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Efficacy of Electrical Resistivity techniques for groundwater prospecting and aquifer mapping in a hard rock terrain of southern India

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ABSTRACT
One dimensional (1D) and two dimensional (2D) electrical resistivity investigations were carried out in a hard crystalline terrain of Karnataka state, South India with an objective of pin-pointing the groundwater location and delineating the aquifer geometry. Based on the interpretation of 1D and 2D resistivity data, sixteen locations were recommended and drilled for exploiting groundwater. The yield of newly drilled bore wells ranged from 0.095 to 19 m^3/hr. On comparing the lithologs and derived layer parameters, it is inferred that the success of the wells depends mostly on fractured granites/gneisses than the weathered layer. Based on the yields of the wells, the valley filled region in the central part (towards east) of the investigated area appears to be more water bearing. To maintain the sustainable yield of these newly drilled bore wells, a few rainwater harvesting pits were also recommended. The efficacy of the VES and ERT methods is well revealed by a good match of layer parameters and litholog data.

Key words: Vertical Electrical Sounding (VES); Electrical Resistivity Tomography (ERT); Aquifer mapping and Groundwater prospects.

INTRODUCTION

Groundwater is widely used for industrial, agricultural and domestic purposes in arid and semi-arid regions of hard rock terrains. Over-exploitation of groundwater in these terrains has caused deepening of groundwater table continuously. Generally, the groundwater flow in hard rock areas is limited to deeper weathered and fractured zones (Rai et al., 2011). Demarcating deeper groundwater horizon needs proper and precise investigation. Among the several geophysical methods available, electrical resistivity technique is considered as an effective one for delineation of water bearing formations more accurately. Experience all over the world shows many wells drilled in hard rock terrains without proper investigations have met with failure. Therefore, a systematic and scientific approach is essential to reduce the failure rate.

Electrical resistivity method is suitable for groundwater investigations to effectively locate water bearing subsurface formations that have wide range of resistivity due to varied composition of geological formations (Keller and Frischknecht 1966; Koefoed 1979). Electrical resistivity techniques have been used effectively by many researchers for mapping of potential water bearing zones in hard rock terrains (Griffiths and Barkar 1993; Hamzah et al., 2007; Dhakate et al., 2008, 2012), delineation and demarcation of salt water intrusion and saltwater-freshwater interface (Nassir et al., 2000; Sherif et al., 2006; Hodlur et al., 2006, 2010; Song et al., 2007; Dhakate et al., 2015).

With the advancement in technology the conventional Vertical Electrical Sounding (VES) is replaced by multi-electrode Electrical Resistivity Tomography (ERT). There are several advantages of using multi-electrode ERT system over the conventional VES (Dahlin, 1996). This is because the multi-electrode scheme is a fast computer-aided data acquisition system and facilitates simultaneous study of both lateral and vertical changes of resistivity below the entire profile length. ERT techniques are useful for mapping accurately location of subsurface geological formations and structures like faults, fractures, joints for delineation of water-bearing zones and geothermal resources (Griffiths and Barker 1993; Loke and Barker 1996; El-Qady 2000). In the present study an attempt is made by carrying out One Dimensional (1D) Vertical Electrical Sounding (VES) using Schlumberger configuration and Two Dimensional (2D) Electrical Resistivity Tomography (ERT) using Wenner-Schlumberger configuration for deciphering the groundwater source and delineating different aquifer zones within a small watershed. Based on interpretation of 1D data of seven sites and 2D data of nine sites, favourable locations were recommended for drilling of bore wells in the study area. The results are found to be encouraging and fruitful.

Hydrogeology of the Study Area

The study area falls in the Ullarthi Kaval watershed covering about 3831ha. It is about 13km from Challakere town of Karnataka state (Figure 1). The investigated area

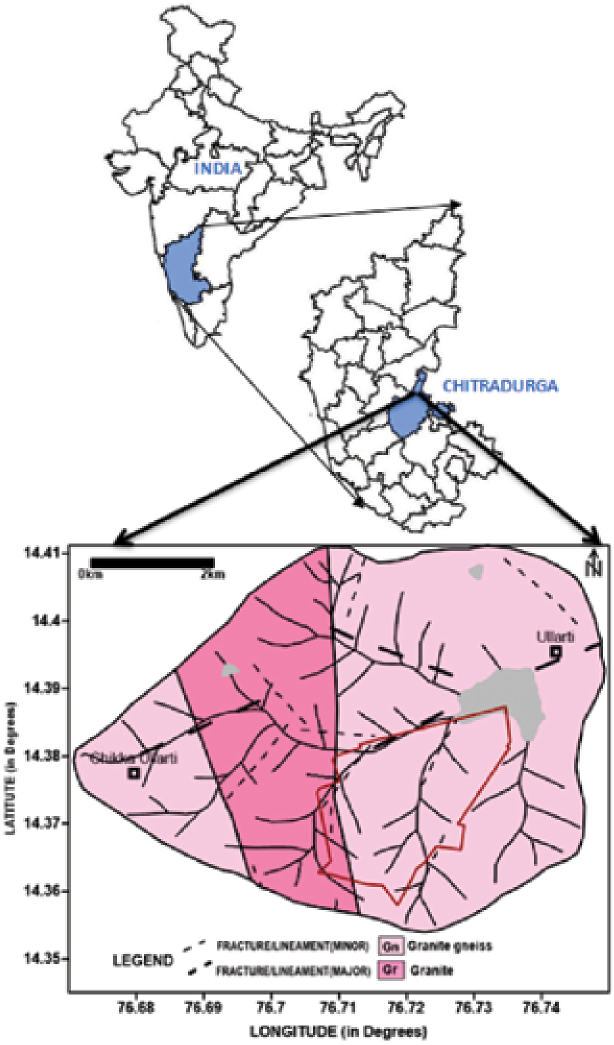

Figure 1. Location map and geology showing major and minor lineaments in the study area.

is spread over about 510ha of land in Ullarthi Kaval village with undulating topography. The drainage pattern is sub-dendritic and the drainage network is flowing towards north and east directions, which joins a tank in Ullarthi Kaval village. The area is considered as a low rainfall region with the average annual rainfall as 450 mm/yr.

Major part of the watershed is covered by rocks of granite-gneisses and only about 10% area on the west is covered by granitic rocks. Hard red soil forms the top layer with boulders in the northern and eastern parts, while the central part consists of sandy soil. The area is devoid of any major fault or fracture zone, only few minor lineaments oriented in NE-SW, N-S direction are inferred (Figure 1).

Groundwater occurs under phreatic condition in the weathered, fractured rock formations of the 'Peninsular Gneissic Group' of rocks comprising granites, granite gneiss and hornblende-schist. The thickness of weathered zone varies from less than a meter near hill slopes and higher altitudes to about 39m in valleys and topographic low areas. The main source of groundwater recharge in the study area is through precipitation. At depth, groundwater occurs in the fractures and fault zones of the crystalline rocks under semi-confined to confined conditions. Groundwater exploration in Challekere Taluk reveals that groundwater bearing zones are encountered from depth 15.4m below ground level (bgl) to 182.9m (bgl). Borewell depths vary from 110-200m (bgl). The yield is between 0.21 to 8.23 lps and transmissivity is between 34.50 to 665.17 m^2/day (CGWB 2007). The lineaments observed in the study area may be the result of faulting and fracturing with increased porosity and permeability. The lineaments identified are of varying dimensions with different orientations (Figure 2a & b).

Geophysical Investigations

In order to assess the groundwater condition in the study area, 45 Vertical Electrical Soundings (VES) using

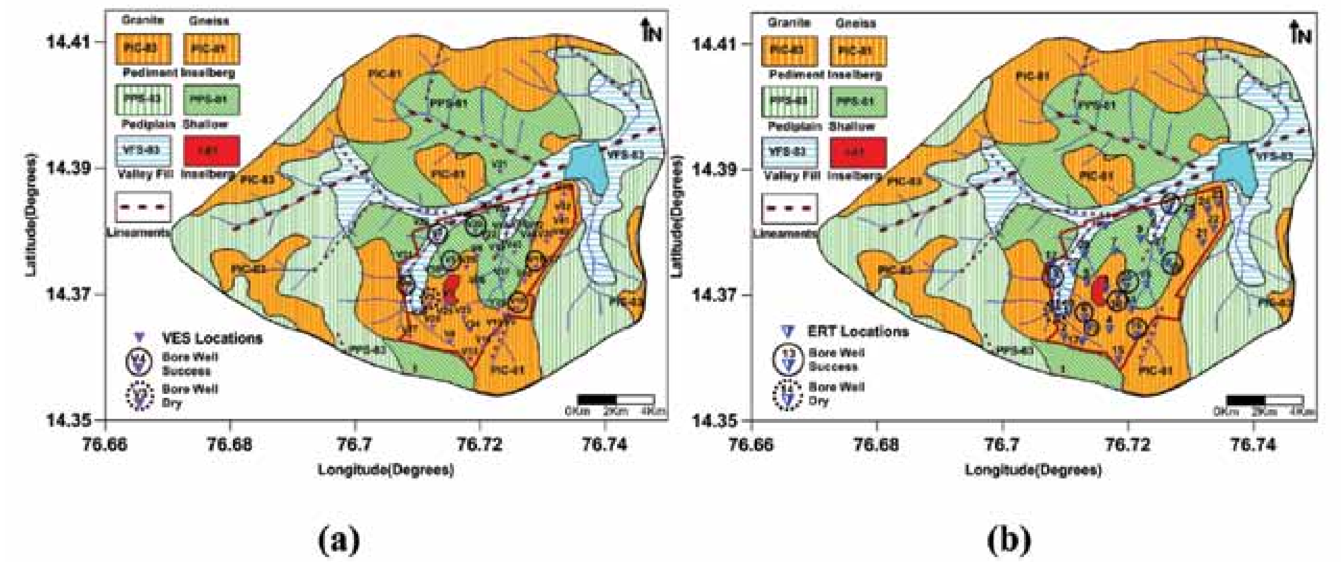

Figure 2. (a) Map showing Geomorphological Features and locations of Vertical Electrical Soundings (VES) & drilled bore wells and (b) Geomorphological Features and locations of Electrical Resistivity Tomography (ERT) & drilled bore wells in the study area.

Schlumberger configuration with the half current electrode separation of 100-200m (Figure 2a) and 31 Electrical Resistivity Tomographs (ERT) using Wenner-Schlumberger configuration were carried out (Figure 2b). On interpreting the data 16 sites were identified for drilling of bore wells. Out of these 16 locations, 14 locations were found to be good for groundwater extraction with yields ranging from 0.095-19 m^3/hr and at 2 locations dry conditions were observed.

DATA INTERPRETATION

Vertical Electrical Sounding (VES)

Initial interpretation of sounding curves is made by conventional curve matching technique, with the field curve matched with the theoretical master curve (Orellana and Mooney, 1966). The theoretical curve that best fits the observed sounding curve specifies the various layers thicknesses and resistivities of the field curve. The results thus obtained were used as initial model parameters for final interpretation by an inversion algorithm in which the layers parameters are iterated until minimum root mean square error is obtained between the field and computed curves. The computer software RESIST was used for this purpose (Jupps and Vozoff, 1975). The results of VES interpretation are given in Table 1.

Electrical Resistivity Tomography (ERT)

To interpret the apparent resistivity data set, the 'RES2DINV' software (Loke and Barker, 1995, 1996) was used. The measured values of apparent resistivity provide a total of two images, in which first image is electrical subsurface structure designated as 'pseudo-section'. In the second step, the apparent resistivity measurements are transformed into true resistivity values using an inversion algorithm (Loke and Barker, 1996) followed by smoothing by least square inversion method. Inversion algorithm divides the subsurface into rectangular blocks and the resistivity of the blocks is adjusted to minimize iteratively the difference between the computed and the measured apparent resistivity values; the root mean square (RMS) error gives a measure of this difference (Sasaki 1992; Loke and Barker, 1996).

RESULTS AND DISCUSSION

Based on interpreted results of VES (Table 1), the following resistivity ranges can be attributed to different sub-surface layers (Table 2). However, it is observed from the lithologs that higher values of resistivity (above 300 Ω-m) corresponding to hard granite/gneissic rock also yielded water due to the presence of fractures, which could not be delineated in the sounding due to their small thickness.

Based on interpretation of VES data (Table 1) seven sites were recommended for drilling of bore well as given in Table 3 and the interpreted soundings curves are shown in Figure 3. VES No 2 falling in Valley Fill (granite complex) geomorphic unit revealed a 24m thick aquifer of 151 Ω-m resistivity. The bore well drilled at this site struck water at a depth of 17m yielding 13.7 m^3/hr (Table 3). Higher yield at this site can be inferred from the low resistivity of aquifer and shallow water table as the site is located in valley fill region. On the other hand, the bore well drilled at VES No. 4 also falling in Valley fill (granite

Table 1. Interpreted Vertical Electrical Sounding results of Ullarthi Kaval Watershed.

VES No.	ρ_1 (Ω-m)	h_1 (m)	ρ_2 (Ω-m)	h_2 (m)	ρ_3 (Ω-m)	h_3 (m)	ρ_4 (Ω-m)	h_4 (m)	ρ_5 (Ω-m)	Total thickness (m)
1	331	0.7	85	4.9	66	13.7	942			19.3
2	225	1.2	151	24.0	2629					25.1
3	526	1.0	64	15.5	3655					16.5
4	515	0.3	174	24.8	255	9.5	1748			34.6
5	455	0.7	84	1.9	600	5.1	114	12.8	1678	20.5
6	217	1.3	33	7.3	147	10.3	1935			18.9
7	889	0.5	392	9.6	2796					10.1
8	636	1.3	87	13.5	2303					14.8
9	55	1.4	25	5.5	223	6.7	4066			13.6
10	124	0.5	284	9.3	19016					9.8
11	167	3.9	59	24.0	197	8.1	1034			36.0
12	948	0.4	156	19.1	508					19.5
13	253	1.9	65	3.1	427	8.2	31	5.1	10003	18.3
14	261	0.5	8.0	3.0	220	4.7	2425			8.3
15	200	1.4	15	5.5	102	6.8	905			13.7
16	227	0.7	72	1.9	175	17.7	2340			20.3
17	274	0.7	127	1.1	367	2.6	56	7.2	920	11.6
18	309	1.5	30	13.2	1266					14.7
19	87	1.5	14	6.6	206	9.4	1121			17.5
20	365	0.5	134	9.4	298	10.1	1960			20.0
21	149	0.7	39	3.5	111	11.7	1908			15.9
22	187	1.6	55	11.6	2537					13.2
23	439	0.7	101	2.4	224	6.6	149	13.5	1484	23.1
24	78	0.5	122	2.2	68	11.7	874			14.4
25	365	0.6	221	2.8	732	13.1	7200			16.4
26	239	0.9	81	10.4	4646					11.3
27	172	1.5	109	17.8	1954					19.3
28	145	0.4	30	0.8	96	31.0	1410			32.2
29	352	0.7	36	3.5	165	21.6	1095			25.8
30	182	0.6	87	4.5	12	16.3	1362			21.4
31	139	0.5	142	17.2	863					17.7
32	119	0.5	80	2.1	125	21.6	798			24.2
33	265	0.7	128	11.1	1348					11.8
34	160	1.4	60	9.0	645					10.4
35	136	1.0	79	2.6	169	23.9	322			27.4
36	196	1.2	106	5.3	64	11.0	1305			17.5
37	152	1.5	89	8.4	161	20.2	775			30.0
38	233	0.9	99	8.7	209	9.9	1848			19.5
39	165	1.2	78	4.7	184	15.5	1227			21.3
40	85	1.0	87	4.6	462	14.1	1880			19.6
41	110	0.5	84	7.5	6101	15.9	1825			23.9
42	285	1.4	1145	6.3	681	23.9	3788			31.6
43	368	0.7	307	3.0	78	13.6	775			17.3
44	339	1.1	222	7.8	369	15.5	1814			24.5
45	106	1.0	141	7.4	128	20.0	460			28.4

Table 2. Resistivity ranges of different sub-surface formation.

Resistivity (Ω-m)	Sub-surface/Lithology formation
55-948	Top Soil
14-150	Weathered Gneissic formation
150-300	Semi-weathered/ fractured Gneissic
>300	Hard Gneissic rock

Table 3. Recommended locations for drilling of bore wells based on Vertical Electrical Soundings (VES) and Electrical Resistivity Tomography (ERT) & drilling results in the Ullarthi Kaval Watershed, Challekere Taluk

VES No./ ERT No.	Geomorphic Units	Layer Resistivity (Ω-m) in which water was struck	Total thickness of aquifer (m)	Depth at which water struck	Yield (m^3/hr)
VES No.2	Valley Fill (Granite)	151	24.0	17m	13.7
VES No.3	Pediment Inselberg (Gneiss)	---	---	Dry	Nil
VES No.4	Valley Fill (Granite)	1748	Last layer	49m	0.6
VES No.5	Pediment Shallow (Gneiss)	1678	Last layer	27m	3.3
VES No.11	Pediment Inselberg (Gneiss)	197	36.0	28m	5.9
VES No.16	Pediment Inselberg (Gneiss)	2340	20.3	49m	3.3
VES No.20	Pediment Shallow (Gneiss)	1960	Last layer	21m	3.3
ERT No. 3	Pediment Inselberg (Gneiss)	934	~10	52m	7.5
ERT No. 6	Pediment Inselberg (Gneiss)	1740	~10	40m	0.095
ERT No.13	Valley Fill (Granite)	165	~26	21m	2.4
ERT No.14	Pediment Inselberg (Gneiss)	---	---	Dry	Nil
ERT No.16	Pediment Inselberg (Gneiss)	789	Last layer	43m	0.6
ERT No.19	Pediment Shallow (Gneiss)	262	Last layer	30m	7.5
ERT No.20	Pediment Shallow (Gneiss)	343	Last layer	30m	5.9
ERT No.26	Valley Fill (Granite)	119	~4	16m	19
ERT No.30	Pediment Inselberg (Gneiss)	609	~5	30m	0.25

complex) unit encountered water at a depth of 49m with a low yield of 0.6 m^3/hr, which may be attributed to the higher range of resistivity of the weathered layer (174 and 255 Ω-m) than that shown in Table 2. The bore well drilled at VES No. 3 falling in the gneissic complex revealed a resistivity of 64 Ω-m for the aquifer, with a thickness of 15.5m. This encountered dry condition. VES No. 5 falling in Pediplain Shallow (gneissic complex) unit revealed an aquifer resistivity of 84 and 114 Ω-m with thicknesses of 1.9 and 12.8m, respectively. Bore well drilled at this site encountered water at a depth of 27m yielding 3.3 m^3/hr. VES No. 11 falls in Pediment Inselberg geomorphic unit (gneiss complex). It revealed an aquifer resistivity of 59 and 197 Ω-m with thicknesses of 24 and 8.1m, respectively. The bore well drilled at this site encountered water at a depth of 28m with a higher yield of 5.9 m^3/hr. This can be attributed to the lower range of resistivity and higher thickness of the aquifer. VES No. 16 falls in Pediment Inselberg geomorphic unit (gneiss complex) and represents aquifer resistivity of 72 and 175 Ω-m with thicknesses of 1.9 and 17.7m, respectively. The bore well drilled at this site encountered water at a depth of 49m with yield of 3.3 m^3/hr. Similarly, VES No. 20 falls in Pediplain Shallow (gneiss complex) unit and has an aquifer resistivity of 134 and 298 Ω-m with thicknesses of 9.4 and 10.1m, respectively. The bore well drilled at this site encountered water at a depth of 21m with yield of 3.3 m^3/hr. The medium range of yield at these two sites (VES 16 and 20) could be due to the higher ranges of resistivity and lower thickness of weathered layer. In general, it is observed that there is a good correlation between interpreted layer parameters and lithologs up to the weathered zone in some cases and even fractured zone in some other cases. The success of these wells was mainly due to the fractured rock, which was not revealed in some cases probably due to its small thickness in comparison to the depth of occurrence. Maximum yield was reported at VES No. 2 in the valley fill region. At this location lower values of resistivity are indicated for the weathered/fractured zone. The observed lithologs for these sites are shown in Figure 4.

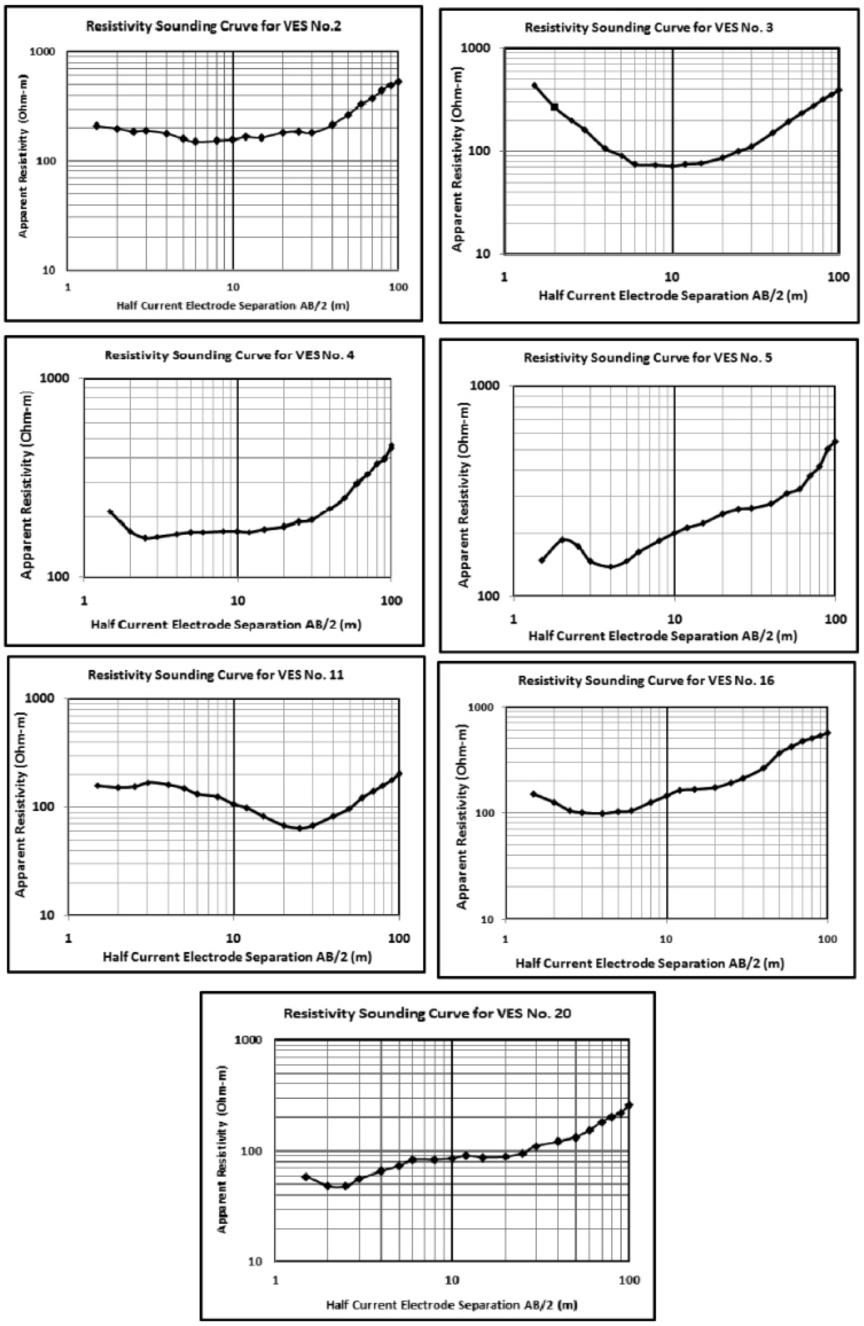

Figure 3. Interpreted Vertical Electrical Soundings curves at the sites recommended for drilling.

Thirty-one ERT using Wenner-Schlumberger configuration with 48 electrode arrangement of 5m inter-electrode separation were carried out (Figure 2b). Based on the interpretation of ERT data, nine sites were recommended for drilling up to 60m. The recommended sites and the results of drilling are given in Table 3. ERT No.3 exhibits low resistivity of 47-77.3 Ω-m from top to about 15m on left side and about 9m on right side of image, representing a water saturated weathered formation underlain by a layer of resistivity of 127-210 Ω-m representing semi-weathered/fractured formation. Below this zone, a hard formation extends up to 18m depth in the central part of the image. This zone is underlain by a slightly high resistivity of >345 Ω-m corresponding to a hard massive formation (Figure 5). The bore well drilled at this site encountered water at 52m with yield of 7.5 m^3/day. ERT No. 6 indicates a well stratified low resistivity values. Resistivity is varying between 80 to 130 Ω-m, along

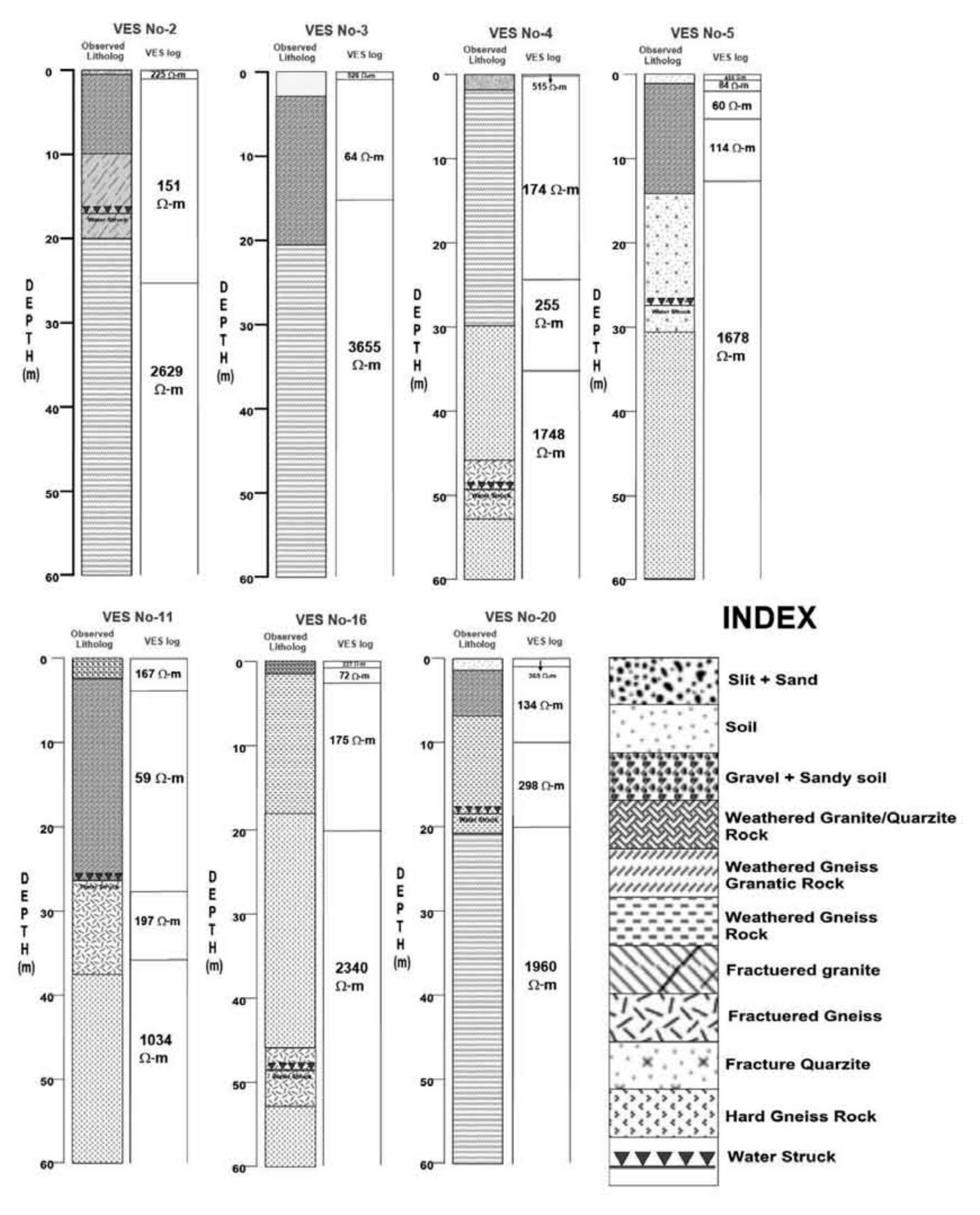

Figure 4. Observed Lithologs at VES Nos. 2, 3, 4, 5, 11, 16 & 20.

the profile, up to a depth of 30m. It indicates a potential aquifer underlain by a semi-weathered/fractured formation (150 and 300 Ω-m) up to 38m depth followed by basement at 50m depth (Figure 5). The bore well recommended up to 60m in the central part of the profile yielded water at 40m depth in the semi-weathered formation, with a reported low yield of 0.095 m^3/day (Table 3). ERT No. 13 indicates highly weathered zone with resistivity <130 Ω-m uniformly stratified up to 24m depth. It is underlain by a semi-weathered formation and further below by hard rock basement (Figure 5). The drilled bore well up to 60m depth struck water at 21m depth (Table 3) with the weathered zone extending to 30m depth, yielding 2.4 m^3/hr. It is significant to note that the top weathered zone of a suitable resistivity and sufficient thickness did not yield water and only deeper fractured zone yielded water in this watershed. ERT image of Profile No.14 indicated well stratified weathered formation of low resistivity <100

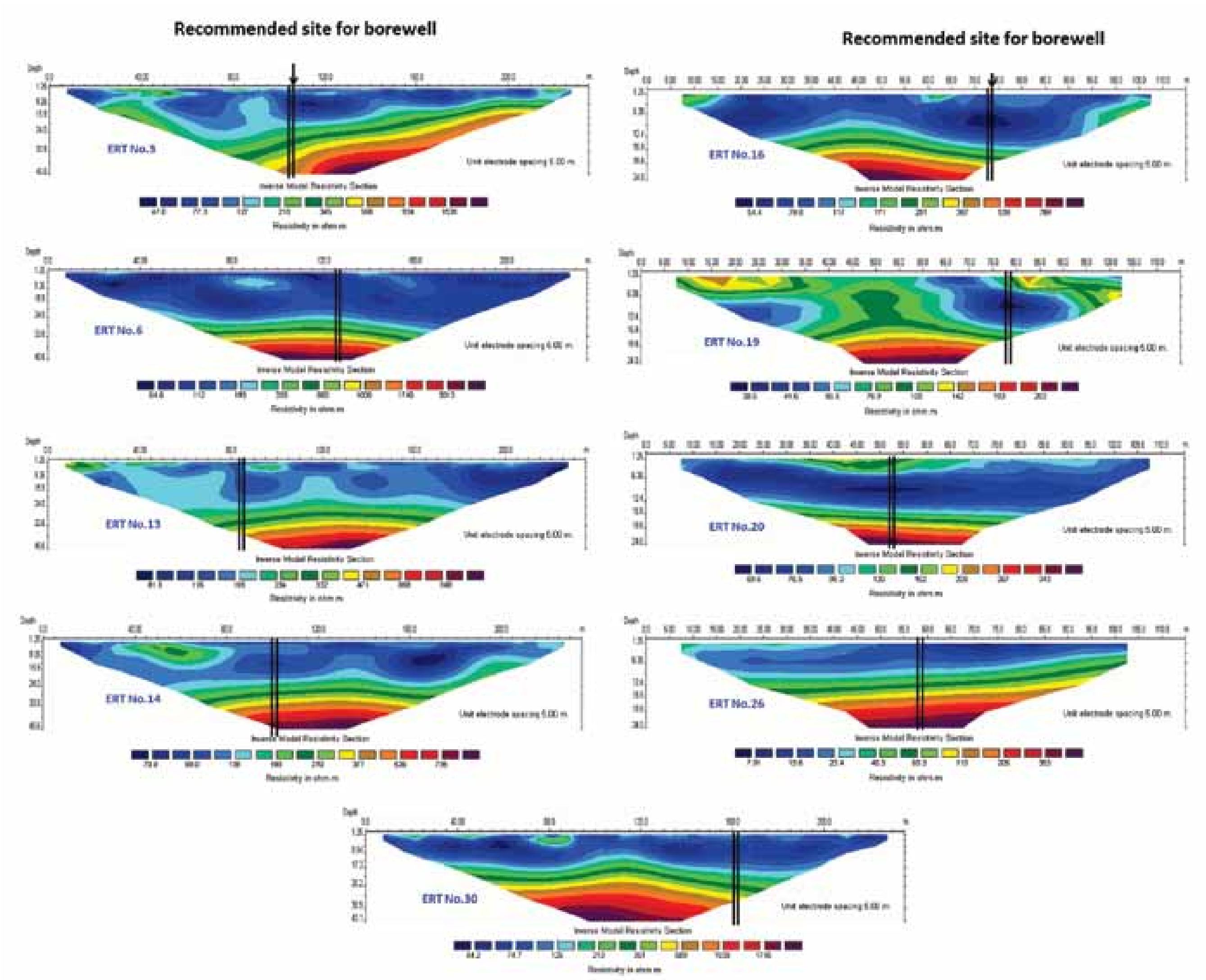

Figure 5. Electrical Resistivity Tomography (ERT) images for ERT No. 3, 6, 13, 14, 16, 19, 20, 26 and 30 recommended for drilling.

Ω-m up to 20m followed by a semi-weathered formation up to 32m depth, which is underlain by the hard rock (Figure 5). A bore well drilled up to 60m depth reported dry condition. ERT Profile No.16 image presented up to 24m depth indicates highly saturated weathered zone up to a depth of 12m all along the profile with slight increase in depth towards right with a resistivity of 79.8 Ω-m. It is followed by a semi-weathered formation having resistivity ranging from 120-250 Ω-m up to 20m depth. Further down it is underlain by the basement (Figure 5). The bore well recommended up to 60m depth struck water at a depth of 43m. In this case also, the top weathered zone has become dry and groundwater potential is only confined to the deep fracture zone of the granite-gneiss terrain, as observed in other parts of the watershed. The yield is 0.6 m^3/hr.

Image of the ERT No. 19 represents low resistivity weathered formation of <100 Ω-m extending up to 20m depth. Slightly lower resistivity of 30.6-41.6 Ω-m was inferred along the edges of the profile. A fracture zone of about 5m thickness revealed above the hard rock having resistivity >300 Ω-m (Figure 5). A bore well recommended up to 60m depth struck water at 30m depth with a high yield of ~7.5 m^3/hr (Table 3). In spite of a thick weathering of top layers at shallow depths, the groundwater potential is limited to the fracture zone only due to recurring droughts in the area. ERT No. 20 indicates occurrence of a well stratified highly weathered formation with very low resistivity of <70 Ω-m extending up to 15m depth. It is underlain by a fracture zone up to 20m depth followed by basement with resistivity >300 Ω-m (Figure 5). A bore well recommended up to 60m depth struck water at 30m depth in the fracture zone (Table 3) with reported well yield of 5.9 m^3/hr. The image of ERT Profile No. 26 represents occurrence of a well stratified low resistivity zone up to

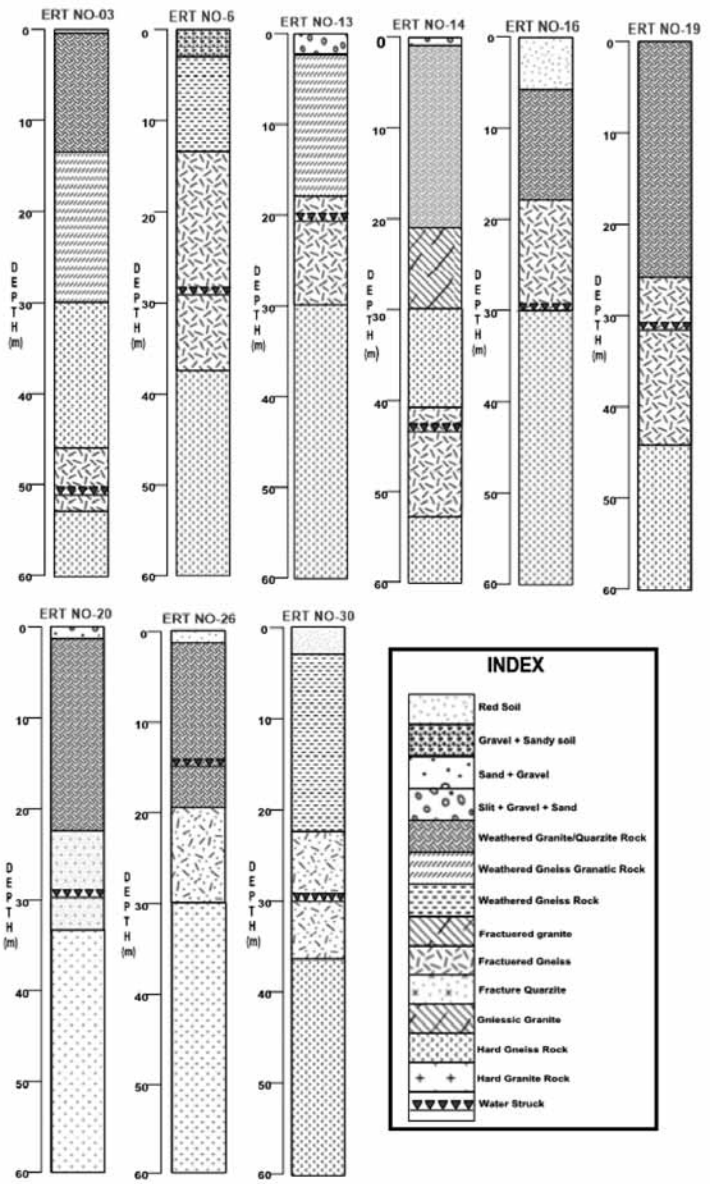

Figure 6. Observed Lithologs at ERT Nos. 3, 6, 13, 14, 16, 19, 20, 26 & 30.

20m depth. The weathered zone is underlain by fracture zone of 5m thickness underlain by hard rock formation (Figure 5). A bore well was recommended on the basis of resistivity of the top formation from the ERT at this location struck water at 16m depth with an yield of 19 m^3/hr. ERT Profile No.30 indicates a uniformly stratified layer of low resistivity of $<100\ \Omega$-m along the profile up to 20m depth, followed by the fracture zone extending up to 25m depth (Figure 5). A bore well drilled at this site, struck water at 30m depth in the fracture zone with a yield of 0.25 m^3/hr. The observed litholog for borewells at ERT Nos. 3, 6, 13, 14, 16, 19, 20, 26 & 30 are shown in Figure 6. These lithologs were compared with the ERT images and found to be well correlated.

Thus, from drilling results of 16 bore wells at various places in the study area, it is observed that the groundwater occurrence and distribution is not uniform. At some places, it is occurring at shallow depths of 16-30m in the weathered formation, while at some other places it is struck at deeper depths of 43-52m in semi-weathered/fractured column. This behavior of groundwater distribution is very common in a crystalline hard rock terrain. It can be observed that, at VES No.3 and ERT No.14 the drilling results show dry condition, even though those sites have low resistivity zones. Based on the observed litholog, a fence diagram was prepared depicting the aquifer geometry of the study area (Figure 7). The fence diagram depicts the thickness of weathered zone is more in the south-western

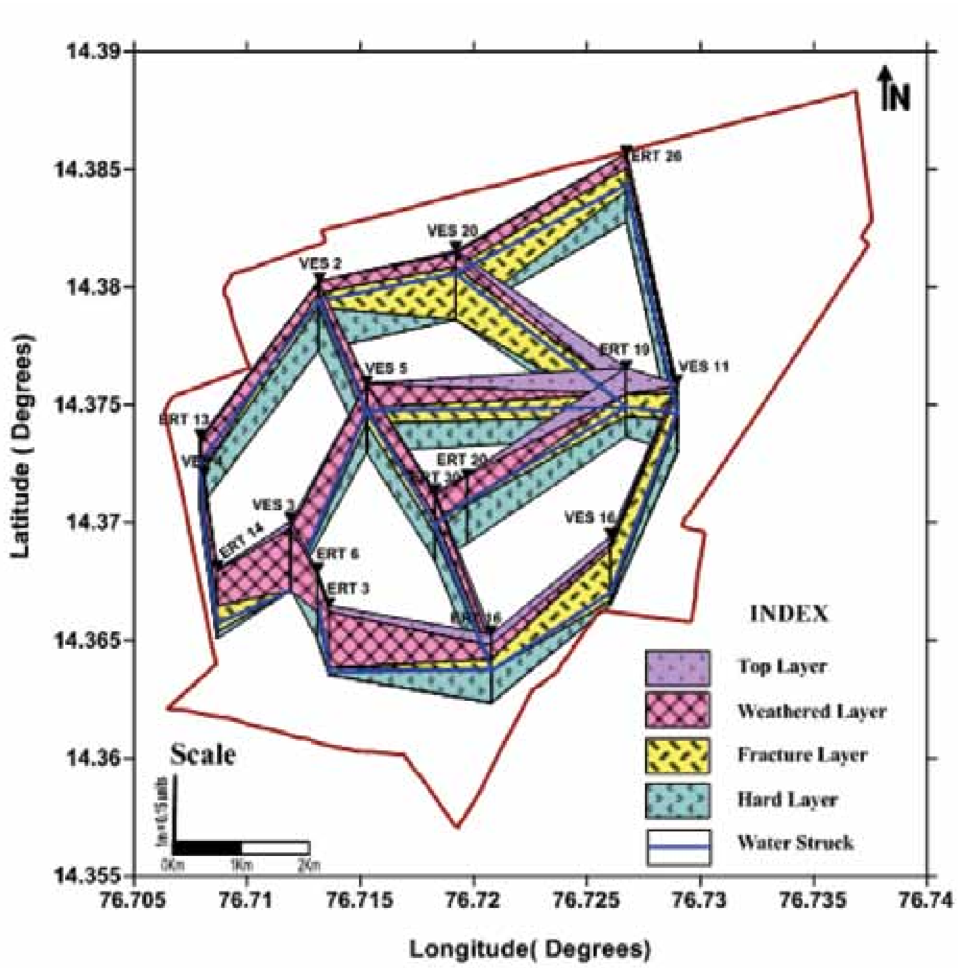

Figure 7. Fence diagram depicting the aquifer geometry of the study area.

part and fractured zone is more towards northern and eastern parts of the study area. From resistivity surveys it is found that in areas where lineaments are intersecting, the thickness of weathering increases. These are therefore, potential areas for the occurrence of groundwater. It is suggested that a few rainwater harvesting pits may be constructed nearby newly drilled borewells for recharging the wells and to maintain sustainable yield throughout the year in a rain fed area.

CONCLUSIONS

Vertical Electrical Soundings at 45 locations with 100-200m spacing using Schlumberger configuration and Electrical Resistivity Tomography at 31 locations using Wenner-Schlumberger configuration indicated highly weathered/ weathered formation with resistivity ranging from 14-150 Ω-m, semi-weathered/fractured formation resistivity ranging from 150-300 Ω-m and hard rock formation with >300 Ω-m in the Ullarthi Kaval watershed. Out of the 16 bore wells drilled on the basis of these studies, 6 high yielding bore wells with >5 m^3/hr yield and 2 dry wells at VES No. 3 and ERT No. 14 were reported. Maximum yield was reported at VES No. 2 and ERT No. 26 in the valley fill regions which also showed lower values of resistivity for the weathered/fractured zone. On comparing the layer parameters and lithology, it is also observed that higher values of resistivity above 300 Ω-m also yielded water due to the presence of fractures. This equivalence problem in resistivity should be kept in mind while recommending wells in virgin areas in a watershed. From the drilling results, it is observed that the area is of very heterogeneous nature with reference to the occurrence and distribution of groundwater resources. Construction of 13 recharge pits close to the newly drilled high yielding bore wells in the Ullarthi Kaval watershed is recommended based on VES and ERT. Thus, the efficacy of the VES and ERT methods is well revealed by the correlation between the layer parameters derived from the above studies and litholog data. The studies also revealed that the integration of geomorphological, remote sensing and resistivity studies is very essential to have high success rate in hard rock terrain.

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Compliance with Ethical Standards

The authors declare that they have no conflict of interest and adhere to copyright norms.

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