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Simulation of Shallow Basaltic Aquifer for Estimating Groundwater Resources in a Watershed of Central India

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Abstract:
Aquifer simulation is essential to understand the groundwater resources and its sustainable management. We have simulated the shallow basaltic aquifer of a watershed in central India acquiring the field data using Visual Modflow ver. 3.1.0. The models are run in the steady state of year 2012, and also in the transient state during year 2012-14. The results indicate that the calibrated water level at the selective sites is matched with the observed water level in the steady state. The simulated well hydrographs of the transient state are also reasonably matched with the observed well hydrographs. In the shallow aquifer, groundwater flows from the west to north-east direction with the velocity range of 0.01 to 0.76 m/d. An average overall input to the shallow aquifer system is ~48.01 MCM. The pumping of the shallow aquifer is estimated to be around 35.92% of the rainfall recharge. The simulated rainfall reserve in the flow model is compared with the results obtained from the GEC norms and information-based model. It indicates that the rainfall reserve is nicely matched with the GEC norms but it is under-estimated compared to the information-based model. This study will support to the decision makers for the management of groundwater resources in this study area.

Keywords: *Shallow groundwater, Flow model, Groundwater reserve, GEC norms, Entropy-based model, Basaltic aquifer, Central India.*

1. INTRODUCTION

Groundwater is a very important and valuable resource in the world; it needs to be maintained properly. However, there are a number of challenges to comprehending a groundwater system. It has been extremely difficult to precisely identify the media in which groundwater is stored due to its invisibility and tremendous heterogeneity. Groundwater resource quantification and comprehension of hydrogeologic processes are necessary prerequisites for the effective and long-term sustainability of groundwater resources (Sophocleous, 2000). Developing and experiment with models that recreate these incredibly complex systems is one method to improve our knowledge of them. Groundwater modelling is a well-known method for analyzing groundwater management performance under the effect of dynamic changes in hydrogeological and climatic factors. The model's output will aid in the development and selection of the best appropriate groundwater exploration and management strategies. However, groundwater flow modelling in a basaltic area is a challenging issue because of the highly variable and heterogeneity of the system (Singhal and Gupta, 1999). Groundwater flow modelling tools (i. e., Modflow) and other numerical models are commonly employed for groundwater resources planning and management (Scanlon and Cook, 2002; Mondal and Singh, 2005; Mondal, 2019). Recently many researchers investigate the groundwater resources using groundwater flow modelling in different kinds of case studies such as groundwater pollution, water budget, seawater intrusion, and management plans (Mondal et al., 2009, Senthilkumar and Elango, 2011; Baneerjee and Singh, 2011; Mondal and Singh, 2012; Singh, 2013; Lathashri and Mahesha, 2015; Neupane et al., 2020; Pawar et al., 2022). The research region is differentiated by higher groundwater pumping for irrigation and household applications, according to the CGWB (2015) report, with the level of groundwater development reaching about 89%. In the region's well hydrographs, there is less evidence of a downward trend. However, if groundwater withdrawals continue to fall at this rate, the watershed's groundwater situation will become serious shortly. Visual MODFLOW is a computer application that uses the Finite Difference Method (FDM) to numerically solve groundwater issues (Harbaugh and McDonald, 1984). Thus, the main objectives of this work are to 1) develop numerical groundwater flow model of shallow basaltic area of central India, 2) explore the aquifer responses due to the diverse stresses, and 3) compare the estimated groundwater resources with the results obtained from the GEC norms and information-based model.

1.1 Description of the Study Area

The study area, an area of 360 km^2 with the geographical coordinates such as longitudes: 78^0 42' to 78^0 59' east and latitudes: 21^0 10' to 21^0 19' north situated in the northwestern part of Nagpur district, Maharashtra, Central India. It is drained by the Chandrabhaga River with the tributaries of Saptadhara River and Morthamnalla that flow from west to east. But this main river ultimately joins the Kolar River outside to the east of the study area (Venkatarao et al., 2019; Ajaykumar, 2022). Geologically, Deccan trap basaltic (area: ~ 313 km^2) of upper Cretaceous-to Eocene age and Gondwana Formation of Permian age (area: ~47 km^2) are observed in the study area (Figure 1). The Gondwana Formation is mainly exposed in the north-eastern part and also a small linear patch

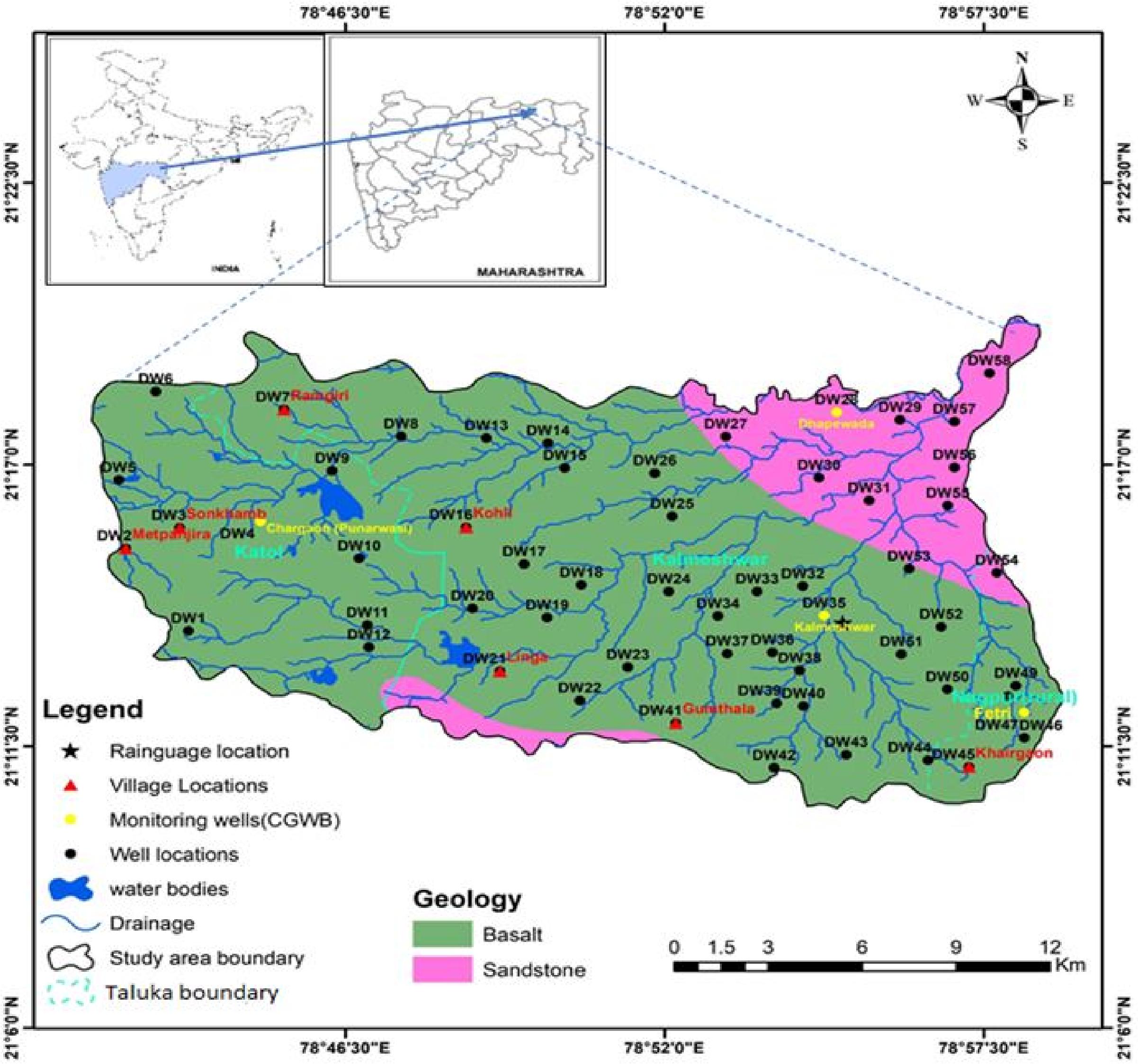

Figure 1: Location map of the study area along with a dense monitoring well and rain gauge station

2. MATERIALS AND METHODS

Groundwater modelling for the Deccan Trap Basaltic (DTB) regions is always a tough problem to solve because of the variety in the aquifer characteristics and the unpredictability of the basaltic aquifer geometry. For successful groundwater modelling, some modelling protocols have to be followed. Figure 2 shows the many phases involved in the flow modelling study. The groundwater flow of the study area was simulated using the FDM computer programme-Visual Modflow ver. 3.1.0 software.

2.1 Governing Equations

Three-dimensional (3-D) groundwater flow equation for the inhomogeneous anisotropic confined aquifer used for groundwater flow model (Rushton and Redshaw, 1979) below as given below:

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

An unconfined condition followed by the Boussinesq equation (Todd and Mays, 2005) as below:

$$\frac{\partial}{\partial x}(K_{xx}h\frac{\partial h}{\partial x})+\frac{\partial}{\partial y}(K_{yy}h\frac{\partial h}{\partial y})=S_y\frac{\partial h}{\partial t}\pm W \qquad (2)$$

where, K_{xx}, K_{yy} and K_{zz} are the hydraulic conductivities along the x, y and z-directions, h is the hydraulic head, S_s is the specific storativity, S_y is the specific yield ($S_y >> S_s$), W is the leakage or groundwater volume fluxes per unit area (positive for outflow and negative for inflow).The coordinates of x, y and z are the Cartesian coordinates. The equation (2) was solved using a finite difference approximation technique using Visual Modflow 3.1.0 software. The starting point for the application of this method was discretization of small square sub-regions in a grid form (McDonald and Harbaugh, 1988). This leads to set of simultaneous algebraic equation, which was solved using the Visual Modflow 3.1.0 modeling code. This code has been widely used and is accepted to produce numerically stable solutions. The method selected for the numerical solution of the algebraic equation set is WHS particularly shallow aquifer in the study.

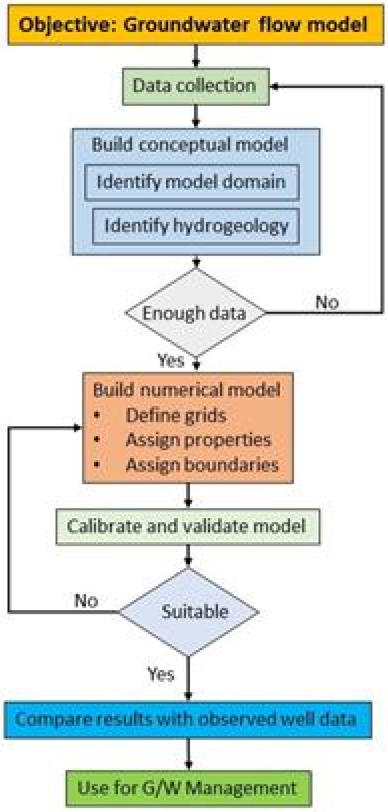

Figure 2: Flowchart for groundwater flow model

2.2 Data Collection

Data acquisition is another significant component in the model designing process. In this work, the data were collected from Groundwater Surveys and Development Agency (GSDA) and Central Ground Water Board (CGWB, 2015), Nagpur. During the years 2012–2014, both the pre- and post- monsoon seasonal groundwater level data were obtained from CGWB (2015). The groundwater level data from 38 typical observation wells were utilized to calibrate the model. A total of 155 VES survey (CGWB, 2015) conducted within the study area were used for the preparation of aquifer geometry. In the present model, evapotranspiration was calculated by using the Penman–Monteith equation.

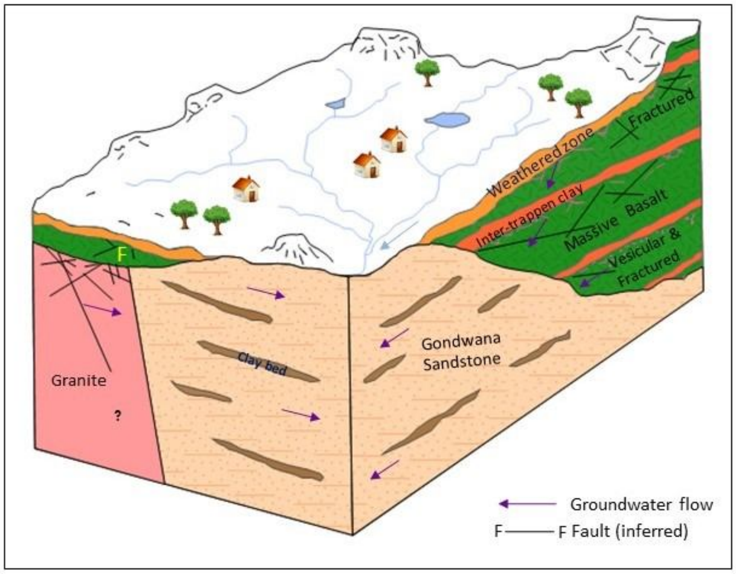

Figure 3: Conceptualization of the area based on major litho-units (modified after CGWB, 2015)

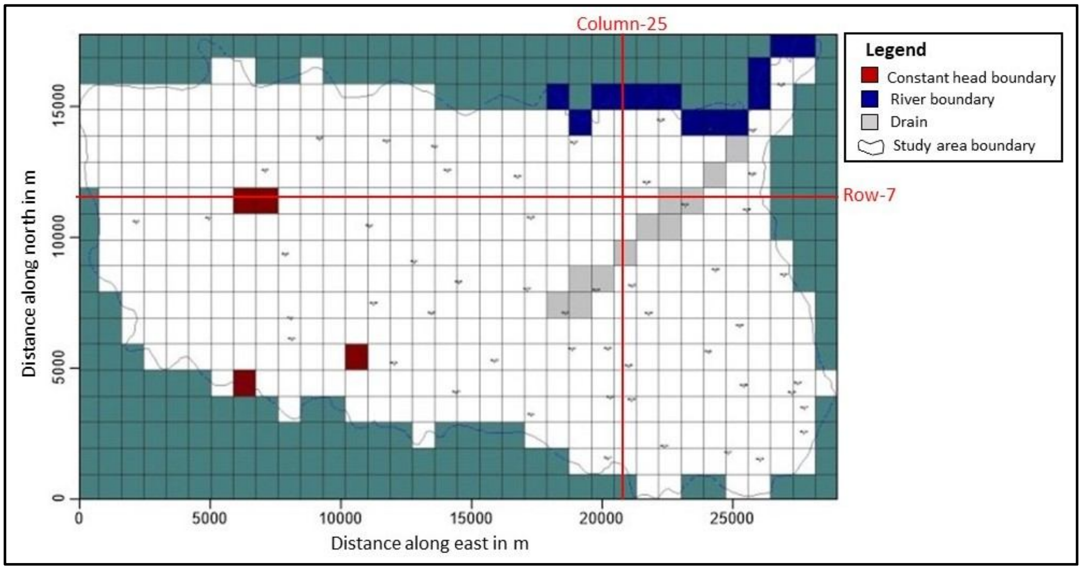

Figure 4: Model grids with active and inactive cells along with the boundary conditions

2.3 Conceptualization, Grid Design and Boundary Conditions

The field data (such as geophysical data) in the study area had been used to conceptualize model area based on geology, major litho-units, and aquifer types, a conceptual major litho-units of the study area had been developed, as shown in Figure 3. In this study, a conceptual model was built based on various boundary conditions, particularly for the hilly parts in the western end of the area and the river boundary in the northeast. A model with two layers was generated for the study area where the first layer is the shallow aquifer herewith. The area of interest (~360 km^2) was arranged into a collection of grid blocks or cells (Figure 4). A coarse uniform grid of 1000m ×1000m was built based on the available data, and the layer top elevation of the model was imported from the SRTM data after filtering to fit the model grid size. The upper layer was characterized to be an unconfined aquifer, whereas the bottom layer classified as a semi-confined aquifer. The first layer, the weathered zone, has a thickness of 4.2-41.7 m, bgl and the fractured layer has a thickness of 30.3-132 m, bgl. The top of the Ist aquifer ranged between 306.0 and 525.0 (m, amsl), whereas the bottom of the IInd aquifer ranged between 201.5 and 410.0 (m, amsl). The region was divided into 612 grids, individual grid size 1000 m×1000 m. There were total of 18 rows and 34 columns considered. Within the region border, about 418 grids, out of 612 grids, were falling active cells (Figure 4). The rest of the grids were depicted as inactive as a result of this. At the watershed's boundary, a no-flow border was established. The river flows through the north-eastern portion area as a river boundary, with river stage ranging from 332 to 305 meters above sea level (m, amsl) in the western and eastern regions, respectively. The width of the river was kept ~20 meters in the western part, and widened to 30 meters in the eastern part. The permeability of the river bottom was high compared to the aquifer and hence it was taken as 2 m/day with its thickness below the river bottom as 1 meter (Mondal et al., 2019). The typical cross-sectional views for the selective row number 7 and column 25 along with these boundaries are shown in Figure 5.

2.4 Aquifer Properties and Applied Stresses

2.4.1 Hydraulic Conductivity

Pumping tests at 21 dug wells conducted by CGWB (2015) were utilized to know the hydraulic conductivity of unconfined aquifer. The results had shown that the range of hydraulic conductivity varied from 6 to 100 m/day. For the most part, the phreatic aquifer was assumed to have a hydraulic conductivity of approximately 12 m/day. The horizontal hydraulic conductivity was multiplied by 0.10 to get the vertical hydraulic conductivity (Todd, 1980; Mondal et al., 2011).

2.4.2 Specific Yield

Due to the high productivity of the weathered and fractured zones and the absence of clay content, a particular yield value of 0.04 was used for the majority of the model area. Though the range of specific yield values for fractured basalt varies between 0.02-0.03 as per the GEC-1997 recommendations. The occurrence of high-yielding drilled wells that can withstand long periods of pumping implies that the phreatic aquifer has a high conductivity and storage value.

2.4.3 Recharge

Vertical recharge is the only source of groundwater in the basin since the watershed was only recharged by precipitation. The estimation of recharge by using the entropy-based approach carried out and was used in the model for the groundwater recharge. Hence, the recharge rates ranged from 80 to 280 mm/year (Mondal and Ajaykumar, 2021). Zones-I, II, III, IV, and V were assigned the recharge rates of 80, 120, 160, 220, and 280 mm/year, respectively **(Figure 6).** The north-western part, which is characterized by undulating hills and valleys, was allocated a lower recharge rate of 80 mm/year

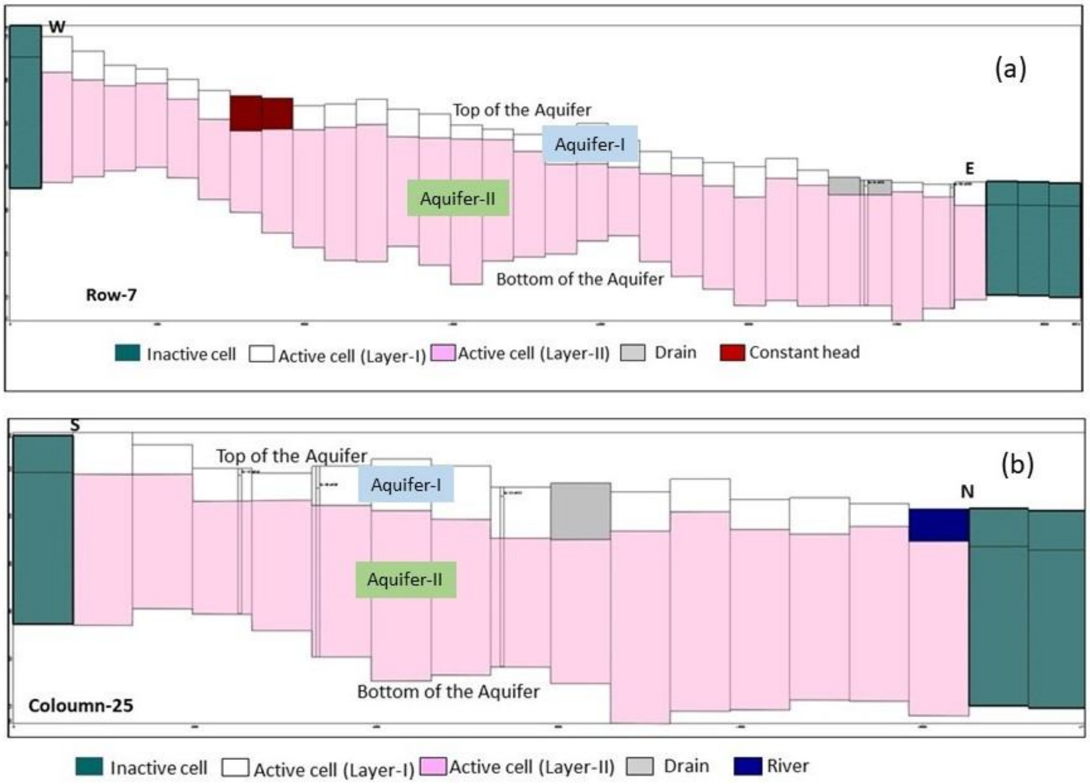

Figure 5: Showing **(a)**. Aquifer layers in horizontal cross-section (row 7), and **(b)**. Aquifer layer in vertical cross-section (column 25) in the modelling area

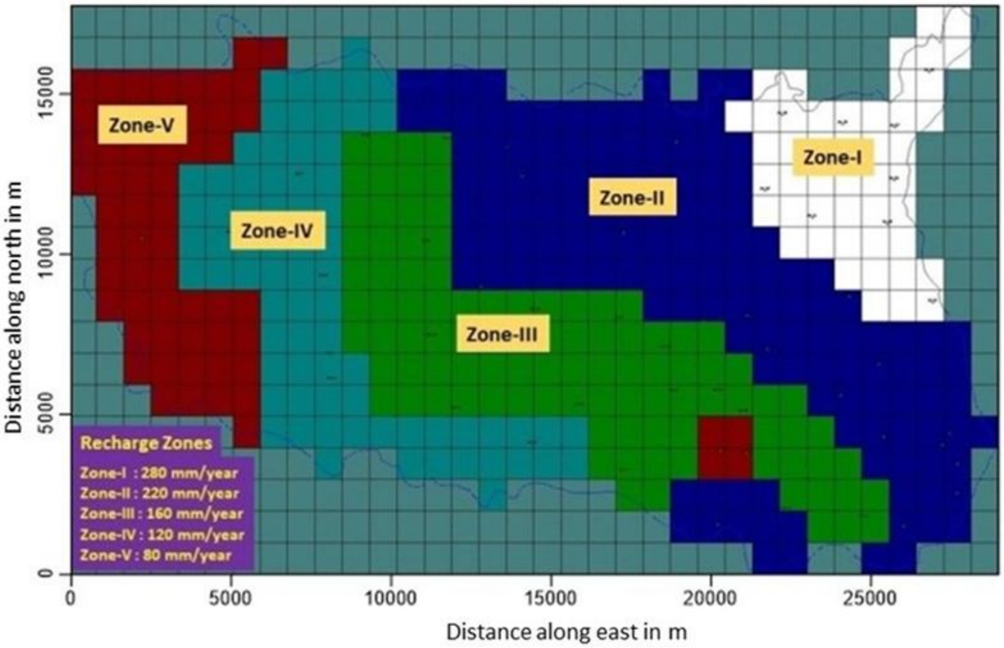

Figure 6: Zone-wise distribution recharge rates in the modelling area

2.4.4 Abstraction

Generally, the pumping from the aquifer occurs during the Rabi season and hence groundwater draft was considered after the month of November. Nearly one hundred ten pumping wells were assigned in the model, as the well locations were known. Pumping rates varying from 100-987 m^3/day, with an average of 635 m^3/day were assigned. Groundwater abstraction for irrigation and industries was about 33 MCM/year (CGWB, 2015). As the groundwater flow in the hilly area was localized, so localized pumping had nothing to do with the regional aquifer system. Hence, groundwater withdrawal from these cells fallen under the hilly region was not used in this model.

3. RESULTS AND DISCUSSION

3.1 Calibration and Validation of the Model

A calibration of flow model refers to proving that the model can provide field-measured head and flows, which are the calibration results. Calibration was achieved by determining a set of factors, such as hydraulic conductivity, recharge, specific yield and pumping, that yield simulated heads and fluxes that matched the field observed values within a pre-determined error range (Anderson and Woessner, 1992). It was accomplished by making incremental adjustments to the model parameters until a close match between the observed and estimated heads was found.

3.2 Steady State Model

Whenever the magnitude and direction of a certain discharge maintain constant over time, it was considered to be in a steady-state. The simulation of the steady-state had been executed from January 2012 to December 2012, and the runtime of the model was 365 days. During trial-and-error runs, the aquifer properties and boundary conditions were employed, with the purpose of achieving minimal residual errors. Thirty-eight observation wells in the shallow basaltic aquifer during the post-monsoon (November 2012) were used for calibration of the steady-state model.

The steady state calibration achieved a minimal RMSE error of 4.07 m. A good relationship established between computed and observed heads with numerical analysis of the steady-state findings had been made, as shown in Figure 7. The special distribution of the calibrated and observed water level contours is presented in Figure 8, which shows that they are closely matched to each other. As per zone budget results, the overall inflow to the aquifer was 13,15,20 m^3 /day or 48.01 MCM, and the overall outflow from the aquifer was 13,15,22 m^3 /day or 48. 12 MCM, and mass balance error was ~0.006%, as presented in Table 1. The output of this steady state model represents that the pumping of the aquifer was estimated to be around 35.92% of the recharge. River leakage also contributes to the outflow value was about 27.39% of the recharge. However, the evapotranspiration value was minimum in the outflow rate influence, which was about 6.10% of the annual recharge. The average groundwater flow velocity in this study area was around 0.34 m/d, ranging from 0.01 to 0.76 m/d.

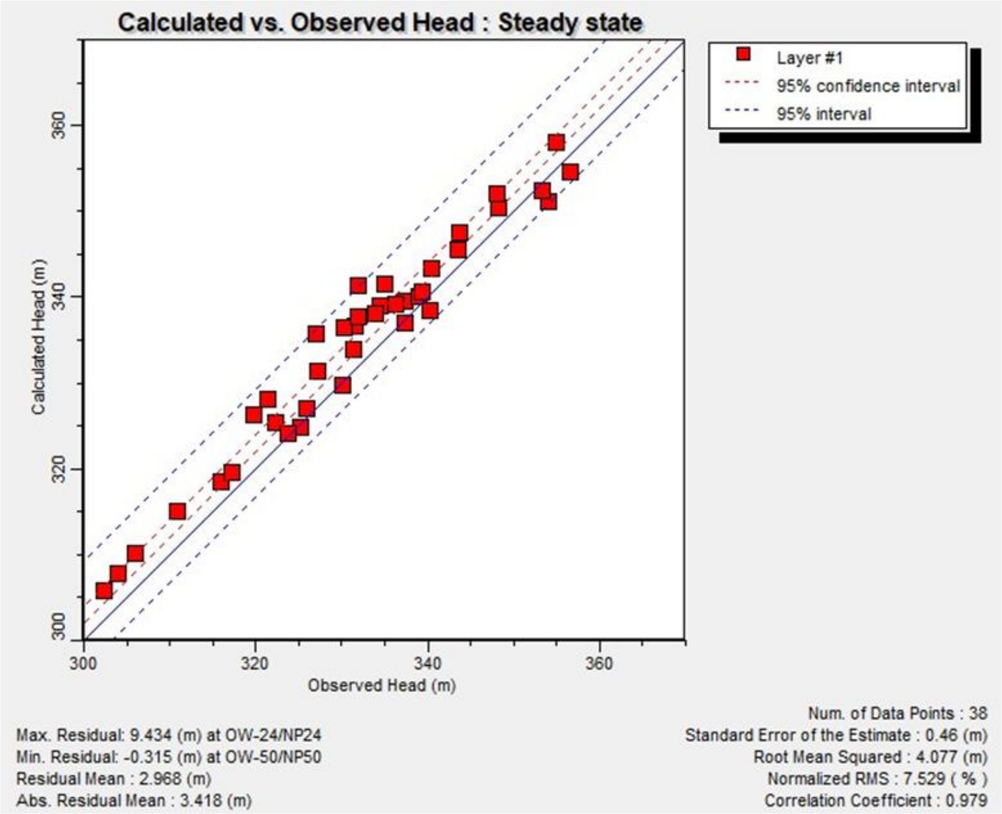

Figure 7: Simulated vs. observed heads in the steady state calibration (November 2012)

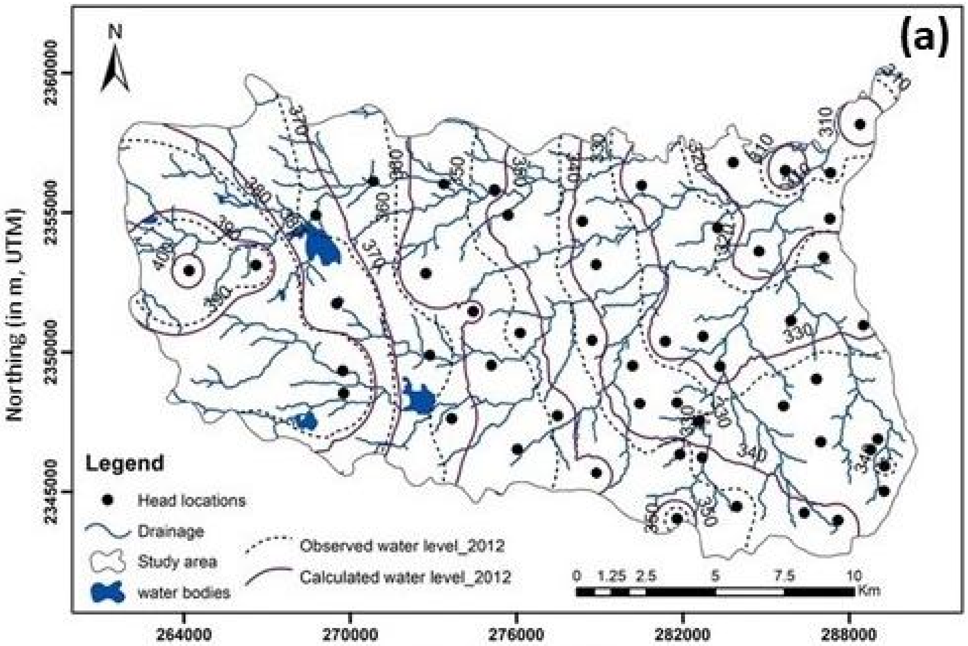

Figure 8: Observed and computed water level contours (m, amsl) during the post- monsoon in the year 2012 in the steady state condition.

Table 1: Volume balance results in the steady state calibration

Parameter (s)	**Inflow (m^3/day)**	**Outflow (m^3/day)**	**Outflow (%) of the recharge**
Recharge	131520	0	----
Constant head	0	-9986	7.59
Pumping	0	-47236	35.92
Drains	0	-30236	22.99
River leakage	0	-36028	27.39
Evapotranspiration	0	-8026	6.10
Total	131520	-131512	----
Error (%)	0.006	----	----

3.3 Transient State Model

Whenever the direction and magnitude of certain discharge change over-time, it is said to be transient or unsteady, or in a non-equilibrium condition. The groundwater level data for these wells had been provided every month since January 2012. For the transient state calibration, groundwater level data from January 2012 to November 2014 was employed. The recharge calculated each year in the study area using an entropy-based technique had been fed into the transient state model. The model had many stress periods, and data for individual stress periods were separately assigned. After entering all of the input parameters for individual stress periods, the model was run for transient state calibration. Figure 9 shows the simulated versus observed hydrographs for the four selected observation wells, representing a good relationship between them (at the wells-DW10, DW18, DW28, and DW50).

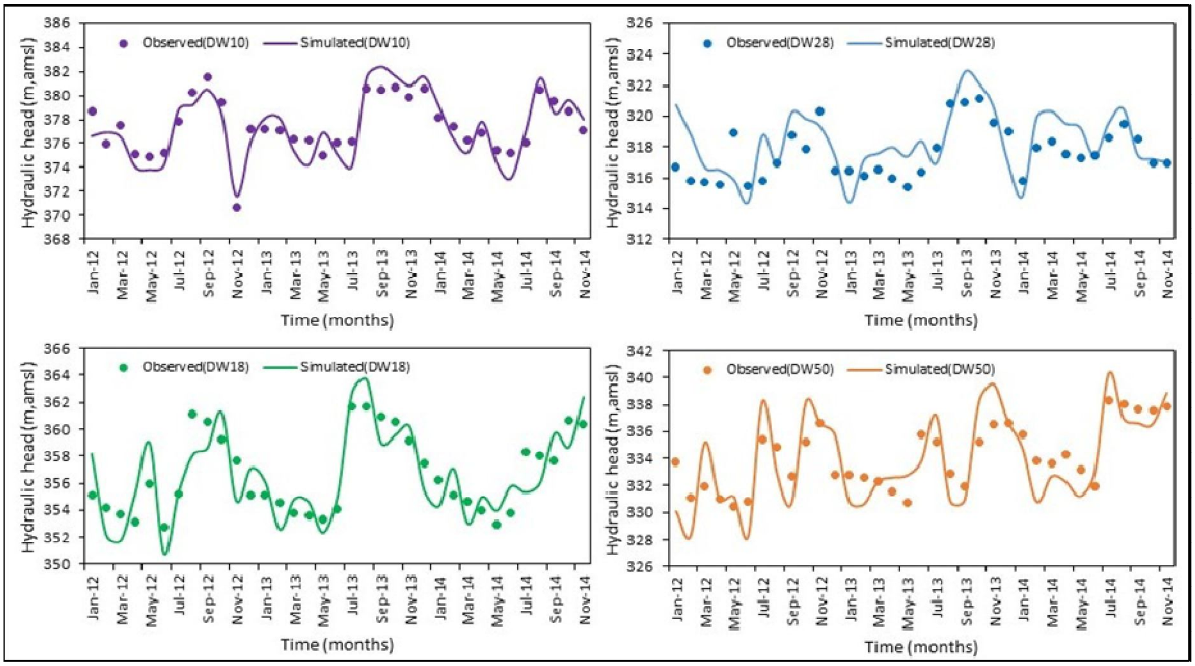

Figure 9: Hydraulic heads of simulated vs observed at four observation wells during the calibration period (at the wells: DW10, DW18, DW-28, and DW50)

3.4 Comparison of Groundwater Reserves

Groundwater reserves of shallow basaltic aquifer had been estimated through simulating groundwater flow and those results were also compared with the other techniques (GSDA-Abstract of District-Nagpur-Restricted, per. comm., GEC, 1997; Chatterjee and Purohit, 2009; Mondal and Ajaykumar, 2021, Ajaykumar, 2022). Based on this groundwater flow model, the calculated groundwater reserve was about 48.01 MCM. The natural groundwater reserve calculated using the GEC norms value was about 48.17 MCM (GSDA-Abstract of District-Nagpur-Restricted, *per. Comm*.). These results were closely matched to each other. Another indirect approach such as the information-based model was carried out by Mondal and Ajaykumar (2021) and used it for the comparison. The estimated GWR was about 65 MCM in the year 2012 (Mondal and Ajaykumar, 2021). Finally, a comparing the outputs obtained from three different methods shows that the result obtained from the information-based model was higher than the numerical groundwater flow model and GEC norms, as shown in Figure 10. It was due to the non-availability of the continuous and dense data sets. Therefore, the best-underestimated results were observed in the flow model. This model is also required to refine with the inflow of additional hydrogeological data.

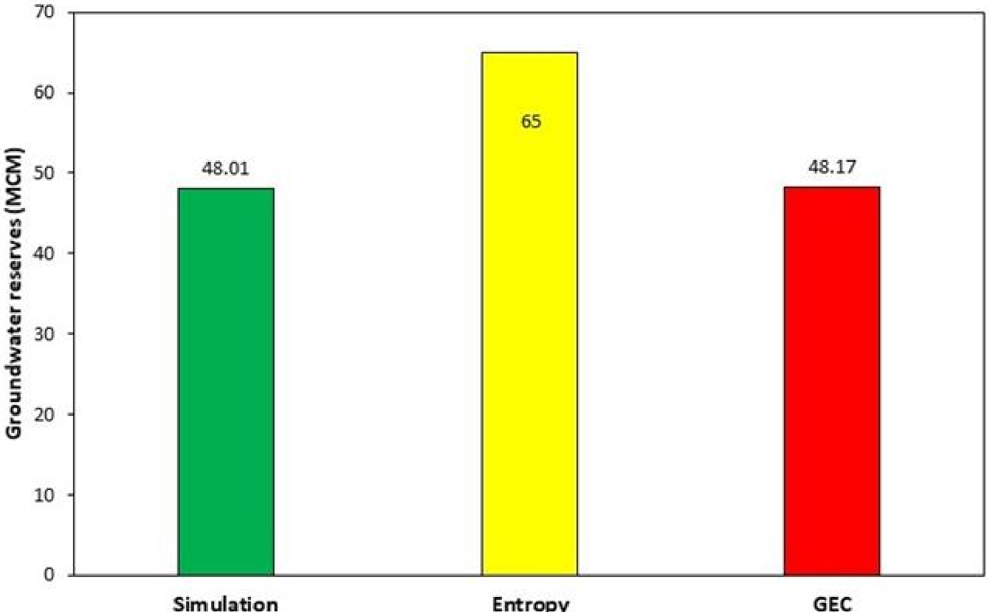

Figure 10: Bar plot of the simulated groundwater reserves compared to the other models

4. CONCLUSIONS

Groundwater flow model of shallow basaltic aquifer in a watershed of central India is developed using the Visual Modflow ver. 3.1.0 for the estimating groundwater resources. This model is simulated in the steady state condition of year 2012. The flow of groundwater is observed from the west to north-east direction with the velocity range of 0.01 to 0.76 m/d. The best-fit is obtained between calculated and observed heads, with a correlation coefficient of R^2:0.96. The simulated numerical flow model indicates that an average input into the shallow aquifer is ~48.01 MCM in the flow domain. The model is also calibrated using the spatio-temporal observation of groundwater heads from 2012 to 2014. The calibrated results are closely matched with the observed well hydrographs, which represent the variations of recharge and abstraction in the study area. Additionally, the comparison findings of groundwater resources reveal that the groundwater recharge is nicely matched with the results obtained from the GEC norms, but it is under-estimated in the comparison of information-based model, which is needed to refine in the inflow of additional hydrogeological data. This simulated model is a preliminary stage and will also support to do research work in future. The decision makers will be benefited for the management of groundwater resources in this area.

5. ACKNOWLEDGMENTS

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6. CONFLICTS OF INTEREST

The authors declare no competing interest.

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