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Full Length Research Paper

Development of conceptual groundwater flow model for Pali Area, India

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Development of representative conceptual groundwater flow model is an important step before translating it into a numerical model. In this paper, a methodology for development of conceptual groundwater flow model has been presented in which spatially distributed values for groundwater recharge has been utilized instead of lump sum average values of recharge normally obtained by water budgeting method. The study also extensively uses GIS for preprocessing of hydrological, hydrogeological and geological data. In our view, the methodology presented here provides better tools for building a conceptual model for tackling groundwater modeling problems.

Key words: Groundwater flow model, conceptual model, groundwater recharge, spatial distribution, Geographical Information System.

INTRODUCTION

Groundwater modeling is an important tool to provide guidance for management of groundwater particularly in the areas where the hydrological cycles are predicted to be accelerated due to climate change (Mall et al., 2006). Groundwater modeling becomes even more important because of rapidly falling groundwater levels due to overexploitation, particularly in the state of Rajasthan which is among the four states/union territories where severe groundwater depletion is occurring as a result of human consumption rather than natural variability (Rodell et al., 2009). To add to the problem, increasing threat to groundwater quality due to human activities has become a matter of great concern. A vast majority of groundwater quality problems present today are caused by contamination and by over-exploitation, or by combination of both (CPCB, 2007). The study area for the present work falls in the part of area where the groundwater depletion rates are very high and the area is experiencing groundwater pollution problem due to rapid industrialization (Rathore et al., 2009; Meena et al., 2009). Therefore, groundwater modeling in such region will provide insight for its management. However, there are many methodological challenges which the researchers need to overcome in order to develop a robust and dependable groundwater model.

This research paper concentrates on designing the methodology for development of a conceptual model which is interdisciplinary and takes stocks of the new innovations.

Groundwater model development of any natural system is preceded by development of a conceptual model which is then converted into a numerical model. The conceptual model is based on the subjective judgment of the analyst. One can expect the conceptual model to be continuously updated as new information is acquired (Bredehoeft, 2005). Once the concepts are formulated, they can be translated into a mathematical frame work resulting into equations that describe the process (Marcer and Faust, 1980). A numerical model so framed provides a tool by which to test the appropriateness of the prevailing concept.

In the generic sense, a conceptual model is a simplified representation of the site to be modeled including the model domain, boundary conditions, sources, sinks and material zones. The purpose of building conceptual model is to simplify the field problem and organize the associated data so that the system can be analyzed more readily (Anderson and Woessner, 1992). The simplifying assumptions are required partly because a complete reconstruction of field system is not feasible and partly

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because there is rarely sufficient data to completely describe the system in full details. The conceptual model should therefore be kept as simple as possible while retaining sufficient capacity to adequately represent the physical elements of the hydrological behavior. However, the model should not be configured or constrained such that it artificially produces a restrained range of prediction outcomes. Problem with approximating reality are magnified while carrying out transport modeling because besides simplifying flow, the solute transport processes are also reduced to a few transport mechanisms which are considered dominant (Spitz and Moreno, 1996).Time and again errors in prediction revolve around a poor choice of the conceptual model.

Development of conceptual model normally involves preparation of water budgeting for estimating groundwater recharge. Water budget preparation is a complex exercise which involves collection of data related to rainfall for number of years, identification of groundwater extraction sources and estimation of gross extraction from each source. Once the data is collected, recharge is estimated by applying water balance equation. However, this method is quite empirical as several assumptions are required to be made while estimating the groundwater recharge. Further, estimated recharge is typically in lump sum form representing the average recharge of a zone in the study area. In the present study, a methodology has been presented in which spatially distributed values of groundwater recharge estimated by using spatial varied data for rainfall, groundwater table variations, hydrogeological zones and several Geographical Information System (GIS) tools has been used for development of conceptual groundwater flow model instead of lump sum value of average recharge for the study area normally used.

LITERATURE REVIEW

The groundwater models can be used as predictive tools with the objective of determination of future conditions or the impact of a proposed action on existing conditions of the subsurface groundwater regime. They may also be used as generic or screening tools in regulatory mode for the purpose of developing management standards and guideline (Bedient et al., 1994). Some of the groundwater modeling studies undertaken by various researchers in India are the flow and contamination transport model for the groundwater regime in upper Palar basin, Dindigul town, Tamil Nadu due to groundwater pollution by tanneries (Gurunadha and Thangarajan, 1999; Mondal and Singh, 2005), the flow and mass transport model to assess the migration of the contaminated plume for the Patancheru Industrial Development Area (Gurunadha et al., 2001) and the mass transport modeling to assess the migration of the contaminated plume for Treatment, Storage and Disposal Facility (TSDF) constructed for disposal of hazardous waste generated by industries in and around Hyderabad city (Gurunadha et al., 2004).

Internationally, extensive research work has been undertaken by a large number of researchers where groundwater modeling has been carried out. Craner (2006) developed a steady-state numerical groundwater flow model using MODFLOW with MODPATH to understand direction of groundwater flow, groundwater age, and nitrate transport pathways of the Southern Willamette Valley, Oregon, USA. The study suggests it may take 10’s of years to see measurable declines of groundwater nitrate in some locations. Almasri and Kaluarachchi (2007) also developed a soil nitrogen dynamic model to estimate nitrate leaching to groundwater. These estimates were used in developing a groundwater nitrate fate and transport model. The framework considers both point and non-point sources of nitrogen across different land use classes. The methodology was applied for the Sumas–Blaine aquifer of Washington State, US, where heavy dairy industry and berry plantations are concentrated. Simulations were carried out using the developed framework to evaluate the overall impacts of current land use practices and the efficiency of proposed protection alternatives on nitrate pollution in the aquifer.

GIS is an important tool in development of conceptual model for any groundwater flow and contaminate transport problem. GIS offers data management and spatial analysis capabilities that can be useful in groundwater modeling. It provides automatic data collection, systematic model parameter assignment, spatial statistics generation, and the visual display of model results, all of which can improve and facilitate modeling (Watkins et al., 1996). Gogu et al. (2001) designed a GIS database that offers facilities for groundwater vulnerability analysis and hydrogeological modeling for the Walloon region in Belgium. A "loose-coupling" tool was created between the spatial-database scheme and the groundwater numerical model interface GMS (Groundwater Modeling System). Following time and spatial queries, the hydrogeological data stored in the database can be easily used within different groundwater numerical models.

Remote sensing is another useful tool in the acquisition of spatially distributed data for groundwater modeling. Airborne geophysical surveys allow for the identification of faults and dikes, changes in lithology and the depth of magnetic features (Doll et al., 2000; Danielsen et al., 2003; Jorgensen et al., 2003). This information is helpful in constructing realistic conceptual models of aquifers. For a phreatic aquifer, where the surface of the terrain is also the upper boundary of the aquifer, surface elevations can be determined by various remote-sensing techniques such as airborne platforms (for example light detection and ranging LIDAR, interpretation of stereo orthophotos or satellite platforms using radar interferometry). Several preprocessed Digital Elevation Models (DEMs) such as

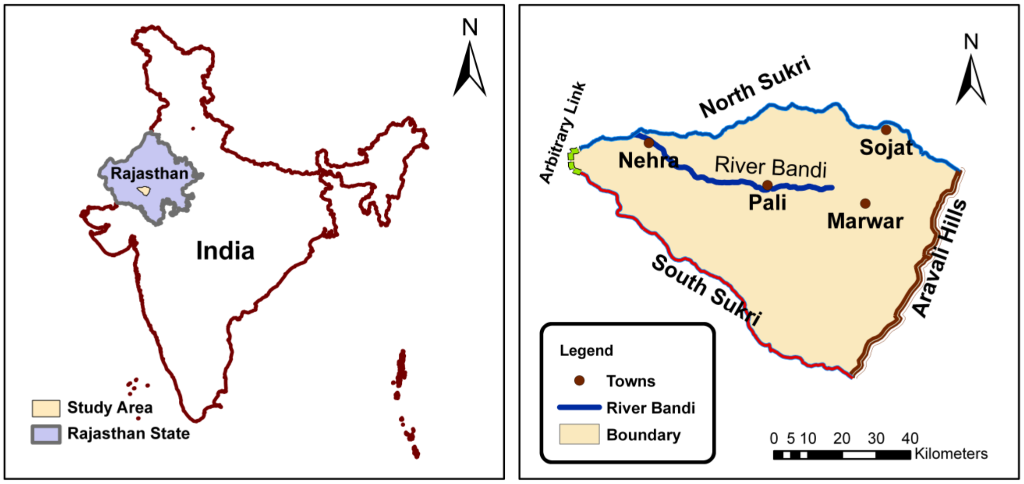

Figure 1. Index Map.

Shuttle Radar Topography Mission (SRTM) and ASTER Global Digital Elevation Model (GDEM) are freely available on internet for obtaining groundwater elevation data.

METHODOLOGY

Preparation of conceptual model

Preparation of conceptual model involves identification of the study area, deciding appropriate boundary conditions, creation of usually three dimensional model of hydrogeological system and estimation of sources and sinks. One of the important sources, especially for phreatic aquifer, is groundwater recharge. In the present study, while developing conceptual groundwater flow model for Pali area, GIS has been extensively used for creation of database and spatial distribution of the groundwater recharge has been calculated for demarcation of recharge zones. Subsequently, conceptual model so developed can be converted into a mathematical model such as 3-D modular finite difference based MODFLOW model (McDonald and Harbaugh, 1988).

Study area and specific boundary conditions

The present study was performed in part of Basin. Index Map of the study area is shown in Figure 1. The climate of the district is arid to semi arid. The average annual rainfall in the district is around 568 mm (SRSAC, 1999). River Bandi, a tributary of Luni River, flows through Pali city and is the major river catering to the water requirements of the people of Pali district (NPC, 2007). The river flows southwest in the Marwar area across the plains of the region and joins River Luni, approximately 58 km west of Pali city at village Lakhar Thumb. It is mostly a dry river except in monsoon season and carries domestic and industrial waste water from the city up to 40 km (NEERI, 1993). The main water bearing formation in the study area is alluvium which comprises of about 60% of the total area. The depth of water table in the study area varies from136 to 380 m from Mean Sea Level (MSL). The groundwater is the main source for domestic and agriculture purposes and is also being used for industrial purposes (Krishna and Govil, 2004).

Pali city has been identified as one of the most polluted areas in the country because of indiscriminate disposal of the industrial effluents generated from the textile industries (RSPCB, 1984). The industries located at Pali are in small scale and are mostly engaged in textile printing and dyeing. The effluent generated from these industries has, among other parameters, low pH, high Total Dissolved Solids (TDS), Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD). As per Rajasthan State Pollution Control Board (RSPCB), quantity of the effluent including the city sewage, being discharged into river Bandi, was approximately 45.6 MLD in year 2004 (RSPCB, 2008). To treat the industrial effluent generated from these units, various common effluent treatment plants have been established and the effluent after treatment is discharged in to river Bandi. The effluent carried by the river during non monsoon season has been found having acidic pH, high TDS, chlorides, sodium, sulphates and nitrates (RSPCB, 2002). The groundwater along the reach of the river has also been found polluted having high TDS, chlorides, calcium and sulphates at many places (Singhal et al., 2008). Figure 2 shows the Map of Pali city, part of river Bandi and location of common effluent treatment plants (CSE, 2006).

As a first step, an area of 5,135 km² along the river Bandi has been identified as study area in order to study the impact of textile industries in an around Pali city. The study area was selected on the basis of likely boundary conditions and the fact that this area has been reported to be most affected area due to pollution of textile industries by many different studies and also includes the catchment area of river Bandi through which the runoff flows during the monsoon season.

In defining the study area, the modeler needs to distinguish the area proposed to be investigated from the adjacent groundwater system. Consequently, a model boundary needs to be defined before taking up any groundwater modeling exercise. Model boundary is the interface between the study area and the surrounding environment (Spitz and Moreno, 1996). Anderson and Woessner (1992) have defined boundary conditions as mathematical statements specifying the dependent variable (head) or the derivative of the dependent variable (flux) at the boundaries of the problem domain. They have also mentioned that regional groundwater divides are typically found near topographic high and may form beneath partially penetrating surface water bodies. In the present case, Northern (136.5 km) and southern (116.5 km) boundaries coincide with existing rivers. Though these rivers are non-perennial and typically forms ground water divide during the monsoon season. During the non monsoon season, ground water gradient below these streams is typically almost flat therefore it may be assumed as no flow boundaries even during non-monsoon period. On the eastern side (76 km) falls the Aravali Hill which as

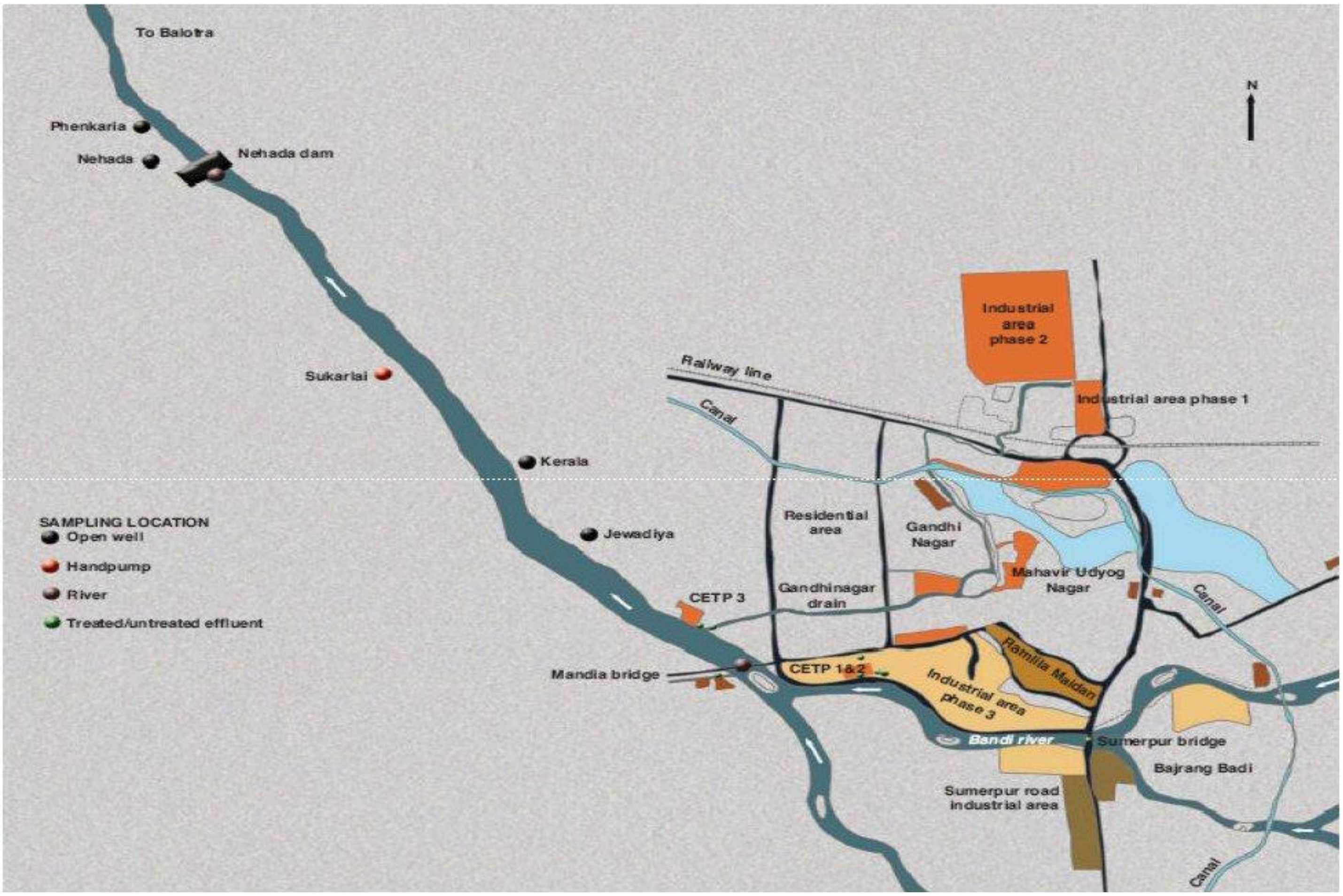

Figure 2. Map of Pali City. Source: CSE (2006).

taken as a no flow boundary. The remaining boundary length of 4.9 km joining the two rivers on western side was assumed as specified flux boundary with flux calculated from water table level data. Figure 3 shows map of the study area with various boundary conditions.

While developing a groundwater model, not only spatial domain is discretized into cells, temporal domain is also discretized into time steps. Typically a year is digitized into 2 to 4 periods based on seasons with the requirement that during one time period, various stresses and parameters exhibit unique relationship or remain constant. In the present study time is discretized into two periods in a year, that is, monsoon and non monsoon. Monsoon season is considered from middle of May to middle of October. Most of the rainfall occurs during this period with low water requirement for agriculture. The remaining period is considered as non monsoon where there is practically no recharge from rainfall and groundwater extraction is more than during the monsoon period.

Creation of GIS database

Utilizing the data obtained from various sources such as Central Groundwater Board (CGWB), State Groundwater Department (SGWD), State Irrigation Department, Survey of India (SoI) and Remote Sensing data, a GIS database consisting of Land use Land Cover Map (LULC) Map, Hydrogeological Map, the hydrostratigraphic units and Ground Elevation Map have been created for the study area.

Land use Land Cover Map (LULC) of the study was prepared using SoI district map as the basic map. Polygons of different land use classes were digitized using GIS tools. Total six types of land use, that is, arable land irrigated, arable land unirrigated, forest land, grass and scrubland, wasteland and urban areas, were identified in the study area. As per the final map, maximum 52.7% of the study area falls under the arable un-irrigated land whereas 24% of the area is covered under grass land and scrub land. Only very small percentage of the land is under the forest (4.28%), waste land (1.35%) and urban area (0.38%). Table 1 gives detailed information on area under different land use types.

District hydrogeology map from SoI was used to digitize broad hydrogeological units within the study area. It is observed that three different type of hydrogeological units exist in the study area with 61.52% of the area as alluvium, 21% of phylite and rest as granite. The area in the western side is mostly alluvium with small patches of granite while eastern area is primarily consisted of hard rock aquifer in the form of phylite. On the northern side, granite is found in the upper part of the study area. Figure 4 shows the hydrogeological map of the study area.

To construct the aquifer system, lithologs of the study area were obtained from CGWB and different similar layers were combined to represent one single layer. For example, older alluvium and younger alluvium layers were represented as single alluvium layer. Likewise, the layers for which thicknesses were not significant were merged in to the board major layers. Accordingly, a three layer

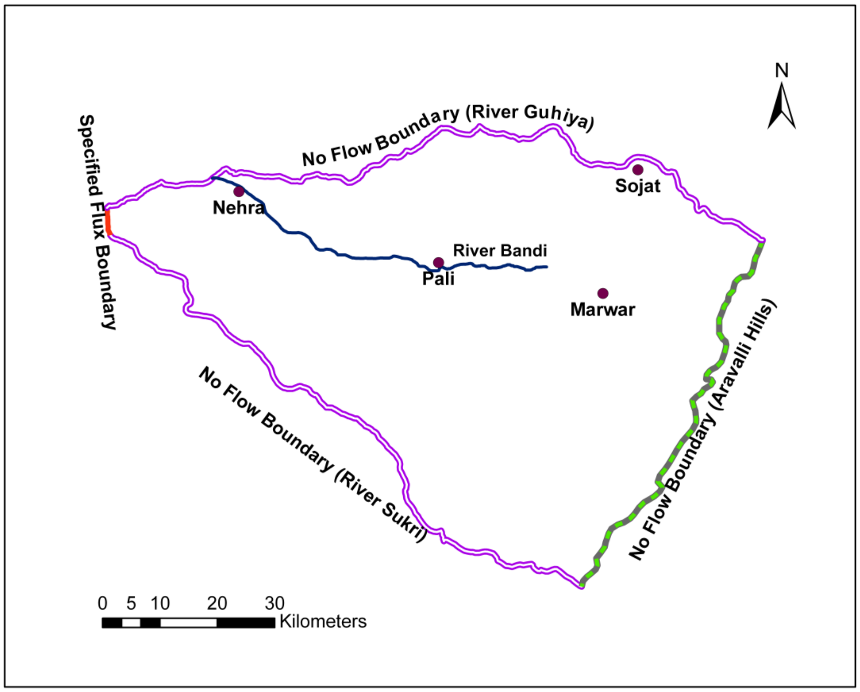

Figure 3. Map of the study area with various boundary conditions.

Table 1. Area under different land use types.

S/No.	Land use type	Area (Sq km)	Percentage of the total study area
1	Areable Land (Irrigated)	840.82	16.39
2	Areable Land (Un-irrigated)	2703.68	52.69
3	Forest land	219.65	4.28
4	Grass and Scrub Land	1278.36	24.91
5	Waste Land	69.02	1.35
6	Urban Area	19.67	0.38

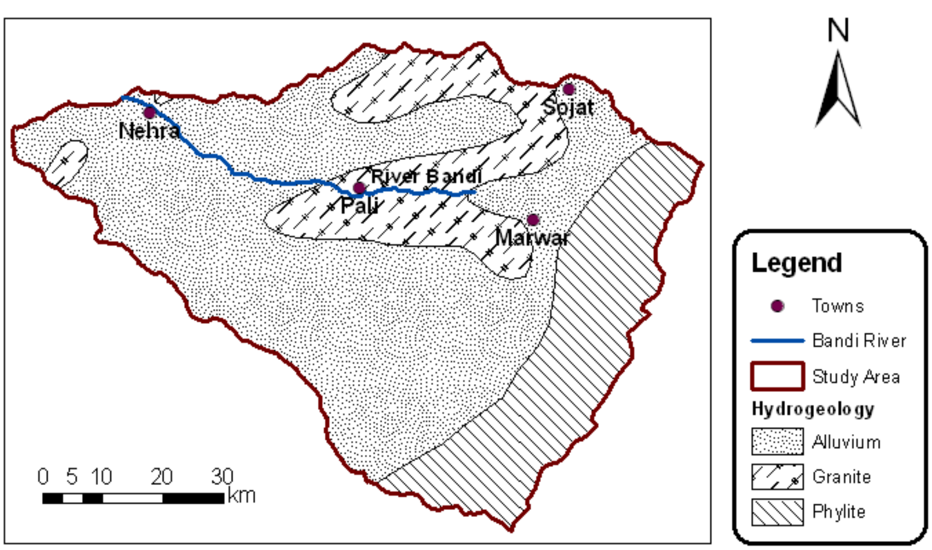

Figure 4. Hydrogeological Map of the study area.

Table 2. Details of a few typical exploratory wells in the study area used for preparation of Hydrostratigraphic Map.

S/No.	Location of the exploratory well	Reduced level (RL) in meters	Total bed thickness (m)	Elevation of alluvium layer (bottom)	Elevation of granite layer (bottom)	Elevation of phylite layer (bottom)
1	Gelawas	158.00	100.00	58.00	58.00	58.00
2	Panata	321.00	75.00	313.00	313.00	246.00
3	Ponchwa Dhani	218.00	100.00	198.00	178.00	118.00
4	Khokhra	275.00	100.00	260.00	235.00	175.00
5	Bagar	295.00	50.00	287.00	245.00	245.00
6	Gudha Badawatan	331.00	30.00	326.00	326.00	301.00

aquifer system consisting of alluvium, granite and phylite has been generated in GIS. Total 25 exploratory well logs were used for preparation of aquifer system.

Table 2 gives details of a few typical exploratory wells which were used for construction of hydrostratigraphic units of the conceptual model.

The borlog data reveals that the total bed thickness has large variations in the study area and it is as low as 27.6 m at Neemla Kheda and as high as 192 m at Mohrakalan. Alluvium is the upper most layer and is found throughout the study area. Its depth varies from 1 m to 149 m. Granite layer is predominately found in the northern western and central part of the study area covering Borlog locations like Mandia, Neemla Kheda, Khardi, Surayata, etc. Depth of granite layer in the study area varies from 6.7 to 77.40 m. Phylite is predominately in the eastern part of the study area along Aravali foothills and covers borlog locations like Melap, Gudha Badawatan, Panata, etc. Depth of phylite layer varies from 3 to 180 m.

Ground Elevation Map of the study area was prepared using ASTER remote sensing data. Japan's Ministry of Economy, Trade and industry (METI) and NASA provides ASTER Global Digital Elevation Model (GDEM), which has been used to generate elevation map of the study area (ASTER GDEM website, 2010). The GDEM is produced with 30 meter postings and has Z accuracies generally between 10 m and 25 m root mean square error (RMSE). GDEM is formatted in 1 x 1 degree tiles as GeoTIFF files (ASTER GDEM Validation Team, 2009). Total 16 scenes falling in coordinates between 71 degree to 75 degree East and 24 degree to 28 degree north were down loaded from website www.gdem.aster.ersdac.or.jp and a mosaic was constructed using the GIS tools. From the mosaic, the data falling in the study area was extracted using extraction tools in spatial analyst tool box in GIS. Figure 5 provides ground elevation map of the study area.

108 monitoring wells maintained by CGWB and SGWD and falling within and around the study area and having consistent record were selected to digitize water table levels. Pre and post monsoon groundwater levels of year 1999 to 2006 of these wells were used to generate cell based raster layers of groundwater rise and fall for each monsoon and non monsoon period. Zonal statistics tool was then used to develop various recharge zones based on spatial distribution of recharge.

DEVELOPMENT OF MODFLOW BASED GROUNDWATER FLOW CONCEPTUAL MODEL

In the present work, Groundwater Modeling System (GMS), which is a comprehensive groundwater modeling environment was used with GIS based graphical preprocessing tools to automate and streamline the modeling process. GMS seamlessly interfaces with MODFLOW and several other preeminent groundwater models, and provides advanced graphical features for viewing and calibrating model results. GMS uses a Conceptual Modeling approach to create and manage numerical models using GIS based objects. The conceptual model approach allows users to build models conceptually independent of their numerical grid. Other powerful GMS features include 3D Model conceptualization, site visualization, advanced geo statistics, and stochastic modeling. GMS also has advanced tools for data import, data export and data visualization and animation (AQUAVEO website, 2010).

In GMS, seven types of coverage were created using various GMS tools. Three files of area coverage for three different aquifer layers namely alluvium, granite and phylite were created and initial values for various hydrological and hydrogeological parameters were assigned as available in the standard literature. Coverage for recharge was created in which values for recharge obtained for all the recharge zones for various time steps were assigned. The coverage files representing study area boundary and Bandi River were also created. The seventh coverage was created for the calibration targets for which 28 well distributed wells were selected as calibration targets out of 108 monitoring wells. Apart from these coverage data files, three 2-D scatter data sets, representing aquifer layer elevations, starting head and ground elevations were also developed. This conceptual model could thus be converted into MODFLOW mathematical model for simulation of groundwater flow. A 3D image of the lithology created by using GMS visualization tools is shown at Figure 6.

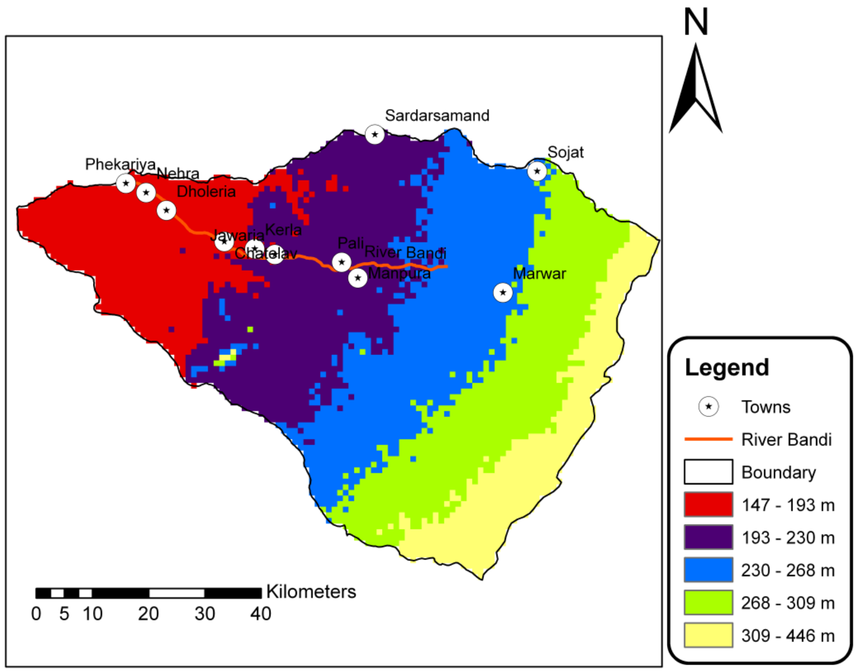

Figure 5. Ground Elevation Map of the study area.

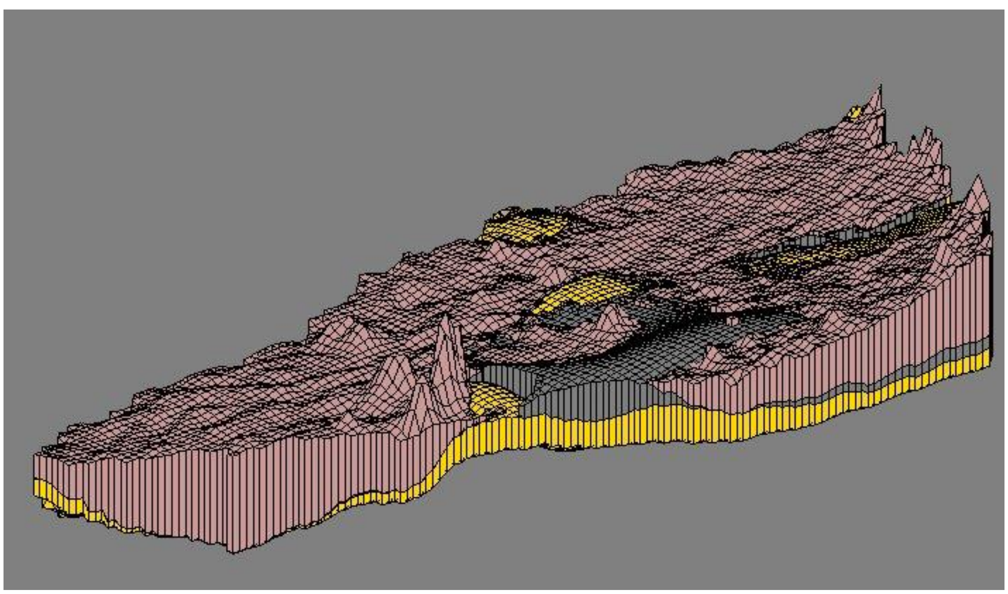

Figure 6. 3D image of the lithology of the study area created by using GMS visualization tools.

CONCLUSION AND PROSPECTIVE

The present study demonstrates a unique methodology for development of conceptual groundwater model in which spatially distributed values for groundwater recharge has been utilized instead of lump sum average values of recharge for the study area obtained by water budgeting method. Further, the study also extensively uses GIS for preprocessing of hydrological, hydrogeological and geological data. In our view the methodology presented here provides better tools for building a conceptual model for tackling groundwater modeling problems. Using various 3- D visualizations tools of the GIS and GMS software, it is possible to create 3-D images of the study area which offer better understanding of the hydrogeology, topography and water table fluctuations of the study area. The study also demonstrated the various simplifications and assumptions which are required to be made for reasonable representation of the actual hydrological and hydrogeological conditions of the study area. The authors are engaged in development of numerical model based on the above conceptual model which is likely to provide fresh insight into the groundwater pollution problem of Pali area.

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