JOURNAL GEOLOGICAL SOCIETY OF INDIA
Vol.85, March 2015, pp.305-312

Electrical Resistivity Survey and Shallow Subsurface Geological Study in Hard Rock Terrain, Southern India

S. Anbazhagan[1], R. Indhirajith[2], S. Uma Maheshwaran[1], A. Jothibasu[1], A. Venkatesan[3] and V. Ramesh[1]

[1]Centre for Geoinformatics and Planetary Studies, Department of Geology, Periyar University, Salem – 636 011
[2]Department of Geology, Periyar University, Salem – 636 011
[3]Department of Geology, Periyar University College of Arts & Science, Mettur -
Email: anbu02@gmail.com; umamahesh05@gmail.com; ajbasu.a09@gmail.com; venkatgeomorph@gmail.com; rameshremote@gmail.com

Abstract: The shallow sub-surface condition of the hard rock terrain is highly heterogeneous and it requires investigation of geology at close interval. The purpose of the present work is to interpret the shallow sub-surface geology to a limited depth (<100m) and to reveal the thickness of the various layers through electrical resistivity survey. In this context, the Nallampalli block located in Dharmapuri district, Southern India is selected. The area is mostly covered by gneissic and charnockitic rocks. In addition to resistivity survey, well inventory data was also collected from field investigations. The thickness of various sub-surface layers such as weathered zone, partially weathered zone, fractured zone and depth to bedrock were estimated. The estimated thickness and resistivity values were correlated with well inventory data. The average resistivity values for weathered, partially weathered, fractured and massive formations in the block are 55Ωm, 96Ωm, <303Ωm and >400Ωm respectively. The average depth to massive rock in the block is 38m below ground level (bgl). Remote sensing data were utilized to assess the sub-surface condition to a limited extent. The results obtained from the electrical resistivity survey and well inventory data have appreciable correlation.

Keywords: Shallow subsurface geology, Electrical resistivity, Remote sensing, Hard rock, Tamil Nadu.

INTRODUCTION

Shallow sub-surface geological investigations conducted for various applications such as engineering construction, groundwater exploration, monitoring seismic activities (Acworth, 1987; Burger, 1992; Mukhopadhyay and Kayal, 2003; Mukhopadhyay et al, 2006; Satyabala and Bilham, 2006; Hassan Imam et al 2013), sub-surface transportation, soil physics and agriculture. Perez-Gracia and Caselles (2009) have carried out geophysical survey to determine the shallow stratigraphy at depth and continuity of the highly resistant soils or rocks. The knowledge of thickness and distribution of shallow resistivity layers is useful for the structural evaluation of historical buildings. Malik et al (2007) and Bhosle et al. (2007) have applied the GPR and remote sensing techniques for delineating shallow structures and active faults in the alluvial plain.

Shallow sub-surface geological study is essential for understanding the hydrogeology of the terrain. Ibe et al., (1992) have carried out shallow sub-surface study to determine the depth of water table, aquifer thickness and geology of a sedimentary basin. Shallow sub-surface geology plays a vital role in underground infrastructure developmental activities such as construction of tunnels and pipelines. It is essential to characterize the shallow sub-surface geology for any developmental activity. The sub-surface lithology, soil chemistry, mineralogy, weathering condition is the crucial factors in urban areas and sensitive to the environment. In the present context, shallow subsurface geological studies were conducted to understand the weathering and fractured conditions through resistivity and well inventory data.

STUDY AREA

The shallow sub-surface studies were conducted in Nallampalli block, Dharmapuri district, Tamil Nadu. The study area is one of the drought prone and overexploited blocks in the state of Tamil Nadu (Fig.1). There are 31 panchayat villages in the block and bounded by Palackodu block in the north, Dharmapuri block in the east, Salem

0016-7622/2015-85-3-305/$ 1.00 © GEOL. SOC. INDIA

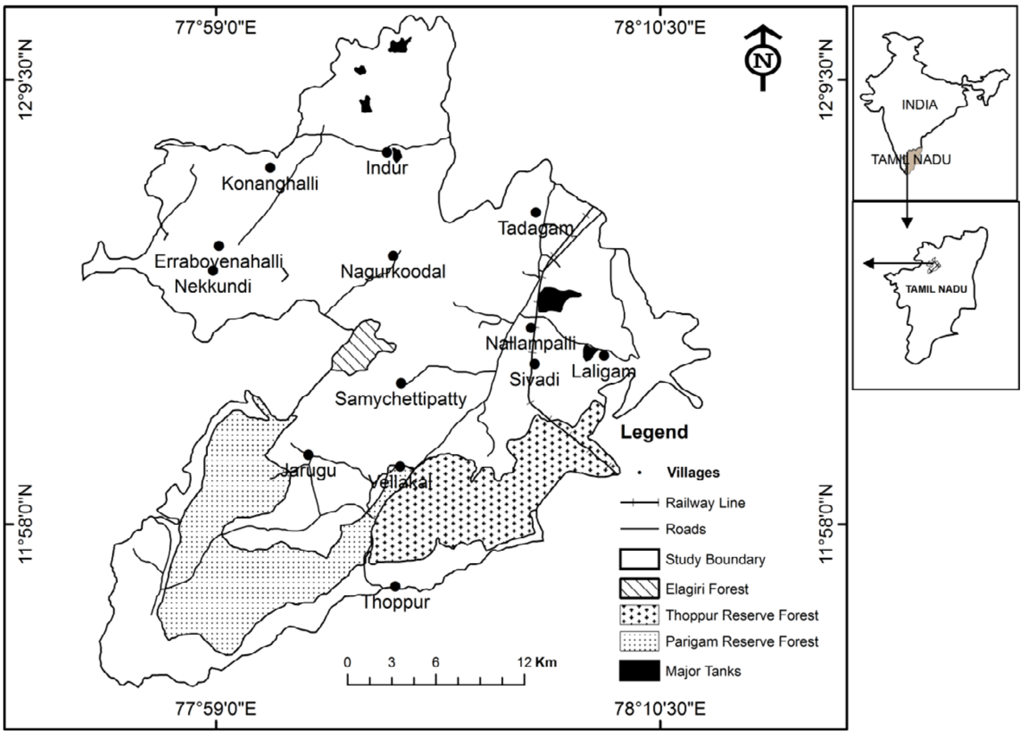

Fig.1. Nallampalli block in Dharmapuri district, Tamil Nadu, selected for shallow subsurface geological studies. The map show locations of VES conducted and electrical resistivity data collected from Groundwater Department (GWD).

district in the south and Pennagaram block in the west. The area is bounded by latitude N 11°53'30" and N 12°11'20" and longitude E 77°55'30" and E 78°11'30". The total geographical area of the block is 925 sq km. The wet and dry agriculture are equally practiced. The wet agriculture is mainly supported by tanks, well irrigation and a small portion under canal irrigation. The average annual rainfall is 800 mm.

GEOLOGY

The major rock types in the block are charnockites, epidote-hornblende gneiss, pyroxene granulite, granitic gneiss and hornblende biotite gneiss which belongs Archaean to upper Proterozoic age. The syenite, pyroxenite, pegmatite, dolerite dykes and quartz veins are in minor extent. The major portion is covered by epidote-hornblende gneiss and charnockite. The thickness of the soil ranges from 0.5 to 2 m. The general strike of the gneiss is NE-SW and dips in SE direction. Strike joints are predominant and at few locations, diagonal joints are also observed. The joints, fractures, and minor faults are the secondary porosities controlling the groundwater movement and occurrences in the area. The weathering condition is significant in granite-gneiss terrain. Dolerite dykes occur at Dokkubodanahalli, Elagiri, Pagalahalli, Adagapadi, Pangunatham, and Echehanahalli villages and quartz veins at Thoppur Reserve Forest area and Dokkubodanahalli.

METHODOLOGY

Electrical resistivity survey is adopted to infer the geometry and properties of shallow sub-surface geology mainly for groundwater exploration, management and mineral exploration. It provides accurate results on shallow sub-surface geological conditions of an area. In the present study, electrical resistivity data, well inventory data and satellite image were utilized for interpreting the shallow sub-surface geological condition. The mapping of surface expressions such as drainage patterns, lineaments, fracture, moisture condition, vegetation and landforms from satellite image provides indirect clues on nature of sub-surface condition in a region.

Electrical Resistivity Survey

Electrical resistivity survey was conducted to infer the variations of resistivity along horizontal as well as vertical directions at selected locations in the block. The variation of resistivity values in horizontal direction is useful for preliminary survey on structural prospecting like delineation of contact zones, dykes, faults and fracture zones.

In the present study, Vertical Electrical Soundings

Table 1 Resistivity and thickness of shallow subsurface layers, Nallampalli block

S. No.	VES Locations	Layer thickness (h) in m / Resistivity (ρ) in Ωm			
		h1 - ρ1	h2 - ρ2	h3 - ρ3	h4 - ρ4
1	Thoppur	2/67	9/143	40/600	α/625
2	Tadagam	4/50	25/500	a/1000	—
3	Dokkubothanahalli	4/83	10/114	17/473	α/1000
4	A.Jettihalli	3/33	4/67	7/333	α/500
5	Elagiri	5/67	20/500	33/333	α/500
6	Appusamuthram	2/20	7/50	33/200	α/500
7	Adiyamankottai	2/33	7/67	28/200	α/1400
8	Laligam	2/20	6/148	a/826	—
9	Palaiyamputhur	4/77	7/90	26/273	α/500
10	Pagalpatti	5/85	8/90	16/387	α/600
11	Balajangamanahalli	4/63	6/75	α/500	—
12	Maniyathahalli	3/70	6/80	α/427	—
13	Somanahalli	16/78	33/110	α/600	—
14	Errabaiyanahalli	2/87	4/90	α/435	—
15	Pungunatham	4/39	26/308	α/625	—
16	Dhalavaihalli	2/105	4/105	α/690	—
17	Nallampalli	2/62	4/70	8/225	α/472
18	Madhemanglam	4/38	8/62	α/472	—
19	Palavadi	4/52	6/90	α/440	—

(Ωm-Ohm metre, α-infinite)

(VES) were conducted at 7 locations with 100m electrode separation (AB/2) adopting Schlumberger configuration. The electrodes were arranged in a linear fashion with accurate distance for getting proper results in VES. In addition, the VES data for 12 locations were collected from State Groundwater Department. Through VES, the thickness (h) of various sub-surface layers including weathered zone, partially weathered zone and fractured zone along with respective resistivity values (ñ) were estimated (Table 1).

Weathered Layer

Electrical resistivity data was used in the interpretation of the thickness of various shallow sub-surface layers such as weathered zone, partially weathered zone, fractured zone and massive rock. The resolution of the output depends upon the nature of terrain, resistivity contrast, homogeneity, layer boundary condition, electrode spacing and alignment. The weathered zones are devoid of any trace of parent rock and comprises of soil horizon. The thickness of weathered layers were interpreted from VES (Seven locations) as well as the resistivity data collected (23 locations) from the Groundwater department. In addition, the weathered zone thickness was measured during well inventory survey. The major soil types in the block are sandy, sandy brown, and clayey sandy. The parent rocks for such soil types are gneisses and charnockites. The thickness of weathered zone varies from place to place for different geological formations. The thickness varies from 2 to 11m below ground level (bgl), in exceptional cases, the weathered zone is developed up to 16m below ground level. In general, the thickness of the weathered zones extends more than 3m (bgl) at many locations and where block cotton soil is predominant for example at A. Jettihalli and Somanahalli (Table 2). The thickness of weathered layer obtained from resistivity as well as well inventory data for each village, were averaged and represented in the Fig.2. Based on thickness of weathered layer, the villages are divided into three categories as low, moderate and high weathered zone respectively and fall in <3m, 3-7m and >7m thickness. The average thickness of weathered layer in the block is 4.5 m and the average resistivity value is 55Ωm.

Partially Weathered Layer

The partially weathered portion comprises of partial weathered material with unaltered parent rock fragments. The depth and thickness of partially weathered zone is inferred from the electrical resistivity survey conducted at different locations and the data collected from the Groundwater department. In addition, the thickness of partially weathered zone also measured from the well

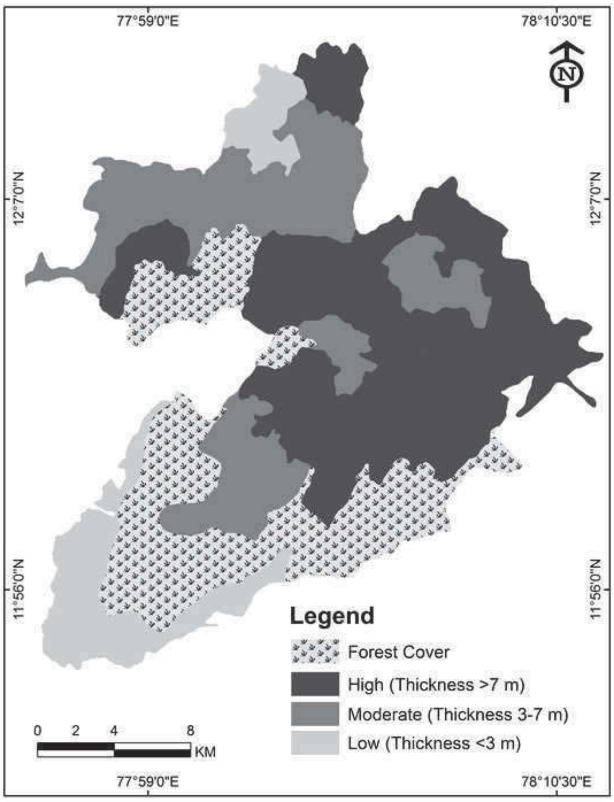

Fig.2. Shallow subsurface lithology: weathered layer comprises of soil and completely weathered formation, generated using electrical resistivity and well inventory data.

Table 2. The thickness of weathered layer, partially weathered layer, fractured zone and depth to massive rock along with respective resistivity values for villages in Nallampalli block. The subsurface geology interpreted from well inventory and electrical resistivity data

S. No	Location	Geology	Soil type	WL (m)	R (Ωm)	PWL (m)	R (Ωm)	FZ (m)	R (Ωm)	DMR (m)	R (Ωm)
1	Thadagam	GG	Bcs	3.9	50	14.3	135	8.8	—	—	—
2	A.Jettihalli	GG	Sbs	10.9	33	20.5	66	12.4	333	14	500
3	Laligam	Ch	Ss	2.1	20	5.3	148	17.3	—	50	826
4	Adiyamankottai	Ep-Hbg	Cssl	4.8	33	8.5	—	31.6	200	41	400
5	Elagiri	GG	Sgs	5.4	66	8.8	66	11.3	200	40	500
6	Palaiyamputhur	Ch	Bcs	4.0	77	7.1	90	26.3	273	50	500
7	Pagalpatti	Ep-Hbg	Bcs	4.6	85	6.8	90	16.3	387	50	600
8	Balajangamanahalli	Ep-Hbg	Sbs	3.8	63	5.9	75	6.2	—	—	—
9	Maniyathahalli (Jarugu)	Ep-Hbg	Css	2.4	70	5.0	80	11.5	—	14	427
10	Somanahalli	Ch	Ss	16.3	78	32.6	110	9	—	—	—
11	Thoppur	Ep-Hbg	Bcs	2.8	66	13.7	142	14.6	—	40	600
12	Errabaiyanahalli	Ep-Hbg	Css	2.8	87	3.6	90	31	—	14	435
13	Pungunatham	Ep-Hbg	Css	1.5	39	7.7	—	26	308	50	625
14	Dokkuboothanahalli	Ep-Hbg	Ss	3.8	83	10.2	114	20.8	473	31	1000
15	Dinnahallai	Ch	Bcs	7.4	85	8.7	170	14	—	—	—
16	Boothanahalli kottai	Ch	Bcs	6.3	21	7.9	65	9	—	—	—
17	Dhalavaihalli	GG	Bcs	1.8	105	3.5	105	—	—	40	690
18	Nallampalli	Ep-Hbg	Sbs	2.8	62	4.7	62	7.2	225	50	407
19	Sivadi	Ep-Hbg	Bcs	3.0	28	24	100	6.7	—	—	—
20	Madhemanglam	Ep-Hbg	Bcs	3.2	38	8.1	62	38	—	50	472
21	Nagarkoodal	Ch	Bcs	3.2	18	33	—	6.7	—	—	—
22	Palavadi	Ch	Bcs	3.3	52	6.0	90	—	—	40	440
23	Appusamuthram	Ch	Bcs	2.3	20	8.5	96	11.3	200	33	500
24	Vellakkal	Ep-Hbg	Bcs	—	—	—	—	13.5	—	—	—
25	Samichettipatti	Ep-Hbg	Bcs	—	—	—	—	15.5	—	—	—
	Average thickness and resistivity value			4.5	55	11	96	18.9	303	38	524

(GG-Granite gneiss, Ch-Charnockite, Ep-Hbg-Epidote-Hornblende biotite gneiss, Bcs-Block Cotton Soil, Sbs- Sandy brown soil, Sgs-Sandy gravel soil, Ss-Sandy soil, Css-Clayey sandy soil, WL-Weathered layer thickness, R-Resistivity, PWL-Partially weathered layer thickness, FZ-Fractured zone thickness, DMR-Depth to massive rock)

sections and borehole lithological data. The thickness of partially weathered zone varies from 2m to 33m and at few locations it becomes the top layer, where weathered zone is absent. The resistivity value of partially weathered zone is in the range of 60Ωm to 160Ωm. There could be an overlap between resistivity value of partially weathered layer, weathered layer and fractured zone. The average thickness of partially weathered zone for each village is estimated from resistivity survey, well inventory measurement and the data collected from the Groundwater Department (Table 2). Based on the thickness of partially weathered zone, the villages in the block are categorized as high, moderate and low thickness zone respectively with >20m, 10-20m and <10m thickness. The average thickness of partially weathered zone in the block is 11m with an average resistivity value of 96Ωm (Fig.3).

Fractured Layer

Fractured zone is an important sub-surface layer in crystalline rocks. It indicates the extent of deformation at a particular location. Moreover, the layer is having secondary porosity and permeability, where groundwater movement and accumulation is significant. The available electrical resistivity data for fractured zone is limited. Only few wells were penetrated to the depth of fractured zone. The average thickness of fractured zone for various rock at different locations is estimated from resistivity and well inventory data. The thicknesses of fractured zone vary from 6.2m to 67m (Table 2). The average resistivity value for fractured zone is 303Ωm**.** The average thickness of fractured zone in Nallampalli block is estimated as 18.9m (Fig. 4).

Depth of Massive Rock

The hard crystalline rocks like granites, gneisses and charnockites have poor porosity (= 1%) with resistivity of several thousand Ωm. These rocks when exposed to weathering get broken and fractured, providing interconnected fissures, which permit percolation of surface water. Surface water percolation accelerates further disintegration and decomposition of rocks resulting in coarse granular material, which contains considerable

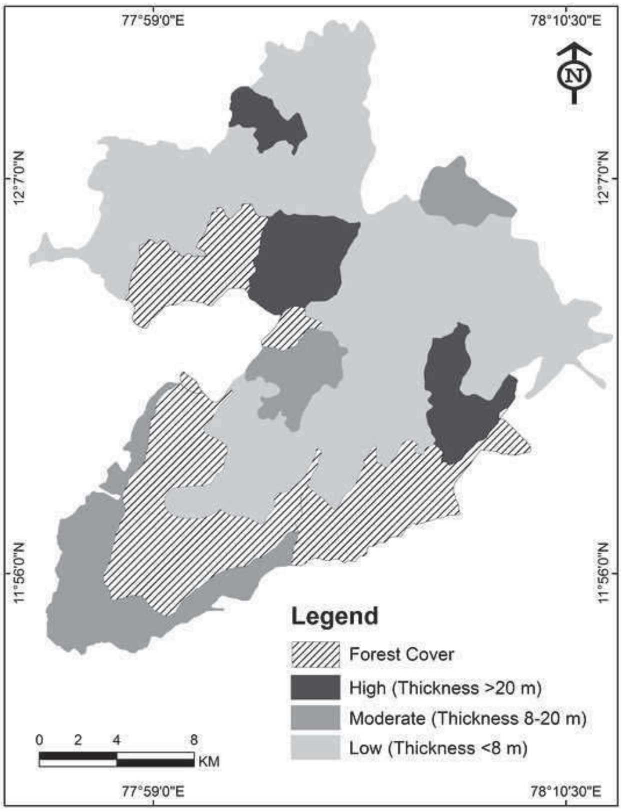

Fig.3 Subsurface lithology: partially weathered layer thickness map, interpreted from electrical resistivity and well inventory data.

quantities of groundwater. Depending on the extent and depth of weathered and fractured condition, the rocks constitutes potential aquifers. The weathered layer sometimes is missing in the sequence and directly massive rock encountered after partially weathered rock. From hydrogeological point of view, the availability of groundwater in massive rock formation is meager due to absence of secondary porosity. In general massive rock is encountered after fractured rock. The depth of massive rock was measured during well inventory survey. However, most of the wells have not penetrated up to the depth of massive rock, in that case, the data obtained from resistivity survey and borehole lithology were useful in determining the depth of massive rock. The available data for depth to massive rock are collected for 16 locations in the block (Table 2). The average depth to massive rock in Nallampalli block is 36m bgl. Laligam, Palaiyampudur, Pagalpatti, Punguanatham, Thalavaihalli, Nallampalli and Madhemangalam are some of the villages have more depth to massive rock. Based on depth to massive rock, the villages were grouped into deep, moderate and shallow depth to massive rock respectively with >40m, 14-40m and <14m depth below ground level (Fig.5).

Remote Sensing and Subsurface Condition

The shallow sub-surface geological information interpreted from electrical resistivity and well inventory survey can be applied to various geological applications. In shallow aquifer study, the aquifer type, thickness, lateral extent and lithological variations within the aquifer need to be assessed. The lateral variations, thickness and depth to massive rock differ drastically in hard rock terrain from place to place. In the present study, apart from electrical resistivity survey, remote sensing data were also interpreted to understand the shallow sub-surface geological condition. Satellite data are helpful to understand the shallow sub-surface geological condition through interpretation of geomorphology, lineaments, drainage pattern and structure (Anbazhagan 1993; Anbazhagan and Saranathan 2000; Anbazhagan et al., 2001). In the present study, Landsat ETM satellite data were digitally processed using ERDAS IMAGINE image processing software. The geomorphic units interpreted from the processed satellite data are shallow pediments, buried pediments, valley fills, structural hills, linear ridges, dykes, residual hills and uplands. Shallow pediments are the plain area with thin veneer of detritus soil and broad undulating terrain. In satellite image, it is

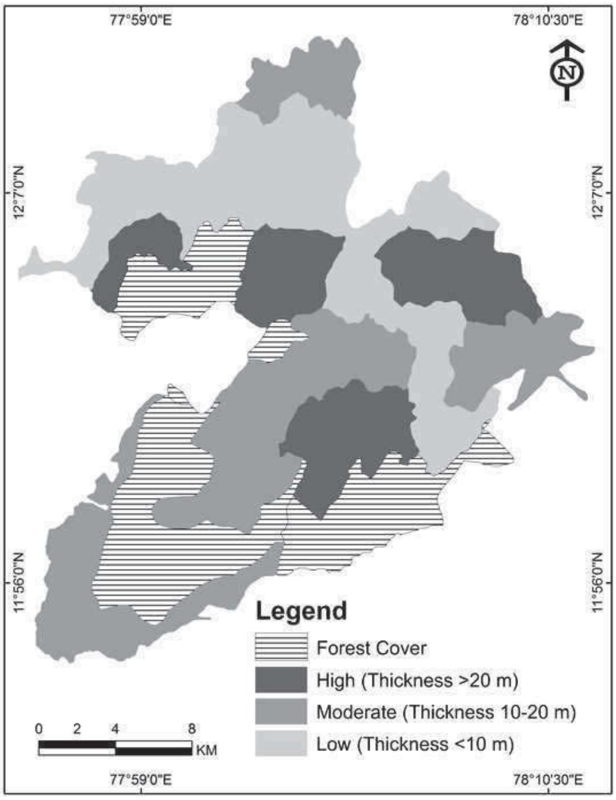

Fig.4 Subsurface lithology: fractured map integrated from electrical resistivity and well inventory data.

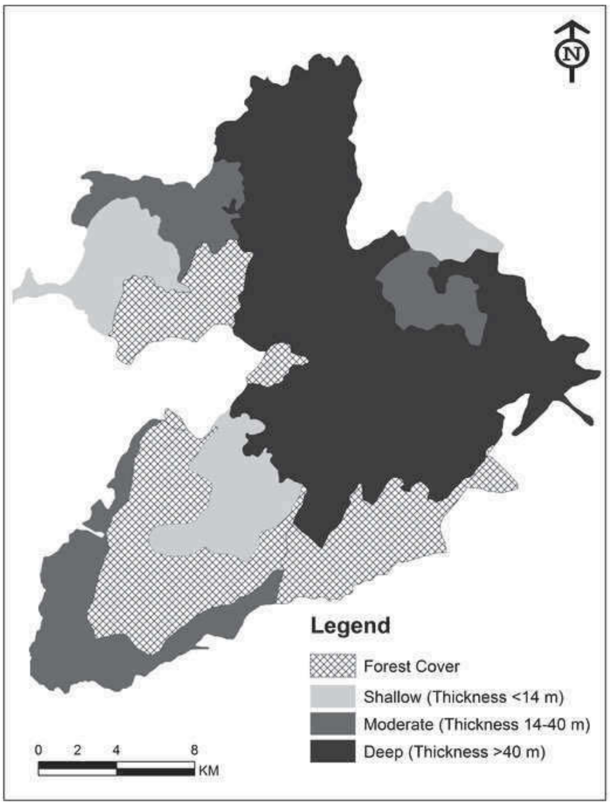

Fig.5. Subsurface lithology: Depth to massive rock, generated using electrical resistivity and well inventory survey.

represented as vast plain area, with occasional outcrops and pale white to white yellowish tonal contrast. Shallow pediments have limited vegetation or cultivation practices and mostly restricted to dry agriculture. This unit is restricted in the northwestern block under the run-off zone with poor recharge condition. The groundwater prospect in shallow pediment is comparatively poor because of limited thickness of weathered zone. Buried pediments cover the western and southeastern parts of the study area. It is characterized by light reddish tonal contrast in color composite image, smooth texture and fine drainage system with moderate weathered condition. Infiltration and percolation of surface water contribute moderate to high recharge in this zone. The weathered and fractured conditions are extend to considerable depth. Groundwater prospect is significant in buried pediment zone. The valley fills in the crystalline rocks are mostly fracture controlled and fluvial origin. Narrow valleys are filled with unconsolidated sediments deposited by streams and rivers. The valley fills are suitable for construction of shallow dug wells and bore wells.

Structural hills are mostly linear to arcute folded hills with definite trends. In colour composite image, structural hills show relief feature with structural trend lines. Denudational hills are formed due to differential erosion and weathering, more resistant land unit as mountains and hills. The structural and denudational hills act as runoff zone rather than infiltration. Denudational hills are interpreted from the satellite image as circular outcrop, relief feature, absence of vegetation and coarse texture with tonal contrast. Ridges and dykes are linear, narrow and strike controlled structural features. Uplands are barren with restricted outcrops, elevated zone associated with sparse vegetation. These zones show smooth to moderate texture, light brown to yellowish tonal contrast in colour composite image. Residual hills are resistant relief feature located in gneisses and charnockites. The geomorphic units and associated shallow sub-surface geological conditions are listed in Table 3. Similarly, the villages are grouped under various categories.

RESULTS AND DISCUSSION

The electrical resistivity data provided valuable information on shallow sub-surface geological condition in

Table 3 Shallow subsurface geological conditions in Nallampalli block, interpreted from remote sensing data

Geomorphic Units	Associated subsurface condition	Villages grouped under various landform units
Structural hill Residual hills, Denudational hills, linear ridge / dykes	Very limited or absence of weathered and partially weathered condition zone, occasionally associated fractured layer	Nagargudal parigam,Nerkkundi,Dhalavayhalli, Balajangamanahalli, Elagiri Maniyadahalli
Shallow pediment	Limited weathered / partially weathered condition	Sesampattiyan kottai, Maniyathahalli, Kell borrikal, Pangunatham,
Buried pediment, Valley fill	Extended weathered and fractured condition	Adhiyamankottai, A.jettihalli, Dokkuboothanahalli, Palaiyamputhur, Pagalhalli, Boothanahalli, Laligam Balajangamanahalli Madhemanglam, Dinnahallai Erraboyanahalli, Mittareddihalli, Dalvayhalli, Palavadi, Gengalapuram, Erraboyenahalli, Sessampatti, Nallampalli, Kovilur, Elagiri, Jargu, Pungunatham, Agraharam, Bandahalli, Bedrahalli, Samichettipatti, Vellakkal, Somanahalli, Tadagam, Echanahalli,, Konnangihalli,

hard rock terrain of Nallampalli block. In addition to resistivity survey, well inventory were conducted to interpret shallow sub-surface layers such as weathered, partially weathered, fractured and depth to massive formation. The results have shown that the weathering condition is significant in the block (2-16m thickness) and the resistivity values for weathered layers range from 21Ωm to 51Ωm. At few locations, the value increased up to 87Ωm, depending on the resistance of the minerals associated with that particular weathered layer. The weathered layers with low resistivity values are totally weathered without any trace of parent rocks. The high resistivity indicated that the weathered layer has fuzzy boundary condition with partially weathered zone and also intermingled with boulders and parent rocks. The clayey sandy soil and black cotton soil are associated with low resistivity and high conductivity zones in the block. The soil development and weathering processes are significant in the block and correlated with the field data. The weathered thickness interpreted from electrical resistivity data mostly coincide with the well inventory data at many locations. The resistivity value and the thickness of weathered layer do not show any definite trend with lithology of the terrain. The weathered layer is underlined by partially weathered zone, where parent rocks fragments are observed in the well section.

The average thickness of partially weathered zone in the block is 11m and respective resistivity value is 96Ωm. Moderate level of partial weathering is observed in almost all geological formations in most of the villages in the block. The thickness of partially weathered zone is significant, for example at A. Jettihalli, Nagarkoodal and Somanahalli mainly controlled by fractures.

The average thickness of fractured zone in the block is 19m with resistivity value of 303Ωm. Fractured condition is well developed in epidote-hornblende-biotite gneiss and charnockites. Once again such locations are controlled by fractures, joints and lineaments. The average depth to massive rock is about 37m bgl, and the maximum depth to massive rock in the block is limited to 50m bgl. The geomorphic units interpreted from remote sensing data were useful to categorize villages and associated shallow sub-surface layers in the block.

CONCLUSION

Electrical resistivity survey provided reasonable results on shallow sub-surface geology to limited depth on weathered, partially weathered, fractured and massive rocks. In this study, an attempt has been made to assess the resistivity values for various layers. The average resistivity values of weathered, partially weathered, fractured and massive rock in the hard rock terrain of Nallampalli block are 55Ωm, 96Ωm, 303Ωm and 523Ωm respectively. This interpretation is correlated with the data obtained from well inventory. It is clear that the type of rock does not directly control the resistivity, however, the extent of weathering and maturity provide low resistivity value. The remote sensing output is useful to categorize the villages into different sub-surface geological condition.

Acknowledgements: The University Grants Commission (UGC) provided financial support through Major Research Project. The authors thank anonymous reviewer for critical comments, corrections and suggestions.

References

Acworth, R.I. (1987) The development of crystalline basement aquifers in a tropical environment. Quart. Jour. Engg. Geol., v.20, pp.265–272.

Anbazhagan, S. (1993) Integrated groundwater study in drought prone Pennagaram, Dharampuri district. Tamil Nadu. Bull. Indian Geol. Assoc., v.26:2, pp.117-123.

Anbazhagan, S. and Saranathan, E. (2000) Influence of Geology, Geomorphology and Structure on Groundwater condition in hard rock terrains of Tamil Nadu, India. *In:* Proceedings of the UGC state conference on 'Groundwater Exploration Technique' pp.1–6.

Anbazhagan, S., Ramasamy, S.M. and Edwin, J.M. (2000) Remote Sensing and Geophysical resistivity survey for Groundwater exploration - A comparative analysis. In: Proceedings of the UGC State Conference on Groundwater Exploration Techniques, pp 177- 181.

Anbazhagan, S., Aschenbrenner, F. and Knolbich, K. (2001) Comparison of aquifer parameters with lineaments derived from remotely sensed data in Kinzig basin, Germany. New Approaches in Characterizing Groundwater Flow, Seiler and Wohnilch (eds), Swets and Zeitlinger Lisse., Munich, Germany, v.2, pp.883-886.

Bhosle, B., Parkash, B. and Awasthi, A.K. (2007) Remote sensing – GIS and GPR studies of two active faults, Western Gangetic Plains, India. Jour. Appld. Geophys., v.163, pp1257- 1277.

Burger, R. (1992) Exploration geophysics of the shallow subsurface: New Jersey, Prentice-Hall, pp 489.

Hassan Imam, M,D., Hossain, D. and Woobaid Ullah (2013) Geoelectrical resistivity survey for the evaluation of hydrogeological condition of Bagerhat Sadar and the Adjacent Areas, Bangladesh. Jour. Geol. Soc. India, v.82, pp.290-294.

Ibe, K.M., Sowa, A.H.O. and Osondu, O.C. (1992) Environmental contamination and other anthropogenic impacts on Otamiri Nworie rivers, Owerri, Nigeria. Nigeria Jour. Min. Geol., v.28, pp.87-91.

Malik, J.N., Sahoo, A.K. and Shah, A.A. (2007) Ground Penetrating Radar investigation along Pinjore Garen Fault: Implication toward identification of shallow subsurface deformation along active fault, NW Himalaya. Curr. Sci., v.93, pp.1422–1427.

Mukhopadhyay, S. and Kayal, J.R. (2003) Seismic topography structure of the 1999 Chamoli earthquake source area in the Garhwal Himalaya. Bull. Seismol. Soc. Amer., v.93, pp.1854-1861.

Mukhopadhyay, S., Tyagi, C. and Rai, S.S. (2006) The attention mechanism of seismic waves in North Western Himalayas. Internat. Geophys. Jour., v.167, pp.354-360

Perez-Gracia, V. and Caselles, J.O. (2009) Integrated near-surface geophysical survey of the Cathedral of Mallorca. Jour. Archaeological Sci., v.36, pp.1289–1299.

Satyabala, S.P. and Bilham, R. (2006) Surface deformation and Subsurface slip of the 28th March 1999 MW=6.4 West Himalaya Chamoli earthquake, from InSAR analysis: Geophys. Res. Lett., v.33. p. L23305.

(Received: 5 July 2013; Revised form accepted: 13 January 2014)