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REPORT

Groundwater-level assessment and prediction using realistic pumping and recharge rates for semi-arid coastal regions: a case study of Visakhapatnam city, India

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Abstract

Water scarcity in urban areas is a common problem in many cities of India, and Visakhapatnam, a fast growing industrial city on the east coast of India, is no exception. Increasing urban population, industrial expansion and shrinking surface-water sources have widened the gap between the demand and supply, resulting in groundwater depletion and saline water intrusion along the coastal region. MODFLOW is a widely used numerical groundwater flow model but requires realistic estimation of field inputs in order to contribute effectively to recommendations for proper management actions. The present study focuses on computing the spatial and temporal variations of model inputs such as pumping and recharge rates using the field data collected from various organizations. The developed PMWIN MODFLOW model provides insight into the present and future trends in the variation of groundwater levels. Observation wells data are used in the model calibration to fix the aquifer parameters through the parameter estimation algorithm PEST. Models are performed for four projected scenarios with different rates of pumping and recharge values. Results indicate the importance of improving the recharge capability of potential areas, to sustain the aquifer's capacity to cope with stresses on groundwater resources. The model results are useful to fix optimum pumping limits in the study area for sustainable groundwater management and will help to prevent disastrous impacts on groundwater potential in the future.

Keywords Groundwater modeling · MODFLOW · Urban groundwater · Coastal aquifers · India

Introduction

Water is naturally available in space and time, but not necessarily in accordance with man's numerous and varying needs. Due to rapid population growth and unsustainable economic development everywhere, there is an increasing problem of resource depletion and environment pollution. In urban cities, this problem is acute, because the demand for water from various sectors, such as drinking water and industry, are growing rapidly in line with population increase, rising incomes and industrial growth. Visakhapatnam is one such city, located in the north of Andhra Pradesh state (India), on the coast. The city is facing shortage of water supply with the crisis growing along with the city's development. In recent decades, the city has been witnessing a rapid expansion of residential and other built-up areas both horizontally and vertically causing reduction in the recharge area and increase in pumpage per unit area. Further, due to the proximity of the Bay of Bengal to the city, all the inundated storm water is being lead to the sea without the least possibility of seepage into groundwater aquifers.

Field studies on groundwater quality in the study area also conclude that salt-water intrusion and groundwater pollution occur in areas close to the seacoast due to the rapid urbanization in and around the city and the consequent over-pumping of groundwater (Srisailanath and Rao 1999; Srinivas Rao and Nageswara Rao 2009; Satyanarayana et al. 2013). Due to inadequate storage for meeting the industrial and domestic water requirements from local sources, Greater Visakhapatnam Municipal Corporation (GVMC) collects water from far off sources to meet the water needs of the city as well as withdrawing groundwater for domestic supply through boreholes or wells, amounting to about 20% of the total supply (Abhishek et al. 2016). Due to deficiency in the municipal

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supply, the population has resorted to unregulated groundwater pumping causing groundwater-level decline at an alarming rate (Ramakrishna et al. 2009). Demands on groundwater may increase in the future because of the shortage of storage space in all the surface sources due to the unpredictable monsoons. Therefore, it is necessary to know the future trends of declining groundwater levels under various stresses in the study area, for better planning for sustainable groundwater management and to prevent disastrous impacts on groundwater potential in the future.

In recent years, groundwater modeling has been playing an important role in studies of groundwater exploration, prediction and remediation for planning, design, implementation and management of groundwater resources. Continued improvements in computer hardware and software, and in spatial databases using geographic information systems (GIS), have been made using three-dimensional (3D) groundwater flow models such as MODFLOW possible. MODFLOW, developed by the US Geological Survey (McDonald and Harbaugh 1988), is probably the most popular numerical model used for groundwater modeling due to its flexible modular structure, ease in handling any complex hydrogeological systems, and its availability in the public domain. Studies by Rejani et al. 2003; Houcyne and Florimond 2006; Heyddy and Laurence 2007; Shiquin et al. 2008; Nepal et al. 2011; Alam and Umar 2013; Zhonggen et al. 2013; Surinaidu et al. 2014 are some of the successful applications of MODFLOW in various fields of groundwater modeling.

Regional studies on groundwater modeling (Maheswaran et al. 2016; Kanak et al. 2017) have also used the PEST model for calibrating aquifer parameters. Recently, Surinaidu et al. 2015 developed a steady-state-groundwater-flow model using MODFLOW to estimate the seepage discharge into a tunnel located in alluvium with scanty exposures of sandstone in Jammu and Kashmir province, India, while Izady et al. 2017 modelled 3D stratigraphic groundwater flow using MODFLOW in a transboundary hard-rock-alluvium aquifer in Oman to estimate groundwater balance and sustainable groundwater extraction rates.

In the present study, an attempt is made to quantify the existing groundwater conditions and to predict probable future trends in the groundwater levels by using PMWIN MODFLOW. The groundwater flow modeling done in the study area considers the impact of rapid urbanization on the groundwater recharge and well abstraction rates. To improve the accuracy in the estimation of input variables such as groundwater pumping and recharge rates, the well extraction quantity rates are estimated based on the monthly ward-wise-water-supply-deficit values, considering a demand of 135 litres per capita per day (lpcd), as per the guidelines of the Central Public Health and Environmental Engineering Organisation (CPHEEO), while the recharge rates are estimated from meteorological data such as rainfall, evapotranspiration (ET) and runoff. Runoff is estimated using the NRCS-CN method, which is widely used for the estimation of peak discharge for small and medium-sized catchments by integrating land use maps, soil information, meteorological data and other field data. The curve number values from the Natural Resources Conservation Service-Curve Number (NRCS-CN) method were adjusted with respect to rapid elevation changes in the terrain of the study area (Mahammood 2003; Ramakrishnan et al. 2009). The PEST module is used in the model calibration to fine-tune the ground parameters, and various future scenarios of pumping and recharge rates are considered to study the fluctuations and forecast the depletion rates of the water table. Finally, the effect of implementing artificial recharge methods in the study area to restore the groundwater potential is studied.

Study area

Visakhapatnam city is located in the state of Andhra Pradesh along the east coast of India at latitude 17°45′ north and longitude 83°16′ east, nestled amongst the hills of the Eastern Ghats and facing the Bay of Bengal to the East. It is the largest city in Andhra Pradesh having an urban area of 533 km^2, and is known for its seaports, natural harbour, shipyard and heavy industries such as steel plant, fertilizer, petroleum, etc. The location map with the present study boundary is shown in Fig. 1.

Physiography

Physiographically, Visakhapatnam can be divided into two parts—the Eastern Ghats Hill ranges in the north, and the southern areas and plains with valleys located in the center of these two hill ranges. The Kailasa Hill range, with a maximum elevation of 484 m above mean sea level (msl) on the north flank of the city stretches from Simhachalam to MVP Colony, while the Bay of Bengal is located on the east. The southern border of Visakhapatnam city is formed by the Yeradakonda Hill range with a maximum elevation of 357 m msl. The marshy land existing in between these two hills makes up the southern boundary of the present study area.

Climate and rainfall

Visakhapatnam and its surroundings have semi-arid conditions. The summer season is from March to May and is followed by the Southwest monsoon, which usually sets in during the month of June and ends in September. The Northeast monsoon comes in October and November, during which period the frequency of cyclonic storms is high in the Bay of Bengal. December to mid-February is generally the season of fine weather. The rainfall and other meteorological data are monitored by the Indian Meteorological Department (IMD) in Visakhapatnam.

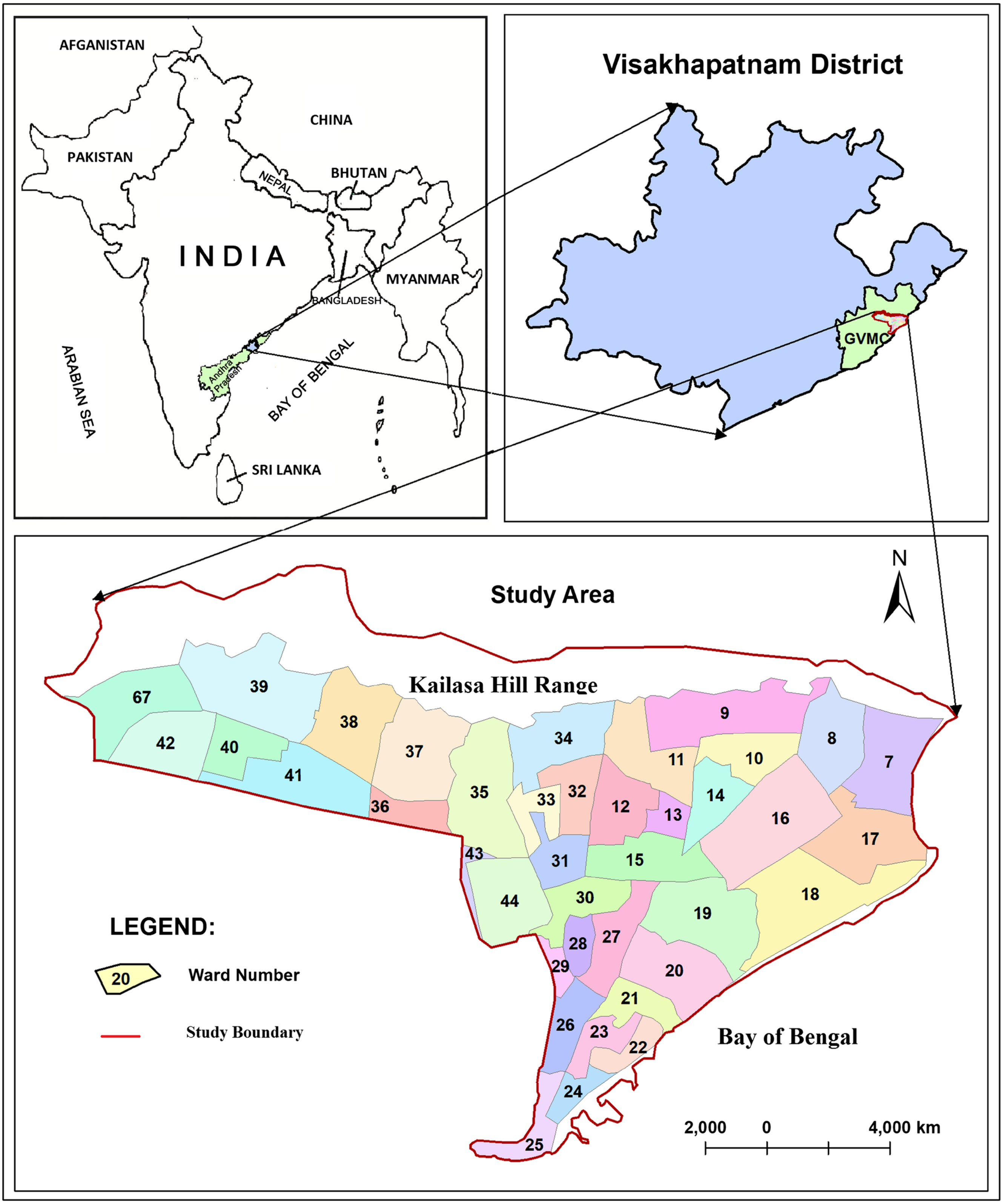


Fig. 1 Location map of Visakhapatnam

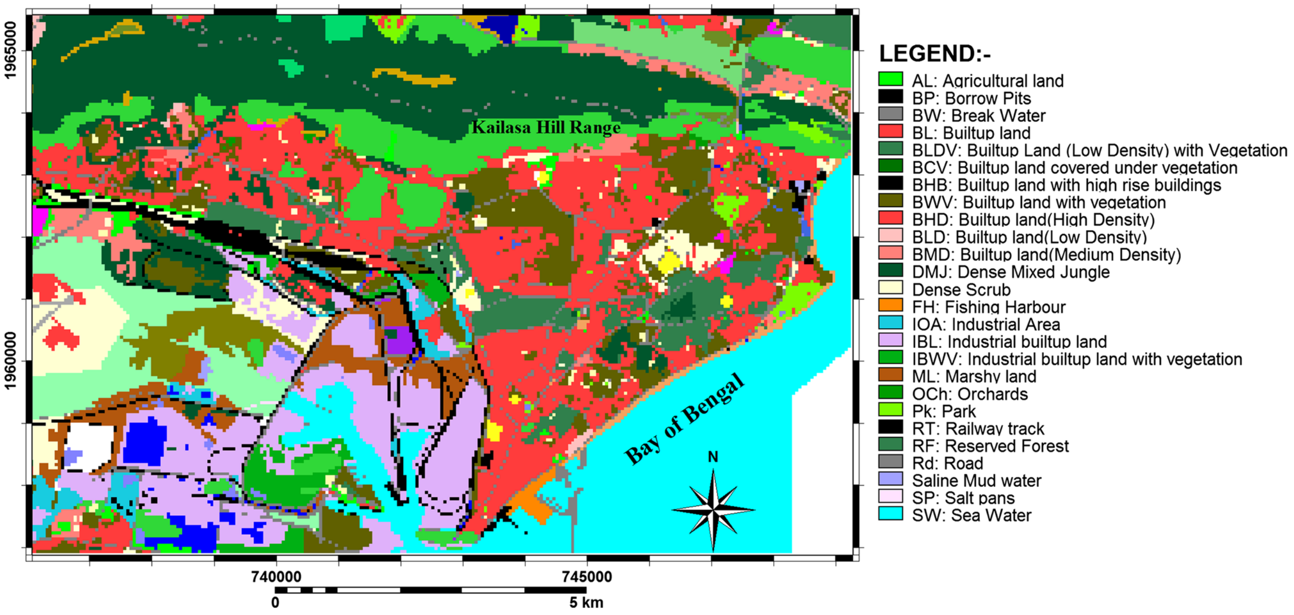


Fig. 2 Land use/land cover map of Visakhapatnam Municipal Corporation for the year 2001

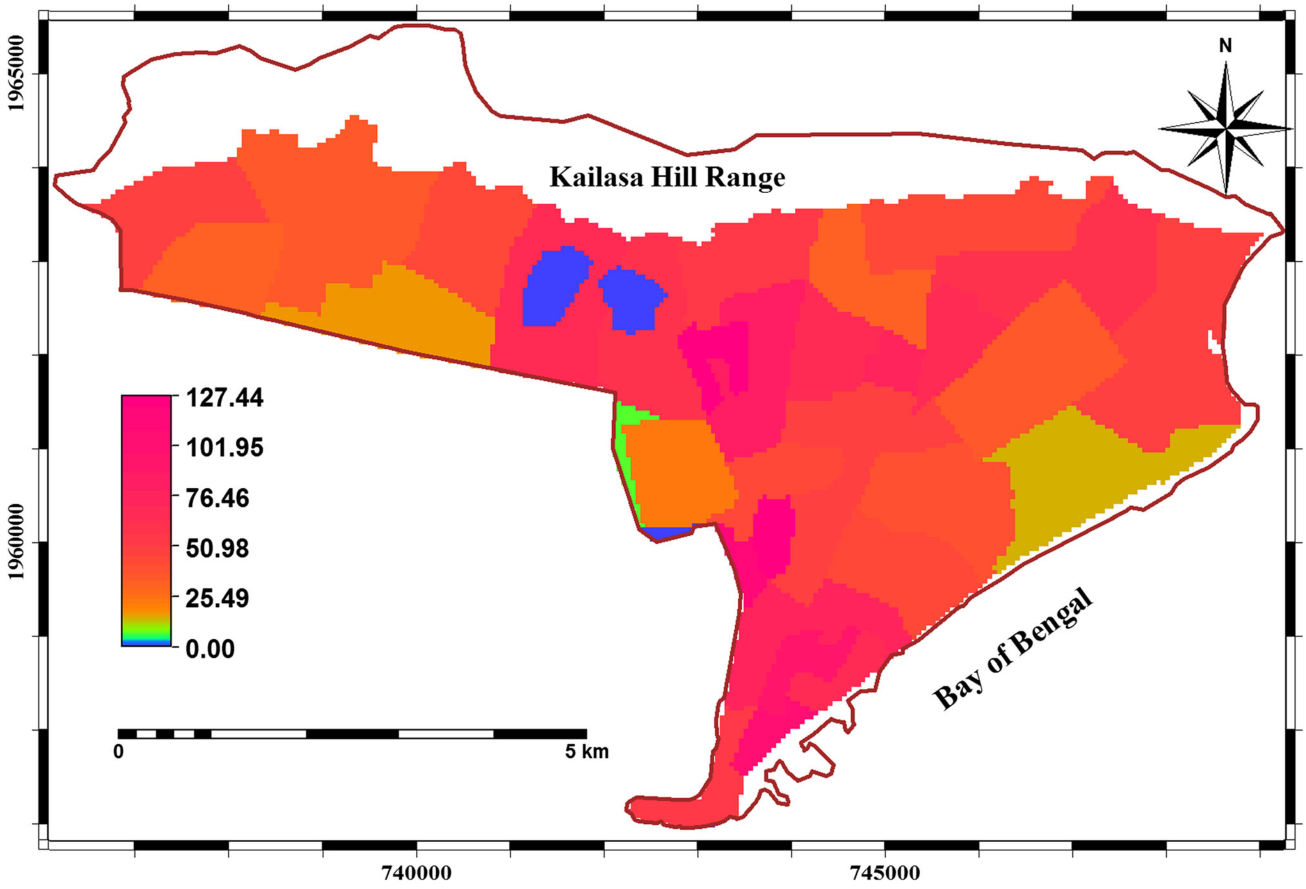


Fig. 3 Ward-wise population density [population/(50 m × 50 m) grid] map in the study area for the year 2012

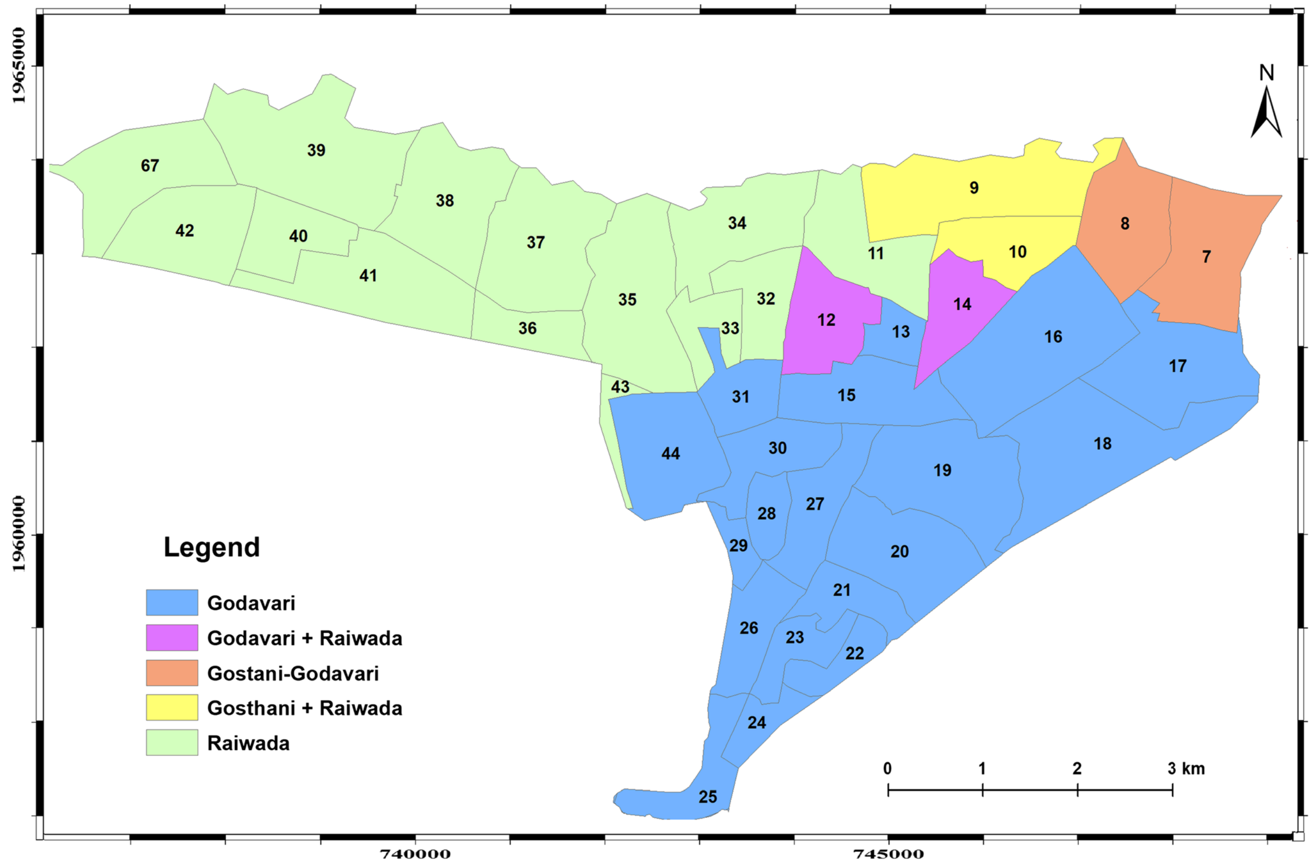


Fig. 4 Ward-wise sources of water supply in the study area

The temperature gets lowered with the onset of the southwest monsoon, falling to a mean minimum of 17.5 °C in January, and rises till May recording a mean maximum of 34 °C. Over the past 15-year period, the rainfall was highly variable with a minimum rainfall value of 584 mm recorded during the year 2002 and maximum rainfall of 1,862 mm for the year 2010, and the mean average rainfall of the city is reported to be 1,125 mm.

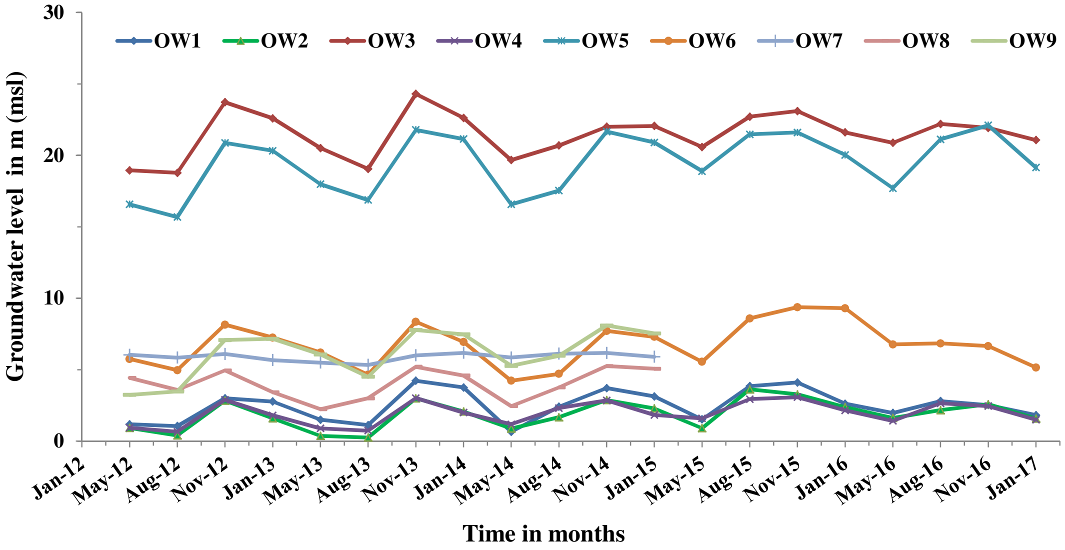


Fig. 5 Temporal variation of groundwater levels of nine observation wells in the study area

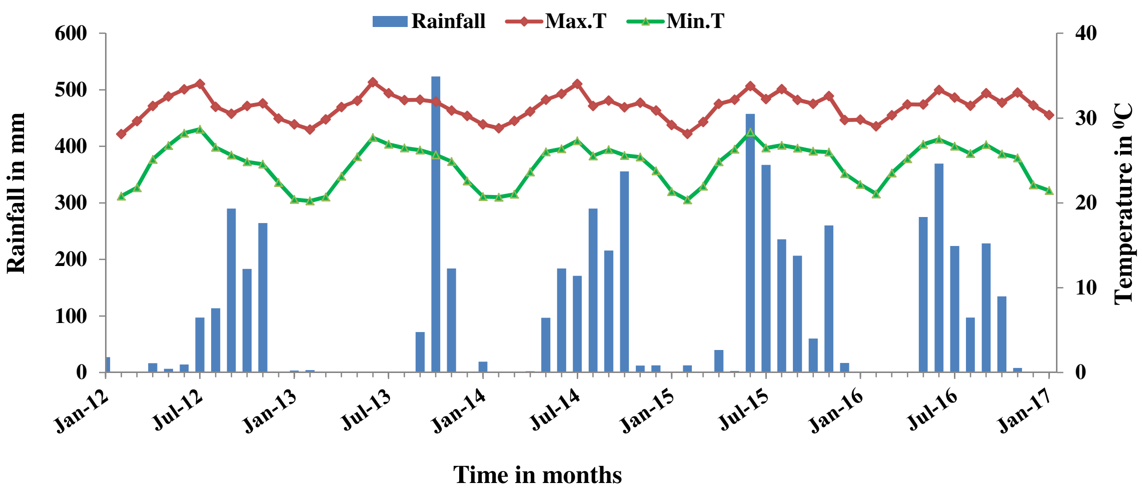


Fig. 6 Monthly rainfall and temperature data of Visakhapatnam

Land use and land cover

Monitoring, mapping and assessment of land use/land cover in temporal sequence are essential for planning and development of land resources. Information for land use planning comprises reliable up-to-date and comprehensive data on the physical, ecological and socioeconomic framework of the region. The national land use/land cover classification for India, which is fairly compatible with the user's needs, was developed by the land use/land cover division under the National Remote Sensing Agency and is used to classify various classes in the present study area. Since the land in the study region is almost saturated with built-up areas, preparation of a land use/land cover map of the study area, as shown in Fig. 2, was done using digital remote-sensing data from IRS-1C LISS III and Panchromatic of Path 104 and Row 60, dated 06 February 2001.

Hydrogeology

As documented in the Central Ground Water Board (CGWB) reports (Srisailanath and Rao 1999; Bhaskara Rao 2012), the groundwater occurs largely under unconfined conditions in all the formations of the study area. However, the nature and occurrence depend upon various factors like rainfall, topography, land form, geology and structure. The hydrogeological conditions in the study area are classified into two types—hard crystalline rocks and unconsolidated sediments—whereby the crystalline rocks consist of hard rocks like khondalites, feldspathic gneisses, charnockites and granites, and the unconsolidated formations include red sediments, colluvium and alluvium, and coastal sands. Groundwater movement in the crystalline formations is due to the secondary porosity developed through weathering and fracturing. The thickness of weathering varies from 5 to 45 m. The alluvium is found in the areas of Narava stream and Hanumanthavaka stream in MVP Colony. Its depth ranges up

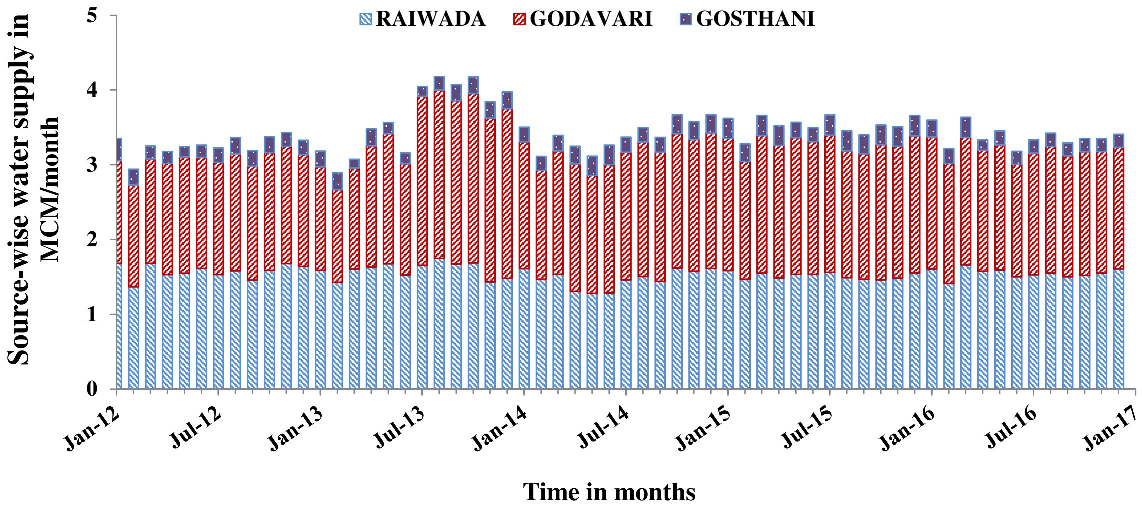


Fig. 7 Monthly domestic water supply data from different sources in the study area

to 10 m with alternating layers of sand, silt, clay and gravel in various proportions. The areas covering Andhra University, Chinna Waltair, Pandurangapuram, RK Beach, Kapuluppada Valley and hill flanks are covered with red sediments having a varying thickness from 10–40 m. The texture of these sediments is largely silty. Wind-blown sands occur along the seacoast. The colluvium occurs along the Kailasa foothill zones.

Population census

The population of Visakhapatnam city is 1.728 million, as per the 2011 census, and this constituted 2.06% of the population of the state, while the geographical area of the GVMC is 533 km^2, which is only 0.196% of the area of the state. The ward-wise population data for the years 2001 and 2011 were collected from the Chief Planning Office (CPO), Visakhapatnam. The overall annual growth rate for the city during the decade 2001–2011 was 2.53%. The incremental increase method is used for estimating the projected population for the corresponding years. The ward-wise-population-density map in terms of the number of people per cell is prepared for every year and the corresponding map for year 2012 is shown in Fig. 3.

Existing sources of water

Greater Visakhapatnam Municipal Corporation (GVMC) supplies drinking water for residences belonging to 72 municipal wards and also to the industries through the Town Service Reservoir. The main surface sources of water for the city of Visakhapatnam are: Mudasaralova Reservoir, Gambheeram Gedda Reservoir, Gosthani River, Thatipudi Reservoir, Mehadri Gedda Reservoir, Raiwada Link Canal, Yeleru Left Bank Canal and Godavari River. The total quantity of water that can be drawn from the above sources is 72.80 million gallons per day (MGD; 330.95 million litres per day (MLD). In addition to the above, 7.5 MGD (34.10 MLD) of groundwater is also drawn through borehole or wells. All of the aforementioned sources are not perennial and, due to a considerable reduction in the inflows to impoundments and rapid growth in the population, the city is experiencing a shortage crisis in the summer seasons. The failure of monsoons to support the water supply makes the water supply situation in the city critical, duly forcing the GVMC to regulate the supplies to domestic consumers so as to make water available for longer durations. In the present study area, the ward numbers and their source-wise water supply by the GVMC are depicted in Fig. 4.

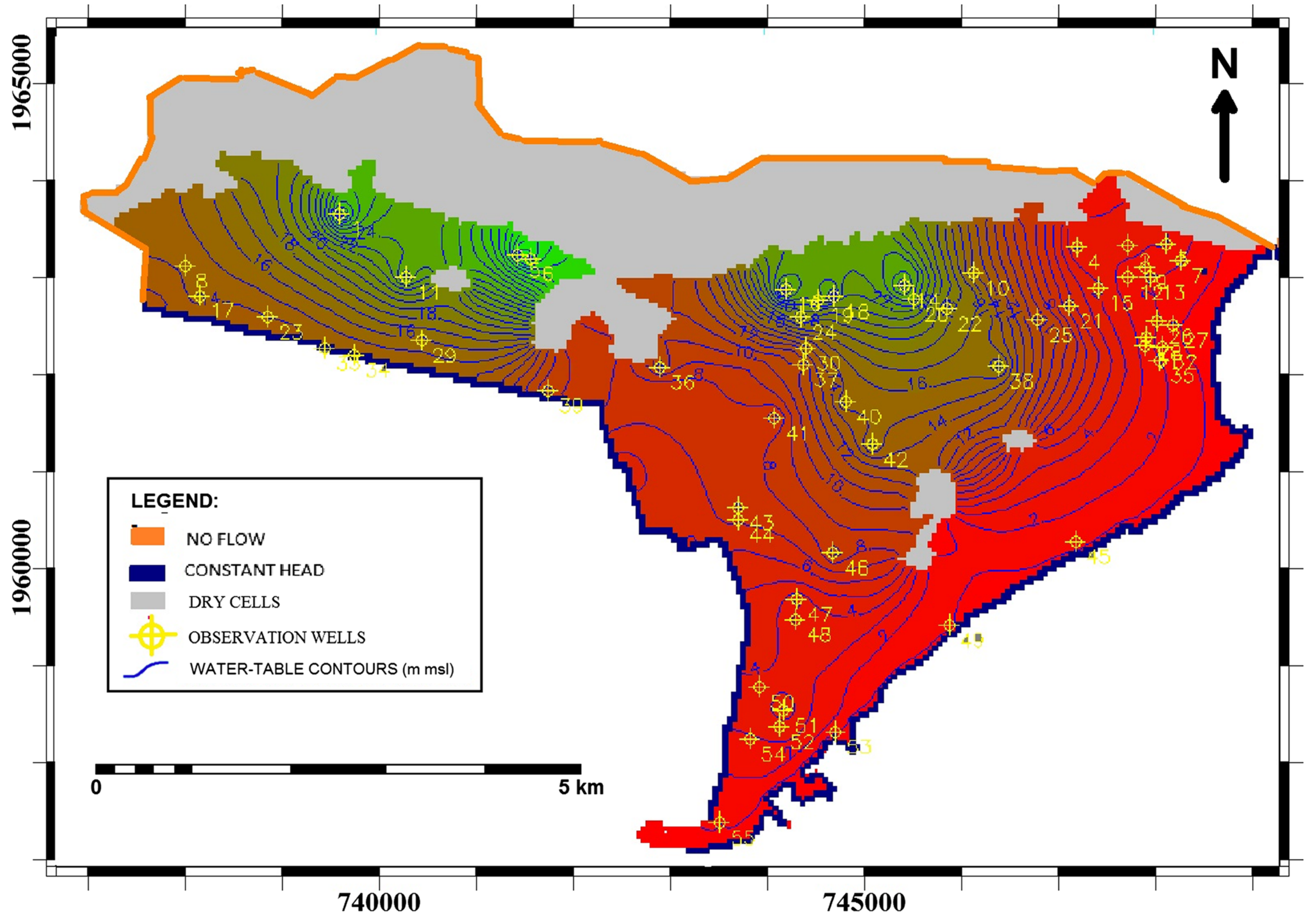


Fig. 8 Steady-state water-table contours and boundary conditions for the study area

Groundwater model development

MODFLOW is a 3D finite-difference-groundwater-flow model. It is currently the most popular numerical model and has a modular structure that allows it to be easily modified to adapt the code for a particular application. MODFLOW simulates steady and transient flow in an irregularly shaped flow system in which aquifer layers can be either confined, unconfined, or both confined and unconfined depending on piezometric head. Flow from external stresses such as flow to wells, areal recharge, evapotranspiration, flow to drains, and flow through riverbeds can be simulated. Hydraulic conductivity or transmissivity for any layer can differ spatially and be anisotropic (restricted to having the principal direction aligned with the grid axis and the anisotropy ratio between the horizontal coordinate directions fixed in any one layer), and the specific yield can be variable. An efficient contouring program is also available to visualize heads and drawdowns from the output of the model. In the present study, Processing MODFLOW is used for simulating steady and transient flow conditions to evaluate groundwater drawdowns in the study area taking into account the impact of rapid urbanization on the groundwater recharge and well abstraction rates. The PMWIN with MODFLOW 2000 version includes the simulation of the saturated–unsaturated flow and transport processes, particle tracking and inverse models to estimate the parameters (Wen-Hsing and Wolfgang 1998). The basic groundwater flow equation in three dimensions used in the flow modeling, with the principal components of the hydraulic conductivity tensor being collinear with coordinates (Rastogi 2007), is given as

$$\frac{\partial\left(K_x h \frac{\partial h}{\partial x}\right)}{\partial x}+\frac{\partial\left(K_y h \frac{\partial h}{\partial y}\right)}{\partial y}+\frac{\partial\left(K_z h \frac{\partial h}{\partial z}\right)}{\partial z}+N=S_y\left(\frac{\partial h}{\partial t}\right) \qquad (1)$$

where the following terms are as defined:

x, y, z, t	Space and time coordinates
K_x, K_y, K_z	Principal components of hydraulic conductivity in x, y, z directions in m/day
h	The head above a common datum which is a measure of the water level at any point in the time and space domain in m
N	Flux of the source or sink in m/day
S_y	Specific yield

Further, groundwater flow modeling can be done conveniently when it is integrated with a geographical information system (GIS). The spatial variation of data such as topography,

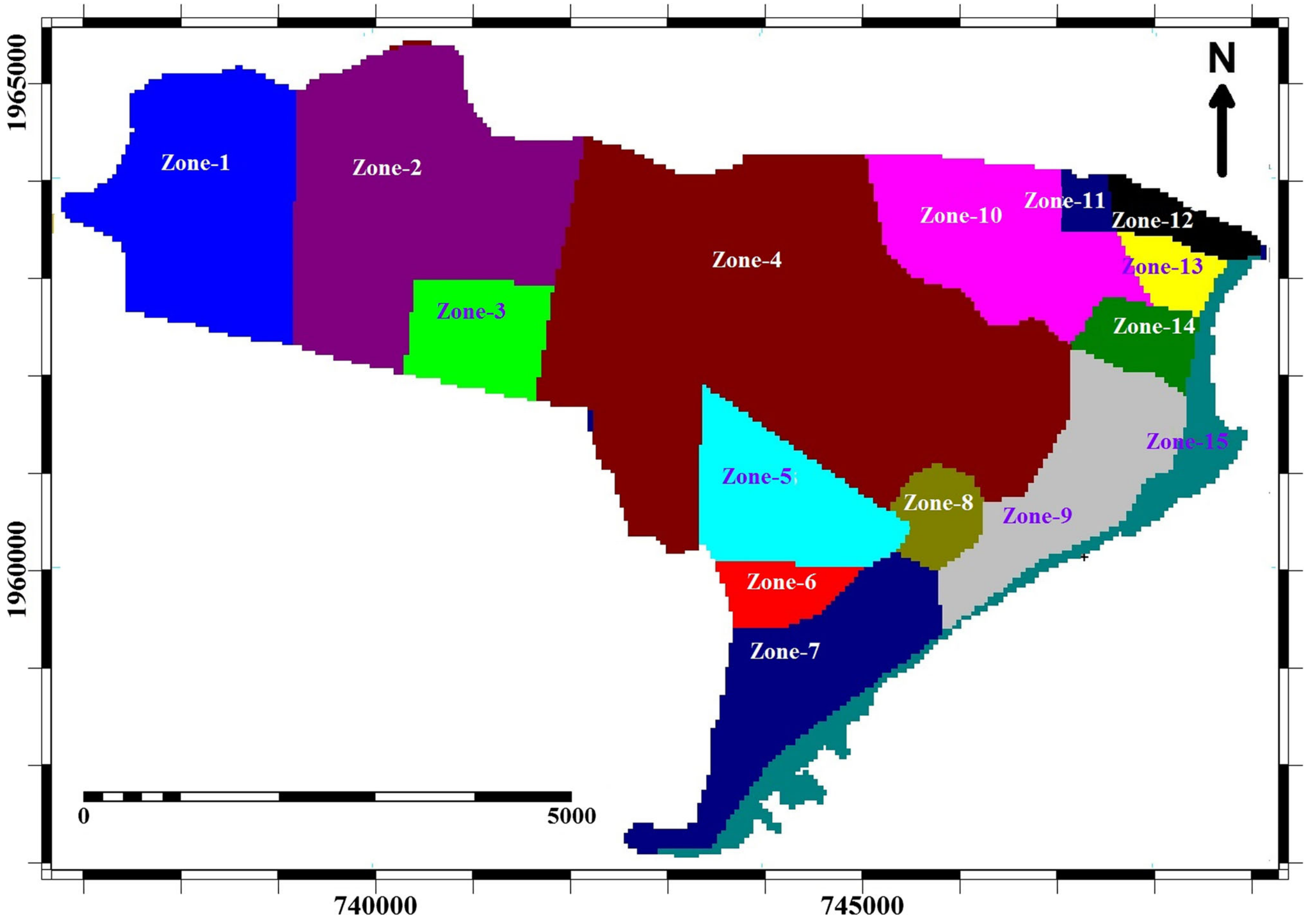


Fig. 9 Demarcation of study area into zones for PEST calibration

lithology, and hydrology in the study area can be represented more accurately using the different GIS layers. GIS facilities have enhanced the speed of groundwater modeling since the manual feeding cell by cell is totally replaced by transfer of GIS layers from the GIS software to MODFLOW in ASCII format. Integrated Land and Water Information System (ILWIS 3.6) is a GIS and remote-sensing software for both vector and raster processing and is used in the current modeling study.

Data acquisition

All the required statistical, hydrological and meteorological parameters for the present study were collected from various state and central departments, however, monthly groundwater levels data were not available. The CGWB monitors groundwater levels four times per year (January, May, August and November) from nine observation wells in the study area. Among them, three wells were not monitored during years 2015 and 2016. Groundwater level data (m msl) from the nine observation wells (OW) are shown in Fig. 5. Apart from that, one dataset of groundwater levels was collected from 55 observation wells spread over the study area, to develop the initial head contour map in the steady-state model run. The daily precipitation, maximum temperature and minimum temperature data were obtained from IMD and are presented in Fig. 6. Out of eight major and minor sources used for water supply to GVMC, Raiwada, Godavari and Gosthani, only three sources are providing the domestic water supply in the study area, including delivery to both domestic and industrial water supply to other wards beyond the study area considered. The domestic water-supply quantities from different sources are obtained by subtracting the individual industrial bulk-supply quantity from their daily collected water-supply quantity. Assuming source-wise, equitable distribution of water to the population of all the covered wards, the mean monthly domestic water supply from various sources—in million m^3/month (MCM/month)— in proportion to the ward population of the study area fed from that source is presented in Fig. 7.

Depiction of aquifer geometry and model domain

In the present study area, the aquifer is coterminous with the watershed boundary. The entire northern boundary of the study area is occupied by Kailasa and Simhachalam hills, which form a no-flow boundary of the model domain. Some of the drainage networks originating from the hills drain off the storm water towards the marshy land in the study area, which constitutes the entire south boundary and is taken as the constant head boundary (CHB), having different head levels according to the terrain elevations. The entire eastern part of the study area along the Bay of Bengal coast is taken as a constant head boundary. The small strip along the north west

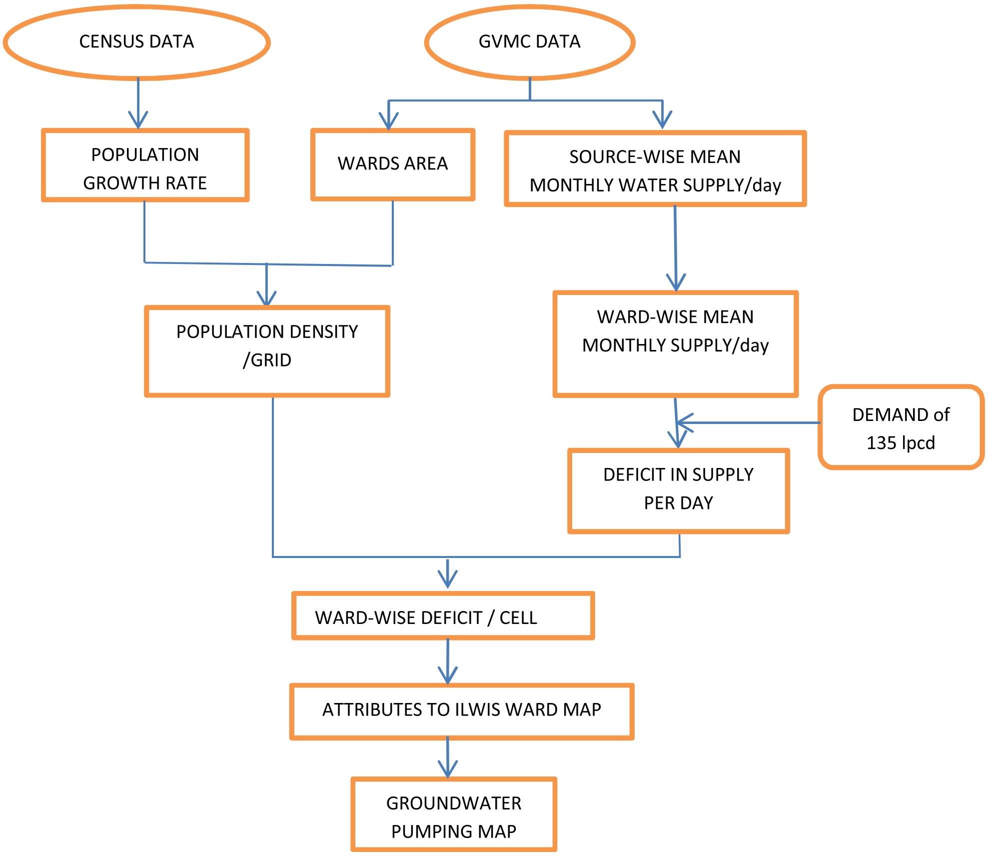


Fig. 10 Flow chart for groundwater pumping estimation

is also taken as a no flow boundary. The boundary conditions of the study area along with the location of 55 observation wells used for developing the steady-state initial heads are shown in Fig. 8. The dry cells in the Fig. 8 indicate high elevation areas with shallow-depth hard-rock strata.

A mesh (grid) size of 50 m × 50 m is selected for the present study, to enable a run with the groundwater model in PMWIN MODFLOW. The aquifer system is taken as an unconfined aquifer in the groundwater model. The top layer of the aquifer, with 50-m cell size, is taken from a digital elevation model (DEM) developed in previous studies (Mahammood 2003). The unconfined aquifer is considered as the first layer and the depth of the second layer is calculated using the Kriging model in ILWIS at the locations of the observed boreholes using the bottom of the fracture zone.

Aquifer parameters

The entire study area is divided into 15 homogeneous and isotropic zones as shown in Fig. 9, according to the soil profile and well-hydrograph data. Hydraulic conductivity and specific yield values were assigned to each zone based on the norms recommended by Ground Water Estimation Committee (GEC 2015) for the existing lithology. After the calibration model run, the hydraulic conductivity values assigned by the PEST model ranged between 0.30 and 6.0 m/day, and the specific yield values ranged from 0.01 to 0.05.

Groundwater extraction by pumping

Groundwater draft/pumping refers to the quantity of groundwater that is being withdrawn from the aquifer. It is a key input in models used to study the groundwater resource estimation. Hence, accurate estimation of groundwater draft is highly essential to improve the model performance. In this study, pumping rates are computed based on the assumption that the net difference between per capita demand and supply is taken as the withdrawal from the groundwater resources. Monthly ward-wise-groundwater-pumping rates are obtained by determining the monthly ward-wise water demand based on the yearly population data and monthly ward-wise surface water supplied by GVMC from various sources of supply.

The census data for the years 2001 and 2011 are used to find the decade ward-wise population-growth rate and the same rate of growth is considered to forecast the ward-wise population for the period from 2012 to 2016. The water supply

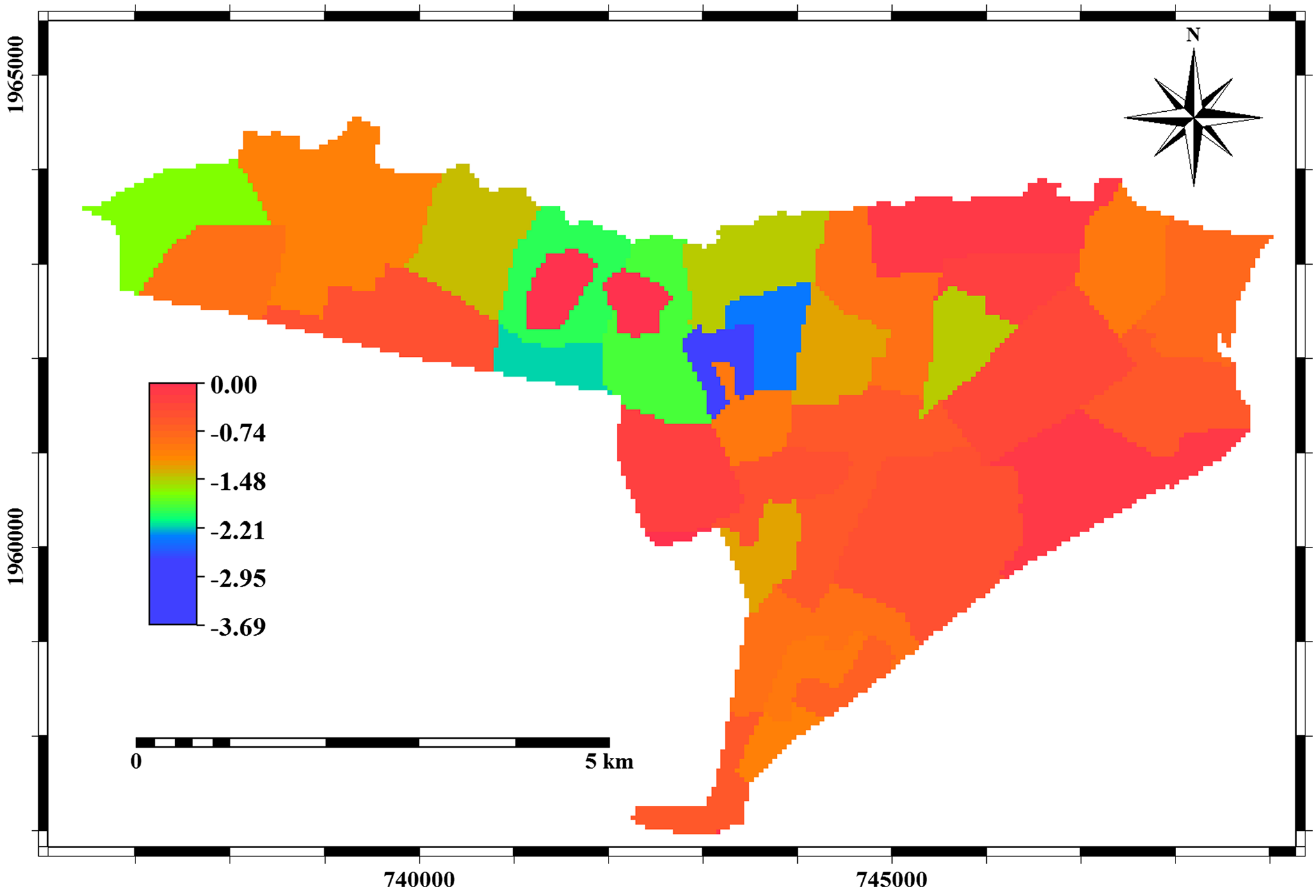


Fig. 11 Typical monthly groundwater pumping rate (m^3/day) map for August 2015

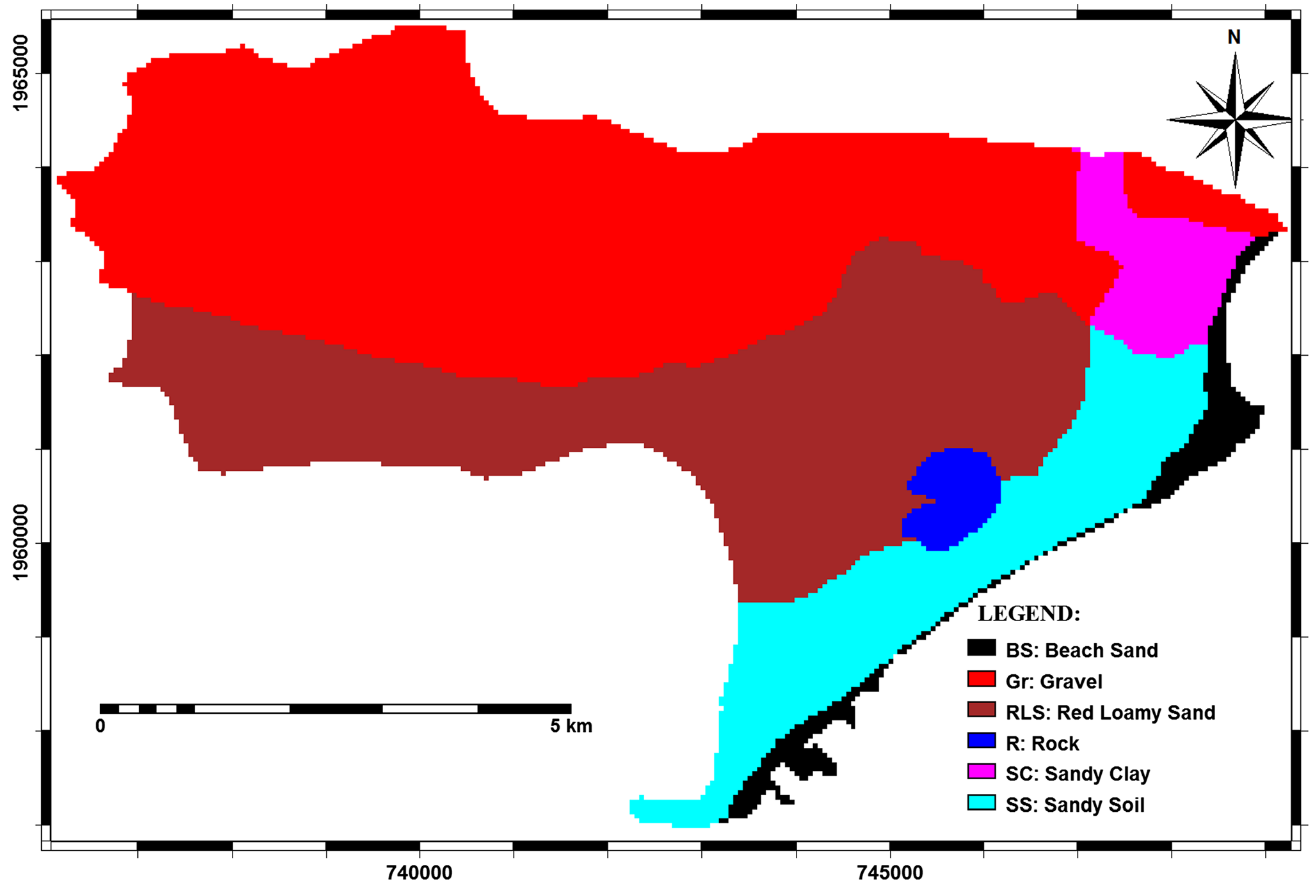


Fig. 12 Soil map of Visakhapatnam urban area

data from GVMC consist of the sources of supply for different wards, and mean monthly domestic and industrial supply data from various sources. The per capita requirement of water is assumed to be 135 lpcd as per CPHEEO guidelines. The difference between demand and surface-water supply gives the deficiency in the water supply, which is to be met from the groundwater reservoir. As per the model grid created in the MODFLOW, the deficit per cell (in m^3/day) is computed by the following equation,

$$Q_i = \frac{\left\{\left(D - \left[\left\{\left(\frac{W_{\mathrm{SR}}}{\sum P_{\mathrm{R}}}\right) + \left(\frac{W_{\mathrm{SGo}}}{\sum P_{\mathrm{Go}}}\right) + \left(\frac{W_{\mathrm{SG}}}{\sum P_{\mathrm{G}}}\right)\right\} 10^9\right]\right)\left(\frac{(P_i)_{\mathrm{year}}}{A_i}\right)(\mathrm{A_c})\right\}}{1000} \quad (2)$$

where the following terms are as defined:

A_c	Area of each cell = 50 m × 50 m
A_i	Area of ith ward in m^2
D	Demand in lpcd
i	Ward number
$(P_i)_{\mathrm{year}}$	Population of ith ward in a year
$\sum P_\mathrm{G}$	Total population covered by Godavari source
$\sum P_{\mathrm{Go}}$	Total population covered by Gosthani source
$\sum P_\mathrm{R}$	Total population covered by Raiwada source
Q_i	Monthly deficit per cell in ith ward (m^3/day)
W_{SG}	Mean monthly Gosthani water supply in MCM/day
W_{SGo}	Mean monthly Godavari water supply in MCM/day
W_{SR}	Mean monthly Raiwada water supply in MCM/day

The methodology to arrive at the monthly deficit values is described in the flow chart shown in Fig. 10. In the present study, the monthly groundwater pumpage maps for the period 2012 to 2016 are developed through ILWIS 3.6 operations by attributing the monthly deficit values to the ward map,

Table 1 Slope classes according to IMSD guidelines

Class	Slope
Nearly level	0–1%
Very gently sloping	1–3%
Gently sloping	3–5%
Moderately sloping	5–10%
Strongly sloping	10–15%
Steep sloping	15–35%
Very steep sloping	Above 35%

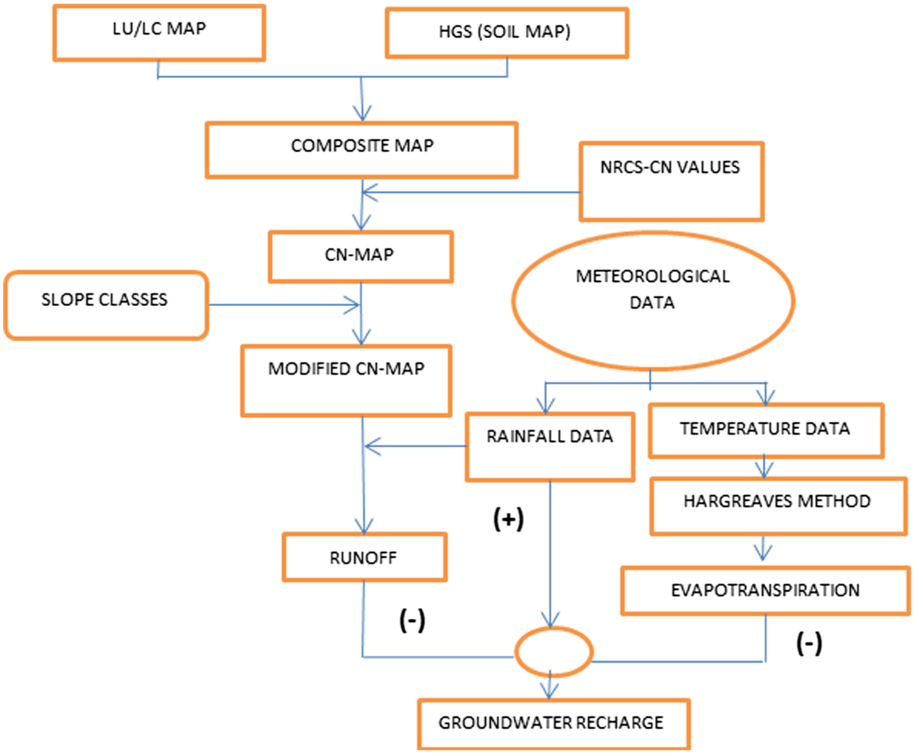


Fig. 13 Flow chart for groundwater recharge estimation

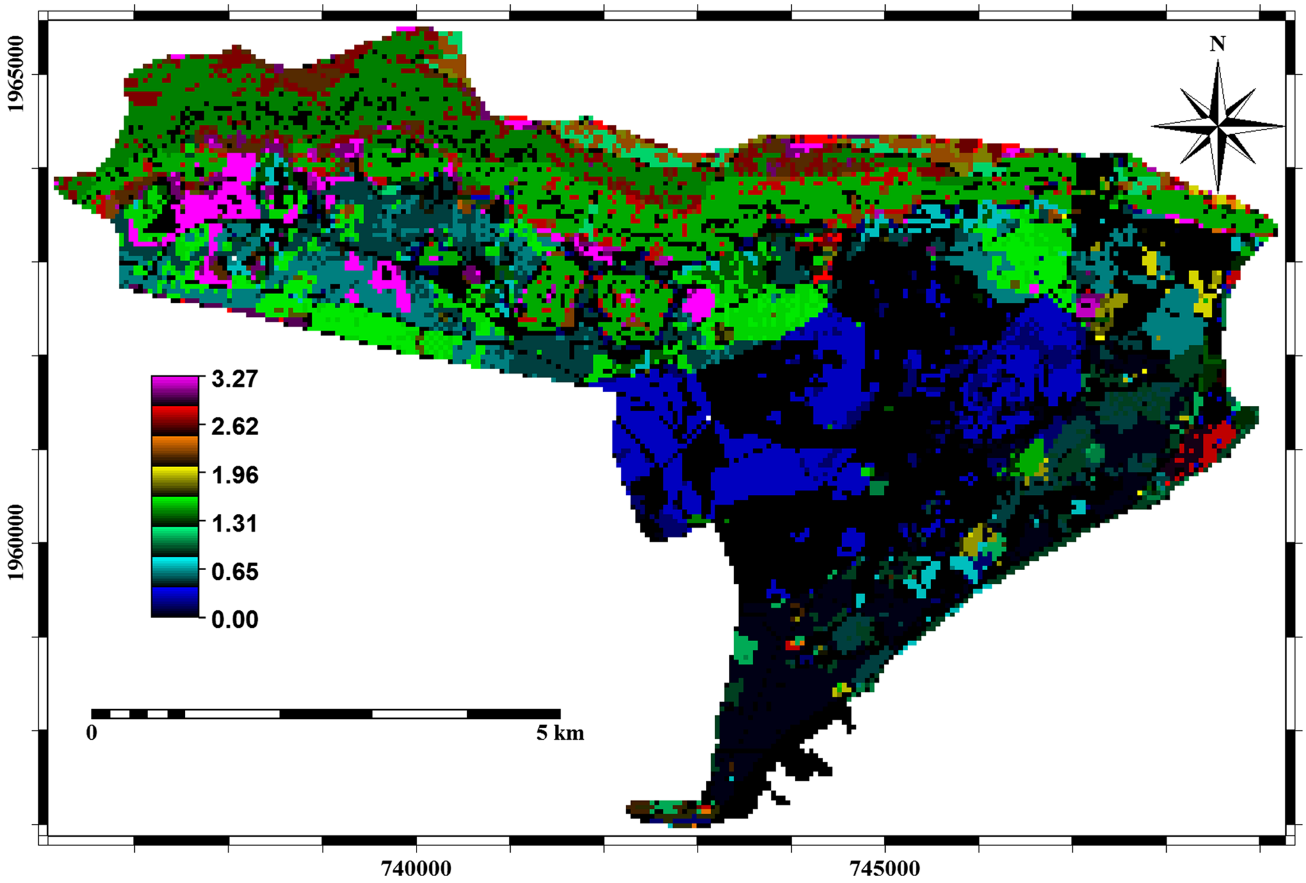


Fig. 14 Typical monthly recharge (mm/day) map for August 2015

Table 2 Calibrated values of the hydraulic conductivity and specific yield after PEST run

Zone no.	Hydraulic conductivity (m/day)	Specific yield
1	1.00	0.019
2	0.50	0.019
3	0.30	0.024
4	0.50	0.030
5	1.47	0.030
6	1.65	0.014
7	1.00	0.030
8	0.50	0.010
9	0.50	0.010
10	5.66	0.030
11	0.64	0.035
12	1.00	0.030
13	1.23	0.025
14	1.60	0.040
15	2.00	0.050

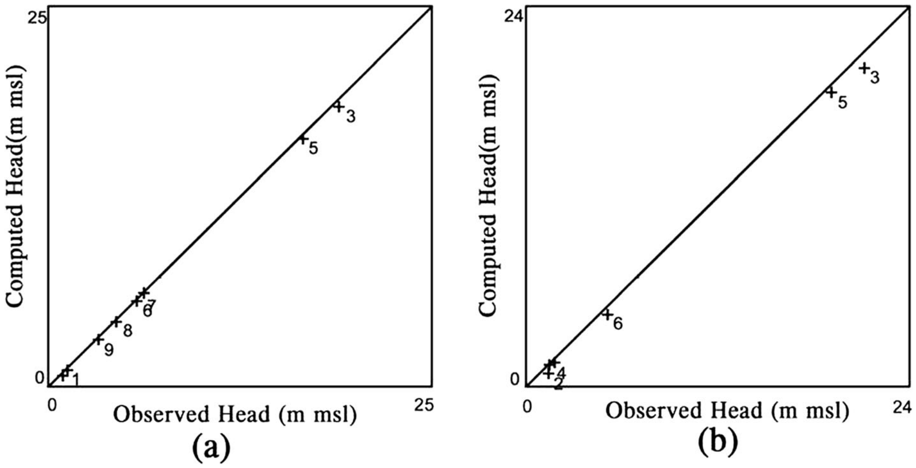
whereby these maps will be input to groundwater modeling studies. The model pumping map for the month of August 2015 is shown in Fig. 11.

Recharge

Recharge is an important parameter for any hydrological model, especially in groundwater modeling. The selection of the appropriate recharge estimation method is important to dictate the required space and time scales of the recharge estimates (Yongxin and Hans 2003). Estimation of seasonal variation of the recharge values requires a large amount of data by conducting a number of pumping tests and groundwater level observations (Surinaidu et al. 2015). In groundwater modeling studies when the ground information is not available, the recharge is taken as a percentage of the mean annual rainfall quantity (Nepal et al. 2011) and its value is adjusted until it satisfies the calibration model run (Heyddy and Laurence 2007). Models such as WetSpass (Houcyne and Florimond 2006; Paul 2006) and SWAT (Zhonggen et al. 2013) are used to compute the recharge in areas consisting of irrigation lands. In the present study, due to the shift and uncertainty in the south west and north east monsoons over the years and rapid elevation variations in the terrain, a conventional method based on meteorological parameters is adopted by which mean monthly recharge can be simulated with spatial and temporal variations.

The Hargreaves method, which has less aridity-bias impact in estimating the ET (Hargreaves and Richard 2003), is used for estimation of monthly evapotranspiration rates. The NRCS-CN method developed by United States Department of Agriculture (USDA) is used for runoff estimation. This method is effective in identifying the hydrologic soil group through the land use/land cover classifications and takes into consideration the influence of the antecedent moisture condition (AMC). The soil map of the study area is shown in Fig. 12. The CN values for the study area are assigned based on the guidelines of the National Engineering Handbook (USDA-SCS 1972). The runoff and recharge are also affected by the slope of the area and the NRCS-CN method is applicable to flat agricultural lands. Therefore, CN values require modification with respect to the slope category of the study area. The slope classification as per the Integrated Mission for Sustainable Development (IMSD 1995) guidelines (Ramakrishnan et al. 2009) shown in Table 1 is used to modify the CN values. The systematic process to compute the recharge is described in the flow chart as shown in Fig. 13. The mean monthly recharge map with spatial variations shown in Fig. 14 is obtained from the cell by cell difference between rainfall and the sum of ET and runoff.

Fig. 15 Scatter plots of OW '1–9' in the transient model at the end of **a** 1,005 days and **b** 1,736 days



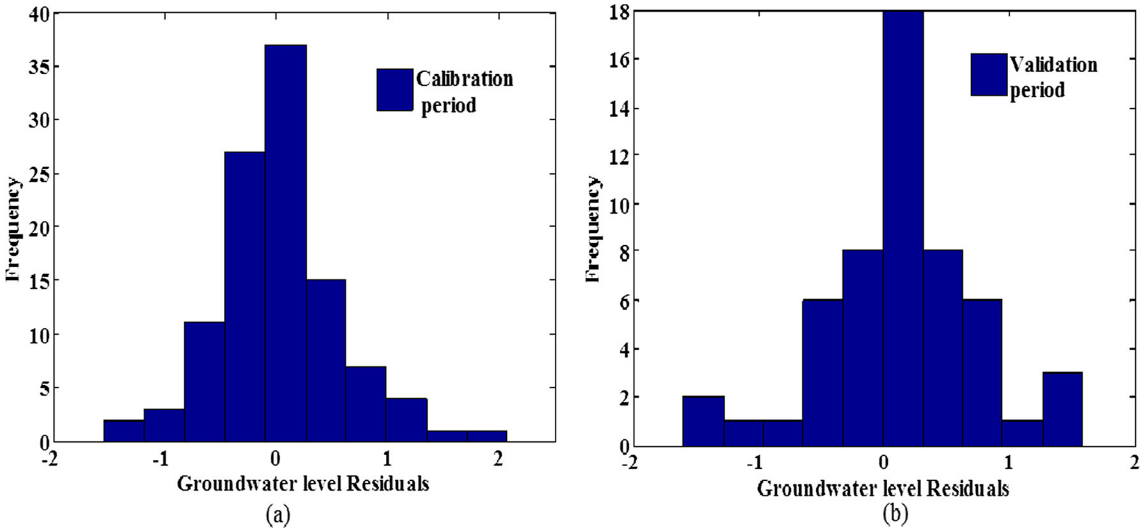


Fig. 16 Error histograms in the transient model during **a** calibration and **b** validation periods

Modeling approach

In this study, the entire transient simulation period is divided into two parts—one for the calibration and the other for validation of the model results with the observed data. The calibration period is from April 2012 to December 2014, while the simulation period for validation is from January 2015 to December 2016. The calibration run period in the model is for 1,005 days with 33 time steps, while it is 731 days for the validation run with 24 time steps, representing the monthly simulation period. For each well only four observation readings per year are available; hence, an overall 108 observation samples from 9 observations wells are used in the model calibration and the remaining 48 samples from 6 observation wells are used in the model validation. The initial heads developed in the steady-state simulation for April 2012 are used as starting hydraulic heads for transient flow simulation.

The PEST module in PMWIN MODFLOW is used for calibrating the model parameters like hydraulic conductivity and specific yield by using the water level data from nine observation wells. The objective in the PEST run is to minimize the sum of squared weighted residuals between the observed and model-computed groundwater levels by changing the input parameters such as hydraulic conductivity and specific yield. The validation model is also run with these calibrated hydraulic conductivity and specific yield values. The resulting model's performance is evaluated using various statistical parameters such as normalized mean square error (NMSE), root mean square error (RMSE), mean absolute percentage error (MAPE), Nash-Sutcliffe efficiency coefficient (Ec) and coefficient of determination (R^2). The following equations represent the method of evaluation of performance criteria.

$$\mathrm{NMSE}=\frac{n-1}{n}\frac{\sum_{i=1}^{n}\left[(h_\mathrm{o})_i-(h_\mathrm{c})_i\right]^2}{\sum_{i=1}^{n}\left[(h_\mathrm{o})_i-\left(\overline{h}_o\right)\right]^2} \quad (3)$$

$$\mathrm{RMSE}=\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left[(h_\mathrm{o})_i-(h_\mathrm{c})_i\right]^2} \quad (4)$$

$$\mathrm{MAPE}=\frac{1}{n}\sum_{i=1}^{n}\frac{\left|(h_\mathrm{c})_i-(h_\mathrm{o})_i\right|}{(h_\mathrm{o})_i} \quad (5)$$

$$\mathrm{Ec}=1-\frac{\sum_{i=1}^{n}\left[(h_\mathrm{o})_i-(h_\mathrm{c})_i\right]^2}{\sum_{i=1}^{n}\left[(h_\mathrm{o})_i-\left(\overline{h}_\mathrm{o}\right)\right]^2} \quad (6)$$

$$R^2=\sum_{i=1}^{n}\frac{\left[(h_\mathrm{o})_i-\left(\overline{h}_\mathrm{o}\right)\right]\left[(h_\mathrm{c})_i-\left(\overline{h}_\mathrm{c}\right)\right]}{\sqrt{\sum_{i=1}^{n}\left[(h_\mathrm{o})_i-\left(\overline{h}_\mathrm{o}\right)\right]^2\sum_{i=1}^{n}\left[(h_\mathrm{c})_i-\left(\overline{h}_\mathrm{c}\right)\right]^2}} \quad (7)$$

where h is the groundwater level in m (msl) and the subscripts o and c represent the observed and computed values respectively, while the bar indicates mean value.

Table 3 Performance statistics of the model during calibration and validation periods

Performance criterion	During calibration	During validation
NMSE	0.006	0.005
RMSE	0.571	0.626
MAPE	0.125	0.118
Ec	0.993	0.994
R^2	0.994	0.995

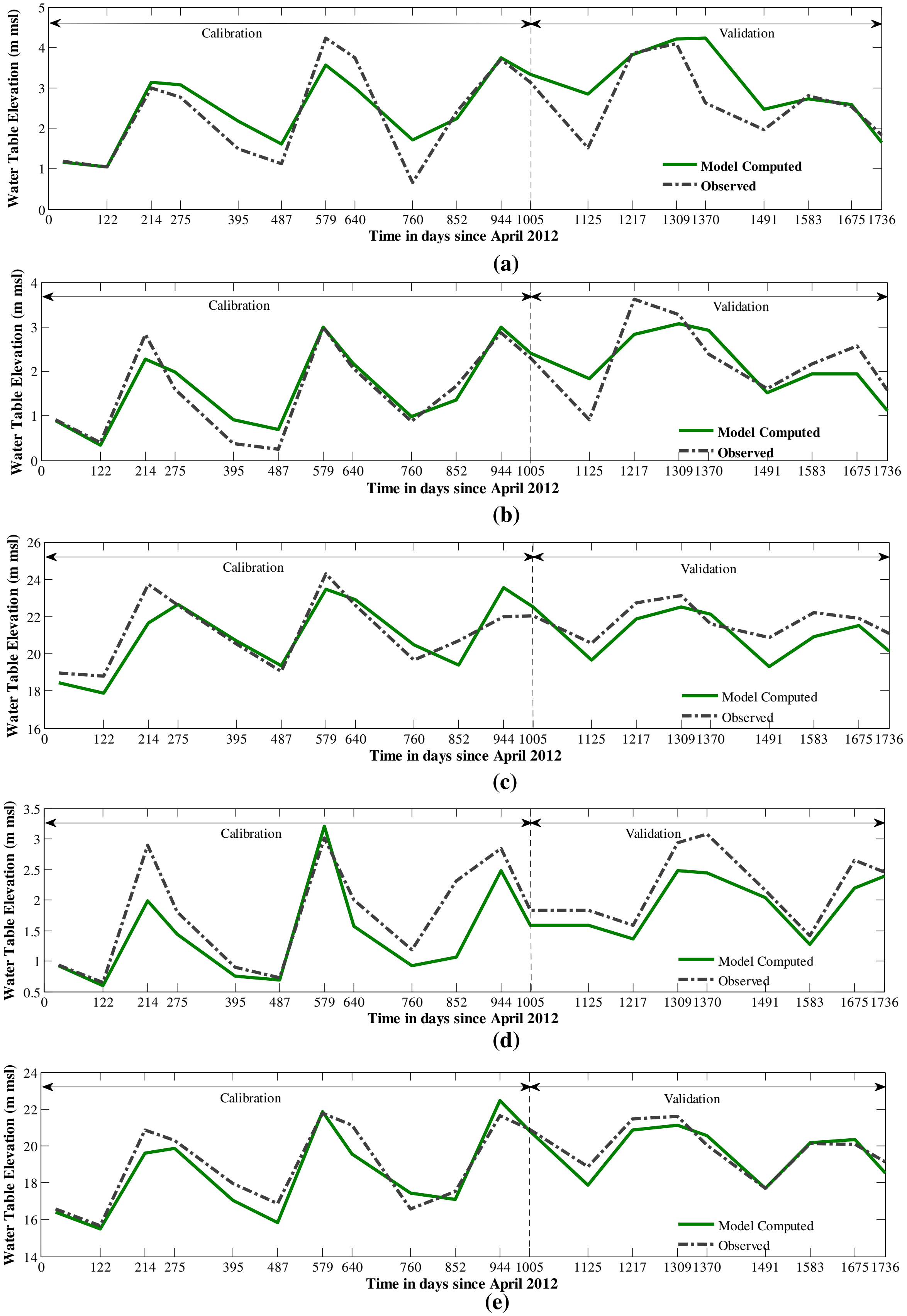


Fig. 17 Comparison of observed and model computed groundwater levels for OW '1–9' (a–i) during calibration and validation periods

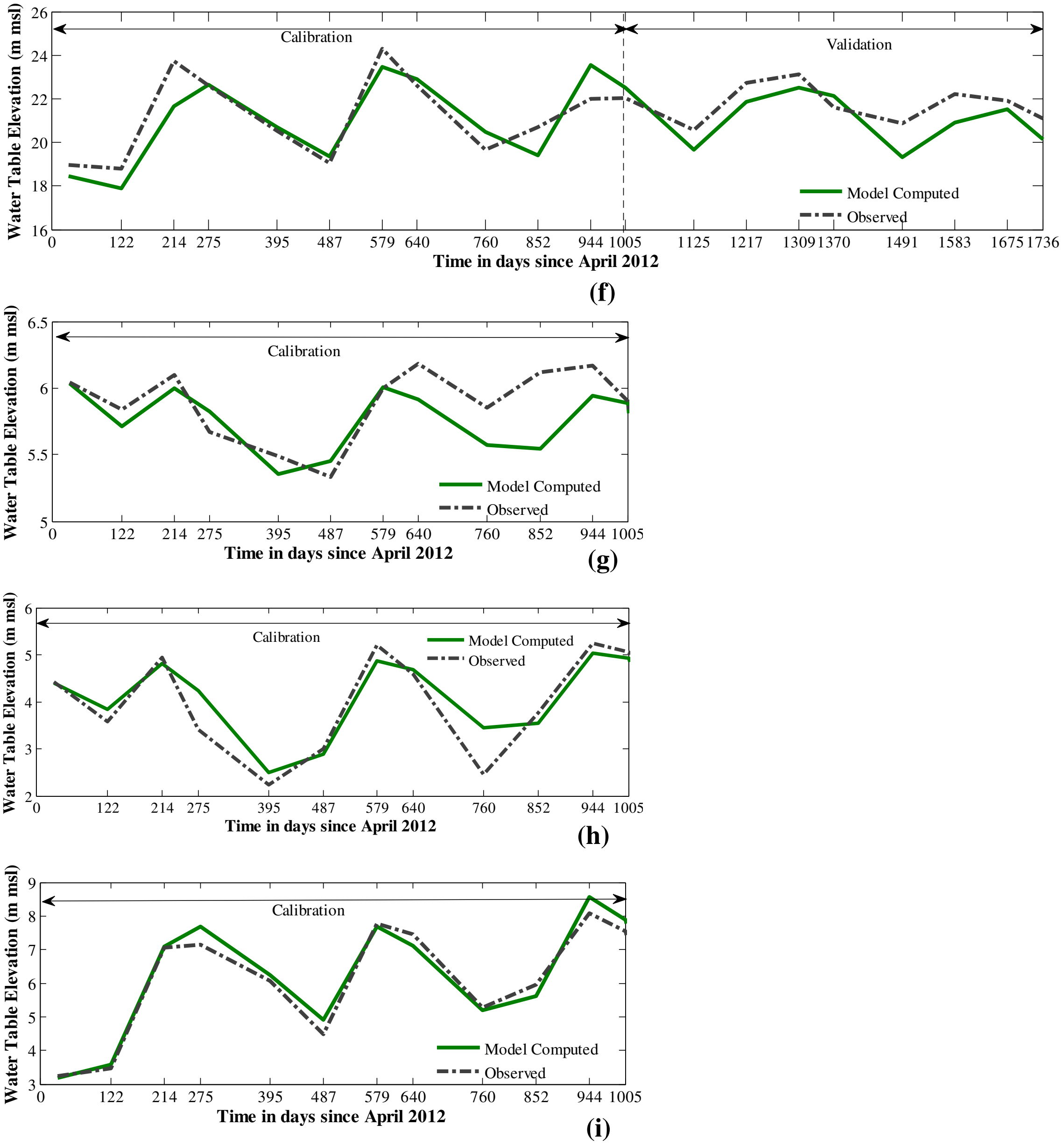


Fig. 17 (continued)

Results and discussion

Transient-state model calibration and validation

After the model calibration is done using PEST, the zone-wise-calibrated values of the hydraulic conductivity and specific yield in the study area were determined (see Table 2), then these values were matched with the field test data conducted by CGWB near to the study area. Sensitivity analysis was performed by changing one parameter value at a time (Anderson and Woessner 2002) during the model calibration, which indicates that the model is most sensitive to hydraulic conductivity followed by the specific yield. The scatter plots in Fig. 15 show correlation between the observed and computed heads corresponding to a simulation run in the transient state at the end of 1,005 and 1,736 days. Comparison between the nine observation well's data and model-computed data shows that all the points in both the scatter plots lie around the 45° line, indicating that the correlation is very good in both the calibration and validation periods of the model.

Figure 16 shows the histograms of the groundwater level residuals during calibration and validation periods. These plots show that about 91% of the data fall within 1 m of the residual error from the observed data during both calibration and validation periods. The maximum and minimum residuals in the model calibration are respectively +2.072 m and

−1.546 m, whereas for validation, the corresponding values are +1.581 and −1.600 m respectively. The performance statistics between the observed and computed heads during calibration and validation periods are shown in Table 3. The results indicate that the model is well calibrated with R^2 and Ec values very close to 1 and NMSE and MAPE values close to zero. The RMSE values in Table 2 for both calibration and validation periods indicate that the model-computed groundwater levels are very close to the reality, with least mean variations of 0.571 and 0.626 m respectively.

The time series plots of the computed and observed groundwater level in observation wells (1–9) of CGWB during calibration and validation periods are shown in the Fig. 17. The location of these wells in the study area is shown in Fig. 18. From these plots it can be observed that the model could well simulate the trend in the observed water levels and almost match with the observed data in the wells, except for a few time periods within a reasonable error.

Figures 18 and 19 show the water-table-elevation-contour maps at the end of 2015 and 2016 respectively. Most of the flow contours are following the ground terrain and flow on the entire east side headed towards the Bay of Bengal and on the south side towards the constant head boundary. However, at the central region of the study area, due to over-pumping of groundwater during the dry seasons, the flow reverses from the constant head boundary into the study area. The dry cells in the study area indicate that hard rock exists below the high-elevation areas. The groundwater levels during the year 2016 show a drastic decline from the previous year due to over-exploitation of the aquifer in some areas, as clearly observed in the central region.

Water balance

The water budgets of the study area at the end of the transient state calibration and validation are presented in Tables 4 and 5. The water budget during the validation period for years 2015 and 2016 is done separately to study the impact of recharge and well abstractions on the groundwater storage. The inflow and outflow columns in the tables indicate the quantity of water entering and leaving the groundwater system, respectively, expressed in MCM. The last column in both tables indicates the % numerical water balance error that occurred

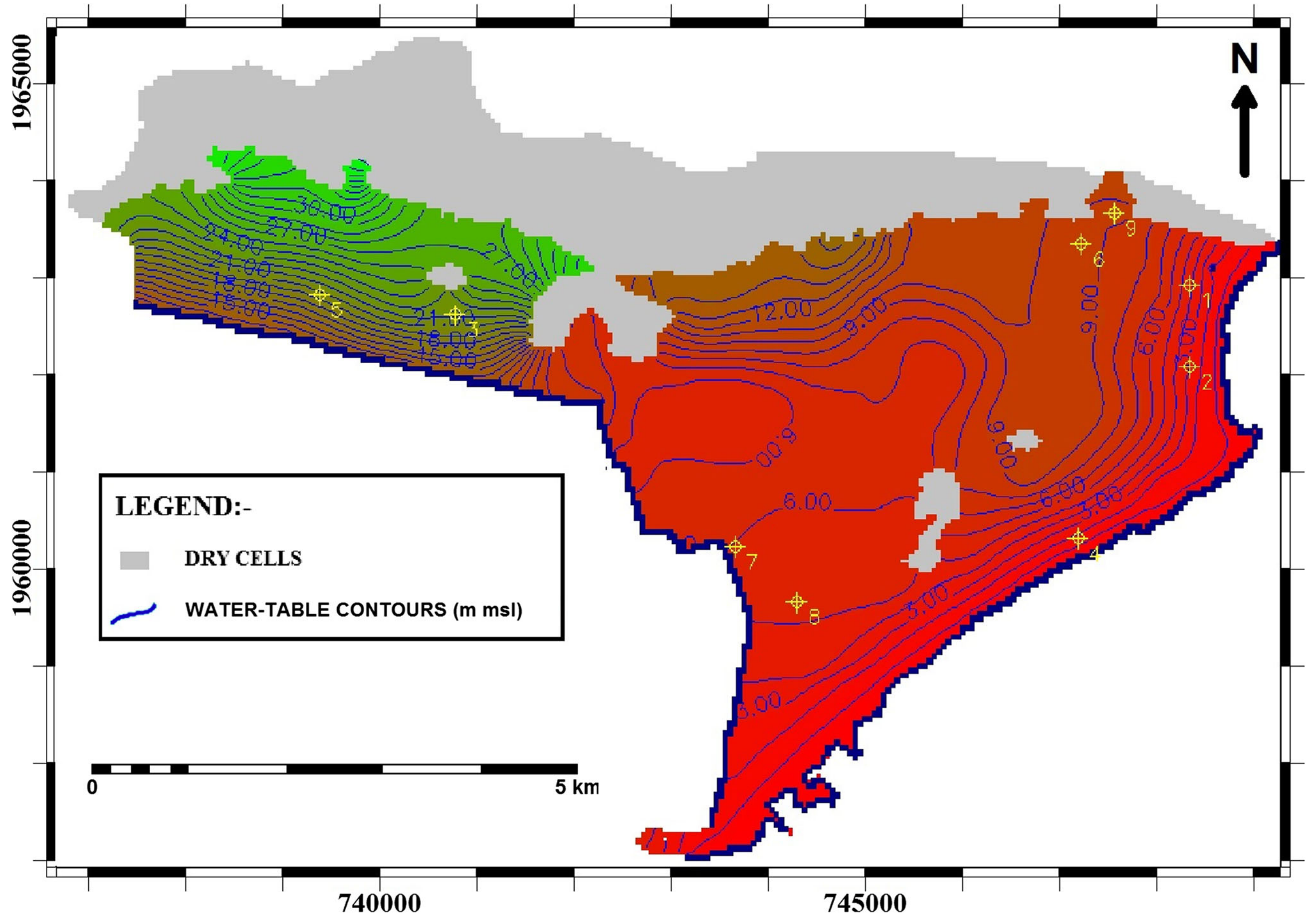


Fig. 18 Water-table-elevation-contour map for December 2015

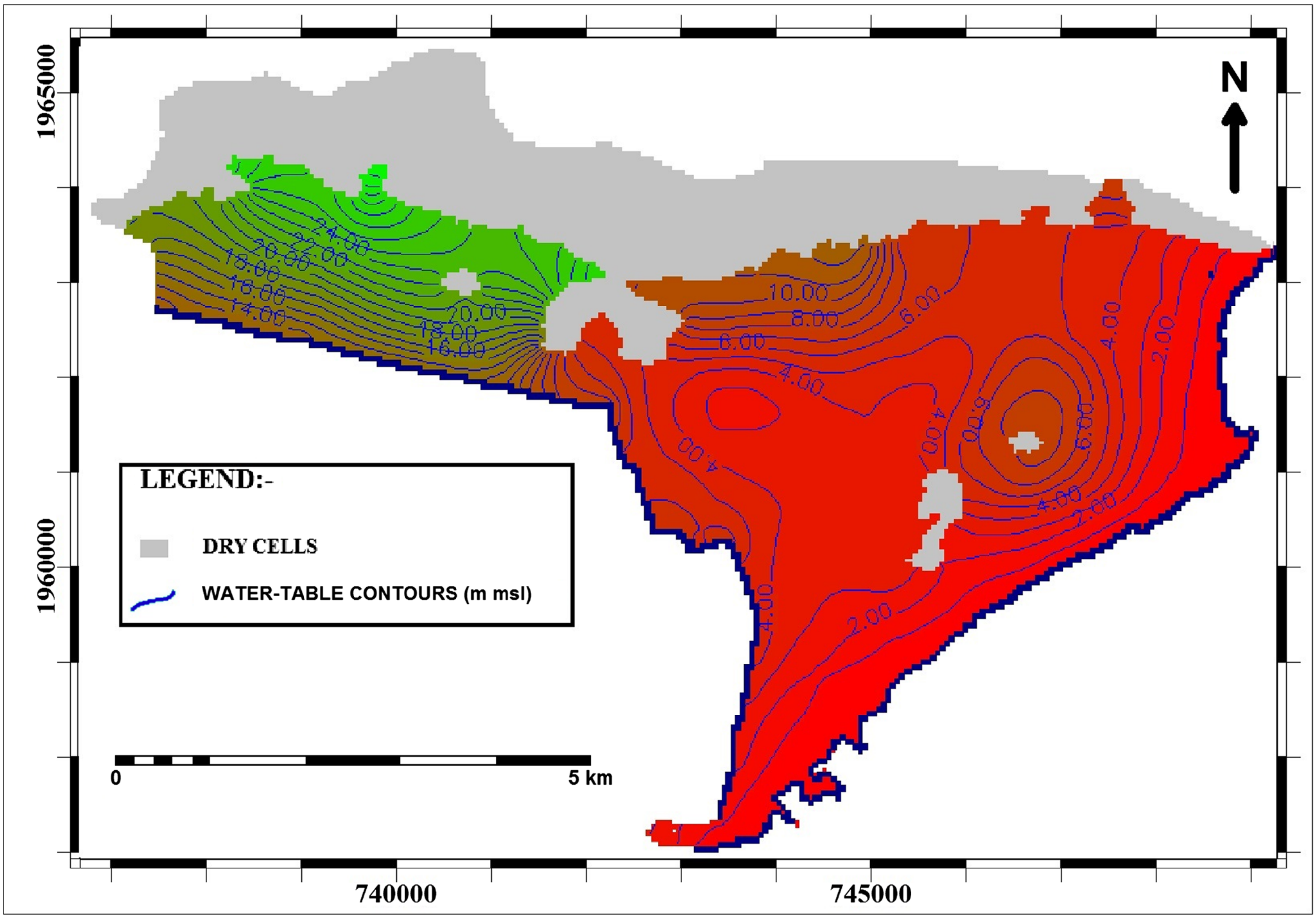


Fig. 19 Water-table-elevation-contour map for December 2016

in the transient state model run during calibration and validation periods. The % error in the water balance is 0.0008% for the calibration period and 0.00 and 0.0015% for 2015 and 2016 years, respectively, of the validation period. This indicates that there exists a perfect water balance between the inflows and outflows of the simulated model. As shown in Table 4, during the calibration period, the groundwater abstraction and net outflow towards the constant head boundary were respectively 77.92 and 26.89% of the groundwater recharge during that period. To meet these outflows, 4.82% of the groundwater recharge quantity declined in the groundwater storage. It is also observed that the inflow from the constant head boundary pertains to the central region of the study area due to maximum pumping rate.

Similarly, the yearly variations were studied during the period of validation. There is a clear difference observed in the water balance and net outflow percentages during 2015 and 2016. Comparing the water supply data from GVMC during 2015 and 2016, it is observed that sources like Gosthani and Godavari had an average monthly shortage in the water supply of 25 and 7% respectively, and there was only a 2% increase of average monthly water supply

Table 4 Transient-state water balance of the study region at the end of the calibration period

Flow parameter	Inflow (MCM)	Outflow (MCM)	Net outflow as a percentage of recharge (%)
Recharge	12.83	–	–
CHB	1.33	4.78	+26.89
Well abstractions	–	10.00	+77.92
Storage	9.04	8.42	−4.82
Total	23.20	23.20	–
Error (error %)	−1.98E-04 (−0.0008%)	–	–

CHB constant head boundary

Table 5 Transient-state water balance during validation at the end of 2015 and 2016

Parameter	Inflow (MCM)		Outflow (MCM)		Net outflow as a percentage of recharge (%)	
	2015	2016	2015	2016	2015	2016
Recharge	5.34	4.51	–	–	–	–
CHB	0.28	0.50	2.55	1.76	+42.46	+27.95
Well abstractions	–	–	3.07	5.38	+57.58	+119.29
Storage	2.81	4.32	2.81	2.19	+0.05	−47.24
Total	8.43	9.33	8.43	9.33	–	–
Error (error %)	1.81E-06 (0.000%)	−1.41E-04 (−0.0015)	–	–	–	–

in the Raiwada source during the year 2016. In the same year, there is a 15.54% lower recharge rate that occurred due to less rainfall. For these reasons, the well abstractions were increased by 75% during 2016, leading to almost double the rate of outflow as a percentage of recharge. As shown in Table 5, the groundwater well abstraction during the years 2015 and 2016 were respectively 57.58 and 119.29% of the annual groundwater recharge. During these 2 years, the net outflows towards the constant head boundary were 42.46 and 27.95% respectively. From the net outflow percentages for the year 2015, it can be observed that the entire annual outflows are met only by the few months of recharge quantity and there is a slight increase in the storage level (0.05%) of the annual recharge, indicating that groundwater storage is in a stable condition during that year. In the year 2016, due to increased well abstraction, the storage quantity decreased by 47.24% of the annual recharge quantity.

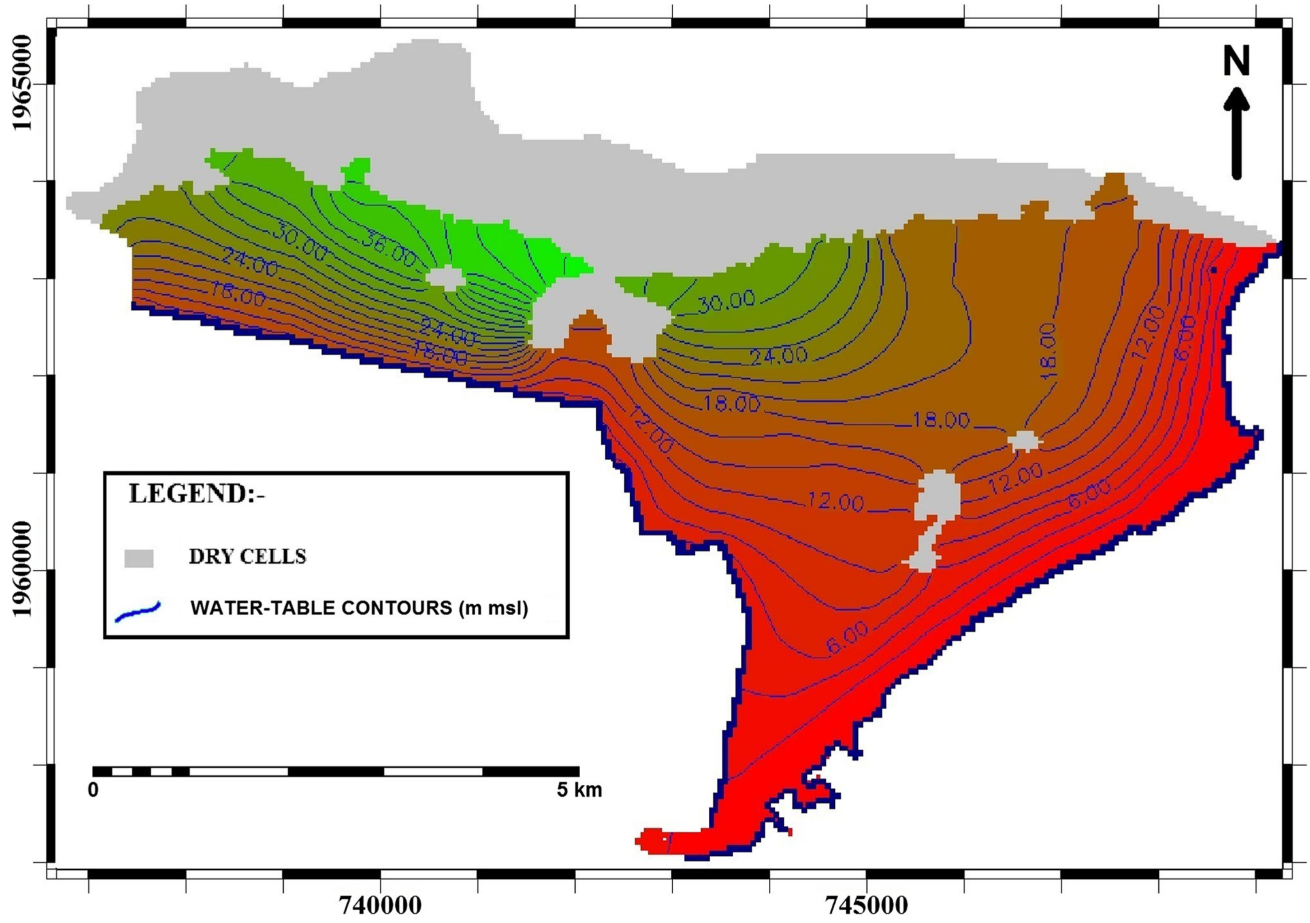


Fig. 20 Water-table-elevation-contour map for scenario I

Future scenarios

The sustainability of the groundwater resource is assessed by simulating the transient model for the next 5 years, between 2017 and 2021. Since there are many uncertainties in the predicted input data to the model, the transient model is tested for four different scenarios. Scenario I is a simulation without any well abstractions, representing the virgin (pristine) conditions so that one can clearly distinguish the areas where over-exploitation of groundwater is taking place. Scenario II assumes that the per capita supply of existing sources of water remains the same as 5 years earlier; therefore, the monthly recharge and well-abstraction data from year 2012 to year 2016 are used for the next 5-year model run. In scenario III, the effect of increased well abstractions from the groundwater system is studied by increasing the well abstraction rate by 10 and 20% for the next 5 years. In scenario IV, the effect of adopting artificial recharge methods in the study area along with the increased well abstraction rates is studied, by considering 10% increase in the recharge capacity for every year, keeping the same pumping rates as in scenario III. The groundwater levels of these scenarios are compared with groundwater levels at the end of the validation period.

In scenario I, where the model simulation is done without any pumping, a progressive rise of the water table varies from 0 to 24.85 m from December 2016 to December 2021 as shown in Fig. 20. The maximum changes in the water levels are observed in the central and the entire north region of the study area, and the water levels towards the constant head boundary have the minimum variations. The resulting contour map indicates that there is tremendous scope for improving the aquifer storage capacity by improving the recharge conditions in the study area.

In scenario II, the well abstractions are replicated with the data from the last 5 years and the computed water heads from the model (as shown in Fig. 21) indicate a gradual decline of 0–0.95 m, with an average decline of 0.3 m throughout the study area. The water-level decline is minimum along the eastern seacoast and maximum in the central region of the study area. This rate of decline will become more acute if the existing surface-water supplies from various sources do not keep up with the increasing demand due to population growth and industrialization in the city.

In scenario III, the effects of gradual and rapid increase in stress on the groundwater resource are considered by

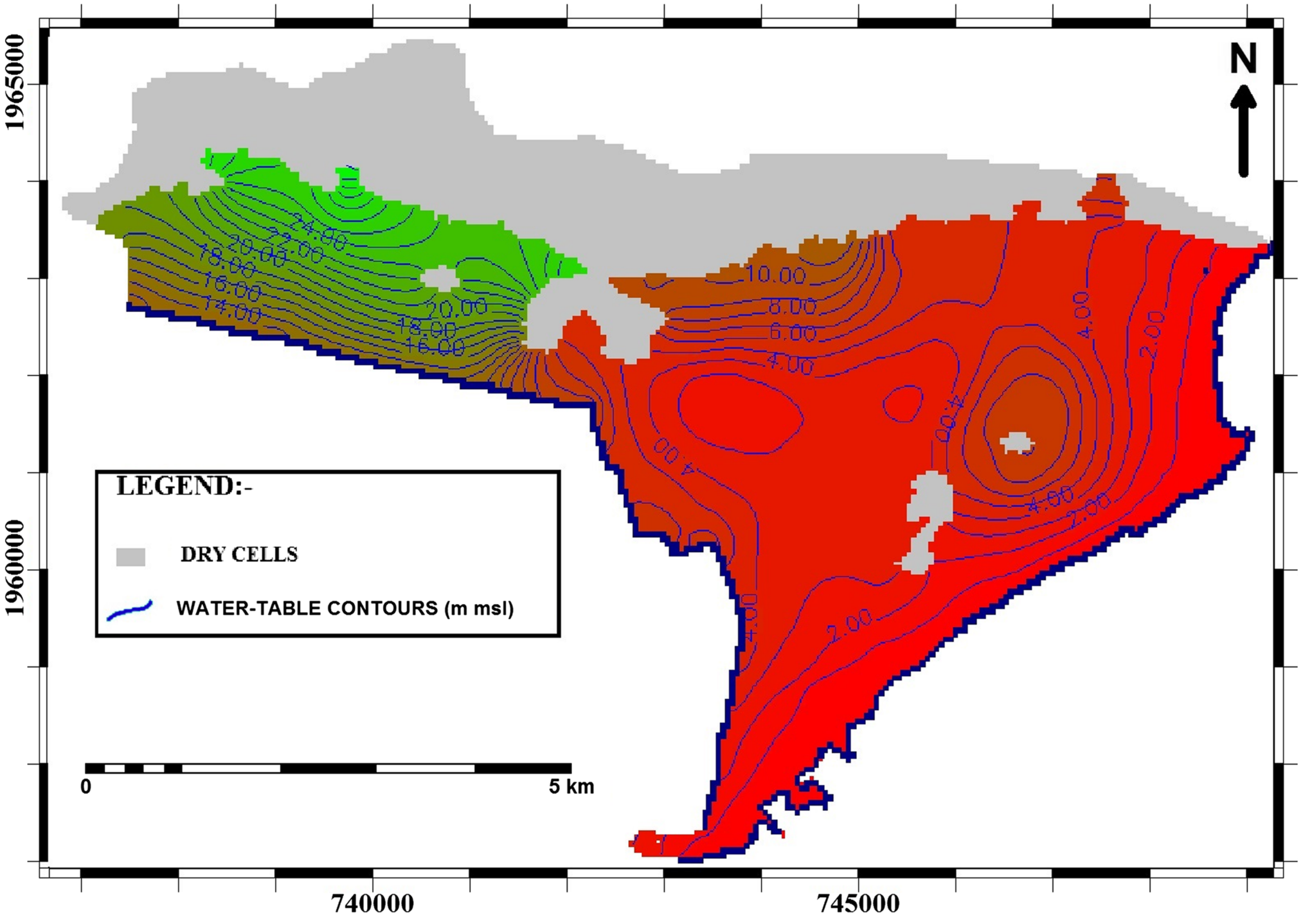
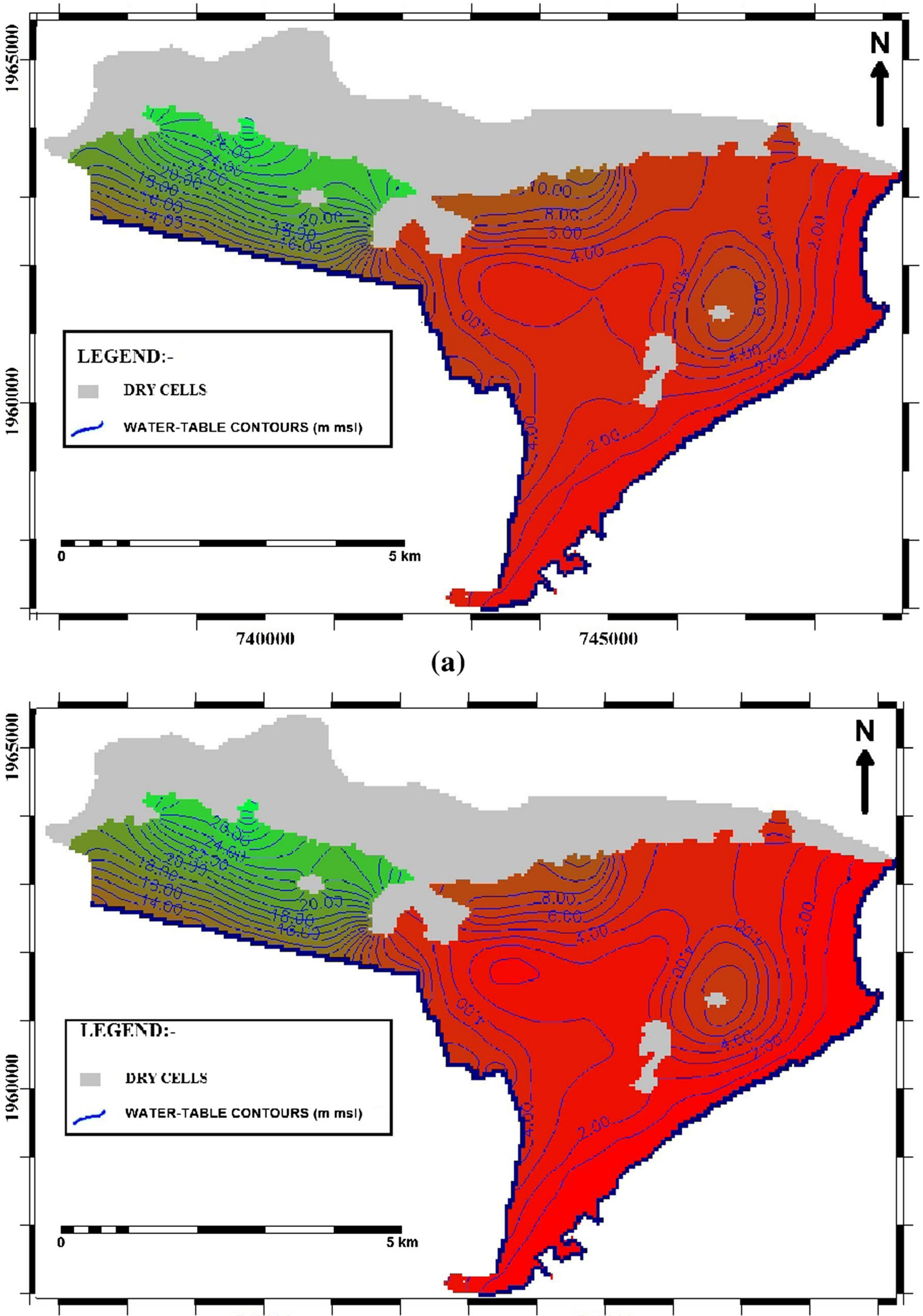


Fig. 21 Water-table-elevation-contour map for scenario II



(a)

(b)

Fig. 22 Water-table-elevation-contour map for **a** scenario III with 10% rise in pumping rate, and **b** scenario III with 20% rise in pumping rate

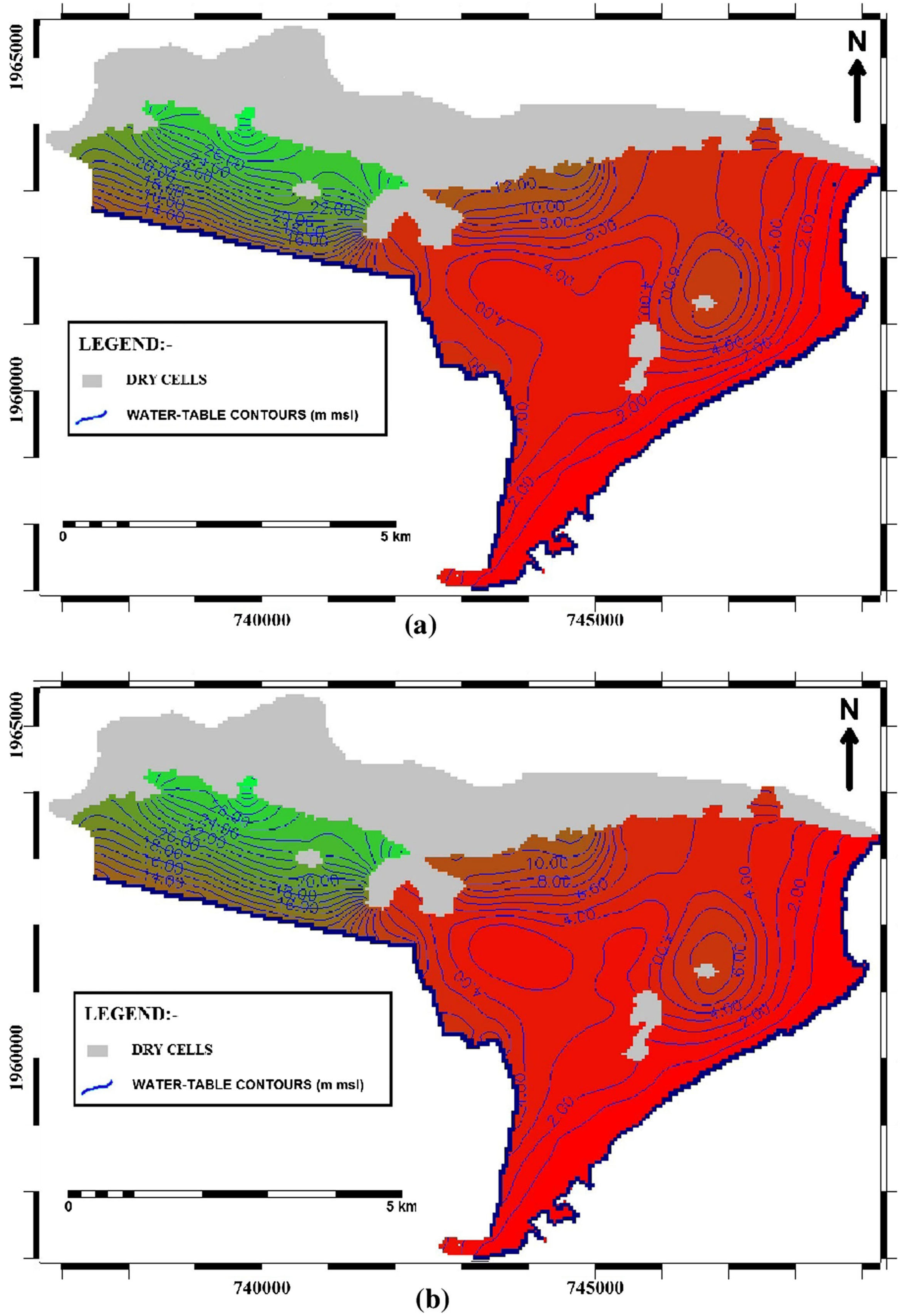


Fig. 23 Water-table-elevation-contour map for **a** scenario IV with 10% rise in pumping rate, and **b** scenario IV with 20% rise in pumping rate

increasing the well abstraction rates by 10 and 20% respectively. When the well abstractions were increased by 10% during the next 5 years, the water table contours showed a decline of 0–1.34 m with an average decline of 0.38 m throughout the study area as shown in Fig. 22a. However, the water level shows relatively more decline, as shown in Fig. 22b, when the well abstractions were increased by 20%, whereby the water level change was from 0 to 1.64 m with an average decline of 0.63 m within the next 5 years.

In scenario IV, the effect of enhancing the net recharge rate only in the groundwater potential areas by various methods of artificial recharge is studied. The recharge quantity is increased by 10%, keeping the well abstraction rate same as in scenario III. In spite of an increase in the well abstraction rate by 10%, the water-table-elevation contours can be restored compared to scenario II, by 0–4.58 m with an average rise of 0.98 m throughout the study area as shown in Fig. 23a. However, in the case of 20% increase in the well abstraction rate, the water-table contours rise by 0–1.7 m with an average rise of 0.36 m throughout the study area as shown in Fig. 23b.

Conclusions and suggestions

The present study focuses on knowing the existing groundwater conditions of the Visakhapatnam city and the future trends of groundwater levels under increasing stress. MODFLOW is used for developing the groundwater flow model in the study area by considering the impact of rapid urbanization on the groundwater recharge and well abstraction rates. Groundwater-level contours for the next 5-year model run were developed under varying stress conditions and the decline rates of the water table were estimated. Based on the simulation results, the following conclusions can be made:

1. The transient model is successfully run during calibration and validation periods. The simulated heads in the observation wells correspond closely with the observed heads with good accuracy. Overall, the model-calibrated sensitivity-analysis results indicate that both hydraulic conductivity and specific yield are the dominant factors influencing the hydrogeology in the study area.
2. Wards in the central region and the entire northern part of the study area are subject to rapid fluctuations in groundwater levels, indicating that these areas are prone to overexploitation of groundwater resources. In addition, ward numbers 7, 17 and 18 along the seacoast are prone to high groundwater depletion rates, which could result in salt-water intrusion in the future, a highly undesirable eventuality.
3. Scenario II results show that even if the same pumping pattern is continued for the next 5 years, the aquifer groundwater capacity will be depleted on an average of 2.03 MCM/year. This decline rate is 45% of the recharge quantity of the year 2016. The results indicate that the groundwater pumping is more than the groundwater recharge, which means the aquifer will lose its capacity and sustainability. A reduction in the well abstraction rate by at least 55% of the present usage may be necessary over the next 5 years for sustainable groundwater management and to prevent disastrous effects on groundwater potential in the future.
4. Comparing the water-table elevation contours of scenario III shows that with 10 and 20% increase in the well abstraction rate over the next 5 years (December 2016 to December 2021), the aquifer-groundwater-resource capacity will be depleted on an average of 2.55 and 4.21 MCM/year respectively. This decline rate is 56.54 and 93.34% of the recharge quantity of the year 2016. To prevent this rate of decline, given the case of 10% increase of pumping in the study area, the surface-water supply from various sources such as Gosthani, Raiwada and Godavari should be increased by 0.13, 58.5, 81.4 MLD respectively. For the case of 20% increase of pumping, the corresponding values are 0.26, 117.0, 162.8 MLD respectively.
5. Scenario IV considers the effect of improving the rate of recharge through artificial recharge methods in the study area. When 10% increase in the recharge quantity in the groundwater potential areas is considered, with the same well abstraction rates as per scenario III, the groundwater levels in many areas will rise in both the schemes and further depletion in the aquifer groundwater capacity can be largely prevented. Therefore, various water conservation methods at suitable sites, such as subsurface dykes and rooftop rainwater harvesting, have to be adopted in the present study area.
6. When the necessary field data are available, the methods used in the study to evaluate the input variables such as groundwater pumping and recharge rates, proved to be more reliable. The sensitivity of these variables can be studied as a further scope to identify the key input parameters.
7. The model results of the present work can be used for risk assessment and they can also be coupled with an optimization management model for conjunctive use of surface water and groundwater so that the rates of groundwater level decline can be brought under control.

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