MethodsX 8 (2021) 101215

Contents lists available at ScienceDirect

MethodsX

journal homepage: www.elsevier.com/locate/mex

Method Article

Efficacy of hydrological investigation in Karumeniyar river basin, Southern Tamil Nadu, India using vertical electrical sounding technique: A case study

S. Arunbose*, Y. Srinivas, S. Rajkumar

Centre for Geotechnology, Manonmaniam Sundaranar University, Abishekapatti, Tirunelveli 627 012, Tamil Nadu, India

A B S T R A C T

In the Karumeniyar river basin, the groundwater demand increases for irrigation, industrial and larger per capita needs, and the recent year's groundwater table is drastically falling due to both natural and anthropogenic activities. In this context, a study on geophysical vertical electrical sounding (VES) using Schlumberger configuration has been carried out across 72 locations in the Karumeniyar river basin to demarcate the subsurface geoelectrical parameters and to identify the groundwater potential zone along with aquifer protective capacity. The acquired data were inverted using the 1D (resistivity variation with respect to depth) inversion approach IPI2Win demonstrated the presence of three to six subsurface geoelectrical layers in the study area with H type sounding curve being dominant. Furthermore, the deciphered result from VES is cross-validated with lithology data of four wells in the study area. Based on the interpreted results the parameters such as longitudinal conductance, overburden thickness, reflection coefficient and basement resistivity were calculated. It revealed that 36 VES location signifies good to moderate aquifer protective capacity. According to the reflection coefficient value and overburden thickness, the basin was divided into four distinct groundwater potential zones as high (42%), medium (38%), low (15%) and very low (5%). The inverse Distance Weighting (IDW) interpolation method is adopted to generate the spatial distribution maps in ArcGIS environment. The findings of the present study provide the vital geo-database for groundwater potential zones in the Karumeniyar river basin and have important implications for designing, intendance and management of sustainable groundwater resources.

- Vertical Electrical Sounding method is a noninvasive, low cost and effective method for locating groundwater potential zone.
- It measures the vertical wise variation of subsurface resistivity distribution based on surface measurement.
- This technique provides a quantitative evaluation of different subsurface layers.

* Corresponding author.
E-mail address: aksharabose1017@gmail.com (S. Arunbose).

https://doi.org/10.1016/j.mex.2021.101215

ARTICLE INFO
Method name: Electrical Resistivity Method
Keywords: VES, Groundwater potential zone, Aquifer protective capacity, Karumeniyar, Geophysics
Article history: Received 22 September 2020; Accepted 3 January 2021; Available online 6 January 2021

Specifications Table

Subject Area:	Earth and Planetary Sciences
More specific subject area:	HydroGeophysics
Method name:	Electrical Resistivity Method
Name and reference of original method:	Vertical Electrical Sounding (VES) Assessment of groundwater prospect and aquifer protective capacity using resistivity method in Olabisi Onabanjo University campus, ago-iwoye, southwestern Nigeria. Bayewu, O. O., Oloruntola, M. O., Mosuro, G. O., Laniyan, T. A., Ariyo, S. O., & Fatoba, J. O. (2018). NRIAG Journal of Astronomy andGeophysics,7(2),347-360. https://doi.org/10.1016/j.nrjag.2018.05.002.
Resource availability:	All information included in the article. No additional resource requirement (software/hardware) No additional data.

Introduction

Groundwater is one of the precious hidden resources and it is ubiquitously distributed in earth. It is stored in the subsurface sedimentary and crystalline rock formation between pore spaces, fractures and joints [1]. Globally, groundwater contributes 36%, 42% and 27% of water for domestic, agricultural and industrial usages [2]. In a semi-arid country like India, 30% of the urban population and 90% of rural people solely depend on groundwater to satisfy their daily water requirements [3]. Over the last two decades, the groundwater crisis is more pernicious in India due to over-extraction and millions of livelihoods are under risk. Recently, 0.6 million Indian peoples are affected by high to an extreme level of water stress and about 0 .2 million people loss of their life per year because of inadequate access to freshwater [4]. The World Bank has stated in the report, if the precaution measurements are not taken, India will become a water stress zone and water-scarce zone by the years 2025 and 2050 [5]. Among the states of India, Tamil Nadu is facing severe water deficiency due to the changes in the hydrological cycle that linked with the poor water resources [6]. In Tamil Nadu, if the groundwater resources properly have not improved, the availability of water per capita has declined 1284 m^3 into 416 m^3 in 2050, facilitating to produce a single meal in a day to the people [6]. All of these current scenarios re-emphasize the need for prior scientific knowledge to ascertain the groundwater potential zone. Various types of indirect and direct methods are employed for groundwater potential zone identification in several areas [3]. Drilling and stratigraphy surveys are the most commonly used methods for evaluating the borehole location and thickness of subsurface water bearing formation [7]. Nevertheless, these techniques are more expensive and highly time-consuming to assess the groundwater in a particular region [8,9]. In this context, the geophysical method is considered as non-invasive, relatively cheap [10,11] and the most effective method for locating groundwater potential zone compare to older conventional techniques [12–14].Complementing the different geophysical methods, the electrical resistivity technique is most widely used for the groundwater potential targets [15,13]. In electrical resistivity methods, primarily the VES have been used for demarcating the groundwater potential zones in various lithological settings. This survey method measures the vertical wise variation of subsurface resistivity distribution based on surface measurement of the potential field [16]. This technique provides a quantitative evaluation of different geoelectrical layers with respect to resistivity and thickness [17,18]. The VES technique has been chosen for the present study because easier field logistics, better vertical resolution, excellent depth sensitivity, relatively economical and the data analysis are straight forward [19,10,20,11]. In recent years, around the world many researchers have extensively used Vertical

Electrical Sounding for the assessment of groundwater potential zone [21–25]. Consequently, much research has also been carried out in various parts of India and the state of Tamil Nadu by various researchers [26–30]. This present study mainly focuses on deciphering the groundwater potential zone in the Karumeniyar river basin employing geophysical vertical electrical sounding (VES).

Study area

Karumeniar river basin is the southeast part of Tamil Nadu state, India that lies mostly in Tuticorin district and partly in Tirunelveli district with the areal extent of 976 km^2. Karumeniyar river, an ephemeral stream in nature associated with hot and semi-arid climatic conditions with annual precipitation of 280 mm. The drainage system originates from the knoll of the western part of the basin and after traversing a total distance of 56.5 km, the river debouches into the Bay of Bengal. It is worthwhile to mention that the river broadens suddenly at Sattankulam village, which indicates more sedimentation and the abrupt break takes place in the slope pattern. At this location number of streams from various directions adjoins with this river for the development of drainage patterns. The river basin area is underlain by geological rock formation of the Archean complex, Tertiary and Quaternary sediments. The archean complex of crystalline rocks occurred in the western part of the basin area (Fig. 2). It is composed of gneiss, charnockite, quartzite, Calc-granulite and Quartzite rocks. Sedimentary rocks confined to the eastern part of the study area include Quaternary alluvium, laterite, kankar, Tufa and Tertiary sandstone and shell limestone. The larger portion of sedimentary terrain in the northeast of Sathankulam and Kuthiraimozhi area found with red sand is locally named as Teri sand. It is formed due to fluvio-aeolian activity during the periods of 4.1 and 2.3 ka [31]. Hard and compact calcareous sandstone is encountered in Panamparai and Tisayannvillai areas. This sandstone is called Panampari sandstone, which is equivalent to the unique formation of Cuddalore sandstone. The principal agricultural crops cultivated in the study area are banana, patty and groundnut. In the study area, groundwater is a key component for both agriculture and domestic purpose. The inhabitants of the study area depend mainly on agriculture as a prime source for their livelihood. The state government has initiated to execute Intra State river linking of Tamiraparani, Karumeniyar and Nambiyar rivers to supply water to the drought prone areas throughout the year [68].

Materials and methods

Vertical electrical sounding is one of the most widely used electrical resistivity surveys. It is based on the surface measurements where a known electrical current fed into the earth via a pair of current electrodes and the resulting potential gradient is explored by an additional pair of potential electrodes. A total of 72 VES surveys were typically carried out in the entire Karumeniar river basin (Fig. 1). The Schlumberger configuration of VES was adopted for this study to infer the groundwater potentiality. The Schlumberger configuration has certain operational, practical and interpretational advantages over the Wenner array [32–34]. The apparent resistivity measurements were acquired by DDR3 model instrument, Global Positioning System to locate absolute coordinate of the survey points, two steel electrodes to inject current into the earth, two non-polarizable porous pot-electrodes to measure potential, reels for winding and unwinding the cables and wires for connection, hammers to planted electrodes into the ground [35]. In the Schlumberger electrode configuration, the current and potential electrodes are kept symmetrically align in a straight line on each side of the investigation point. The current electrodes are placed central position and the potential ones put in the outer side of the survey area. For a series of measurements the potential electrodes MN retained at the same location, while the current electrodes AB are moved progressively far apart on each side. The resistivity value was obtained by simultaneously increasing the interval between half electrode spacing AB/2 in successive steps. However, the separations between current electrodes distance increases, which results in a very low value in measured potential difference. To overwhelm this, the potential electrodes distance should be increased accordingly to yield adequate voltage [35–37]. The greater expansion of the current electrodes provides deeper investigation about the subsurface

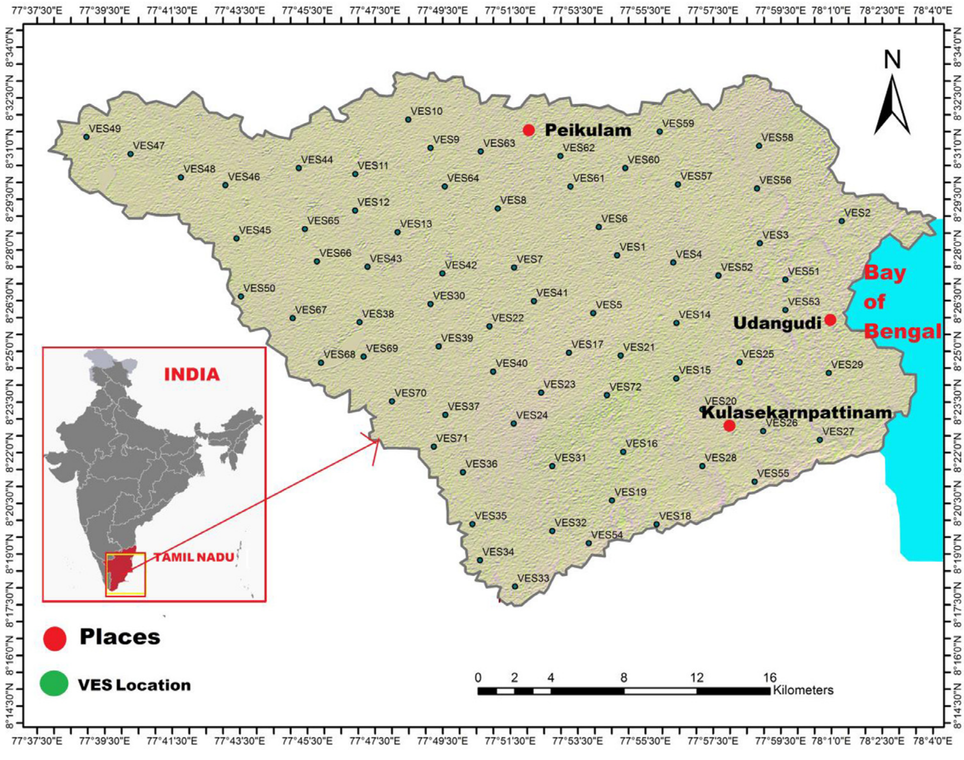

Fig. 1. Study area showing VES locations.

stratification [38–40]. The half spacing of potential and current electrodes ranged from 0.5 to 10 and 2 to 100 m, respectively. Even though naturally occurring self-potential or SP in the ground is precisely nullified, direct and reverse mode measurements were performed to eliminate the impact of small range inhomogeneities by averaging both measurements [41]. VES method is used to determine the depth wise changes of resistivity values. The ratio of potential difference (ΔV) picked up by the potential electrodes and applied current (I) between current electrodes provide the resistance (R). At every VES location, the obtained field data were converted into apparent resistivity (ρ_a) by multiplying the resistance with geometric factor (K) [41].

The field data obtained have been analyzed using computer software (IPI2win) which gives an automatic and manually interpretation of the apparent resistivity [42]. The degrees of closeness were maintained and iterated between theoretical and observed VES curves until the best data fit is reached. To reduce the effects of lateral inhomogeneity and noisy signatures were smoothened in resultant VES curves [43]. The RMS error of entire VES data ranged from 2% to 4.3%. The interpreted 1d model unravels the subsurface information about geoelectrical layers, thickness and depth. All these VES results were taken into the ArcGIS platform version 10.3 year 2014. Inverse Distance Weighting (IDW) interpolation method is used to generate the spatial interpolation maps in the ArcGIS software. The field data was affected due to the man-made electrical currents into the ground and natural telluric origin its lead to create the noise in the observed data. The degree of noise in the acquired field data also depends on the current and potential electrodes distance, electrodes mutual direction, current density, the subsurface resistivity distribution and moisture level in to the ground. Those factors affect the minor variation in the layer thickness.

Table 1
Aquifer protective capacity rating [60].

Longitudinal conductance (S)	Productive capacity rating
>10	Excellent
5–10	Very good
0.7–4.9	Good
0.2–0.69	Moderate
0.1–0.19	Weak
<0.1	Poor

Hydraulic parameters

The primary parameters derived from VES results such as thickness and resistivity values [59] were used to establish the secondary hydraulic parameters like longitudinal conductance, transverse resistance, longitudinal resistivity, transverse resistivity, longitudinal conductance and coefficient of anisotropy are called as Dar Zarrouck parameters [44]. These parameters help to elucidate the subsurface lithology and structural behavior with less ambiguity. The significance of these parameters has been described by different authors [45–53] in different areas. When the electrical current passes horizontally to the bedding plane, it is considered as longitudinal conductance (S) and when the flow of electrical current is transverse to the bedding plane is referred to as transverse resistance [54,55]. Consider a number of geoelectrical layers with a thickness of $h1$, $h2$, $h3$, $h4$,……hn and resistivities of $\rho 1$, $\rho 2$, $\rho 3$, $\rho 4$ ….. ρn respectively, are involved in a geoelectrical section, their longitudianal conductance and transverse resistance are expressed by the following:

When current passing through the length of the vertical column, the sum of each layer resistances from bottom to top is

$$T = \sum_{i=1}^{n} \rho i h i = \rho 1 h 1 + \rho 2 h 2 + \rho 3 h 3 + \cdots\cdots\cdots\cdots + \rho n h n \ \left(\text{ohm.m}^2\right) \tag{1}$$

When the current flowing horizontally through the column of length, the sum of individual conductance in parallel is,

$$S = \sum_{i=1}^{n} \frac{hi}{\rho i} = \frac{h1}{\rho 1} + \frac{h2}{\rho 2} + \frac{h3}{\rho 3} + \ldots\cdots\cdots\cdots\cdots\cdots + \frac{hn}{\rho n} \ \left(\text{ohm}^{-1}\right) \tag{2}$$

The coefficient of electrical anisotropy is an estimation of the degree of inhomogeneity in a subsurface basement terrain, which tends to increase with primary and secondary structural features like beddings, foliations, fractures, faults, joints, a higher degree of weathering and near-surface effects [56,57]. The coefficient of anisotropy (λ) can be measured from combining both average longitudinal resistivity (RS) and average transverse resistivity (RT)

$$\lambda = \sqrt{\frac{\text{RT}}{\text{Rs}}} \tag{3}$$

The reflection coefficient (RC) for the VES locations was calculated by the following equation propounded by Olayinka [58] and Bhattacharya and Patra [43],

$$r = \frac{(\rho_n - \rho(n-1)}{((\rho_n + \rho(n-1)} \tag{4}$$

Where,
ρ_n is the electrical resistivity of the nth geoelectrical layer
$\rho_n - 1$ is the electrical resistivity of the nth overlying geoelectrical layer

Table 2
Longitudinal conductance and protective capacity rating of aquifer in the study area.

Longitudinal conductance Ω^{-1}	VES location	Protective capacity
0.208046938	VES1	Moderate
0.164430642	VES2	Weak
0.518629452	VES3	Moderate
0.109566211	VES4	Weak
0.461676073	VES5	Moderate
0.319248651	VES6	Moderate
0.624741333	VES7	Moderate
0.783918596	VES8	Good
0.723696723	VES9	Good
0.331984216	VES10	Moderate
0.500063087	VES11	Moderate
0.3874725	VES12	Moderate
0.268535516	VES13	Moderate
0.122089468	VES14	Weak
1.945608832	VES15	Good
5.020204283	VES16	Very good
2.058147451	VES17	Good
4.37419705	VES18	Very good
1.029168197	VES19	Good
0.311177804	VES20	Moderate
0.004510338	VES21	Poor
0.242020002	VES22	Moderate
1.84452459	VES23	Very good
4.326451507	VES24	Good
6.013086392	VES25	Very good
0.100338324	VES26	Weak
1.344894437	VES27	Good
1.532946193	VES28	Good
0.518482037	VES29	Moderate
0.305597379	VES30	Moderate
0.183175514	VES31	Weak
2.21747506	VES32	Good
1.33547205	VES33	Good
0.504672897	VES34	Moderate
1.619723169	VES35	Good
0.448343467	VES36	Moderate
0.192036948	VES37	Weak
0.55198617	VES38	Moderate
0.509290544	VES39	Moderate
1.714644013	VES40	Good
0.568574866	VES41	Moderate
0.131356326	VES42	Good
0.350351022	VES43	Moderate
0.22551477	VES44	Moderate
0.758959861	VES45	Good
0.526751003	VES46	Moderate
0.176264301	VES47	Weak
0.672273035	VES48	Moderate
0.455922257	VES49	Moderate
0.659706324	VES50	Moderate
1.636618606	VES51	Good
1.030309128	VES52	Good
1.628576571	VES53	Good
2.163590781	VES54	Good
0.593544054	VES55	Moderate
0.605865027	VES56	Moderate
0.755266358	VES57	Good
0.307752223	VES58	Moderate
0.19028614	VES59	Good
0.19634771	VES60	Good

(*continued on next page*)

Table 2 (*continued*)

0.149082653	VES61	Good
7.50108849	VES62	Very good
0.389991711	VES63	Moderate
0.164615527	VES64	Weak
0.450980087	VES65	Moderate
0.803298725	VES66	Good
1.05587808	VES67	Good
0.381292517	VES68	Moderate
0.164625881	VES69	Weak
10.84817912	VES70	Excellent
0.144644429	VES71	Weak
0.26307195	VES72	Moderate

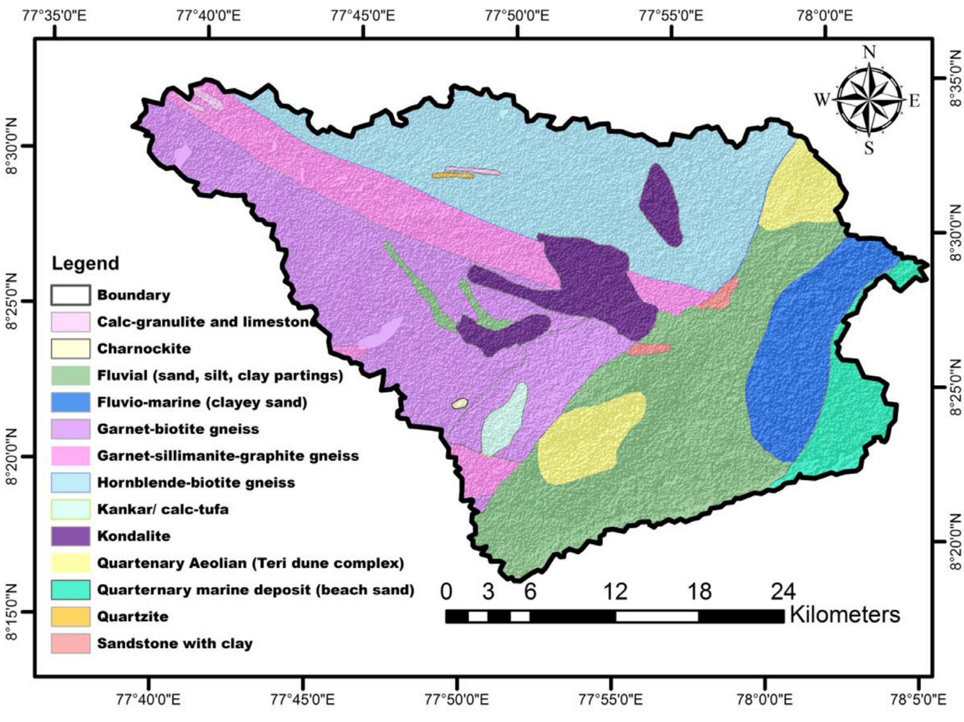

Fig. 2. Geology map of the study area.

Results and discussion

Aquifer protective capacity

To evaluate the protective capacity rate of the aquifer, the longitudinal conductance values were used. The ability of the earth medium to retard and filter percolating ground surface waste effluents is a measure of its protective capacity. The degree of protection from the infiltrating pollutants into an aquifer is directly proportional to its longitudinal conductance [61,62]. Based on the aquifer protective capacity rating (Table 1) [60], the 72 VES locations were classified into excellent to poor. The longitudinal conductance value of the study area ranges from 0.102 to 10.848 Ω (Table 2). The locations VES2, VES4, VES14, VES26, VES31, VES37, VES47, VES64, VES69, and VES71 are designated as weak productive capacity. The sounding locations VES8, VES9, VES15, VES17, VES19, VES24, VES27,

Table 3
Groundwater potential of the study area.

VES	Reflection coefficient (no unit)	Overburden thickness (m)	Ground water yield
VES1	−0.64441619	10.39	Medium
VES2	−0.612903226	18.26	High
VES3	−0.240572172	25.57	High
VES4	0.421933086	8.08	Very low
VES5	0.987822075	23.214	Medium
VES6	0.964835165	36.67	Medium
VES7	0.902392798	27.13	Medium
VES8	0.88731104	12.16	Low
VES9	−0.967516685	76.35	Medium
VES10	0.816176471	9.04	Low
VES11	0.785925488	18.76	High
VES12	0.869300912	9.04	Low
VES13	−0.479905437	49.335	High
VES14	−0.329763498	22.87	High
VES15	−0.838565022	37.69	Medium
VES16	−0.721632197	46.13	High
VES17	0.494880546	47.835	High
VES18	−0.926256614	48.55	Medium
VES19	0.801541426	23.68	High
VES20	−0.21274409	41	High
VES21	−0.21274409	8.54	Very low
VES22	0.745076586	14.04	High
VES23	0.99407659	21.38	Medium
VES24	−0.926270342	49.187	Medium
VES25	0.98397385	45.71	Medium
VES26	−0.808898614	9.02	Low
VES27	−0.997463538	19.14	Medium
VES28	−0.492978566	18.53	High
VES29	−0.996940733	23.08	Medium
VES30	0.290650407	24.89	High
VES31	−0.916192883	39.44	Medium
VES32	0.957995147	58.28	Medium
VES33	0.384615385	25.43	High
VES34	0.759201497	20.3	High
VES35	0.785552707	14.39	High
VES36	0.812753252	21.27	Medium
VES37	0.896953742	23.87	Medium
VES38	0.986262984	21.484	Medium
VES39	0.759315822	11.549	Very low
VES40	0.994427676	33.36	Medium
VES41	0.750961254	23.67	High
VES42	0.887212466	8.24	Low
VES43	0.576098723	27.24	High
VES44	0.661166117	11.7	Very low
VES45	0.843317972	14.39	Medium
VES46	0.990959437	36.83	Medium
VES47	0.849980567	7.25	Low
VES48	0.970479705	24.81	Medium
VES49	0.541284404	15.62	High
VES50	0.650927487	15.47	High
VES51	0.99701641	23.25	Medium
VES52	0.801490629	23.676	High
VES53	0.994918685	34.74	Medium
VES54	−0.31042654	15.96	High
VES55	−0.679520137	18.53	High
VES56	−0.895289923	26.38	Medium
VES57	0.998015334	7.9	Low
VES58	0.900640159	14.39	Medium
VES59	−0.207126949	23.97	High
VES60	−0.826241135	22.91	Medium
VES61	−0.774058577	16.72	High

(*continued on next page*)

Table 3 (*continued*)

VES	Reflection coefficient (no unit)	Overburden thickness (m)	Ground water yield
VES62	−0.968433251	48.12	Medium
VES63	−0.576271186	22.86	High
VES64	0.962729185	8.24	Low
VES65	0.976455587	3.35	Low
VES66	−0.553744269	35.19	High
VES67	0.530669668	32.98	High
VES68	0.929051704	6.98	Low
VES69	0.962649577	8.24	Low
VES70	0.665236052	18.4	High
VES71	0.577385159	16.707	High
VES72	−0.419689119	27.9	High

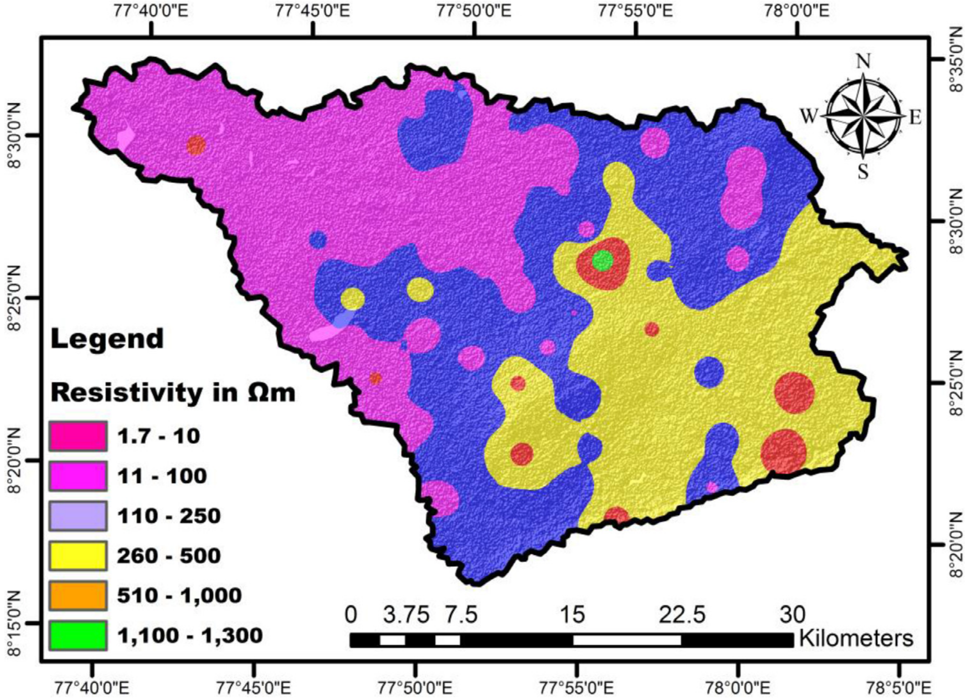

Fig. 3. Spatial distribution of resitivity of first gelectrical layer.

VES28, VES32, VES33, VES35, VES40, VES42, VES45, VES51, VES52, VES53, VES54, VES57, VES59, VES60, VES61, VES66, VES67 exhibit good productive capacity. The VES locations VES1, VES 3, VES 5, VES 6, VES7, VES10, VES11, VES12, VES13, VES20, VES22, VES29, VES30, VES34, VES36, VES38, VES39, VES41, VES43, VES44, VES46, VES48, VES49, VES50, VES55, VES56, VES58, VES63, VES65, VES68, and VES72 falls under weak productive capacity. Poor productive capacity is obtained in VES number 21. The majority number of VES locations is characterized by moderate to good aquifer protective capacity, thus revealed that the underlying aquifer in the study area is not prone to contamination. The high value of longitudinal conductance was obtained in VES 16, VES18, VES25, VES62, and VES 72. It may be the presence of relatively clayey overburden and thick sequences of the subsurface. Hence those areas are characterized by a high value of longitudinal conductance and offer higher preventive capability to the underlying aquifer [63]. Consequently, the low value of longitudinal conductance observed in the

Table 4
Interpreted VES parameters.

VES	$\rho 1$	$\rho 2$	$\rho 3$	$\rho 4$	$\rho 5$	$h1$	$h2$	$h3$	$h4$
VES1	1284	38.8	8.39			2.39	8		
VES2	391	105	25.2			1.36	16.9		
VES3	46.9	7.21	95.4	58.4		1	1.87	22.7	
VES4	218	62.2	153			1.77	6.31		
VES5	94.8	13.3	55.7	9092		1	0.914	21.3	
VES6	22.1	73.7	208	11,622		2.17	6.3	28.2	
VES7	48.7	41.2	803			9.03	18.1		
VES8	17.8	192	12.3	206		1	2.36	8.8	
VES9	205	52.6	255	4.21		1.85	28	46.5	
VES10	96.3	25	247			1	8.04		
VES11	57.8	36.2	302			1.76	17		
VES12	42.9	148	17.2	246		1	2.01	6.03	
VES13	74.2	238	19.2	313	110	1	0.895	2.04	45.4
VES14	523	1001	149	75.1		2.96	3.01	16.9	
VES15	440	164	14.4	6674		3.55	6.84	27.3	
VES16	232	46.2	7.47	22		3	6.83	36.3	
VES17	63.5	2.96	8.76	0.711	97.9	1	0.335	16.9	29.6
VES18	579	233	8.92	0.‘142		2.59	7.26	38.7	
VES19	148	20.6	187			2.88	20.8		
VES20	333	175	349	118	76.6	1.13	1.19	4.78	33.9
VES21	492	3043	42.7			1	7.54		
VES22	212	46.6	319			3.54	10.5		
VES23	562	276	7.15	2407		2.18	6.2	13	
VES24	169	3.33	11.1	20.3	0.777	0.777	4.61	19.1	24.7
VES25	198	346	40.2	3.53	437	1	1.81	23.8	19.1
VES26	181	74.4	7.86			2.64	6.38		
VES27	618	12.6	0.016			2.24	16.9		
VES28	373	8.42	3.03			3.29	20.4		
VES29	582	225	34.4	0.0527		1	5.08	17	
VES30	349	6344	69.8	127		1	2.79	21.1	
VES31	593	3172	182	7.96		2.14	4.9	32.4	
VES32	125	25.1	1170			3.28	55		
VES33	230	16.8	37.8			3.23	22.2		
VES34	214	38.6	282			1	19.3		
VES35	17.5	38.9	7.11	59.2		1	2.79	10.6	
VES36	133	43.9	425			2.37	18.9		
VES37	122	61.2	137	2522		1	1.87	21	
VES38	327	5.5	52.7	7620		1	0.984	19.5	
VES39	50.1	9.64	118	19.7	144	1	0.869	2.18	7.5
VES40	57.2	438	31.6	14.4	5154	1.59	3.31	7.86	20.6
VES41	17.8	102	42.1	296		1	1.87	20.8	
VES42	39.6	91.2	1526			2.87	5.37		
VES43	37.8	97.9	364			4.44	22.8		
VES44	19.3	61.6	302			1	10.7		
VES45	21.2	147	15.3	180		1	2.79	10.6	
VES46	40.1	75.5	16627			3.33	33.5		
VES47	69.7	38.6	476			1	6.25		
VES48	5.1	202	869	6350		2.56	19	31.1	
VES49	45.6	15.3	37.5	126		1.16	1.16	13.3	
VES50	14.2	258	20.7	97.9		1	2.47	12	
VES51	355.7	10.5	7028			6.25	17		
VES52	148.45	20.575	186.72			2.876	20.8		
VES53	339	17.7	6949			6.24	28.5		
VES54	312	103	9.8			4.01	18.9		
VES55	1.53	7.78	1.17	5.82		3.17	5.84	9.39	
VES56	19.3	8.93	505	27.9		2.28	4	20.1	
VES57	191	8.92	8980			1.22	6.68		
VES58	66.6	27.8	55.1	1054		1	2.79	10.6	
VES59	60.5	19.5	271	178		1	1.87	21.1	
VES60	132	32.5	5.53	2.91		1	3.66	11.3	

(*continued on next page*)

Table 4 (*continued*)

VES	ρ1	ρ2	ρ3	ρ4	ρ5	h1	h2	h3	h4
VES61	94.1	400	106	13.5		1	1.42	14.3	
VES62	10.8	91.2	6.03	0.0967		1	2.62	44.5	
VES63	79.7	199	46.5	12.5		1.52	5.34	16	
VES64	82.2	231	37.2	1959		1	1.87	5.37	
VES65	45.9	6.21	267			2	2.2		
VES66	109	249	105	30.5	8.76	1	2.79	10.6	20.8
VES67	61.6	14.7	41.7	136		1.5	6.28	25.2	
VES68	29.4	15.3	416			2.39	4.59		
VES69	79.6	231	37.3	1960		1	1.87	5.37	
VES70	87.1	29.4	5.61			1.63	16.9		
VES71	9.88	299	1116			0.907	15.8		
VES72	105	35	274	112		1.74	6.06	20.1	

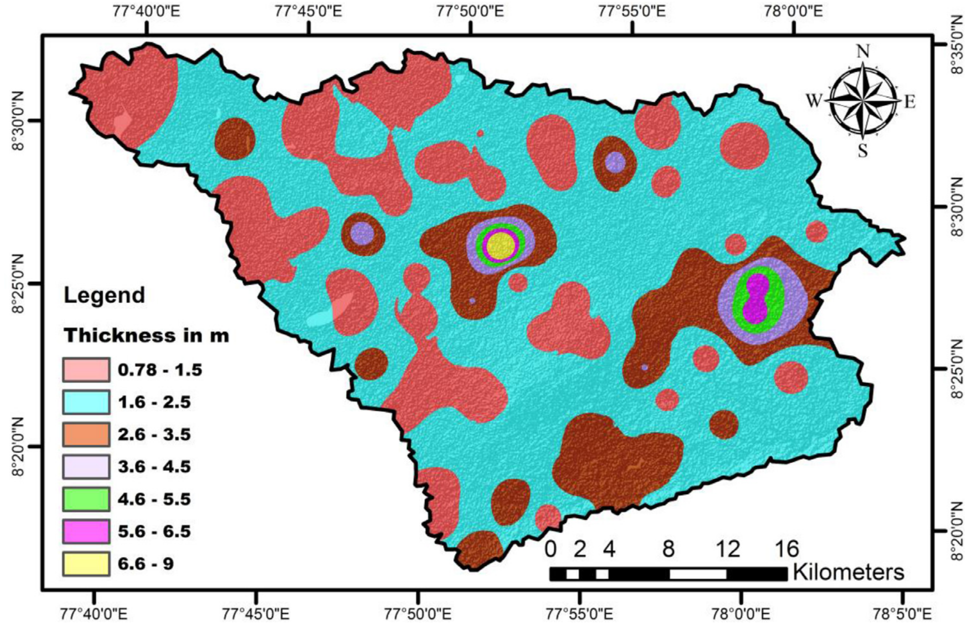

Fig. 4. Spatial distribution of thickness of first gelectrical layer.

VES stations 21, 26, 4, 31 and 14, which indicates the absence of an overburden clayey impermeable layer, leading to the agricultural and anthropogenic contaminants to permeate subsurface aquifer [64]. A very high value of S obtained at VES70 with the respective depth of 18.4 m, which might be the basement with a fracture.

Groundwater potential evaluation

Generally, a reflection coefficient (RC) is a key parameter for evaluating the groundwater potential of the study area rather than relying on the resistivity of the basement terrain [65]. The lower value of the reflection coefficient (less than 0.8) shows intensely weathered or fractured bedrock that favors more for high groundwater potential [65]. The low reflection coefficient, coupled with the high overburden thickness is considered a good aquiferous region [66]. The reflection coefficient and overburden thickness obtained from interpreted VES results is used to identify the groundwater

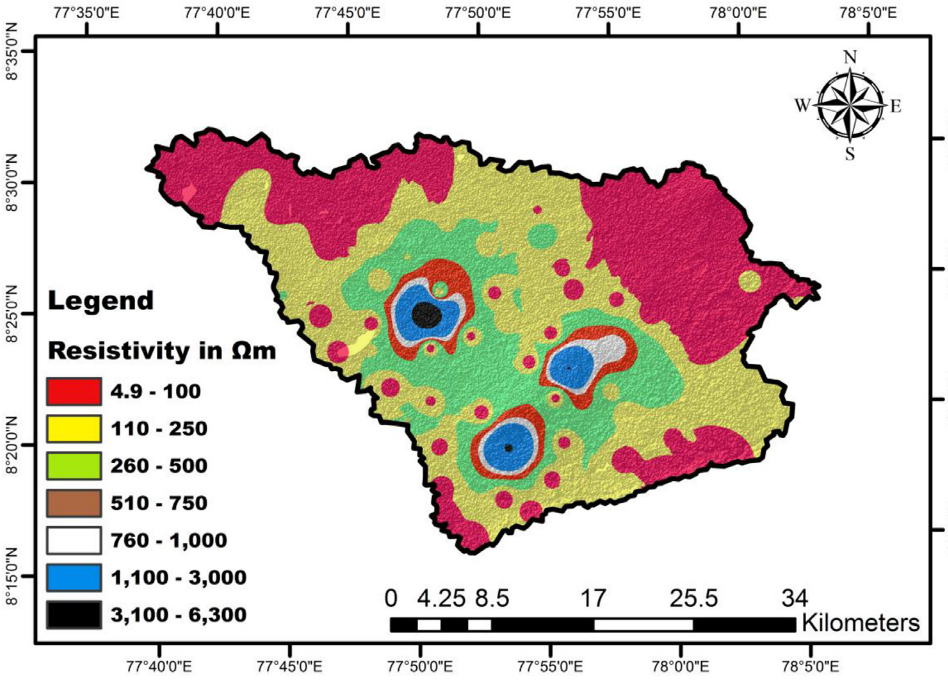

Fig. 5. Spatial distribution of resitivity of second gelectrical layer.

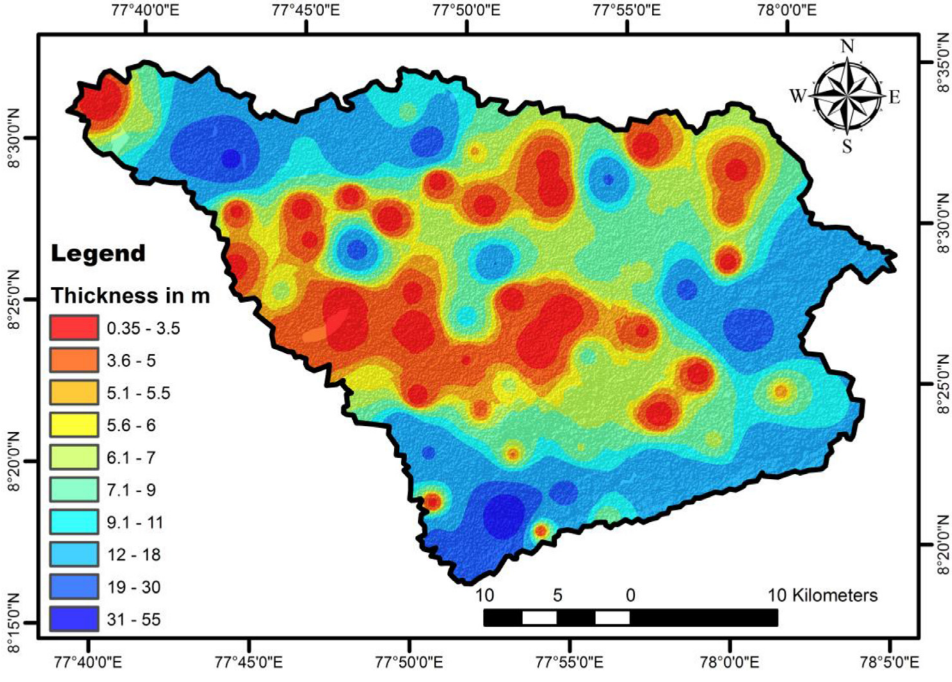

Fig. 6. Spatial distribution of thickness of second gelectrical layer.

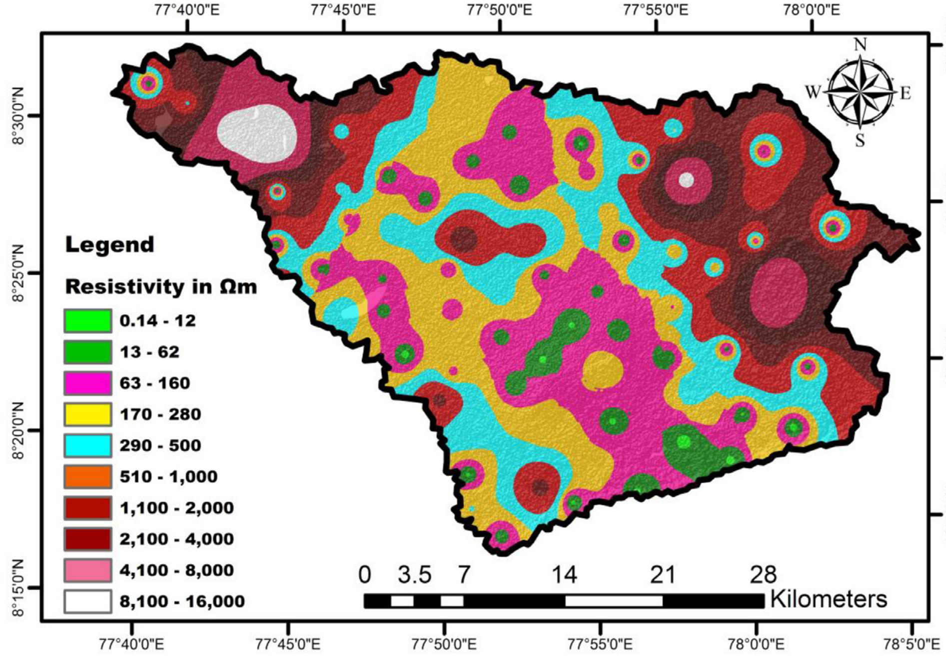

Fig. 7. Spatial distribution of resistivity of third gelectrical layer.

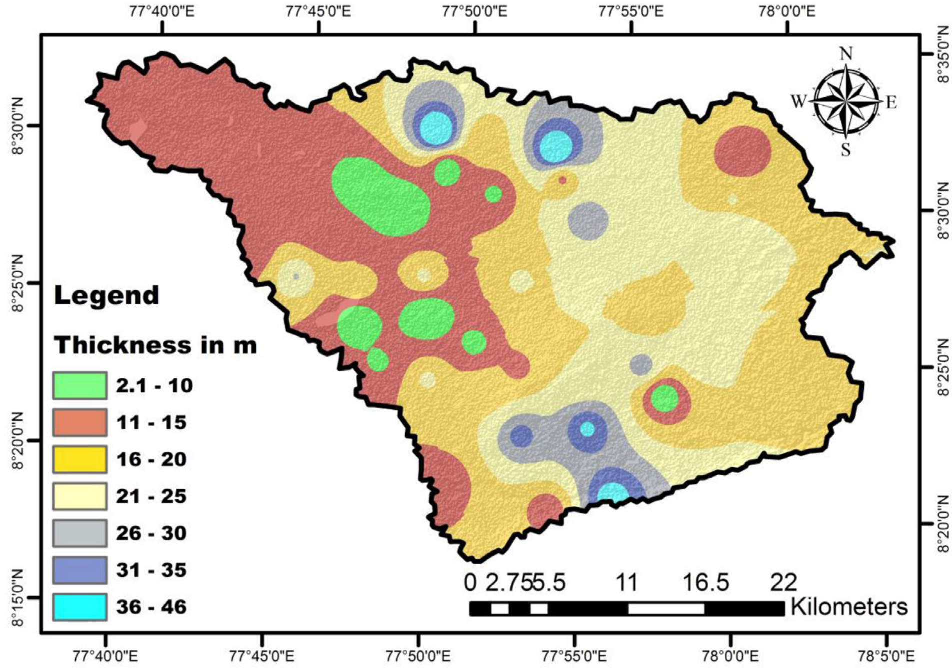

Fig. 8. Spatial distribution of thickness of third gelectrical layer.

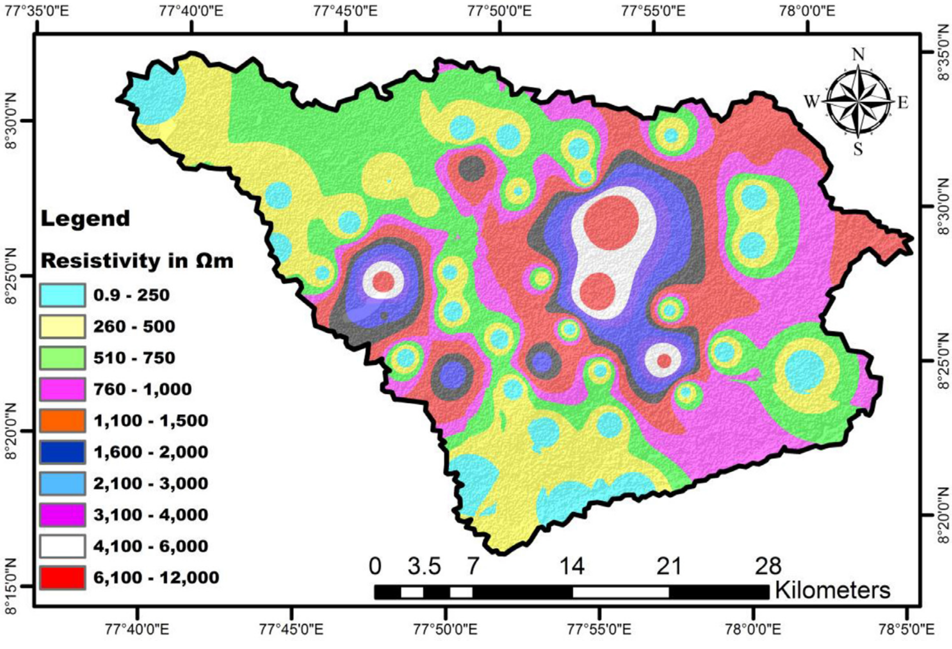

Fig. 9. Spatial distribution of thickness of fourth gelectrical layer.

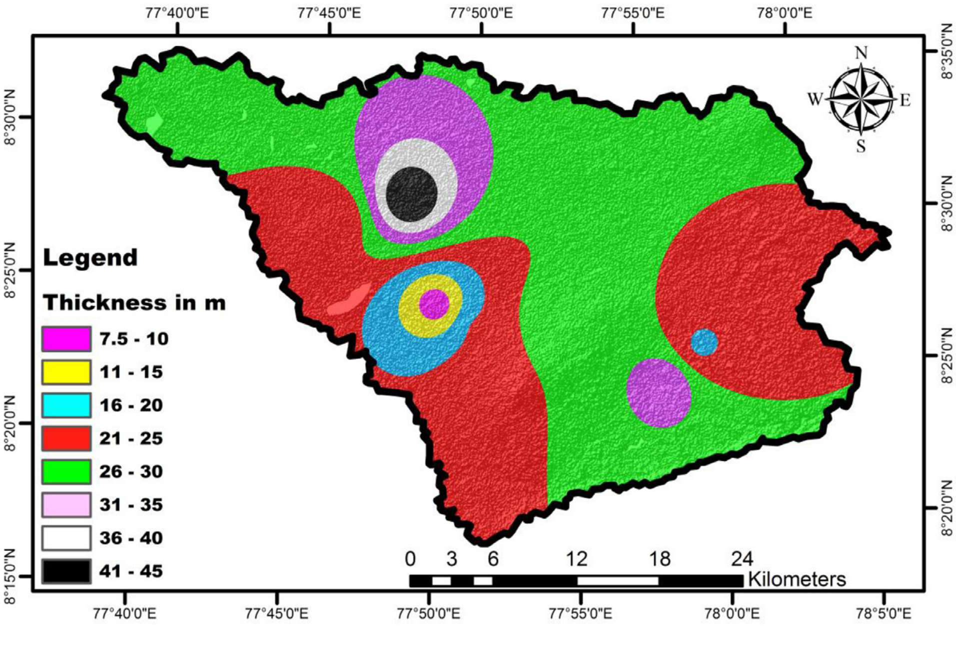

Fig. 10. Spatial distribution of thickness of fourth gelectrical layer.

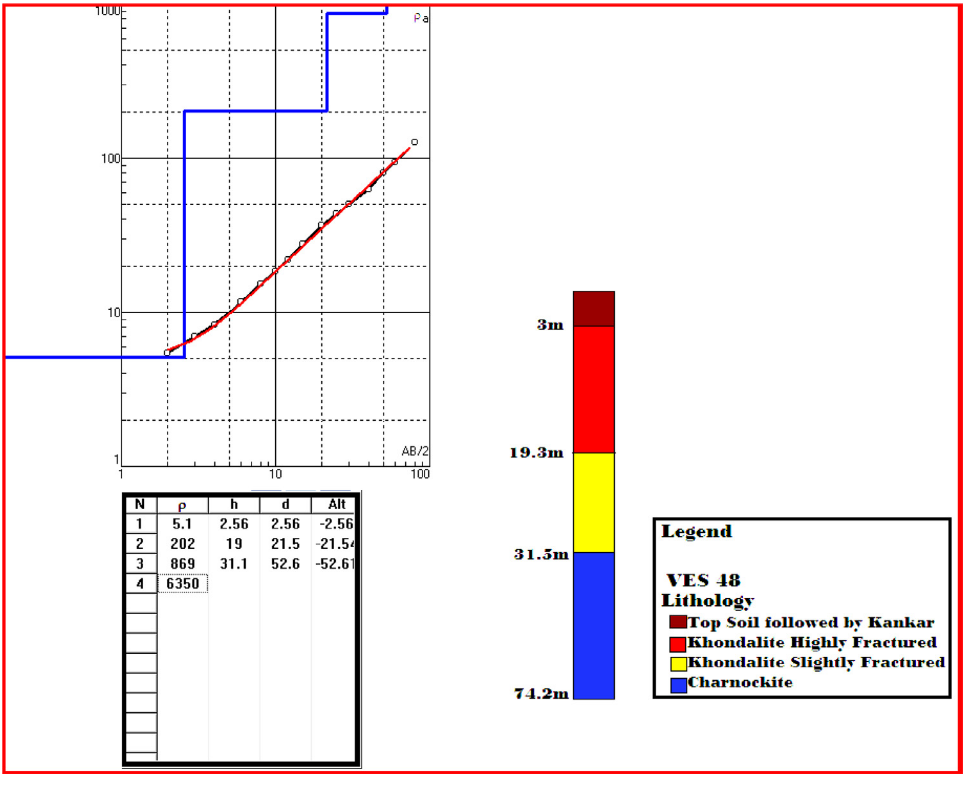

Fig. 11. Correlation of VES 48 data with litholog.

potential in the study area. The overall reflection coefficient values range from −0.2 to 0.99. Based on the reflection coefficient and overburden thickness value (Table 3), the study area has been classified into three categories, viz, good, medium and poor. To investigate the groundwater potential of the Karumeniyar river basin, the following basic criteria were applied [67].

i) The location where the overburden thickness more than 13 m and the reflection coefficient value is lower than 0.8 were characteristics by high groundwater yield.
ii) The location where the overburden thickness more than 13 m and the reflection coefficient value is higher than or equal to 0.8, were characteristics by medium groundwater yield.
iii) The location where the overburden thickness lower than 13 m and the reflection coefficient value is higher than 0.8 were characteristics by low groundwater yield.
iv) The location where the overburden thickness lower than 13 m and the reflection coefficient value is lower than 0.8 were characteristics by very low groundwater yield.

Based on the above mentioned criteria, the groundwater potential map (Fig. 2) of the study area was divided into four distinct groundwater potential zones. This reveals that the areal extent 42% of the total area exhibits high groundwater potential, whereas the area of 38% is found with medium groundwater potential, and the area of 15% fall under low potential, however, the area of 5% have identified very low groundwater potential conditions. It demonstrates that the higher groundwater potential is mainly concentrated downstream of the river basin at the eastern part of the basin underlain by sedimentary basement rock. However, the western and some stripes in the northern part of the study area have moderate to low groundwater potential zones due to the massiveness of rock.

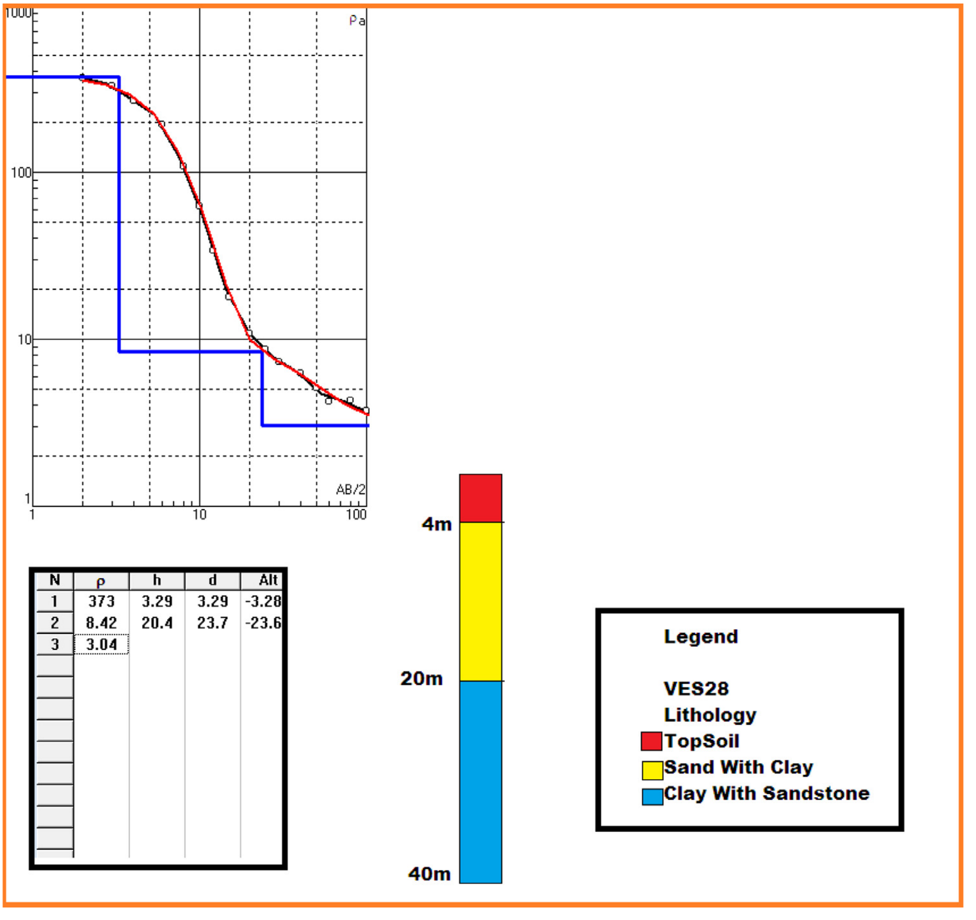

Fig. 12. Correlation of VES 28 data with litholog.

Geoelectrical section

From the interpreted VES result, among the seventy two out of 30 VES are found to have three geoelectrical layers, whereas the remaining curves have identified as four to five subsurface layers. The H-type VES curve was predominant in the study area followed by H type (24%), KH type (13%), HK type (10%), A type (8%), Q type (8%), HA type (7%), KQ type (7%), QQ type (6%), QH type (5%), AA type (3%), KHK type (3%), HKQ type (1%), HAK type (1%), KQQ type (1%), K type (1%), HKH type (1%) and KQH type (1%). Table 4 shows the obtained subsurface resistivity and thickness values of the study area. It is surmised that the maximum value of first layer resistivity is 1284 Ω m, the second layer resistivity is 6344 Ω m and the maximum resistivity of the third layer is 16627 Ω m. The low resistivity value less than 10 Ω m observed in locations VES 18, VES 55, VES 27, VES 29 along the eastern portion of the study area that indicates the predominant of seawater intrusion [67]. The value of subsurface resistivity is increasing towards Archean formation at locations VES5, VES6, VES30, VES38, VES 46, VES 53, VES 57, signifies aquifer free from pollutant. The maximum thickness value of the first and second layers is 9.03 m and 55 m, respectively. The higher amount of geoelectrical layer thickness was noted in VES32 represented by Tertiary formation. The spatial interpolation map of resistivity and thickness of each geoelectrical layer as depicted in Figs. 3–10. To assess the accuracy of VES results, these results are correlated with the nearby litholog data procured from – Central Ground Water Board (CGWB) (Fig. 3). The VES station 48 is situated in Sathankulam and has four layer AA type sounding curve (Fig. 11). This type of curve is generally obtained in hard rock area were four different layers of subsurface with different resistivity were found. The resistivity (ρ) of the first layer is 5.1 Ω m with a thickness of 2.56 m, signifying topsoil followed by kankar. The resistivity of the second layer is 202 Ω m with a thickness of 19 m that corresponds to highly fractured khondalite. The third layer is characterized by slightly fractured khondalite with a thickness of 31.1 m and resistivity of 869 Ω m. The fourth bottom layer is identified as a charnockite that has a resistivity of 6350 Ω m. The VES station 28 is located near Kulasekarapattinam and comprises three layer Q type curve (Fig. 12). The first topsoil layer has a resistivity of 373 Ω m and 3.29 m thick. The resistivity of the second layer is 8.42 Ω m with a thickness of 20.4 m that corresponds to sand with clay. The third bottom layer is characterized by clay with sandstone with a resistivity of 3.04 Ω m. The known litholog data of four locations has strongly correlated with VES results, except for some minor variations.

Conclusion

The geophysical vertical electrical sounding (VES) technique has proven to be an effective tool for the delineation of subsurface geoelectrical characteristics in the Karumeniyar river basin. The suggested methodology has deliberated the groundwater protective capacity, groundwater potentially and subsurface lithology in the study area. The study area is confined with hard rock and sedimentary regions of southern Tamil Nadu. Hence fractured and weathered layers, sandy and clayey layers may be the target of groundwater. In hard rock terrain, the considerable low electrical resistivity and favorable thickness with an appreciable depth of weathered and fractured layers constitute the loci for the aquifer. The obtained result of VES data infers that the basin comprised of four to five subsurface layers and major sounding curves A, H and K are identified. The VES results have been cross-validated with litholog data in proximity to four different well locations. The interpreted results revealed that the 24 locations (33%) in the study area have identified as good aquifer productivity. The 10 locations in the study area (11 %) associated with weaker productive capacity, it is evident to the groundwater vulnerable to contamination that may result from saline water intrusion, sewage water, surface runoff water and the disposal of effluent and indiscriminate waste. Based on the reflection coefficient and aquifer thickness, the basin area was classified into four distinct groundwater potential zones as high (42%), medium (38%), low (15%) and very low (5%). The spatial interpolation maps of layer resistivity and thickness depict that groundwater potential is present in the eastern side of the basin associated with sedimentary terrain. The identified groundwater potential zones from the proposed study are preferred for drilling. This study recommends eradicating the water demand transfer of water from surplus regions to water deficit areas.

Declaration of Competing Interest

I declare that, I am submitting the manuscript entitled “Efficacy of hydrological investigation in Karumeniyar river basin, Southern Tamil Nadu, India using vertical electrical sounding technique: a case study” to the journal without any known conflicts of interest. S. Arunbose

References

[1] J.O. Oseji, M.O. Ofomola, Predicting the aquifer characteristic in the headquarters of Ndokwa land, Online J. Earth Sci. (4) (2010) 35–37.
[2] R.G. Taylor, B. Scanlon, P. Döll, M. Rodell, R. Van Beek, Y. Wada, L. Konikow, Ground water and climate change, Nat. Clim. Change 3 (4) (2013) 322–329 a.
[3] R. Agarwal, P.K. Garg, Remote sensing and GIS based groundwater potential & recharge zones mapping using multi-criteria decision making technique, Water Resour. Manag. 30 (1) (2015) 243–260, doi:10.1007/s11269-015-1159-8.
[4] NITI Aayog – Annual Report, Government of India. (2017–2018) https://www.niti.gov.in/writereaddata/files/document... /Annual-Report-English.pdf.
[5] India: India's Water Economy, Bracing for a turbulent futureAgriculture and Rural Development Unit South Asia Region Report No. 34750-IN, Document of the World Bank, 2006.

[6] P.M. Natarajan, M. Ponnavaiko, S. Kalloikar, G. Rangaraju, S. Ganesh, Sustainable Water Resources Development in Tamil Nadu, India Through Water Security Pathways, XVI World Water Congress, International Water Resource Association, Cancun, Quintana Roo, Mexico, 2017.
[7] M.K. Jha, V.M. Chowdary, A. Chowdhury, Groundwater assessment in Salboni 14 Block, West Bengal (India) using remote sensing, geographical information system and 15 multi-criteria decision analysis techniques, Hydrogeol. J. 18 (7) (2010) 1713–1728.
[8] Roscoe Moss Co, in: Handbook of Ground Water Development, John Wiley & Sons, New York, 1990, pp. 34–51.
[9] CW Fetter, in: Applied Hydrogeology, 4th ed., Prentice Hall, Englewood Cliffs, NJ, 1994, pp. 543–591.
[10] A. Stampolidis, P Tsourlos, P. Soupios, T.H. Mimides, G. Tsokas, G. Vargemezis, A. Vafidis, Integrated geophysical investigation around the brackish spring of Rina, Kalimnos Isl., SW Greece, J. Balk Geophys. Soc. 8 (3) (2005) 63–73.
[11] S. Chidambaram, G.S Kumar, M.V. Prasanna, A. John Peter, A.L. Ramanathan, K. Srinivasamoorthy, A study on the hydrogeology and hydrogeochemistry of groundwater from different depths in a coastal aquifer: Annamalai Nagar, Tamil Nadu, India, Environ. Geol. 57 (2009) 59–73.
[12] D. Muthuraj, Y. Srinivas, N. Chandrasekar, Delineation of groundwater potential areas – a case study from Tirunelveli district, Tamil Nadu, India, Int. J. Appl. Environ. Sci. 5 (2010) 49–56.
[13] P.D.S. Devi, S. Srinivasulu, K.K. Raju, Delineation of groundwater potential zones and electrical resistivity studies for groundwater exploration, Environ. Geol. 40 (10) (2001) 1252–1264.
[14] D.K. Todd, Groundwater Hydrology, second ed., Wiley, New York, (1980).
[15] O. Anomohanran, S.O. Akporido, Hydro-geophysical investigation of saltwater intrusion into freshwater aquifer in Burutu, Nigeria, Int. J. Hydrol. Sci. Technol. 5 (2) (2015) 149, doi:10.1504/ijhst.2015.070088.
[16] D. Kumar, S. Ahmed, N. Krishnamurthy, B. Dewandel, Reducing ambiguities in vertical electrical sounding interpretations: a geostatistical application, J. Appl. Geophys. 62 (1) (2007) 16–32, doi:10.1016/j.jappgeo.2006.07.001.
[17] J.S. Kayode, A.O. Adelusi, M.N.M. Nawawi, M. Bawallah, T.S. Olowolafe, Geo-electrical investigation of near surface conductive structures suitable for groundwater accumulation in a resistive crystalline basement environment: a case study of Isuada, southwestern Nigeria, J. Afr. Earth Sci. 119 (2016) 289–302, doi:10.1016/j.jafrearsci.2016.04.009.
[18] A. Zohdy, G.P. Eaton, D.R. Mabey, Application of surface geophysics to groundwater investigations: techniques of water-resources investigations of the United States Geological Survey, (1974) 2 116.
[19] P. Soupios, M. Kouli, F. Vallianatos, A. Vafidis, G. Stavroulakis, Estimation of aquifer parameters from surficial geophysical methods. A case study of Keritis Basin in Crete, J. Hydrol. 338 (2007) 122–131.
[20] D. Kalisperi, P. Soupios, M. Kouli, P. Barsukov, S. Kershaw, P. Collins, F. Vallianatos, Coastal aquifer assessment using geophysical methods (TEM, VES), case study: Northern Crete, Greece, in: Proceedings of the 3rd IASME/WSEAS International Conference on Geology and Seismology (GES '09), Cambridge, UK, 2009, pp. 24–26.
[21] E.S. Joel, P.I. Olasehinde, T.A. Adagunodo, M. Omeje, I. Oha, M.L. Akinyemi, O.C. Olawole, Geo-investigation on groundwater control in some parts of Ogun state using data from shuttle radar topography mission and vertical electrical soundings, Heliyon 6 (1) (2020) e03327, doi:10.1016/j.heliyon.2020.e03327.
[22] M. Aoudia, A Issaadi, M. Bersi, D. Maizi, H. Saibi, Aquifer characterization using vertical electrical soundings and remote sensing: a case study of the chott Ech Chergui basin, northwest Algeria, J. Afr. Earth Sci. 170 (2020) 103920.
[23] O.K. Ezema, J.C. Ibuot, D.N. Obiora, Geophysical investigation of aquifer repositories in Ibagwa Aka, Enugu state, Nigeria, using electrical resistivity method, Groundwater Sustain. Dev. 11 (2020) 100458, doi:10.1016/j.gsd.2020.100458.
[24] B.E. Oguama, J.C. Ibuot, D.N. Obiora, Geohydraulic study of aquifer characteristics in parts of Enugu north local government area of Enugu state using electrical resistivity soundings, Appl. Water Sci. 10 (5) (2020), doi:10.1007/s13201-020-01206-2.
[25] I.C. Oli, C.A. Ahairakwem, A.I. Opara, A.C. Ekwe, I. Osi-Okeke, O.O. Urom, H.M. Udeh, V.C. Ezennubia, Hydrogeophysical assessment and protective capacity of groundwater resources in parts of Ezza and Ikwo areas, southeastern Nigeria, Int. J. Energy Water Resour. (2020), doi:10.1007/s42108-020-00084-3.
[26] N. Jamal, N.P. Singh, Electrical resistivity in the delineation of groundwater potential zones: a case study from Kota, Rajasthan, India, Arabian J. Geosci. 13 (15) (2020), doi:10.1007/s12517-020-05464-x.
[27] G. Gnanachandrasamy, C. Dushiyanthan, T. Jeyavel Rajakumar, J. Chen, Comprehensive hydro-geophysical prospecting to delineate fresh water zone in the coastal aquifer, South India, J. Hydrol. (2020) 125415, doi:10.1016/j.jhydrol..125415.
[28] K. Vinodh, S. Senthilkumar, B. Gowtham, S. Krishnaraj, Delineate subsurface and groundwater investigation of Ongur watershed, South India, Int. J. Civil Environ. Agric. Eng. 2 (1) (2020) 17–33, doi:10.34256/ijceae2012.
[29] S. Rajkumar, Y. Srinivas, N.C Nair, S. Arunbose, Groundwater quality and vertical electrical sounding data of the Valliyar river basin, south West Coast of Tamil Nadu, India, Data Brief 24 (2019) 103919, doi:10.1016/j.dib.2019.103919.
[30] N.C. Nair, Y. Srinivas, S. Rajkumar, S. Arun Bose, Geoelectrical investigation to delineate the groundwater potential aquifers in Chittar river basin, southern India, Int. J. River Basin Manag. (2019) 1–16, doi:10.1080/15715124.2019.1700514.
[31] R. Jeyangondaperumal, in: Teri Red Sands, Tamil Nadu, Landscapes and Landforms of India, Springer, Netherlands, 2014, pp. 211–216.
[32] A. Zohdy, G.P. Eaton, D.R. Mabey, Application of surface geophysics to groundwater investigations: techniques of water-resources investigations of the United States, Geol. Surv. 1 (2) (1974) 116.
[33] V.L.S. Bhimasankaram, V.K. Gaur, Lectures on Exploration Geophysics for Geologists and Engineers, Association of Exploration Geophysicists, Centre Exploration Geophysics, Hyderabad, India, 1977.
[34] S.H. Ward, in: Resistivity and Induced Polarization Methods in Geotechnical and Environmental Geophysics, Society of Exploration Geophysicists, Tulsa, 1990, pp. 147–189.
[35] W.M. Telford, L.P. Geldart, R.E. Sheriff, in: Applied Geophysics, 2nd ed., Cambridge University Press, Cambridge, 1990, p. 770.
[36] A. Binley, A. Kemna, DC resistivity and induced polarization methods, in: Y Rubin, SS Hubbard (Eds.), Hydrogeophysics, Springer, Dordrecht, 2005, pp. 129–156.
[37] K. Ernstson, R. Kirsch, Geoelectrical methods, in: R Kirsch (Ed.), Groundwater Geophysics a Tool for Hydrogeology, Springer, Heidelberg, 2006, pp. 85–117.
[38] A. Roy, A. Apparao, Depth of investigation in direct current methods, Geophysics 36 (1971) 943–959.

[39] A. Roy, A. Apparao, The two-electrode system of resistivity prospecting, in: Proceedings of the Symposium on 'Exploration Techniques for Metalliferous Deposits' Held at Khetri, Rajasthan, India, 1971 March 27–28.
[40] G.D. Koefoed, Geosounding Principles, Resistivity Sounding Measurements, Elsevier, New York, 1979.
[41] P.V. Sharma, in: Environmental and Engineering Geophysics, 28, Cambridge University Press, Cambridge, 1997, pp. 280–296. 231, 265–269.
[42] C. Bobachev, IPI2Win: A Windows Software for an Automatic Interpretation of Resistivity Sounding Data, Moscow State University, 2002 Ph.D..
[43] P.K. Bhattacharya, H.P. Patra, Direct current geoelectric sounding: principles and interpretation, in: Methods in Geochemistry and Geophysics: Series-9, Elsevier Publishing Company, 1968, p. 135.
[44] R. Maillet, The fundamental equations of electrical prospecting, Geophysics 12 (4) (1947) 529–556, doi:10.1190/1.1437342.
[45] J.P. Henriet, Direct application of the Dar-Zarrouk parameters in ground water surveys, Geophys. Prospect. 24 (1976) 344–353.
[46] U.K. Singh, R.K. Das, G.K. Hodlur, Significance of Dar-Zarrouk parameters in the exploration of quality affected coastal aquifer systems, Environ. Geol. 45 (2004) 696–702.
[47] K.P. Singh, Nonlinear estimation of aquifer parameters from surficial resistivity measurements, Hydrol. Earth Syst. Sci. Discus. 2 (2005) 917–938.
[48] A.C. de Oliveira Braga, W.M. Filho, J.C. Dourado, Resistivity (DC) method applied to aquifer protection studies, Braz. J. Geophys. 24 (2006) 573–581.
[49] A.T. Batayneh, A hydrogeophysical model of the relationship between geoelectric and hydraulic parameters, central Jordan, J. Water Resour. Prot. 1 (2009) 400–407.
[50] C.N. Ehirim, C.N. Nwankwo, Evaluation of aquifer characteristics and groundwater quality using geoelectric method in Choba, Port Harcourt, Arch. Appl. Sci. Res. 2 (2010) 396–403.
[51] C. Nwankwo, L. Nwosu, G. Emujakporue, Determination of Dar Zarouk parameters for the assessment of groundwater resources potential: case study of Imo State, south eastern Nigeria, J. Econ. Sustain. Dev. 2 (2011) 57–71.
[52] Y. Srinivas, D. Hudson Olivera, A. Stanley Raja, D. Muthurajb, N. Chandrasekar, Estimation of conductance anomalies in subsurface through Dar-Zarrouk parameters by resistivity inversion method, Int. J. Phys. Math. Sci. 3 (2012) 140–151.
[53] A.U. Utom, B.I. Odoh, A.U. Okoro, Estimation of aquifer transmissivity using Dar Zarrouk parameters derived from surface resistivity measurements: a case history from parts of Enugu Town (Nigeria), J. Water Resour. Prot. 4 (2012) 993–1000.
[54] W.M. Telford, L.P. Geldart, R.E. Sheriff, DA. Keys, Applied Geophysics, Cambridge University Press, New York, 1978.
[55] P.C. Chandra, Groundwater Geophysics in Hard Rock, CRC Press, 2015.
[56] M.P. Billings, Structural Geology, Prentice-Hall, Englewood Cliffr, NJ, 1972.
[57] S.B. Maliek, D.C. Bhattacharya, S.K. Nag, Behavior of fractures in hard rocks – a study by surface geology and radial VES methods, Geoexploration 21 (1973) 529–556.
[58] A.I. Olayinka, Electromagnetic profiling and resistivity sounding for groundwater investigations near Egbeda-Kabba, Kwara State (now Kogi State) Nigeria, J. Min. Geol. 26 (2) (1990) 243–250.
[59] A.C. Braga, W. Malagutti Filho, J.C. Dourado, Resistity (DC) method applied to aquifer protection studies, Rev. Brasil. Geofís. 24 (4) (2006), doi:10.1590/s0102-261x2006000400010.
[60] M.I. Oladapo, O.J. Akintorinwa, Hydrogeophysical Study of Ogbese Southwestern, Nigeria, Glob. J. Pure Appl. Sci. 13 (1) (2007) 55–61.
[61] O. Abiola, P.A. Enikanselu, M.I. Oladapo, Groundwater potential and aquifer protective capacity of overburden units in Ado-Ekiti, southwestern Nigeria, Int. J. Phys. Sci. 4 (3) (2009) 120–132.
[62] G. Shailaja, M. Laxminarayana, J.D. Patil, V.C. Erram, R.A. Suryawanshi, G. Gupta, Efficacy of anisotropic properties in groundwater exploration from geoelectric sounding over trap covered terrain, J. Indian Geophys. Union 20 (5) (2016) 453–461.
[63] A.I. Olayinka, Non uniqueness in the interpretation of bedrock resistivity from sounding curves and its hydrological implications, Water Resour. NAH 7 (1&2) (1996) 55–60.
[64] M.O. Olorunfemi, M.A. Olorunniwo, Geoelectric parameter and aquifer characteristics of some parts of southwestern Nigeria, Geol. Appl. E Hydrogeol. 2 (1985) 99–109.
[65] O.O. Bayewu, M.O. Oloruntola, G.O. Mosuro, T.A. Laniyan, S.O. Ariyo, J.O. Fatoba, Assessment of groundwater prospect and aquifer protective capacity using resistivity method in Olabisi Onabanjo University campus, Ago-Iwoye, southwestern Nigeria, NRIAG J. Astron. Geophys. 7 (2) (2018) 347–360, doi:10.1016/j.nrjag.2018.05.002.
[66] H.P. Patra, S.K. Adhikari, S. Kunar, Groundwater Prospecting and Management, Springer Hydrogeology, 2016, doi:10.1007/978-981-10-1148-1.
[67] S. Yasala, H. Oliver, A. Stanley Raj, N. Chandrasekar, Delineation of groundwater potential zones along the coastal parts of Kanyakumari district, Tamilnadu, J. Ind. Geophys. Union 18 (3) (2014) 356–362.
[68] PWDPublic Work Department Irrigation Policy Note, Government of Tamil Nadu, 2019 reterived from https://cms.tn.gov.in/sites/default/files/documents/pwd_irrigation_e_pn_2019_20_0.pdf .