

Research Article

## Pore resistivity variation by Resistivity imaging technique in sedimentary part of main Gadilam river basin, Cuddalore District, Tamil Nadu, India

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**Abstract**

Electrical resistivity is the only property of physics which give information of subsurface moisture content in the formation, Hence geophysical electrical resistivity survey was carried out to investigate the nature of shallow subsurface formations and geological contact in the main Gadilam river basin of Cuddalore District in Tamil Nadu. Twenty-seven vertical electrical soundings (VES) were conducted by Schlumberger configuration in the basin. Data is interpreted by curve matching techniques using IPI2 WIN software, layer parameters like apparent resistivity ( $\rho_a$ ) and thickness (h) interpretation were exported to Geographic Information System (GIS). Interpretation distinguishes three major geoelectric layers like topsoil, sandy clay layer, clayey sand layer along the contact zone in the basin. Interpreted VES sounding curves are mostly four-layer cases of QH, H, HA and KH type. Investigation demarcates lithology of subsurface and hydrogeological set up by employing maximum possible electrode sounding to infer saline water and freshwater occurrence based on resistivity signals. Zone of groundwater potential map was prepared with the combination of resistivity ( $\rho = \rho_1 + \rho_2 + \rho_3 + \rho_4$ ) and corresponding thickness ( $T = T_1 + T_2 + T_3 + T_4$ ). High resistivity value of  $>200 \Omega \text{ m}$  and low resistivity value of  $<10 \Omega \text{ m}$  show the occurrence of alkaline and saline water within the formation aquifers as a result of possible rock water interaction and saline water dissolution. Four-layer resistivity cases from the matched curve (namely KH, AH, QA, and KA type) show the resistivity distribution/variation. It separates the freshwater depth with from 1 to 140  $\Omega \text{ m}$  in fluvial sediments. Flood basin, sandstone and clay layer with low resistivity value of 3.16 - 7.5  $\Omega \text{ m}$  indicates contact with saline and freshwater aquifer. The Iso - resistivity map delineates saline water and freshwater zones with in the fourth layer cases in the same locations to indicate the irrational way of abstracting groundwater, resulting in saltwater ingress.

**Keywords:** GIS, Hydrogeology, Lithology, Resistivity, Saline water, Thickness - VES

**INTRODUCTION**

Geophysical resistivity investigations are performed for studies related to groundwater occurrence. Geophysics

provides tools for studying earth interior by various physical properties depending on the method used (Oguama *et al.*, 2019; Ibuot *et al.*, 2017; Chakravarthi *et al.*, 2007). The resistivity profile indicates horizontal

change in resistivity, which can be compared with steeply dipping interface between two geological formations in the subsurface (Gautam and Biswas 2016; Biswas and Sharma 2016). The geo-electrical resistivity method (GERM) of geophysical prospecting has been utilized for several years for the resistivity discrimination of underlying litho units (George *et al.*, 2017; Ekanem, 2020) and determines the resistivity of subsurface layers (including aquifer zones) at different depths in the event of low dipping (Prasanna *et al.*, 2009). The occurrence of water and saline water of resistivity in the subsurface rock by electrical technique is widely applied to characterize the aquifer (Alile *et al.*, 2011) and determine distinctive groundwater pollution (Ezeh 2011; Hussain *et al.*, 2016a; Hussain *et al.*, 2017). Early stage of geophysical studied for groundwater has been traced back to unconsolidated alluvial and semi-consolidated sedimentary tracts. Lately, greater significance is given to the investigation of subsurface water in hard rock and sedimentary regions, like the present study area (Deepa *et al.*, 2016; Devaraj *et al.*, 2018). The occurrence of pore water in subsurface soil, porosity and salinity of the water is used to delineate resistivity and its corresponding thickness in different layer/zones (Gopinath *et al.*, 2015; Kayode *et al.*, 2016; Mehmood *et al.* 2020). The advantage of applying resistivity method with different values of resistance in  $\Omega\text{m}$  is much larger than other geophysical properties (Kalinski *et al.* 1993). Various workers in coastal areas have used bulk resistivity value to show the contrast between saline filled formations saturated with freshwater (Ginsberg and Levanton, 1976; Frohlich *et al.* 1994). Saline water intrusion in the coastal formation is a serious problem in most areas of world and occurs as an indicator for aquifer response (Custodio, 1997; Todd and Mays, 2005; Gopinath *et al.*, 2015). By applying Schlumberger array in Curinor Korinbasin, southeast of Iran and area with high yield were identified through depth thickness and groundwater environment in the shallow aquifer (Lashkaripour, 2003; Nejad *et al.*, 2012) investigated the subsurface layers and aquifer characteristics of the same area. Demarcation of the groundwater potential and recharge zones in Champavathi river basin, India, using electrical resistivity methods and identified high porosity and permeability zone using secondary resistivity parameters (Jagadeeswara Rao *et al.*, 2003). Effective use of VES was vertical and horizontal section utilizing Schlumberger and Wenner array was attempted by (Al-Amri, 1996) in central Arabian shield for groundwater prospecting and delineating shallow alluvial aquifer and fracture zone as groundwater potential zones. VES surveys were also conducted in shale for the evaluation of resistivity and depth to basement by resistivity method in the combination of iso-apparent resistivity to classify freshwater and saltwater of the basin (Balasubramanian *et al.*, 1985; Kopsiaftis *et al.*,

2009).

Sedimentary part of main Gadilam River basin, the study featured in the Cuddalore district, Tamil Nadu, due to development, expanding industrialization and through agriculture has resulted in decline water level and saline ingresses aquifers. In the majority of the basin, subsurface water is the only alternative to fulfill the agriculture, domestic and industrial demand of water. The main objective of the study was to infer geophysical electrical resistivity layer parameter and its thickness with the above data pseudo cross section is constructed to infer vertical variation of resistivity as layer section in VES profile. Four layer resistivity cases were mapped spatially to study the variation of resistivity with reference to geology in space.

## MATERIALS AND METHODS

### Study area

Part of the Gadilam river basin forms a total length of about 57 km in the Kallakriuchiand Cuddalore districts of Tamil Nadu, India. It lies between  $11^{\circ}37'42.51''\text{N}$  and  $11^{\circ}49'46.52''\text{N}$  latitudes and  $79^{\circ}20'44.54''\text{E}$  and  $79^{\circ}47'22.21''\text{E}$  longitudes (Fig. 1). It occurs within the Survey of India topographic sheets of 58 M/5, 6, 9, 13, 10 and 14, covering a total area in a plain portion of about  $663.65\text{ km}^2$ . The study areas altitude occurs from 109 m AMSL in south to -4 m BMSL in the east.

### Geological settings of Gadilam river basin

Two geologic formations, namely Tertiary Cuddalore-Sandstones, Laterite and Quaternary Alluvial formations are found to prevail in the basin. It is characterized by both Archean crystalline aquifers and Tertiary Quaternary sedimentary rocks. The lithology of the basin shows that hard basement rocks are exposed in the western part of the study area and sedimentary formation in the east with a faulted contact between both (Aravindan *et al.*, 2004). The Ponnaiyar River (Main river of Gadilam) is bounded in the northern part of Gadilam basin and in south by Neyveli Tertiary upland and confluences in the Bay of Bengal at Devanampatinam, East of Cuddalore. Since the accessibility of surface water is insufficient during the lean period, the demand for irrigation in the Gadilam river basin is met by substantial development of groundwater. The topography of the basin is flat and slopes towards the north northeast with maximum altitude of 40 m along the southeastern part of the study area. The area lies in tropical and humid climate with a temperature of maximum range between  $36.5$  and  $36.9\text{ }^{\circ}\text{C}$  with mean ranging from  $31.0$  to  $37.5\text{ }^{\circ}\text{C}$ . The study area is occupied by Pliocene deposits receives precipitation with the influence of southwest and northeast monsoons (CGWB 2015). The annual average rainfall in the basin is about  $1,085\text{ mm/year}$  from northeast and southwest monsoon

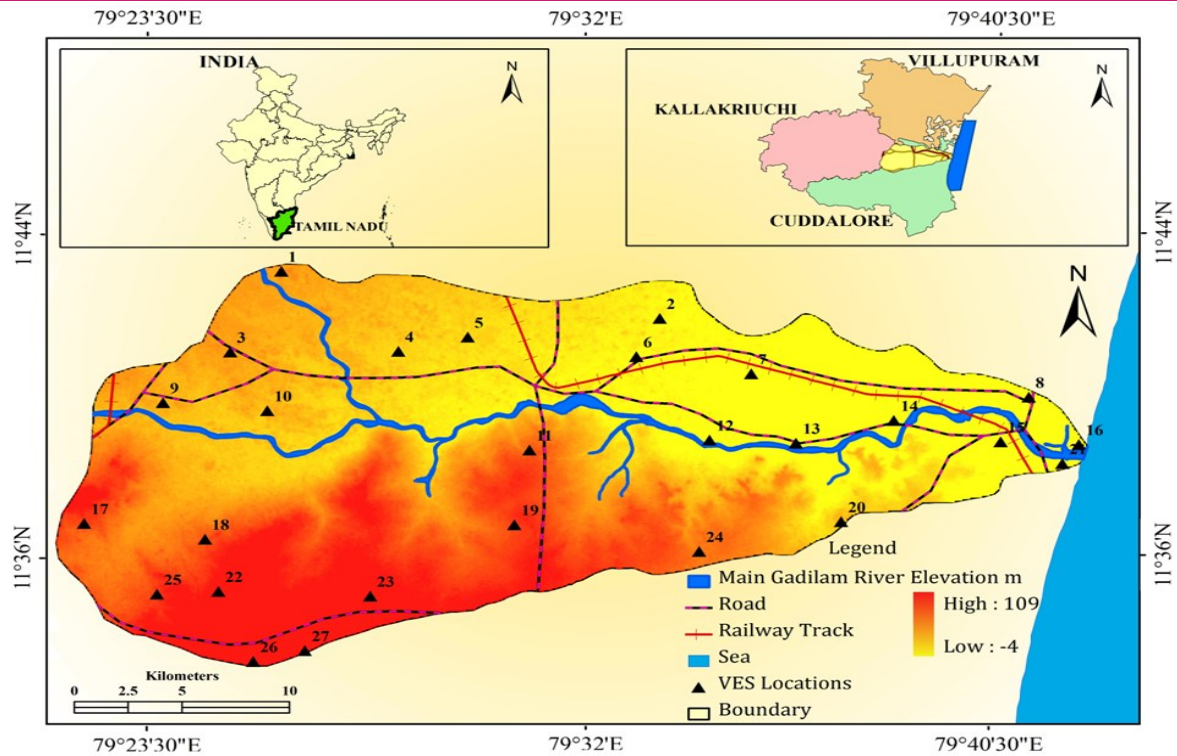


Fig. 1. Location, VES soundings and Elevation of the Gadilam river basin.

season, contributes 58 % and 31.71 %, respectively. To the study area south, includes two large open cast mines (I and II), one small (Mine IA) lignite mines and its associated industries, including two thermal power plants that are operated by NLIL (Neyveli Lignite India Limited), a government of India public sector undertaking. The important large scale groundwater extraction corporations in this basin are NLIL and Small Industrial Promotion Corporation of Tamil Nadu (SIPCOT) complexes south of Cuddalore port south-east of study area are the major industries that prevails for maximum and domestic consumption requirement in the basin. EID parry sugar factory is located within the basin at Nellikuppam west of Cuddalore in the east of basin.

**Litho-stratigraphy and hydrogeology**

The present area is underlined by various geological formations; throughout the course of river Gadilam encounters different rock types and formations (Table 1 and Fig. 2). Gadilam river originates from the hard rock region situated in the west and passes through the

hornblende-biotite gneiss, Tertiary Cuddalore-Sandstone formation and Quaternary formation in sedimentary part, which includes alluvial plain deposits, argillaceous sandstone, clay with limestone bands/lenses, fluvial deposits, sandy limestone, laterite and deltaic plain includes palaeo tidal flat deposit with clays, sands and beach ridges of grey-brown sand (Subramanian and Selvan 2001). Geological details were investigated during field work by using projected geological map of Cuddalore district, published by Geological Society of India. At some locations, sandstone is found intercalated within lenses of clay and underlined by fluvial sand with a depth ranging below the ground from 2 and 22 m from Azhagap-samudram are isolated at depths from 22-50 m investigated in field work. Flood plain, fluvial and tidal flat deposits cover mostly in the east. The aquifers occur in Cuddalore sandstone and alluvium to study the saline - freshwater interface, which ultimately is helpful for the scientific development of both shallow and deeper aquifer in this area which is good potentiality.

Table 1. Litho-stratigraphy of Gadilam river basin (after Subramanian et al., 2001).

Period	Epoch	Formation	Lithology
Quaternary	Recent to Sub recent	Alluvium and laterite	Soils, Alluvium and Brown Sand, Clays and laterite
-----Unconformity-----			
Tertiary	Mio-Pliocene	Cuddalore – Sandstones	Argillaceous and Calcareous Sandstone, Clay with Limestone bands/lenses, Lignite, Hornblende -biotite gneiss and Sandy Limestone, Tidal flat deposit

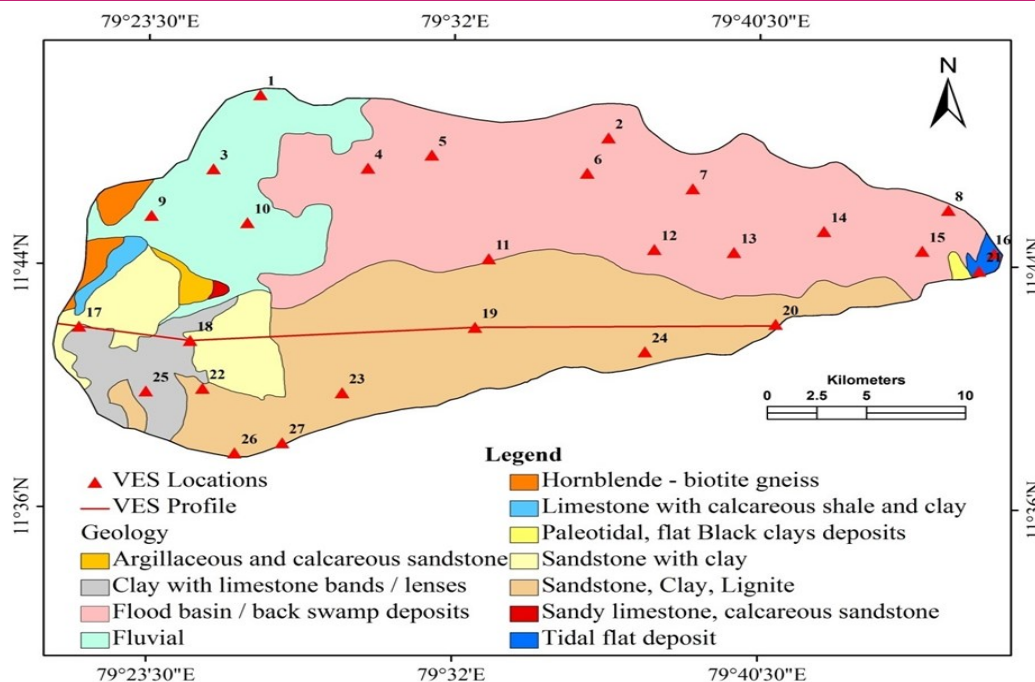


Fig. 2. Geology and VES Profile-cross section of the Gadilam river basin.

**Data acquisition and interpretation**

Twenty seven (27) Vertical Electrical Sounding (VES) locations have been carried out in the basin using DDR3 resistivity meter by applying Schlumberger array configuration (Fig. 1). The apparent resistivity of sub-surface formation was determined. An investigation was conducted by placing four electrodes in a line. A known current is passed through the two extreme electrodes. Electro Motive Force (EMF) measured within two potential electrodes measure the potential difference of the ground. Apparent resistivity arrived by applying the formulae.

$$\rho_a = KR, \tag{1}$$

Where, K is geometric factor,

R is ground resistance of the depth and

$\rho_a$  is the apparent resistance measured, which depends on the current electrode (AB) and potential electrodes (MN) and its configuration as.

$$\rho_a = \frac{\pi \left( \left( \frac{AB}{2} \right)^2 - \left( \frac{MN}{2} \right)^2 \right)}{MN} \left( \frac{\Delta V}{I} \right) \tag{2}$$

The minimum and maximum electrode spacing adopted for the present study with maximum current electrode (AB/2) spacing of 100m across the area distance varying from 1 and 150m, and the potential electrode (MN/2) spacing varies from 0.5 to 15m, respectively.

Where, a is the selected electrode spacing,  $\Delta V$  is the potential difference displayed between two central electrodes and

I is current passed into the ground through two outer electrodes and measured simultaneously with a potential difference.

Apparent resistivity values measured at each point attributes were plotted against electrode spacing (a) on bi-logarithmic graph sheets (Fig. 3). Curves were observed for the number and nature of layering by curve matching technique was performed for the quantitative interpretation of curves. Output curve matching (layer resistivities and thickness) was input in the system to model in an iterative modeling tool utilizing IPI2 WIN version 3.0.1.e (Bobachev et al. 2003). The degree of uncertainty of the computed model parameters and

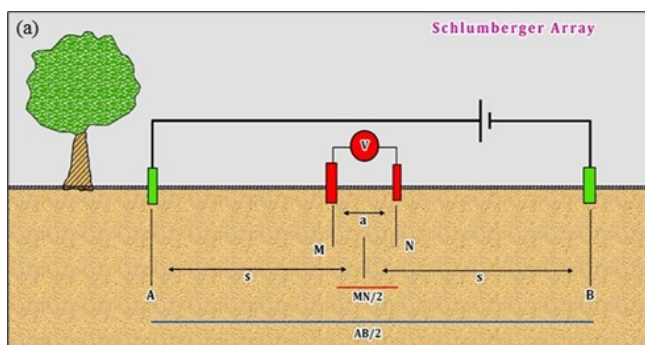


Fig. 3. a). Schlumberger configuration, b). lateritic soil outcrop and the mining site at Visur RF.

**Table 2.** Resistivity, Thickness and curve types for geoelectrical sections of the Gadilam River basin.

VES No.	Location Name	Resistivity ( $\Omega\text{m}$ )				Thickness (m)				Error %	Curve Type
		$\rho_1$	$\rho_2$	$\rho_3$	$\rho_4$	h1	h2	h3	h4		
1	Poigai Arasur	51.6	24.6	3.2	14.1	0.86	2.53	2.31	103	8.12	H
2	Chinna pagandai	19.1	97	8.39	59.8	0.318	0.449	0.795	1.89	3.18	QH
3	Karuveppilalayam	47.6	10.6	2.81	167	0.851	11.3	13.9	-	3.21	QH
4	Rayappalaiyam	16	83.9	11	158	0.294	0.469	1.02	3.38	3.42	QH
5	Ammapetai	38.7	137	20.8	38	0.351	0.485	6.12	7.14	3.42	QH
6	Mel kavrapattu	56.5	14.3	5.09	1326	0.699	3.68	44.2	-	3.36	H
7	Vazhapattu	14	23.6	12.9	3144	0.635	4.03	98	-	7.82	HA
8	Manjakkuppam	42.1	507	7.03	2217	1.61	2.48	53.7	-	4.04	KA
9	Thirunamanallur	29.3	5.73	8.47	457	0.576	2.84	43.6	-	3.19	A
10	Sivapatnam	18.35	7.345	2.105	4.982	0.6547	6.006	6.251	28.77	1.00	AH
11	Panikankuppam	57.6	2476	141	349	0.335	0.512	22.9	28.4	6.4	Q
12	Sanniyasipettai	70	21.1	91.9	12.9	1.19	0.971	2.9	38.8	2.71	QH
13	Kil Arungunam	39.8	2.15	22.7	4.6	0.792	1.01	1.6	32.8	5.77	QH
14	Tiruvandipuram	24.1	4.95	347	2.99	0.977	1.05	3.11	7.57	7.53	HA
15	Tiruppappuliyur	17.3	1.21	0.271	579	0.42	1.17	2	-	4.97	HA
16	Vanniyarpalaiyam	47.1	13.2	3.42	1047	0.44	19.1	16	-	8.47	HA
17	Arinattam	107	1997	33.5	2938	1.74	1.65	85.8	-	3.74	KH
18	Olaiyampalayam	24.1	6.475	83.99	6.077	0.6	0.7416	1.658	14.37	1.6	AH
19	Nadu Kattuppalaiyam	55.6	17.6	1585	258	1.2	73.4	-	-	6.4	QA
20	Vellakarai	31.9	2533	96.4	6.47	0.359	0.709	28.7	28.4	8.85	KA
21	Chellankuppam	38.3	4.28	2.71	1048	1.32	4.09	26.9	-	2.77	H
22	Chinna Odappankuppam	119	10.4	39.7	887	1.71	8.81	85.8	-	2.95	QH
23	Perperiyankuppam	112	1840	11.8	39774	3.7	2.08	5.85	9.43	8.48	KH
24	Arachchikkuppam	35.5	1666	6.57	72.4	0.363	0.83	4.35	26.2	6.54	KQ
25	Pudupettai	24	17.2	3.73	11.7	0.744	3.46	5.63	55.1	4.98	H
26	Vadakkirupu	35.6	720	8.32	626	0.334	0.592	2.53	-	7.19	KH
27	Kattukodalur	81	491	98.3	15.1	0.388	0.326	12.4	11.8	6.68	QA

goodness of fit in the curve matching algorithm is expressed in terms of curve fitting with error <10. Resistivity of different layers and respective depth, thickness are displayed by many inversions in the model of all VES curves and resolved with the fitting error. These results were inputted in the GIS platform; their attributes were added and analyzed in Arc/GIS version 10.5 software in spatial analyst tool used to map interpolation.

## RESULTS AND DISCUSSION

The VES data values were interpreted and processed for the resistivity, thickness and curve types of different subsurface layers for geoelectrical-lithological layers

with maximum current separation (Table 2) (Bethrand Ekwundu Oguama *et al.*, 2020; Eyankware *et al.*, 2020; Sholichin and Tri Budi Prayogo, 2019). 1D data version give information along with designated profiles and the depth (Waswa *et al.* 2015). The curve types obtained after partial curve matching range from simple 4-layers KH type (11.11%), 6-layer HA type (14.81%), 3-layer QA type (3.70%) and 5-layer KA type (7.41%). Curves generated from the field measurements are shown in (Table 2,3 and Fig. 4) the inferred geoelectric-lithology interpretation (Bayewu *et al.*, 2018).

### Vertical electrical sounding (VES)

The VES data was hand plotted in the field as a reference while performing curve matching technique for

verification in IPI2 WIN software (Table 2). Higher resistivity of 39774 Ωm was observed in Perperiyankuppam to infer it as laterite in the southern part of the basin. The low resistivity value of 0.27 Ωm was confined to Tiruppappuliyur to interpret as marine clay inand around Cuddalore in the eastern part of the basin.

$$\text{Curve} = \frac{\text{Total resistivity layer thickness}}{\text{Total number of resistivity sounding}} \times 100 \tag{3}$$

From the data (Table 3) 25.93% of the basin is dominated by QH type curve indicating  $\rho_1 > \rho_2 > \rho_3 > \rho_4 > \rho_5 > \rho_6 < \rho_7$ , 14.81% of the area represent descending-ascending H type indicating  $\rho_1 > \rho_2 < \rho_3 > \rho_4$  and 14.81% by HA type indicating  $\rho_1 > \rho_2 < \rho_3 < \rho_4$ , 11.11% of the basin is KH type indicating  $\rho_1 < \rho_2 < \rho_3$ , 7.41% by KA, AH and QA types curve  $\rho_1 < \rho_2$ ,  $\rho_1 < \rho_2$ , and  $\rho_1 > \rho_2$  and 3.70% by A, Q and KQ type curve as  $\rho_1 < \rho_2$ ,  $\rho_1 > \rho_2$  and  $\rho_1 < \rho_2$  types, respectively. Curve types reveal alternate resistive-low resistivity and low resistivity-high resistive layers reflecting the unconsolidated formations as sand and clay with alternate high to low resistivity sub surface layer of study area.

**Goelectrical and pseudo cross sections 1D**

Resistivity pseudo cross section along (Fig. 4) which encompasses locations (Arinattam, Olaiyampalayam, Nadu Kattuppalaiyam and Vellakarai) was compared with resistivity values obtained from the inversion of

**Table 3.** VES curve types for various VES locations in the Gadilam river basin.

Curves types	No of VES curves
H	1, 6, 21, 25
QH	2, 3, 4, 5, 12, 13, 22
HA	7, 14, 15, 16
KA	8, 20
A	9
AH	10, 18
Q	11
KH	17, 23, 26
QA	19, 27
KQ	24

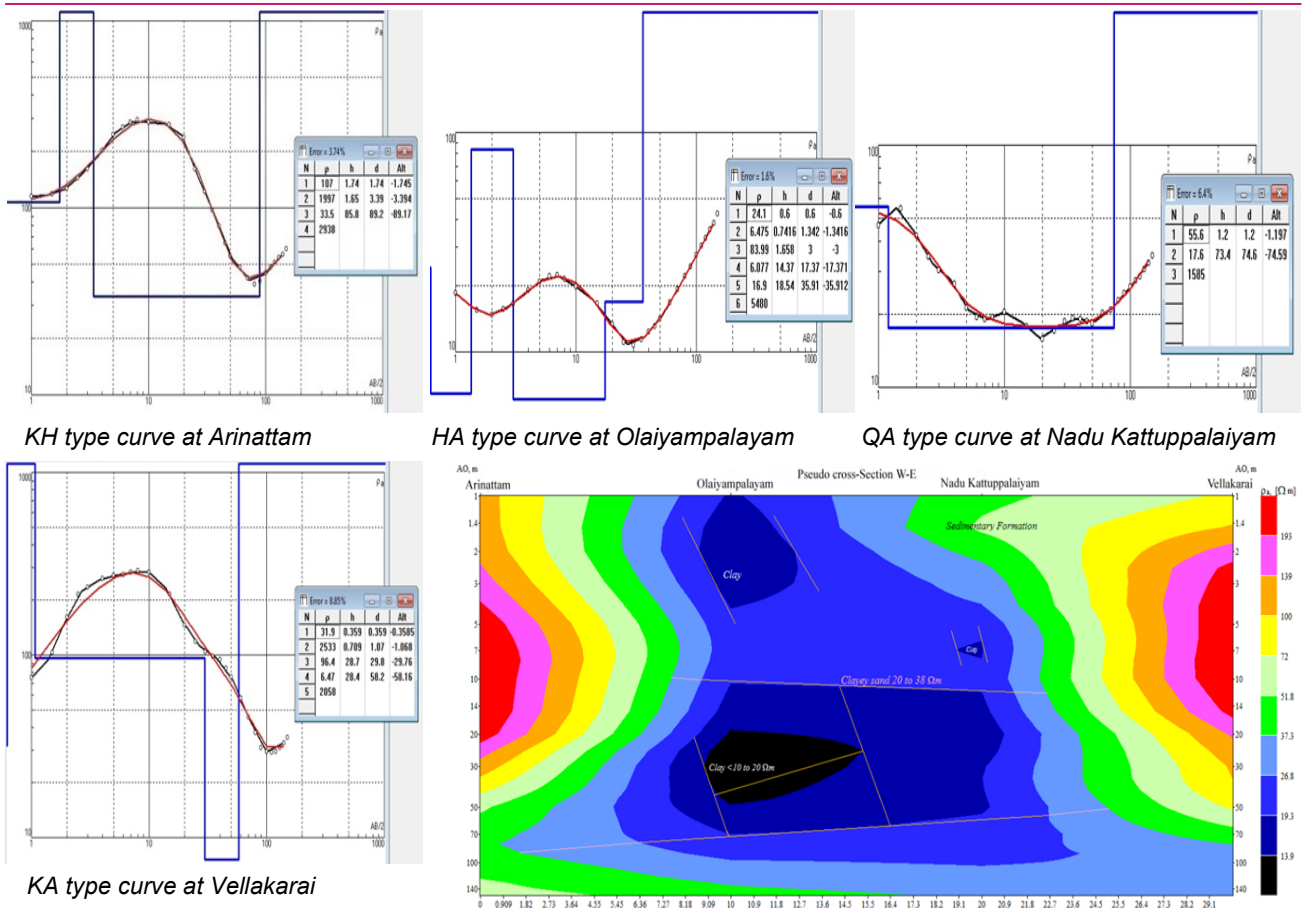
VES as a 1D layered model. Resistivity of the pseudo cross section ranged between 13.9 and 193 Ωm occur irrespective of depth. Higher resistivity ranges were observed in location Olaiyampalayam up to a depth of 20 to 40 m and extending laterally up to Nadu Kattuppalaiyam. Depth between 1 to 4 and 13.9 to 60 m, electrical resistivity values occur between 13.9 and 37.3 Ωm indicate the saline nature of formation (Zohdy *et al.* 1974; Gopinath *et al.* 2018) and found to extend up to Vellakarai. Low resistivity values at Nadu Kattuppalaiyam irrespective of depth indicated the over-drafting of groundwater from the aquifers, which might trigger saline water up to shallow depths.

**Spatial variation of resistivity and thickness**

The resistivity of the first layer-topsoil range from 14 to 119 Ωm was observed at Vazhapattu a low resistivity indicate sand saturated with water and Chinna Odappankuppam has high resistivity, with thickness between 0.29 and 3.70 m as observed in Rayarppalaiyam and Perperiyankuppam. It may be dry topsoil with less porosity and low permeability in this formation. The South-western part of the study area is represented by the poor conductive (100 to 200 Ωm) high resistivity zone to indicate sandstone and hornblende biotite gneiss. A good conductive low resistivity range indicates the sedimentary rocks (Fig. 5a). A second layer, resistivity values from 1.21 to 2533 Ωm was observed up to above high resistivity zones; low resistivity zones occur at Vellakarai and Tiruppappuliyur with a thickness ranging from 0.33 and 73.40 m observed at Kattukodalur and Nadu Kattuppalaiyam were lithology layer of flood basin, sandstone and clay occur in north and southern part of the basin. In (Fig. 5b), low resistivity values from less than 10 to 100 Ωm occur in the northwestern, south and eastern part of the basin in fluvial, flood basin, clay with limestone, sandstone, sandy limestone, paleotidal and tidal flat deposits from sedimentary rocks in the northwestern part near the hard rock contact to the southeastern part with saline and freshwater interface in the formation. Third layer resistivity value from 0.27 to 1585 Ωm was observed at Tiruppappuliyur, low resistivity at Nadu kattuppalaiyam and high resistivity with a thickness ranging from 0.80 to 98 m was observed in Chinna pagandai and Vazhapattu. The good conductive low resistivities indicated sedimentary rock underlined by fluvial, paleotidal and tidal flat deposit,

**Table 4.** Minimum, Maximum and Average value of resistivity (Ωm) and thickness (m) of Gadilam river basin.

	Resistivity (Ωm)				Thickness (m)			
	Layer 1	Layer 2	Layer 3	Layer 4	Layer 1	Layer 2	Layer 3	Layer 4
Min	14.00	1.21	0.27	2.99	0.29	0.33	0.80	1.89
Max	119.00	2533.00	1585.00	39774.00	3.70	73.40	98.00	103.00
Average	46.41	471.58	98.45	2045.34	0.87	5.73	22.23	26.47



**Fig. 4.** Typical apparent resistivity curve and geoelectrical layer parameters as KH, HA, QA, KA types.

which implies the occurrence of saline water influvio – marine sediments, flood basin, hornblende biotite gneiss, sandstone with clay and sandy limestone, which displays the presence of freshwater as indicated in northwest and southeast of the study area (Fig. 5c). Fourth layer resistivity value from 2.99 to 39774  $\Omega$ m was inferred in Tirvandipuram as low resistivity zone in saline sand and in Perperiyankuppam as higher resistivity in laterite with a thickness between 1.89 and 103 m observed in locations Chinna pagandai and Poigai arasur was represented by prevailing fine mixed sandstone and clay (Fig. 5d). High resistivity values of >200  $\Omega$  indicated hard nature of groundwater and low resistivity of <10  $\Omega$ m indicate mixing of the aquifer with saline water in the freshwater system (Parasnis, 1997).

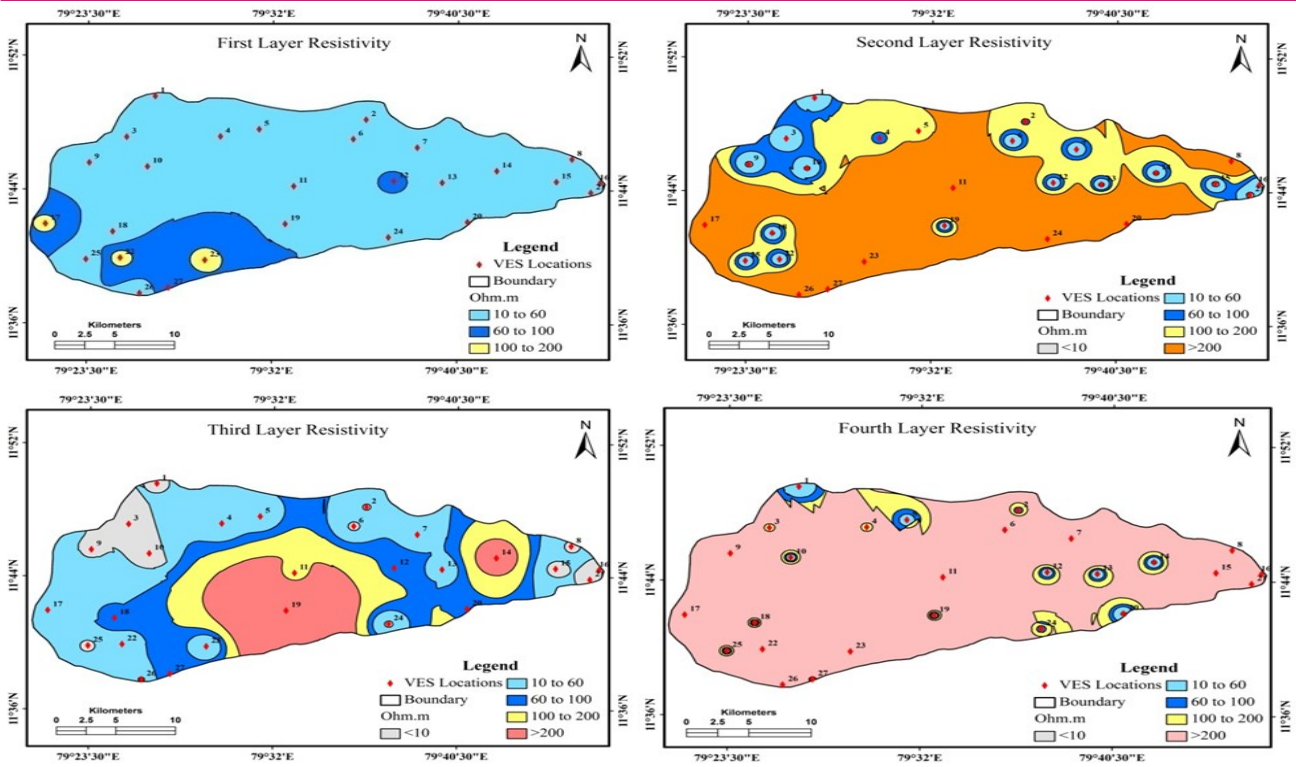
**Histogram of the study area**

The resistivity of the topsoil range from 14 to 119  $\Omega$ m, with a thickness between 0.29 and 3.70 m (Table 4 and Fig. 6a,b). In the second layer, clay with limestone, sandstone and marine sediments were standard with resistivity values from 1.21 to 2533  $\Omega$ m with an average thickness of 5.73 m. Second layer was demarcated as shallow aquifer (Quaternary and Pliocene - Tertiary aquifers) due to the occurrence of litho units to indicate as shale and clay, gravels, sandy limestone and tidal

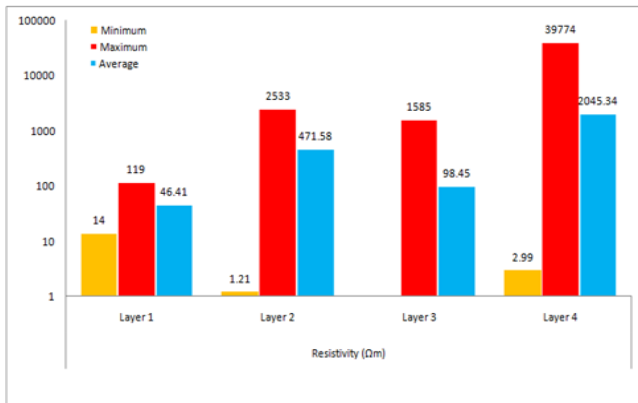
flat deposits (Gopinath and Srinivasamoorthy, 2014; Gopinath et al., 2017; Devaraj et al., 2018). Low resistivity (0.27  $\Omega$ m) was observed at Tiruppappuliyur and higher resistivity (39774  $\Omega$ m) observed in Perperiyankuppam both in the eastern and southern part of basin. Higher resistivity value outlines aquifer zones free from pollution and a low resistivity value (0.27  $\Omega$  m) signifies the saline pollution of formation (Parasnis, 1997). The third layer resistivity range between 0.27 and 1585  $\Omega$ m with an average thickness of 22.23 m, representing the occurrence of flood basin/back swamp deposits and sandstone, clay deposits, finely mixed with marine sand. The fourth and fifth layer identified in the aquifer system with resistivity values between 2.99 to 39774  $\Omega$  m, respectively. Higher resistivity observed in locations Perperiyankuppam (39774  $\Omega$ m) signifies uncontaminated lateritic aquifer and low resistivity ranges (2.99  $\Omega$ m and 2.13  $\Omega$ m) in locations Tiruvendipuram and Panikankuppam indicates the dominance of saline water and clay (Richardson, 1992).

**Conclusion**

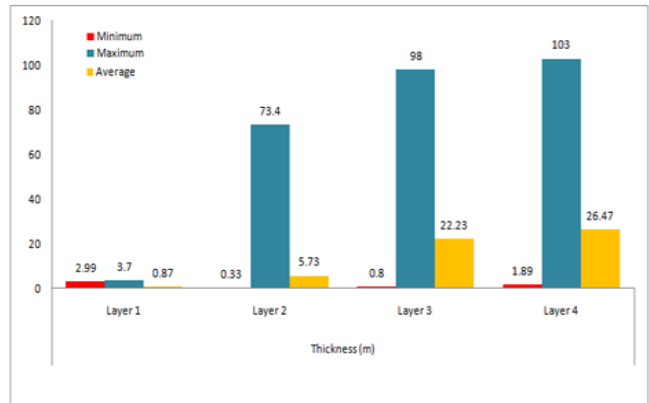
The study was performed by vertical electrical sounding to delineate salinity and freshwater along the contact zone of hard rock and sedimentary area in the study



**Fig. 5.** Spatial distribution of four-layer Resistivity a) first layer resistivity in  $\Omega\text{m}$ , b) second layer resistivity ( $\Omega\text{m}$ ), c) third layer resistivity ( $\Omega\text{m}$ ), d) fourth layer resistivity ( $\Omega\text{m}$ ).



**Fig. 6a.** Resistivity ranges of the layer showing the minimum, maximum and average values.



**Fig. 6b.** Thickness ranges of the layer showing the minimum, maximum and average values.

area indicated that existing water was directly related to recharge from rivers and canals. In the VES data, 25.93% of the basin indicate QH type curve as  $\rho_1 > \rho_2 > \rho_3 > \rho_4 > \rho_5 > \rho_6 > \rho_7$ , 14.81% of the area represented descending-ascending H type to indicate  $\rho_1 > \rho_2 < \rho_3 > \rho_4$  and 14.81% by HA type as  $\rho_1 > \rho_2 < \rho_3 < \rho_4$ , 11.11 in the basin KH type indicated  $\rho_1 < \rho_2 < \rho_3$ , 7.41% by KA, AH and QA types curve  $\rho_1 < \rho_2$ ,  $\rho_1 < \rho_2$ , and  $\rho_1 > \rho_2$  and 3.70% by A, Q and KQ type curve as  $\rho_1 < \rho_2$ ,  $\rho_1 > \rho_2$  and  $\rho_1 < \rho_2$  types, respectively. Pseudo cross sections at depth delineate extractable water from the aquifers; might lead to saline water ingress below shallow depth. In coast high resistivity of 39774  $\Omega\text{m}$  was observed in the south and low

resistivity values (0.27  $\Omega\text{m}$ ) were confined to the east of the basin near the coast. The higher resistivity  $>200 \Omega\text{m}$  and less resistivity of  $<10 \Omega\text{m}$  indicate the interaction of aquifers due to saline water ingress into the freshwater system and rock water pollution in the southern and western part. Resistivity of the first layer-top soil range from 14 to 119  $\Omega\text{m}$ , with thickness between 0.29 and 3.70 m. Second layer, resistivity values from 1.21 to 2533  $\Omega\text{m}$  with thickness range from 0.33 to 73.40 m. Third layer resistivity values from 0.27 to 1585  $\Omega\text{m}$  with thickness range from 0.80 and 98 m. Fourth layer resistivity values from 2.99 to 39774  $\Omega\text{m}$  with a thickness range between 1.89 and 103 m. Maximum thickness and resistivity occur in the above layer to indicate the



consolidation of sediments and oxidation as laterites. Spatial resistivity maps signifying along east and north part of the basin where saline water was found to occur from the second layer and extend upto fourth layer might be due to inappropriate with drawal of groundwater from the shallow aquifer and due to occurrence of salinity adjacent to the coast. In other locations in the northwestern and eastern parts of the basin, the higher resistivity range indicate the presence of alkalis in the contact zone and fresh subsurface water movement in the tertiary aquifer. This area may be categorized as good subsurface in the groundwater potential zone with a low resistivity value above 10  $\Omega$ m adjacent to the coast and in the middle part of this sedimentary aquifer to confirm its occurrence in coastal and tertiary aquifers.

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## Conflict of interest

The authors declare that they have no conflict of interest.

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