

Groundwater model to predict the impact due to textile units at Pali

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Abstract Pali in the state of Rajasthan has been identified as one of the problem areas in the country where industrial and anthropogenic activities have caused serious environmental degradation. Groundwater flow model has been developed for the Pali area in Rajasthan based on MODFLOW-2000 using the preprocessor GMS and GIS database to predict the groundwater flow regime of the study area. Sensitivity analysis has been carried out using the calibrated and validated groundwater flow model considering variations in rainfall and, as a consequence, modified groundwater recharge rates. The study concludes that the variations in the water table are more prominent in the eastern side of the study area. However, the area around river Bandi remains unaffected, indicating that variation in rainfall does not have a significant impact on the post-monsoon groundwater regime in this area. The flow model developed in the study was also used to carry out analysis on the impact of different land uses and hydrogeological areas on the change in water table in post- and pre-monsoon seasons. The work presented here could be employed to develop a contaminant transport model of the area.

Keywords Groundwater flow model · Rainfall variability · Land use · Hydrogeological areas

Introduction

Groundwater model is one of the most important tools that are widely used around the world to answer many questions

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raised for the management of groundwater resources. It is a useful tool to assist in problem evaluation, design remedial strategy, and conceptualize and provide additional information for decision making. Groundwater modeling becomes even more important in the areas where groundwater resources are depleting at an alarming rate. Rajasthan state is among the four states/union territories in India where severe groundwater depletion is occurring as a result of human consumption rather than natural variability (Rodell et al. 2009).

In addition to depleting groundwater resources, increasing threat to groundwater quality due to human activities has become another matter of great concern. Part of the Pali district of Rajasthan state has been taken up as study area for the work presented in the paper. This area is witnessing high rate of groundwater depletion and also experiencing groundwater pollution due to rapid industrialization (Rathore et al. 2009; Meena et al. 2009). Therefore, groundwater modeling of this region will provide useful insight for its management.

Textile dyeing, printing, and hand processing have been an old-age commercial activity in the western part of Rajasthan. Pali is a famous industrial town in Rajasthan primarily having small-scale textile units. The pollution problem at Pali relates to the unregulated growth of textile processing industries. Pali City is drained by river Bandi which is a seasonal river and flows through the city. The industries located in and around Pali City generate highly polluted industrial effluents which have been regularly disposed off in Bandi River. Due to indiscriminate discharge of effluents generated from textile units, concentration of total dissolved solids (TDS), sulfates, chlorides, alkalinity, and sodium absorption ration (SAR) are high in the groundwater in the impact zone, indicating the adverse impact of textile effluent discharged into river which seeps into the recharge wells at villages near the river bank (NPC 2010). Pali has suffered heavily in terms of groundwater pollution, land degradation, and loss of natural vegetation. It has been identified as one of the problem areas in the country

where industrial activity has caused rigorous environmental degradation (CPCB 2007).

Literature review

Application of remote sensing and geographical information system (GIS) has fundamentally changed our thoughts and ways to manage our natural resources in general and water resources in particular. The use of GIS in conceptualization, characterization, and numerical simulation of groundwater flow systems is well demonstrated (Pradhan 2009a, b; Manap et al. 2012; Al Rawashdeh et al. 2013; Neshat et al. 2013; Ndatuwong and Yadav 2013). Manap et al. (2013) used GIS coupled with remote sensing for groundwater potential mapping in an area of the upper Langat Basin, Malaysia. In the present work, remote sensing and other auxiliary data have been used to develop the GIS database of the study area.

Groundwater modeling has long been used as a scientific tool by practicing engineers, groundwater resource planners, and decision makers in developed countries, and it is being applied by academicians, scientists, and researchers in developing countries also (Mondal and Singh 2005; Gurunadha Rao et al. 2008; Kushwha et al. 2009; Surinnaidu et al. 2011; Rahnama and Zamzam 2011; Arora and Goyal 2012). Rao et al. (2011) developed a three-dimensional steady-state finite difference groundwater flow model to quantify groundwater fluxes and analyze the subsurface hydrodynamics in the basaltic terrain for the alluvial aquifer of the Ghatprabha River, located in the central-eastern part of Karnataka in southern India.

Pali in the state of Rajasthan, India, has attracted researchers from varied fields and backgrounds, and work on impact assessment of textile effluents on various sectors of physical environment has been taken up by many institutions and individual researchers. The Rajasthan State Pollution Control Board (RSPCB 1984) provided an outline of the problem faced at Pali. The report says that major pollutants present in the combined effluent are high alkalinity, COD, BOD, TDS, chlorides, sulfates, etc. The Central Pollution Control Board also undertook a study in the area to carry out inventory of the industries, assessment of pollution load being discharged in the river Bandi, and assessment of the extent of pollution of the groundwater (CPCB 1990). The State Ground Water Department, Government of Rajasthan, conducted a detailed study on groundwater pollution due to textile industries along the river Bandi and characterized the effluent generated from various process streams as well as the combined effluent from cotton cloth processing (SGWD 1992).

The Central Ground Water Board (CGWB) reported intensive groundwater pollution along river Bandi, west of Pali town, due to effluent from several textile units (CGWB 1994). Singh and Ram (1997) carried out a survey and sampling of the ground and surface water as well as the industrial effluents

and concluded that the affected area along Bandi River was 219 km². Singhal et al. (2008) observed that surface and groundwater quality is significantly affected in the area around Mandiya and Punayta where major outfall exists from textile industries. Rathore et al. (2009) demonstrated that groundwater upstream at Pali has high dissolved oxygen, low salinity, sodium, chloride, and sulfate. Likewise, Meena et al. (2009) found toxic heavy metals and other parameters in Pali area higher than permissible levels specified for drinking water in the Indian standards in the groundwater used for potable purposes.

It is evident that most of the research work carried out at Pali is limited to survey, collection, and analysis of data related to groundwater and surface waters. However, there are limited studies, if any, which have used modern tools like remote sensing, GIS, and groundwater modeling to analyze the problem and suggest remedial measures.

Study area

For the present study, part of the Pali district has been taken as study area. The study area for developing groundwater model was defined after thoroughly studying the problem area in terms of its hydrology, hydrogeology, general groundwater flow direction, and morphological features. Aravali hill range was taken as a no-flow boundary on the eastern side of the study area. North Sukri River and South Sukhri River were respectively taken as northern and southern boundaries of the study area. These rivers have been considered as specified flow boundaries. Figure 1 shows the map of the study area along with various boundaries as discussed above (Singhal and Goyal 2011a).

The physical framework of the study area was defined by defining the ground elevation, land use and land cover, hydrostratigraphy, and soil types of the study area. The collected data was analyzed and thematic maps were prepared in GIS. Ground elevation map of the study area was prepared using ASTER remote sensing data (ASTER GDEM website 2010). A total of six types of land use, i.e., arable land irrigated, arable land unirrigated, forest land, grass and scrubland, wasteland, and urban areas, were identified in the study area. Figure 2 depicts the land uses and land cover map of the study area.

It is observed that three different types of hydrogeological units exist in the study area with 61.5 % of the area as alluvium, 21 % as phyllite, and the rest as granite. The aquifer system was constructed based on 28 litho logs of study area obtained from CGWB. For hydrological and hydrogeological analyses of the study area, data related to water level in the monitoring wells, rainfall data of the rain gauge stations, and stream network of the study area were gathered from different sources and converted into desired formats/maps.

river Bandi was modeled as the only source of recharge other than rainfall as all the treated/partially treated waste water

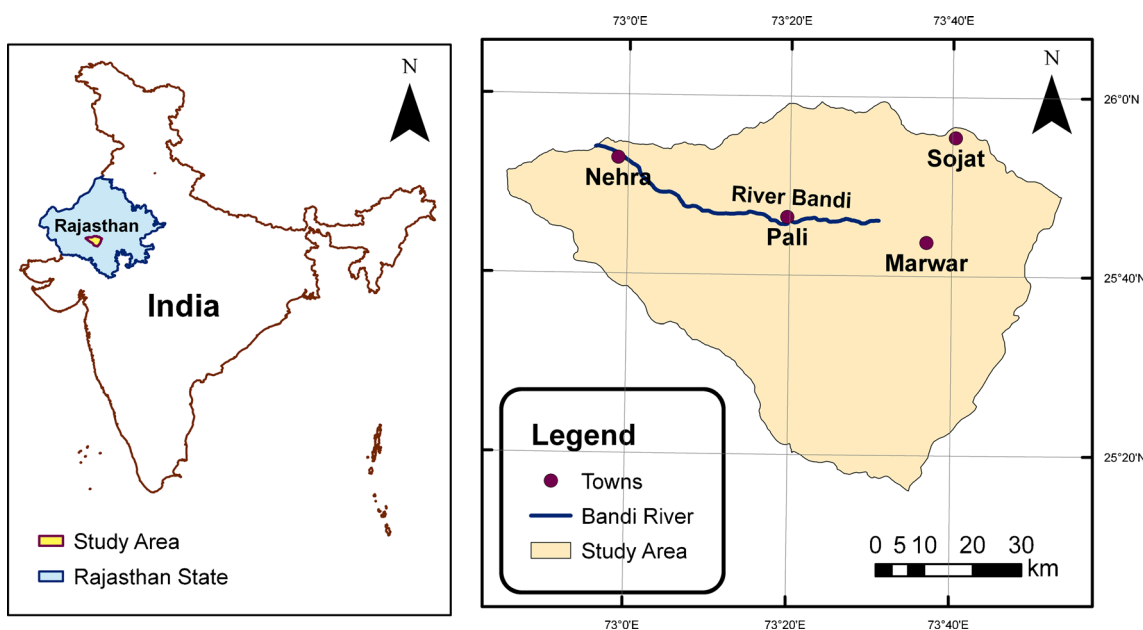


Fig. 1 Study area

from the textile units and the domestic wastewater of Pali town is discharged in the river. No data related to river head gauge is being maintained by the State Water Resources Department. In the absence of any data related to river head, river head was estimated using the data available regarding discharge from the industries and domestic effluent in the river.

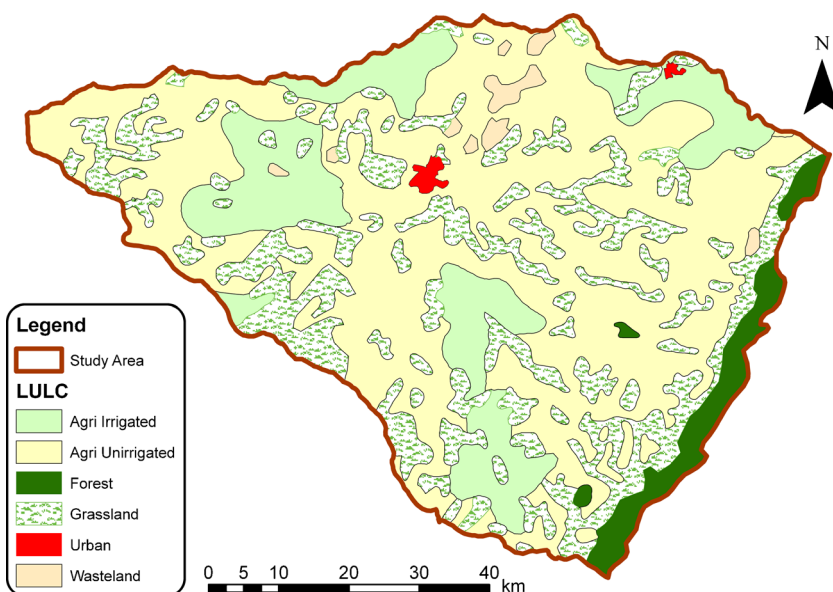
Water budget study of the study area was carried out by calculating recharge or extraction of groundwater based on water balance method which uses groundwater table fluctuation for finding changes in the storages. In this method, the statistical average of rise or fall is used to determine change in storage. However, the arithmetic averaging of fluctuations may not sufficiently address the spatial variability of the

groundwater table. Therefore, a methodology was developed to establish correlation between average rainfall and change in storage volume based on the historical data for different land use types for monsoon and non-monsoon periods (Singhal 2012). This relationship was then used to estimate recharge rates for different land use and hydrogeological types.

Development of groundwater model

Development of a representative conceptual groundwater flow model is an important step before translating it into a numerical model. Therefore, a conceptual groundwater flow

Fig. 2 Land use and land cover map of the study area



model for the study area was developed using spatially distributed values for groundwater recharge instead of lump sum average values normally obtained by water budgeting method (Singhal and Goyal 2011a). Arc GIS 9.2 software was extensively used for preprocessing of hydrological, hydrogeological, and geological data. GIS tools have been extensively applied to the study area to estimate the annual recharge and draft over a 4-year period (Singhal et al. 2013).

In the present work, partially penetrating ephemeral rivers have been taken as model boundaries wherever more appropriate boundaries were not available in near vicinity. It is expected that the flux at these boundaries is likely to be small and may not vary much from time to time. However, a method is required to calculate the average flux through such boundaries. Therefore, a GIS-based methodology was developed for the estimation of flux across “specified flow” boundaries and estimation of distributed recharge for groundwater model using historical groundwater levels, hydrogeological, and land use/land cover map (Singhal and Goyal 2011b).

Conversion of a groundwater flow conceptual model into a mathematical MODFLOW-based model is a very important step in the modeling exercise. In the present case study, Layer-Property Flow (LPF) was used as a flow package, whereas a preconditioned conjugate gradient method (PCG2) was chosen as a solver package. Firstly, various coverages like coverage representing study area boundary, various sources/sinks, calibration targets, and coverages for different aquifer layers and for recharge were set up, and initial values for various hydrological and hydrogeological parameters were assigned as available in the standard literature. Apart from these coverages, 2D scatter data sets representing aquifer layer elevations, starting head, and ground elevations were also developed. These coverages and 2D scattered data sets were then used to set up a mathematical MODFLOW-based finite difference model. Global and LPF packages were also set up which specify starting heads, top and bottom elevation arrays, stress periods, and finite difference grid. Finally, MODFLOW Model Checker was run to check for errors. It is important to choose a correct finite difference grid and to set up the various packages (Singhal and Goyal 2011c).

The model was calibrated using a trial-and-error method. The calibration process was started with a root mean square error (RMSE) value of 6.19 m. A calibration target of ± 3 m of the observed heads was used in the calibration. The calibration process was completed with a RMSE value of 2.87 m (Singhal 2012). The sensitivity analysis and validation of the model was performed as described by Anderson and Woessner (1992). Water level values of post-monsoon 2003 for the monitoring wells were used as starting head values for validation, and the water level values from post-monsoon 2003 to pre-monsoon 2007 were used for validation targets. In the validation process, the calibrated values of aquifer parameters, stresses, and boundary conditions were used. The model was

run, and it was observed that the RMSE value was 2.98 m which is less than the specified tolerance criteria of ± 3 m of the observed heads. Besides the above, various error statistics were generated along with the simulated groundwater level. The simulated groundwater levels have been compared with the observed levels, and it was observed that there is a good match between the two. Time series graphs were also prepared for selected wells which showed reasonably good match between observed and computed head values (Singhal 2012). Figure 3 shows one such graph for well no. 177 which represents a good match between simulated groundwater levels and the observed levels.

Prediction from groundwater model

It was decided to run the developed groundwater flow model considering variations in rainfall which may be expected due to climate change and to carry out sensitivity analysis to determine its impact on the groundwater flow regime. Kumar et al. (2006) has stated that increase in rainfall from the baseline period (1961–1990) to the end of the twenty-first century ranges between 15 and 40 % among the models. Accordingly, it was decided to develop various scenarios (see Table 1) decreasing and increasing the rainfall by 25 % with respect to long-term average rainfall to understand the impact of any variations in the rainfall. For comparison of different scenarios, one of the scenarios, S₁, of no change in monsoon rainfall was used. Methodology developed in the present work for recharge estimation was extended with

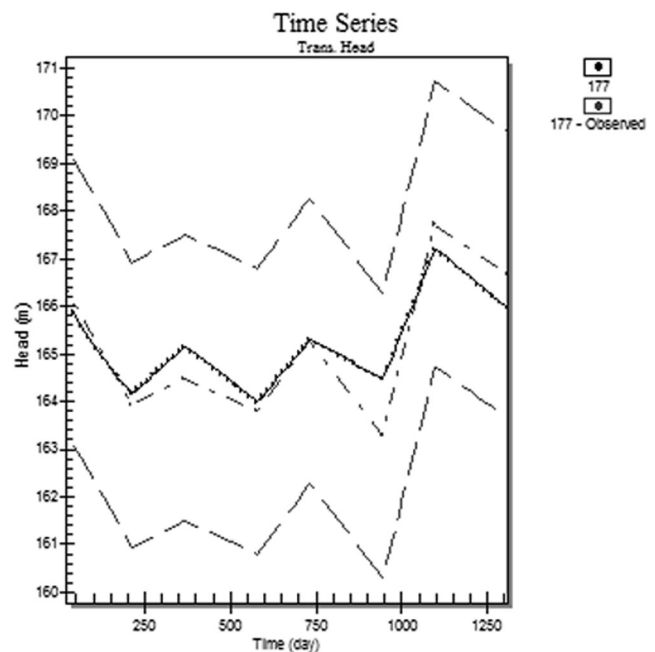


Fig. 3 Variations in computed head in time series for well no. 177

Table 1 Various scenarios to model rainfall variability

Series number	Scenario	Description
1	S ₁	Prediction of head values for normal long-term average rainfall
2	S ₂	Prediction of head values in the case where rainfall is 25 % less than the normal long-term average rainfall
3	S ₃	Prediction of head values in the case where rainfall is 25 % more than the normal long-term average rainfall

varied rainfall to predict the recharge coefficients for different land use/land cover classes for different scenarios. A long-term average rainfall value of 452 mm was taken for the monsoon period for district Pali on the basis of published data on rainfall by the Irrigation Department, Government of Rajasthan (Singhal 2012). The value was used to calculate corresponding average groundwater recharge values for various land use types. For non-monsoon period, the average rainfall data in non-monsoon periods for the year 1999 to 2006 was calculated and used as a long-term average value for non-monsoon rainfall. For predicting various scenarios, average normal rainfall was increased or decreased based on the scenario considered. Accordingly, the recharge factors were estimated for the monsoon and non-monsoon periods for various rainfall scenarios.

Validation model was run from May 2007 to May 2032 for predicting the head values for 15-, 20-, and 25-year periods. The values for predicted head were extracted for each scenario by using various tools available in Groundwater Modeling System (GMS). To analyze the impact of rainfall variability as per the different scenarios on the groundwater regime, the net rise or fall in water table as compared to water levels in 2007 for post-monsoon and pre-monsoon seasons was calculated for year 2031 for all the three scenarios. Table 2 contains the

data related to the rise and fall in water table for some of the points in the study area for all these cases pre- and post-monsoon with respect to water levels in 2007.

As can be seen from the table, the magnitude of change in water table depth is highest for scenario S₃ and lowest for scenario S₁. Also, the difference between pre- and post-monsoon change in water table depths is not very significant in scenarios S₁ and S₂ for most of the points. The point data for each scenario in Table 2 was converted into layers with the help of an interpolation tool in Arc GIS, and the rise/fall in water table for the change in water table between predicted values of post-monsoon groundwater level in year 2031 and post-monsoon groundwater level of starting year 2007 was analyzed for all the three scenarios.

Figure 4 shows the change in water table between year 2007 and year 2031 for all the scenarios for post-monsoon season. In case of scenario S₁, it is evident that there is not much variation in the study area in the rise/fall of water table in years 2007 and 2031. In scenarios S₂ and S₃, a moderate reduction and rise of 25 %, respectively, from the normal average rainfall have been envisaged. In these scenarios, variations in the water table are more prominent in the eastern side of the study area. However, the area around river Bandi remains unaffected in these two scenarios, indicating that variation in rainfall does not have a significant impact on the post-monsoon groundwater regime in this area.

Likewise, three scenarios were analyzed for pre-monsoon season. The impact in pre-monsoon season was also in similar lines as in the scenario for post-monsoon season.

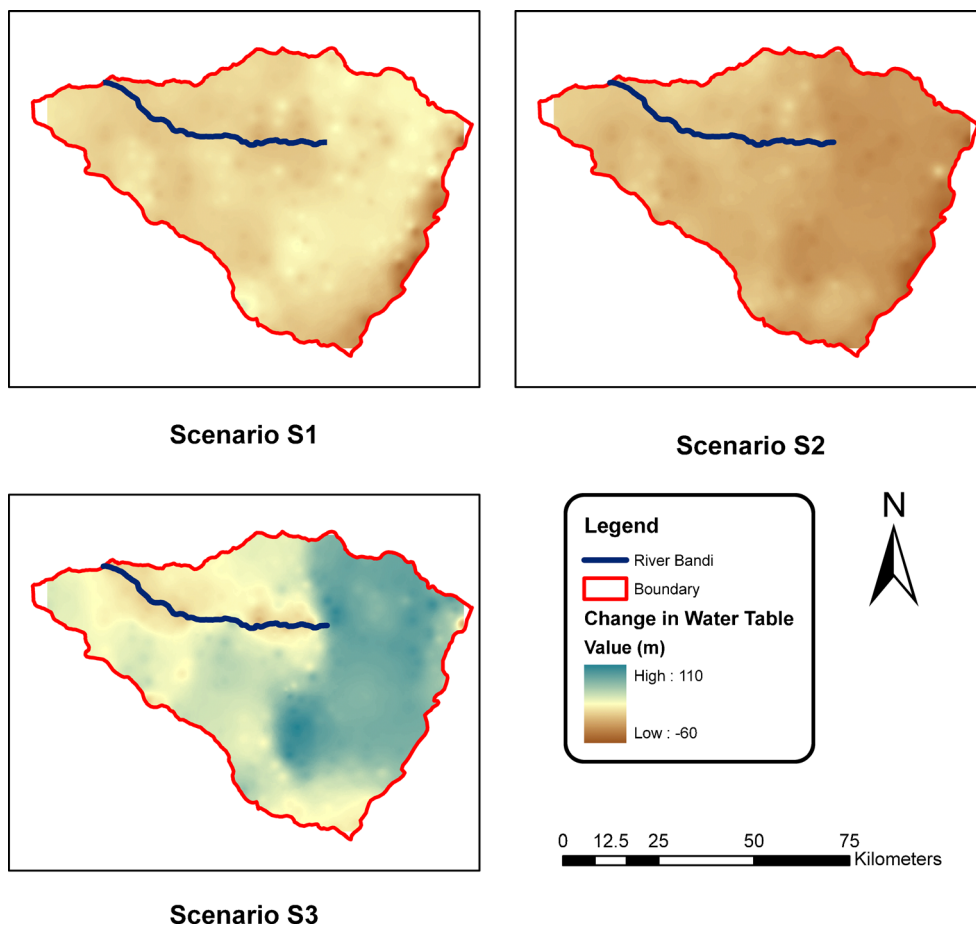
Results and discussions

An attempt was made to investigate the impact of different land uses and hydrogeological conditions available in the study area on the change in water table depth in various scenarios discussed above for post-monsoon and pre-monsoon seasons.

Table 2 Change in water table depth (in meters) for some of the points in the study area for all the scenarios with respect to water levels in 2007

X coordinate	Y coordinate	Scenarios					
		S ₁		S ₂		S ₃	
		Pre-monsoon	Post-monsoon	Pre-monsoon	Post-monsoon	Pre-monsoon	Post-monsoon
332,500	2,872,500	8.7	8.9	10.1	9.6	33.5	34.8
352,500	2,872,500	8.6	9.3	-21.5	-23.2	73.0	75.7
325,500	2,861,500	3.1	4.3	-3.9	-3.5	20.8	22.0
343,500	2,858,500	-2.3	-2.2	-12.1	-13.2	24.0	26.4
363,500	2,858,500	13.5	14.7	-21.7	-21.6	67.5	71.3
343,500	2,802,500	-2.2	-2.3	-21.8	-22.8	19.4	20.6
357,500	2,801,500	-21.0	-19.9	-22.7	-22.4	19.3	21.8
357,500	2,800,500	-21.8	-20.7	-23.2	-23.3	16.9	19.3

Fig. 4 Change in water table between predicted water level of year 2031 and level in year 2007 for post-monsoon season



Accordingly, the mean change in water table depth for each scenario was calculated with the zonal statistics tool available in the spatial analyst tool box of Arc GIS for all the land uses and hydrogeological conditions. Results for post-monsoon season for different scenarios for various land uses are given in Table 3 (Singhal 2012).

As can be observed from Table 3, a maximum change of -22.5 m in water table depth in year 2031 with respect to year 2007 in scenario S₁ in post-monsoon season occurs in forest land. Change in water depth for arable land (irrigated), arable

land (unirrigated), and waste land is in the range of 9.5 to 10.5 m only. A minimum change of -0.2 m occurs in urban area though the total urban area in the study area is only 0.38 % and therefore has been considered insignificant. In the case of S₂ and S₃, forest land shows maximum decrease and increase in both scenarios. However, change in water table depth in arable land (irrigated) and arable land (unirrigated) which together form about 69 % of the total study area will be to the tune of 46.4 and 52.3 m, respectively, in scenario S₃. It is therefore evident that rainfall variability which may be expected due to climate change will have a profound impact on water table in the future as predicted by the model.

Table 3 Mean change in water table depth (in meters) for different scenarios for various land uses for post-monsoon season

Land use type	Mean change in water table in different scenarios (post-monsoon season) in meters		
	S ₁	S ₂	S ₃
1 Arable land (irrigated)	10.5	-9.2	46.4
2 Arable land (unirrigated)	9.7	-13.2	52.3
3 Forest land	-22.5	-35.1	53.8
4 Grass and scrubland	6.4	-14.1	50.3
5 Waste land	9.5	-7.3	41.6
6 Urban area	-0.2	-13.7	23.3

Table 4 Mean change in water table depth (in meters) for different scenarios for various hydrogeological areas for post-monsoon season

Hydrogeological area	Mean change in water table in different scenarios (post-monsoon season) in meters		
	S ₁	S ₂	S ₃
1. Alluvium	9.6	-10.4	47.3
2. Granite	8.3	-12.5	48.5
3. Phyllite	1.3	-24.1	62.7

Change in mean water table depth for different scenarios for various hydrogeological areas for post-monsoon season is depicted in Table 4 which shows that change in water table depth for alluvium and granite is similar across all the scenarios though the highest change is predicted for phyllite for all the scenarios except for scenario S₁ which shows a very small increase of only 1.3 m. A decrease in rainfall by 25 % in scenario S₂ has resulted into change in water table depth to 10.4 and 12.5 m for alluvium and granite, respectively, indicating profound impact on water table depth in these hydrogeological areas. Similar changes were observed in the pre-monsoon season (Singhal 2012).

From the above analysis of mean change in water table depth for different scenarios for various land uses and hydrogeological areas for post-monsoon seasons, it is evident that rainfall variability in the study area which may be expected due to climate change will have a significant impact on the water table and availability of total groundwater for various land uses specially the arable irrigated and unirrigated lands which form about 70 % of the study area.

Conclusions

In the work presented in this paper, a groundwater flow model has been developed for the Pali area in Rajasthan using MODFLOW-2000 to predict groundwater flow regime and to model the variability of rainfall and subsequent variations in groundwater recharge to capture its impact on groundwater regime. The calibration and validation results of the model confirm that the groundwater model for the area has been well calibrated and is capable of predicting future state of groundwater system in response to variation in rainfall. Three different scenarios were developed by varying the rainfall by 25 % as compared to the normal average rainfall, and the impact of rainfall variability on future groundwater regime in pre- and post-monsoon seasons of year 2031 with respect to year 2007 was evaluated.

The study concluded that in scenario S₁, there is not much variation in the study area in the rise/fall of water table in year 2007 and 2031. However, in scenarios S₂ and S₃, the variations in the water table are more prominent in the eastern side of the study area. The area around river Bandi remains unaffected in these two scenarios, indicating that variation in rainfall does not have a significant impact on the post-monsoon groundwater regime in this area. Scenarios constructed for non-monsoon season have also shown similar results as in the case of monsoon season. Analysis of the impact of different land uses and hydrogeological areas on the change in water table in post-monsoon and pre-monsoon seasons indicates that rainfall variability will have a profound impact on the water table in the future as predicted by the model.

The work presented here could be employed to develop a contaminant transport model for the area to predict the

contamination level of pollutant in the future and how it relates to the groundwater flow regime predicted by the flow model. The predictions could also be used to prepare climate change adaptation strategies for the area and could assist in preparing future water budget and allocation of water resources for various competitive uses like human consumption, agriculture, industrial, etc.

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