24. Kuenen, P. H., Experiments in geology. *Trans. Geol. Soc. Glasgow*, 1958, **23**, 1–28.
25. Lowe, D. R., Subaqueous liquefied and fluidized sediment flows and their deposits. *Sedimentology*, 1976, **23**, 285–308.
26. Collinson, J., Sedimentary deformation structures. In *The Geological Deformation of Sediments* (ed. Maltman, A.), Chapman and Hall, London, 1994, pp. 95–125.
27. Chakraborty, A., Upward flow and convolute lamination. *Senckenbergiana Marit*., 1977, **9**, 285–305.
28. Allen, J. R. L., The possible mechanics of convolute lamination in graded beds. *J. Geol. Soc. London*, 1977, **134**, 19–31.
29. Hildebrandt, C. and Egenhoff, S., Shallow marine massive sandstone sheets as indicators of palaeoseismic liquefaction – an example from the Ordovician shelf of Central Bolivia. *Sediment. Geol.*, 2007, **202**, 581–595.
30. Cojan, I. and Thiry, M., Seismically induced deformation structures in Oligocene shallow marine and eolian coastal sands (Paris basin). *Tectonophysics*, 1992, **206**, 79–89.
31. Visher, G. S. and Cunningham, R. D., Convolute laminations; a theoretical analysis; example of a Pennsylvanian sandstone. *Sediment. Geol*., 1981, **28**, 175–188.
32. Elliot, R. E., A classification of subaqueous sedimentary structures based on rheological and kinematical parameters. *Sedimentology*, 1965, **5**, 193–209.
33. Owen, G., Soft sediments deformation in Upper Proterozoic Torridonian Sandstones (Applecross Formation) at Torridonian, northwest Scotland. *J. Sediment. Res.*, 1995, **A65**, 495–504.
34. Sorauf, J. E., Flow rolls of Upper Devonian rocks of south-central New York state. *J. Sediment. Petrol.*, 1965, **35**, 553–563.
35. Davies, N. S., Turner, P. and Sansom, I. J., Soft-sediment deformation structures in the Late Silurian Stubdal Formation: the result of seismic triggering. *Norwegian J. Geol.*, 2004, **85**, 233–243.
36. Foix, N., Paredes, J. M. and Giacosa, R. E., Paleo-earthquake in passive-margin settings, an example from the Paleocene of the Golfo San Jorge, Basin, Argentina. *Sediment. Geol.*, 2008, doi:10.1016/j.edgeo.008.
37. Owen, G. and Moretti, M., Determining the origin of soft-sediment deformation structures: a case study from Upper Carboniferous delta deposits in south-west Wales, UK. *Terra Nova*, 2008, **20**, 237–245.
38. Rossetti, D. F. and Góes, A. M., Deciphering the sedimentological imprint of paleoseismic events: an example from the Aptian Codó Formation, northern Brazil. *Sediment. Geol*., 2000, **135**, 137–156.
39. Raj, R., Mulchandani, N., Bhandari, S., Maurya, D. M. and Chamyal, L. S., Evidence of a Mid–Late Holocene seismic event from Dhadhar river basin, Gujarat alluvial plain, western India, *Curr. Sci*., 2003, **85**, 812–815.
40. Einsele, G., Chough, S. K. and Shiki, T., Depositional events and their records – an introduction. *Sediment. Geol*., 1996, **104**, 1–9.

ACKNOWLEDGEMENTS. We are grateful to the Director, Wadia Institute of Himalayan Geology, Dehra Dun and the Principal, DBS (PG) College, Dehra Dun, for constant encouragement and providing necessary facilities.

Received 5 January 2008; revised accepted 23 December 2009

Quantitative hydrogeological and geomorphological analyses for groundwater potential assessment in hard rock terrains

P. N. Ballukraya[1,]* and R. Kalimuthu[2]

[1]Department of Applied Geology, University of Madras, Chennai 600 025, India
[2]Tamil Nadu Water Supply and Drainage Board, Chennai 600 005, India

Hydrogeological and geomorphological parameters have been quantitatively correlated with groundwater availability. Weathered rock thickness has the highest control on availability of groundwater followed by lineament density whereas drainage density is seen to have minimum influence. A poor correlation is noticed between borewell depth and yield. The amplitude of seasonal variations in groundwater levels is noted to be higher in the low lying plains compared to the hilly regions. The groundwater potential zonation map, prepared using data merging techniques and assigning weightages based on the quantitative analyses of parameters on a GIS platform shows that more than 45% of borewells falling in the area under the category of excellent water availability are high-yielding.

Keywords: Geomorphology, groundwater potential zonation maps, hard rock hydrogeology, quantitative analysis.

QUANTITATIVE availability and chemical quality of groundwater is influenced by various natural environments such as geology, topography and geomorphology apart from anthropogenic factors. Rock type, rock structure, presence and density of fractures, joints and lineaments, degree and extent of weathering, landforms types, drainage density, soil type and land cover are some of the generally used parameters in deciding the suitability of an area for groundwater development[1]. In most groundwater development projects, these parameters are considered and groundwater potential zonation maps prepared by assigning weightages and merging them on a geographic information system (GIS) platform[2–4]. However, the individual weightages of each of the parameters (themes) are assigned based on general perceptions rather than a quantitative analysis of these parameters. Subba Rao[5] has used quantitative methods of characterizing hydrogeomorphological parameters to identify recharge sites in hard rock areas. The present study is an attempt to understand the extent of geological and geomorphic controls on the availability of groundwater, in an area underlain by hard crystalline rock formations.

The upper Swetha watershed, forming part of the Vellar river basin is located partly in the Namakkal and

*For correspondence. (e-mail: ballukraya@hotmail.com)

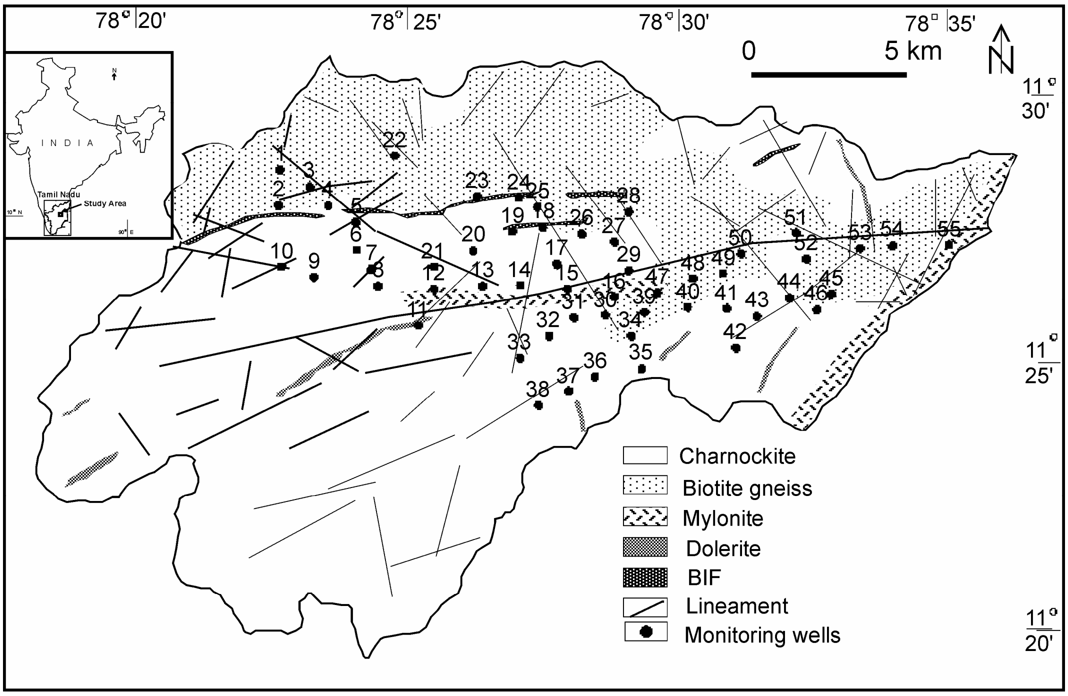

Figure 1. Geological map of the study area showing location of monitoring wells.

Table 1. Landform classification of the study area

Geomorphic unit	Structural hill	Residual hill	Inselberg	Pediment	Shallow buried pediment	Deep buried pediment	Valley fill
Area covered (sq. km)	170	15.5	1.5	86	18	75	2
% area covered	46.2	4.0	0.45	23.4	4.9	20.5	0.55

partly in Salem district of Tamil Nadu (11°19′25″N to 11°30′45″N and 78°17′30″E to 78°36′15″E). The study area forms a compact groundwater basin, in that it is bounded by topographic highs along most of its boundary (Figure 1). The Kollimalai hills (housing the famed hill resort), a part of the Eastern Ghat hills, occupies about 31% of the study area, which is about 368 sq. km in extent.

The upper Swetha watershed is topographically a rugged terrain, with nearly one half (187 sq. km) of the area occupied by hills. The central and eastern parts of the area (181 sq. km) are mainly low-lying plains. The Swetha river is the principal drainage and is an ephemeral stream with flows during October–January period. The geomorphological mapping of the area was done with the help of satellite imageries (IRS 1B LISS II, April 1992) and aerial photographs and also limited field checks, using the integrated mission for sustainable development (IMSD) guidelines[6]. The area consists of landforms such as structural and residual hills, pediments and valley fills along with a few water bodies. Table 1 details the results of the landform analysis carried out as stated here. The drainage pattern is mostly dendritic to sub-parallel with radial and trellis pattern dominant in the hilly regions. The drainage density varies from 4.8 km/sq. km in the hills to 0.2 km/sq. km in the plains. Annual rainfall is 844 mm with about 50 rainy days (70-year average). The area enjoys a sub-tropical climate with moderate humidity (49–68%) and temperature (min: 11°C; max: 42°C).

Charnockitic rocks, occupying majority of the hills mostly (66%) underlie the area (Figure 1). The foliation trend varies from place to place due to complex structural pattern observed here. Hornblende–biotite gneiss underlies about 29% of the area, mostly in the plains. Banded iron formations occur as narrow linear bands, striking east west to ENE–WSW, with steep dips in several places. A few bands of pyroxene granulites are also found in the northeastern areas. Dykes (dolerite) and veins (quartz, pegmatite) also occur sporadically in many places. Most of the sub-basin, except for the hilly terrains is covered by weathered rock of varying thickness.

Well-developed joints are noticed in the area, which can be broadly divided into four sets, viz. N–S, E–W, NE–SW and NW–SE based on their trend. Structurally the entire area falls in the Attur valley, which is part of the Bhavani–Athur mega-lineament. Lineaments are considered important in the occurrence and movement of groundwater, particularly in areas underlain by crystalline rocks[7,8]. In the study area, lineament mapping was carried out from the satellite imageries and aerial photographs using the methodology proposed by Mabee *et al.*[9] which consists of three steps, viz. collection of lineament data using multiple observers and multiple data; reproducibility tests and domain overlap analysis. A total of 78 lineaments were identified, of which five are more than 5 km long (Figure 1). The lineament density (cumulative length of lineaments per unit area) varies from 0.5 to 2.52 km/sq. km.

The area has a fairly high density of water wells, particularly in the plains. Both dug wells and borewells are popular in the area. Rectangular dug wells are the most common irrigation-water abstraction structures, with a depth range of 15–35 m. The density of dug wells varies from 12 to 25 per sq. km in the plains. Ninety-six irrigation and 357 drinking water borewells were also inventoried in the area for this study. The depth of these borewells varies from 50 to 170 m (Figure 2). The average depth of the borewells has been increasing over the years from 62 m in 1976 to 140 m in 2000. The yield of these borewells varies from very low to a maximum of 400 litres per min (lpm), with the average of 25 lpm for the borewells drilled during the period 1970–80 to 70 lpm for those drilled during the period 1996–2000. However, there is no relationship between well depth and yield in these borewells as indicated by an insignificantly low-correlation coefficient of only 0.02, though if borewells drilled in any particular year are considered, the correlation coefficient is found to be in the range of –0.57–1.0. This wide variation is probably due to the fact that most of the water is obtained from fracture aquifers which may or may not be encountered in borewells uniformly.

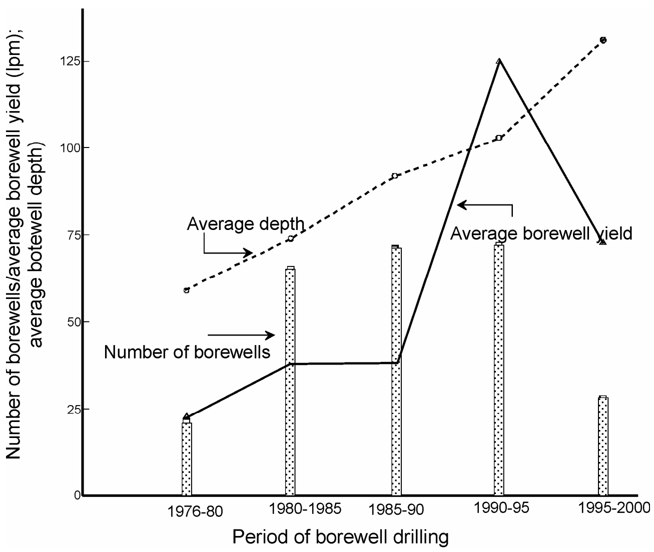

Figure 2. Progressive changes in groundwater development in the study area.

A network of 55 dug wells, all tapping the weathered rock zone, was set up in the area (Figure 1) for monitoring the groundwater levels twice a year, in the months of July and January (pre- and post-recharge) during the period July 1997 to January 2000. In addition, monthly groundwater levels were also monitored in 20 selected wells during January 1999 and January 2000 to study seasonal fluctuations. Figure 3 shows the groundwater levels prevailing in the area during July 1999 and January 2000. Two prominent groundwater troughs, in the central part of the area can be seen along with two groundwater mounds reflecting the state of groundwater development in the area.

Groundwater level fluctuation is comparatively more in the area of the troughs (6–9 m) as compared to other places (4–5 m). The hydraulic gradient generally follows the topography and is steeper on the western side (slope = 0.133) as compared to the eastern parts (slope = 0.042). The monthly water levels show that September is the period in which the groundwater levels reach their lowest while in January they are at their shallowest. This is the result of adequate recharge following rains during October–December months. Figure 4 shows the average ground-

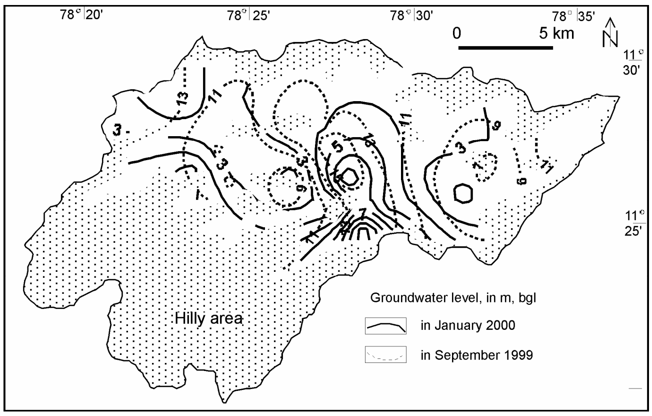

Figure 3. Groundwater levels in the study area.

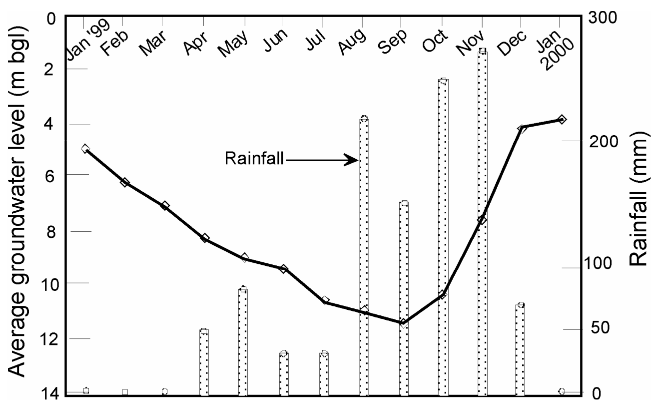

Figure 4. Seasonal rainfall and groundwater level fluctuation in the study area.

Table 2. Quantitative analysis of borewell yields and geomorphic and geological parameters

Parameters	Number of borewells	Average yield (lpm)	Percentage of borewells yielding (lpm)		
			<10	10–50	>50
Landform					
Pediment	107	47	25	52	22
Shallow buried pediment	68	61	15	62	23
Deep buried pediment	179	83	13	55	32
Land use					
Dry crop	202	54	24	52	24
Wet crop	91	95	15	44	41
Ground slope					
<1%	162	77	8	64	28
1–3%	133	62	25	45	30
>3%	44	36	30	52	18
Lithology					
Biotite gneiss	178	78	17	49	34
Charnockite	141	54	17	62	21
Thickness of weathered rock					
<5 m	68	47	29	59	12
5–10 m	182	63	16	55	29
>10 m	82	83	10	49	41
Proximity to lineaments					
Borewells on or close to lineament	70	89	17	43	40
<250 m from lineaments	92	60	14	59	26
250–500 m	77	61	22	52	26
>500 m from lineaments	114	63	16	62	22
Lineament density (km/sq. km)					
<0.5	95	59	19	61	20
0.5–1.5	200	64	20	53	27
>1.5	33	110	10	45	45

water levels (of all the 20 wells) during the period January 1999–January 2000, along with monthly rainfall in the area. It is seen that the declining trend of the groundwater level is reversed only from September, when it starts to rise, continuing this trend till January. The rate of decline in the water levels from January onwards is not uniform, the slope being gentlest during July–September period, which reflects the recharge–discharge conditions prevailing at the time. Though August received substantial rainfall, there was no rise in water levels till October, due to the time taken for the infiltrating waters to reach the water table and/or heavy withdrawal of groundwater for irrigation during the period.

A quantitative analysis was carried out taking into account various parameters and the yield of borewells in the area. The results are given in Table 2. For the purpose of convenience, the borewells were grouped into three categories: those yielding less than 10 lpm; 11–50 lpm and more than 50 lpm. This has brought out several interesting features in relation to the well yields and the geohydrological parameters.

Rock type as well as extent of weathering is an important consideration in availability of groundwater. Borewells located in areas underlain by gneissic rocks have significantly higher yield as compared to charnockites; the percentage of high-yielding wells also is more in areas underlain by gneissic rocks. The thickness of weathering appears to have considerable influence on groundwater availability since the average yield of borewells in areas with thicker weathered rock is nearly double that of zones with less than 5 m of weathered rock thickness. The percentage of high-yielding wells also follows the same trend. However, it is to be noted that most of the groundwater yield in the borewells is from the deep seated fractures in the bedrock rather than the weathered rock zone itself.

Lineaments are generally associated with zones of higher weathering/fracturing and thus considered to be potential sites for locating high-yielding wells[1,8,9]. Superposition of the borewells on the lineament map of the study area (Figure 5) however shows that this is not really the case in this area in that borewells along any given lineament are of all yield ranges from low-yielding to high-yielding. Also, there are several high-yielding wells in areas without any lineaments. An analysis shows that while 40% of borewells located on or very close to the lineaments are high-yielding (>50 lpm), 17% of borewells in the same zone are low-yielding. Also, 22% of borewells located 500 m or more away from lineaments are high-yielding. If lineament density (cumulative length of lineaments in unit area) is considered, 45% of borewells are high-yielding in zones having a density of more than 1.5 km^{-1}, though a significant 20% of wells located in low density areas are also high-yielding.

Geomorphological analysis shows that deep buried pediments (with thick regolith cover) have relatively better groundwater potential with an average well yield of 83 lpm per borewell as compared to pediments wherein the average yield is only 47 lpm. The borewells in wet crop areas yield significantly more than those in dry crop areas. Areas with flat topography are also seen to be having better groundwater potential compared to undulating topography.

The individual hydrogeological and geomorphic parameters can be merged to get a single groundwater potential map of the area after assigning appropriate weightages to individual parameters. From Table 2, the ratios of the highest average yield to the lowest average yield as well as percentage of high-yielding wells in different categories are considered and their average is taken as the contribution of the parameter to well yield. For example, in the case of landform, the ratio of average yield of deep buried pediment (83 lpm) to pediment (47 lpm) is 1.8 and that of percentage of high-yielding wells is 1.5 (32/22). The average of these two values is 1.65, which is taken as the significance of this particular parameter. Thus the ratios obtained for other parameters are: ground slope – 1.85; lithology – 1.5; land use – 1.75; weathered thickness – 2.6; proximity to lineament – 1.65; lineament density – 2.1 and drainage density – 1.05. The minimum and maximum values thus are 1.05 and 2.6, which are then reclassified into five categories (Table 3). Weathered rock thickness has the maximum ratio of 2.6 and thus gets the highest maximum weightage of 5 whereas drainage density has the lowest ratio of 1.05 so its maximum weightage is 1. The weightages for different classes within one parameter are distributed depending on the number of classes and its range of weightages. Thus, in deep buried pediment area having weathered rock thickness of more than 20 m, ground slope of less than 0.011, underlain by granitic gneisses, having wet crop, located very close to a lineament and with highest lineament density will score the maximum cumulative weight, of 2 + 5 + 3 + 2 + 3 + 2 + 4 = 21. Drainage density is ignored as it apparently does not have any significance in this area. The weightages thus arrived at are given in Table 4. The result of such a data merging exercise, carried out on GIS platform is shown in Figure 6, wherein the entire area has been divided into five categories (poor, moderate, good, very good and excellent yielding zones with cumulative weightages of <5, 5.1–9, 9.1–13, 13.1–17 and >17) from the viewpoint of groundwater potential. This zonation map is then validated by superimposing the existing borewells (as various yield classes) on it and checking for their correspondence. From an analysis of the results of this exercise, it is seen that only 12% of borewells located in the zone earmarked as 'moderate' are high-yielding while 41% of the wells are high-yielding in the area categorized as 'excellent'. Similarly, 60% of wells are poor-yielding in the area marked as 'poor' while only 15% of borewells in this zone are high-yielding (Table 5). The results can be further refined by calibrating the model so as to get the best comparison between the actual field results in the various potential zones by slight modification of the weightages assigned to individual parameters.

The study reveals that geomorphic and geological factors control the availability of groundwater to a significant extent. Fluctuations in groundwater levels have greater amplitudes in deep buried pediments than in shallow pediments which is probably due to the fact that the thickness of productive aquifer zone is much more in deep pediments, leading to construction of deeper wells, resulting in a larger quantity of groundwater being abstracted and consequently greater lowering in water levels. Borewells located in the deep buried pediments are seen to be more successful than in pediment zones. Considering the fact that almost the entire yield in a borewell comes from deep fracture aquifers present in the unweathered bedrock, it is inferred that a thicker regolith develops in an area where the rocks are highly fractured and jointed and which extend to much deeper levels, thus creating conditions favourable for accumulation of

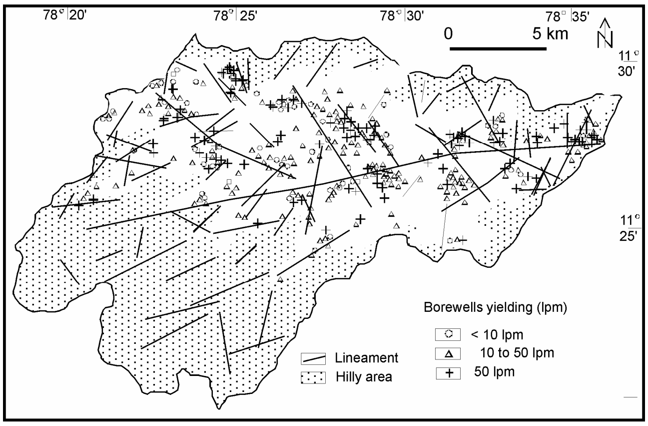

Figure 5. Yielding pattern of borewells and lineaments.

Table 3. Range of ratios and weightages for the five zones

Weightage	Ratio range	Classification
1	1.05–1.36	Poor
2	1.361–1.67	Moderate
3	1.671–1.98	Good
4	1.981–2.29	Very good
5	2.291–2.6	Excellent

Table 4. Assignment of weightages for various themes and classes

Parameter	Ratio (high/low)	Weightage range	Category	Weightage
Landform	1.65	1 to 2	Hills, inselbergs	1.0
			Pediment	1.33
			Shallow pediment	1.66
			Deep pediment and valley fills	2.0
Weathering	2.6	1 to 5	<5 m	1
			5–10 m	2
			10.1–15 m	3
			15.1–20 m	4
			>20 m	5
Land use	1.65	1 to 2	Dry crop	1
			Wet crop	3
Ground slope	1.85	1 to 3	<0.011	3
			0.012–0.033	2
			>0.033	1
Lithology	1.5	1 to 2	Charnockite	1
			Biotite gneiss	2
Proximity to lineament	1.65	2	Close to lineament	2
			<250 m	1.65
			251–500 m	1.33
			>500 m	1
Lineament density	2.1	4	<0.5 km^{-1}	1
			0.51–1.50 km^{-1}	2.5
			>1.51 km^{-1}	4

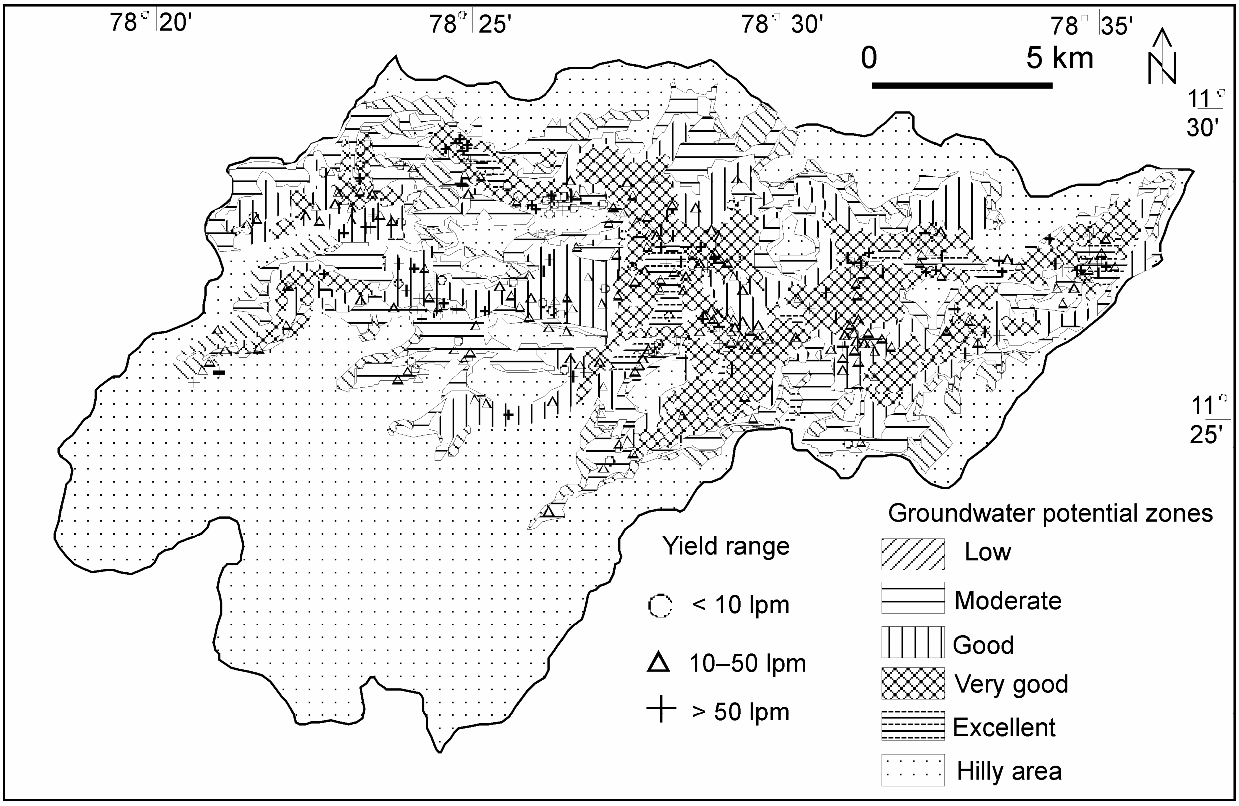

Figure 6. Groundwater zonation map of the study area.

Table 5. Result of analysis of data after merging all parameters

Groundwater potential zones	Percentage of borewells yielding (lpm)		
	<10	10–50	>50
Poor	60	40	0
Moderate	32	56	12
Good	17	52	21
Very good	15	53	32
Excellent	15	44	41

groundwater. This is possibly the reason why a larger percentage of borewells located in the plains are high-yielding than those which are located in areas with steeper ground slopes. The higher average yield in gneissic rocks is mainly due to the fact that they are comparatively more brittle and hence develop higher degree of fracturing and jointing – an essential condition for creation of the secondary porosity and permeability. This is further supported by the fact that wells located in areas with the thicker weathering are more likely to give higher yields, since greater degree of jointing promotes deeper weathering in rocks. Lineaments have been closely identified with water-yielding capacity in hard rocks despite some not-so very encouraging results of in-depth studies with regard to lineaments and groundwater yields[8,10]. In the study area, analysis shows that proximity to and density of lineaments do have some influence on groundwater availability, though not a definitive one. The percentage of high-yielding borewells located close to identified lineaments is nearly double that of wells located far away from them; similar is the result with respect to lineament density as well. However, like in most other geological/geomorphic parameters, there is a significant percentage of high-yielding borewells away from the lineaments as well as low-yielding borewells close to lineaments.

This study demonstrates the importance of quantifying the significance of various geomorphic and geohydrological parameters in groundwater potential assessment investigations. As these parameters individually influence the groundwater availability in an area, a combination of these parameters will be effective in identifying areas with maximum possibility of higher well yields. The zonation map generated using field verified weightages will then form a base map for planning further groundwater development in an area.

1. Krishnamurthy, J. and Srinivas, G., Role of geological and geomorphological factors in groundwater exploration: a study using IRS LISS data. *Int. J. Remote Sensing*, 1995, **16**, 2595–2618.
2. Rokade, V. M., Kundal, P. and Joshi, A. K., Groundwater potential modeling through remote sensing and GIS: a case study from Rajura taluka, Chandrapur district, Maharastra. *J. Geol. Soc. India*, 2007, **69**, 943–948.
3. Prasad, R. K., Mondal, N. C. and Singh, V. S., Evaluation of groundwater resource potential using GIS in Kurampalli watershed of Andhra Pradesh. *J. Geol. Soc. India*, 2008, **71**, 661–669.
4. Akram Javed and Wani, M. H., Delineation of groundwater potential zones in Kakund watershed, Eastern Rajastan, using remote sensing and GIS techniques. *J. Geol. Soc. India*, 2009, **73**, 229–236.
5. Subba Rao, N., A numerical scheme for groundwater development in a watershed basin of basement terrain: a case study. *Hydrogeol. J.* (online), 2008, p. 18.
6. IMSD, Integrated mission for sustainable development, Technical guidelines (unpublished report), National Remote Sensing Agency, Hyderabad, 1995.
7. Banks, D., Rohr-Torp, E. and Skarphagen, H., Groundwater resources in hard rock: experiences from the Havaler study, SE Norway. *Appl. Hydrogeol.*, 1994, **2**, 33–42.
8. Per Sander, Minor, T. B. and Chesley, M. M., Ground-water exploration based on lineament analysis and reproducibility tests. *Groundwater*, 1997, **35**, 888–894.
9. Mabee, S. B., Hardeastle, K. C. and Wise, D. U., A method of collecting and analyzing lineaments for regional-scale fractured-bedrock aquifer studies. *Groundwater*, 1994, **32**, 884–894.
10. Ballukraya, P. N., Hydrogeophysical investigations in Namagiripettai area of Namakkal district, Tamil Nadu. *J. Geol. Soc. India*, 2001, **58**, 239–249.

ACKNOWLEDGEMENTS. R.K. thanks the authorities of TWAD Board, Chennai for the permission to carry out research as well as all other facilities extended during the study period. We also thank the referee for his constructive suggestions which has helped in improving the quality of the article.

Received 3 March 2009; revised accepted 23 December 2009