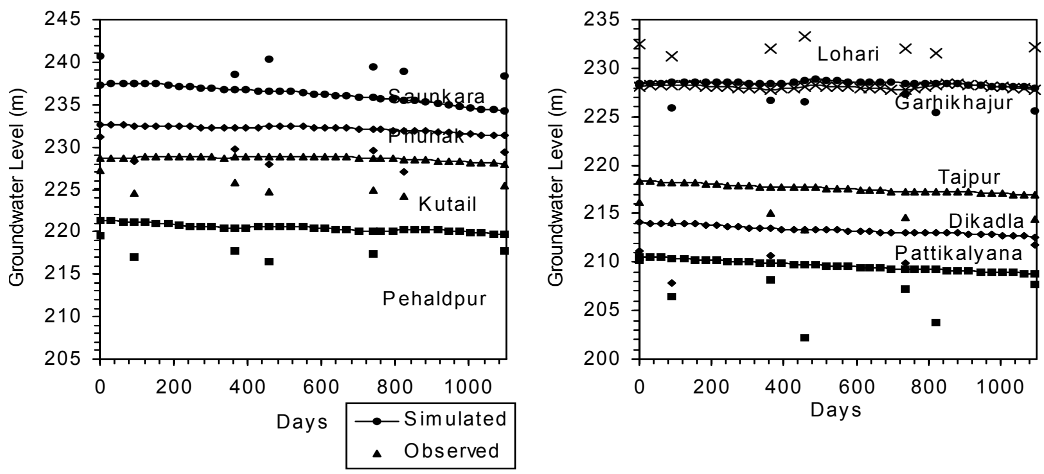

Fig. 5 Observed and simulated groundwater level hydrographs for Aquifer II.

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%)

Table 3 Area (%) falling under different groundwater depths.

Groundwater depth below ground level (m)	Year 2005	Year 2015
2	12.8	12.8
3	18.2	17.6
5	28.6	25.9
10	61.1	43.7
15	87.0	65.6
20	98.5	82.2
25	100.0	90.2
30		95.5
35		99.0
40		100.0

2015. The model results indicated deterioration in groundwater regime in the study area. The groundwater table declined 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 2005 has increased to 37 m. Thus, there is overall deterioration in the groundwater scenario in the whole area.

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 the second aquifer were not so good. The area simulated is comparatively large (more than 7500 km^2) with limitations in data availability in space and time, particularly for the semi-confined aquifer. For this aquifer, the aquifer parameters were known at only eight 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 groundwater situation in future.

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