

Chapter 10

Development of a Three-Dimensional Mathematical Groundwater Flow Model in Raipur City Area, Chhattisgarh, India



Suvendu Kumar Sahu and D. C. Jhariya

Abstract Groundwater is one of the most important natural resources. In the current situation, it is important to consider the condition of groundwater to suggest a proper exploration pattern and management strategy to fulfill the need of society without changing its natural characteristics. Among the methods suggested for the overall assessment of aquifer characteristics, groundwater modeling is considered as an effective management tool to study the aquifer response with different hydrological stress conditions. This present study is concentrating on the study of aquifer conditions in Raipur city with the suggestion of a fruitful management strategy. In order to understand the causes of water table declination, a two-layered finite-difference flow model was formulated for the region by using Visual MODFLOW software. Water level data of 21 well have been collected from all over the study area. Data such as, hydrological data, empirical values, and equations were used for the development of the groundwater transient flow model, water budget estimation, and to know the impact of over-pumping on the aquifer system.

Keywords Groundwater model · MODFLOW · Groundwater · Raipur city Chhattisgarh

10.1 Introduction

The high demand of groundwater for the swiftly growing population has increased the rate of requirement and trigger the effective management of available groundwater resources. The management of water resources needs a proper assessment and visualization of its overall structure and which is effectively visualize with the help of groundwater modeling software. The groundwater modeling has consid-

S. K. Sahu · D. C. Jhariya (✉)

Department of Applied Geology, National Institute of Technology Raipur, G.E. Road, Raipur, Chhattisgarh 492010, India

e-mail: dcjhariya.geo@nitrr.ac.in

ered as a multidisciplinary management tool which can carry out multiple functions like furnishing a framework for arranging hydrological data, assessing the behavior and properties of the aquifer system, and allowing both quantitative and qualitative prediction of responses of the system on applied stress condition (Rojas and Dassargues 2007; Senthilkumar and Elango 2004). Researchers all over the world have attempted the development of groundwater modeling for the effective management of groundwater resources in their respective areas (Akbariyeh et al. 2018; Lee et al. 2005; Yehia et al. 2013).

As the capital city, Raipur is experiencing rapid growth. The consumption of groundwater in the city has been noticeable increases to satisfy the growing demand for groundwater for domestic and agricultural purposes. Due to the over-extraction of groundwater, the water table in the area is showing a trend that is gradually falling with time to time (Central Ground Water Board 2012–13; Khan and Jhariya 2018). This study has been designed by considering this scenario by investigating the aquifer condition with present stress conditions and as a result, it suggests a possible management strategy to overcome the withstanding groundwater-related issues. The objectives of this study that has considered to solve the problem are (a) development of a flow model to assess the flow pattern and budget, (b) development of a transient flow model to assess the water table and to forecast for 14,600 days, and (c) fixing a suitable pumping rate and to decide recharge site as a management strategy for groundwater extraction without harming the natural aquifer condition.

10.2 Materials and Method

10.2.1 Study Area

The area selected for the current study is falling under the Raipur district and is bounded by two water bodies, namely Kharun River and Chhokra Nala (Fig. 10.1). The study area falls under Survey of India toposheet no. 64G/11 and 12 in a scale of 1:50,000. The area is located in between latitude 21°12' N to 21°25' N and longitude 81°31' E to 81°42' E. The total area is around 192 km² with an almost gentle sloped landmark. It is situated about 300 m above mean sea level. The climate of the area is tropical, warm, and semi-arid with temperatures varying from 10 to 40 °C. The average humidity is more or less 55%. The southwest monsoon is prominent in the area. It receives an average rainfall of 1230 mm from June to September (Central Ground Water Board 2016–17).

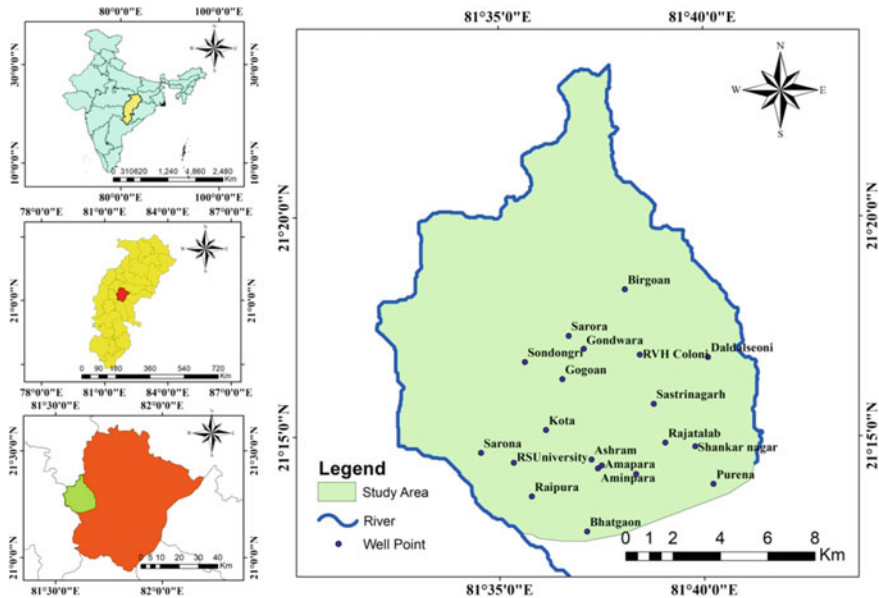


Fig. 10.1 Location of study area

10.2.2 Local Geology

The study area mainly consists of sedimentary rocks of the Precambrian age, coming under the Raipur group of the Chhattisgarh supergroup. Raipur group of rocks is consisting of Bejepur, Charmuriya, Gunderdehi, Chandi, Tarenga, Hirri, and Maniyari formations. The Raipur group is underlined by the Chandrapur group and overlain by the Mesozoic Gondwana supergroup (Table 10.1). Rocks of the Raipur group are mainly argillite-carbonate sequence and consist of limestone, shale, dolomite, and sandstone (Vaidyanadhan and Ramakrishnan 2010).

The Chandi formation is the major geological unit of the Raipur group which is exposed in the Raipur city. Its thickness varies from 103 to 136 m (Sinha et al. 2002). Chandi formation comprises Deodonger shale, limestone, and sandstone. The nature of the limestone exposed in the city is cavernous and jointed. Chandi formation overlies the Gundardehi formation with a sharp contact. Gundardehi formation occurs in the Raipur city comprises mainly shale and limestone.

10.2.3 Hydrogeology

The aquifer of the area is defined by the Chandi formation and is categorized under unconfined aquifer type. Groundwater in the aquifer is mainly occupied in fractures

Table 10.1 Stratigraphic succession of Raipur group of Chhattisgarh supergroup after Das et al. (1992) and Deb (2004)

Group	Formation (thickness in m)	Lithology
Raipur group (1900 m)	Maniari shale (70)	Purple shale, dolomite, gypsum
	Hirri dolomite (70)	Gray dolomite
	Tarenga shale (180)	Dolomitic shale, shale-chert beds, purple shale, limestone
	Chandi limestone (670)	Stromatolitic dolomite, limestone, glauconitic sandstone, shale
	Gunderdehi shale (430)	Shale with limestone interbeds, arenite-shale, ignimbrite
	Charmuria limestone (490)	Phosphatic limestone with shale interbeds, cherty limestone and phosphatic dolomite, chert-shale interbeds
	Bijepur shale (100)	Green and brown calcareous shale with sandy interbeds
Unconformity.....
Chandrapur group (400 m)		

and solution cavities developed in the formation. The length of casing installed in the formations varies from 8.00 to 40.00 m with respect to the variable thickness of this formation. The average numbers of fractures encountered in the formations are of 2–12 numbers, within an average depth of 13–137 m. Determined yields are varying from 0.1 to 40 m³/day in the study area with a maximum drawdown of 35.47 m. The static water level of the area is varying between 1.99 and 18.07 mbgl (Central Ground Water Board 2011).

10.2.4 Model Conceptualization

The hydrogeological system of the study area is conceptualized according to the overall picture that developed from the detailed study of geology, geomorphology, borehole lithology, well location, and data of water level fluctuation. Groundwater in the area is distributed in both Chandi and Gundardehi formations. Based on the collected information, the model is conceptualized as a single-layered unconfined aquifer having a variable thickness from 80 to 190 m.

10.2.4.1 Boundary Condition

The study area is surrounded by Kharun River on the north and west side and Chhokra Nala is on the eastern side. Both rivers are considered as constant head boundaries. The third boundary is the southern one, which covers 1150 km is considered as a specified flux boundary. The flux across the boundary has been assigned from the amount of flow calculated from the existing datasets (Fig. 10.2).

10.2.4.2 Grid Design

The model grid of the study area was discretized into 646 cells including 17 columns, 19 rows, and 2 layers. The cross-sectional length of the layers is 19 km toward north–south and 17 km toward east–west, respectively (Fig. 10.3).

10.2.4.3 Initial Groundwater Head

Initial groundwater head is one of the important parameters uses in the ground-water modeling has been collected during seasons of pre-monsoon and post-monsoon during the years of 1998–2000. The water level data of twenty numbers wells from different locations of the study area have been processed and converted into water table data for assigning the initial head value (Table 10.2).

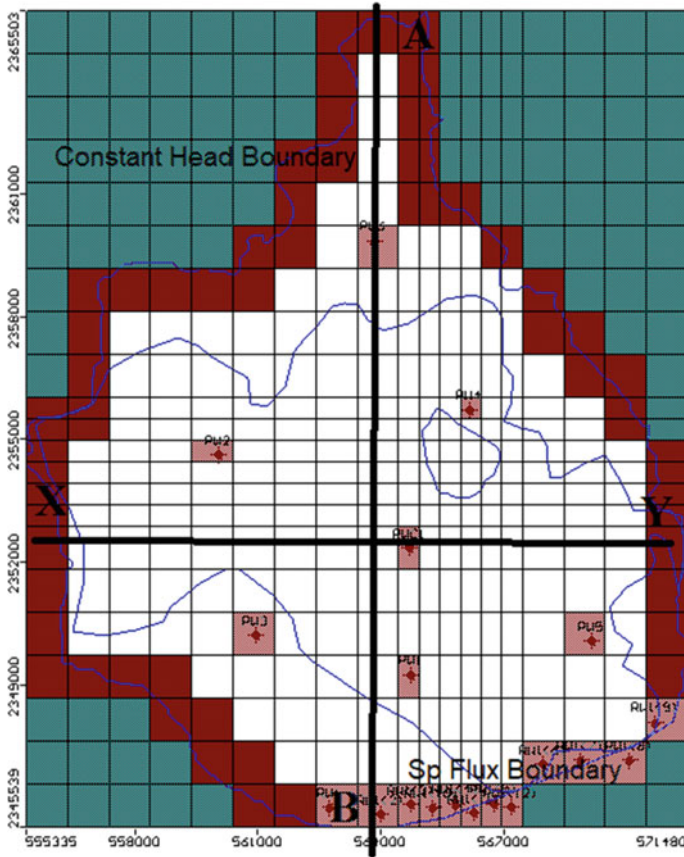


Fig. 10.2 Discretization of study area

10.2.4.4 Aquifer Characteristics

Major aquifer parameters like hydraulic conductivity (K), transmissivity (T), storativity (S), and specific yield (S_y) were gathered from the groundwater exploration report of Chhattisgarh state (CGWB 2011). Hydraulic conductivity (K) is varying between 10 and 21 m/day. Specific yield ranges from 0.01 to 0.025. The thickness of the aquifer varies from around 80 to 190 m. The reported value of storativity is between 3.0×10^{-5} and 3.7×10^{-4} , and transmissivity is 69–1500 m²/day (Central Ground Water Board 2016).

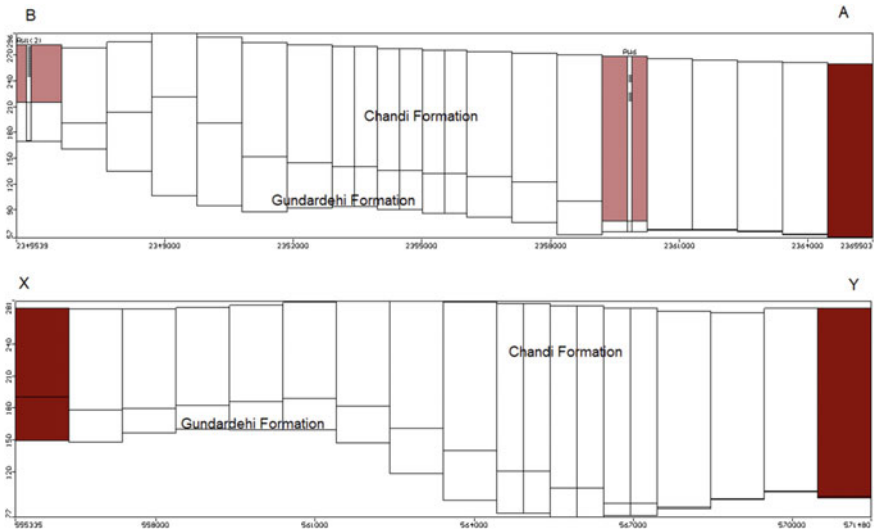


Fig. 10.3 Cross-sectional view along AB and XY

10.2.4.5 Groundwater Abstraction and Recharge

The major utilization groundwater withdrawal in Raipur city is for agriculture and domestic use. Throughout the year, majority of the localities in the Raipur city depends on groundwater source for different activities related to agriculture. The rate of discharge of groundwater on average is determined as 13,400 m³/day. It shows an increasing trend with 5% in each successive year. Groundwater extraction was calculated based on the population report of census 2001 and 2011, which is about 22 l per capita per day (lpcd).

Rainfall is the main source of groundwater recharge in the area. Rainfall data are collected from annual reports of the Central Ground Water Board (Central Ground Water Board 2016–17) and as per the Groundwater Resources Estimation Committee report of the Government of India, infiltration capacity ranges from 15 to 20% (GREC 1997).

10.2.5 Model Description

The developed model is an anisotropic and heterogeneous three-dimensional groundwater flow model. The model is developed by considering equivalent porous media (EPM) approach. It is considered to possess constant density, described by partial differential equation (Brown et al. 1998; Ding et al. 2014; McDonald and Harbaugh 1988; Wei et al. 2018).

Table 10.2 Pre- and post-monsoon water level data of different well

Area	Latitude	Longitude	Elevation (m)	1998 Jan DTW (m)	1998 May DTW (m)	1999 Jan DTW (m)	1999 June DTW (m)	2000 March DTW (m)	2000 June DTW (m)
Bhatgaon	21.21389	81.61889	289.99	6.26	5.1	10.7	11.78	11.48	12.03
Raipura	21.22729	81.59645	285.83	2.27	6.3	5.25	6.75	5.94	7.69
Sarona	21.24394	81.57584	276.16	2.32	3.22	3.42	3.47	3.22	3.52
Kota	21.25255	81.6023	297.23	7.44	7.89	8.76	9.04	8.94	9.33
Ashram	21.24123	81.62076	302.58	1.46	1.54	1.58	1.72	1.62	1.78
Amapara	21.23898	81.62498	297.67	2.4	6.63	3.01	3.68	3.76	4.83
Burapara	21.23567	81.63891	302	8.7	9.7	10.34	11.87	11.68	12.95
Amnpara	21.2379	81.62337	298.45	1.27	1.13	2.63	2.39	3.22	2.67
Sondongri	21.27844	81.59385	281.99	2.22	1.74	2	2.22	2.05	2.23
Sarora	21.28833	81.61167	281.84	2.52	8.35	4.2	8.76	5.92	8.82
Gondwara	21.28337	81.61779	276.49	1.41	5.7	6.12	7.75	7.68	8.6
Goguan	21.27188	81.60907	276.18	2.99	8.35	3.1	8.67	3.97	9.05
Birgoan	21.30574	81.63464	294	8.6	9.37	9.78	10.35	10.86	11.34
RVH Coloni	21.28109	81.64063	288	5.66	6.96	4.51	7.86	7.25	7.96
Rajatalab	21.24757	81.65086	273.83	2.05	1.18	1.42	1.77	2.71	3.07
Daldalseoni	21.28008	81.66837	286.6	1.07	2.36	1.67	2.02	2.87	6.53
RSUniversity	21.24012	81.58918	261.66	4.74	6.82	5.76	7.12	7.43	8.09
Sastrinagarh	21.26237	81.6462	293.99	3.77	4.05	4.07	4.16	3.13	4.52
Shankar nagar	21.24611	81.66306	295.39	7.46	8.12	8.4	9.36	9.74	10.03
Purena	21.23177	81.67038	293.5	2.38	4.15	2.3	5.74	6.94	7.58

$$\frac{d}{dx} \left[K_{xx} \frac{dh}{dx} \right] + \frac{d}{dy} \left[K_{yy} \frac{dh}{dy} \right] + \frac{d}{dz} \left[K_{zz} \frac{dh}{dz} \right] - Q = S_s \frac{dh}{dt}$$

where

K_{xx}, K_{yy}, K_{zz}	Hydraulic conductivity along x, y, z axes
h	Head
Q	Volumetric flux per unit volume
S_s	Specific storage coefficient.

The simulation of the model has been attempted with the help of three-dimensional finite-difference MODFLOW and Visual MODFLOW.

10.3 Model Calibration

Model calibration can simply achieve by minimization of the error in the final result. The model has been calibrated to match or reduce the difference between computed value and the observed/field value by changing the influencing factors such as aquifer parameters and stress value (Akbariyeh et al. 2018; Vetrinurugan et al. 2017). Here, two steps of calibration have been used. The first one is a trial and error method, and the second best method is the trial and error followed by the PEST (parameter estimation) method (Doherty et al. 1994). The steady-state calibration was adopted for the year 1998. The primary special distribution of hydraulic conductivity was 20 m/day obtained from the available data, and the corresponding value was distributed in three zones based on lithological properties to compare the historical water table values. During trial and error, calibration different hydraulic conductivity values were adopted. After trial and error calibration, the PEST was used for improvisation of the steady-state calibration.

Transient state calibration was adopted for the year 1998–2001. Similarly, to the parameter hydraulic conductivity here, storage coefficient has been used with trial and error calibration. Finally, to get the improved calibration minor change of hydraulic conductivity value of steady state was made by keeping all other parameters constant. Calibration targets are arbitrary defined as for steady state, normalized root mean squared (NRMS) is 3.63%, absolute residual mean (ARM) is 1.3 m, root mean squared (RMS) is 1.996 m and for transient state NRMS is 4.87%, ARM is 1.67 m, and RMS is 1.999 m (Fig. 10.4).

The model simulation was operated out under a transient state for a duration of 14,600 days from the year 2000 to 2040. PEST and trial and error were used for the calibration of the transient model. After numerous trial runs a fair match between observed and computed head was obtained. There is very little difference between the calibrated value of hydraulic conductivity of steady and transient states. Observed

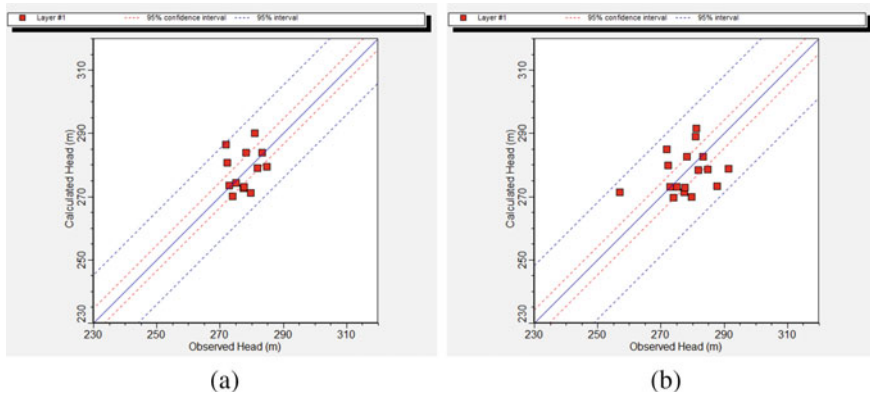


Fig. 10.4 Calibration: **a** comparison of observed and computed groundwater head in steady state. **b** Comparison of observed and computed groundwater head in the transient state

and simulated head values are comparable and having an alike trend for the duration from 1998 to 2000 and from 2000 to 2040.

This study reveals that the groundwater head is maximum at the southeast side and minimum at the northwest side which follows the general topographic trend. The flow of groundwater is from the southeast to the northwest side in this study area. The transient groundwater table of this area with the present average pumping rate from 2000 to 2040 is given in Fig. 10.5.

10.4 Sensitivity Analysis

Sensitivity analysis has been performed during model calibration by changing parameters such as hydraulic conductivity, recharge, and specific yield one by one to match the computed data with observed data. Sensitivity analysis is to determine the input parameters that have much more influence on the output result. Sensitivity analysis helps to understand the response of the aquifer system to different parameter conditions (Sathe and Mahanta 2019; Senthilkumar and Elango 2004). Here, hydraulic conductivity is the most sensitive parameter for this aquifer system by changing the hydraulic conductivity value 3–8 m/day for different spatial distribution, it matches the computed value with real-time aquifer condition.

10.5 Results and Discussion

The developed steady and transient flow model have concluded an idea about the present and transient groundwater flow direction, water table changing pattern with

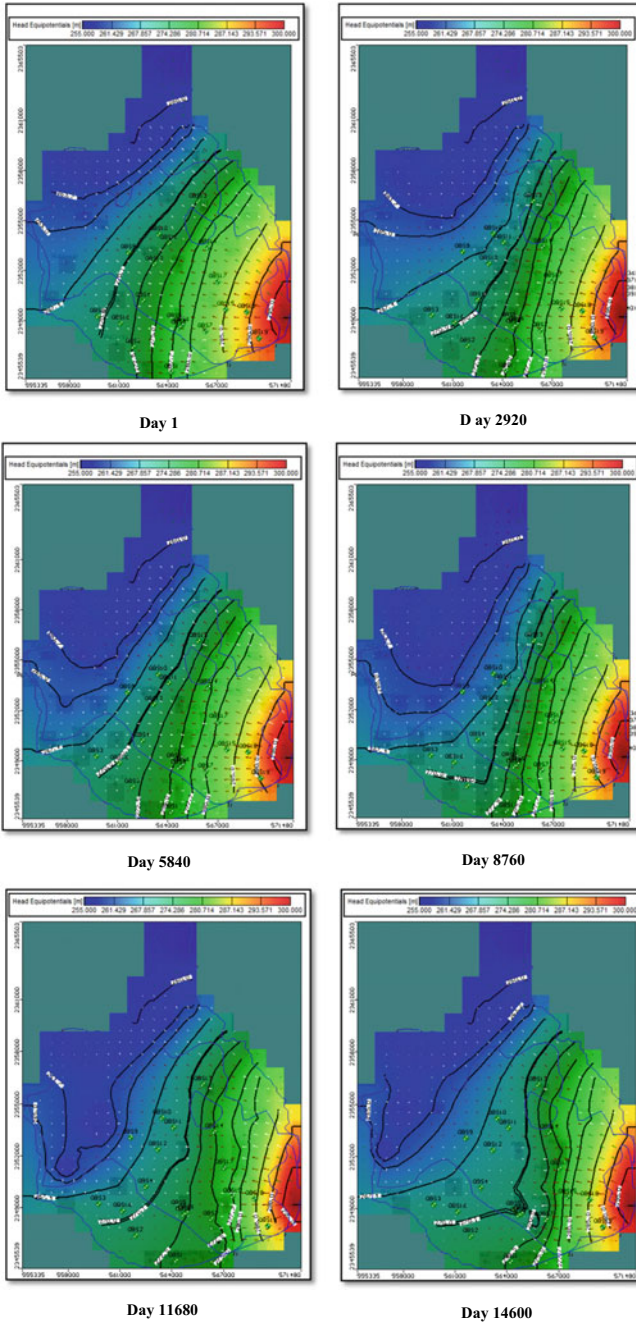


Fig. 10.5 Transient water table with persisting pumping rate

reference to applied stress, water budget, and pumping strategy as a mitigation plan for future water table decline to protect the aquifer of the study area for a long duration. While considering groundwater flow direction, the water table is higher in the southeast part and sequentially lower down toward the northwest side so groundwater is flowing from southeast to northwest by following the general topographic trend and from the steady-transient flow model has shown an output like the water table will deplete near about seven meter from 2001 to 2040 with the persisting stress condition (Fig. 10.5). Flow budget is not balanced by total inflow with total outflow. Total outflow is higher than the total inflow in this aquifer system.

10.6 Prediction and Assessment

10.6.1 *Scenario One (Groundwater Condition with Persisting Pumping Rate)*

In and around, Raipur city people depend on agriculture so they extract water for domestic and cultivation purposes. Simulation with the persisting average pumping rate of 13,400 m³/day with increasing 5% each year resulting groundwater table in the Raipur city area will decrease up to seven meters up to 2040 (Fig. 10.5).

10.6.2 *Scenario Two (Groundwater Condition with 22% Less Pumping Rate)*

The second scenario is all about the management strategy to reduce the water table depletion by minimize the water extraction and establishing a recharge well. The promising step for the management is minimizing pumping from the area (Abu-El-Sha'r and Hatamleh 2007; Rejani et al. 2007; Yehia et al. 2013). By numerous trial and run with keeping the all other parameters constant, if the pumping rate will be reduced 22% than the persisting pumping rate and three recharge well will establish in Ashram, Hatband, and Urla area with an average recharge rate of 110 m³/day to 25 m screen depth, then there will be very little change in the water table. The transient flow model with the prescribed suggestion is shown with different duration (Fig. 10.6).

10.7 Conclusion

The transient flow model of the Raipur city area has provided an idea about the present scenario of the aquifer and its behavior to persisting stress conditions. The

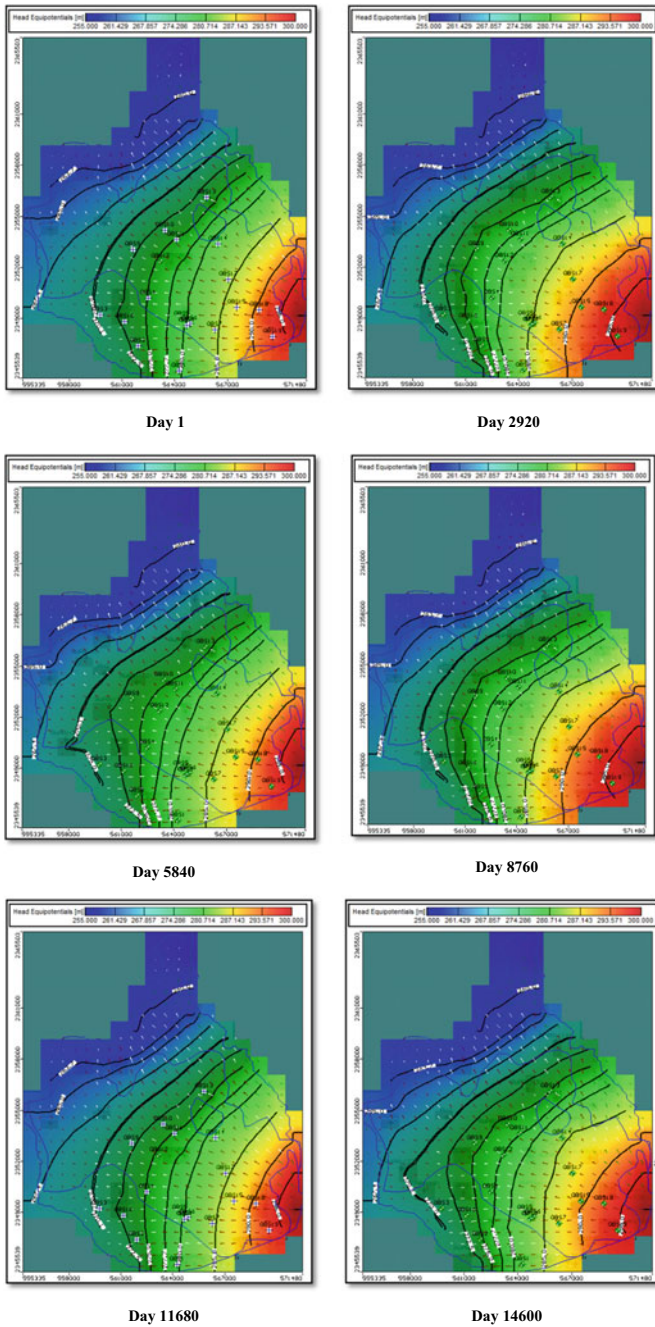


Fig. 10.6 Transient water table with a suggested strategy

developed model is simulated with a fair level of accuracy. Based on the simulation result, the followings can be reckoned and directed for the study area:

- a. This study represents the flow direction, i.e., from southeast to northwest direction, and water budget is not balanced with higher outflow in static condition with present stress condition.
- b. The transient model has given a conclusion like with an average pumping rate of 13,400 m³/day which is persisting stress condition, the water table will deplete nearly seven meters by 2040, which indicates that the study area is under the threat of depletion of the water table.
- c. Lastly, the most promising management strategy for the study area is to reduce the 22% pumping rate than the persisting pumping rate and establish a recharge well at Ashram, Hatband, Urla area by which the water table will be maintained same.

References

- Abu-El-Sha'r WY, Hatamleh RI (2007) Using modflow and MT3D groundwater flow and transport models as a management tool for the Azraq groundwater system. *Jordan J CivEng* 1:153–172
- Akbaryeh S, Hunt SB, Snow D, Li X, Tang Z, Li Y (2018) Three-dimensional modeling of nitrate-N transport in Vadose zone: roles of soil heterogeneity and groundwater flux. *J Contam Hydrol* 15–25
- Brown PL, Guerin M, Hankin SI, Lowson RT (1998) Uranium and other contaminant migration in groundwater at a tropical Australian uranium mine. *J Contam Hydrol* 295–303
- Central Ground Water Board (2011) Ground water exploration in Chhattisgarh State Ministry of Water Resources. Central Ground Water Board, pp 67–68
- Central Ground Water Board (2012–13) Groundwater brochure of Raipur District, Chhattisgarh
- Central Ground Water Board (2016) Aquifer mapping in Bemetara and Saja blocks, Bemetara district, Chhattisgarh. Central Ground Water Board, pp 22–25, 37–39, 62
- Central Ground Water Board (2016–17) Groundwater year book Chhattisgarh. Central Ground Water Board, pp 7, 82
- Das DP, Kundu A, Das N, Dutta DR, Kumaran K, Ramamurthy S, Thanavelu C, Rajaiya V (1992) Lithostratigraphy and sedimentation of Chhattisgarh basin: Indian minerals. 46:271–288
- Deb PS (2004) Lithostratigraphy of the neoproterozoic Chhattisgarh sequence: its bearing on the tectonics and Palaeogeography. *Gondwana Res* 7:323–337
- Ding F, Yamashita T, Lee HS, Pan J (2014) A modelling study of seawater intrusion in the Liao Dong bay coastal plain, China. *J Mar Sci Technol* 22(2):103–115
- Doherty J, Brebber L, Whyte P (1994) PEST: model-independent parameter estimation. User's manual. Watermark Computing, Corinda, Australia
- GREC (1997) Groundwater Resources Estimation Committee report of the groundwater resources estimation methodology. Government of India, New Delhi, p 107
- Khan R, Jhariya DC (2018) Hydrogeochemistry and groundwater quality assessment for drinking and irrigation purpose of Raipur City, Chhattisgarh. *J Geol Soc India* 91:475–482
- Lee MS, Lee KK, Hyun Y, Clement TP, Hamilton D (2005) Nitrogen transformation and transport modeling in groundwater aquifers. *J Ecol Model* 143–159
- McDonald MG, Harbaugh AW (1988) A modular three-dimensional finite-difference ground-water flow model. U.S. Geol Surv 6A1:89

- Rejani R, Jha MK, Panda SN, Mull R (2007) Simulation modelling for efficient groundwater management in Balasore Coastal Basin, India. *Water Resour Manage* 22:23–50
- Rojas R, Dassargues A (2007) Groundwater flow modelling of the regional aquifer of the Pampa del Tamarugal, northern Chile. *Hydrogeol J* 15:537–551
- Sathe SS, Mahanta C (2019) Groundwater flow and arsenic contamination transport modeling for a multi aquifer terrain: assessment and mitigation strategies. *J Environ Manage* 213:166–181
- Senthilkumar M, Elango L (2004) Three-dimensional mathematical model to simulate groundwater flow in the lower Palar River basin, southern India. *Hydrogeol J* 12(4):197–208
- Sinha UK, Kulkarni KM, Sharma S, Ray A, Bodhankar N (2002) Assessment of aquifer system using isotope techniques in urban centers Raipur, Calcutta and Jodhpur, India. No. IAEA-TECDOC-1298
- Vaidyanadhan R, Ramakrishnan M (2010) *Geology of India*. Geological Society of India, p 1475
- Vetrimurugan E, Senthilkumar M, Elango L (2017) Solute transport modelling for assessing the duration of river flow to improve the groundwater quality in an intensively irrigated deltaic region. *Int J Environ Sci Technol*
- Wei X, Bailey RT, Records RM, Wible TC, Arabi M (2018) Comprehensive simulation of nitrate transport in coupled surface subsurface hydrologic systems using the linked SWAT-MODFLOW-RT3D model. *Environ Model Softw* 1–33
- Yehia MM, Monem M, Mansour NM, El-Fakharany MA (2013) Using modflow and MT3D groundwater flow and transport models as a management tool for the quaternary aquifer, East Nile Delta, Egypt. *Int J Sci Commer Humanit* 1:219–233