Research Article

Delineation of Fractured Aquifer Using Numerical Analysis (Factor) of Resistivity Data in a Granite Terrain

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In hard rock terrain, fractured aquifers comprise the major source of groundwater availability where the phreatic aquifer is desaturated. Identification of fracture zones in hard rock terrain and potential groundwater source delineation had been a perennial problem in hydrology. The purpose of this paper is to highlight the study over a small watershed area, in a granite terrain, wherein an attempt was made to delineate and map the fractured aquifer using numerical (factor) analysis of the conventional vertical electrical sounding data, which was obscure in curve matching technique. This numerical approach in concatenation with resistivity imaging or other techniques would prove to be an effective tool in groundwater exploration.

1. Introduction

The quest for water for all purposes in life has drifted from ordinary search for surface water to ground water through boreholes with the advent of technology. Rapid industrialization, population growth, agricultural related activities, and natural climatic imbalance have forced mankind into overexploitation of natural resources, of which groundwater is one of the vital commodities. Groundwater in lithological formations is generally identified by several physical parameters of the subsurface which are determined by geophysical methods such as electrical resistivity methods, seismic methods, magnetic methods, and gravity methods. By and large, vertical electrical sounding (VES) with mostly Schlumberger and Wenner configurations is conventionally practised in different parts of the world [1, 2] by geologists from Central Groundwater Board, Geological Survey of India, State Groundwater Division, Universities, and so forth. It is reported that the electrical resistivity method for groundwater exploration in a sedimentary environment has proven reliable [3]. Several investigation records have shown that the depth to aquifer differs from place to place depending on various factors like variational geothermal and geostructural occurrence [4, 5].

The resistivity investigations in hard rock regions by and large reflect in A, H, or HA type of sounding curves.

In hard rock terrains especially granites and charnockites, deciphering the actual depth to the aquifer zone using conventional resistivity curve matching technique is difficult. Hence, drilling of bore wells and tapping fractured aquifer at desired location and depth, based on data interpretation by conventional method, may not yield aquifer zones at interpreted depth. In this paper the basic resistivity (VES) data from granite terrain was subjected to a semiquantitative approach, namely, factor analysis, in order to eliminate the suppression effect from the overburden and to refine the depth to aquifers in a granite terrain. The hindrance in clarity to the fractured aquifer depth had compelled in examining the raw data of VES within a small area of 2 sq.km. in a granite terrain of Nalgonda district, Andhra Pradesh, Indian subcontinent. The factor analysis showed good correlation with the actual aquifer depth drilled. This technique was adopted by geologists, hydrologists, and consultants in the field of groundwater exploration of different state and other groundwater divisions.

The geology of the study area under discussion mainly comprises pink feldspathic granite with different degree of weathering resulting in vertical and oblique joints and fractures. The soil thickness varies from 20 cm in the elevated part to a maximum of 4 m in valleys and plains. The soil is mostly loamy, sandy loam, and loamy sandy and is classified as red soils. The thickness of weathered granite residuum varies

widely and ranges between 8 and 20 m. Shallow, horizontal to inclined fractured and fissured granites occurred beneath the weathered zones extending up to 30–75 m below ground level. Major part of the watershed (central area) is undulating plain country with isolated residual hills, while the western side is occupied by north-south trending hill ranges. The topographic elevation varies from 730 m above mean sea level (AMSL) to 312 m AMSL, and the slope of the watershed is towards ESE. The entire watershed area can be classified into four important geomorphic units, namely, denudation hills, dissected pediment, valley fills, and pediplain. The prime source of groundwater in the watershed area occurs under both phreatic and semiconfined conditions in the weathered and fractured granites.

2. Study Area

The study area under discussion is located in semiarid climate zone of Indian subcontinent with average annual rainfall of 500 mm. As mentioned earlier, the area is situated in Nalgonda district, Andhra Pradesh, lying between latitude 17.8 and 17.158 N and longitude 78.88 and 79.8 E. There are several irrigation and development projects implemented in the district to uplift and sustain the declining groundwater status. In general the groundwater abstraction is on the higher side with about 55556 bore wells and about 109380 dug wells existing in the district [6]. The study area comprising ~2 sq.km. is located at a distance of about 75 km East South East (ESE) of Hyderabad city, India. The agricultural sector in the study area mainly depends on groundwater resource for cultivation. The study area forms the part of Krishna river catchment and is characterized by rugged terrain with hills and plains [7]. The drainage pattern of the area is parallel to subparallel in the western part and subdendritic to dendritic in nature in the eastern part as seen in Figure 1.

The area under study is devoid of dependable and sustainable irrigation facility. Surface water irrigation facilities in the form of minor irrigation tanks locally termed as Cheruvu in the area are dry for the last 4-5 years due to continuous chronic drought condition in the area. Hence the agricultural sector is mainly dependent on groundwater for sustaining the basic need for cultivation, during pre-monsoon periods. Survey on well inventory in the study area revealed few tens of open wells and large number of dug-cum-bore and bore wells drilled up to the maximum depth of 80 m. Yield test carried out for dug-cum-bore and bore wells was not prospective in more than 50% of the cases due to the occurrence of massive rocks and dry fracture zones. The study area has three bore wells (BW-1, BW-2, and BW-3) drilled 60 m, 55 m, and 58 m, respectively, trending NNW and SSE direction along the course of the rivulet, as shown in Figure 1.

3. Materials and Methods

Geophysical prospecting of groundwater refers to both surface and subsurface exploration. Geoelectric sounding (VES) survey using Schlumberger configuration was conducted in the study area, using resistivity meter of IGIS, Hyderabad

(India) make, with accessories. Schlumberger configuration was adopted to acquire deeper current penetration. Seven geoelectric soundings were carried out in the study area, along the alignment of the existing bore well. The bore wells BW-1 and BW-2 are separated by 55 m and BW-2 and BW-3 are 40 m apart. VES sites were chosen accordingly, covering almost equidistance from each bore well site. The Schlumberger electrode array employed in each VES was with the maximum half current electrode spacing ($AB/2$) of 150 m. The depth of current penetration using the Schlumberger electrode array is $1/3$ to $1/4$ of $AB/2$ [8, 9], which was deemed sufficient and a depth of the order 38 m to 50 m was achieved. The axis of all the geoelectric soundings was aligned EW, perpendicular to the course of the rivulet cum groundwater flow direction in the area.

3.1. Resistivity Method. The resistance offered by the opposite faces of a unit cube of material to direct current is termed as electrical resistivity. Unit of resistivity in geophysical literature is connoted as the ohm·m. The resistance (R) of the material having a resistivity (ρ) over a length (L) and surface area of current flow (A) is represented by

$$R = \rho \frac{L}{A}. \quad (1)$$

The above relation is known as Ohm's law, which governs the resistivity of the geological formation. Resistivity is generally high under dry conditions and decreases with moisture or clayey material. Presence of water in voids, cracks, or fractures even in minor amounts eases the path for current passage and makes the geological formations relatively conductive.

3.2. Acquisition and Processing of Resistivity Data. The resistivity of the subsurface formation is measured using four electrodes, two metal bars for passing current into the ground (current electrodes) and two nonpolarizable porous pots for potential variation measurements (potential electrodes). The current of electrical intensity (I) is introduced between current electrodes which can be identified as A and B. The potential difference produced as a result of current flow is measured with potential electrodes represented as M and N. If Δ^r represent the potential difference, then the resistivity measurement is represented as

$$KX \frac{\Delta^r}{I}, \quad (2)$$

where K represents the geometric factor or configuration factor, which depends upon the electrode arrangements pertaining to a particular electrode configuration. Also the resistivity measured in the field is apparent, since the passage of current through geological formations is heterogeneous in nature. The acquired resistivity data of a vertical electrical sounding (VES) is plotted on a double log sheet, in order to accommodate both the spacing and apparent resistivity variations.

FIGURE 1: Location map of the study area with bore well location.

3.3. Interpretation of Resistivity Data. The data acquired from VES survey is subjected to quantitative interpretation so as to attain fairly good information about the subsurface (depthwise lithostratigraphic sequence) at the center of each VES. There are two methods in sounding interpretation, namely, (a) *direct method* and (b) *indirect method*. Of the two, the indirect method is discussed in this paper, as all the VES soundings are interpreted using this method. This method is based upon comparing the field curves with the sets of theoretical curves which are generated through computation processes. There are several catalogues of theoretical master curves calculated for a variety of layered lithological structure. The monograph by Bhattacharya and Patra [10] explains in detail about the principle and technique of interpretation by curve matching [11]. If the response of subsurface is

of more layered nature, then the partial curve matching technique is adopted for interpretation.

During the computation, the derived geoelectric model from curve matching interpretation of the sounding data under processing is fed into computer based software like MS-RESIST, IPI2 Win Version 3.0.1, and so forth to generate best fit theoretical curve along with the RMS error. If the RMS error is lower than 2.5 (general acceptance factor) then the model derived from curve matching technique is usually accepted to be one of the suitable subsurface geoelectric layered sequences present at the investigated site. The final geoelectric layered sequences are transformed into hydrogeological conditions for further consideration in point of exploration and decision making.

3.4. Calculation of “Factor” from Apparent Resistivity Data. Factor analysis is a statistical method used to describe the variability among observed and correlated variables in terms of a potentially lower number of unobserved variables called factors. The resistivity variation in lithology with increasing depth is more prominent in vertical electrical sounding compared to other investigation methods [12]. Processing and interpretation of VES data bring out numerous geo-electrical layers. In order to decipher and locate potential pay zones, the inference drawn from the layered parameters needs to be combined with local hydrological conditions. In granite terrain, mostly the existence of potential pay zones is in semiweathered or fractured granite. The apparent resistivity field data pertaining to such terrain hardly shows any significant change in the geoelectric trend which would be possibly interpreted as a separate geoelectric layer. Under such circumstances the apparent resistivity data is subjected to a calculation wherein the ratio of apparent resistivity of a particular separation of AB/2 to the cumulative apparent resistivities of earlier separations is calculated. The ratio is called “factor” as follows:

$$F\rho_a^{10} = \frac{\rho_a^{10}}{\sum \rho_a^{8,0}}, \quad (3)$$

where 1.5, 8, and 10 indicate the AB/2 positions.

The results are generally decimal followed by numerical values and two consecutive values pertaining to respective depths will be the same if there is a fracture at that depth. In the above manner, the factor for all the current electrode separations observed while doing VES is calculated. The factor versus AB/2 on a double log scale is then plotted to identify flat segments at places which represents probable fracture zones/pay zone.

4. Results and Discussion

The bore wells in the study area as mentioned were logged manually, based on the lithological samples collected at the time of drilling and also the information recorded in the driller's dairy. Drilling of BW-1 had encountered a fractured aquifer (pay zone) at a depth of 48–52 m with a yield of 25,000 litres/hour. Similarly drilling at BW-2 had encountered two fracture zones at 8–12 m and 43–47 m. The latter happened to be the aquifer zone with a yield of 20,000 litres/hour. In the same continuity the BW-3 had encountered the fractured aquifer at 38–44 m with a yield of 16,000 litres/hour. A lithological section was attempted for the drilled bore wells with respect to mean sea level to depict the depth to the aquifer.

Further to geophysically trace the depth to the fractured aquifer at each drilled bore well location, VES was carried out. Three vertical electrical soundings, namely, 1, 4, and 6, were carried out near BW-1, BW-2, and BW-3, with AB/2 separation 100 m, 150 m, and 130 m, respectively, along EW orientation. Interpretation of the apparent resistivity plot using IPI2Win Version 3.0.1 for the three VES was carried out, but the results did not show any significant variation or change in resistivity at depths as mentioned by the driller. The

sounding data was then subjected for factor calculation; the results are shown in Table 1. The results revealed presence of fracture zones at different depths.

The apparent resistivity and its corresponding factor plot for the three VES are attempted on a double log scale as shown in Figure 2. The flat section in the factor plots highlighted in red boxes, corresponding to respective AB/2 separation, indicates the presence of fractured granite. The factor analysis of VES-1 showed a flat segment between current electrode separations of AB/2: 50 and 55. The BW-1 drilled was up to 60 m and the aquifer zone encountered during drilling was at 48 to 52 m. Hence the error limit between the factor calculation and actual aquifer depth is around 5%.

Similar to VES-1, factor analysis for VES-4 and VES-6 also showed flat segment (presence of fracture zone) between 40 to 45 m and 35 to 40 m, respectively. Apart from these, there are a couple of more fractures deciphered in the factor calculation but at deeper levels. The drilled depths of the bore wells were restricted to 50 m to 55 m; hence the other deeper fractures deciphered through factor analysis are not considered in discussion. The BW-2 and BW-3 had encountered aquifer zone during drilling at 43–47 m and 38–44 m, respectively. Hence the error limit between the factor calculation and actual aquifer depth is around 5% for BW-2 and 8% for BW-3, respectively.

Factor calculation was able to decipher fractured aquifer zones in the drilled bore well sites which were obscure in two/multilayer curve matching technique, and also the zones identified were at different depths. Based on these observations, intermittent distances between the bore wells were investigated to map the extent and continuation of the fractured aquifer zone. Electrical resistivity survey VES-2, VES-3, VES-5, and VES7 with AB/2 separation 150 m, 110 m, 130 m, and 130 m, respectively, along EW direction parallel to the previous VES orientation was carried out. In concurrence with the interpretation of the apparent resistivity plot of VES-1, VES-4, and VES-6 the electrical soundings VES-2, VES-3, VES-5, and VES-7 also showed no significant variation or change in resistivity pertaining to the depths encountered at the time of drilling.

Similar to the previous soundings, factor calculation was attempted for the soundings VES-2, VES-3, VES-5, and VES-7. As reported in the earlier factor calculation for VES-1, VES-4, and VES-6, here again similar flat segments were observed at depths 50 to 55 m, 35 to 40 m, 40 to 45 m, and 30 to 35 m, respectively, corresponding to their respective AB/2 separation indicating the presence of fractured granite aquifer. Based on the local geology, drilling information and factor calculation, a lithological section was attempted to map the aquifer zone as shown in Figure 3. The change in depth to the fractured zone (aquifer) between VES-2 and VES-3, approximately 10 m from BW-1 (VES-1), was due to the presence of a fault. Satellite imagery analysis and geomorphological investigation revealed that a fault extending NW-SE passes through the study area as shown in the inset in Figure 3. Later a 2D resistivity imaging was carried out in the N-S orientation, which revealed the presence of the fault in the above described orientation. Probably this might

TABLE 1: Factor calculation for corresponding AB/2 and app. resistivity.

AB/2 in m	Boreholes drilled in these locations													
	VES-1		VES-4		VES-6		VES-2		VES-3		VES-5		VES-7	
	Factor	ρ_a	Factor	ρ_a	Factor	ρ_a	Factor	ρ_a	Factor	ρ_a	Factor	ρ_a	Factor	ρ_a
1.5		45.28		417.09		40.62		44.48		46.13		315.44		29.68
2	1.008834	45.68	0.661248	275.8	1.018464	41.37	0.973471	43.3	1.008888	46.54	0.7912757	249.6	1.060984	31.49
2.5	0.519899	47.29	0.259637	179.9	0.565801	46.39	0.518683	45.53	0.520881	48.27	0.2859975	161.6	0.616315	37.7
3	0.355949	49.21	0.141729	123.7	0.360648	46.3	0.361863	48.24	0.355470	50.1	0.1702356	123.7	0.438455	43.35
4	0.280967	52.67	0.067918	67.68	0.317151	55.4	0.293914	53.36	0.287008	54.83	0.0814263	69.24	0.347771	49.46
5	0.237830	57.11	0.040229	42.81	0.270775	62.3	0.241326	56.69	0.235206	57.83	0.0477827	43.94	0.256156	49.1
6	0.201487	59.89	0.033722	37.33	0.240988	70.46	0.209294	61.03	0.197860	60.09	0.0387122	37.3	0.217668	52.41
8	0.169462	60.52	0.028725	32.87	0.235586	85.48	0.194907	68.73	0.179719	65.38	0.0337923	33.82	0.159862	46.87
10	0.151395	63.23	0.029256	34.44	0.199902	89.62	0.170875	72	0.154974	66.51	0.0337025	34.87	0.122831	41.77
12	0.131031	63.01	0.029225	35.41	0.167900	90.32	0.137628	67.9	0.130467	64.67	0.0307524	32.89	0.109551	41.83
15	0.108037	58.76	0.029799	37.16	0.129150	81.14	0.114920	64.5	0.109039	61.1	0.032021	35.3	0.09772	41.4
18	0.091064	54.88	0.030759	39.5	0.101494	72	0.106574	66.69	0.094601	58.79	0.0325481	37.03	0.079259	36.86
20	0.077669	51.07	0.031133	41.21	0.087126	68.08	0.099401	68.83	0.083559	56.84	0.0328927	38.64	0.073259	36.77
22	0.068120	48.27	0.031057	42.39	0.079001	67.11	0.085974	65.45	0.074659	55.03	0.0324551	39.38	0.068537	36.92
25	0.060724	45.96	0.031614	44.49	0.069071	63.31	0.074438	61.54	0.067162	53.2	0.032149	41.61	0.064575	37.17
28	0.055192	44.31	0.031644	45.94	0.063537	62.26	0.066466	59.04	0.062379	52.73	0.0338623	43.83	0.062404	38.24
30	0.053132	45.01	0.031394	47.02	0.059405	61.91	0.062451	59.16	0.058806	52.81	0.0333137	44.58	0.06253	40.71
35	0.049554	44.21	0.035398	54.68	0.057859	63.88	0.057379	57.75	0.058516	55.64	0.0348865	48.24	0.06254	43.26
40	0.048176	45.11	0.037782	60.43	0.057879	67.6	0.058146	61.88	0.058510	58.89	0.039608	56.68	0.064341	47.29
45	0.047796	46.91	0.037732	62.63	0.060710	75.01	0.056256	63.35	0.052470	55.9	0.039612	58.93	0.067738	52.99
50	0.047210	48.55	0.038926	67.05	0.059524	78.01	0.058674	69.79	0.051263	57.48	0.0402943	62.32	0.071378	59.62
55	0.047208	50.84	0.040329	72.17	0.061718	85.7	0.058678	73.89	0.052292	61.64	0.0422266	67.94	0.074009	66.23
60	0.050374	56.81	0.042526	79.17	0.063557	93.7	0.059244	78.98	0.054087	67.09	0.043903	73.62	0.076536	73.56
70	0.056104	66.46	0.045789	88.87	0.069995	109.75	0.063600	89.81	0.060987	79.74	0.0521737	91.33	0.088008	91.06
80	0.062868	78.65	0.045750	92.86	0.070262	117.88	0.067480	101.35	0.065678	91.11	0.057101	105.17	0.09577	107.81
90	0.067956	90.36	0.055785	118.41	0.070277	126.19	0.071585	114.77	0.065668	97.08	0.057103	111.18	0.09576	118.13
100	0.071976	102.21	0.059156	132.57	0.081632	156.88	0.071582	122.98	0.074482	117.34	0.0635124	130.72	0.10649	143.94
110			0.061911	146.95	0.084208	175.04	0.077386	142.47	0.077548	131.27	0.0653707	143.09	0.110763	165.66
120			0.064117	161.61	0.087642	197.52	0.080434	159.54			0.0671315	156.55	0.113322	188.26
130			0.066831	179.25	0.088282	216.4	0.082234	176.23			0.0666616	165.89	0.114282	211.37
140			0.067502	193.15			0.083147	192.84						
150			0.067509	206.21			0.084579	212.47

FIGURE 2: Apparent resistivity and factor plot for the VES.

FIGURE 3: Lithological cross section based on factor calculation.

be one of the causes that the well yield drastically reduced from BW-1 to BW-3.

5. Conclusion

One of the limitations in two-layer curve matching technique of VES data is to identify deep seated fracture zones in hard rock terrain. The overburden thickness cumulatively adds to the effect of the underlying lithological layers, hence suppressing the effect of independent layer pertaining to respective depth. The practical utility of factor calculation of VES data is to minimise the effect of overburden thickness to a greater extent, which in turn helps in detecting and mapping the spatial extent of hidden fractured zones. Resistivity sounding is widely practiced by several government and autonomous agencies in the field of groundwater exploration

in different provinces of the world. This technique of factor analysis can be adopted with better understanding of local hydrogeology, geomorphology, and so forth and can be extended for groundwater exploration in different geological terrain where surface water for drinking and/or agricultural practice is scarce.

Conflict of Interests

The author declares that there is no conflict of interests regarding the publication of this paper.

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