

Integrated approach of geospatial visualization and modeling for groundwater management in hard rock terrains in Nagpur Urban Area, India

Tauseef Ahmad Ansari¹ · Yashwant B. Katpatal¹ · A. D. Vasudeo¹

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Abstract Groundwater management requires complete visualization of aquifer characteristics to understand scientific aspects and hence remains a challenge, especially in hard rock terrains. In the present research paper, a comprehensive approach using 3D stratigraphic model, fence diagrams and numerical modeling has been proposed to understand the groundwater status for effective recharge. The stratigraphy, groundwater flow, and groundwater fluctuations for the period 1999–2010 were analyzed. The total volume of formations, volume of voids, storage capacity, and quantities of recharge of unconfined aquifer system in the Nagpur urban area were estimated. The steady state groundwater flow model of Basalt formation was calibrated to evaluate the subsurface system using Processing Modflow (PMWIN 5.3.2). The calibrated hydraulic head is compared with field observed head. The comparative spatial analysis presents a simple integrated approach in identifying zones with falling groundwater trends suitable for groundwater recharge in hard rock terrain in Nagpur urban area.

Keywords Stratigraphic model · Groundwater model · Fence diagram · Modflow · Hard rock terrains · Geographical Information System

✉ Tauseef Ahmad Ansari
sirftauseef@gmail.com

Yashwant B. Katpatal
ybkatpatal@rediffmail.com

A. D. Vasudeo
avasudeo@yahoo.com

¹ Department of Civil Engineering, Visvesvaraya National Institute of Technology, South Ambazari Road, Nagpur, Maharashtra 440010, India

Introduction

In developing countries, water availability is under stress due to urbanization and exponential population growth causing a need for supply of domestic and industrial water in sufficient quantities. Groundwater is an important source of fresh water throughout the world which provides approximately one third of the world's freshwater consumption (Singh 2013). Groundwater occurs in the rock formations and weathered zones, hence, aquifer dimension, aquifer geometry, and aquifer properties viz. porosity and permeability must be considered with groundwater fluctuations to visualize the groundwater availability (CGWB 2009). Use of a conceptual three-dimensional (3D) stratigraphic and groundwater flow model based on the field data may be critical to analyze and visualize the problems related to groundwater management, especially in complex stratigraphic set up.

Remote sensing (RS) and geographical information system (GIS) techniques can be employed to identify the artificial groundwater recharge regions for management (Agarwal et al. 2013). Studies on groundwater modeling have been focused on several aspects viz. GIS-based numerical modeling (Gaaloul 2014; Wang et al. 2008; Varade et al. 2012), groundwater flow in complex superficial deposits using geological framework (Turner et al. 2015), modeling using Modflow for groundwater inflow estimation in coal mines (Surinaidu et al. 2014), etc. The long-term problems related to current and future challenges in modeling, especially in hard rock terrains, may be too complex and may vary with change in parameters (Ojha et al. 2013). In a hard rock terrain, modeling may predict the changing trends of groundwater with pumping and suggests the withdrawal rates and total allowed draft (Varalakshmi et al. 2014). Salamasi and Azamathulla (2013) have proposed successive over relaxation (SOR) for solving Laplace's differential equation. Ghazaw et al. (2014) have shown that groundwater recharge through artificial recharge

wells may improve the groundwater availability in the arid region.

Managed aquifer recharge through different sources requires correct visualization of the aquifer characteristics (Zekri et al. 2014). Use of a conceptual stratigraphic and groundwater flow model based on the field data may be critical to visualize the problems related to groundwater management, especially in complex stratigraphic set up. The study presents a comparative analysis of groundwater conditions based on integration of three-dimensional stratigraphic modeling and groundwater modeling in hard rock Basaltic terrain. For the study area, 3D stratigraphic model, fence diagrams, and numerical modeling have been proposed to understand the groundwater status for effective recharge. The results of flow simulation analysis have been compared with the GIS-generated spatial model based on field observations. The study also identifies the wells with falling groundwater trends which can be used for groundwater recharge to improve the future groundwater scenario in Nagpur urban area.

Study area

Nagpur city lies in central India on the Deccan plateau and is growing rapidly with “Radial” growth with an area of 220 km² (Fig. 1). Nagpur has tropical wet and dry climate. The city experiences extreme temperatures in summer season

from March to June. The maximum and minimum temperatures recorded in Nagpur are 49.7 and 3.9 °, respectively while the average annual rainfall is 1055 mm. The aquifer set up in Nagpur urban area includes several geological formations in unweathered to weathered condition. The subsurface aquifer system in Nagpur urban area has varied hydrogeological characteristics with five different geological formations viz. Recent Alluvium, crystalline Basalt, Lameta limestone, Gondwana sedimentary, and Archaean metamorphic formations (Katpatal and Chavan 2012). Around 60 % of the city (west and south Nagpur) has Basaltic formation and the Archaean and Gondwana formations are exposed in north Nagpur. The central part has a small strip of Lameta formation between Archaean and Basaltic cover. The weathering zones in all the formations are the potential unconfined aquifer systems. Drainage pattern is dendritic in north of the city, while it is linear in south which helps in understanding the surface flow directions (Fig. 1). The general surface slope is from west to east and the highest elevation level is 358.25 m while lowest elevation is 284.79 m.

Methodology

Assessment of aquifer dimension and geometry is a prerequisite for an efficient and sustainable groundwater resource management and replenishment (Beigi and Tsai 2014). The

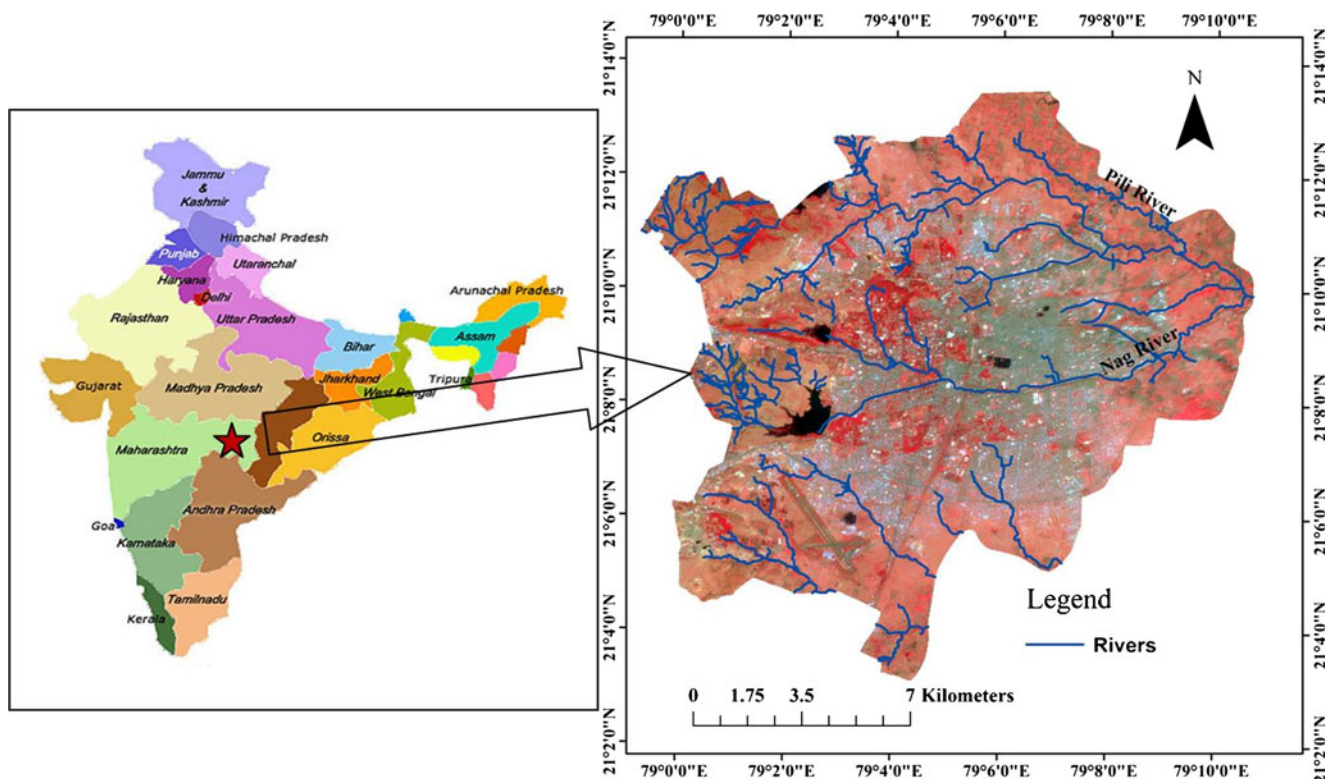
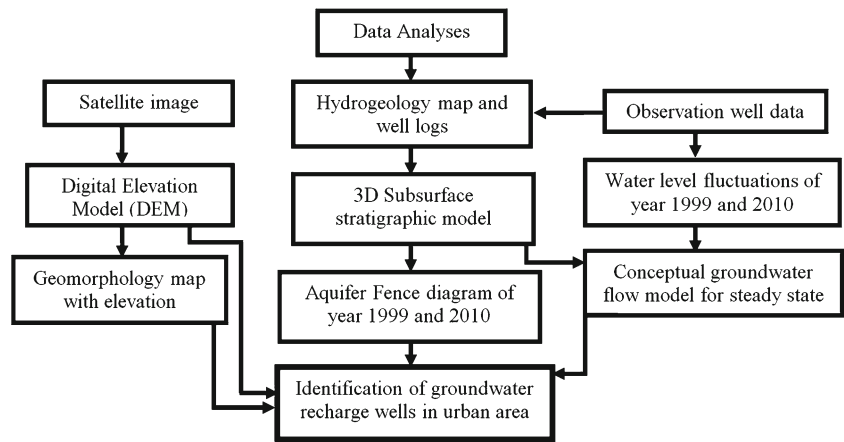


Fig. 1 Location map of study area

Fig. 2 Flow diagram of methodology

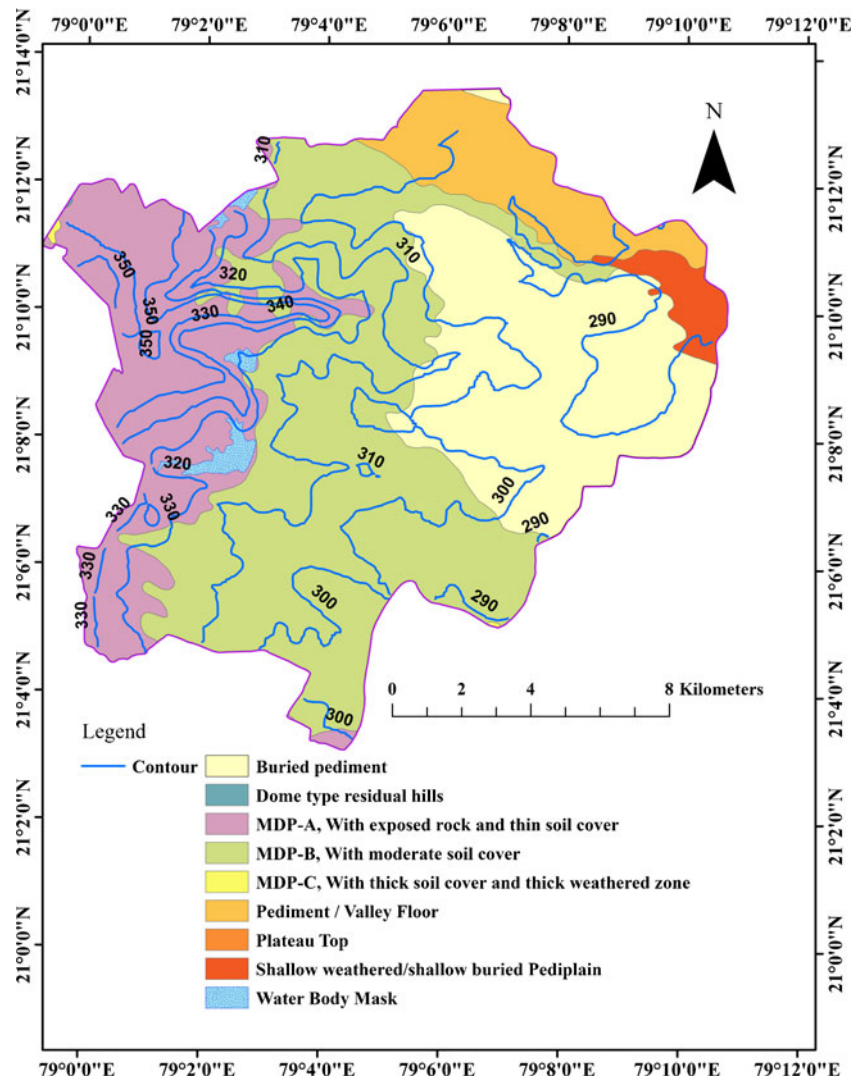


stratigraphic information at micro level is necessary to evaluate the unconfined and confined aquifer system. Hence, combination of three-dimensional stratigraphic model showing the depth and thickness of geological formations, groundwater surface generation using geographic information system

(GIS), delineation of hydrogeological characteristics of formations from groundwater fluctuation data, and the groundwater flow estimation using groundwater modeling have been used.

Groundwater level data from central ground water board (CGWB) for the period 1999–2010 was used to analyze the

Fig. 3 Geomorphological setup within Nagpur urban area



groundwater fluctuations. Through integration of the results obtained from various analyses (Fig. 2) discussed in the following section, the groundwater status of the study area for effective recharge of wells was identified.

Geomorphological set up

Geomorphological map prepared from IRSP6 LISS IV data and digital elevation model (DEM) as geomorphology of an area includes study of landforms and provides information on runoff-infiltration process which is an important aspect for evaluation of the groundwater resources of an area (Fig. 3).

Three-dimensional stratigraphic modeling

Well log data was interpolated in Rockworks software to generate 3D stratigraphic model, to delineate the geometry and dimensions of each stratigraphic formation in succession of their occurrence and age (Fig. 4) and hence helps in understanding the groundwater potential.

Stratigraphic sections to visualize aquifer set up

Stratigraphic sections provide the aquifer geometry and sequence of their occurrence in a preferred section line. Hence, the section lines are aligned along the observation wells so as to monitor the changes in groundwater level with changing aquifer set up. Stratigraphic section lines AB, CD, EF, GH, IJ, and KL have been demarcated in the area covering all the

stratigraphic formations (Fig. 5). With the help of DEM and stratigraphic formation map, subsurface stratigraphic profiles along specified lines are generated (Fig. 6).

Aquifer fence diagram to visualize groundwater fluctuations

Aquifer fence model for the year 1999 (Fig. 7) and 2010 were generated to observe the decadal fluctuations in the pre monsoon and post monsoon groundwater levels within the Nagpur urban area.

Groundwater flow modeling

The groundwater levels and fluctuations can be utilized for generating the subsurface flow pattern based on the hydrological parameters for Basaltic formation (Katpatal et al. 2014). Groundwater modeling was performed considering steady state condition where hydraulic head and flow directions were obtained. The conceptual groundwater flow model was simulated by assuming boundary conditions with steady state for single unconfined layer in Basaltic formation viz. thickness of aquifer, recharge rates, permeability, etc.

The water budget equation for Basalt formation is found to be satisfied for steady state condition. The processing MODFLOW software was used to simulate the model. The widely used numerical groundwater flow equation (Eq. 1) for confined or unconfined aquifer is assumed and used to calibrate the groundwater flow model.

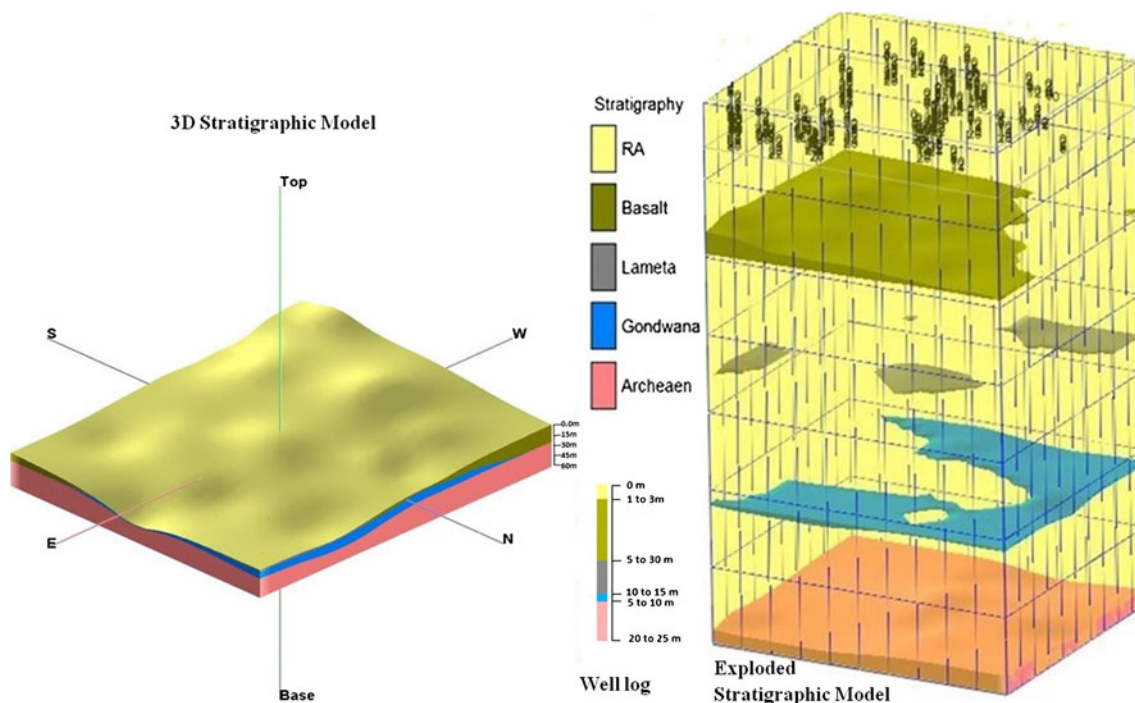
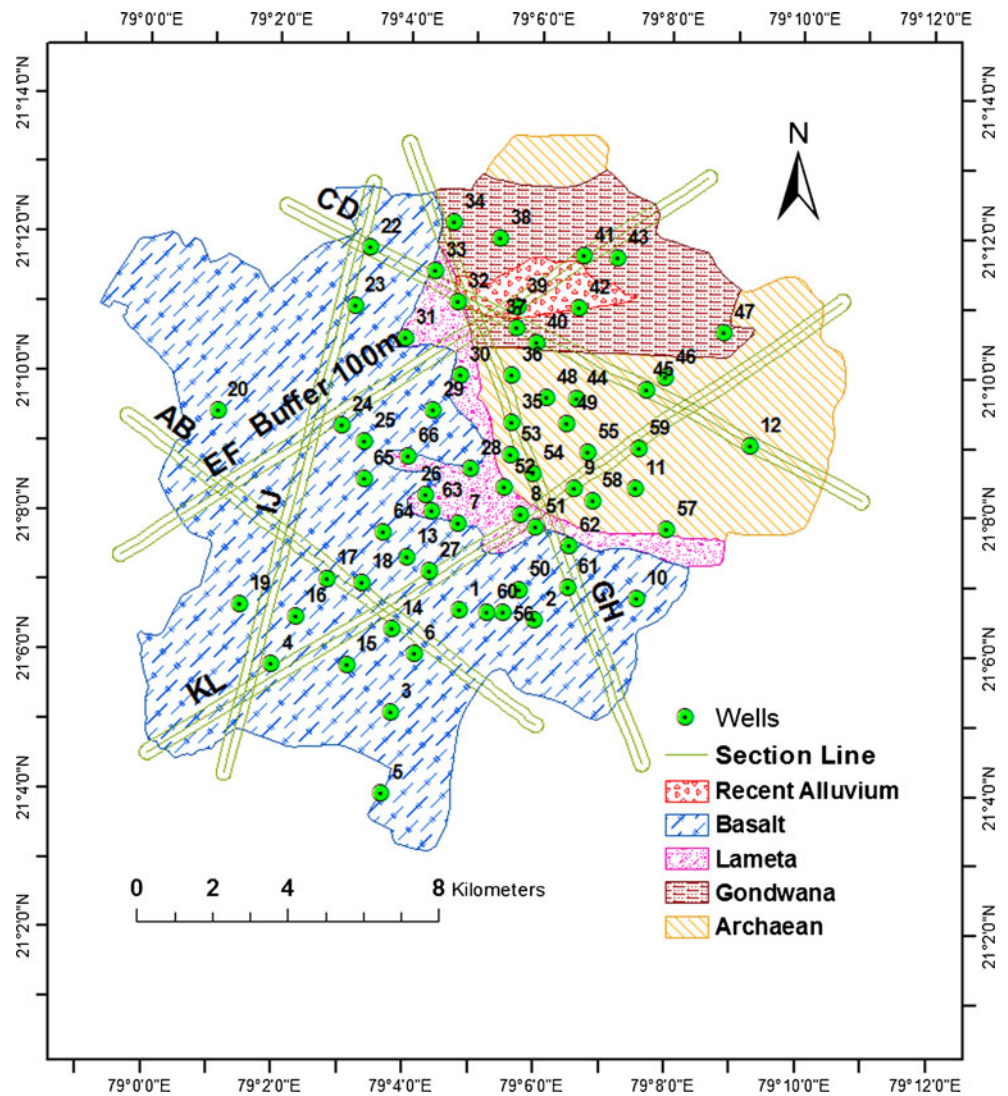


Fig. 4 3D stratigraphic model of Nagpur urban area.

Fig. 5 Stratigraphic classes with section lines selected for generation of profiles in Nagpur urban area



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

where, K_{xx} , K_{yy} , and K_{zz} are the hydraulic conductivities along x , y , and z coordinates that are assumed to be parallel to the major axes of hydraulic conductivity (m/day), h is the potentiometric head (m), $\pm W$ is the volumetric flux per unit volume (per day), S_s is the specific storage of the porous material (m^{-1}), and t is the time (days).

Results and discussions

The study demonstrates the use of three-dimensional stratigraphic model, geological sections, fence diagrams, and spatial models showing groundwater level fluctuations generated using GIS and flow simulation to visualize a complete scenario of groundwater recharge. As discussed in the

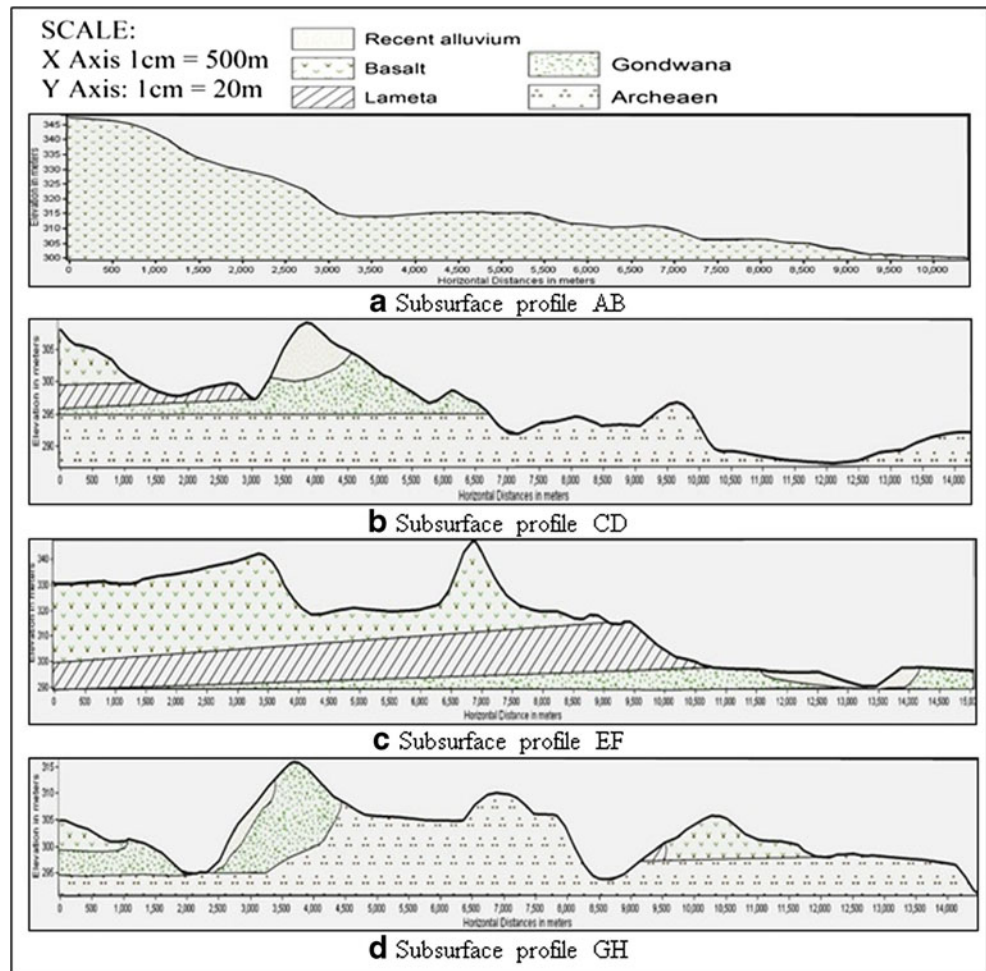
“Methodology” section, the aquifer dimensions and set up were derived from stratigraphic models and groundwater fluctuations were represented by fence diagrams and heads were estimated through flow modeling.

Visualizing the aquifer geometry using geomorphology, 3D stratigraphic model, and stratigraphic profiles

Geomorphology map (Fig. 3) indicates that the eastern part is covered with exposed rock and thin soil cover while the central part of the area is covered with buried pediments and moderate soil cover. The pediment and shallow weathered zones in the northeast of the study area indicate favorable geomorphological conditions for groundwater recharge.

The stratigraphic model (Fig. 4) distinctly reveals the subsurface stratigraphic scenario of the Nagpur urban area showing five stratigraphic formations such as Archaean, Gondwana, Lameta, Basalt, and Recent Alluvium. The exploded model shows the sequence and dimensions of each

Fig. 6 Subsurface stratigraphic profiles along selected section lines



stratigraphic unit while the well log shows all the formations in vertical sequence.

Well numbers, stratigraphic section lines, and stratigraphic formations have been shown in Fig. 5. In profile AB,

Fig. 7 Aquifer fence diagram for the year 2010 showing pre and post monsoon groundwater levels

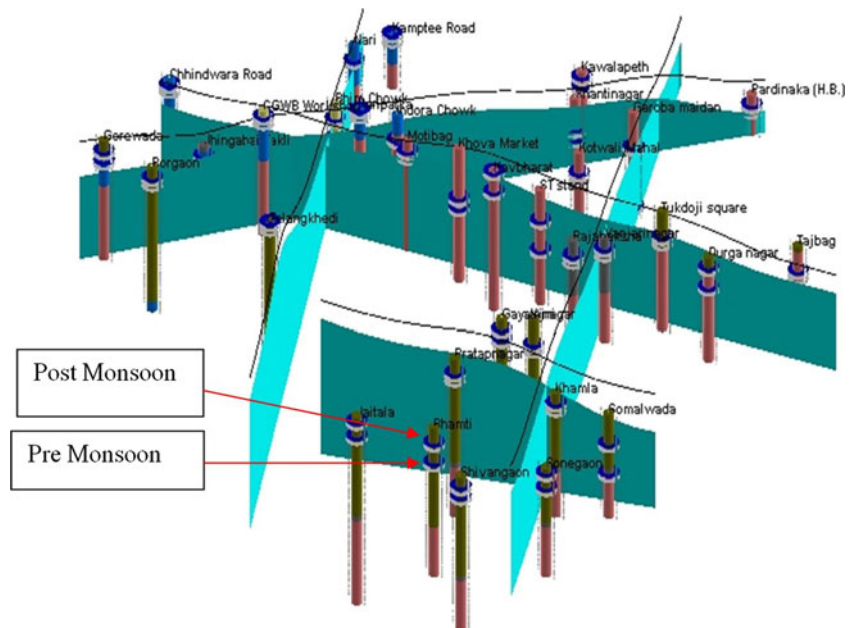
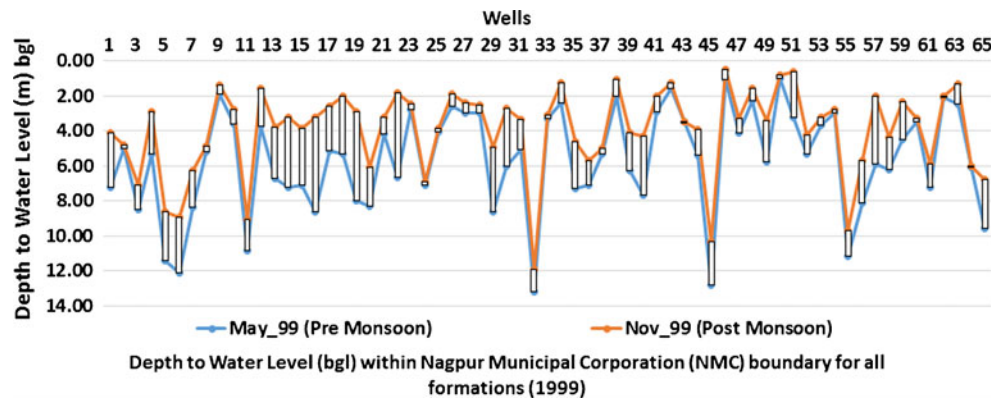


Fig. 8 Depth to water level within Nagpur Municipal Corporation (NMC) boundary 1999 (pre and post monsoon)



weathered Basaltic formation is evident with surface slope towards east. Profile CD shows Basalt, Lameta, Gondwana, and Archaean formations exposed and Archaean forming the basement. In profile EF, it may be observed that Basalt formation conceals the Lameta formations having a thickness of around 10–15 m, underlain by 5–10-m-thick Gondwana formation. Towards east, a small deposition of Alluvium may be noticed. Profile GH shows Gondwana formation forming confining conditions between Basaltic and Archaean formations in the north while Archaean formations are exposed in unconfined conditions in the south.

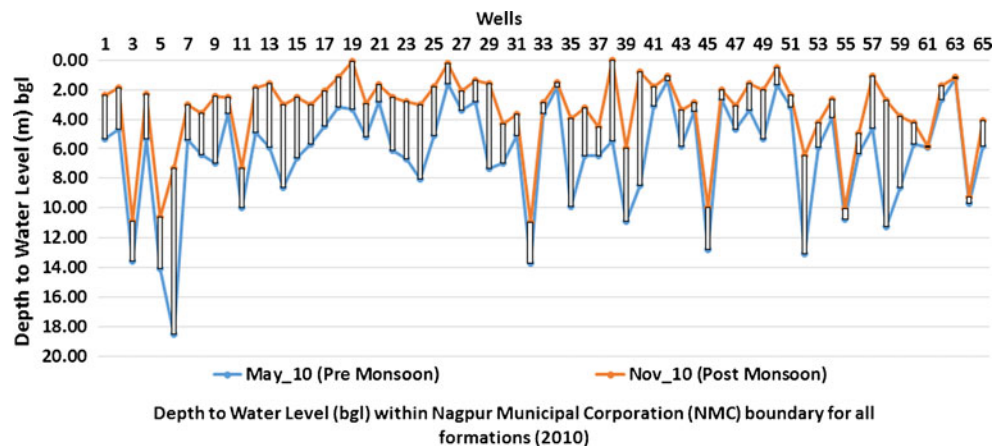
It may be observed in Figs. 4 and 6 that the alluvium of recent age occurs in very limited extent along the rivers at lower elevations. It comprises of sand, silt, and clay. The thickness of alluvium is 1 to 3 m. The Basaltic lava flows (Deccan Traps) upper cretaceous to lower Eocene age are horizontal and occupy the major portion in the western and southern parts of the city. The thicknesses of these formations vary from 5 to 30 m. The Lameta formations occur as elongated strip in central and southeast part of the city and comprise of sandstone, variegated clays, limestone, and cherty limestone. The northern parts of the Nagpur urban area have Gondwana group of rocks exposed which comprise of sandstones and shale. The Archaean rocks forming the basement are mainly of igneous origin and formed due to cooling of magma. These rocks are found in the northeast and eastern parts of the city.

Groundwater level fluctuations

The groundwater levels in the observation wells in Nagpur urban area were analyzed for the period 1999–2010. Aquifer fence diagrams have been generated for the year 1999 and 2010. In aquifer fence diagram of year 2010 (Fig. 7) the lower blue circle in stratigraphic formation shows groundwater level in the pre monsoon and the upper blue circle shows groundwater level in post monsoon period in the respective years. The maximum fluctuation observed is 12 m at Somalwada in south Nagpur while minimum was in east Nagpur. The fluctuations in groundwater levels are related to quantity of recharge and flow directions depicted through modeling.

Groundwater level fluctuation (bgl, in m) was more in the well nos. 6, 14, 16, 19, 22, 29, 24, 38, 39, and 65 in the weathered Basaltic formations. The pre monsoon groundwater levels are deeper suggesting more withdrawals and post monsoon groundwater levels are shallower indicating recharge but low groundwater potential of Basaltic aquifer system. Similarly, considerably high fluctuations are observed in well nos. 35, 40, 45, 52, and 59 in the Archaean formation; 38 and 39 in Gondwana; 9 in Lameta, and 57 and 58 in Recent Alluvium (Fig. 8, 9). The central Nagpur area has shallow groundwater levels (between 0.5 and 2 m bgl) as compared to north, east, and south part.

Fig. 9 Depth to water level within NMC boundary 2010 (pre and post monsoon)



The land use over central Nagpur includes high, medium, and low dense built up areas. Peripheral Nagpur urban area has crop land which causes maximum withdrawals and hence groundwater is showing declining trends. Groundwater level fluctuation map for years 1999 and 2010 was generated using kriging interpolation technique in GIS. The comparison of the post monsoon groundwater levels in 1999 and 2010 has been shown in Fig. 10. It may be noticed that the groundwater table shows declining trends during the period 1999–2010 in the Basaltic aquifers system which is located in central as well as western Nagpur. Further, a rise in groundwater table may be noticed in Gondwana and Archaean formations present in north and northeast Nagpur urban areas.

Groundwater storage capacity

The groundwater storage capacity was estimated using the hydrogeological characteristics of stratigraphic formations (Table 1). The total aquifer volume and volume of voids in each stratigraphic unit represents the maximum groundwater storage potential of the stratigraphic unit. The total groundwater potential of the aquifer system, based on aquifer volumes estimated through 3D stratigraphic model and the respective porosities of each geological formation determined in lab by water absorption test, is estimated to be 248.74 Mm³ (Table 1).

Table 1 Hydrogeological characteristic of stratigraphic formations

Formation	Aquifer volume (Mm ³)	Porosity (%)	Volume of voids (Mm ³)
Deccan traps (Basalt)	1270.75	5	63.53
Lameta (cherty limestone)	83.25	4	3.33
Gondwana (sandstone/shale)	223	11	24.53
Archaean (schist/gneisses)	2629.25	6	157.55
Total	4206.25	5.9	248.74

For assessing the groundwater recharge potential in each stratigraphic formation, the correlation was done between rainfall and post monsoon rise in groundwater level (Fig. 11). It may be observed that the value of coefficient of correlation between rainfall and rise in groundwater level is high in Recent Alluvium, Basaltic formations, and Archaeans (Fig. 11) while it is low in Lameta and Gondwana formations. This is due to higher storage capacities of fractured weathered Basalt (Madhnure 2014) and Gondwana sandstone formations.

Groundwater flow modeling

The groundwater flow modeling has been performed using MODFLOW software to delineate the groundwater flow

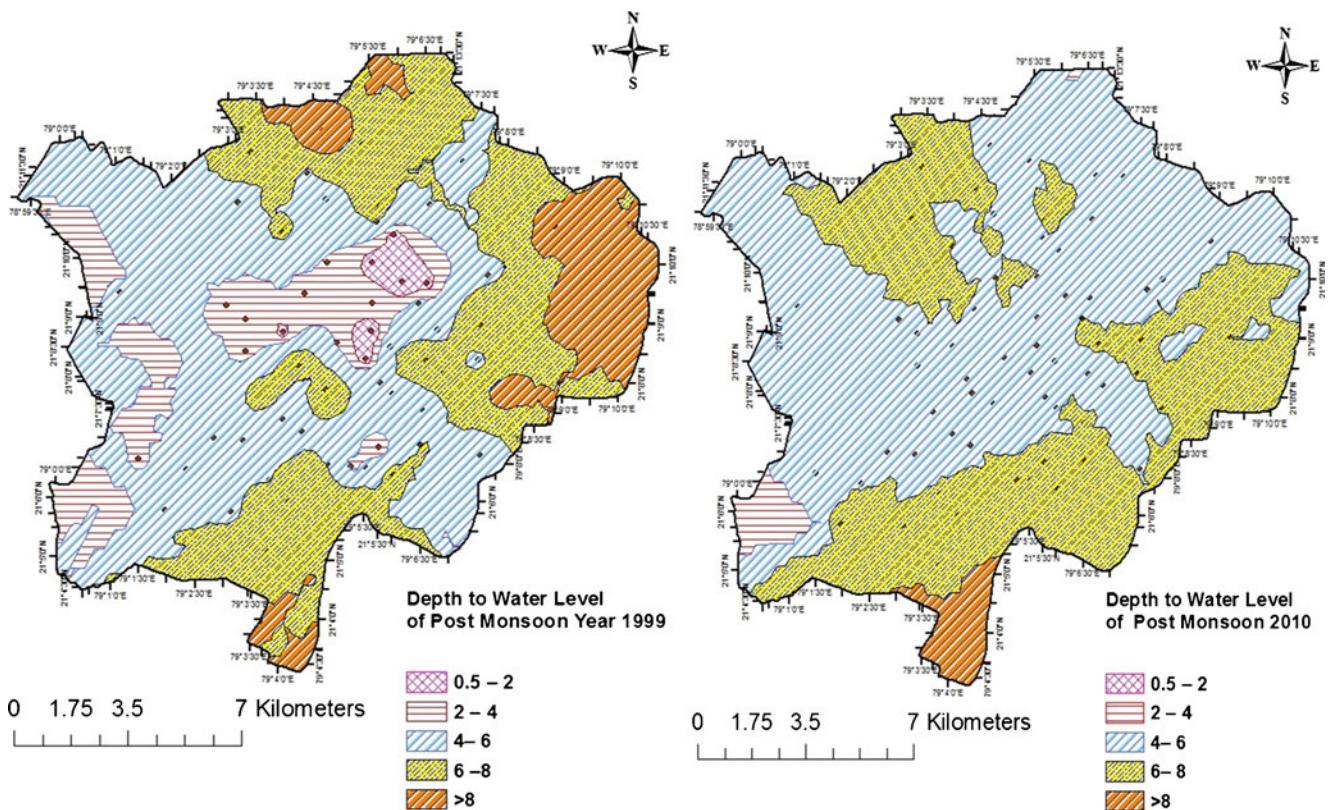
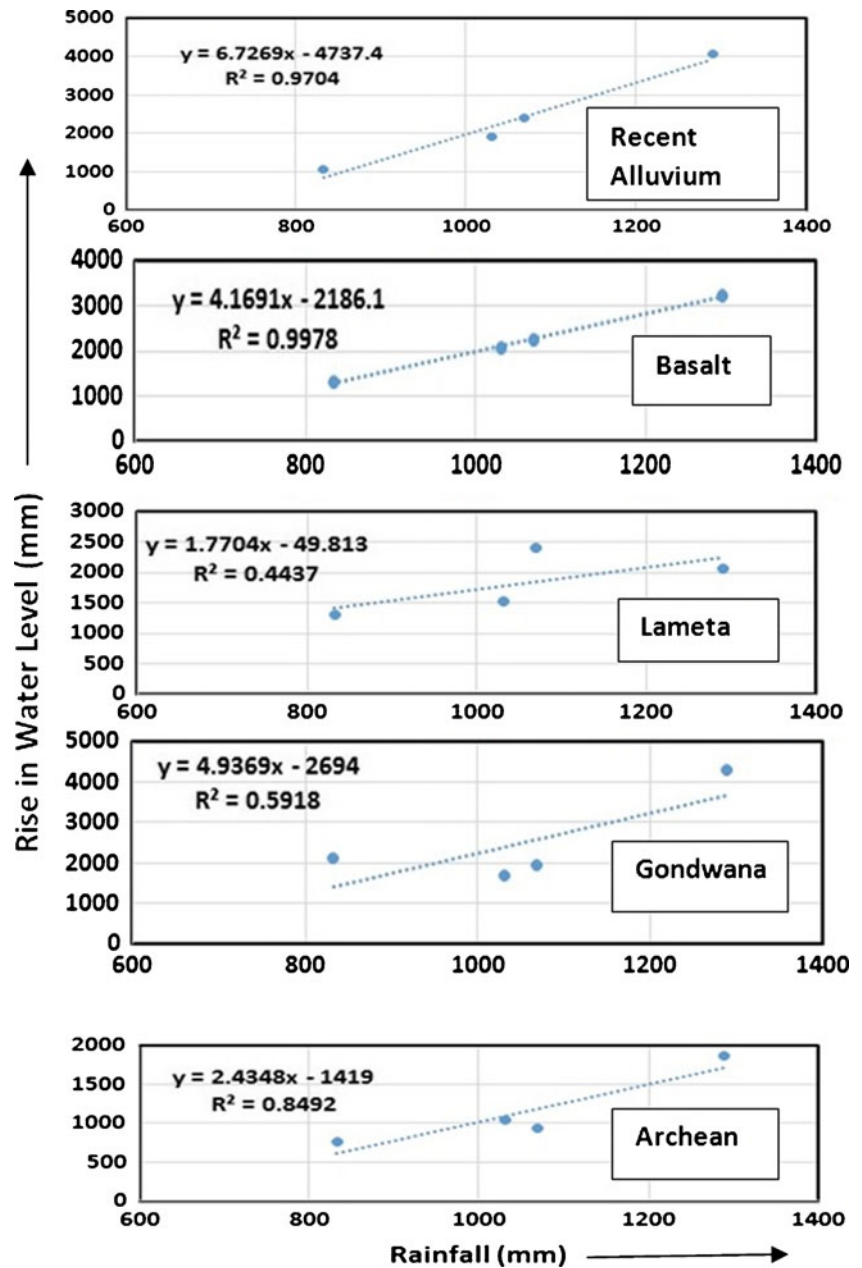


Fig. 10 Comparison of post monsoon groundwater levels of 1999 and 2010 (in bgl)

Fig. 11 Correlation between rainfall and rise of groundwater levels in stratigraphic formations during 1999–2010



directions. For modeling, an active area of 128.83 km² with cell size of 300 m × 300 m in Basaltic terrain was considered since more than 60 % of area within study is occupied by Basaltic formation. The Nag and Pili River flows through the urban area from west to east. The no flow or constant head boundaries of the active area have been assigned on the basis of topographic divides and extent of Basaltic aquifer. Groundwater level of May 1999 was assigned as the initial head of the aquifer. The value of estimated porosity, hydraulic conductivity, and recharge flux were assigned (Tables 2 and 3) for Basalt aquifer system (CGWB 2007, Varade et al. 2014; Katpatal et al. 2014). Water balance of Basalt formation is estimated to be 0.0560 Mm³.

Table 2 Specification of the conceptual groundwater model

Parameters	Layer
Grid size	300 × 300 (m)
Formations	Basalt formation
Layer type	Unconfined (single layer)
Saturated thickness of the aquifer (m)	11.03
Time (days)	120
Initial hydraulic head (above msl)	311.489

Table 3 Aquifer characteristics of the Deccan trap (Basalt) formation

Parameters	Ranges	Source
Hydraulic conductivity, K (m/day)	0.1 to 82.96	Varade.et al. (2014) CGWB 2009
Porosity	5 %	Estimated using Gravimetric test in lab
Recharge flux (m/day/cell)	4.3155×10^{-4}	Estimated as per GEC Report, India. (CGWB 2009)

Boundary conditions

The boundary conditions of no flow or constant head have been assigned (Fig. 12) on the basis of topographic divides and extent of basaltic aquifer.

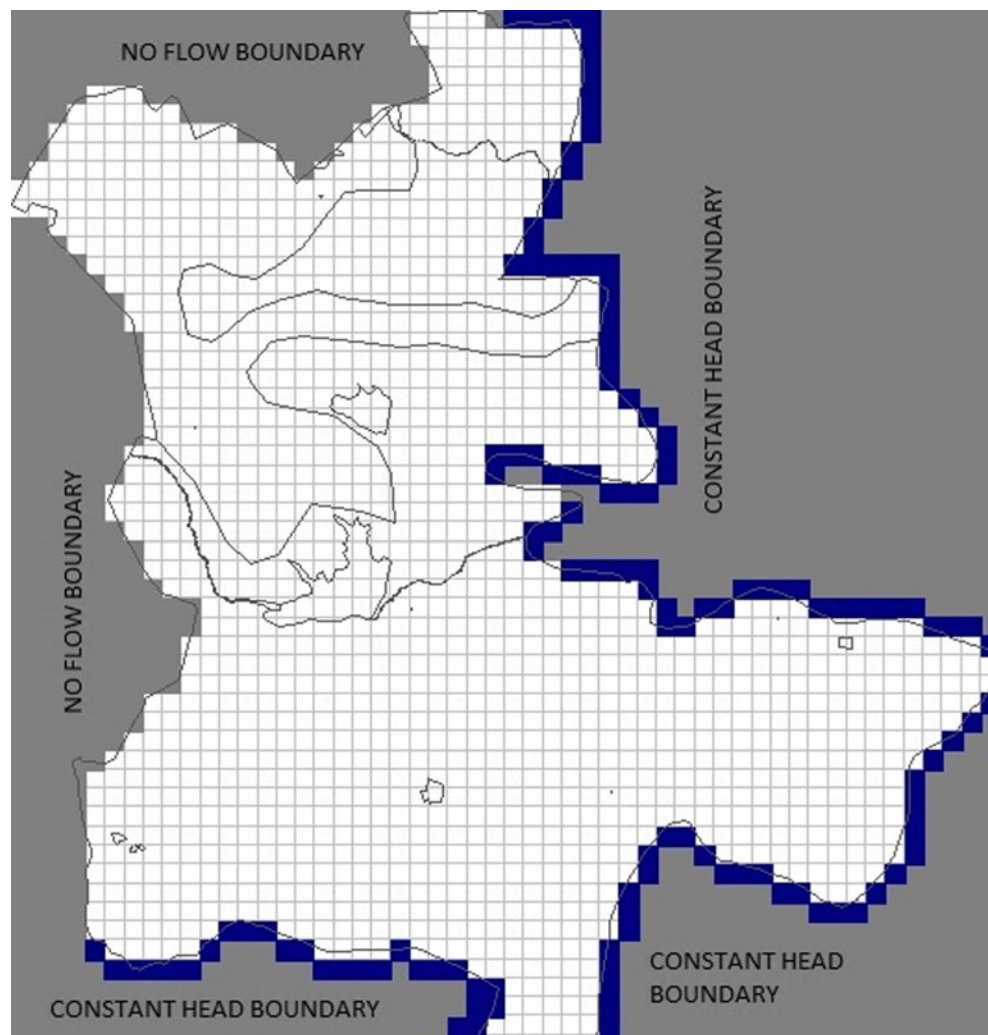
Aquifer parameters

Porosities of all formations were determined in the lab through water absorption method from which storage capacities and total potential of the aquifers were estimated. The specifications of the conceptualized groundwater model and the aquifer

parameters of Deccan Trap Basalt used in modeling are presented in Tables 2 and 3, respectively.

Calibration of model

Initially, the model was calibrated for single stress period (1 day) and the parameters of initial hydraulic head were assumed to be constant. Hydraulic conductivities are iteratively adjusted within limit until the calibrated head matched with the field hydraulic head (observed head for 120 days). The model is found suitable where the simulated heads (marked in the box) almost matched with field hydraulic heads

Fig. 12 Boundary conditions used to simulate the groundwater model

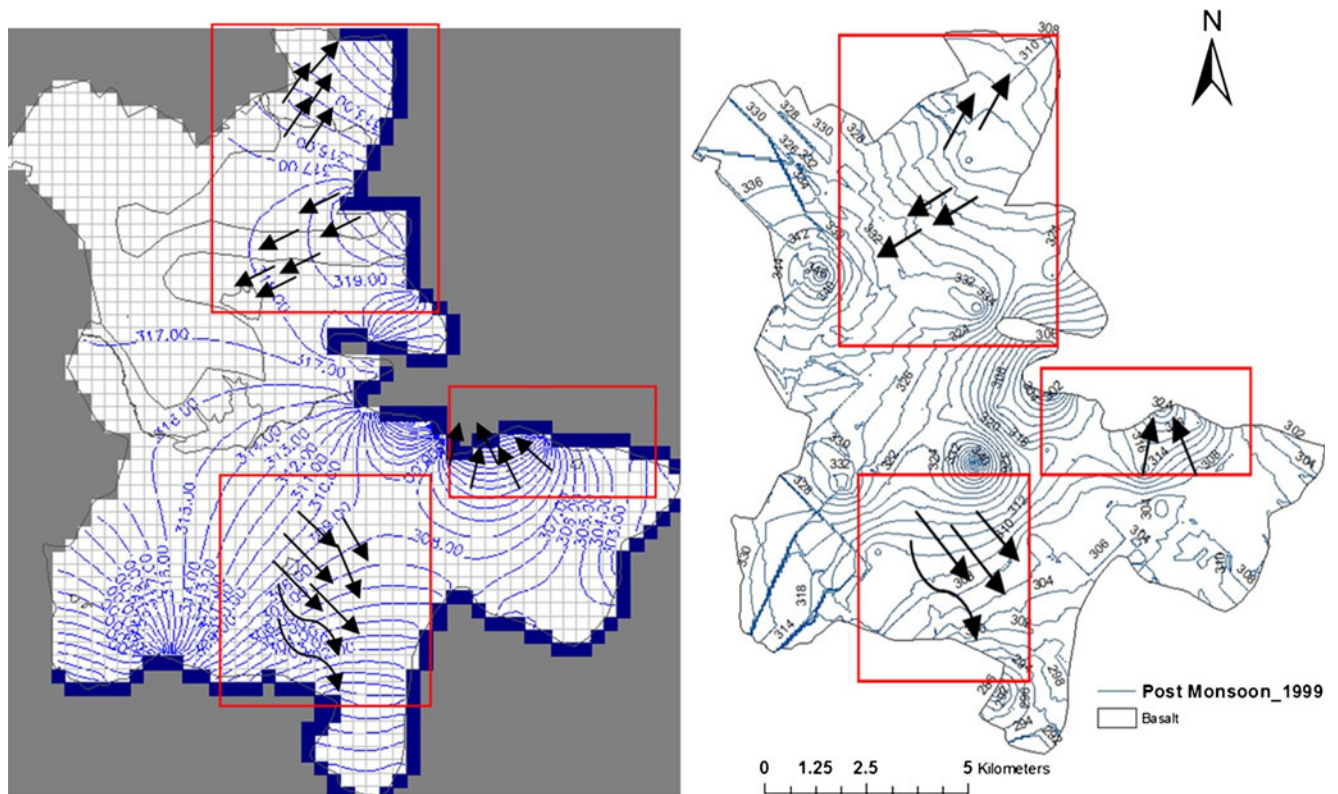


Fig. 13 Comparison of estimated and observed heads with steady state condition for 1999

generated through Kriging interpolation technique in GIS from field data (Fig. 13).

Recharge flux

Rainfall is the main recharge source of the aquifer in Nagpur urban area. Recharge is calculated using Eq. (2) suitable for the hard rock terrains suggested by the groundwater estimation committee (CGWB 2009).

$$R = H A S_y \tag{2}$$

where R = ground water recharge, H = Water level fluctuation (m), A = area (sq. km)

and S_y = specific yield.

For the year 1999, the groundwater recharge within modeled area is 6.67 Mm³.

Groundwater recharge scenario

The present study illustrates integrated approach to visualize the geometry of the aquifer system of the Nagpur urban area to implement the appropriate groundwater recharge methodology and strategy. The total groundwater potential of the aquifer system, based on aquifer volumes estimated through 3D stratigraphic model and the respective porosities of each lithological class is estimated to be 248.74 Mm³. It may be noticed that the west part of the city has crystalline Basalt exposed,

Table 4 Groundwater recharge estimated from Eq. (2) for geological formations (1999–2010)

Formations	Average rainfall (mm)	Average water level fluctuations (m) (1999–2010)	Specific yield (%)	Average annual recharge (Mm ³) (1999–2010)	Well numbers
Archean	1055.45	1.15	0.015	0.85	1, 12, 35, 36, 40, 44–46, 48, 49, 52–56, 59
Basalt		2.21	0.025	7.13	1–8, 10, 13–20, 22–25, 27, 29–31, 33, 34, 50, 51, 61, 62, 64–66
Gondwana		2.52	0.08	5.04	38, 39, 42
Lameta		1.82	0.015	0.35	26, 28, 32, 63, 69
Recent Alluvium		2.36	0.1	1.10	37, 41, 43, 57, 58, 60
Total				14.47	64

which has groundwater storage capacity as a function of the extent of weathering and vesicles present in them. The Basalts are overlain on Gondwana formations and Metamorphics at different places which has higher groundwater storage

capacity. Thus, the annual groundwater recharge has been estimated using Eq. 2 (Table 4). The total annual groundwater recharge has been estimated to be 14.47 Mm³ while the storage capacity of the unconfined aquifers in study area has been

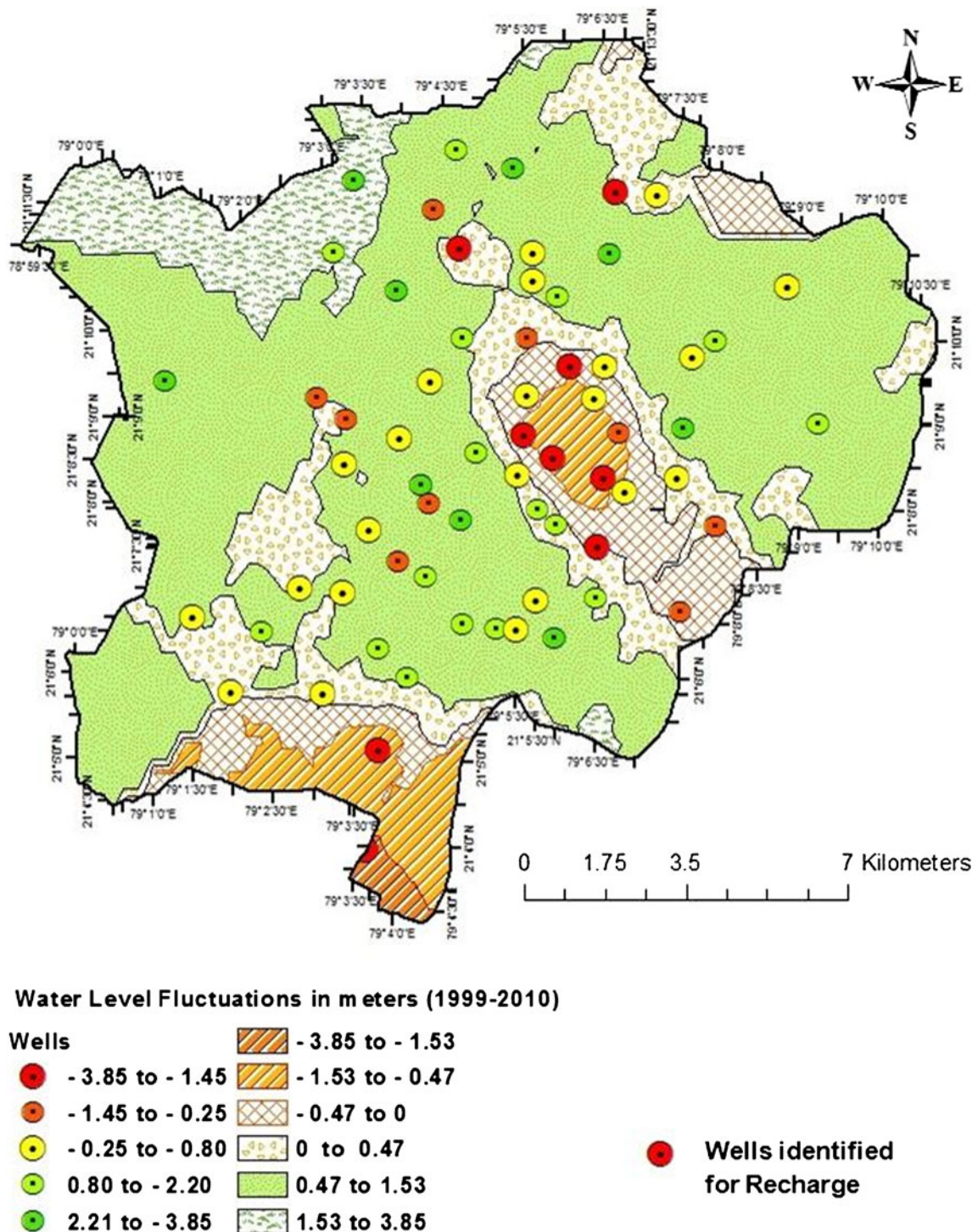


Fig. 14 Groundwater level scenario in NMC boundary between 1999 and 2010 with identified groundwater recharge wells

estimated as 248.74 Mm³. Hence, there is scope of enhancing the groundwater recharge through identification of the recharge sites. Gondwana formations are exposed in the northern parts of Nagpur. The porosity of Gondwana formation is 11 % (Table 1) which is highest and groundwater recharge may be done here by the surface recharge techniques.

Based on the integrated approach suggested earlier utilizing the aquifer set up revealed by stratigraphic profiles, wells showing declining groundwater trends, and the groundwater flow directions revealed by modeling, the recharge wells have been identified within the study area which have been shown in red color (Fig. 14). These wells belong to Gondwana and Basalt formations. These recharge sites have been selected as these formations consist of medium to coarse-grained friable sandstone and vesicular basalt, respectively. Weathering, fracturing, and joints play an important role in the storage while weathering widens the fractures and joints in Basalt formation (Madhnure 2014). Also, flow modeling (Fig. 13) indicates that in Basaltic terrain, groundwater flow is from these wells to other directions. The falling groundwater trends are associated with densely populated areas in central Nagpur and south Nagpur. These are the sites which must be taken up for groundwater recharge. Since, these sites are present within dense built up urban areas, recharge through direct injection wells is proposed.

Conclusions

The study illustrates that an integrated approach using three-dimensional stratigraphic modeling, geological sections drawn through bore log data, groundwater fluctuations represented by fence diagrams, and interpolation in GIS and groundwater flow directions delineated by flow modeling not only helps in visualizing the aquifer dynamics correctly but also is useful in identifying the recharge sites for groundwater recharge. DEM generated indicates that the surface flow in Nagpur urban area occurs from west to east, further indicating subsurface flow follow the same direction. A three-dimensional stratigraphic model allowed visualization of subsurface stratigraphy of the Nagpur urban area and study shows that this approach may help in calculating volumetric groundwater output from geologic formations. The geological sections drawn across various alignments confirmed the aquifer dimensions and their set up which were used to estimate the total groundwater potential of each stratigraphic unit as well as the total groundwater potential in the unconfined zone within Nagpur urban area. Aquifer modeling delineated the groundwater flow directions which were matched with filed data. It may be concluded that the geometry and dynamics of the unconfined aquifer system comprising of various stratigraphic

formations may be visualized using the integrated approach adopted in the present study. The study also indicates the groundwater recharge sites which can be used for groundwater development and management the groundwater scenario.

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