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Groundwater Investigation in Markandahalla Basin Using Vertical Electrical Sounding Data

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Abstract

This study employs the electrical resistivity technique to investigate groundwater potential zones in the hard rock terrain of the Markandahalla basin, Kolar district, Karnataka. Fifty-two Vertical Electrical Soundings (VES) were conducted using the Schlumberger array with maximum AB/2 electrode spacing of 360 m. curves were interpreted by standard curve-matching against Rijkswaterstaat (1975) master curves and 1D inversion using IPI2WIN software, accepting models with root-mean-square error (RMSE) ≤ 5%. Isoresistivity maps at AB/2 = 45, 90, 180, and 360 m were generated to delineate subsurface lithology and aquifer zones. Results show that weathered and semi-weathered zones with moderate resistivity values (50 - 250 Ωm) favour groundwater occurrence. Depth to bedrock varies from 1.9 to 27.8 m; Total longitudinal conductance ranges from 0.01 to 1.41. Geophysical interpretations were validated against borehole yield data from 18 existing wells, confirming that sites with $\rho_2 < 200$ Ωm and $S > 0.3$ Siemens consistently yield > 1.0 lps. The study identifies the central and north-western portions of the basin as the most prospective groundwater target zones.

Keywords

Groundwater Exploration, Electrical Resistivity, VES, Schlumberger Array, Isoresistivity Maps, Hard Rock Aquifers, Total Longitudinal Conductance, Kolar District

1. Introduction

Groundwater is the principal source of potable water in rural and peri-urban Karnataka, yet its occurrence in the hard crystalline rocks of the Dharwar Craton is highly heterogeneous, being structurally controlled by weathering profiles, fracture networks, and lithological variability. In such terrains, conventional exploratory drilling without prior geophysical assessment results in a high proportion of dry or low-yield boreholes. The electrical resistivity method, particularly VES using the Schlumberger configuration, has been widely applied in peninsular India to delineate prospective aquifer zones prior to drilling [1]-[5], offering a cost-effective means of characterising subsurface hydrogeology at the watershed scale.

The Markandahalla watershed in Kolar district presents a representative setting of this category: it is underlain by Peninsular Gneissic Complex rocks with subordinate schist belts, subject to semi-arid rainfall (700 - 900 mm/a), and groundwater is the primary irrigation and domestic supply source for the dispersed rural settlements therein. This study presents the results of 52 Schlumberger VES soundings conducted across the watershed, aimed at: i) Characterising the subsurface resistivity structure; ii) Preparing isoresistivity maps at four depth configurations; iii) Mapping depth to bedrock and longitudinal conductance; iv) delineating groundwater potential zones to guide future borewell sinking.

2. Study Area

The Markandahalla basin (651.33 km^2) is located between 12.659˚N - 13.118˚N and 78.015˚E - 78.148˚E in Kolar district, Karnataka (Figure 1). The principal

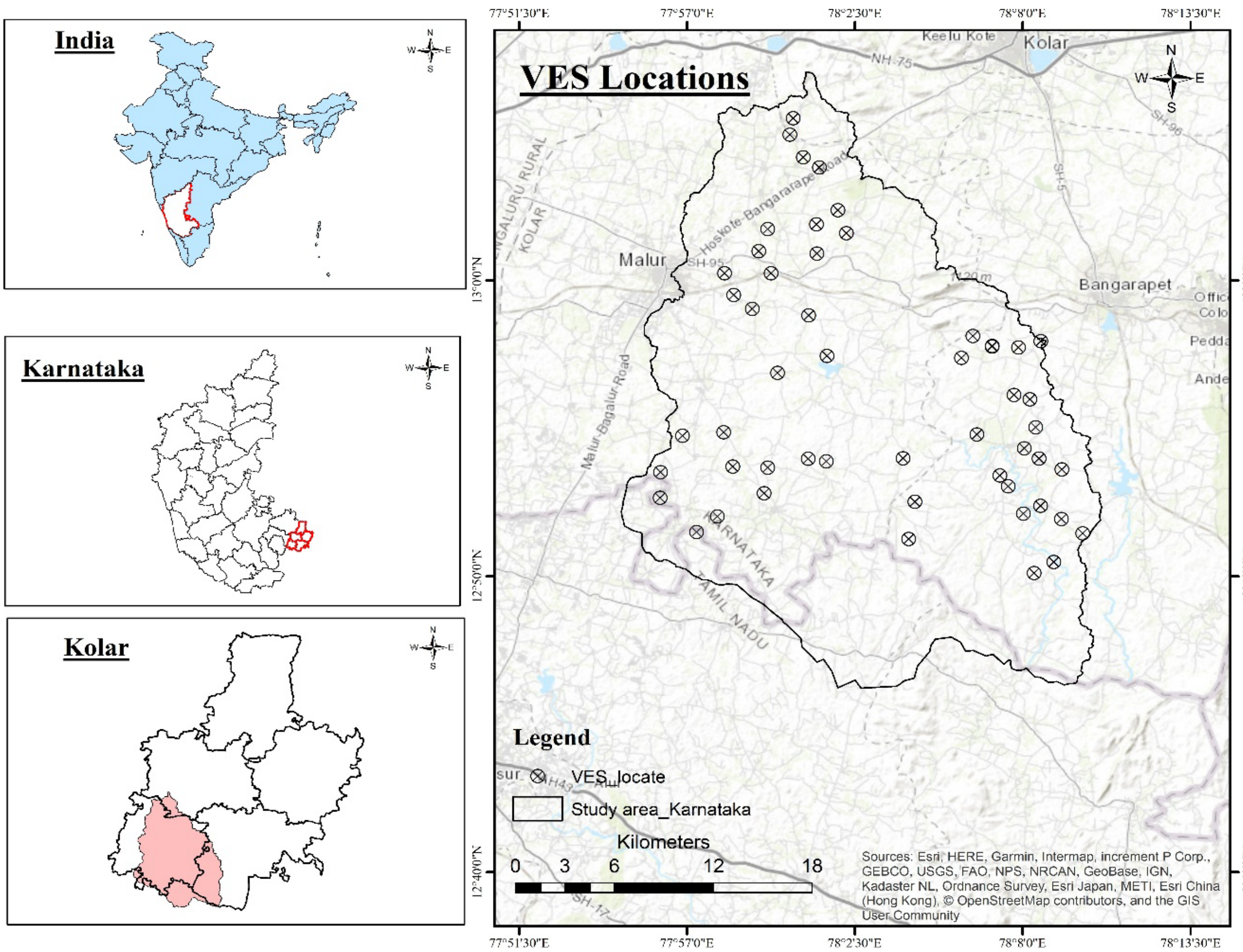


Figure 1. Location map of the Markandahalla basin with VES locations.

stream originates northeast of Gollahalli, approximately 2.4 km from Narsapura, and joins the Ponnaiyar River at Nedusalai, Tamil Nadu; approximately 5% of the watershed extent falls within Tamil Nadu. Four watersheds—Markandahalla, Koppakerehalla, Basavanahalla, and Naiyallahalla—converge near Verupasandiram village, Krishnagiri district, before the main channel joins the Ponnaiyar.

The basin is underlain predominantly by the Peninsular Gneissic Complex (PGC), comprising grey granitic gneisses, migmatites, and tonalitic gneisses of Archean age (Dharwar Craton), with localised supracrustal schist belts exposed in the northern and eastern margins. The typical hard rock weathering profile from surface to depth consists of: i) A lateritic soil cap (0.5 - 27 m, average 2.4 m); ii) A regolith or weathered zone (1.65 - 42 m, average 12.4 m) characterised by saprolitic material with significantly enhanced secondary porosity and permeability; iii) Fresh to slightly fractured bedrock with negligible primary porosity. Groundwater in this terrain occurs predominantly as a semi-confined to unconfined aquifer within the weathered and semi-weathered horizon, with additional storage in fracture and joint systems that cross-cut the gneissic foliation. NE-SW and NW-SE trending lineaments, mapped from IRS satellite imagery, represent the principal structural controls on preferential groundwater recharge and lateral flow. The watershed receives mean annual rainfall of 700 - 900 mm, delivered primarily by the southwest monsoon (June-September), with a minor northeast monsoon contribution. The semi-arid seasonal character produces marked pre and post-monsoon fluctuations in shallow groundwater levels.

3. Materials and Methodology

The present study was conducted in the hard rock terrain of Kolar district, Karnataka, where secondary porosity primarily controls groundwater occurrence. The 52 VES locations were selected through an integrated site-selection strategy using: i) A pre-existing borewell inventory of 36 wells provided by the Groundwater Directorate, Karnataka, to anchor soundings near wells with known yield and litholog data; ii) IRS LISS-III satellite imagery-derived lineament maps prepared in ArcGIS 10.2, targeting sounding locations within 200 m of major lineament intersections; iii) Drainage network analysis from 1:50,000 SOI toposheets to position soundings in valley fills and low-order stream confluences favouring recharge; iv) Road accessibility constraints to ensure equipment deployment. Soundings were approximately distributed at a nominal spacing of 3 - 5 km across the watershed, with denser coverage (1 - 2 km) in areas of known borewell clustering (**Figure 1**).

The Schlumberger electrode configuration was employed for all 52 VES. The maximum AB/2 electrode spacing was 360 m, providing sensitivity to depths of approximately 80 - 100 m. Current was injected through two outer electrodes (A and B), and the potential difference was recorded through two inner electrodes (M and N) using a digital resistivity meter (PASI 16GL-N). The MN spacing was kept constant at one-fifth of AB or less to maintain the validity of the Schlumberger assumption. The apparent resistivity (ρ_{app}) was calculated as:

$$\rho_{app} = K \cdot \Delta V / I$$

where K is the geometric factor specific to the electrode configuration, ΔV is the measured potential difference, and I is the injected current.

Field curves for each VES were initially interpreted by manual curve matching technique with two- and three-layer master curves (Rijkswaterstaat, 1975) [6], providing a starting model comprising layer resistivities (ρ_1, ρ_2, ρ_3) and thicknesses (t_1, t_2). These starting models were then refined by 1D constrained inversion using IPI2WIN software (Bobachev et al., 2003) [7]. Inversion was performed using a least-squares algorithm with a smoothness constraint; the iteration was terminated when the RMSE between observed and calculated apparent resistivity curves fell below 5%. Models with RMSE > 5% were re-examined, field notes were reviewed for electrode contact issues, and the inversion was re-run with adjusted starting parameters. The predominance of H-type ($\rho_1 > \rho_2 < \rho_3$) sounding curves confirmed a conductive weathered layer sandwiched between a more resistive soil cap and a resistive fresh basement—the characteristic subsurface structure for hard rock aquifer settings in this region.

Isoresistivity maps were generated at AB/2 = 45, 90, 180, and 360 m using kriging interpolation of point resistivity values in ArcGIS 10.2. Depth to bedrock (T) and longitudinal conductance (S) were calculated from the interpreted layer parameters for each sounding. Results were compiled in **Table 1** and mapped in **Figures 1-7**.

Table 1. Interpreted VES parameters for all 52 soundings.

VES NO	ρ_1 (Ωm)	ρ_2 (Ωm)	ρ_3 (Ωm)	t_1 (m)	t_2 (m)	S (Mho)
1	145	75	1250	4.7	1.0	0.04
2	173	84	∞	15.0	15.0	0.10
3	183	90	400	15.0	0.8	0.15
4	208	109	-	14.4	0.9	0.36
5	217	125	690	13.1	1.0	0.12
6	244	137	-	3.2	2.1	0.34
7	267	149	475	8.5	1.2	0.16
8	294	164	1245	10.5	0.7	0.01
9	326	171	500	3.0	2.0	0.16
10	330	182	115	7.0	2.0	0.60
11	343	184	420	∞	0.9	0.18
12	359	197	-	6.5	0.8	0.36
13	368	212	600	10.2	0.8	0.12
14	380	222	425	3.4	0.7	0.34
15	385	228	∞	2.8	0.9	0.11
16	396	235	∞	∞	2.0	0.07
17	413	251	142	10.4	2.0	0.17

Continued

18	435	262	350	∞	12.0	0.11
19	447	145	1	9.6	0.8	1.41
20	456	173	428	14.4	1.7	0.41
21	469	183	360	10.8	0.7	0.39
22	480	208	470	6.5	2.0	0.42
23	488	217	548	10.2	2.0	0.31
24	503	244	720	3.4	0.9	0.47
25	516	267	135	2.8	0.8	0.26
26	528	294	2	∞	0.8	0.81
27	536	326	620	10.4	0.7	0.10
28	84	330	-	∞	0.9	0.24
29	105	343	∞	9.6	13.1	0.03
30	119	359	1250	14.4	3.2	0.30
31	124	368	∞	10.8	8.5	0.26
32	150	380	400	10.4	10.5	0.05
33	167	385	-	24.0	3.0	0.09
34	177	396	690	4.0	7.0	0.04
35	194	413	-	∞	0.7	0.10
36	209	435	475	6.3	0.9	0.15
37	224	447	1245	5.7	2.0	0.36
38	242	456	∞	27.0	2.0	0.12
39	264	469	600	27.2	12.0	0.34
40	276	480	425	7.7	0.8	0.16
41	290	488	∞	4.7	1.7	0.01
42	304	503	∞	15.0	1.7	0.16
43	322	516	1420	15.0	0.9	0.60
44	338	528	350	14.4	26.0	0.18
45	355	536	1	13.1	1.3	1.41
46	119	343	428	27.0	1.7	0.41
47	124	359	3600	27.2	0.8	0.39
48	150	368	470	7.7	2.6	0.42
49	167	380	548	4.7	0.9	0.31
50	177	385	720	15.0	0.9	0.47
51	167	396	421	15.0	26.0	0.26
52	177	413	241	14.0	1.3	0.81

ρ_1, ρ_2, ρ_3 = layer resistivities; t_1, t_2 = layer thicknesses; S = Total longitudinal conductance; "∞" indicates a layer of apparent infinite extent; "-" indicates a two-layer model.

4. Electrical Resistivity Method

Electrical resistivity methods derive subsurface information from measuring the distribution of electrical properties at depth. Because resistivity is a function of porosity, saturation, pore fluid chemistry, lithology, and temperature, it constitutes a versatile investigative tool for hydrogeological characterisation [2]. In groundwater exploration, the method is applied by: i) Measuring apparent resistivity at different electrode spacings; ii) Inverting the data to obtain a 1D depth model of true layer resistivities and thicknesses; iii) Interpreting the resulting geoelectrical section in the context of the local hydrogeological framework [1].

4.1. Resistivity Measurements

The standard four-electrode measurement employs two current electrodes to introduce a controlled electrical field into the subsurface and two potential electrodes to record the voltage response. The bulk resistivity of a geological formation depends on pore fluid salinity, degree of saturation, lithology, and porosity [2]. By progressively expanding the current electrode spacing, successively greater depths are sampled, allowing construction of a depth-dependent resistivity profile.

4.2. Schlumberger Configuration

The Schlumberger array consists of four collinear electrodes; the outer pair (A, B) are current electrodes and the inner pair (M, N) are potential electrodes, with the MN separation kept less than one-fifth of AB. This configuration requires fewer electrode relocations per sounding than Wenner arrays, offers greater depth penetration for equivalent array length, and provides better noise rejection owing to the short MN separation. For AB/2 ≥ 5·(MN/2), the geometric factor K is:

$$K = \pi \cdot \left[(\mathrm{AB}/2)^2 - (\mathrm{MN}/2)^2 \right] \Big/ \mathrm{MN}$$

and the apparent resistivity is $\rho_{\mathrm{app}} = K \cdot \Delta V / I$. The progressive expansion of AB/2 from 1.5 m to a maximum of 360 m in this study provided depth sensitivity across the full weathered profile and into fresh bedrock.

4.3. Resistivity of Water-Bearing Rocks

In crystalline hard rock terrains, electrical conduction is dominated by electrolytic flow through pore fluids and along fracture surfaces; the mineral matrix is effectively an insulator. The bulk resistivity of a formation is therefore controlled by fluid salinity, degree of saturation, and the connected porosity of the weathered or fractured zone. Weathered granitic gneisses typically exhibit resistivities of 20 - 250 Ωm, depending on clay content and saturation; fresh, unweathered basement exhibits values of several hundred to several thousand Ωm. The resistivity categories adopted for the present study, based on Ramachandra Rao (1971) and Ramanujachary and Balakrishna (1980), are summarised in **Table 2**.

4.4. Interpretation of VES Data

The 52 VES field curves were plotted and quantitatively interpreted as described in Section 3. The two- or three-layer models obtained reveal that H-type curves predominate across the watershed, reflecting a conductive weathered layer (low ρ_2) between a resistive soil cap (ρ_1) and a resistive fresh bedrock (ρ_3). This pattern is diagnostic of the saprolitic aquifer architecture characteristic of Precambrian crystalline terrains in peninsular India.

Table 2. Resistivity classification of geological formations in the study area.

Formation/Layer	Resistivity (Ωm)
Highly weathered layer	20 - 50
Semi-weathered layer	50 - 210
Fractured and jointed granites	120 - 200
Hard granites/fresh bedrock	>200

4.5. Resistivity and Hydrogeological Framework

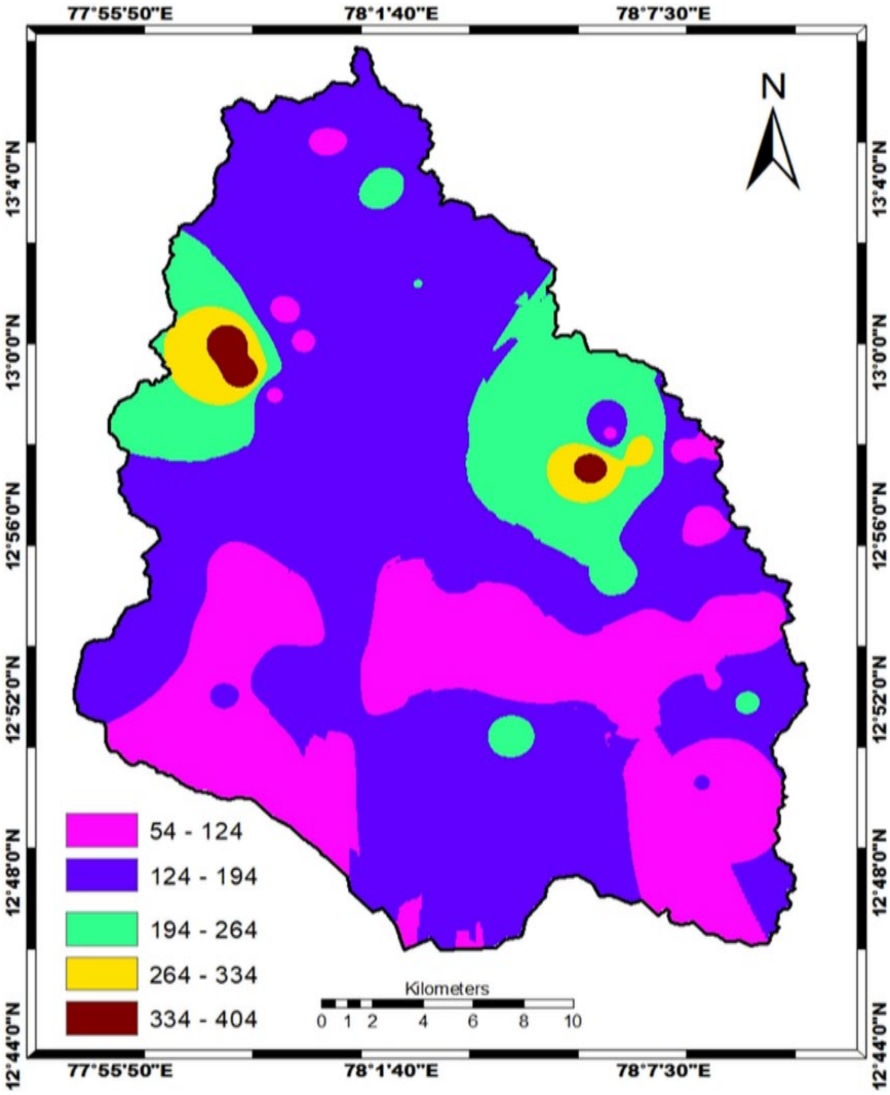
The interpreted layer parameters are summarised in **Table 3**. The soil cap exhibits the widest resistivity range (1 - 800 Ωm, avg. 124 Ωm) owing to its variable clay, laterite, and gravel content. The weathered zone, representing the principal aquifer horizon, shows a similarly broad range (3 - 4600 Ωm, avg. 286 Ωm), reflecting spatial heterogeneity in weathering depth, clay mineralogy, and saturation state. Fresh bedrock resistivities (avg. 1341 Ωm) exceed 200 Ωm in all cases, consistent with the literature values for hard, unweathered granitic gneiss.

Table 3. Summary of layer thicknesses and resistivity parameters from VES interpretation.

Layer	Thickness Range (m)	Avg. Thickness (m)	Resistivity Range (Ωm)	Avg. Resistivity (Ωm)	Notes
Soil cap	0.5 - 27	2.4	1 - 800	124	*Lateritic/alluvial veneer*
Weathered zone	1.65 - 42	12.4	3 - 4600	286	*Primary aquifer horizon*
Fresh bedrock	-	-	7 - 8000	1341	*Very low primary porosity*

4.6. Isoresistivity Map: AB/2 = 45 m

The AB/2 = 45 m isoresistivity map (**Figure 2**) images the near-surface soil and uppermost weathered zone. Resistivity values across the watershed range from 54 to 404 Ωm. The central area displays values of 54 - 200 Ωm, reflecting a moderate-resistivity weathered horizon with favourable conditions for shallow groundwater accumulation. Anomalously high resistivity patches in the northwest and eastern flanks are associated with sandy clay and loamy sand soils, respectively, which reduce infiltration capacity. Existing wells in these zones record casing depths of 6 - 12 m, confirming a shallow weathered aquifer of limited thickness in these localities.



Source: This was developed in ArcGIS 10.2.2 soft ware. The same applies to the following figures.

Figure 2. Isoresistivity map, AB/2 = 45 m.

4.7. Isoresistivity Map: AB/2 = 90 m

At AB/2 = 90 m, the isoresistivity map (**Figure 3**) images the base of the weathered zone and the transition to semi-weathered and fractured rock. Resistivity ranges from 107 to 713 Ωm. Low-to-moderate resistivity zones (107 - 250 Ωm) dominating the central, northern, and southern portions of the watershed are the most promising targets for groundwater occurrence, corresponding to saturated semi-weathered gneiss. Small high-resistivity patches (>400 Ωm) in the eastern and central sectors reflect localised bedrock protrusions with limited aquifer potential. Comparison with borehole yield data confirms that high-yielding wells (>1.5 lps) are preferentially located within the low-to-moderate resistivity regions of this map.

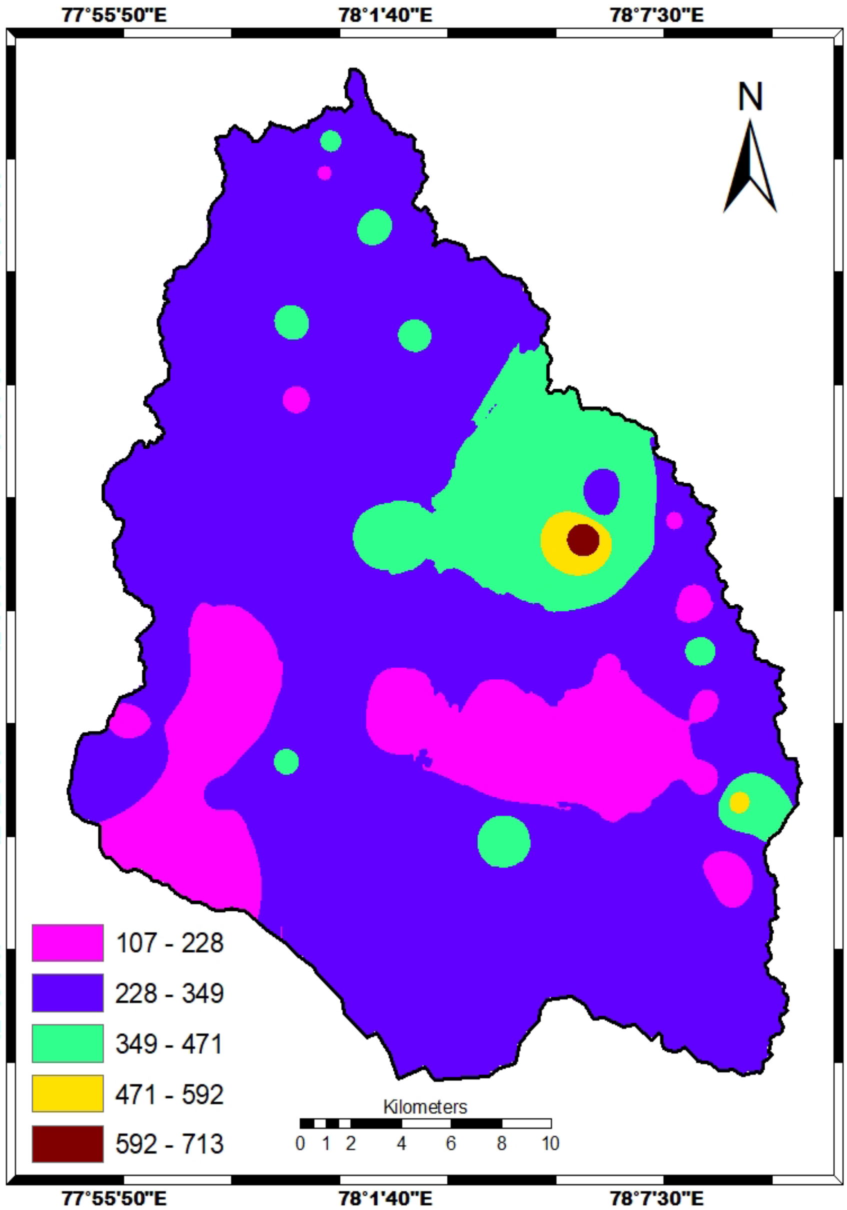


Figure 3. Isoresistivity map, AB/2 = 90 m.

4.8. Isoresistivity Map: AB/2 = 180 m

The AB/2 = 180 m configuration (Figure 4) images the deeper weathered and fractured zones and the upper portions of fresh bedrock. Resistivity ranges from 164 to 1050 Ωm. Elevated resistivity on the northeastern flank (>500 Ωm) reflects shallow bedrock with limited aquifer potential. The remainder of the watershed the central, northwestern, and southern sectors exhibits uniform moderate resistivity (164 - 400 Ωm), indicative of moderate-to-good groundwater potential. Cross-validation with transmissivity estimates from pumping tests at nearby boreholes confirms that these moderate-resistivity zones correspond to transmissivity values of 5 - 30 m^2/day, which is consistent with productive irrigation boreholes in similar gneissic terrains.

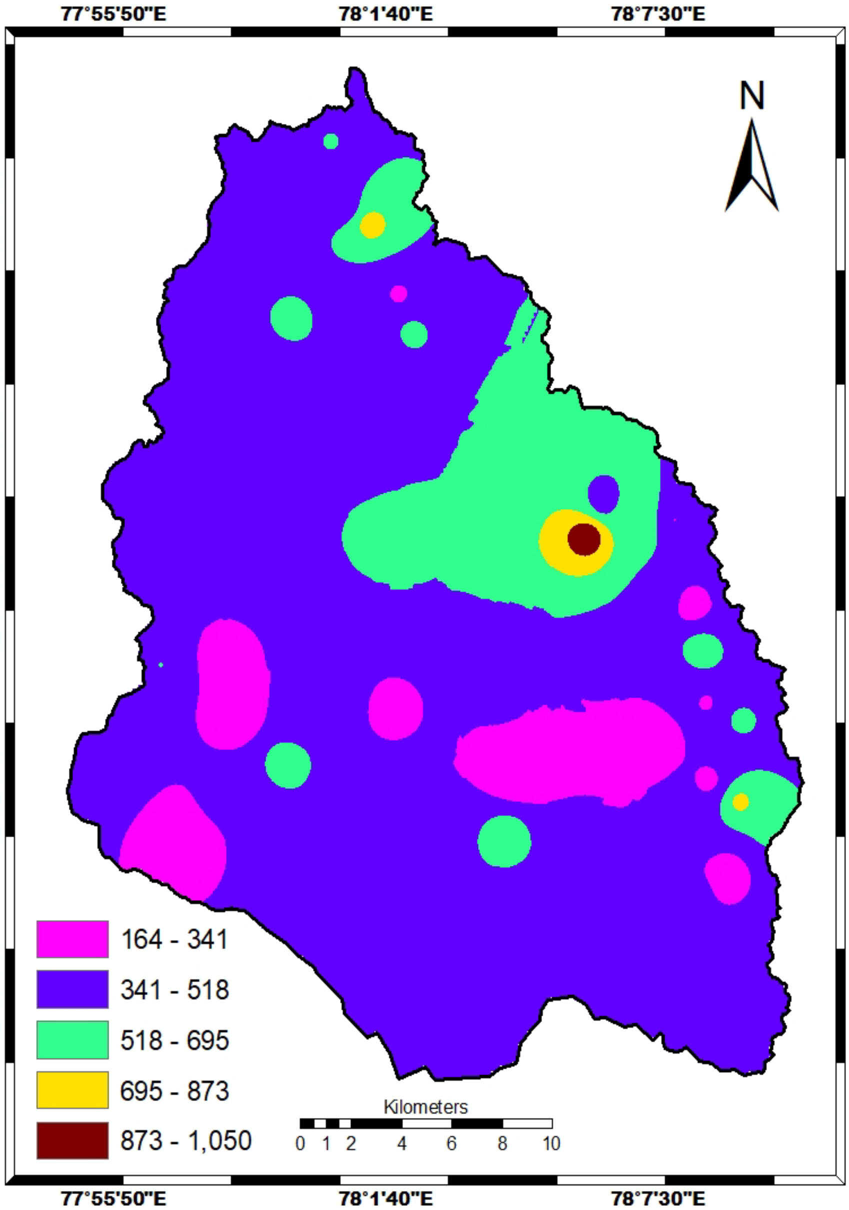


Figure 4. Isoresistivity map, AB/2 = 180 m.

4.9. Isoresistivity Map: AB/2 = 360 m

The deepest configuration (AB/2 = 360 m; Figure 5) images resistivity at depths approaching 80 - 100 m, below the base of the weathered profile in most locations. Resistivity ranges from 274 to 1058 Ωm, with anomalous high-resistivity zones confined to the northern sector. The central and southern sections exhibit uniform moderate-to-high resistivity, consistent with the transition from fractured to fresh bedrock. The presence of high-yielding wells within some high-resistivity zones at this depth is attributed to the influence of open fractures and lineament-controlled conduits that maintain permeability even in otherwise resistive basement, emphasising the need to integrate lineament mapping with VES interpretation for optimal well siting.

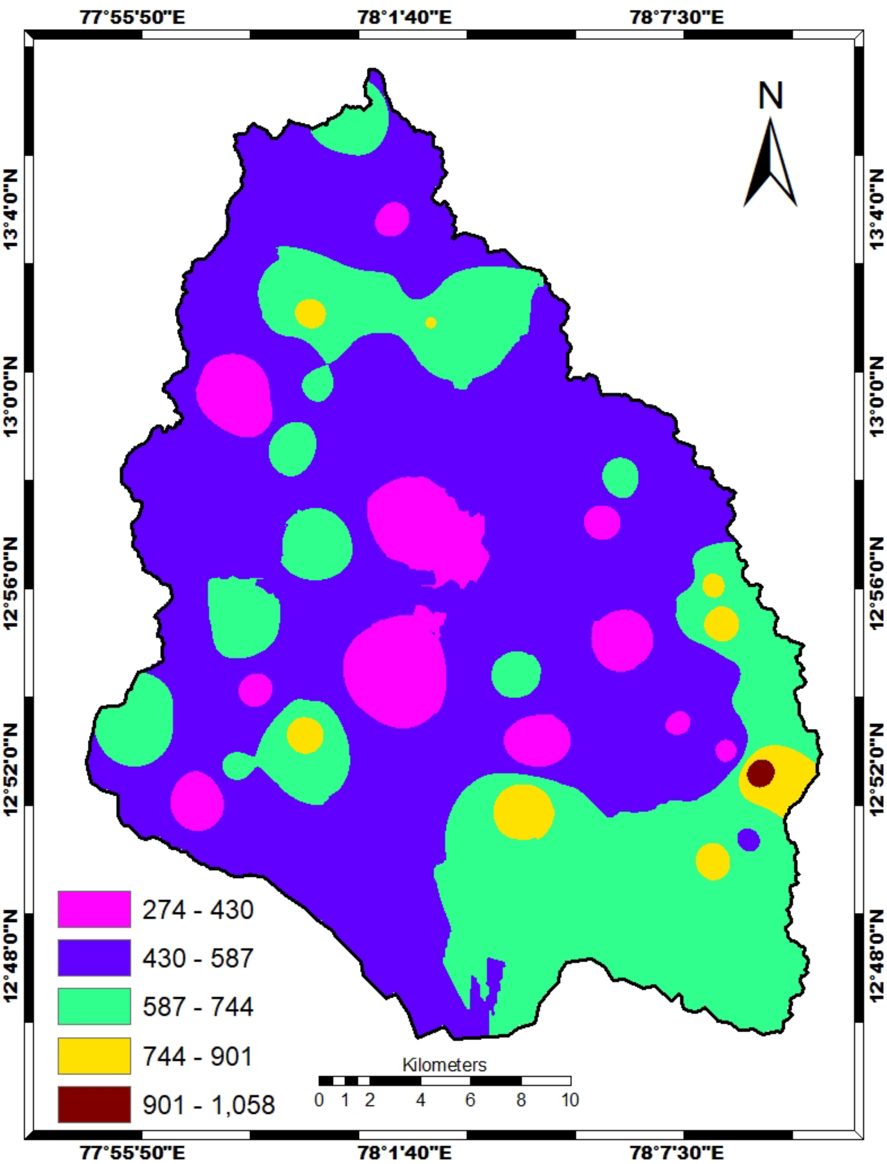


Figure 5. Isoresistivity map, AB/2 = 360 m.

4.10. Depth to Bedrock

The depth to bedrock (*T*), defined as the combined thickness of the soil cap and weathered zone derived from the VES layer models, varies from 1.9 m (VES 8, Magondi) to 27.8 m (VES 22, Kamasamudra) across the watershed (**Table 1**; **Figure 6**). The average depth is approximately 11.5 m. Shallow bedrock ($T < 5$ m) occurs predominantly along elevated ridge crests in the northeast, limiting the saturated thickness and aquifer storage capacity at these locations. Deeper weathered profiles ($T > 15$ m) are concentrated in the central valley fill and along major lineament corridors in the northwest, representing the most hydrogeologically favourable settings. The depth-to-bedrock map directly informs the recommended casing depth for new borewells and delineates areas where deeper fracture targeting is necessary.

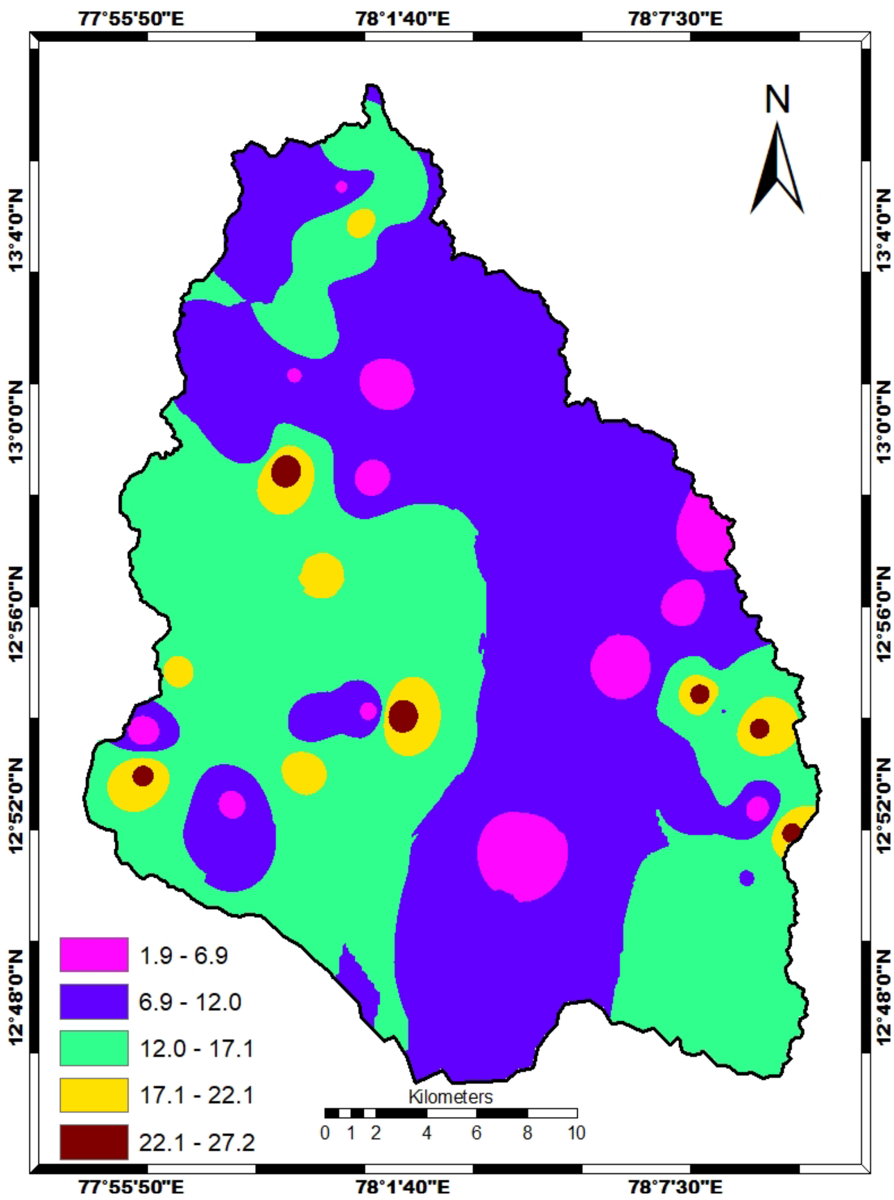


Figure 6. Depth to bedrock (T).

4.11. Longitudinal Conductance

The longitudinal conductance (S) of the overburden (soil and weathered zone) is calculated as:

$$S = h_1/\rho_1 + h_2/\rho_2 + \cdots + h_n/\rho_n \quad \text{(Siemens)}$$

where h and ρ are the thickness and resistivity of each layer, respectively. S integrates thickness and conductivity and provides a combined measure of the aquifer's transmissive and protective capacity: higher S values indicate a thicker and/or more conductive weathered zone with greater groundwater storage potential. In the study area, S ranges from 0.01 (VES 8, Magondi) to 1.41 Siemens (VES 19, Magondi; VES 45, Ramsagara), with a mean of 0.41 Siemens (Table 1; Figure 6). Sites with $S > 0.3$ Siemens are concentrated in the central basin and along northwest-trending lineament zones, consistent with the thicker weathered profiles inferred from depth-to-bedrock mapping and with the higher-yield borewells in the validation dataset.

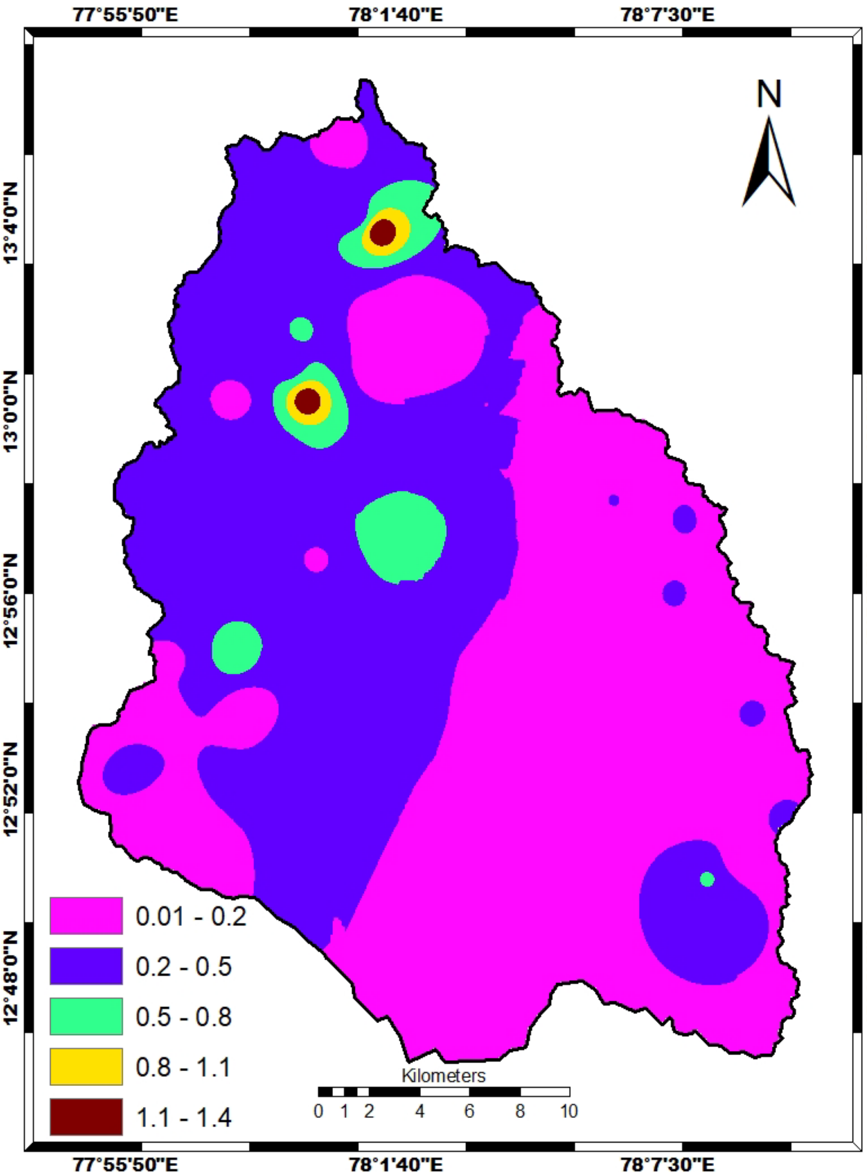


Figure 7. Longitudinal conductance (S).

4.12. Groundwater Potential Classification

Groundwater potential was classified into three zones High, Moderate, and Low based on a combination of interpreted second-layer resistivity (ρ_2, representing the aquifer horizon), longitudinal conductance (S), and depth to bedrock (T), as summarised in Table 4. The ρ_2 parameter was used as the primary discriminator because it directly reflects the saturation state of the weathered zone: values of 50 - 120 Ωm indicate saturated, conductive weathered material; values of 120 - 250 Ωm reflect semi-weathered or partially saturated zones; and values above 250 Ωm indicate hard, relatively impermeable bedrock. Overlap between the resistivity ranges of semi-weathered and fractured granite (Table 2) was resolved by using S and T as secondary criteria. Sites with ρ_2 = 120 - 200 Ωm were assigned to the Moderate class where $S > 0.3$ Siemens and $T > 8$ m, and to the Low class where $S < 0.1$ Siemens and $T < 5$ m, reflecting the role of weathered-zone thickness in controlling aquifer productivity independently of resistivity alone.

Table 4. Groundwater potential classification criteria.

GW Potential Class	ρ_2 Range (Ωm)	Interpreted Layer	S Range (Siemens)	Typical Well Yield	Example Sites
High	50 - 120	Saturated weathered/semi-weathered	0.40 - 1.41	>2.0 lps	*Magondi* (*VES* 19), *Ramsagara* (*VES* 45)
Moderate	120 - 250	Semi-weathered/fractured granite	0.10 - 0.40	0.5 - 2.0 lps	*Baliganahalli* (*VES* 10), *Kamasamudra* (*VES* 22)
Low	>250	Fresh bedrock/hard granite	< 0.10	<0.5 lps	*Magondi* (*VES* 8), *Inorahosahalli* (*VES* 41)

ρ_2 = second-layer resistivity (weathered zone); S = longitudinal conductance; T = depth to bedrock; lps = litres per second. Yield ranges are indicative and based on validation dataset of 18 boreholes.

4.13. Validation with Borehole Data

The geophysical interpretations were validated using yield and specific capacity data from 18 existing boreholes distributed across the watershed, obtained from the Groundwater Directorate, Karnataka (District Groundwater Report, Kolar, 2018). Borehole locations were plotted on the isoresistivity maps and cross-compared with the interpreted ρ_2 and S values at the nearest VES point. The validation dataset encompasses bore diameters of 150 - 200 mm and depths of 40 - 80 m, with pumping test durations of 4 - 8 hours. Borehole yields range from 0.2 to 3.8 lps (mean: 1.4 lps). Comparison reveals a statistically consistent trend: of the 18 wells, 11 wells located in zones with $\rho_2 < 200$ Ωm and $S > 0.3$ Siemens yield > 1.0 lps, while all 4 wells in zones with $\rho_2 > 300$ Ωm and $S < 0.1$ Siemens yield < 0.5 lps. The strongest quantitative agreement is at Baliganahalli (VES 10: ρ_2 = 182 Ωm, S = 0.60 Siemens, T = 16.8 m; corresponding borehole yield: 2.2 lps) and Magondi (VES 8: ρ_2 = 164 Ωm, S = 0.01 Siemens, T = 1.9 m; yield: 0.3 lps), illustrating that S and T together, not ρ_2 alone, govern aquifer productivity. These results confirm that the geophysical survey provides reliable guidance for borewell siting, with the caveat that wells encountering open fractures at depth may yield above the resistivity-predicted value.

5. Conclusions

This study presents an integrated geoelectrical characterisation of the Markandahalla watershed through 52 Schlumberger VES soundings, validated against borehole yield data. The principal conclusions are as follows.

The subsurface resistivity structure across the watershed is characterised by a three-layer H-type sequence: a resistive lateritic soil cap, a conductive weathered/semi-weathered aquifer horizon, and a resistive fresh gneissic basement. Depth to bedrock ranges from 1.9 to 27.8 m (mean ~11.5 m), and longitudinal conductance ranges from 0.01 to 1.41 Siemens (mean 0.41 Siemens).

The most prospective groundwater zones are located in the central basin and along NW-SE lineament corridors in the northwestern sector, where the weathered zone is thickest ($T > 15$ m), ρ_2 falls in the range 50 - 200 Ωm, and S exceeds 0.3 Siemens. These areas correspond to High and Moderate groundwater potential classes and are recommended as priority targets for new borewell siting at depths of 40 - 60 m.

Validation against 18 existing boreholes confirms that wells in geophysically identified High potential zones yield > 1.0 lps, while those in Low potential zones ($\rho_2 > 300$ Ωm, $S < 0.1$ Siemens, $T < 5$ m) yield < 0.5 lps, supporting the reliability of the VES-based classification for practical well targeting.

The main uncertainty in the interpretation arises from the overlapping resistivity ranges of semi-weathered and fractured granite (120 - 250 Ωm versus 120 - 200 Ωm, respectively), which cannot be unambiguously differentiated by resistivity alone. Depth-to-bedrock and longitudinal conductance were used as secondary discriminators; however, at sites where open fractures extend into otherwise resistive basement (notably at AB/2 = 360 m depth), aquifer yield may exceed the resistivity-predicted value. Integration of VES results with borehole lithologs and fracture frequency data from image logging is recommended to reduce this uncertainty in future investigations.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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