Method Article

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

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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.

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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 m³ into 416 m³ 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 Karumeniayar river basin employing geophysical vertical electrical sounding (VES).

Study area

Karumeniayar 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 km². Karumeniayar 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, Karumeniayar 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 Karumeniayar 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
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 ($\Delta V$) 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 ($\rho_a$) 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 \( h_1, h_2, h_3, h_4, \ldots, h_n \) and resistivities of \( \rho_1, \rho_2, \rho_3, \rho_4, \ldots, \rho_n \) respectively, are involved in a geoelectrical section, their longitudinal 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

\[
T = \sum_{i=1}^{n} \rho_i h_i = \rho_1 h_1 + \rho_2 h_2 + \rho_3 h_3 + \ldots + \rho_n h_n \text{ (ohm.m)}
\]  

(1)

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

\[
S = \sum_{i=1}^{n} \frac{h_i}{\rho_i} = \frac{h_1}{\rho_1} + \frac{h_2}{\rho_2} + \frac{h_3}{\rho_3} + \ldots + \frac{h_n}{\rho_n} \text{ (ohm}^{-1})
\]  

(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 \( \lambda \) can be measured from combining both average longitudinal resistivity (RS) and average transverse resistivity (RT)

\[
\lambda = \sqrt{\frac{RT}{RS}}
\]  

(3)

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

\[
r = \frac{(\rho_n - \rho(n - 1))}{((\rho_n + \rho(n - 1))}
\]  

(4)

Where,
\( \rho_n \) is the electrical resistivity of the nth geoelectrical layer
\( \rho_n - 1 \) is the electrical resistivity of the nth overlying geoelectrical layer
| Longitudinal conductance $\Omega^{-1}$ | VES location | Protective capacity |
|--------------------------------------|--------------|---------------------|
| 0.208046938                         | VES1         | Moderate            |
| 0.164430642                         | VES2         | Weak                |
| 0.518629452                         | VES3         | Moderate            |
| 0.109566211                         | VES4         | Weak                |
| 0.46167073                          | VES5         | Moderate            |
| 0.319248651                         | VES6         | Moderate            |
| 0.624741333                         | VES7         | Moderate            |
| 0.783918596                         | VES8         | Good                |
| 0.723696723                         | VES9         | Good                |
| 0.331984216                         | VES10        | Moderate            |
| 0.50063087                          | VES11        | Moderate            |
| 0.3874725                           | VES12        | Moderate            |
| 0.268535516                         | VES13        | Moderate            |
| 0.122089468                         | VES14        | Weak                |
| 1.945608832                         | VES15        | Good                |
| 0.50204283                          | VES16        | Very good           |
| 2.058147451                         | VES17        | Good                |
| 4.37419705                          | VES18        | Very good           |
| 1.029168197                         | VES19        | Good                |
| 0.31177804                          | VES20        | Moderate            |
| 0.00450338                          | 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                |
| 2.21747306                          | 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)

| Conductance Value | Location | Protective Capacity |
|-------------------|----------|---------------------|
| 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           |
| 0.1446444429      | 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| -0.644441619                     | 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| 0.81676471                      | 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                   | Medium            |
| VES18| -0.926256614                      | 48.55                    | Medium            |
| VES19| 0.801541426                       | 23.68                    | High              |
| VES20| -0.21724409                       | 41                       | High              |
| VES21| -0.21724409                       | 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                        | 47.835                   | Medium            |
| VES26| -0.80889614                       | 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 | 0.530696968                    | 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 resistivity 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 | $\rho_1$ | $\rho_2$ | $\rho_3$ | $\rho_4$ | $\rho_5$ | $h_1$ | $h_2$ | $h_3$ | $h_4$ |
|-----|---------|---------|---------|---------|---------|-------|-------|-------|-------|
| 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 | 747 | 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 | 715 | 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 | 786 | | | 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 | 796 | | 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 | 71.1 | 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)
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 resistivity of second geological layer.

Fig. 6. Spatial distribution of thickness of second geological 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.
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.
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 ($\rho$) of the first layer is 5.1 $\Omega$ m with a thickness of 2.56 m, signifying topsoil followed by kankar. The resistivity of the second layer is 202 $\Omega$ 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 $\Omega$ m. The fourth bottom layer is identified as a charnockite that has a resistivity of 6350 $\Omega$ 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 $\Omega$ m and 3.29 m thick. The resistivity of the second layer is 8.42 $\Omega$ 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 $\Omega$ 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 Karumeniayar 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 Karumeniayar 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

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