Groundwater System Modelling and Sensitivity of Groundwater Level Prediction in Indo-Gangetic Alluvial Plains

Prabhakar Shukla and Raj Mohan Singh

Abstract The aquifer systems in the Indo-Gangetic alluvial river systems are recharged by rains and also by seepage from the irrigation canal commands. Groundwater resource is threatened due to rising water demand for advancement in the agricultural sector together with rapid industrialization. Utilization of groundwater at a rate greater than annual recharge constitutes unsustainable groundwater development. The problems of excessive groundwater extraction in the tail reaches of canal commands are common. In such areas, there is considerable potential for sustainable groundwater management through groundwater system modelling. Present work simulates the groundwater system in Sai–Gomti interfluve region which is a part of Indo-Gangetic alluvial plain in Uttar Pradesh, India. Groundwater simulation was carried out using Visual MODFLOW. The study area comprises mainly of agricultural land and is part of Sharda Sahayak Canal System in Uttar Pradesh. Visual MODFLOW was calibrated and validated for water level data available for 9 years (2005–2013). The effect of change in recharge rate and withdrawal rate is also investigated to predict the corresponding changes in water levels. Groundwater level was predicted beyond five years for future. Deterministic as well as fuzzy sensitivity analysis is performed to characterize uncertainty in predicted groundwater levels due to possible uncertainty in hydraulic conductivity and porosity.

Keywords Groundwater simulation · Visual MODFLOW
Sai–Gomti interfluve region · Sensitivity analysis · Fuzzy variable

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Introduction

Major urban settlements worldwide face depletion of water resources due to increasing water demands of fast-growing population and rising industrial water needs (Munoz et al. 2003; Lorenzen et al. 2010; Liu et al. 2008; Romano and Preziosi 2010). The Sai–Gomti interfluvial region in India is an example of such a case, imposing obligations of integrated water resource management (Livingston 2009; Foster and Choudhary 2009; CGWB 2009). The inefficient water distribution network and growing urban population further accentuate the water demand in the Sai–Gomti interfluvial region. This has resulted in installation of a number of licensed and unlicensed groundwater extraction wells, resulting in reduced groundwater level. Groundwater depletion threatens many riparian ecosystems in arid and semi-arid regions of the world. Groundwater irrigation demand has been growing steadily over the past decades, for many reasons including the unreliability of the traditional large canal schemes and the increasing need of farmers to manage their own irrigation applications. Therefore, proper groundwater system modelling and management is imperative. Chakravorty et al. (2014) investigated the effect of conjunctive water use on waterlogging in lower Gandak basin of Bihar. Groundwater flow modelling of Hindon–Yamuna interfluve region, western Uttar Pradesh, was conducted by Alam and Umar (2013). Gosh and Kashyap (2012) utilized optimization technique in precalibrated simulation model of groundwater flow. Optimized sustainable groundwater extraction management of Lucknow city was carried out by Singh et al. (2013). Ahmed and Umar (2008) investigated water balance studies in parts of Krishna–Yamuna interstream area in western Uttar Pradesh. Local scale groundwater flow model was developed by Ebraheem et al. (2004); Palma and Bentley (2007) for groundwater resource management. Groundwater system modelling of Azraq basin, Jordan, was performed by Abdulla et al. (2000).

In the present study, groundwater system modelling in Sai–Gomti interfluvial region of Uttar Pradesh in India has been performed. The effect of change in recharge rate and withdrawal rate has been investigated to predict the corresponding changes in water levels up to five years of the future period. Also, deterministic as well as fuzzy uncertainty analysis is performed to characterize uncertainty in predicted groundwater levels due to hydraulic conductivity and porosity.

Groundwater System Simulation

The equation describing steady, 2D areal flow of groundwater through a non-homogeneous, anisotropic and saturated aquifer can be written in Cartesian tensor notation (Pinder and Bredeoeft 1968; Srivastava and Singh 2014) as:

$$\frac{\partial}{\partial xi} = \left(T_{ij} \frac{\partial h}{\partial xj} \right) = W; \quad i,j = 1, 2 \tag{1}$$

where T_{ij} = transmissivity tensor; h = hydraulic head; W = volume flux per unit area (+sign = outflow and −sign = inflow); and xi, xj = Cartesian coordinates.

In the present study, Visual MODFLOW groundwater model has been used for the simulation of groundwater flow processes. It solves numerically the 3-D groundwater flow equation (Eq. 2) for porous media by finite-difference method. Equation (1) can be further expanded as (McDonald and Harbaugh 1988):

$$\frac{\partial}{\partial x} \left(K_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_{yy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial x} \left(K_{zz} \frac{\partial h}{\partial z} \right) - W = S_s \frac{\partial h}{\partial t} \tag{2}$$

where x, y, z are Cartesian coordinate axes, h = potentiometric head $[L]$, K_{xx}, K_{yy}, K_{zz} = hydraulic conductivities along x, y, and z axes $[LT^{-1}]$, W = volumetric flux/unit volume and represents sources and/or sinks of water $[T^{-1}]$, S_S = specific storage of the porous material $[L^{-1}]$ and t = time.

Study Area

The location map of study area is shown in Fig. 1. The study area comprises the districts of Barabanki, Raebareli, Sultanpur, Pratapgarh and Jaunpur, in Uttar Pradesh, India. It lies between latitude 26° 45′ 36″ and 25° 41′ 60″N, and longitude 81° 6′ 36″ and 82° 49′ 12″E and is estimated to be 8287 km². The study area is bounded by River Gomti in north direction and Sai River in south direction. The confluence of Sai–Gomti River in Jaunpur district forms an eastern extremity of the area. The area is representative of the whole of the Sharda Sahayak Canal command. It is expected that the methodology adopted and conclusions arrived at would be applicable elsewhere in the canal command area.

(a) **(b)** **(c)**
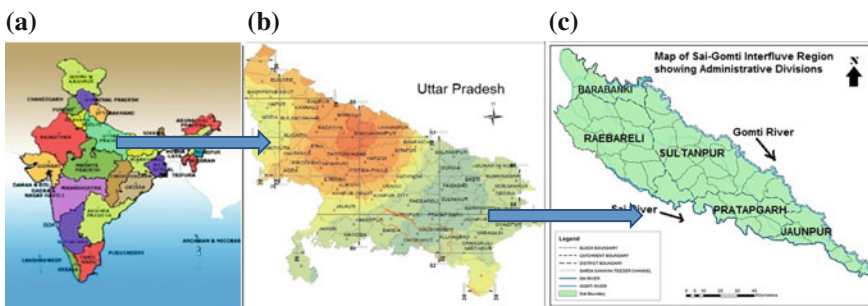
Fig. 1 Location map study area: **a** India. **b** Uttar Pradesh. **c** Sai–Gomti interfluve region

Geology of Study Area

The Sai–Gomti interfluvial plain forms a part of central Ganga Plain. It is underlain by soft/unconsolidated sediments of enormous thickness which varies from place to place. The observations of deep drilling study conducted by CGWB (2009) indicated that it is 487 m thick at Janauli in Raebareli district where granite basement was encountered; 399 m at Kandhai in Pratapgarh district (Vindhyan sandstone as basement) and 745 m at Leduka in Jaunpur district. The alluvium comprises alternation of sand–silt–clay sequence, which sometimes gets admixed with concentrations of calcium carbonate or Kankar as called in local language.

MODFLOW Model Design and Software

A number of groundwater simulation models (GMS, FEFLOW and Visual MODFLOW) have been used for accessing the response of groundwater system. The performance of all three models is comparable, and any of these can be used for the simulation of groundwater system. In the present study, finite-difference groundwater model Visual MODFLOW has been used for groundwater system modelling. The Visual MODFLOW is a strong numerical code for groundwater flow regime representation and related physical processes. Visual MODFLOW is a three-dimensional groundwater flow modelling environment for practical applications and contaminant transport simulations. It solves a system of equations describing the major flow and related processes in the hydrological system using finite-difference methods. It is being extensively used worldwide to carry out research in the field of groundwater resource management (Ahmed and Umar 2008, Ghosh and Kashyap 2012, Singh et al. 2013 and Chakravorty et al. 2014). A full description of the capabilities of MODFLOW can be found in McDonald and Harbaugh (1988). The steps include design of grid, selecting time steps, setting boundary and initial conditions, preliminary selection of values for aquifer parameters and hydrologic stresses (Anderson and Woessner 1992). The following steps are considered in the model design of Sai–Gomti interfluve region:

1. **Design of Grid**: The Sai–Gomti interfluve region is bounded by rivers Sai and Gomti on the southern and northern sides, respectively. The area of 8287.50 km^2 has been divided into equal sizes of grid network of 30 columns and 86 rows. Thus, the area has been divided into 2580 square cells based on the available data sets for groundwater system modelling.
2. **Layer**: Single-layer groundwater flow model has been developed based on the available information related to aquifer characteristics, rainfall and other data sets of study area.

3. **Hydraulic Parameters**: Due to inadequacy of the data on aquifer parameters, the figures for hydraulic conductivity and specific yield were adopted from similar contiguous areas. The input value of hydraulic conductivity (K) was taken as 7.0 m/day and specific storage value of 0.001/m with coefficient of storage (S) as 0.15. These values were modified during the process of calibration of the model. After the parameter estimation (PEST) run, these values were modified as hydraulic conductivity (K) = 6.005 m/day and specific storage value of 0.900/m with coefficient of storage (S) as 0.16.
4. **Stress Period**: Simulation time has been divided into stress periods. The stress period is defined as that period of time in which all the stresses (recharge, boundary conditions, pumping rate, etc.) on the system do not change. A stress period of 8 years (2005–2013) has been considered.
5. **Specification of Boundary Condition and Recharge Estimation**: River Sai and River Gomti have been assigned river boundary condition. Cluster of few grid cells in western part of the area is simulated as general head boundaries, as these grid cells are not bounded by either of the rivers. Heads were assigned to general head boundaries with the help of water level data. The areal recharge due to rainfall has been taken as 20% of rainfall as per Groundwater Estimation Committee (GEC 1997) recommendations. The estimated values were applied to the respective grid in the model using recharge boundaries.

Model Calibration and Validation

The purpose of model calibration is that the model can replicate field-measured heads and flows. Calibration can be carried out by trial-and-error adjustment of parameters or by using an automated parameter estimation (PEST). In the present study, automated parameter estimation (PEST) technique has been used.

Steady-State Calibration

The aquifer system was taken to be in steady state during November 2005. It was chosen to run and calibrate the model under steady state for this period using 36 observation wells in the study area. The groundwater head in the aquifer model was computed by using Visual MODFLOW. Waterloo Hydrogeologic Software (WHS) solver package of MODFLOW has been used for groundwater flow computation. The computed water level accuracy was judged by comparing the mean error with mean absolute and root mean square (RMS) error (Anderson and Woessner 1992). Mean error is 0.005 m, and RMS error in the present simulation is 0.08 m. The correlation coefficient is observed as 0.94. The absolute residual mean is 0.056 m.
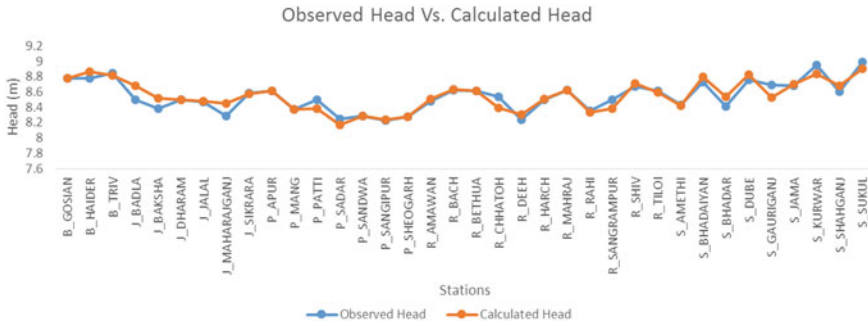
Fig. 2 Observed head versus calculated head for the year 2013

Transient State Calibration

The model was calibrated in transient state from 2005 to 2012 (7 years). Visual MODFLOW uses boundary conditions imposed by the user to determine the length of each stress period. After a number of trial runs, computed water levels were matched reasonably well to observed values. The RMS error for the transient state model is 0.442 m. The calibrated model provided hydraulic conductive (K) value as 6.005 m/d and coefficient of storage (S) as 0.23.

Model Validation

The calibrated model was validated with the available data of year 2013, and acceptable difference between observed and calculated values was observed. Figure 2 shows a comparison between observed and calculated head values for the year 2013. The correlation coefficient value was observed as 0.98.

Results and Discussion

Groundwater Level Prediction

Calibrated and validated groundwater simulation model is further employed to predict groundwater scenarios. Groundwater level for the Sai–Gomti interfluve region has been predicted during the period of 2014–2018. Two different scenarios were considered to predict the groundwater level.

Scenario 1: Constant recharge and increase in abstraction rate
In this scenario, the ongoing abstraction rate was increased by 20% during the period of 2014–2018. It was observed during prediction run that the areas near
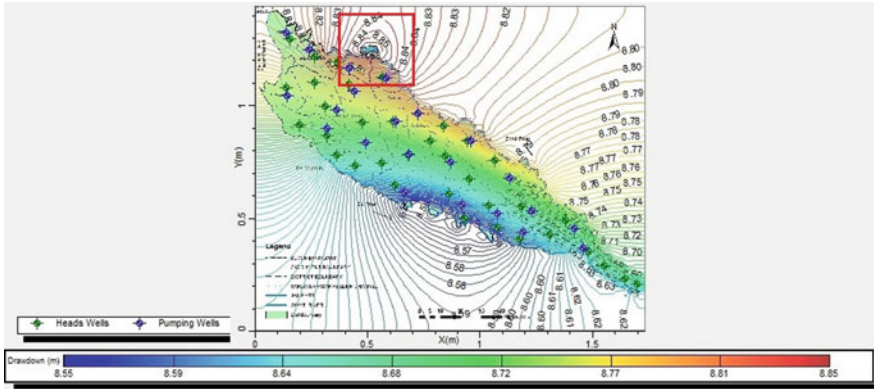
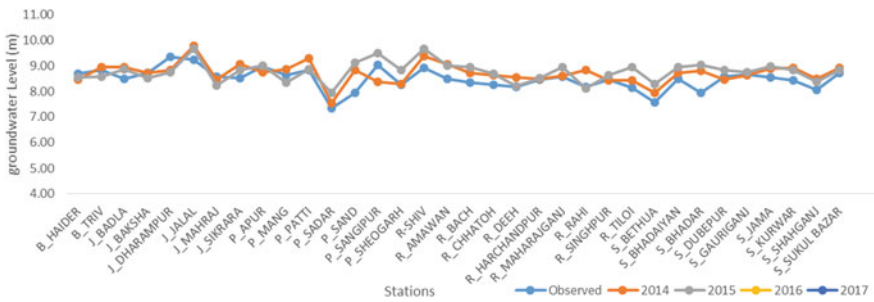**Fig. 3** Groundwater level in scenario 1

Fig. 4 Predicted groundwater level trend in study area under scenario 1

River Gomti are significantly affected as shown in Fig. 3. The blocks, Goasainganj, Trivediganj, Haidergarh, Jagdishpur, Sukul bazar, have higher groundwater level ranging between 8.76 and 8.85 m as shown in Fig. 4.

Scenario 2: Reduced recharge and increase in abstraction rate
In this scenario, combined effect of reducing recharge by 20% and increasing abstraction rate by 20% was examined. It was observed that the maximum groundwater level increased as compared to scenario 1. The maximum groundwater level of 8.90 m in Haidergarh block of Barabanki followed by Trivediganj Musafirkhana, Kurwar blocks of Sultanpur and Shivgarh, Singhpur block of Raebareli district (Fig. 5).

Predicted groundwater level from 2014 to 2018 is also plotted for different well locations (Fig. 6). In general, there is declining trend of groundwater level in study area, as shown in Fig. 6. A sector of economy such as agriculture is most affected due to decline of groundwater level. Consequently, food production, manpower and employment are affected which also affect the society in general.
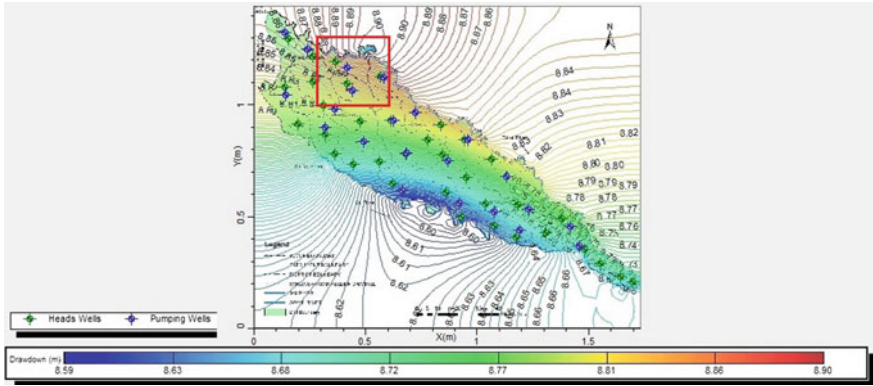
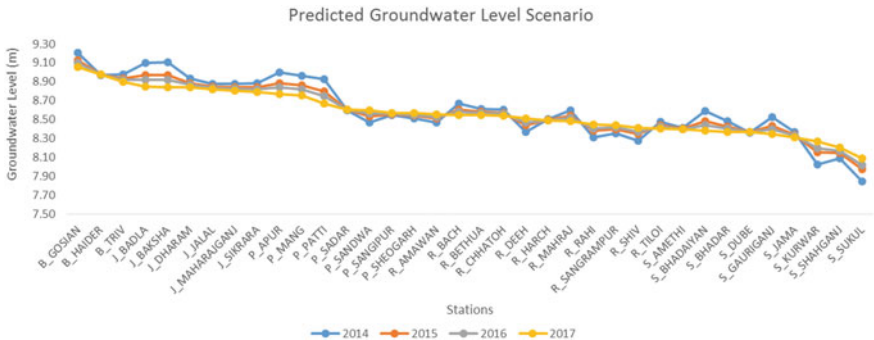**Fig. 5** Groundwater level in scenario 2

Fig. 6 Predicted groundwater level trend in study area under scenario 2

Uncertainty Analysis

Groundwater systems are composed of soil, water and many non-deterministic components. A systematic uncertainty analysis provides perception of the level of confidence in model estimates. Fuzzy numbers are used as alternative tool to address the parametric uncertainty when the model input parameters are limited or imprecise (Singh 2011). In the present study, fuzzy α-cut technique is utilized for uncertainty in hydraulic conductivity and porosity of groundwater flow model Visual MODFLOW. This technique uses fuzzy set theory to represent uncertainty in the parameters. Figure 7 shows a parameter P represented as a triangular fuzzy number with support of A_0. The wider the support of the membership function, the higher the uncertainty. The fuzzy set that contains all elements with a membership of $\alpha \ \varepsilon \ [0, 1]$ and above is called the α-cut of the membership function. At a resolution level of a, it will have support of $A\alpha$. The higher the value of a, the higher the confidence in the parameter (Li and Vincent 1995).

Fig. 7 Fuzzy number, its
support and α-cut
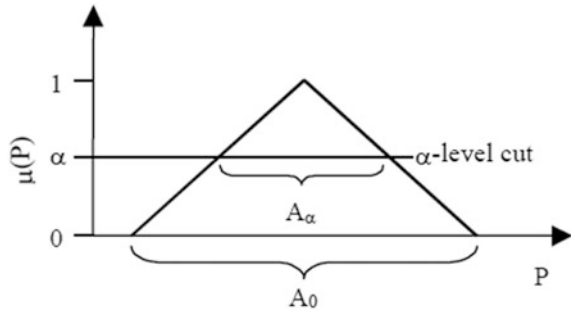
Fuzzy alpha-cut technique is based on the extension principle, which implies that functional relationships can be extended to involve fuzzy arguments and can be used to map the dependent variable as a fuzzy set. An alpha-cut is the degree of sensitivity of the system to the behaviour under observation. At some point, as the information value diminishes, one no longer wants to be "bothered" by the data. In many systems, due to the inherent limitations of the mechanisms of observation, the information becomes suspect below a certain level of reliability (Abebe et al. 2000). Membership functions define the degree of participation of an observable element in the set, not the desirability or value of the information. The membership function is cut horizontally at a finite number of α-levels between 0 and 1 (Fig. 7). For each α-level of the parameter, the model is run to determine the minimum and maximum possible values of the output. This information is then directly used to construct the corresponding fuzziness (membership function) of the output which is used as a measure of uncertainty.

In the present study, uncertainty analysis is performed to access the uncertainty associated with hydraulic conductivity and porosity of groundwater flow model Visual MODFLOW. Two different uncertainty scenarios, i.e. ±10 and ±15%, have been assumed for the assessment of uncertainty associated with above parameters. In case of hydraulic conductivity, the resulting uncertainty in both the uncertainty scenarios is found below 1%, which suggests that the head value is least sensitive to hydraulic conductivity up to ±15% uncertainty, while, in case of porosity, resulting uncertainty is observed to be zero.

Sensitivity Analysis

The purpose of a sensitivity analysis is to quantify the uncertainty in a calibrated model caused by uncertainty in the estimates of aquifer parameters, stresses and boundary conditions (Kumar and Elango 2004). Sensitivity analysis is typically performed by changing one parameter value at a time (Anderson and Woessner 1992). In the present study, the sensitivity of model with respect to hydraulic conductivity was examined. The model was run with changes in hydraulic

Table 1 Sensitivity analysis of hydraulic conductivity

S. No.	Variation in K	K (m/d)	RMSE (m)
0	No change	6.005	0.94
1	Increased by 5%	6.31	0.94
2	Increased by 10%	6.60	0.95
3	Increased by 15%	6.90	0.95
4	Decreased by 5%	5.71	0.92
5	Decreased by 10%	5.40	0.92
6	Decreased by 15%	5.11	0.91

conductivity, and RMSE value was calculated comparing the observed head value and model-simulated head values. The results are obtained from sensitivity analysis (Table 1) with changes in hydraulic conductivity values up to ±15%. Results revealed that the model is sensitive to decrease in hydraulic conductivity (K) value up to 15% compared to similar percentage of increase in K values. Lower values of RMSE are obtained for decrease in K values.

Conclusions

In this study, a groundwater system model has been developed for Sai–Gomti interfluve region, Uttar Pradesh, India. Groundwater system modelling has been performed using groundwater flow model Visual MODFLOW. The groundwater system has been simulated in both steady state and transient state for 8-year stress period. Further, this calibrated and validated model has been utilized to predict the groundwater levels from year 2014 to 2018 considering the effect of varying pumping and recharge rates. The observations from the different scenarios showed declining water level trend in study area. The maximum groundwater level of 8.90 m was observed during scenario 2 in Haidergarh block of Barabanki followed by Trivediganj Musafirkhana, Kurwar blocks of Sultanpur and Shivgarh, Singhpur blocks of Raebareli district. Also, sensitivity and parametric uncertainty analyses were performed using deterministic as well as fuzzy α-cut techniques. The analysis results revealed that the model is more sensitive to negative changes (decreased values) in hydraulic conductivity compared to positive changes (increased values) up to 15%. The simulation results show that the groundwater level is declining in Sai–Gomti interfluve region. This may be possible due to excess withdrawal of groundwater mainly for agricultural activities.

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