Case Study

Groundwater Flow Modeling of a Hard Rock Aquifer: Case Study

V. Varalakshmi[1]; B. Venkateswara Rao[2]; L. SuriNaidu[3]; and M. Tejaswini[4]

Abstract: The present study area is primarily underlain by granites, basalts, and a little bit of laterites. Groundwater occurs under unconfined to semiconfined conditions, in weathered and fractured formations, respectively. A three-dimensional groundwater flow model for the Osmansagar and Himayathsagar catchments—a semiarid hard rock area in India with two conceptual layers—is developed under transient conditions using visual *MODFLOW* software for the period 2005 to 2009. The 15–20 m top layer is a weathered zone, followed by second 20–25 m-layer fractured zone based on hydrogeophysical studies and borehole lithologs. The groundwater recharge estimation is achieved with the help of geographical information system (GIS) and the water table fluctuation method that is well fitted into the flow model with an average recharge value of 21% of the average annual rainfall. The results derived from modeling indicate that the average input to the aquifer system is 321.96 million cubic meters (mcm), and the output is 322.14 mcm. If the same withdrawal is continued up until the year 2020, the water level is believed to decline more than 45 m over the entire study area. To avoid this critical stage, the present draft should be decreased by nearly 40%. **DOI: 10.1061/(ASCE)HE.1943-5584.0000627.**

Author keywords: Groundwater flow model; Transient state; Hard rock aquifer; Groundwater recharge and draft.

Introduction

A hard rock aquifer occupies the first few tens of meters from the top (Detay et al. 1989; Taylor and Howard 2000) that is subjected to the weathering process (Wyns et al. 2004). Groundwater occurs in the weathered and fractured layers under unconfined to semiconfined conditions, which have specific hydrodynamic properties from the top to the bottom. Quantification of groundwater resources and understanding of hydrogeologic processes are a basic prerequisite for efficient and sustainable management of groundwater resource development and management (Sophocleous 1991; Van der Gun and Lipponen 2010). This is particularly vital for India, where 80% of the Indian peninsula is covered with hard rocks, coupled with a widely prevalent semiarid climate (Pathak 1984). Because of the increasing demand of water for agriculture, industries, and ever-growing population requirements, the abstraction of groundwater has increased in the last few decades. The heavy demand for groundwater sometimes leads to excessive groundwater withdrawals, which is often reflected in a serious imbalance between groundwater draft and recharge at a later stage. Aquifer modeling is an established tool to study the behavior of the groundwater regime under spatio-temporal variation of input and output stresses. The findings in turn help to evolve and select optimal groundwater exploitation and management policies. However, modeling of an aquifer in a hard rock region is quite a difficult task because of high heterogeneity (Singhal and Gupta 1999; Bridget et al. 2003; Nico and David 2007). This inherently renders the discretization of the medium and interpolation of the hydrogeological parameters to be relatively difficult and at times unrealistic. In spite of these difficulties, many researchers have successfully used numerical models in estimating the regional groundwater budget in hard rocks, mountainous regions, and in karst aquifer groundwater systems (Rani and Chen 2010; Majumdar et al. 2009; Bridget et al. 2003; Surinaidu et al. 2013a, b). Therefore, in the present study, various hydrogeological factors are appropriately considered to represent the hard rock aquifer system to a satisfactory degree on a regional scale using a USGS finite difference numerical model.

The area chosen for aquifer modeling is the catchment areas of the Osmansagar and Himayatsagar reservoirs. The area is across the Musi and Musa rivers and supplies the drinking water for the city of Hyderabad. It is situated between 17°10′–17°50′ N and 78°10′ to 78° 50′ E, covering an area of 2,030 km^2 (Fig. 1). The drainage pattern is dendritic to subdendritic and trelliss (Gurunadharao et al. 2008). The terrain is flat to gently undulating, except for a few hillocks and valleys. The region is primarily underlain by a peninsular gneissic complex that includes a variety of granites, magmatites of various phases, and enclaves of older metamorphic rocks belonging to the Archean age. These are intruded by various acidic (pegmatite, aptite, quartz veins/reefs) and basic intrusives of dolerite and gabbros. Major dykes of dolerite composition cut across the country rocks in different directions. The predominant soils in the basin are sandy loam, clay loam, black cotton soils, and rocky soils. The riverbed is mostly deposited with sandy soils. Groundwater occurs under unconfined to semiconfined conditions in weathered and fractured formations, respectively.

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Literature Review

Groundwater modeling is increasingly recognized as a powerful quantitative tool available to hydrogeologists for evaluating groundwater systems. A groundwater model is a simplified version of the real system that approximately simulates the input/output stress and response relations of the system (Wang and Anderson 1982; Anderson and Woessner 1992; Middlemis 2000). Among the most-used approaches in groundwater modeling, three techniques can be distinguished: the finite-element method (Zienkiewicz 1971; Pinder and Gray 1977; Yeh and Huff 1983; Voss 1984; Istok 1989; Kazda 1990), the analytical element method (Freeze and Witherspoon 1966), and the finite difference method (Pinder and Bredehoeft 1968; Trescott et al. 1976; McDonald and Harbaugh 1988). All techniques have their own advantages and disadvantages with respect to availability, costs, user friendliness, applicability, and required knowledge of the user. In the present study, groundwater flow modeling is achieved under a steady and transient state condition using visual *MODFLOW* software with the finite difference method.

Narasimha Reddy et al. (1994) estimated the regional groundwater budget in the Dullapally watershed, a hard rock area, using water-balance models and validated with numerical flow models in a transient state. Johnson (2007) used a *MODFLOW* package to construct a groundwater flow model in a mountainous hard rock area to prioritize the collection of data by doing a sensitivity analysis. Dehotin et al. (2011) created a two-dimensional groundwater model to handle vertical and horizontal aquifer heterogeneities. Mondal et al. (2011) estimated the average groundwater at various sections of the paper. For example, the recharge in a hard rock area in southern India is approximately 80–250 mm/year, which is equivalent to 12–37% of the annual rainfall. The total groundwater abstraction is approximately 80.43% of the annual groundwater recharge.

In the study area, the Environmental Protection Training and Research Institute (EPTRI) and the National Geophysical Research Institute (NGRI) has found that the total input and output for the catchments of the Osmansagar and Himayatsagar reservoirs are 33.69, 36.99 mcm and 83.62, 82.68 mm, respectively, under 8–10% of recharge conditions. Gurunadharao et al. (2008) found the groundwater draft in the catchments of the Osmansagar and Himayatsagar reservoirs to be 35 and 77 mcm, respectively. Mahesh Kumar (2004) developed a steady-state groundwater flow for Northeast Musi Basin using the finite difference method and *MODFLOW* package by assuming 8–10% of annual recharge. Sarada (2006) developed a steady-state groundwater flow model of the upper Musi basin using a *MODFLOW* package. The groundwater draft (output) was estimated to be approximately 177.5 mcm; the river leakage was estimated to be 120 mcm; and the outflow to be 0.4 mcm. The entire Musi basin is simulated by Massuel et al. (2007). In this study, the authors found the mean annual simulated recharge to be 1,176 mcm (17% of total rainfall), whereas the annual pumping was estimated to be 1,235 mcm. In the present study, a transient-state groundwater flow model has been developed for the catchments of the Osmansagar and Himayatsagar reservoirs by using 21% recharge from the total rainfall.

Model Setup of the Study Area

A three-dimensional (3D) finite-difference groundwater flow model was constructed using Visual *MODLFOW* software (Waterloo Hydrogeologic 2002). This finite-difference, block-centered, 3D modeling package can simulate transient groundwater flows for different hydrogeological systems (McDonald and Harbaugh 1988). The grid network size can be selected conveniently based on the objective of the modeling process, available data, elements of the conceptual model, and modeler experiences (Mohammadi 2011). In the present study, the simulated model is of the catchment of the Osmansagar and Himayathsagar reservoirs, which are divided into a grid consisting of 80 rows and 80 columns, and of a two-layered aquifer model covering an area of $63,502 \text{ m} \times 57,165$ m (Fig. 2). The resulting mesh consists of $1,000 \text{ m} \times 1,000$ m square blocks. The grid selection was made depending

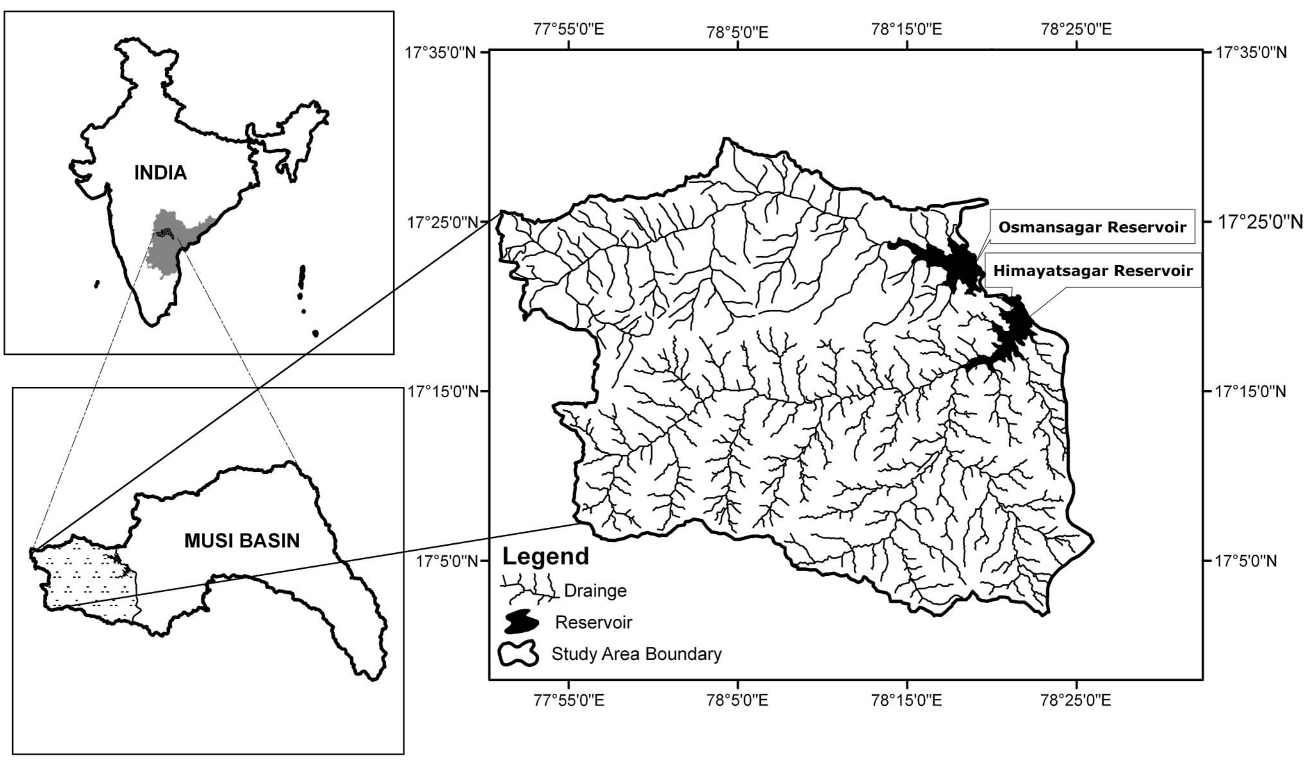

Fig. 1. Location map of the study area

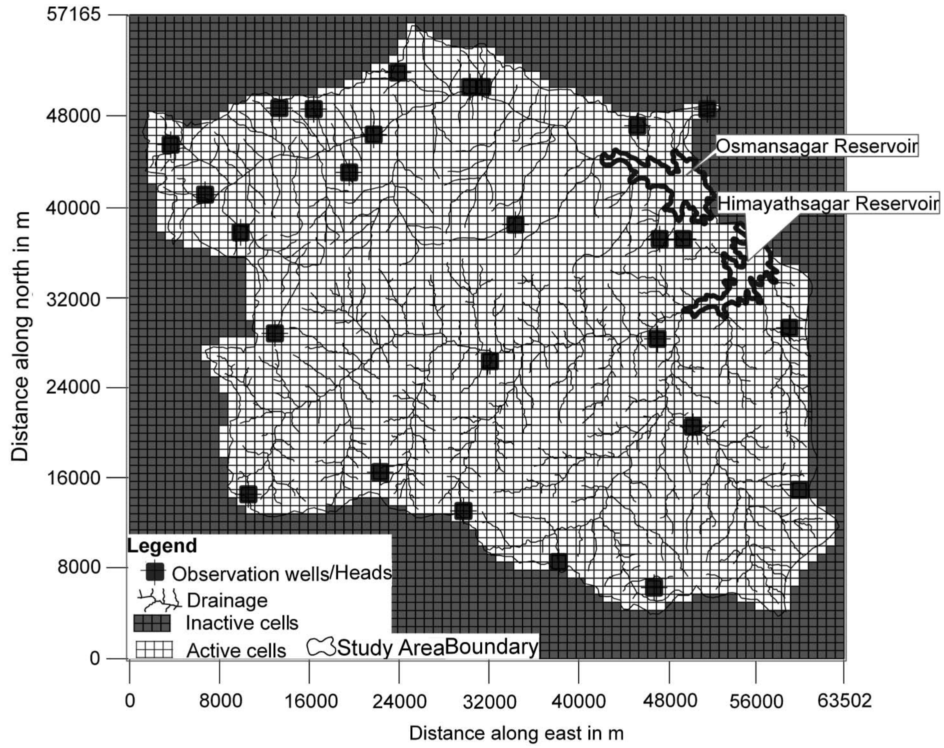

Fig. 2. Model grid domain

on the data availability. The available data were adequate to represent the fluxes across the watersheds. Based on the analysis of 1D and 2D resistivity data in the study area, the two-layer model is considered for the modeling because these two layers are the only saturated water columns. The first layer consists mostly of a 15–20 m weathered zone and is underlain by a 20–25 m-thick fractured zone. The simulated vertical section has a total thickness of approximately 35–45 m. The top layer represents the weathered portion in the system, which is typically designated as an unconfined layer, and the second layer represents the fractured zone and is assumed to represent semiconfined to unconfined conditions with variable T and S (Figs. 3 and 4). Both layers are hydraulically connected (Briz-Kishore and Bhimasankaram 1982)

The basic assumptions made regarding the aquifer modeling are that the Musi and Musa rivers are ephemeral rivers and may become affluent and influent depending on the river flows and surrounding groundwater conditions; thus, they are simulated by the *MODFLOW* river package. No flow occurs across catchment boundaries, as these boundaries coincide approximately with groundwater divides and continuous leakage will occur to the fractured zone from the overlying weathered zone. As the aquifer is a closed one with a streamlet, some outflow may take place. Seepage from

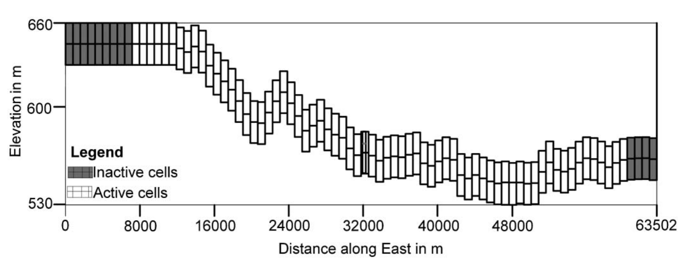

Fig. 3. Horizontal cross-section of aquifer layers (row 44)

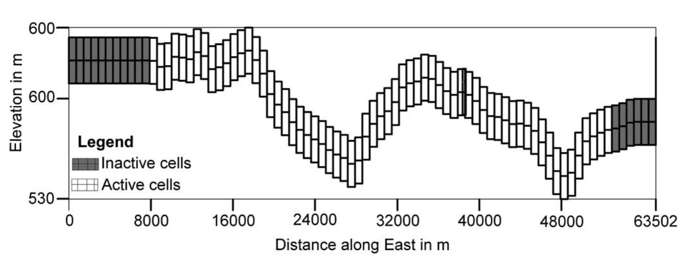

Fig. 4. Vertical cross-section of aquifer layers (column 44)

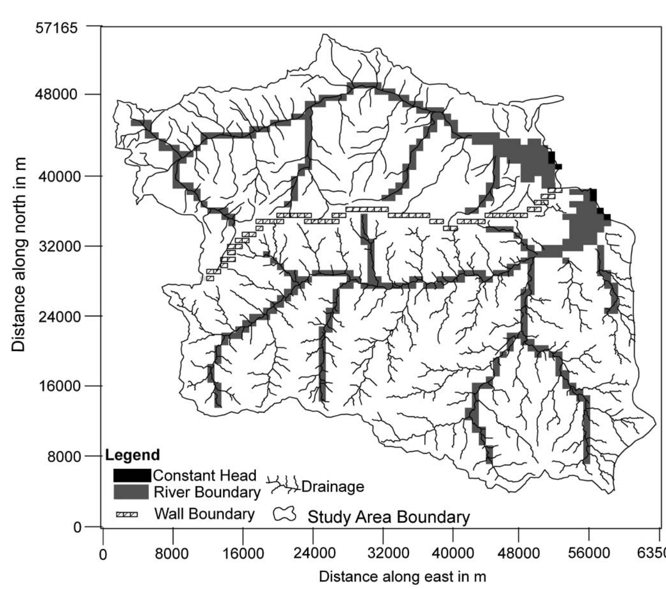

Fig. 5. Boundary conditions in the study area

Table 1. Aquifer Parameters

Name of administrative area (Mandal)	Yield (LPH)	Transmissivity T (m^2/d)	Hydraulic conductivity K (m/d)
Granites			
Maharajpet	3,000	31.65	—
Khanapur	14,400	81.66	—
Moinabad	3,600	43.94	—
Reddipalli	11,200	52.88	2.91
Janwada	10,000	46.12	3.42
Shabad	—	7.40	—
Maharajpet	2,160	31.65	—
Vattinagulapalli	18,000	282	—
Moinabad	3,600	43.94	—
Himayatsagar	5,688	36.5	—
Gaganpahad	18,000	155	—
Emmulanara	9,000	89.86	—
Maheswaram	10,080	129.1	—
Basalts			
Chevella	4,100	9.1	—
Malkapur	3,500	6.87	0.15
Appareddyguda	8,000	13.74	1.14
Kammeta	5,500	9.0	0.001
Chevella	4,583	9.1	—

the surface water bodies and streams are additional input to the watershed recharging system (Venkateswara Rao 2006). The delay in recharge to the aquifer is inappreciable, and the hydrogeological parameters do not change during the period for which the aquifer is simulated.

Boundary Conditions

The boundary conditions are a key component of the conceptualization of a groundwater flow system (Franke et al. 1987; Reilly 2001). The *MODFLOW* river package is used to incorporate surface water boundary conditions into the groundwater flow model (Fig. 5). Lakes, streams, and drains contribute to the groundwater system based on the gradient between the surface water body and groundwater regime. The surface water and aquifer interaction was simulated by assigning water levels and streambed elevations of the streams in the study area. The outflow towards the Musi River, at the west in the study area, was simulated as a constant head of 540 and 530 m, respectively, for the Osmansagar and Himayatsagar reservoirs in the model. The river stage elevation of the water body is the elevation of the water surface of the surface water body. The river bottom elevation is the elevation of the stream. Conductance is a numerical parameter that represents the resistance to flow between the surface water body and the groundwater.

The transmissivity and permeability distribution were taken from pumping test data (Table 1). Lithologs were collected from NGRI, Central Ground Water Board (CGWB), and Andhra Pradesh State Ground Water Department (APSGWD). The estimated transmissivity of the fractured granites ranges between 7 and 290 m^2/day and the specific yield of phreatic aquifer ranged between 0.01 and 0.04. The transmissivity range of vesicular basalts varied from less than 1 to approximately 198 m^2/day. The average specific yield of the weathered basalt and laterite was 0.01 and 0.02, respectively (EPTRI and NGRI 2005). Because there were few hydraulic conductivity values estimated in the area, the authors used a zonal pattern rather than nodal interpolation. The hydraulic conductivity values ranged between 1.8 m/d and 3.6 m/d and are shown in Fig. 6. The storage coefficient of 0.0002 for the basaltic terrain and 0.00028 for granitic terrain was assumed, based on earlier studies (Limaye 2010).

Evapotranspiration (ET) of groundwater may occur when the water table is near or above the ground surface (top of layer 1). Because of limited data in the present model, potential evapotranspiration (PET) is calculated using the Thornthwaite equation (Thornthwaite 1948) for Rajendranagar mandal, and the same value is assumed for the entire region with some alterations for model calibration. The calculated PET values during the period 2005 to 2009 are presented in Table 2. In this model, PET varies between 1,676 and 1,851 mm/year. Evaporation from reservoirs

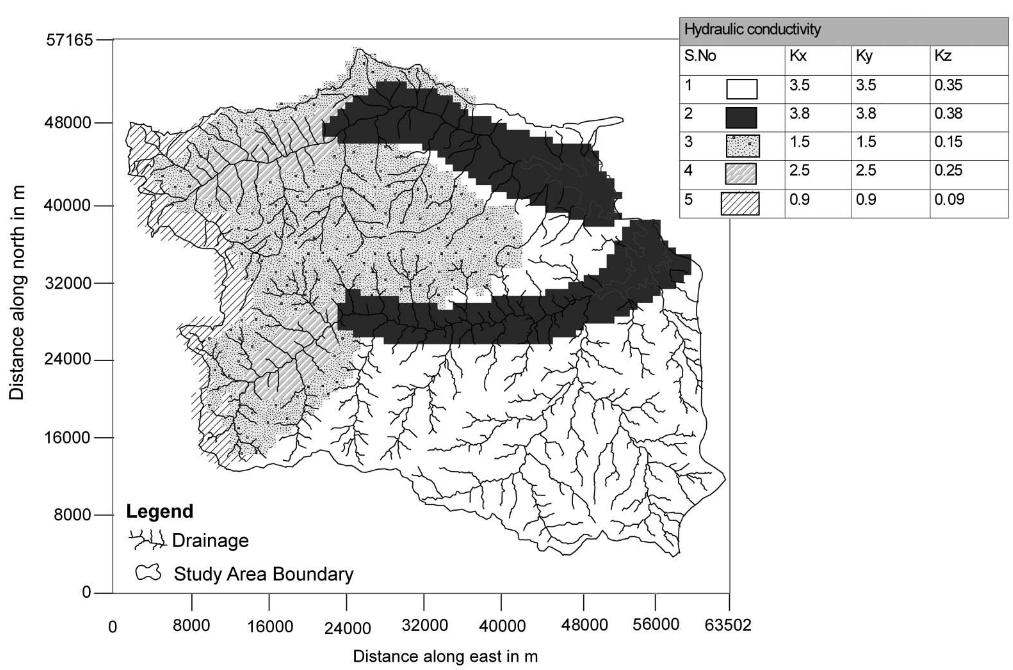

Fig. 6. Hydraulic conductivity distribution in the study area

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Table 2. Variations in Monthly PET during 2005–2009

	Years (mm)				
Months	2005	2006	2007	2008	2009
January	70.83	51.54	58.34	74.0	54.2
February	76.52	59.96	70.66	81.1	63.9
March	144.03	136.52	159.79	151.3	141.0
April	220.63	215.88	222.99	228.2	221.8
May	311.52	275.38	316.40	320.8	282.5
June	281.27	209.59	209.78	290.0	214.7
July	198.12	202.15	131.55	202.6	206.9
August	143.08	141.66	153.00	146.7	146.9
September	124.85	136.39	128.90	128.5	141.6
October	115.20	115.01	108.63	118.7	119.4
November	53.95	78.67	57.71	57.2	82.8
December	48.98	53.02	65.04	51.6	57.4
Total	1,789.03	1,675.83	1,682.83	1,850.84	1,733.05

is approximately 2,311 mm/year, which is adopted from the Hyderabad Municipal Water Supply and Sewage Board (HMWS & SB).

Input and Output Stresses

Recharge to the groundwater regime resulting from monsoon rainfall, seepage from surface water bodies, and irrigation return seepage from fields contribute as inputs to the aquifer system. The outflow occurs primarily through groundwater withdrawal from wells for irrigation and evapotranspiration, and acts as output.

Estimation of Groundwater Recharge by Water Table Fluctuation Method

In the present study, premonsoon and postmonsoon groundwater levels are observed in the year 2005, 2006, 2008, and 2009 at 26 locations covering the catchment areas of the Osmansagar and Himayatsagar reservoirs. These levels are reduced to mean sea level and the difference between premonsoon and postmonsoon levels are contoured using *Arc GIS* software. The water-level fluctuation contours for the year 2005 are shown in Fig. 7. Areas between successive contours of the groundwater-level fluctuations (Fig. 7) are estimated by using the *Arc GIS* software and the specific yield (S_y) values of different formations are adopted from the recommended values of the Ground Water Estimation Committee [Ground Water Estimation Committee (GEC) 1997]. Based on local geology, the recharge is estimated by using the formula

$$\text{Recharge} = \text{Geographical area} \times \text{Water table fluctuation} \times \text{Specific yield} \tag{1}$$

Table 3. Percent Rainfall Converted into Groundwater Recharge

Year	Rainfall (mm)	Rainfall (mcm)	Total amount of recharge (mcm)	Percent rainfall converted into groundwater recharge
2005	955.45	1,952.43	416.10	21.31
2006	603.12	1,207.27	239.69	19.85
2008	898.39	1,892.16	441.80	23.07
2009	720.39	1,532.00	313.27	20.56
Average	789.35	1,597.17	347.62	21.19

The average annual rainfall during the years 2005 to 2009 in the study area and the estimated recharge resulting from rainfall is shown in the Table 3. The percentage of rainfall converted into groundwater recharge is also shown in this table. On average, nearly 21% of rainfall joins the groundwater by direct infiltration of rainfall and by recharge through various water-conservation structures such as tanks, reservoirs, and check dams. These observations are almost tallying with the earlier studies carried out by International Crops Research Institute for the Semi-Arid Tropics

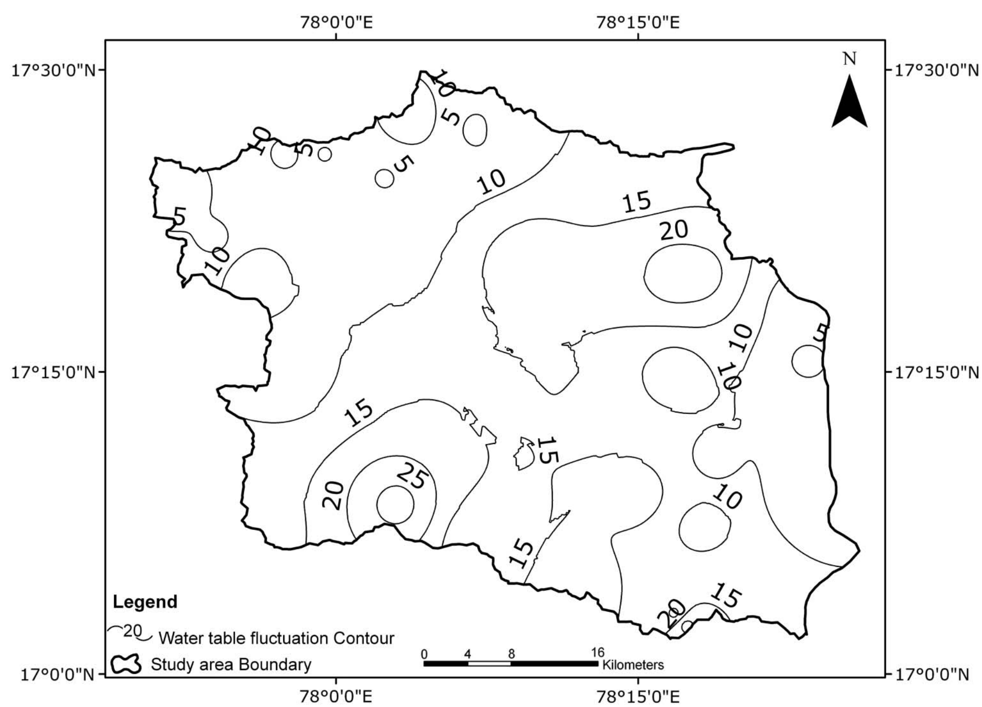

Fig. 7. Water table fluctuation contours during the year 2005

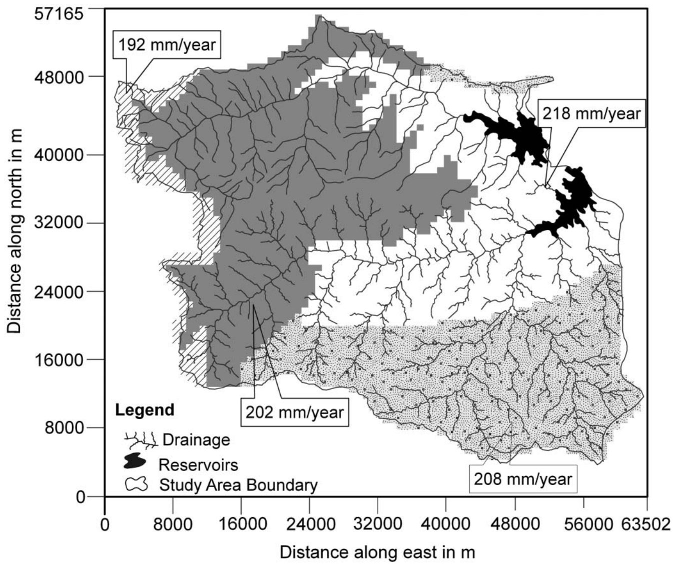

Fig. 8. Recharge distribution in the study area during steady-state calibration

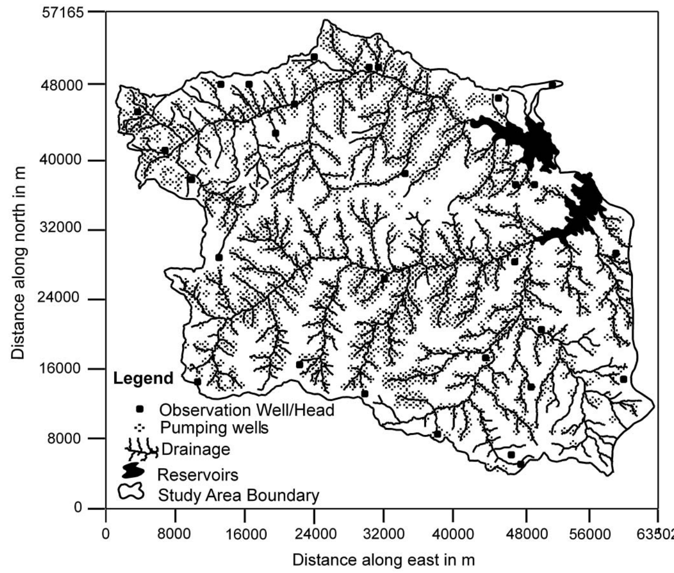

Fig. 9. Pumping well distribution in the study area

[International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) 1976]. Hence, the recharge at the rate of 21% of the rainfall has been considered in the model and fed through a recharge package to the aquifer system. It was slightly altered in different blocks during the model calibration as shown in Fig. 8.

Estimation of Groundwater Draft

The groundwater draft has been assigned using a well package. The study area is primarily dependent on groundwater for its irrigation because of scanty rainfall and fewer surface water resources. Most of the mandals (administrative units) use more than 70% of the available groundwater resources. In this paper, the groundwater draft has been estimated based on the unit draft method with 100% well census data for the year 2005, and the irrigated area statistics method during the period 2006 to 2009 (Table 4).

Table 4. Mandal Wise Groundwater Use of the Study Area

Mandal name	Number of wells	Groundwater use (mcm) 2005	2006	2007	2008	2009
Chevella	4,405	12.10	10.07	10.07	11.70	11.70
Moinabad	2,124	24.12	19.98	20.98	20.98	20.98
Shabad	1,674	24.57	16.00	16.75	19.00	21.00
Shankarpally	3,627	23.22	20.82	20.82	20.82	20.82
Shamshabad	2,194	27.24	17.63	17.63	21.65	21.65
Nawabpet	1,275	8.52	6.70	7.94	7.94	7.94
Vikarabad	793	5.08	3.51	4.51	4.51	4.51
Pudur	951	7.57	5.50	6.03	7.57	7.57
Pargi	976	7.87	5.86	5.86	7.87	7.87
Maheswaram	22.64	22.73	13.45	13.45	13.45	22.73
Rajendranagar	87	0.88	0.88	0.88	0.88	0.88
Bantaram	50	0.23	0.23	0.23	0.23	0.23
Kandukur	41	0.36	0.36	0.36	0.36	0.36
Mominpet	15	0.08	0.08	0.08	0.08	0.08
Kondurg	427	3.09	3.09	3.09	3.09	3.09
Kothur	1,086	11.63	8.48	8.48	11.63	11.63
Shadnagar	351	3.07	2.07	2.07	3.07	3.07
Total	22,340	182.42	134.71	139.23	155.83	166.11

In the unit draft method, the groundwater draft is estimated by multiplying the number of wells of different types available in the area with the unit draft fixed for each type of well in that area. The standard unit drafts recommended (GEC 1997) are as follows: a dug well with pump set at 0.65 ha; a bore well set at 1.30 ha; a shallow tube well set at 2.05 ha; a tube well set at 4.10 ha; and a deep tube well set at 5.25 ha.

In the irrigated area, the statistics method for the groundwater draft is estimated by multiplying the acreage of different irrigated crops (cultivated using groundwater) with that of the crop water requirement for each crop. The adopted crop water requirement for Paddy is 0.95 m for the monsoon and 1.2 m for the nonmonsoon period. For irrigated dry and horticulture it is 0.2 m and 0.15 m for monsoon period and 0.45 m and 0.6 m for nonmonsoon period, respectively (after deducting 50% of rainfall, i.e., 0.25 m). By this

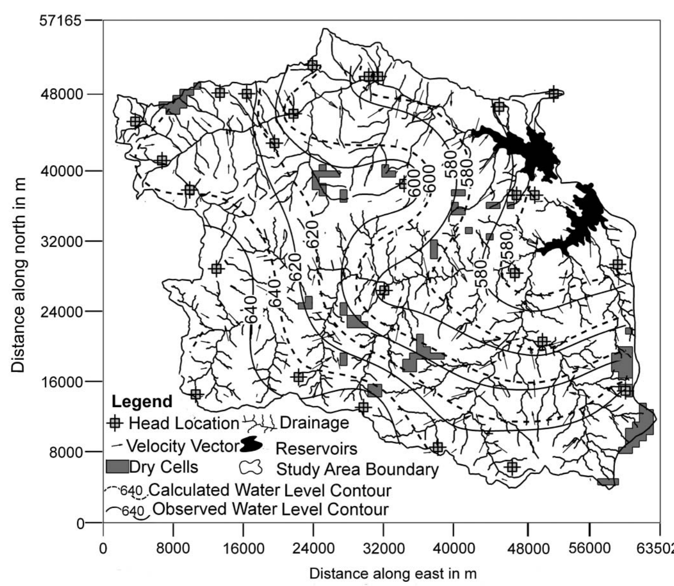

Fig. 10. Contour maps of observed and computed water levels in m from above mean sea level (amsl) during steady-state calibration

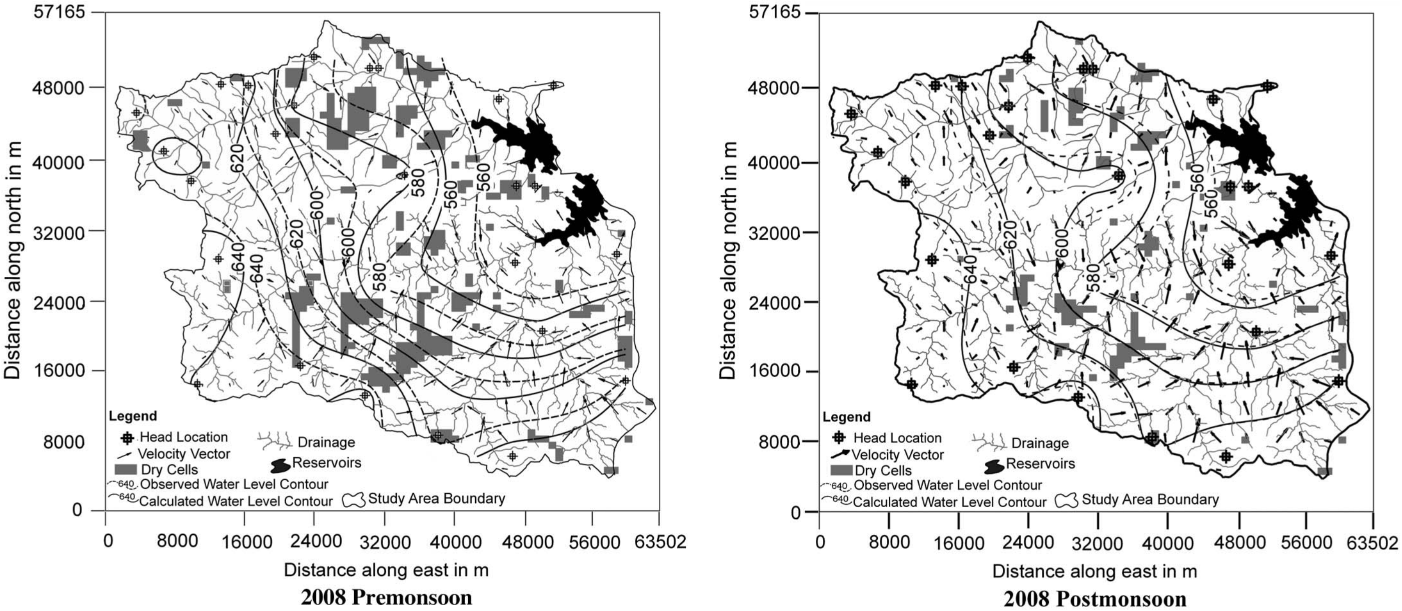

Fig. 11. Comparision between observed and computed water levels during transient state calibration

Table 5. Groundwater Balance under Transient-State Condition

Year	Input	Output	Balance
2005	369.59	370.07	−0.471
2006	254.97	255.12	−0.15
2008	376.65	376.73	−0.08
2009	286.64	286.67	−0.03
Average	321.96	322.14	−0.18

method, the total groundwater draft for irrigation was calculated using the following formula:

$$\text{Total draft} = \text{Area irrigated} \times \text{Crop water requirement} \qquad (2)$$

Table 4 shows that the groundwater draft is more in the mandals of Moinabad, Maheswaram, Shabad, Shankarpally, Shamshabad, and Chevella. The groundwater withdrawal in the catchment areas was simulated appropriately through well package with groundwater pumping rates varying between 100 and 500 m^3/day per grid, considering the urbanization, land use etc. (Fig. 9).

Calibration and Validation of the Model

A steady-state calibration is accomplished for the year 2005 postmonsoon. The general groundwater flow direction is from west to east. The total input to the aquifer is 354.26535 mcm, and the total output is 354.26955 mcm. This indicates that the deficiency of recharge of 0.0042 mcm is responsible for the decline of the water table in the region. The computed and observed water levels during steady state are shown in Fig. 10. The calibrated steady-state model conditions have been used as initial conditions for the transient model. The transient-state groundwater flow model was developed for a five-year period from November 2005 to November 2009, and the contour maps of computed and observed water levels are shown in Fig. 11.

This map shows that the general groundwater flow direction is from west to east, that the observed and calculated water levels are closely related to each other in postmonsoon, and that more dry cells are observed in premonsoon. This is because the premonsoon groundwater levels are decreasing by more than 40 m in some places, resulting from overexploitation in the catchments for irrigation

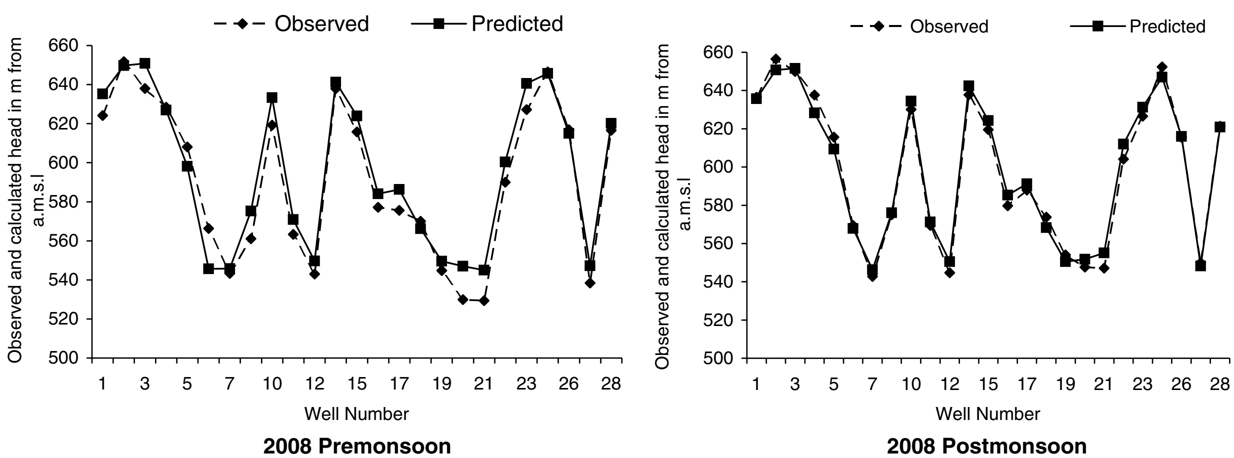

Fig. 12. Observed and predicted groundwater levels in m during validation

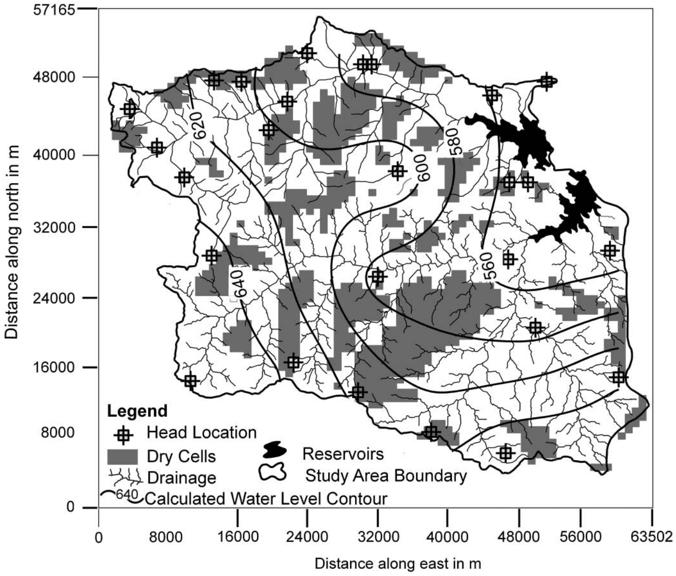

Fig. 13. Calculated water level contours in *m* during 2020 for same draft

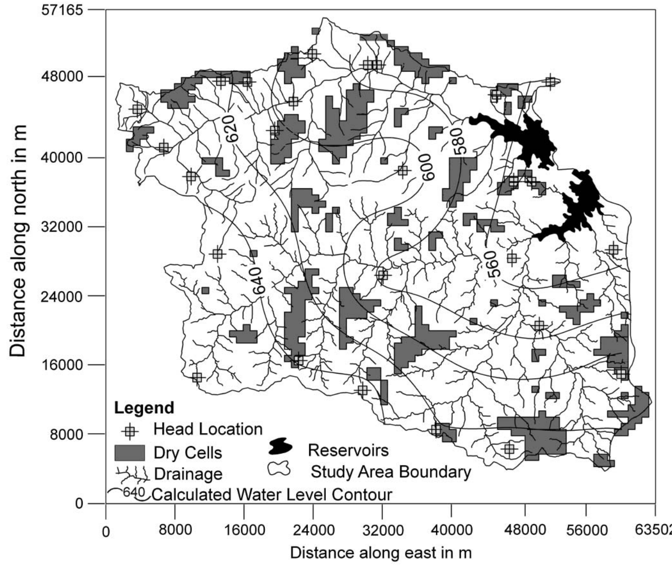

Fig. 14. Calculated water level contours in *m* during 2020 after decreasing the draft

and no recharge during the nonmonsoon period. This indicates a deficiency in storage in the water balance during the study period (Table 5). The minimum and maximum deviation between the observed water levels and the calculated water levels varies between −0.335 and 27.71 m, and the RMS error is at a minimum (0.6) in postmonsoon and at a maximum (15) in premonsoon during the study period.

To understand the dynamic response of the aquifer parameters, a sensitivity analysis is carried out for 20% increment and 20% decrement of the aquifer parameters by keeping only one parameter as a variable while others are kept constant. From this analysis, the groundwater recharge and storage coefficient show a more sensitive variation when compared with hydraulic conductivity.

Because of the uncertainties in estimating the aquifer parameters, stresses, and boundary conditions in the calibration, the process of model validation will help to establish greater confidence in the prediction process. The model calibration was done using 2005 and 2006 groundwater heads, and validation was done for 2008. The minimum and maximum deviation between the observed and the predicted groundwater heads varied between 0.3 and 22.41 m for premonsoon, and −0.6 and 9.9 m for postmonsoon, respectively. The RMS error observed is 6.97 and 5.7 for pre- and postmonsoon seasons, respectively. Fig. 12 shows that the model is able to predict the accurate values in the postmonsoon season when compared with the premonsoon season. However, the overall performance of the model does not deter the user in using the model for prognostics.

Prognostics

As a logical culmination to the aquifer modeling studies, it is natural to know the aquifer response in the future by increasing, decreasing, and continuing the existing draft. The calibrated model and the information on the likely patterns of recharge and discharge can be used to estimate the futuristic aquifer response. If the recharge and discharge are considered to be unchanged, the decrement in depth of water level for the year 2020 is shown in Fig. 13. This figure shows that if the same withdrawal continues until 2020, the water level declines by more than 45 m over the entire study area. The decrement in water level of more than 45 m is indicated as dry cells, and the drawdown in the remaining area also increases from 5 to 20–30 m. To avoid this critical stage, the present draft should be decreased by 40%. There is no chance of increasing the draft in Shankarpally, Moinabad, and Shamshabad mandals. Therefore, by decreasing the draft in the mandals of Shabad, Chevella, Maheswaram, and Nawabpet by 50%, there is a chance to increase the draft in the mandals of Vikarabad, Pargi, and Pudur by 40%. By reducing the groundwater draft, there is a possibility of storing 0.00181 mcm in the year 2020 for future water use. The obtained water level contours are presented in Fig. 14. These results are in good agreement with the predictions of Ahmad et al. (2007) for the Maheswaram watershed. The groundwater draft in the Maheswaram watershed was 12 mcm during the year 2002. If the same draft continued until 2019, 40% of the bore wells would be dried up. To avoid this situation they suggested that the paddy field area be reduced by 40% and the area of vegetables and flowers be increased by 30%.

Conclusions

The Himayatsagar and Osamansagar catchments are sensitively balanced with finite groundwater resources, and are at risk of being overexploited in the coming decades. Therefore, a three-dimensional groundwater flow model for both the Osmansagar and Himayathsagar catchments with two conceptual layers is developed under transient conditions using visual *MODFLOW* software for the period 2005 to 2009. The top layer is considered to be a 15- to 20 m weathered zone followed by second layer with a 20–25 m fractured zone based on hydrogeophysical studies and borehole lithologs. The model indicates that the average input to the aquifer system is 321.96 mcm, and the output is 322.14 mcm. On average, nearly 21% of rainfall joins the groundwater by direct infiltration of rainfall and by recharge through various water conservation structures such as tanks, reservoirs, and check dams. The results indicate that there is no chance to further increase the groundwater draft in the Shankarpally, Moinabad, and Shamshabad mandals, and there is a scope for further groundwater withdrawals in the mandals of Vikarabad, Pargi, and Pudur. The results of the forecast scenarios suggest that the groundwater levels will fall by

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more than 45 m by the end of 2020 if the present rate of pumping continues. The results also suggest that a reduction of 40% groundwater use will increase the groundwater levels in the future.

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