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1D Geoelectrical Resistivity Survey for Groundwater Studies in Coastal Area: A Case Study from Pearl City, Tamil Nadu

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Abstract: Geoelectrical resistivity method involving vertical electrical sounding (VES) was carried out in a sedimentary environment to determine the suitability of the method for sub-surface groundwater investigations. The EC and TDS hydrochemical data in the study area clearly showed the influence of seawater intrusion. The abundance of the major cations and anions are in the following order, $Na^+ > Ca^{2+} > Mg^{2+} > K^+ = Cl^- > HCO_3^- > SO_4^{2-} > CO_3 > NO_3 > PO_4$. Results suggest that the groundwater in this study area is very hard and alkaline in nature. As indicated by Piper trilinear diagram, NaCl and Ca^{2+} - Mg^{2+} – Cl^- - SO_4^{2-} facies are the dominant hydrochemical facies in the groundwater of Pearl city. The VES method by Schlamberger electrode array was applied in 12 locations, which is expected to represent the whole area. The resistivity meter (aquameter CRM 5OO) was used to collect the VES data by employing a Schlumberger electrode configuration, with half current electrode spacing (AB/2) ranging from 2 to 180 m and the potential electrode (MN) from 1 to 50 m. The resistivity data is then interpreted by WINSEV 1-D inversion program geoelectric software to entirely describe the aquifer system as well as the occurrence of groundwater. The outputs of sub-surface layers with resistivities and thickness presented in contour maps and 2-D views by using SURFER software were created. Accordingly, three zones with different resistivity values were detected, corresponding to three different formations: (1) a transition zone of sandy soil (aeolian deposits) thick formation, (2) strata's saturated with fresh groundwater in the east disturbed by the presence of sandy shell limestone horizons, (3) a water-bearing formation in the west containing low saltwater horizons. The bedrock is encountered at an average depth of 95m. This study indicates that the groundwater reservoirs are mainly confined to the alluvial aquifer.

Keywords: VES, Schlumberger electrode, WINSEV, Sandy Shell limestone, Water-bearing formation, Tamil Nadu.

INTRODUCTION

Due to rapid urban development in Pearl city, Tamil Nadu, India and the adjoining places, there is an increase in demand for the utilization of groundwater. Because of the over exploitation of groundwater, the groundwater level has declined in recent times which warrants groundwater assessment for sustainable utilization within the study area. An adequate supply of drinking water is one of the pre-requisites for every type of developmental programme. For this reason the efforts connected with the location, development and conservation of groundwater supplies are of a fundamental economic importance for any country. Groundwater supplies like any other kind of buried natural resources of the earth are becoming progressively more difficult to locate (Selvam et al. 2010). Accordingly any new technique which will assist in the location of borehole site and eliminate the sinking of unproductive wells in large numbers is of a great value. Complementing the more traditional water finding methods, modern geophysical investigation techniques are more capable for locating water bearing formations than the older conventional methods. (Chidambaram et al. 2009; Devi et al. 2001; Muthuraj et al. 2010).

The most commonly employed geophysical method in groundwater exploration are electrical resistivity and seismic (mostly refraction) techniques. Other methods such as gravity and magnetic are used for mapping the concealed features of the bed rock which is an indirect means of locating favourable areas for groundwater. Geophysical electrical resistivity methods due to simplicity of its technique has been extensively used for groundwater investigation by many workers (Majumdar et al. 2000; Bhattacharya and Patra 1969; Oluronfemi and Fasuyi 1993; Kumar and Riyazuddin, 2008; Srinivasamoorty et al. 2011) and considered to be the most suitable method for groundwater investigation in most geological environment. The Vertical Electrical Sounding (VES) method has been chosen for this study because the interpretation, field works are simple and analysis of data is less tedious and economical. (Selvam and Sivasubramanian, 2012a; Zohdy, 1989).

The Sclumberger electrode array is commonly adopted in the VES technique due to its field logistic advantage of having to move only two electrodes at a time. Where large depth of investigation is required, large electrode spacings are adopted. This is also the case when the substratum is very conductive due to high clay content or saline water intrusion and current flow lines converge, leading to shallow depth of investigation (Telford et al. 1990). There are cases where total spread length of up to two kilometers has been used (Choudhury et al. 2001). Such large linear electrode spread may be difficult to accomplish in built up area due to lack of space. Hence depth of investigation is reduced and geoelectrical results are inconclusive and to make recommendations is difficult. Several algorithms have been developed to perform 3D resistivity modeling and inversion. 3D forward algorithms based on the finite difference, finite element, and integral methods have been presented by several authors (e.g., Zhang et al. 1995; Loke and Barker 1996; Zhao and Yedlin, 1996; Spitzer, 1998; Tsourlos and Ogilvy, 1999; Yi et al. 2001; Pidlisecky et al. 2007). In the present study, the author used the results of the integrated interpretation of gravity and resistivity data through 1D inversions using special algorithm.

The main purpose of the present study is to provide information on the sub-surface geology and groundwater occurrence for hydrogeologic interpretations using an integration of the geoelectric resistivity measurements, and hydrochemical data obtained from irrigation wells. A discussion on the relationship between the resistivity, obtained on the land surface, and the water resistivity, measured directly from water samples is included to evaluate the usefulness and limitation of the resistivity data in sub-surface hydrogeologic investigation.

STUDY AREA

Pearl city (Thoothukudi) is located strategically close to the east-west international sea routes on the southeast coast of India. It is a coastal town with a sea port and has been recently upgraded as corporation. Historically, Thoothukudi is famous for its maritime activity and pearl culture. It was the seaport of the Pandyan kingdom and was later taken over by the Portuguese in 1548, captured by the Dutch in 1658, and ceded to the British in 1825. The lighthouse built in 1842 marked the beginning of the history of harbour development in the city. Thoothukudi was established as a municipality in 1866. It attained the status of corporation on 5th August, 2008 after 142 years (Selvam, 2012b). The city was industrially developed after the port construction and became district head quarters in the year 1986. After the formation of the district head quarters, the economic development was boosted and began to develop rapidly. The study area covers 112 sq. km and lies between 8°43' - 8°51' N latitude and 78°5' - 78°10' E longitude (Fig.1). Topographic elevation varies from few meters (near the coastline) to 27 m (amsl) in western part of the study area. The slope is gentle in the western and the central part and nearly flat in the eastern part. Rainfall data from seven stations over the period of 1901- 2008 were utilized and a perusal of the data shows that the normal annual rainfall over the district varies from about 570 mm to 740 mm. It is minimum around Arasadi (577.4 mm) and in the central eastern part of the Tuticorin district (582.8 mm). The district is covered by black cotton soil in the west with isolated red soil patches in high ground. The sandy soil is present in the coastal tract. Alluvial soil is restricted to river flood plain and coastal part. Alkaline and saline soils are also noticed at places. Thoothukudi is covered by long and extensive sandy beach. It trends in north-south direction. Well developed sandy beach is identified below south harbour breakwater. This beach is dominated by an admixture of quartz, feldspars and mica. The study area is covered with black soils in the western part, red soil (sandy loam to sandy soil) in the central part and alluvial sandy soils (Coastal area) in the eastern part (Selvam et al 2014a, b, c). The maximum soil thickness is about 3 m. The sandy soils originated from sandstones and they have low soil moisture retentively. The alluvium soils are wind-blown sands and shells constitute beach sand and coastal dunes, which have very low soil moisture. The important aquifer systems is unconsolidated and semi-consolidated formations and weathered and fractured crystalline rocks. The porous formations include sandstones of Tertiary age. The recent formations comprising mainly sands, clays and gravels are confined to major drainage courses(Fig.1). The maximum thickness of alluvium is 45.0 m bgl, whereas the average thickness is about 25.0 m. Groundwater occurs under confined conditions in these formations and is being developed by means of dug wells and filter points. The productive zones are encountered in the depth range of 29.5 to 62 m bgl (Selvam et al. 2015a, b, c).

MATERIALS AND METHODS

Aquameter CRM 500

Electrical prospecting makes use of a variety of principles, each based on some electrical properties or characteristics of the earth's material. A lot of equipments

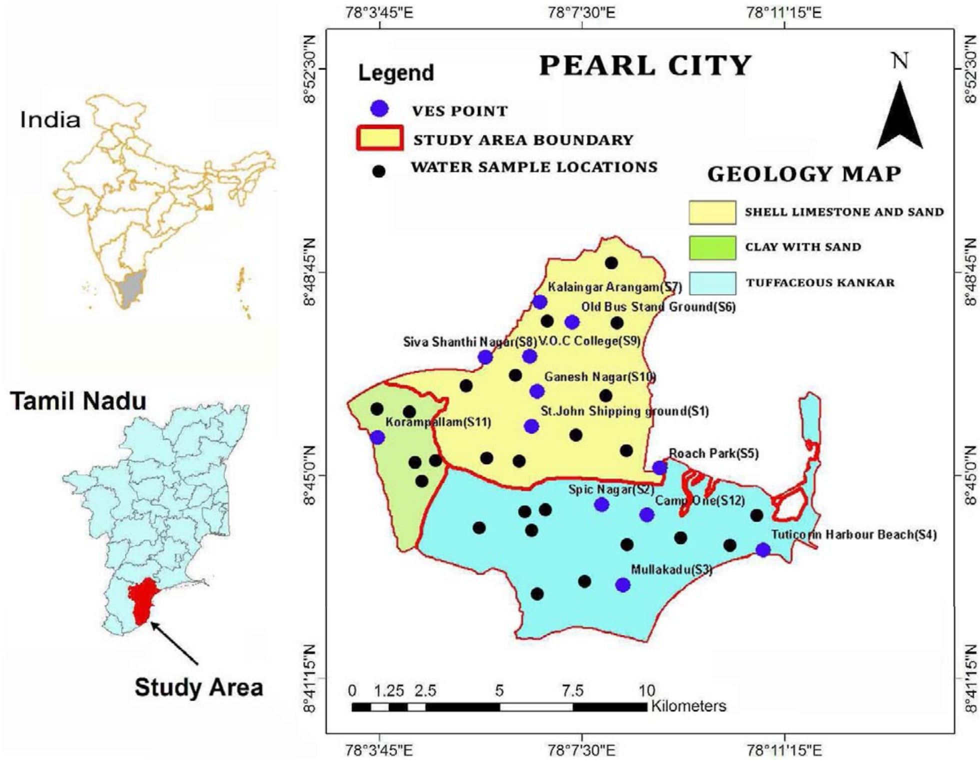

Fig.1. Geology and location map of the sounding area

are available for data acquisition. Some of the common equipments for electrical resistivity measurements are Aquameter-CRM (Computer Resistivity Meter). The aquameter CRM 5OO consists of a generator and a receiver housed in a single cabinet. It possesses a signal facility of averaging 4,6,46 and 64 signals and an option of using 5 to 500Ma current setting in 5 ranges. ΩV/I is calculated automatically and displayed in digital form in KΩ, Ω or mΩ. SP (Self Potentials) cancellation is done automatically. It takes only 6 to 8 seconds to measure the resistance, after canceling the SP and display the values. Another advantage of this equipment is the error diagnosis due to poor contacts, unwanted current settings, resistance setting, low battery power and many more. The accuracy of the measurement is ±8% up to 0.003 Ω.

Field Work

The field work was done in the summer season (June 2012). The ground was dry and adequately conductive. The field work started with the construction of a base map. This is an enlarged topographic map of scale 1:25,000 of the area. A surveillance trip was made with the aid of this map. Location of stations for resistivity profiles, location of the well drilled in the area were made. Charts were constructed for electrode displacements. The actual field work involved a total of 8 people who performed different operations that were required for obtaining resistivity profiles.

The electrode array used was the Schlumberger arrangement where the potential electrodes positions were apparently kept constant and the current electrodes were moved outwards symmetrically about their centre of spread. Measurement for each profile started with a potential electrode separation of 0.2 meter and current electrode spacing of 1 metre. A and B are current electrode positions, M and N are potential electrode positions. AB/2 is the distance from centre of electrode spread to either of the current electrode position, MN/2, half the potential electrode spread. At AB/2 = 30m and 180m respectively, the separation MN/2 of the potential electrode position was increased. This was done because at this distance, the resistance readings displayed was small, and distance MN was increased and appreciable readings were displayed. This increase in potential electrode spacing was absorbed by the formula for calculating the apparent resistivity for the electrode spread. The effect of the change is completely diminished when looping (repeating readings for 2 already occupied current electrode positions with the new potential electrode spread) was made. A maximum separation of 50 meters for potential electrodes and between 180 meters and 210 meters for the current electrodes was realised. The possibility of very long spread measurements was limited because of accessibility in the field. The sounding stations were geo-referenced in the Universal Traverse Mercator (UTM) Zone 31 with a GARMIN 12 Global Positioning System (GPS).

Data Acquisition and Presentation

A Vertical Electrical Resistivity (VES) survey at 12 locations using Schlumberger method were undertaken to find out the aquifer characteristics of the area and to understand the electrical distribution along the vertical direction. The combination of all type of curves recorded in the study area indicate the presence of multilayers in homogeneous formation. The apparent resistivity values were plotted against AB/2 on double – log graph sheets. The manner in which apparent resistivity values increase or decrease with electrode separation forms the basis for choosing the shape of the field curve that can perform quantitative interpretation of the sub- surface resistivity distribution. (Singh et al. 2002; Ochuko, 2011; Selvam, 2012c). The interpretation of resistivity data of the present investigation has been carried out using WINSEV software program version 6.1 distributed by Koefoed in 1979. This software helps in interactive semi-automated interpretation of the field data. There are large number of problems connected with groundwater exploration and exploitation that could be investigated with the help of geophysical method (Raju and Reddy, 1998; Yadav and Abolfazli, 1998; Al-Garni 2006; Mondal et al. 2011a, b). The interpretation of resistivity data gives the depth, thickness and resistivity of the different layers at that location. The depth variation are further highlighted in the stitched geoelectrical which was constructed between Vertical Electrical soundings (S1-S12) by the sections obtained from individual 1D inversion of the sounding data, its 1D interpretation of the sounding data does not indicate lateral changes or distributions of resistivity. The advantage of the electrical resistivity method is that quantitative modeling is possible using either computer software or published master curves. The resistivity inferred from the observed data in the field is used to estimate the aquifer characteristics.

Groundwater Sample Techniques

A total of 25 groundwater samples have been collected from open wells and bore wells, well distributed within the study area during June 2012 and analyzed to understand the chemical variations of water quality parameters using standard methods (APHA 1995).The samples were collected in 1 liter high density polyethylene (HDPE) bottles pre-washed with dilute hydrochloric acid and rinsed three times with the water sample before filling and labeled accordingly. The samples were stored at a temperature 4° C prior to analysis in the laboratory. Samples were analyzed in the laboratory for the physico-chemical parameters like pH, electrical conductivity (EC), total hardness (TH), total dissolved solids (TDS) and major cations like calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), and anions like bicarbonate (HCO_3), carbonate (CO_3), chloride (Cl), nitrate (NO_3), and sulfate (SO_4), phosphate (PO_4) using the standard methods given by the American Public Health Association (APHA 1995). These parameters are tabulated in Table1. pH, EC and TDS were measured using portable water quality analyzers. Major cations (Ca, Mg, Na, and K) were determined using ICP-Mass Spectrometer while the bicarbonate (HCO_3), and Total hardness (TH) were analyzed by volumetric method and sulphate (SO_4) was estimated by the spectrophotometeric technique and nitrate (NO_3) was determined by ion chromatography. Chloride (Cl) by volumetric titration using $AgNO_3$ and K_2Cr, HCO_3 and carbonate (CO_3) was determined by Portamess using HCl, phenolphthalein, methyl orange by titration method. All concentrations are expressed in milligrams per liter (mg/l), except pH and EC.

RESULTS AND DISCUSSION

Summary of Hydrochemistry

Table 2 summarizes results of the various physical and chemical parameters including statistical measures such as minimum, maximum, average and standard deviation of analyzed groundwater samples from the study area. Results were compared with the standard guideline values recommended by the World Health Organization (WHO, 2004). The pH values ranges from 7.1 to 10.2 with an average value 7.7. The pH value as low as 7.1 was recorded in Meelavitan and the highest was found in Jothi nagar near Sankarapari with a value of 10.2. This shows that the groundwater of the study area is dominantly of alkaline in nature. TDS values ranges from 530 to 10200 mg/l, with an average value is 3016 mg/l. Higher content value of TDS can be attributed to the contribution of salts from the thick mantle of soil and weathered media of the rock and further due to higher residence time of groundwater in contact with

Table 1. Physiochemical groundwater parameters in study area

Water quality parameters	Units	Water quality parameters	Units
pH	-	Mg	mg/l
EC	µS/cm	HCO_3	mg/l
TDS	mg/l	CO_3	mg/l
Na	mg/l	Cl	mg/l
K	mg/l	SO_4	mg/l
Ca	mg/l	PO_4	mg/l

the aquifer body. Most of the samples exceed the 1500 ppm which may be attributed to infiltration from the sewage canals, unprotected drainages and industrial wastes. The EC values ranges from 350µs/cm to 19100 µs/cm with an average value 4887 µs/cm. Higher EC value may be due to seawater intrusion (Selvam et al. 2013a). These groundwater samples had been classified in a more systematic manner by using dominant cations and anions. Sulphate (SO_4) concentration varies from 19 to 1272 mg/l with an average value of 354.72 mg/l. The Chloride (Cl) concentration varies from 36 to 5885 mg/l with an average value of 899.41 mg/l. The maximum allowable limit of Cl is 600mg/l. High concentration of Cl may be injurious to people suffering from diseases of the heart and kidneys (Selvam et al. 2013b and 2013c). Calcium (Ca) ion concentration varies from 11-570 mg/l with an average value 139.6 mg/l. The magnesium (Mg) ion concentration varies from 15-442 mg/l with an average value 118 mg/l.

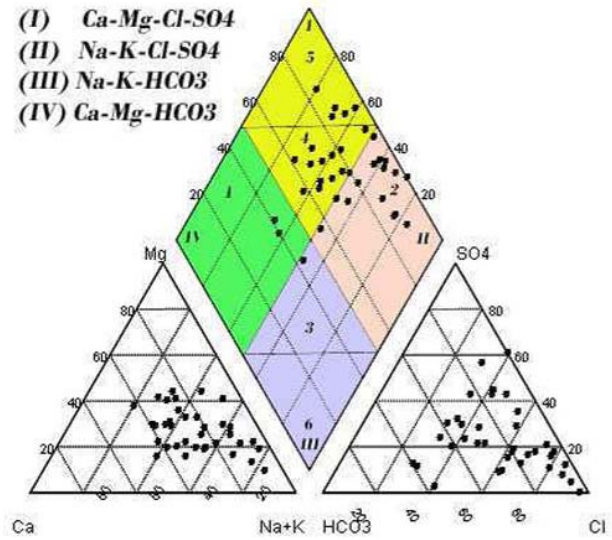

Fig.2. Piper plot of the study area

Hydro-chemical Facies

The Piper diagram (Piper, 1994) is extensively used for determining the hydrochemical facies. Aquachem software is used for the plotting. In the study area majority of samples belong to Ca^{2+} - Mg^{2+} – Cl^{-} - SO_4^{2} and Na^{+} - K^{+} – Cl^{-} - SO_4^{2-} type (Fig:4). From the plot it is observed that the alkalis (Na^{+} and K^{+}) exceeds the alkaline earths (Ca^{2+} and Mg^{2+}) and strong acids exceeds weak acids (Fig.2).

Results of VES data

The distribution of 12 sites used for the study is given in Fig. 1 and the results are presented in Table 3. The results are analyzed both qualitatively and quantitatively in the light of the available geological and hydrogeological information in order to locate groundwater potential zones. The 12 VES data with a maximum AB/2 separation of 180 m were obtained from WWDSE. The apparent resistivity value of all VES are gridded and contoured within the area of interest and the result of sounding are presented in the form of apparent resistivity pseudo-sections and apparent resistivity contour maps of different depth levels, i.e., AB/2 value. SURFER-8 software was used.

Qualitative Interpretation

The qualitative interpretation of VES is done by analyzing the iso-apparent resistivity maps ((Son, 2011). This method helps in learning the general information about the geological structure and the changes in geoelectrical section of an area. From the interpretation of VES curves 5 to 6 sub-surface layers are indicated in the study area. The resistivity of the first layer (p1) ranges from 3.8 to 184 ohm-m and thickness ranges from 0.33 to 4.1m. The resistivity is diagnostic of sandy soil and reflects the various composition and moisture content of the top soil. This may act as a confining layer but because of the small clay layer it may be susceptible to pollution. The following stations with high resistivity are S2, S6, S7, S10 and S11 (Fig.3). The resistivity of the second layer (p2) ranges from 0.93 to 65 ohm-m and the thickness ranges from 0.93 to 30m.This layer is composed of calcretic clay and does not act as a confining layer. The average thickness of the second layer is 7.6 m (Fig.4). The resistivity of the third layer (p3) ranges from 1.2 to 2346 ohm-m and the thickness of the layer 4.6 to 45m. It generally consists of weathered/ fractured rocks and may or may not be saturated with water (Fig.5). From the iso-apparent resistivity map of the second layer, it is observed that a low resistivity zone is found (<43 ohm-m except S4 and S12). The p4 (resistivity of the Fourth layer) of this area ranges from 0.99 to 899 ohm-m, and the thickness between 6.4 to 29m (Fig. 6). The depth to basement is not uniform in the basin as depicted by VES-S7 (899 ohm-m)

Table 2 Statistical measures such as minimum, maximum, average and standard deviation in pre -monsoon period

Water quality parameters	pH	EC	TDS	Na	K	Ca	Mg	HCO_3	CO_3	Cl	SO_4	PO_4	NO_3	TH
Minimum Concentration	7.1	350	530	27	5	11	15	0	0	36	19	0.1	0	138.18
Maximum Concentration	10.2	19100	10200	1400	400	570	442	756	168	5885	1272	0.1	14	2642.46
Average	7.6	4887.7	3016.11	408.77	63.41	139.66	118.08	293.25	46	899.41	354.72	0.1	5.65	835.07

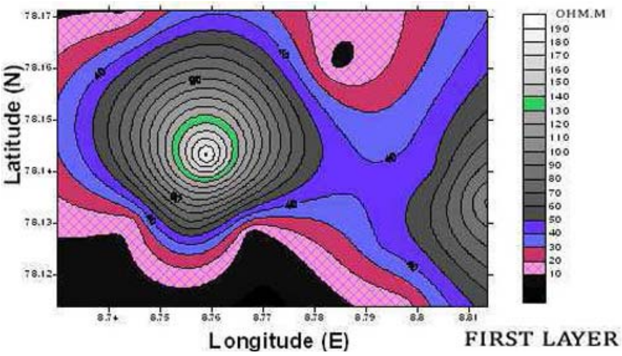

Fig.3. Contour map of top and first layer resistivity along with VES positions in the study area

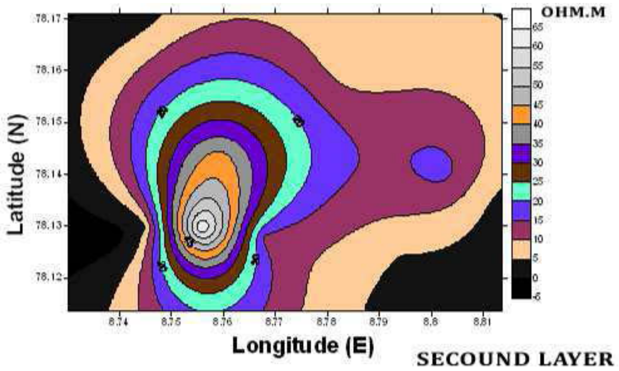

Fig.4. Contour map of second layer resistivity along with VES positions in the study area

and VES-S10 (22 ohm-m). On the basis of sounding data it has been found that the depth to bedrock is found to be greater. Hence, these areas are more suitable for groundwater development. The fifth geoelectric layer (p5) and sixth geoelectric layer (p6) has resistivity ranging from 2.1-2510, 13-584 ohm-m respectively. The thickness of this sixth geoelectric layer is not defined since it is the last layer. Depth and thickness of sub-surface layers were identified and the dimension of the aquifer and type of bedrock were also determined (Fig.7).

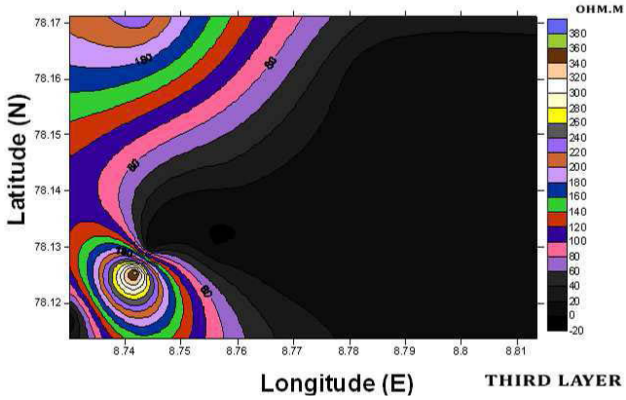

Fig.5. Contour map of third layer resistivity along with VES positions in the study area

Model Parameters

The VES data S4 and S12 can be explained by a two layer model in which the top layer has a resistivity of 7.9 and 8.5 ohm-m and a thickness 3-4.1 m. This is followed by layers having resistivity of 1.7 and 1.9 ohm-m. The basement resistivity is 381 and 234 ohm-m respectively (Table 3). The VES data S2, S3, S7 and S11 can be explained by a three layer model in which the top layer has a resistivity almost 5.7-103 ohm-m and a thickness 0.75-3.2 m. This is followed by 0.93-65 ohm-m and 1.3-15 m and further followed by layers having resistivity of 417-899 ohm-m, which is very high. The top layer is covered with top soil and followed by weathered zone which is underlain by basement. The VES data S5, S6, S8 and S9 can be explained by a four layer model in which the top layer has a resistivity of 7-4634 ohm-m and a thickness 1-2.6m. This is followed by layers having resistivity of 2.1-17 ohm-m and 1.2-6.8 ohm-m and a thickness 1.4-7.6 m and 9.3-11 m, respectively, which is underlain by a fourth layer having a resistivity of 3.5-12 ohm-m and a thickness of 8-29 m. Basement resistivity value is 173-2510 ohm-m. The VES data S1 and S10 can be explained by a five layer model in which the top

Table 3. Analyzed vertical electrical sounding (VES) data of study area

Name of VES	p1	p2	p3	p4	p5	ñ6	h1	h2	h3	h4	h5	Depth to basement in meter
S1	3.8	14	3.4	0.99	2.1	90	0.33	0.93	4.6	23	13	46
S2	68	65	1.3	438			3.2	1.4	27			32
S3	5.7	0.93	2.7	588			0.75	7.5	19			27
S4	8.5	1.7	2346				3	24				27
S5	7	6.5	1.2	3.5	302		2.6	2.2	11	16		32
S6	46	17	6.8	3.7	173		1	1.4	10	29		41
S7	103	2.7	2.5	899			2.2	7	12			21
S8	14	2.1	3.8	13	2510		1.6	7.6	9.3	8		26
S9	14	2.3	3.6	12	288		1.6	7.2	11	9.1		29
S10	184	43	32	22	5.9	22	0.71	1.2	8.5	6.4	584	600
S11	42	5.4	15	417			2.8	30	45			78
S12	7.9	1.9	381				4.1	26				30

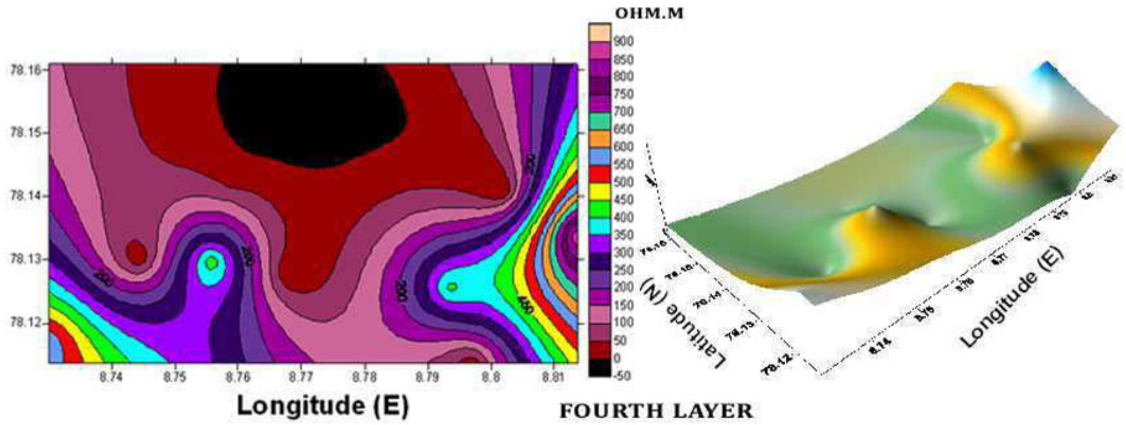

Fig.6. Contour map of fourth layer resistivity along with VES positions in the study area

layer has a resistivity almost 3.8 and 184 ohm-m and a thickness 0.33 and 0.71 m. This is followed by 14-43 ohm-m, 3.4-32, 0.99-22 and 2.1-5.9 ohm-m. This is followed by layers having resistivity of 22-90 ohm-m. The top layer is covered with top soil and followed by weathered zone which is underlain by basement.

Quantitative Interpretation

The two geoelectrical parameters used in this computation are resistivity (p) and thickness (h) of layer. In the case of two-layered ground surface, the simplest sounding curves are the ascending and descending types. An ascending type curve (p1< p2) is characterized by either topsoil or weathered layer followed by hard compact basement and designated as resistive basement. In descending type curve (p1> p2), a compact top layer is overlaid by a thick clay layer or saline water aquifer and is called conductive basement.

In a three layered ground surface, four types of sounding curves are possible. If p1, p2 and p3 are resistivities of three successive layers from surface, the possible sounding curves are 'A' type (p1 <p2< p3), 'Q' type (pl>p2> p3), 'H' type (p1 >p2< p3) and 'K' type (p1 <p2> p3). 'A' type curve is obtained in typical hard rock terrain having thin conductive topsoil and therefore the resistivities of the layers continuously increase with depth. A sounding curve with a continuously decreasing resistivity is called 'Q' type and such curves are usually obtained in coastal areas where saline water predominates. 'H' type curves are obtained generally in hard rock terrains consisting of dry top soil (first layer) of high resistivity followed by either a water saturated or weathered layer of low resistivity and then a compact hard rock of very high resistivity at the bottom. Sounding curves of 'K' type show a maximum peak flanked by a low resistivity values. Such curves are obtained in basaltic areas, where compact and massive traps exist between top black cotton soil and bottom vesicular basalt. These types of curves will be present in the coastal areas due to the freshwater aquifer occurring in between clayey layer at the top and a saline zone in the bottom. The different layer thickness and apparent resistivity values obtained from 12 VES stations are given in Table 4 along with curve types. Due to the distinctive characteristics features in the field of the apparent resistivity curves, the VES stations show different types of curves (Fig 8 and Fig 9). These types were defined in terms of the number of geoelectrical layers and their respective resistivity relationships.

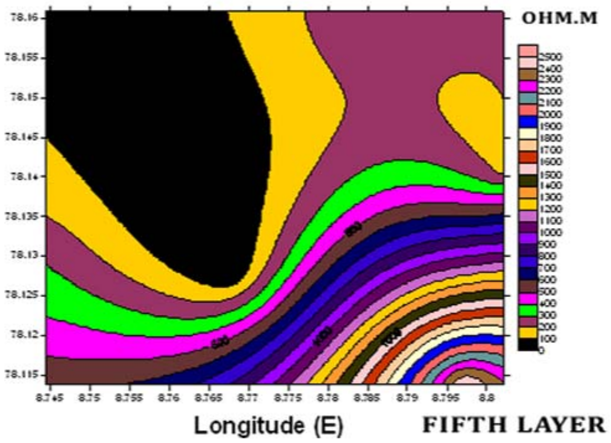

Fig.7. Contour map of fifth layer resistivity along with VES positions in the study area

The VES Location S4 and S12 were classified as H and K curve type and reflect the presence of three geoelectric layers where the layers resistivity relationship is p1>p2<p3 and p1<p2>p3. The curve is H and K type which show similar shape of field curves with layer resistivity's decreasing with depth. Such curve behavior undoubtedly proves the presence of a low-resistivity layer at the bottom of the section. The VES location S2, S3, S7 and S11 were classified as HK HA QH and KH curve type and reflect the presence of four geoelectric layers where the layers

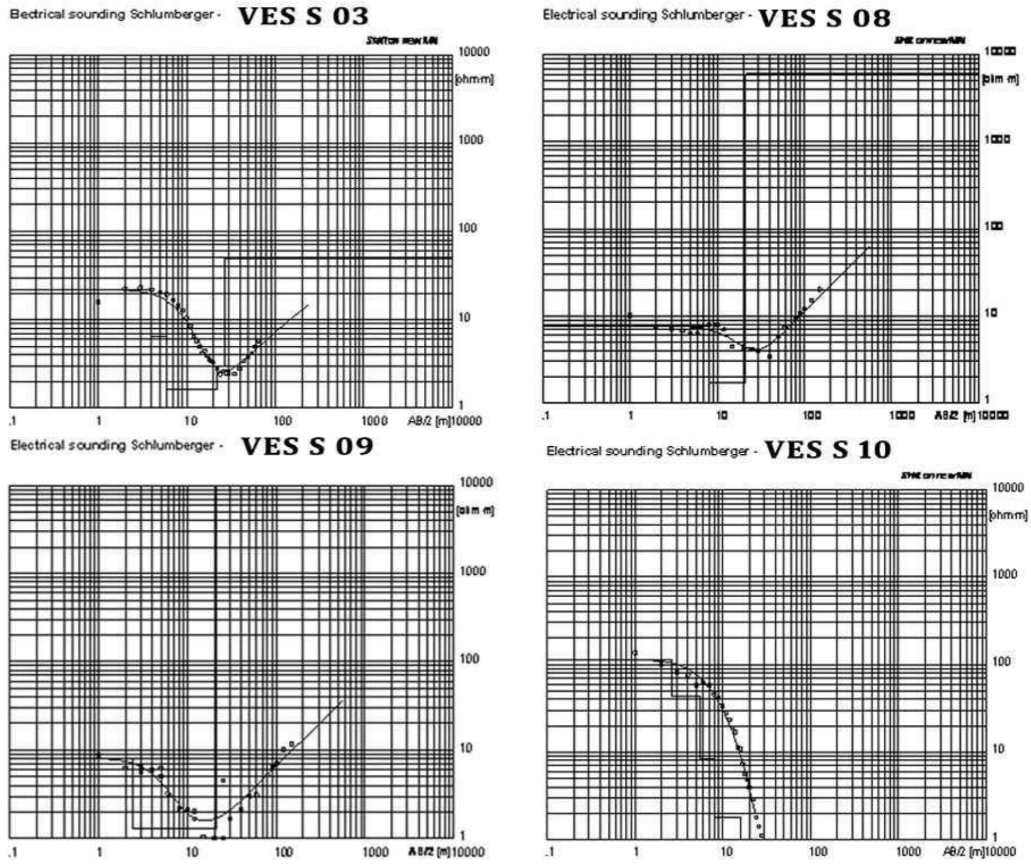

Fig.8. Typical Superimposed VES Curves/ Data Points for Schlumberger Arrays

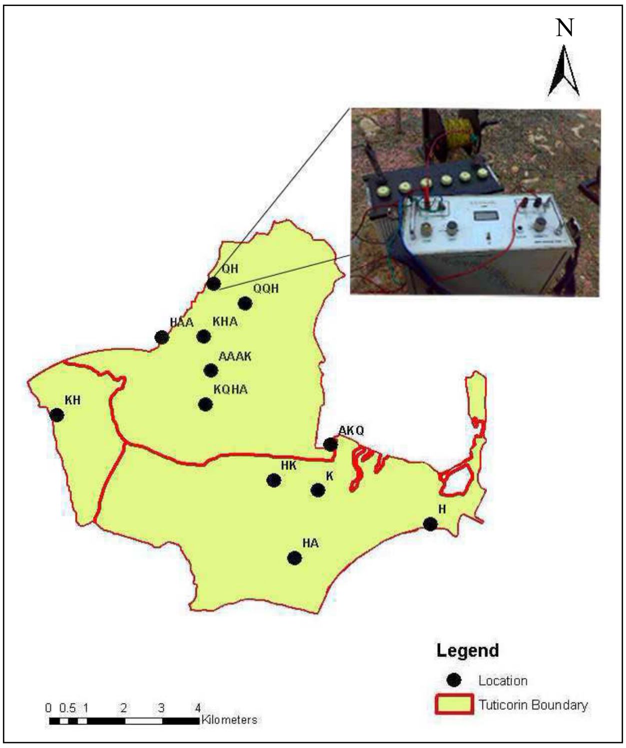

Fig.9. Curves type of the study area

resistivity relationship is p1>p2<p3>p4, p1>p2<p3<p4, p1>p2>p3<p4 and p1<p2>p3<p4. The VES location S5, S6 S8 and S9 were classified as AKQ QQH HAA and KHA curve type and reflect the presence of five geoelectric layers where the layers resistivity relationship is p1<p2<p3>p4> p5, p1>p2>p3>p4<p5, p1>p2<p3<p4<p5, and p1<p2>p3 <p4<p5. On the basis of sounding data alone it has been found that the depth to bedrock is found to be greater in the study area. Hence, these areas are more suitable for groundwater development. The VES location S1 and S10 were classified as KQHA and AAAK curve type and

Table 4. Qualitative analysis of curve types where ρ represents resistivity of the layer

Sounding Name	Location	Curve	Curve Type
S1	St. John Shipping Land	p1<p2>p3>p4<p5<p6	KQHA
S2	Spic Nagar	p1>p2<p3>p4	HK
S3	Mullakadu	p1>p2<p3<p4	HA
S4	Tuticorin-Harbor Beach	p1>p2<p3	H
S5	Roach Park	p1<p2<p3>p4>p5	AKQ
S6	Old Bus stand Ground	p1>p2>p3>p4<p5	QQH
S7	Kalingar Arangam Ground	p1>p2>p3<p4	QH
S8	Siva Shanthi Nagar	p1>p2<p3<p4<p5	HAA
S9	V.O.C College Ground	p1<p2>p3<p4<p5	KHA
S10	Ganesh Nagar	p1<p2<p3<p4<p5>p6	AAAK
S11	Korambalam	p1<p2>p3<p4	KH
S12	Camp I	p1<p2>p3	K

reflect the presence of six geoelectric layers where the layers resistivity relationship is p1<p2>p3>p4<p5<p6 and p1<p2<p3<p4<p5>p6 (Fig. 9).

CONCLUSIONS

In the studied area the alluvial deposits of sand, sandy clay, clayey sand and gravel as well as the medium-to-coarse shell limestone, weathered/fractured sandy shell limestone and the basement rocks constitute the main aquifer component. The resistivity of the aquifer increases towards the west due to decreasing salinity of water and/or clay content. Very wide ranges and high standard deviations of hydrochemical parameters such as TDS, EC, Cl^-, K, SO_4, Mg suggest the groundwater in the coastal aquifer shows seawater mixing and anthropogenic contamination and most of the water sample exceed the maximum permissible limit of WHO standards. Results suggest that the groundwater in this study area is very hard and alkaline in nature. The NaCl and Ca^{2+} - Mg^{2+} – Cl^- - SO_4^{2-} facies are the dominant hydrochemical facies in the groundwater of study area. The groundwater in the entire study area was contaminated by saline connate water, therefore for such areas deep boreholes are recommended.

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