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Groundwater flow modeling in a part of Ganga-Yamuna Interfluve region

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ABSTRACT

Groundwater is the main source of water supply and irrigation in the Ganga-Yamuna interfluve region. Heavy withdrawal of groundwater has set a declining trend of water table over the decade. The groundwater withdrawal is continuously on the rise resulting in overexploitation and also quality deterioration. Therefore, proper groundwater system modeling and management is imperative. Groundwater flow modelling has been performed in this work to simulate the groundwater flow system in a part of Ganga-Yamuna interfluve region of eastern Uttar Pradesh, India. Groundwater simulation model Visual MODFLOW has been utilized to simulate the flow processes in the study area. The model simulates groundwater flow over an area of about 1908.95 km^2. The horizontal flows and recharge from rainfall were considered with proper boundary conditions. Visual MODFLOW was calibrated and validated for water level data available for 8 years (2005 to 2013) under steady and transient conditions. Aquifer parameters (hydraulic conductivity and storativity) are tuned and optimized using PEST (Parameter Estimation) analysis. Calibrated and validated model was further employed to predict the groundwater levels under possible changes in recharge and pumping up to 2020. Results

obtained from the study reveals the composite dynamics of rainfall, groundwater recharge, groundwater level and pumping in the study area.

Keywords: Groundwater simulation, Visual MODFLOW, Ganga-Yamuna interfluve region, groundwater level, aquifer parameter optimization

1. INTRODUCTION

Groundwater is the most reliable source of water for industries, domestic and irrigation activities. The increasing dependence on groundwater as reliable source of water has resulted in decline in groundwater levelin various parts of the country (Mayuri Prajapati et al. 2015; Kuldeep Tiwari et al. 2015; Ruby Pandey et al. 2015). In this scenario of declining groundwater level, it is necessary to investigate the groundwater system with respect to recharge, withdrawal and storage capacity and groundwater system modelling for groundwater management (Grechushnikova et al. 2015). Groundwater management has been subject of much research. The effect of conjunctive use on water logging in lower Gandak basin of Bihar was investigated by Chakravorty et al. (2014) to observe the effects of conjunctive use of surface and groundwater on water logging scenarios. Alam F and Umar R (2013) simulated the behavior of groundwater flow system in Hindon-Yamuna interfluve region, western Uttar Pradesh. Optimized sustainable groundwater extraction management of Lucknow city was carried out by Singh et al. (2013). Ahmed et al. (2008) studied the groundwater flow system in Yamuna-Krishni inter-stream region using steady and transient state numerical groundwater flow model to investigate the effects of further groundwater development.

The present work simulates the groundwater system using groundwater system model Visual MODFLOW to predict the groundwater level in Ganga-Yamuna interfluve region in eastern Uttar Pradesh, India. Also, the sensitivity of the model to hydraulic conductivity has been performed by fluctuating the hydraulic conductivity over a range of values and observing the response of model and determining the RMSE of the simulated groundwater heads to the measured heads.

2. GROUNDWATER SYSTEM SIMULATION

The equation describing steady, 2-D 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:

$$\frac{\partial}{\partial x_i} = \left(T_{ij}\frac{\partial h}{\partial x_j}\right) = W; \quad I,j = 1,2 \qquad (1)$$

Where, T_{ij}= Transmissivity tensor; K_{ij} = hydraulic conductivity tensor; b = saturated thickness of aquifer; h = hydraulic head; W = Volume flux per unit area (+ sign = outflow and - sign = inflow); and xi, $x j$ = Cartesian coordinates.

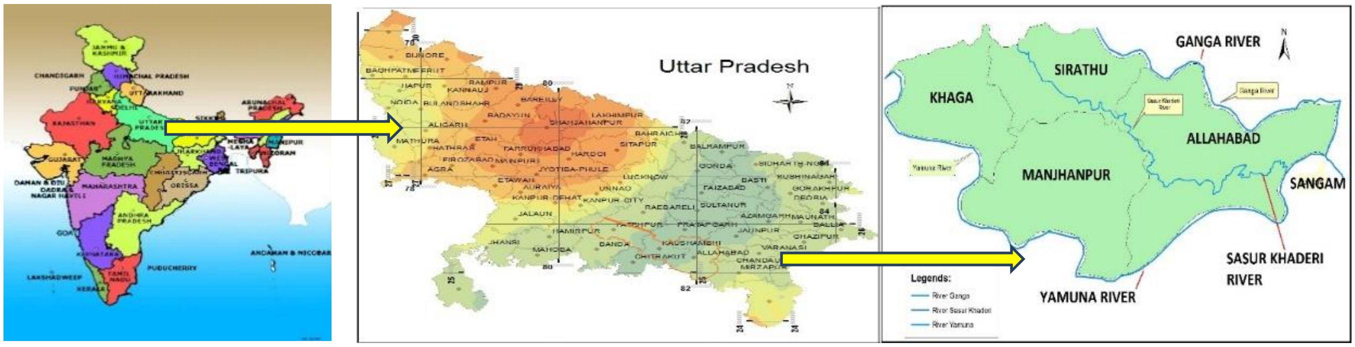
In present study, Visual MODFLOW groundwater model has been usedfor the simulation of groundwater flow processes. It solves numerically the 3-D groundwater flow equation (Equation 2) for porous media by finite-difference method. The equation 1 can be further expandedas (McDonald and Harbaugh, 1988):

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

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.

3. STUDY AREA

The study area is a part of Ganga-Yamuna interfluve region in eastern Uttar Pradesh, India. The location map of study area is shown is Figure 1. This study covers the Sirathu and Manjhanpur towns of Kaushambi district, Khaga town of Fatehpur district, and Allahabad district, Uttar Pradesh, India. The study area is bounded between Latitude 25^{0}40’53.15” N to 25^{0}28’36.52” N and Longitude 81^{0}0’8.09” E to 81^{0}53’21.34” E. The total area covered in present study is 1095 km^2.The study area is bounded by Ganga river as the northern boundary and Yamuna river as the southernboundary. An intermittent river, SasurKhaderi, joins the Yamuna river in Karelibagh, Allahabad. The confluence of Ganga and Yamuna river at Allahabad forms the eastern extremity of study area. The study area has tropical climate as the average maximum temperature ranges between 43°C-45°C which may rise up to 46°C during peak summers. The minimum average temperature is 8-9°C which may fall as low as 4°C during peak winter months (December-January). The average rainfall of the study area is 960 mm and the monsoon season is spread between July-September.



(a) (b) (c)

Figure 1 Location map studies are: (a) India (b) Uttar Pradesh (c) Study area

4. MODEL INPUTS AND BOUNDARY CONDITIONS

In present study, Visual MODFLOW groundwater model has been used for the simulation of groundwater flow processes. The area of 1908.95 km^2 has been divided into equal sizes grid network of 47 rows and 40 columns. Thus, the area has been divided into 1880 equi-dimensional cells. Each cell represents area of 1.015 km^2.Due to shortage of the data related with aquifer parameters, the data of hydraulic conductivity and specific yield were adopted from the similar contiguous areas and the available reports. 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.

4.1. Stress Period

In present study, stress period of 8 years (2005-2013) has been considered. Inflow and outflow are the main constraints of stresses in groundwater system. Recharge due to rainfall and return flow from irrigation are main components of inflow in groundwater systems. Block-wise groundwater draft figure (CGWB, 2009 and CGWB, 2011) has been used for cell-wise distribution of draft.

4.2. Hydraulic Parameters

The input value of hydraulic conductivity (K) was taken as 5.0 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) = 5.25 m/day and specific storage value of 0.1/m with coefficient of storage (S) as 0.35.

4.3. Recharge

Recharge due to inflow from river/canal and head dependent boundaries would be taken care by the model automatically depending on the heads in the boundaries. The areal recharge due to rainfall has been taken as 20% of rainfall. The estimated values were applied to the respective grid in the model using recharge boundaries.

4.4. Boundary Conditions

Boundary conditions describe the exchange of flow between model and external system. The specification of boundary conditions is the critical and complex task in groundwater flow modeling (Midllemis, 2000). It is considered as one of the most important aspects of calibrating and validating the model. In present study, the northern boundary of model is bounded by Ganga River and southern boundary of the model is bounded by Yamuna river. These two boundaries intersect each other at confluence of Ganga and Yamuna River at Sanagm, Allahabad. SasurKhadeririver joins the Yamuna River in Karelibagh, Allahabad and this river has been assigned river boundary condition. Cluster of few grid cells in western part of the study area have been 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.

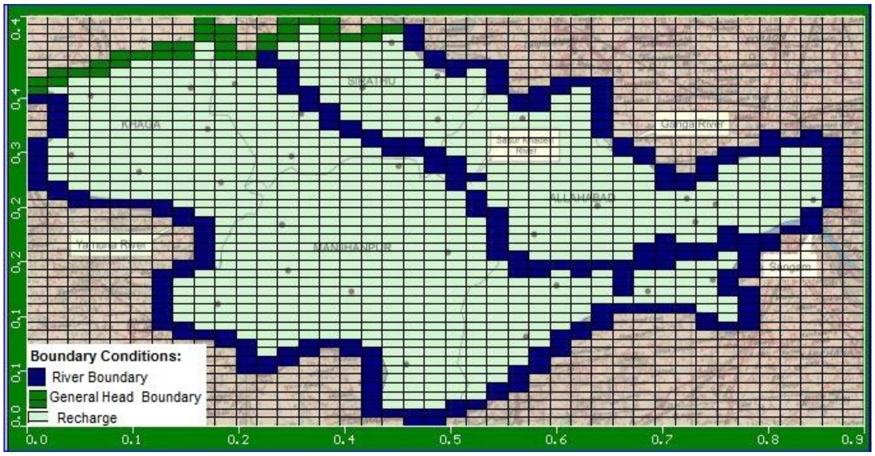


Figure 2 Map showing grid pattern and boundary conditions

5. MODEL CALIBRATION AND VALIDATION

The model was simulated with initial and boundary conditions, input values of aquifer parameters. During initial run, the difference between the observed and computed water table were noticeable and thus minor calibrations of aquifer parameters was performed. During calibration, minor adjustments of initial values of aquifer parameters were adopted. The calibration was performed using 36 observation wells in the study area. The model was calibrated, in steady state and transient state using data sets from year 2005 to 2013 (8 years). After a number of trial runs, the computed head obtained with the calibrated parameters showed a close match with the observed head.The Mean error was noticed as 0.022 m after calibration of model and RMSE was observed as 0.902. The absolute residual mean was found to be 1.204 m.

6. PREDICTIONS AND SENSITIVITY ANALYSIS

Three different scenarios were considered to predict the behavior of the groundwater regime in Ganga-Yamuna interfluve region during the period 2014-2020. These scenarios are explained below.

Scenario 1: Increase in current withdrawal rate

During this prediction scenario the current withdrawal rate was increased by 20% from 2014 to 2020, over a period of 6 years. The initial recharge was kept constant throughout the prediction period. It was observed during this prediction run that the blocks: Samsabad, Silraha, Kadipur, KoraonDevkharpur, MalakBuzurg in Sirathu, Kaushambi district; TiyaraJamalpur, Arka, Newari in Manjhanpur, Kaushambi district; and Parsana, Shamspur, Gohri in Allahabad district are significantly affected. The drawdown of 12.19 m was observed in these areas as shown in Figure 3.

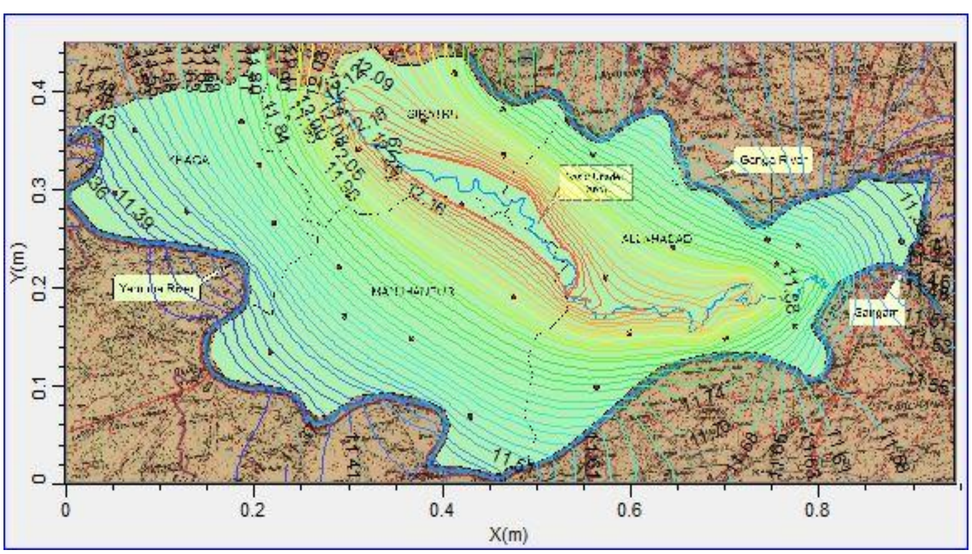


Figure 3 Drawdown prediction in scenario 1

Scenario 2: Decrease in recharge

The combined effect of increased withdrawal rate by 20% and reduced rainfall by 20% was studied in this prediction scenario. The combined effect of both these factors revealed that the almost all the blocks in study area have declining water level trend with maximum drawdown of 12.26 m in Badanpur block of Sirathu, Kaushambi district (Figure 4). The drawdown in this scenario was observed to be higher as compared to scenario 1.

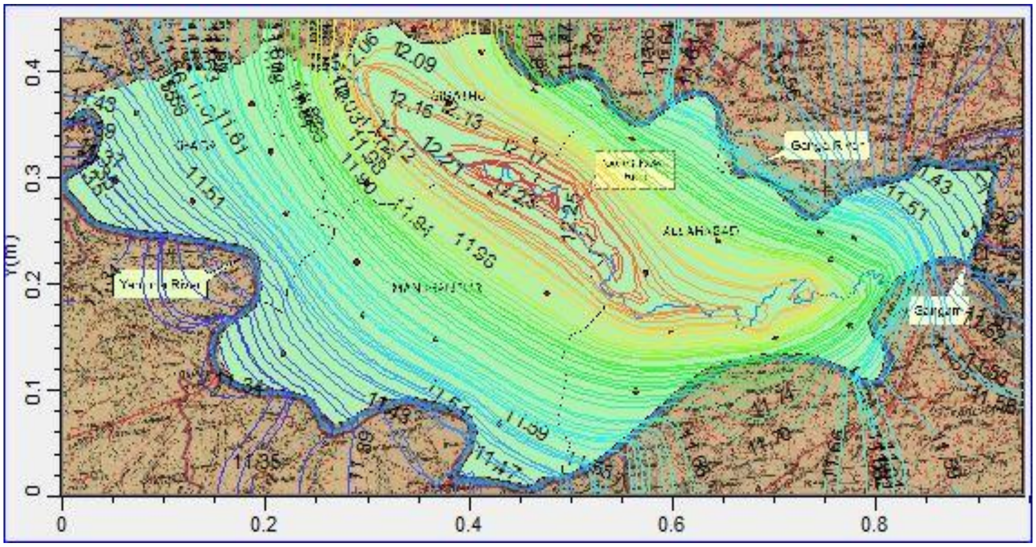


Figure 4 Drawdown prediction in scenario 2

Scenario 3: Introducing recharge through canal

In order to mitigate the groundwater depletion at some locations in study area, additional recharge of 300 mm/year was applied over the study area. This is a practically possible scenario. The recharge from surface water structures and through water harvesting reduced drawdown to 12.13m in affected areas (Figure 5).

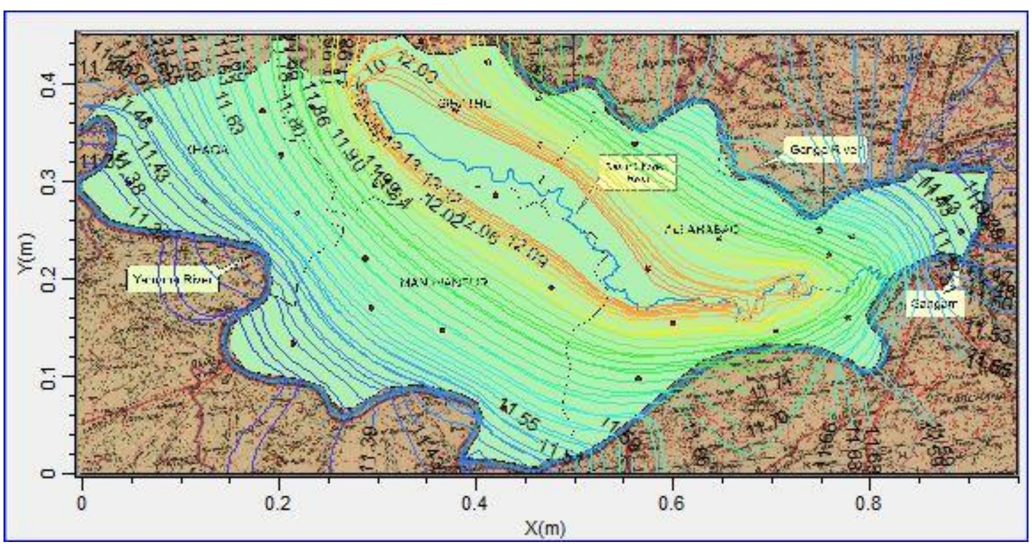


Figure 5 Drawdown prediction in scenario 3

6.1. 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 S.and Elango, 2004). Sensitivity analysis is typically performed by changing one parameter value at a time (Anderson and Woessner, 2002). In the present study, the sensitivity of model with respect to hydraulic conductivity was examined. The model was run with changes in hydraulic conductivity and RMSE value was calculated comparing the observed head value and model simulated head values. The results obtained from sensitivity analysis (Table 1) with changes in hydraulic conductivity values up to ±15 percent. Results revealed that the model is sensitive to decrease in hydraulic conductivity (k) value up to 15 percent compared to similar percentage of increase in k values.

Table 1 Sensitivity analysis of hydraulic conductivity

Sr. No.	Variation in K	K (m/d)	RMSE (m)
0	No change	5.25	0.902
1	Increased by 5%	5.51	0.895
2	Increased by 10%	5.78	0.896
3	Increased by 15%	6.04	0.893
4	Decreased by 5%	4.99	0.881
5	Decreased by 10%	4.72	0.879
6	Decreased by 15%	4.46	0.873

7. CONCLUSION

In this study, a groundwater model has been developed for a part of Ganga-Yamuna interfluve region in eastern Uttar Pradesh, India. Visual MODFLOW is utilized to simulate groundwater flow system in both steady state and transient state for 8 years stress period. Further, calibrated model was employed for prediction of drawdown from year 2014 to year 2020 considering effect of varying pumpage and recharge rates. The maximum drawdown of 12.26m was observed during scenario-2 in Badanpur block of Sirathu, Kaushambi district. In addition, sensitivity of model to hydraulic conductivity was examined by varying the values and observing model response. 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 percent.

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