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Delineating the characteristics of saline water intrusion in the coastal aquifers of Tamil Nadu, India by analysing the Dar-Zarrouk parameters

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Abstract: Tuticorin, located in the southeastern part of Tamil Nadu, is a coastal aquifer on which Vertical Electrical Sounding (VES) was conducted, thereby analysing the interpreted subsurface resistivity layer parameters covering around 112 km^2 area of the study region. VES is an essential tool for investigating hard rock terrains of coastal aquifers and perceive an idea about the groundwater quality. In this study, Dar-Zarrouk (D-Z) parameters like longitudinal conductance (Sc), transverse resistance (Tr) and anisotropy (λ) are analysed as these are well-established parameters in delineating the occurrence and distribution of both fresh and saline water aquifers. These parameters are also very persuasive in investigating complex subsurface parameters (resistivity and conductivity) within saline water intruded coastal region environment. After conducting a thorough survey, the resistivity results reflect that the sediments are enriched with saltwater, clay with moderate freshwater and freshwater-bearing formations. The analysis shows that the D-Z parameters offer a helpful and assured answer in demarcating the saline, moderate fresh, and freshwater aquifers. Therefore, the behaviour and patterns of the D-Z parameters in space established the existence of saline water and freshwater aquifer structures in the coastal aquifers over a vast area.

Key words: Vertical Electrical Sounding (VES), Dar-Zarrouk (D-Z) parameters, coastal aquifers, Tamil Nadu

1. Introduction

Groundwater is an inevitable and valuable resource in society's development, but this water resource present within the complex basement struc-

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ture of hard rocks is overexploited to meet demand for urban growth and rapid industrialization (*Gautam et al., 2017; Sarkar et al., 2020; Karunakalage et al., 2021*). The main aquifer unit is established by the fractured/jointed and or saturated weathered region, whereas the sand/clayey-sand horizon that covers the weathered zone also comprises a significant quantity of groundwater (*Satpathy et al., 1976*).

Exploration and variation of subsurface aquifers in the coastal parts has become a main concern. The electrical resistivity method has been extensively used for exploration of groundwater in the coastal aquifers around the world (*Urish and Frohlich, 1990; Batayneh et al., 2010; Kura et al., 2014; Khaki et al. 2016*) and also for the delineation of sea water intrusion studies (*Ebraheem et al. 1997; Hamzah et al. 2007; Omosuyi et al. 1999; Voudouris 2006*). Application of electrical resistivity method has also been carried out in many coastal parts of India which were contaminated with sea water intrusion (*Sankaran et al. 2012; Gopinath et al. 2018; Gopinath et al. 2019; Senthilkumar et al. 2019*).

Industrial activities occurring near the eastern coastal belt (8 km west of Tuticorin, Tamil Nadu) enormously degraded the groundwater quality around the industrial area, and also saline water intrusion may create a problem for the people. In order to locate freshwater aquifer in the study region, a thorough survey has had been carried out because the freshwater aquifers are usually intruded upon and occupied by the saline water as they lie close to the seashore. This objective is fulfilled by the resistivity technique, which plays a significant role in exploring and demarcating fresh and saline water around the coastal region (*Gautam and Biswas 2016; Bhattacharya and Patra 1968; Zohdy 1989*). However, there seem to be some discrepancies like repeatedly delaying in data resolution and control of the stigma of ambiguity due to certain geophysical resemblances in the behaviour of saline water aquifers, freshwater aquifers, and clay layers (*Kumar et al., 2020*). In such a situation, additional expression at resistivity data interpretation and other geophysical data parameters becomes essential to provide supplementary, more accurate and assured support, leading to reliable solutions, though demarcating the saline and freshwater aquifer systems. This research work aims to present the analysis of Dar-Zarrouk (D-Z) parameters (*Zohdy, 1989*) like the longitudinal unit conductance (Sc), transverse unit resistance (Tr), anisotropy (λ), and their significant application in fresh, moderately fresh, and saline water enriched aquifers present in the coastal regions.

2. Geological and hydrogeological set-up

The area of study is situated within 8.77–8.85° N and 78.04–78.17° E coordinates along the eastern coastal belt and west of Tuticorin town of Tamil Nadu. This topographical altitude lies at 26.22 m amsl to a few meters amsl from west-east slopes and Tuticorin town. It establishes a SIIL watershed covering 112 km^2 area and is drained by NW–SE direction oriented ephemeral stream network (Fig. 1). The slopes are gentle in the west and the central part whereas almost at a level in the eastern part of the watershed.

On the north eastern side of SIIL premises, lies the groundwater trough. The region receives rainfall brought by northeast monsoon during the months of October to December. IMD records 568 mm of long term average annual rainfall in the town of Tuticorin. However, daily rainfall 2006 reported in the SIIL rain gauge station indicated that events of substantial high intensity daily rainfall have been above average compared to the previous years

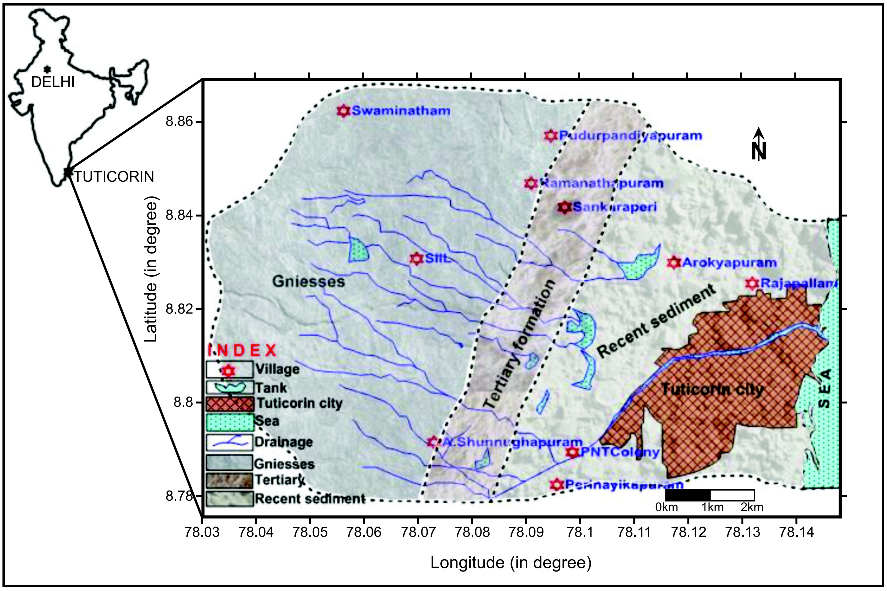

Fig. 1. Location and geological map of the study area.

(since 2000). Indian Council of agricultural science (ICAR) classified this region as agro climate zone, experiencing semi-arid tropical climate and suitable for cultivating crops like cotton, maize, medicinal plants. On the other hand certain portions of land are fallow/barren covered with thorny shrubs, dry grass and palms.

The watershed is underpinned by Archean age with charnockite, gneiss and quartzite, tertiary age of calcareous shale, sandstone and recent alluvium (Fig. 1). The detailed lithostratigraphy is illustrated in Table 1 after *Balasubramanian et al. (1985)*. Regarding the pedology of the area; black soil, red soil like sandy loam to sandy soil and alluvial soil dominates west (in and around SIIL plant), central part and eastern part (soil thickness is 3 m) respectively. The sandy soils and alluvium soils have poor retentivity soil moisture. Hydrogeologically, the watershed opens up for access to plethora of open and bore wells, tapping fractured and phreatic aquifers and most of them lie at a depth of less than 20 m. The depths of the open wells vary from 7–12 m while the depths of bore wells vary from few metres to 70 m (maximum). The sandy zone is the principal aquifer system in Tertiary and alluvial regions. During pre-monsoon period the static water range varies between 1.8–14.45 m bgl and 0.9–12.86 m bgl in post-monsoon period. In the SIIL premises and the coastal region, groundwater is present at a shallow depth.

Table 1. Lithostartigraphy of the study region (*Balasubramanian et al., 1985*).

Age	Type of formation/direction	Lithology
Archean	finely foliated; NW–SE	crystalline and metamorphic rocks
	weathered, jointed and broken; western part	quartzite ridge
Tertiary (recent to subrecent)		calcareous grit, sandstone, shale limestone

3. Methodology

3.1. Electrical Resistivity method

Electrical resistivity method employing vertical electrical soundings (VES) survey with Schlumberger configuration was carried out using four electrodes at twenty eight different locations with 100 m electrode spacing. In resistivity survey, the current is injected into the ground with the support of two metal electrodes, and potential difference between the potential electrodes is measured to determine the electrical properties of the lithology. The apparent resistivity (ρ) is calculated for every electrode by the given equation:

$$\rho = k\frac{V}{I}\,, \tag{1}$$

where V is the voltage, I is current and k is the geometrical factor.

Two parameters; apparent resistivity (ρ_i) and thickness (h_i) defines a geoelectrical layer, where 'i' indicates the location of layer in a section. Value of apparent resistivity and thickness gives the subsurface variation in resistivity along the vertical direction.

3.2. Dar Zarrouk (D-Z) parameters

Transvere unit resistance (Tr) and Longitudinal unit conductance (Sc) are the Dar Zarrouk (D-Z) parameters which are effective in resistivity surroundings (*Maillet, 1947*). Tr is defined as resistance normal to the face whereas Sc is defined as the conductance parallel to the face for a unit cross section. They are adequate for estimating groundwater potential dispersal by using graphs, several characteristics of groundwater and geology (*Kalenov, 1957; Kunetz, 1966; Keller and Frischknecht, 1966; Henriet, 1976; Satya, 1979; Rama Rao, 1980; Prakasa Rao, 1983; Singh et al. 2004*). The different Dar-Zarrouk parameters are calculated from thickness and resistivity of VES data which are as follows:

(i) Longitudinal unit conductance (Sc):

$$\mathrm{Sc} = \frac{h_1}{\rho_1} + \frac{h_2}{\rho_2} + \frac{h_3}{\rho_3} + \ldots\ldots + \frac{h_n}{\rho_n} = \sum_{i=1}^{N} \frac{h_i}{\rho_i}\,, \tag{2}$$

(ii) Transverse unit resistance (Tr):

$$\mathrm{Tr} = \rho_1 h_1 + \rho_2 h_2 + \rho_3 h_3 + \ldots\ldots + \rho_n h_n = \sum_{i=1}^{N} \rho_i h_i\,, \tag{3}$$

(iii) The average longitudinal resistivity is:

$$\rho_L = \frac{\mathrm{H}}{\mathrm{Sc}}\,, \tag{4}$$

(iv) The average transverse resistivity is:

$$\rho_t = \frac{\mathrm{Tr}}{\mathrm{H}}\,, \tag{5}$$

(v) Anisotropy (λ):

$$\lambda = \frac{\sqrt{\mathrm{Tr}} \cdot \mathrm{Sc}}{\mathrm{H}} = \sqrt{\frac{\rho_t}{\rho_L}}\,. \tag{6}$$

On analysing the above Dar-Zarrouk parameters, a conclusive and easily pertinent solution is delivered which helps in knowing the geophysical performance of fresh, moderate-fresh and saline aquifers.

4. Results and Discussions

4.1. Interpretation of geoelectrical data

The resistivity and thickness of different layers estimated earlier gives an initial understanding on sounding curves through partial curve matching. These curve matching techniques results in layered parameters which are interpreted finally using a 2D inversion technique (IP2Win) (*Kurniawan, 2009*). The inversion software computes the modelled data from the field data (Fig. 2). The interpreted layers are compared with resistivity values of different aquifer system, thus expressing range of resistivity for numerous layers (Table 2). The aquifer resistivity and thickness of each layer from 28 VES locations and curve types (K and H-type) in the study region are given in Table 3. Based on aquifer resistivity value range and its water bearing characteristics a contour amp of groundwater zone variation (fresh, moderate-fresh and saline) have had been identified and illustrated (Fig. 3). On examining the spatial variation contour map, it is revealed that resistiv-

Table 2. Resistivity ranges of aquifer type.

Aquifer types	Resistivity in ohm-m
<10 ohm-m	indicative of the presence of sand and clay saturated with seawater
10–50 ohm-m	sand or clay horizon with brackish water/sandstone, shell limestone, with or without water
50–150 ohm-m	semi weathered/fractured/jointed/poorly connected fractured
>300 ohm-m	hard rock or bedrock

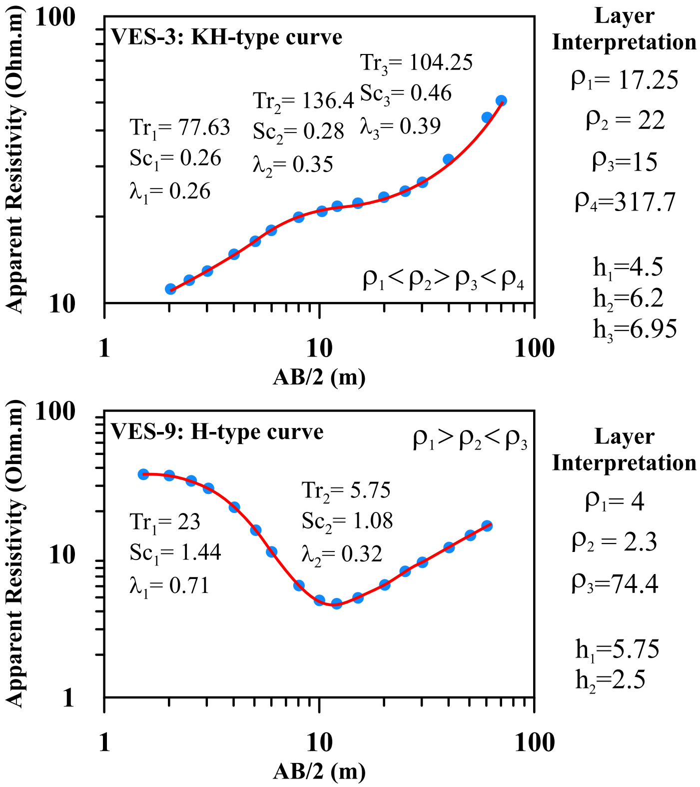

Fig. 2. Interpreted resistivity sounding curve from VES-3 and VES-9 with values of Tr, Sc and λ for respective layers.

ity of the aquifer range from 2.25-75 ohm. At VES locations; S-1, S-4 (West Archean complex), S-8, S-22, S-23 and S-26 (tertiary formation of central part) gives resistivity value of freshwater >50 ohm-m. While the set-up of VES locations S-2, S-3, S-10, S-11, S-12, S-15, S-16, S-19, S-20, S-25, S-27 (Archean) and S-5, S-6, S-7, S-13, S-17, S-20, S-28 (Tertiary formation) gives the resistivity range of fresh groundwater 10–50 ohm-m, at the same time, the VES locations; S-9, S-14, S-18, S-21, S-2 (saline water zones) and S-9, S-14, S-21, S-24 (recent sediments near the coast) arrangement gives resistivity value <10 ohm-m of saline groundwater.

The results proves that the units are present in an overlapping manner which means an interpreted layer might be expected to have freshwater but can turn out to be a clay layer or saline because resistivity of sand and salt

Table 3. Interpreted apparent resistivity, thickness and total depth of all layers with curve types for sounding locations.

S. No.	VES	ρ_1 [Ωm]	ρ_2 [Ωm]	ρ_3 [Ωm]	ρ_4 [Ωm]	ρ_5 [Ωm]	h_1 [m]	h_2 [m]	h_3 [m]	h_4 [m]	Total depth [m]	Types of curve
1	S-1	60.5	40	120	64.7	–	1.15	5.55	3.35	–	10.05	HK
2	S-2	13.35	8.468	27.85	12.12	94.06	2.1	3.1	2.8	5.5	13.5	HKH
3	S-3	17.25	22	15	317.7	–	4.5	6.2	6.95	–	17.65	KH
4	S-4	31.8	132	74.9	961	–	1.7	7.8	5.4	–	14.9	KH
5	S-5	20.12	10	25.5	15	140.8	1.6	1.34	6.33	8.13	17.4	HKH
6	S-6	5	20	36.5	–	–	8	5.5	–	–	13.5	A
7	S-7	10.5	22	12	90	–	1.03	6.8	7.41	–	15.24	KH
8	S-8	56.48	10.62	72.94	36.25	–	1.49	5.3	9.95	–	16.74	HK
9	S-9	4	2.3	74.4	–	–	5.75	2.5	–	–	8.25	H
10	S-10	12	25	15	133	–	2.21	11.5	9.3	–	23.01	KH
11	S-11	12.3	26.5	16.5	283	–	3.5	9.5	8.6	–	21.6	KH
12	S-12	13.21	24.5	15.21	78.76	–	3.3	9.8	12.33	–	25.43	KH
13	S-13	10.12	16.5	11.5	310	–	1.41	5.25	6.27	–	12.93	KH
14	S-14	10	2.6	49	–	–	5.5	16	–	–	21.5	H
15	S-15	12.53	30	15.6	161.4	–	2.8	7.12	9.28	–	19.2	KH
16	S-16	10	16	66.1	–	–	9.6	1.14	–	–	10.74	A
17	S-17	11.7	22.5	11.93	175.9	–	1.2	5.3	9.5	–	16	KH
18	S-18	15.12	10.2	2.54	56.7	–	1.42	5.45	7.36	–	14.23	H
19	S-19	32.1	12.5	20	141	–	6.8	6	9	–	21.8	HA
20	S-20	5	15	10.2	150	–	3.5	5.5	0.15	–	9.15	AA
21	S-21	5	10	2.14	8.29	–	2.5	6	11.5	–	20	KH
22	S-22	7.5	21.5	67.1	108	–	1.5	5.5	13.3	–	20.3	KH
23	S-23	65.5	25.5	100.52	10.5	500	1.2	6.5	22	5	34.7	HKH
24	S-24	1.25	8	2.5	80.5	–	7	0.5	2.5	–	10	H
25	S-25	10.5	45	11.2	268	–	1.89	7.5	8.5	–	17.89	KH
26	S-26	6.19	33.2	55	619	–	1.2	7.9	4.79	–	13.89	A
27	S-27	11.6	20.35	10.5	189.65	–	1.5	6.12	6.5	–	14.12	AH
28	S-28	12.36	35	18.86	225	–	6.65	5.65	9.5	–	21.8	KH

water interferes with each other. To combat such condition a better analysis and interpretation method must be created for remaining data for achieving an improved solution in delineation of fresh and saline aquifers. The D-Z parameters offer a very persuasive and easily applicable solution for understanding geophysical activity of freshwater and saline aquifers. Values of D-Z parameters (Sc, Tr and λ) acquired from 28 sounding data (Table 4) are

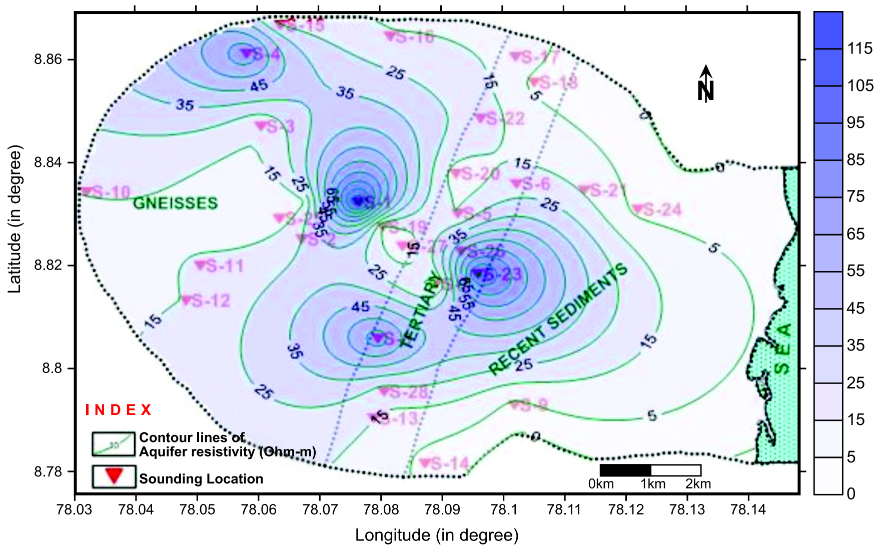

Fig. 3. Location of VES data and contour map of aquifer resistivity.

calculated to have an idea about total interpretation depth (*Zohdy, 1989; Zhdanov and Keller, 1994*). These D-Z parameters are assessed through various arrangements of resistivity and thickness attained from the VES models (Fig. 4a), and thus they give a improved understanding of the subsurface isolated layers for the assessment of a border between saline and fresh groundwater (*Batayneh, 2013*). Typical characteristics curves for H and K-type curves and its relation to subsurface aquifers are given in Fig. 4b.

4.2. Evaluation of longitudinal unit conductance (Sc)

A spatial variation contour map is prepared with a 0.20 mhos contour interval illustrating longitudinal unit conductance (Sc) estimated from 28 sound numbers (Fig. 5a), giving Sc range value of 0.18 to 6.7 mhos. The variation in Sc value indicates change in layers having low resistivity (*Orellana, 1963; Henriet, 1976; Zohdy, 1989; Rajesh et al., 2002*). In VES locations; S-9, S-14, S-18, S-21, S-24 have >2 mhos Sc value indicating saline water zone. While the moderate-fresh water zone is identified by Sc range 0.18–0.146 mhos with minimum value at S-5 and maximum value at S-12 VES location (Archean complex). In VES locations; S-2, S-3, S-5, S-6, S-7, S-10, S-11, S-12, S-13, S-15, S-16, S-17, S-19, S-20, S-25, S-26 and S-27 have Sc value

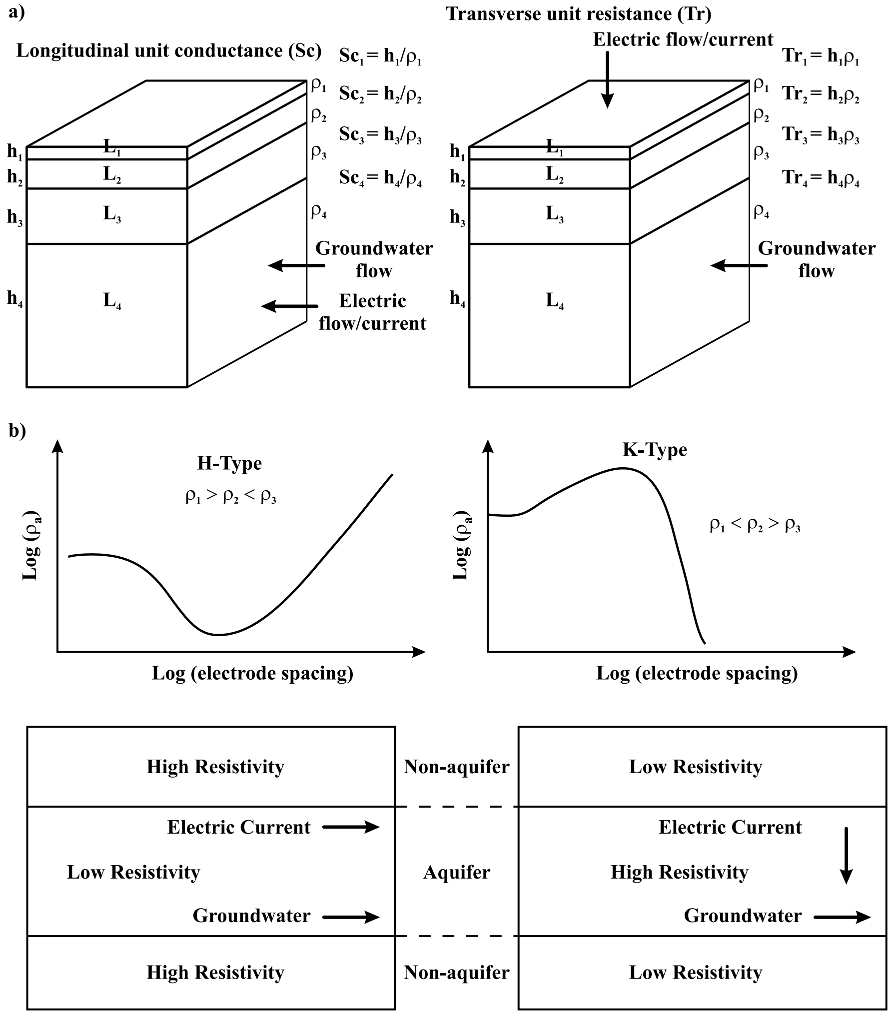

Fig. 4. (a) Subsurface layered model showing the longitudinal conductance (Sc) and transverse resistance (Tr), and (b) characteristic shapes of K- and H-type resistivity curves (after *MacDonald et al., 1999*).

1.0–2.0 mhos indicating brackish groundwater zone. The VES locations; S-1, S-4, S-8, S-22, S-23 and S-26 have Sc value 0.18–0.98 mhos with minimum value at S-4 (Archean) and maximum value at S-23 (Tertiary) thus delineating fresh groundwater zone.

Table 4. Values of Dar-Zarrouk parameters of all sounding locations with depth.

VES	Village name	H (meter)	Sc (mhos)	Tr (ohm-m^2)	λ
S-1	SIIL-1	10.05	0.19	693.58	1.13
S-2	Terku Virpandiyapuram-I	13.50	1.08	198.93	1.08
S-3	Kumaragiri	17.65	1.01	318.28	1.01
S-4	Swaminathan	14.90	0.18	1488.12	1.11
S-5	Pandarampatti	17.40	1.00	328.96	1.04
S-6	Sankaraperri	13.50	1.88	150.00	1.24
S-7	Meelavittam	15.24	1.02	249.34	1.05
S-8	SIPCOT-Office	16.74	0.66	866.19	1.43
S-9	PNT-Colony	8.25	2.52	28.75	1.03
S-10	Tattaparrai	23.01	1.26	453.52	1.04
S-11	Vadakku Silukkanpatti-I	21.60	1.16	436.70	1.04
S-12	Vadakku -Silukkanpatti-II	25.43	1.46	471.23	1.03
S-13	Ramkrishnapuram	12.93	1.00	173.00	1.02
S-14	Korampallam	21.50	6.70	96.60	1.18
S-15	Swaminathan-Nayinapuram	19.20	1.06	393.45	1.06
S-16	Nayinapuram	10.74	1.03	114.24	1.01
S-17	Velayathapuram(E)	16.00	1.13	246.63	1.05
S-18	Pudur Padiyapuram(S)	14.23	3.53	95.75	1.29
S-19	SIIL-2	21.80	1.14	473.28	1.07
S-20	Mauthan	9.15	1.07	101.53	1.14
S-21	Mappilai Urani-2	20.00	6.47	97.11	1.25
S-22	Pudur Padiyapuram	20.30	0.65	1021.93	1.27
S-23	Milavittan	34.70	0.97	2508.29	1.42
S-24	Mappilai Urani-3	10.00	5.66	19.00	1.04
S-25	Kumar Ettaiyapuram	17.89	1.11	452.55	1.25
S-26	Terku Virpadiyapuram-2	13.89	0.52	533.16	1.20
S-27	Pandarampatti (S)	14.12	1.05	210.19	1.05
S-28	Pandarampatti-Milavittam	21.80	1.20	459.11	1.08

The variation in Sc value range estimated from VES data is illustrated in a graphical plot which clearly shows the three distinguished groundwater zones; saline, moderate-fresh and fresh (Fig. 5b). In contrast to this, an anomaly could be seen in Fig. 5b graphical plot which does not bear any imprints of S-1, S-4, S-8, S-22, S-23 and S-26 sounding numbers, as they lie within moderate fresh and saline aquifer. Since the analysed depth of

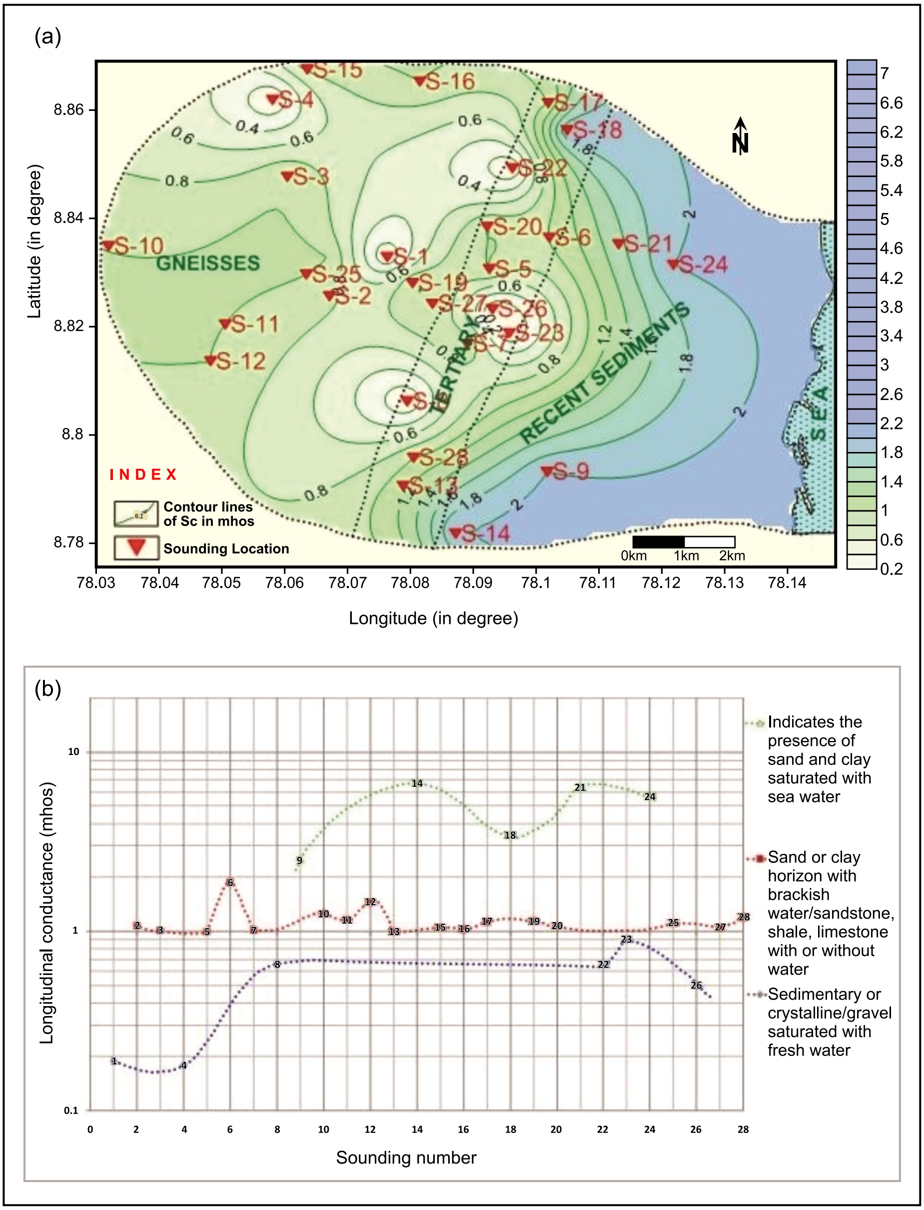

Fig. 5. (a) Contour map of longitudinal conductance (Sc) and, (b) graphical study of longitudinal conductance.

these sounding numbers do not penetrate the saline aquifer system, so they gets eliminated from the Sc value range inferred for saline groundwater zone. Unlike the sounding numbers; S-9, S-14, S-18, S-21 and S-24 whose analysed depths are 8.25, 21.5, 14.23, 20 and 10 m respectively, actually lies beyond the saline aquifer zone. Therefore these sounding numbers refers the moderately fresh zone restricting itself just at the inception of freshwater aquifer. In saline water graphical plot, these sounding numbers are also considered outliers. The graphs do not display any overlap and distinguish the saline, moderate, and freshwater characters very clearly. Variation of the saline, moderate, and freshwater aquifer matrix can cause variation in these ranges, especially in their sand and clay content. However, as the range domain is wide apart for each type of aquifer, these differences have minimum impact so that any kind of uncertainty or misunderstanding could be avoided while separating freshwater and saline aquifers.

4.3. Evaluation of Transverse unit resistance (Tr)

A contour map is prepared with Tr values calculated from 28 sound numbers with a contour interval of 100 ohm-m^2 (Figs. 6a and b) clearly illustrating salty, moderate-fresh and fresh aquifer zones. The high Tr values indicate increasing thickness of material having high resistivity. Tr values estimated gives value range of 19–2508.29 ohm-m^2, showing minimum value at sound location S-24 (Mappilai Urani-3 village) and aquifer presence is defined at S-23 (Milavittan village, Tertiary formation). The Tr value range of 105.53–471.23 ohm-m^2 gives moderate-fresh water zone with minimum value at S-17 (Tertiary formation) and maximum value at S-12 (Archean complex). At the same time, Tr value range of 533.15–2508.29 ohm-m^2 delineates freshwater aquifer zone with minimum value at S-26 (Tertiary formation) and maximum value at S-23 (Tertiary formation). The contours of saline, moderate-fresh and freshwater are distinct and do not overlap with each other. The graphical plot of Tr values display range that are easily visible and have no overlapping characters, clearly illustrating that the sound numbers S-9, S-14, S-18, s-21 and s-24 marks the saline water zone. Therefore, by a large distance, the graphs distinguish themselves from each other, identifying the saline, moderate-fresh and freshwater aquifer zone quite efficiently.

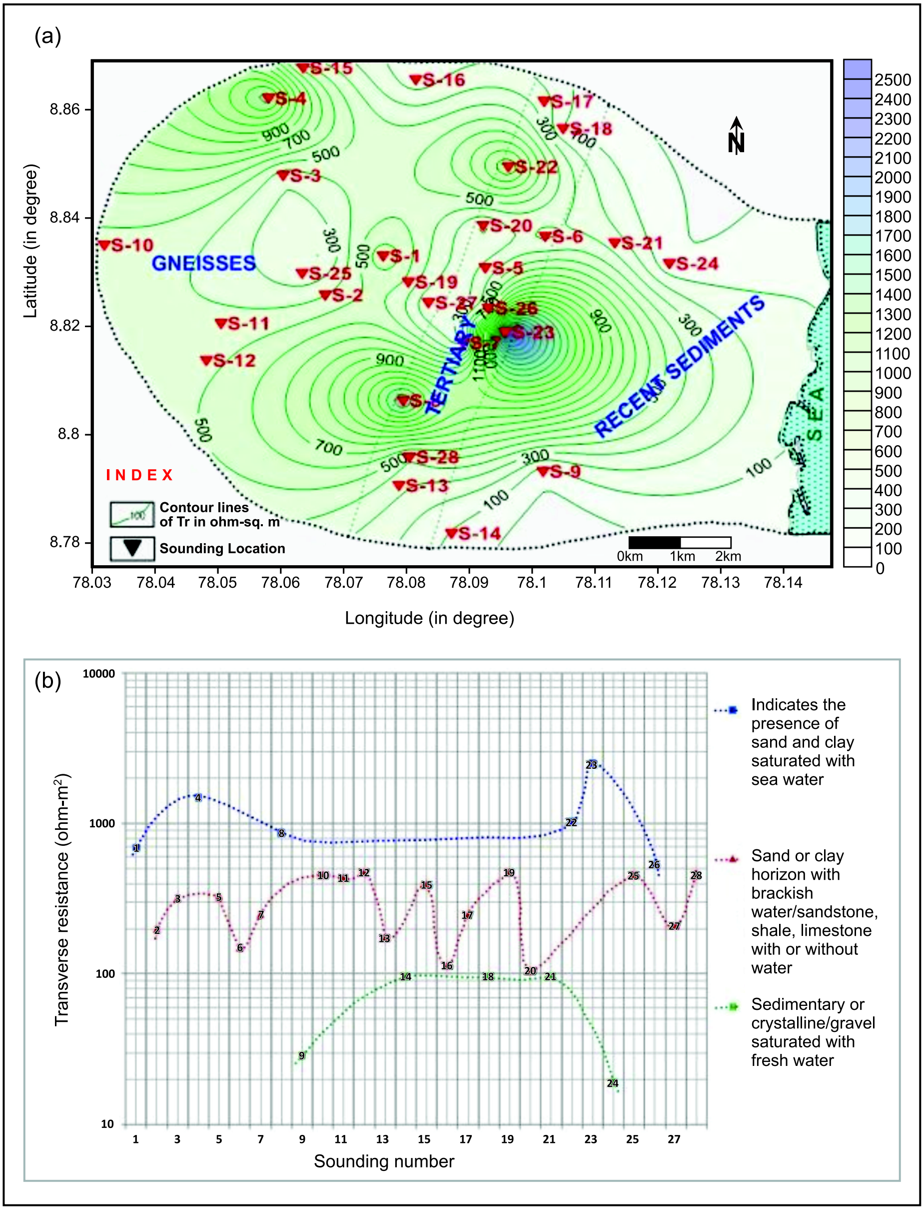

Fig. 6. (a) Contour map of Transverse resistance (Tr) and, (b) graphical study of transverse resistance.

4.4. Evaluation of coefficient of anisotropy (λ)

The coefficient of anisotropy (λ) measures the anisotropism extent of an aquifer system (Table 5) and its value increases with increase in hardness of rock (*Balasubramanian et al., 1985*). The λ estimated in the study region varies between 1.01–1.43 with minimum value at S-20 (near Mauthan village, Tertiary) and maximum value at S-8 (near SIPCOT office, tertiary sediments). We have considered that, principle directions are in symmetry so the 0.5 value can be rounded to 1.0 so as to tie with range proposed by *Kunetz (1966)*.

Table 5. Anisotropy coefficient value for different aquifer lithology.

Aquifer lithology	Anisotropy value (λ)
Alluvium	1.02–1.10
Sandstone and shale	1.05–1.15
Slates	1.40–2.25
Graphite	2.0–2.8
Intrusive bodies like dyke, sills, batholiths	>2.0
Interbedded anhydrite and shale (NE Colorado)	4.0–7.5 (*Kunetz,1966*)

A contour map (Fig. 7a) is prepared using the λ values of 28 sounding data with a contour interval of 0.02. The anisotropy graphical plot depicts overlapping without any clear differentiation among saline, moderate and freshwater aquifers (Fig. 7b). The variation of the saline, moderate, and freshwater aquifer matrix can cause variation in these ranges, especially in their sand and clay content. However, as the range domain for each type of aquifer is narrowly divided, such differences have a limited impact on uncertainty or misunderstanding when separating the study area's saline and freshwater aquifers.

4.5. Implication of D-Z parameters

The interpretation of the D-Z parameters for two representative VES data (VES-3 and VES-9) is shown in Fig. 2. The D-Z parameters (Sc, Tr and λ) have successfully delineated the three groundwater zones. The respective resistivity values are <10 ohm-m, 10–20 ohm-m and 20 ohm-m for saline, moderately fresh and fresh groundwater zones (Table 2). While the resistiv-

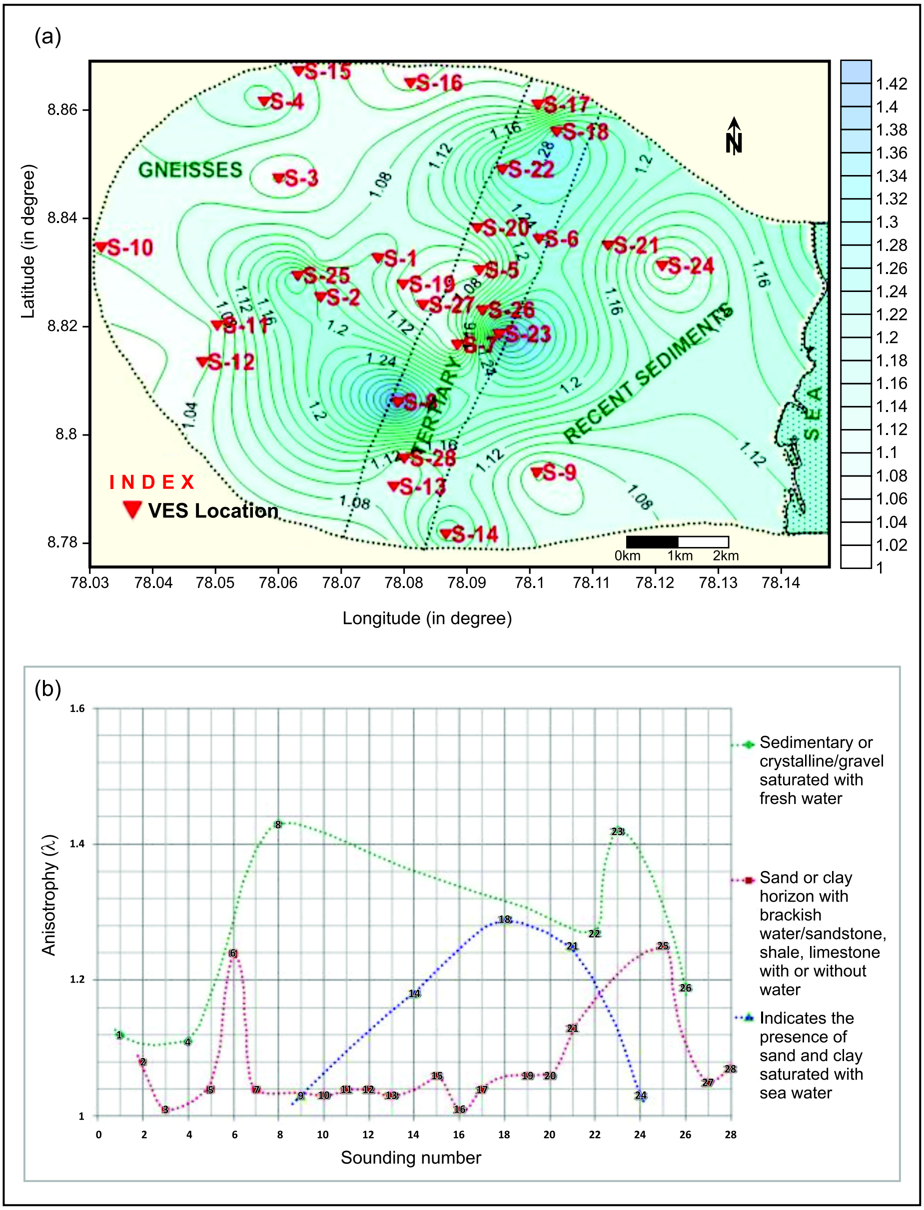

Fig. 7. (a) Contour map of aquifer anisotropy (λ) and, (b) graphical study of coefficient of anisotropy.

ity values establish a sense of speculation and insecurity, the D-Z parameters are quite simple, obvious and without any overlapping existence. A definite resistivity value for salty, moderate fresh and freshwater aquifers is difficult to assign, as it depends on several variables that are outside the niche of this paper. When the interpretation is accompanied by readily recognizable geophysical parameter, the persistent ambiguity in the interpretation of resistivity data can be greatly reduced. Therefore, D-Z parameters will certainly help the interpretation of the resistivity data and reduce the risks of uncertainty. The broadly varying ranges of saline, moderate fresh and freshwater aquifer D-Z parameters have advantages over the analysis of resistivity data (Table 6). A striking difference could be seen in both the graphical & contour analysis for saline, moderate- fresh and freshwater but there lies a strong agreement between graphical plot and contour map for saline and freshwater aquifer. A vertical section is prepared from seven VES data (resistivity and thickness) along WNW–ESE profile to show the

Table 6. Dar-Zarrouk parameters applicable for saline, moderate fresh and fresh water aquifers (after *Batayneh, 2013*).

Longitudinal unit conductance (Sc)	Fresh water aquifers	Less than 1.0 mhos by contours
		0.18–0.98 mho by graphs
	Moderate Fresh water aquifers	1.0–2.0 mhos by contours
		1.0–1.46 mho by graphs
	Saline water aquifers	Greater 2.0 mhos by contours
		2.5–6.4 mho by graphs
Transverse unit resistance (Tr)	Freshwater aquifers	Greater than 500 ohm-m^2 by contours
		500–2508.29 ohm-m^2 by a graph
	Moderate Freshwater aquifers	100–500 ohm-m^2 by contours
		105.53–471.23 ohm-m^2 by a graph
	Saline water aquifers	Less than 100 ohm-m^2 by contours
		19–97.11 ohm-m^2 by a graph
Coefficient of anisotropy (λ)	Freshwater aquifers	Randomly change by contours
		Randomly change by a graph
	Moderate Freshwater aquifers	Randomly change by contours
		Randomly change by a graph
	Saline water aquifers	Randomly change by contours
		Randomly change by a graph

subsurface resistivity distribution of the area (from shore to inland). Also, the total D-Z parameters (Sc, Tr, λ) interpreted from the studied aquifer are also shown to see the nature of the subsurface and its relation with the saline water intrusion zones (Figs. 8a,b).

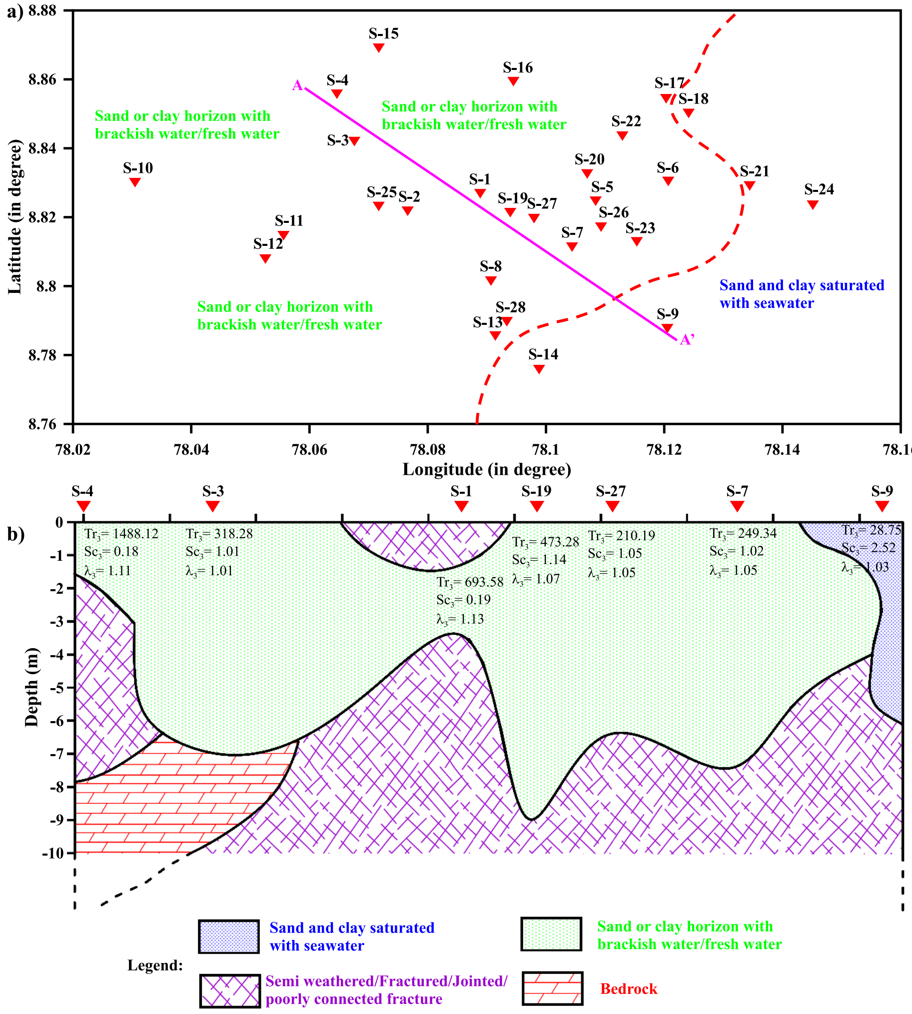

Fig. 8. (a) Map of the profile from seven VES data along NNW–SSE and, (b) subsurface section based on the lithological variation along with longitudinal conductance (Sc), transverse resistance (Tr), anisotropy (λ) for all layers and distribution of aquifer zones with Brackish/fresh water.

4.6. Application of Dar-Zarrouk parameters in regional study

The analysis of D-Z parameters gives a close observation to the subsurface aquifer which might be very crucial in planning for exploration of saline and freshwater aquifer. They provides clue for overcoming the confusion induced by the perception of resistivity values These D-Z parameters are site specific and the ranges or values can vary from places to places. Both the Tr and Sc values characterized groundwater into saline, moderate fresh/brackish and fresh aquifer zones. The VES locations; S-1,S-4 (Archean) and S-8, S-22, S-23 and S-26 (Tertiary) gives fresh groundwater zone, while the S-9, S-14, S-21 and S-24 (recent) and S-18 (Tertiary) VES locations indicates saline groundwater zone and the remaining VES locations falls under brackish groundwater zone. Thus, from the analysis and evaluation it can be determined that most of the area (middle and west) is occupied by moderate freshwater aquifer system. The saline zone lies close to sea because of seawater intrusion whereas the freshwater zone prevails within the Archean and Tertiary sediments (Fig. 9).

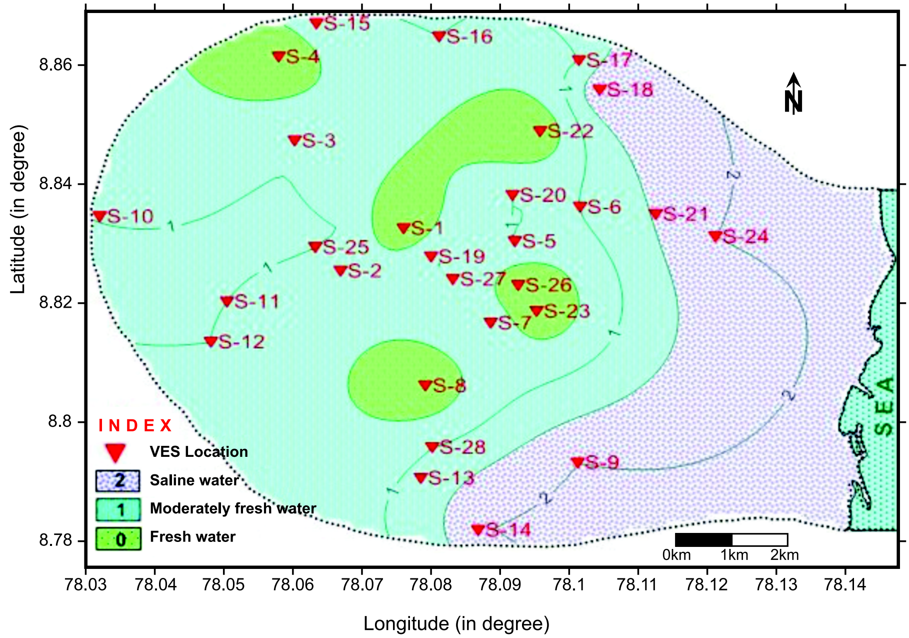

Fig. 9. Distribution of freshwater zones in the study area.

5. Conclusion

The subsurface layer parameters (resistivity and thickness) of twenty eight vertical electrical sounding was interpreted along the coastal aquifer of Tuticorin, Tamil Nadu. The study was specifically carried out to demarcate the saline, moderate fresh and fresh groundwater zones. However, in many cases such VES data fails to distinguish the boundaries between saline and fresh water. In such apprehensive situation Dar Zarrouk parameters such as Transverse unit resistance (Tr), Longitudinal unit conductance (Sc) and coefficient of anisotropy (λ) will be very much helpful to determine the saline and fresh water aquifer zones. These parameters accurately interpret as well as restrict the boundaries between the different groundwater zones and also decrease the risk of uncertainty. The final evaluation depicts that the freshwater zone lies in archean and tertiary sediments, moderate freshwater in central and west and saline water near the sea due to the intrusion of seawater.

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