Application of a resistivity survey and geographical information system (GIS) analysis for hydrogeological zoning of a piedmont area, Himalayan foothill region, India

M. Israil · Mufid Al-hadithi · D. C. Singhal

Abstract A Geographical Information System (GIS) has been used for the integration of the results of 70 vertical electrical soundings and hydrogeological data in the piedmont zone of the Himalayan foothills region of Uttaranchal, India. Indian remote sensing (IRS) LISS-III data has been used to prepare thematic maps for the geomorphology and slope maps of the area. The ranges of electrical resistivity values have been assigned to the different formations by calibrating electrical resistivity values with the borehole data. Electrical resistivity, groundwater level monitoring, and borehole and remote sensing data have been integrated in the GIS analysis to delineate the hydrogeological zoning in the study area. Suitable weights were assigned to the different features affecting the groundwater potential. The total score for a particular location is translated in terms of groundwater potential of the area. The results indicate that the southern part of the study area has a very good groundwater potential for meeting the demand of water for irrigation and domestic purposes whereas the steeply sloping area in the northern part, having high relief, has a poor groundwater potential. The resulting delineation of groundwater potential zones are in general agreement with the available yield data of the tube wells.

Résumé Un système d'information géographique (SIG) a été utilisé pour l'intégration de résultats en provenance de 70 sondages électriques et données hydrogéologiques dans la zone de piedmont, au pied de l'Himalaya dans la région de Uttaranchal en Inde. Des données du satellite IRS LISS-III ont été utilisées pour préparer des cartes thématiques sur la géomorphologie et les pentes de la zone d'étude. Les valeurs de résistivités électriques ont été assignées aux différentes formations en les calibrant sur les données de sondages. La résistivité électrique, la piézométrie, et les données de sondages et de télédétection ont été intégrées dans une analyse par SIG pour délimiter les zones hydrogéologiques de l'aire d'étude. Des poids ont été assignés aux différents éléments affectant le potentiel en eau souterraine. Le résultat final pour une localisation particulière est traduit en terme de potentiel en eau souterraine. Les résultats indiquent que la partie Sud a un potentiel très bon pour la demande en eau domestique et eau d'irrigation, tandis que les zones plus pentues dans la partie Nord, caractérisée par un relief élevé, présente un potentiel assez pauvre. La délinéation globale des zones à différents potentiels s'accorde assez bien avec les données disponibles concernant la capacité des puits.

Resumen Se ha utilizado un Sistema de Información Geográfica (SIG) para la integración de los resultados de 70 sondeos eléctricos verticales y datos hidrogeológicos en la zona piamonte de la región al pie de los Himalaya de Uttaranchal, India. Se han utilizados datos de sensores remotos Indios (IRS) LISS-III para elaborar mapas temáticos de la geomorfología y mapas de pendientes del área. Se han asignado los rangos de valores de resistividad eléctrica a diferentes formaciones mediante la calibración de valores de resistividad eléctrica con datos de barrenos. Se han integrado datos de resistividad eléctrica, monitoreo de niveles de agua subterránea, y barrenos, y datos de sensores remotos mediante un análisis SIG para delimitar la zonificación hidrogeológica del área de estudio. Se asignaron pesos apropiados a las diferentes características que afectan el potencial del agua subterránea. El puntaje total de un lugar particular se ha transformado en términos de potencial de agua subterránea del área. Los resultados indican que la parte sur del área de estudio tiene muy buen potencial de agua subterránea para satisfacer la demanda de agua por riego y uso doméstico mientras que el área de pendientes pronunciadas en la parte norte, de alto relieve, tiene potencial pobre de agua subterránea. La delimitación de zonas potenciales de agua subterránea encaja muy bien con los datos disponibles de rendimiento de pozos entubados.

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Introduction

The rate of withdrawal of groundwater in the piedmont area is increasing continuously due to the increasing pace of population growth accompanied by agricultural and industrial development. Hence, it is essential to locate potential sites for groundwater exploration in the area to meet the increasing water demand for agricultural, domestic and other uses. Viable methodologies for exploration of groundwater need to be developed to assess the aquifers in the piedmont zone of the Himalayan foothill region.

The Himalaya is skirted by an upper piedmont zone along its southern margin and is referred as "*Bhabhar*" in northern India. The lower piedmont zone located farther southward is referred as "*Tarai*". The *Bhabhar* zone presents several difficulties in groundwater exploration and development due to the occurrence of thick deposits of poorly sorted sediments, a deep water table, and the associated drilling problems. Consequently, the cost of developing groundwater in the area is prohibitive and is just sufficient for domestic use.

The Lower Piedmont is separated from the Upper Piedmont by a line of springs in the study area. The lithology of the strata, derived from boreholes, shows the presence of coarse-grained sand, clays, and gravel (boulders and pebbles). Due to the occurrence of interbedded clays the groundwater occurs in confined to semi-confined conditions in the *Tarai* zone. In view of the above-mentioned problems associated with developing groundwater, hydrogeological zoning is essential for obtaining sustainable supplies in the area.

Integrated remote sensing surveys and GIS have been used for evaluating the groundwater occurrence in order to locate artificial recharge zones and identify suitable sites for artificial recharge of groundwater in hard rock terrain (Saraf and Chaudhary 1998; Murthy 2000; Srivastava and Bhattacharya 2000; Obi Reddy et al. 2000; Pratap et al. 2000). These techniques evaluate only the surface hydrogeological features and do not provide reliable data on the subsurface features of the aquifer system. For a better understanding of groundwater conditions in a multi-aquifer system viz. in the piedmont zone, geophysical methods can provide a better estimate of the depth and thickness of the aquifer system. Thus, by integrating the depth information at various points, one may estimate the horizontal extent of the water-bearing formations. By combining the data on the surface hydrogeological features with subsurface information obtained from the geophysical surveys, one may define a more reliable groundwater potential model. Venkateswara Rao and Briz-Kishore (1991) have used the geophysical and hydrogeological methods for the estimating the groundwater potential in arid and semi-arid areas of south India, where more than 80% of the land is underlain by crystalline rocks. They have calculated the groundwater potential by taking the sum of products of weight multiplied by the rating of the parameters which influence the occurrence of groundwater. Edet and Okereke (1997, 2002) used a similar approach for the Oban massif, Nigeria and calculated the groundwater potential in the area. Shahid and Nath (1999) have also used the integration of remote sensing, and electrical sounding data for spatial hydrogeological modeling of a soft rock terrain in the Midnapur District, West Bengal, India. The purpose of the present study is to delineate the groundwater potential in the piedmont zone, situated in the Himalayan foothill region of India, using integrated data on hydrogeology, remote sensing and electrical resistivity integrated with a Geographical Information System (GIS) analysis. The study area is located between latitudes 29° 50' 00" and 30° 11' 21" N and longitudes 77° 54' 19" and 78° 06' 21" E, falling in Ratmau-Pathri Rao watershed (Fig. 1) in Haridwar district of Uttranchal, India, covering an area of about 437 km^2.

Methodology

Remote sensing data is processed using image processing software ERDAS (ERDAS 1997) to enhance Linear Imaging Self-Scanning System (LISS-III) image for interpretation of the hydrogeological features, which in turn are digitized using GIS software (ArcView 3.1) to generate a hydrogeomorphological map of the study area (Fig. 2). A slope map is generated from the elevation contours in the Survey of India (SOI) topographic map on a 1:50,000 scale. Resistivity and thickness of aquifers, resistivity of the unsaturated zone and depth of the clay formation have been delineated from the interpretation of electrical sounding data and by calibrating the resistivity values with the available borehole data.

A contour map of the depth to water level has been prepared using the data recorded from the 21 observation wells for two years 2002 and 2003. The water level data were recorded for each year in two consecutive seasons, pre-monsoon (May) and post-monsoon (October) respectively. The depth to water level map for the post-monsoon (October 2002), prepared with the help of GIS is shown in Fig. 3. Different thematic maps are integrated by assigning suitable weights to the different features affecting the groundwater potential. Finally, a map of groundwater potential zones is prepared on the basis of total scores of different locations in the area by logical reasoning.

The Upper Ganga canal passes through the southern part of the study area (Fig. 1) and is affecting groundwater conditions in its vicinity. Local recharge from the canal results in more or less saturation in the bank. Environmental tritium and oxygen-18 isotopes studies reveal that the canal acts as a source of local recharge in an elongated zone about 5 km wide all along its length. It has been estimated that the Upper Ganga canal contributes 27 % of the total recharge to the shallow aquifer at a site located about 2 km from the canal (Someshwar Rao et al. 2002).

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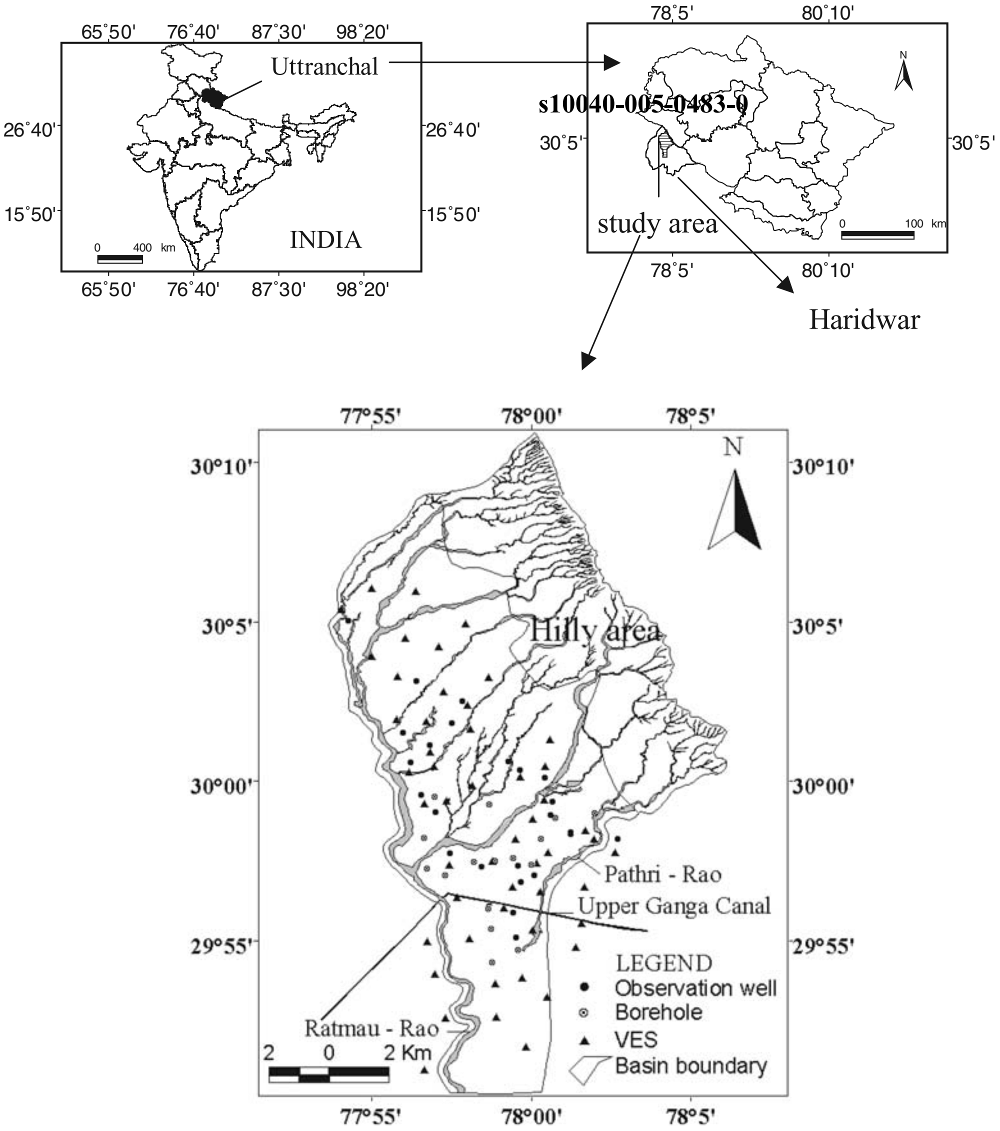

Fig. 1 Location map of the study area showing observation wells, boreholes and Vertical Electrical Sounding (VES) points

GIS based data generation and analysis

An integrated geographic database, consisting of spatial and two-dimensional data, has been generated for the study area. The spatial data consists of thematic maps generated from topographic maps and remote sensing data while the two-dimensional data is derived primarily from ground checking during field survey and from the available literature. These data have been stored in the GIS databank.

Based on hydrogeological characteristics, the area is classified into four geomorphic units. The geomorphic boundaries are digitized on the enhanced image through GIS and used to generate the hydrogeomorphological map is shown in Fig. 2. The Upper Piedmont zone (covering 194 km^2 of the area) also known as *Bhabhar*, bordering the Siwalik hill on the northeast side of the area, is comprised of unconsolidated coarse material. From a groundwater point of view this belt provides an excellent area for recharge and infiltration. The monitored depth to groundwater level in this unit varies from 11 to 29 m and groundwater prospects in this belt are good. The Lower Piedmont (*Tarai*), covering about 107 km^2 of the area, is separated from the Upper Piedmont (*Bhabhar*) by the spring line (Fig. 2). The aquifers are under confined to semi-confined conditions, with monitored piezometric levels in this unit ranging from 2 to 7 m below the ground surface, and the groundwater prospects are very good.

Topographic information has been collected from the Survey of India (SOI), topographic sheet on a 1:50,000 scale and a Triangulated Irregular Network (TIN) has been generated from topographic contours (20 m interval) and spot elevations. A slope percent map has been generated from the TIN data. Nearly 40% of the total area has slopes of 0–1%. The steep slopes (more than 10%) are found in the northern and northeastern parts of the *Bhabhar* zone.

Twenty one observation wells, shown in Fig. 1, have been used to monitor the depth to groundwater level in the study area for the years 2002 and 2003. Each year groundwater levels have been monitored in two seasons, pre-monsoon (May) and post-monsoon (October) respectively. The depth

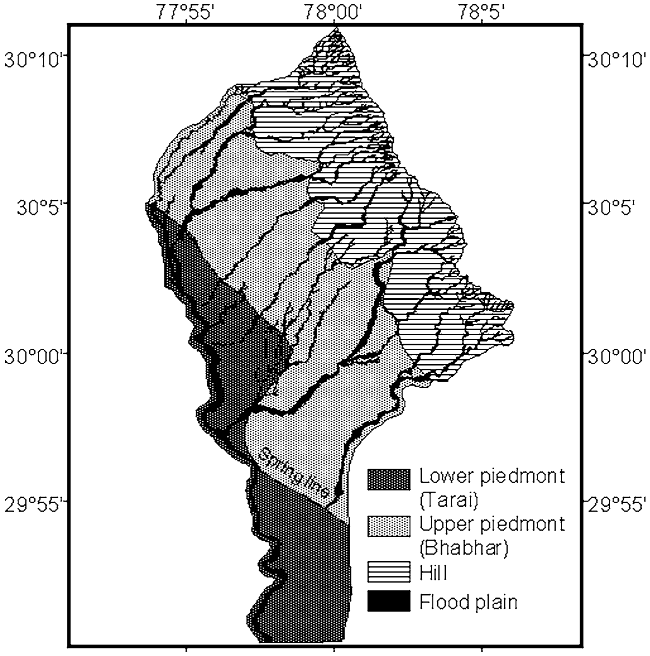

Fig. 2 Hydrogeomorphology of the area

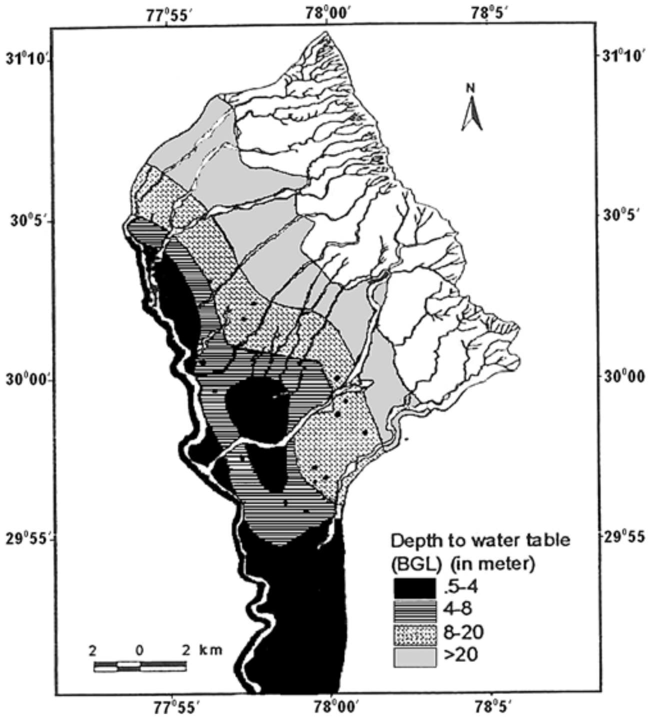

Fig. 3 Map of depth to groundwater level (bgl). Black dots show the locations of observation wells

to groundwater level maps have been generated using ArcView (3.1 version) software for pre-monsoon (pre-rainy season) and the post-monsoon (post-rainy season) respectively. Figure 3 shows an example of the thematic map showing the water level depth for the post-monsoon of 2002. The water level fluctuation between pre-monsoon and post-monsoon in 2002, varies in the range of 1.51–2.20 m and 0.80 -1.09 m in the *Tarai* and *Bhabhar* zones respectively. Whereas, it is 1.20–2.0 m and 0.50–0.95 m in the *Tarai* and *Bhabhar* zones respectively in 2003.

Resistivity data collection and interpretation

To delineate the detailed aquifer geometry, Vertical Electrical Soundings (VES) at 70 sites (Fig. 1) were recorded using the Schlumberger configuration (Zhdanov and Keller 1994) with maximum electrode spacing of about 900 m and the recordings were made at station intervals of about 2 km and less. The electrode spacing is sufficient to provide information about the resistivity variation near the surface and deeper than 100 m, which is capable of delineating the shallow and deeper aquifer system. To study the directional behavior of resistivity variation, the data are also collected in the perpendicular direction at the same point. An automatic computerized interpretation method (Zohdy 1989) has been used to obtain true resistivity and depth from the measured apparent resistivity data at each site. The program generates a large number of layers for each sounding data set. Some of these layers may be geologically irrelevant. To reduce the number of layers an edge-preserving and smoothing technique (Israil et al. 2004) is applied. The layer reduction method is based on a recent technique introduced for the noise reduction applied to the seismic data (Luo et al. 2002). The technique looks for the most homogenous fragment around each point in the model parameters (resistivity and depth) set and assigns the average value of the selected fragment to that parameter. This may be explained by considering the following five-point edge-preserving smoothing (EPS) operator. For any depth location at index *i*, one first calculates standard deviations for five shifted windows given by:

- Window 1: $(R_{i-4}, R_{i-3}, R_{i-2}, R_{i-1}, R_{i+0})$,
- Window 2: $(R_{i-3}, R_{i-2}, R_{i-1}, R_{i+0}, R_{i+1})$,
- Window 3: $(R_{i-2}, R_{i-1}, R_{i+0}, R_{i+1}, R_{i+2})$,
- Window 4: $(R_{i-1}, R_{i+0}, R_{i+1}, R_{i+2}, R_{i+3})$,
- Window 5: $(R_{i-0}, R_{i+1}, R_{i+2}, R_{i+3}, R_{i+4})$,

Here, R_i represents the resistivity of the *i*th layer of the model obtained using Zohdy's resistivity interpretation method. Next, one selects the window that has the minimum standard deviation, calculates the average over the selected window, and assigns the average as final value for the *i*th layer resistivity. Repeating this process for all layer resistivity values will yield the final model. The technique has been applied to eliminate the irrelevant layer in the resistivity depth model.

For the geological interpretation, the resistivity values are calibrated with the known lithology from available borehole data in the study area. The lithological correlation of resistivity values obtained from the interpretation of measured apparent resistivity on one site in the *Bhabhar* zone is shown in Fig. 4. The resistivity of the top unsaturated zone varies in the range of 128 – 424 ohm-m. The water table is indicated by the resistivity of 26 ohm-m at the depth of 15 m bgl. The depth to water level recorded at this

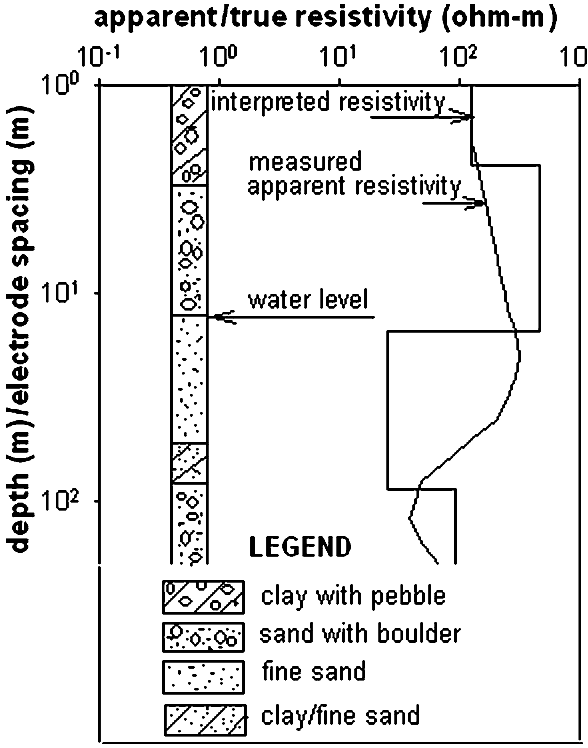

Fig. 4 Lithological correlation of resistivity data at a site in the *Bhabhar* zone

site is 13 m. Therefore, the shallow aquifer is represented by a resistivity of 26 ohm-m. The deeper aquifer is represented by the resistivity of 74 ohm-m at a depth below 67 m bgl. Thus the resistivity data is capable of delineating the aquifer system. Such resistivity–lithology correlations at different sites in the study area were used for defining the resistivity ranges for various lithological units such as the saturated and unsaturated zones, clay units and resistivity of the shallow and deeper aquifers.

The resistivity of the unsaturated zone generally varies in the range of 90–500 ohm-m in the *Bhabhar* zone. However, in the places where the boulders are exposed near or on the surface, the resistivity of the near surface layer reaches 1000 ohm-m. The thickness of the unsaturated layer extends up to 30 m in the *Bahbhar* zone. The wide range in resistivity of the unsaturated layer suggests existence of varying percentages of boulders and pebbles in the formation. The resistivity of the near surface layer in the *Tarai* zone varies in the range of 10–170 ohm-m. The low resistivity (10 ohm-m)) of the near surface layer in the *Tarai* zone indicates the presence of clay. The shallow aquifer in the *Bhabhar* zone is represented by resistivity values in the range of 25–170 ohm-m, whereas in the *Tarai* zone it is 20–80 ohm-m. The detailed resistivity variation of the shallow aquifer zone is shown in Fig. 5. The variation of the shallow aquifer thickness in the study area is shown in Fig. 6. The maximum thickness of the aquifer is observed in the *Tarai* zone which gradually decreases towards the *Bahbhar* zone in the northeastern and western parts (Fig. 6). The presence of clay interbeds indicates that the groundwater occurs in confined, semi-confined and unconfined conditions.

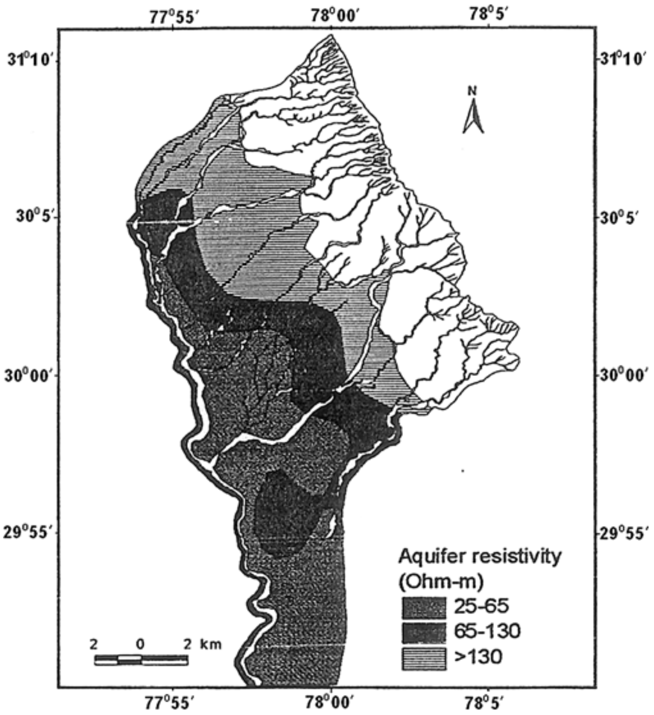

Fig. 5 Resistivity of the shallow aquifer

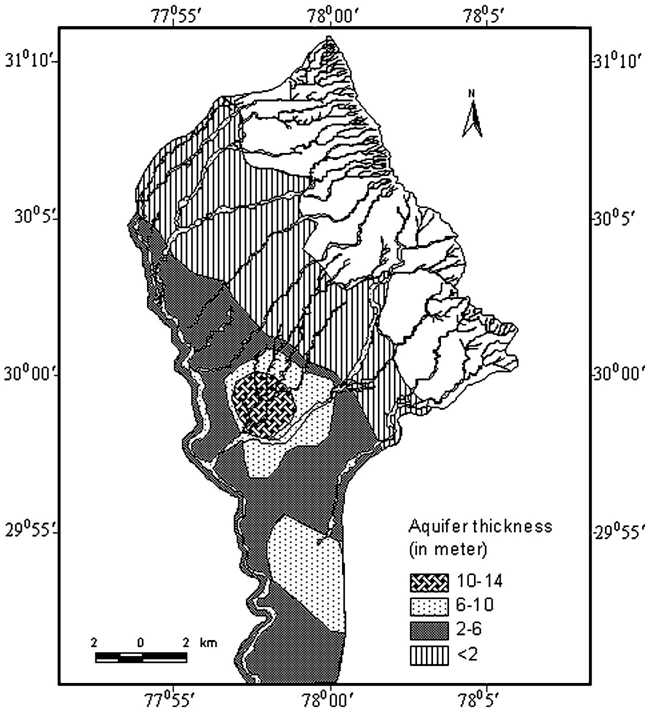

Fig. 6 Thickness of the shallow aquifer in the area

The resistivity of the clay layers varies in the range of 10–20 ohm-m in the *Tarai* zone, which reaches 37 ohm-m in the *Bhabhar* zone. The increase in resistivity of the clay layers in the *Bhabhar* zone indicates the occurrence of varying percentages of kankar (small size boulders) in the clay.

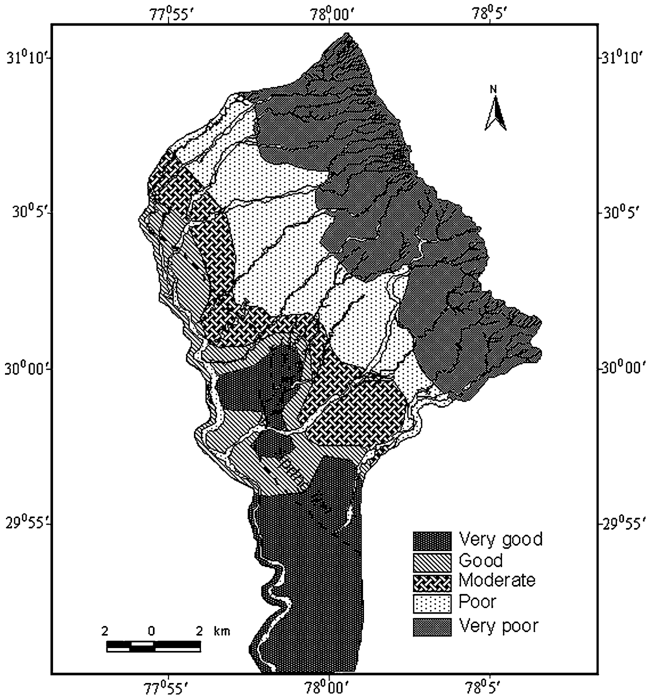

Fig. 7 Groundwater potential map of the area

Integration of GIS and results

The hydrogeological properties are assigned different weights based on their influence on the groundwater potential. Different units in each theme are assigned ranks from 1 to 4 on the basis of their importance with reference to their groundwater potential. The final score of each unit of a theme is equal to the product of rank multiplied by respective weight. The classification of these weights and rank of each theme and unit are shown in Table 1. The thematic maps are overlaid step by step to generate a composite map of the area. The groundwater potential for each zone has been defined on the basis of the total score of various themes. Thus the entire area is qualitatively divided into five different groundwater potential zones namely very good (greater than 16), good (12–16), moderate (8–12), poor (4–8) and very poor (less than 4). These zones are shown in a thematic map in Fig. 7, which shows that the groundwater potential in the northern part of the study area (covering about 134 km^2 of the area) is very poor, due to the very steep slopes and the resulting low infiltration and rapid runoff. In the middle part the groundwater potential is moderate to good (covering 110 km^2 of the area). The southern part of the study area, covering 87 km^2, has a very good groundwater potential. The remaining area, about 99 km^2, has poor groundwater potential. The generated groundwater potential map is validated from the yield data obtained from tube wells located in the different groundwater potential zones. A well in a zone of moderate to very good yield will have a discharge of 120–250 m^3/h while in a moderate to good zone it is expected to be of the order of 60–225 m^3/h.

Table 1 Rank, weights and scores of properties for various themes with respect to groundwater potential

Theme	Weight	Classes	Rank	Score
Hydrogeomorphology	5	Lower Piedmont	4	20
		Upper Piedmont	2	10
		Hill	1	5
Depth of clay unit (meter)	4	1–7	4	16
		7–20	3	12
		20–25	2	8
		>25	1	4
Depth to water table (meter)	4	0.5–4	4	16
		4–8	3	12
		8–20	2	8
		>20	1	4
Aquifer thickness (meter)	3	>10 m	4	12
		6–10	3	9
		2–6	2	6
		<2	1	3
Slope percent	2	0–1	4	8
		1–5	3	6
		5–10	2	4
		>10	1	2
Resistivity of unsaturated zone (ohm-m)	1	>600	4	4
		400–600	3	3
		250–400	2	2
		20–250	1	1
Resistivity of aquifer (ohm-m)	1	>130	3	3
		65–130	2	2
		25–65	1	1

Conclusions

Integrated hydrogeological, electrical resistivity and GIS techniques have been used to interpret the hydrogeological zoning in relation to the groundwater potential evaluation in the piedmont zone of the Himalayan foothills region, India. Electrical resistivity data have provided the estimation of aquifer depth, resistivity, unsaturated zone resistivity and depth to clay units. Integration of resistivity data along with the other surface and subsurface hydrogeological information, using a weighted method in the GIS analysis, has shown that locations which score more than 16 are considered to have a very good groundwater potential whereas locations with scores generally less than 4 have poor groundwater potential. The interpreted distribution in space of groundwater potential is in general agreement with the yield data of existing tube wells in the study area.

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References

Edet AE, Okereke CS (1997) Assessment of hydrogeological conditions in basement aquifers of the Precambrian Oban massif, southeastern Nigeria. J Appl Geophys 36:195–204

Edet AE, Okereke CS (2002) Delineation of shallow groundwater aquifer in the coastal plain sands of Calabar area (Southern Nigeria) using surface resistivity and hydrogeological data. J African Earth Sci 35:433–443

ERDAS (1997) ERDAS Imagine, Tour Guides. ERDAS, Inc., Atlanta, USA, 454 p

Israil M, Pravin K, Gupta Tyagi DK (2004) Determining sharp layer boundaries from straightforward inversion of resistivity sounding data. J Indian Geophys Union 8(2):125–133

Luo, Y, Maher Marhoon, Saleh AI Dossary, Mohammed Alfaraj (2002) Edge-preserving smoothing and applications. Leading Edge February 136–158

Murthy KSR (2000) Groundwater potential in a semi-arid region of Andhra Pradesh: A geographical information System approach. Int J Remote Sens 21(9):1867–1884

Obi Reddy GP, Chandra Mouli K, Srivastav SK, Srinivas CV, Maji AK (2000) Evaluation of groundwater potential zones using remote sensing data- A case study of Gaimukh watershed, Bhandara district, Maharashtra. J Indian Soc Remote Sens 28(1):19–32

Pratap Kamleshwar, Ravindran KV, Prabakaran B (2000) Groundwater prospect zoning using remote sensing and Geographical Information System: A case study in Dala-Renukoot Area, Sonbhadra District Uttar Pradesh. J Indian Soc Remote Sens 28(4):249–263

Saraf AK, Chaudhary PR (1998) Integrated remote sensing and GIS for groundwater exploration and identification of artificial recharges sites. Int J Remote Sens 19(10):1825–1841

Shahid S, Nath SK (1999) GIS Integration of remote sensing and electrical sounding data for hydrogeological exploration. J Spat Hydrol 2(1):1–12

Someshwar Rao M, Bhism Kumar, Singh UK, Nachiappan RP, Jagmohan (2002) Exploring recharge sources and zones for deeper aquifers using environmental isotopes: A case study. Proceeding of Int. conference on Water resources management in arid region(WARMAR), pp 61–76

Srivastava PK, Bhattacharya AK (2000) Delineation of groundwater potential zones in a hard rock terrain of Bargarh District, Orissa using IRS data. J Indian Soc Remote Sens 28(2/3):129–140

Venkateswara Rao B, Briz- Kishore BH (1991) A methodology for locating potential aquifers in a typical semi- arid region in India using resistivity and hydrogeological parameters. Geoexploration 27:55–64

Zhdanov MS, Keller GV (1994) The geoelectrical methods in geophysical exploration. Elsevier, Amsterdam

Zohdy AAR (1989) New method for automatic interpretation of Schlumberger and Wenner sounding curve. Geophysics 54(2):245–253

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