



Spatial assessment of Groundwater Quantity and Quality: A case study in parts of Chidambaram Taluk, Cuddalore District, Tamil Nadu, India

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Abstract

The purpose of this study was to determine the geophysical and geochemical characteristics of the groundwater quantity, quality analysis using GIS (Geographical Information System), in parts of Chidambaram taluk, Cuddalore district. The (vertical electrical soundings) VES was carried out at 10 locations to understand the subsurface lithology. GIS were used to determine the geospatial changes and physico-chemical characteristics in our study area such as Ca^{2+} , Mg^{2+} , HCO_3^- , Cl^- , Na^+ , K^+ , SO_4^{2-} , NO_3^- , pH, EC and TDS. From iso-resistivity spatial plot results, it is found that the northern part of our study area shows saline intrusion. The hydrochemical study reveals that most of the samples are found suitable for drinking in our study area. The ionic concentration was found to exceed the amount of permissible limit in few locations. A higher amount of Ca^{2+} , Mg^{2+} , Na^+ , and K^+ concentrations were observed in the northern part of the study area. It is helpful for the fast-growing population of the study area to better human beings and the ecosystem.

Keywords GIS · Groundwater · Hydrogeochemical · Vertical Electrical Sounding—VES

Introduction

Groundwater forms one of the essential sources of potable water. The rate of groundwater withdrawal is increasing continuously due to a faster rate of population growth accompanied by agricultural and industrial development (Roy et al. 2021). This has increased the concern on groundwater resource evaluation and its management for sustainable development (Chebet et al. 2020; Kadam et al. 2021). The sustainable management of water resources has a new urgency in the face of the growing population, increased economic development, which is mounting demand for more and better food and increased hydrologic variability caused

by a climatic change (Jeen et al. 2021). For assessing and delineating groundwater, geophysical techniques have been applied since the ancient centuries. The electrical resistivity method has been widely used for geophysical exploration techniques, which provides information about the subsurface lithology. In groundwater exploration studies, electrical resistivity is one of the most common methods worldwide (Todd 1980a, b; Alile et al. 2011; Gopinath et al. 2019a, b, c; Kalaivanan et al. 2019). In saline clay and saline sand cases, almost the same resistivities with different formations are difficult to sort out using electrical sounding. Combining geochemical data with geophysical data resolves these differentiating problems (Gurunandha Rao et al., 2011; Gopinath et al. 2018; Nageswara Rao et al. 2018; Rajkumar et al. 2019; Ayogu et al. 2021). The analysis of geochemical data helps gain insight into hydrogeological conditions and contamination sources observed from the results obtained (Srinivasamoorthy et al. 2011; Stanly et al. 2021).

In developing countries like India, about 80% of the diseases were linked to dirty water due to contamination (Prasad 1998; Olajire and Imeokparia 2001; Limbachiya 2011; David et al. 2011; Khadri et al. 2013). Various researches reveal that urban and agricultural activities are the primary source of influence for the contamination of groundwater directly or indirectly (Kumar et al. 2006;

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Giridharan et al. 2008; Fantong et al. 2009; Ramkumar et al. 2011; Kim et al. 2012; Gopinath et al. 2018, 2019a, b). Mapping is essential for evaluating and understanding surface and groundwater pollution studies (Gnanachandrasamy et al. 2012; Xenixd et al. 2003). GIS is a powerful method for storing data easily integrated and correlated for spatial studies to get the desired output. Since GIS is a broad platform, it is used by various scientists in diverse fields for their research work (Anbazhagan and Nair 2005; Burrough and Donnell 1998).

The main purpose of this research work is to delineate various physical and chemical parameters of the groundwater samples in the study area. The study of aquifer properties is an essential technique for resolving multiple problems in geochemical studies (Hem 1989; Gibbs 1970; Srinivasamoorthy 2005). In addition, there is a significant rise in water demand for commercial and municipal use (Sofios et al. 2008). Since the availability of clean drinking water is considered a top priority in the coastal areas of Tamil Nadu and any civilized society, the present work aims to research the geophysical and geochemical characteristics of groundwater quantity and GIS quality analysis.

Study area

The study area is situated in and around the Chidambaram taluk, in the northern latitude of $11^{\circ} 27' 42''$ and $11^{\circ} 21' 51''$ and East longitude of $79^{\circ} 40' 13''$ $79^{\circ} 48' 41''$ forming a part of Cuddalore District (Fig. 1). Vellar River is one of the major rivers which drains in our study area. The

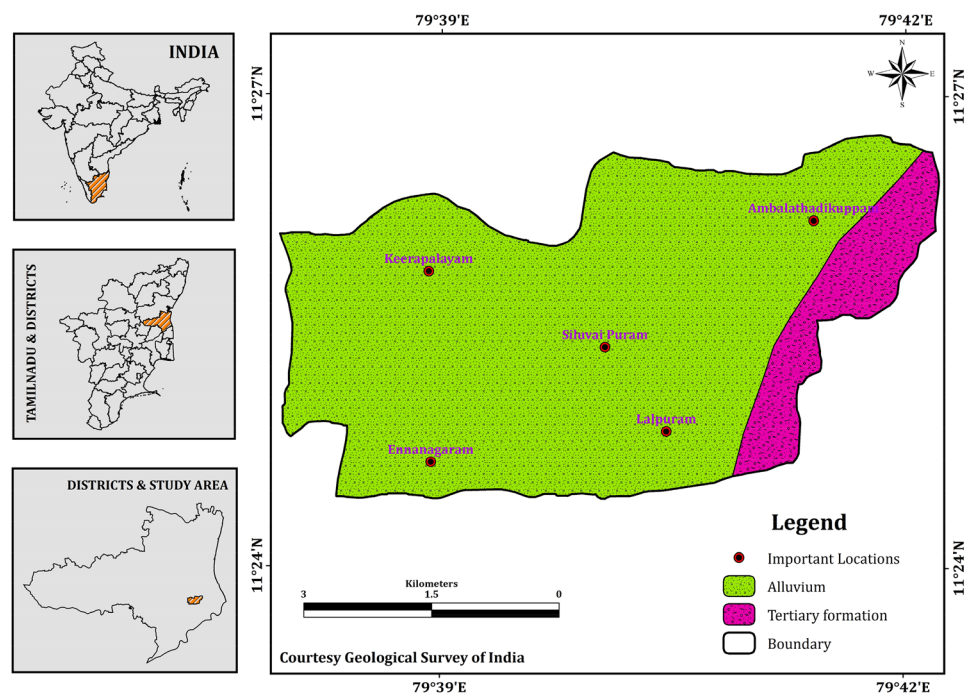
Headquarters of this district is Cuddalore, and it is located 181 km North of the State capital Chennai. It is bounded by Villupuram and Nagapattinam district on north and south. On east and west, it is determined by the Bay of Bengal and Perambalur district.

In the north, our study area is defined by Gadilam and Pennaiyar rivers. Also, in the south, it is drained by Vellar and Kollidam rivers. The elevation ranges between 20 and 100 m above mean sea level. The central high land area stretches roughly north–northeast to south–southwest in the center part of the basin. Thus, resulting parallel to sub-parallel and dendritic type of drainage pattern is found in the basin. Along the course of Vellar, there are many sharp bends. These bends are also seen with it to indicate the emerged Manimuktha Nadi. The major structural lineaments of Cuddalore sandstone and laterite are trending towards NNE to SSW, and the formation dip due to SE. High drainage density is observed in the central and western parts of the basin. Comparison of the geological conditions with the drainage and topography of the area reveals that geology has a dominant role in the basin.

Geological setting

Our study area has been geologically classified into hard rock and sedimentary formations. Nearly 80% of the site in this district is covered by the sedimentary formation of Tertiary and recent alluvial deposits. The building consists of Sands, sands Clays, and unconsolidated sandstones mottled in color with lignite seams. The river deposits of

Fig. 1 Geology and key map of the study area



Vellar, Gadilam, Pennaiyar and Manimukhtha rivers are spread over the Cuddalore Sandstone. The thickness of the sand ranges between 6 and 12 m. This alluvial formation also acts as a potential aquifer. This alluvial consists of unconsolidated sands, gravels, clay. The entire Chidambaram Taluk is covered by alluvial deposits of the Vellar River with good groundwater potential with some quality problems. The study area covers the majority portion of the alluvial plain. A small amount of the site covers tertiary formation shown in Fig. 1.

Materials and methods

Geophysical survey (Vertical Resistivity Survey)

Schlumberger array is one of the frequently used methods for determining resistivity. In this work, Schlumberger configuration is used for measuring apparent resistivity in the field. Vertical electrical sounding was conducted in 10 locations (Fig. 2) using a DDR3 model resistivity meter. The soundings were performed using the Schlumberger configuration with AB/2 spacing ranging from 2 to 100 m. The obtained field apparent resistivity data were analyzed using IPI2Win v.2.0 software to determine the layer's resistivity and thickness (Fig. 3). The interpreted data created iso-resistivity, and iso-layer thickness maps to access the potential groundwater zones. In recent decades, resistivity data interpretations have been made using software necessary to handle many data. Modern computer software is readily available, allowing sounding curves to be studied interactively and automatically efficiently.

Groundwater sampling and analysis

Hydrogeochemical research requires proper site selection for the collection of groundwater samples and an appropriate analysis method. Sampling sites were located, taking several factors into considerations like lithology, structure, and geomorphology. A sampling of groundwater has been carried out in the Cuddalore taluk between pre-monsoon and post-monsoon. The groundwater sampling locations are shown in Fig. 2. The parameters analyzed are pH (Power of Hydrogen), EC (Electrical Conductivity), TDS (Total Dissolved Solids), TH (Total Hardness), Major cations (Ca^{2+} , Mg^{2+} , Na^+ , K^+), and anions (HCO_3^- , Cl^- , SO_4^{2-} , NO_3^-). Whereas NO_3^- determined pre-monsoon season. The determined hydrogeochemical data were analyzed using WAT-CLAST (Chidambaram et al. 2003). The pH was calculated using a digital pH meter. Alkalinities were analyzed by the standard titrimetric method.

The GIS plays a crucial role in combining various spatial data. Analytical data help in identifying the resolution of saline water intrusion problems and other chemical parameters. GIS (Geographic Information System) is used to represent the data spatially and is also helpful in comparing the various spatial maps generated. The resulting outcome of spatial maps and empirical findings will indicate the water quality in that area. The inverse distance weighted (IDW) represents the spatial data by interpolating the distance between them (Burrough and Mc Donnell 1998; Sarath Prasanth et al. 2012). The node value and the data used in interpolation were calculated by sum up of all average weighted points (Table 1).

Result and discussion

Vertical electrical data acquisition and analysis

The interpreted values of resistivity and layer thickness are presented in (Table 1) for a better understanding of the subsurface lithological variation and to delineate potential groundwater zones. An attempt has been made to prepare pseudo-resistivity sections considering VES locations and various geochemical parameters. The resistivity and thickness value for the first layer vary from 1.29 to 56.7 $\Omega\text{-m}$ and 0.5 to 3.68 m, respectively. In the first layer, the low resistivity value in VES-10 and the higher value are observed in VES-4. The second layer resistivity value ranges from 0.0846 to 18.3 $\Omega\text{-m}$, high resistivity is found in VES-6, and low resistivity is found in VES-8. The second layer thickness is varied from less than 0.086–14.7 m, and less thickness is found in VES-8, and high thickness is found in VES-4. In the third layer, low resistivity of 0.143 $\Omega\text{-m}$ was found

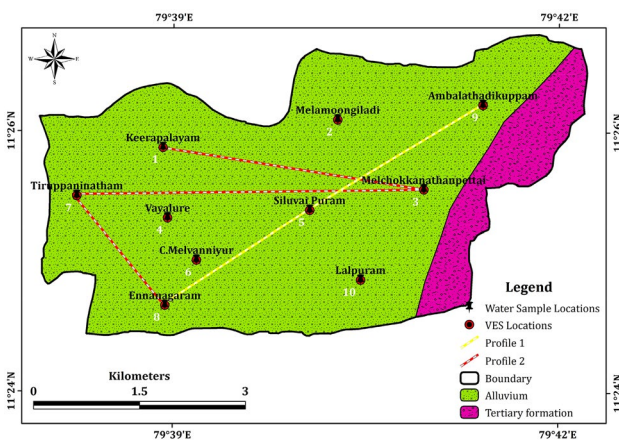


Fig. 2 Groundwater and VES sample location map of the area

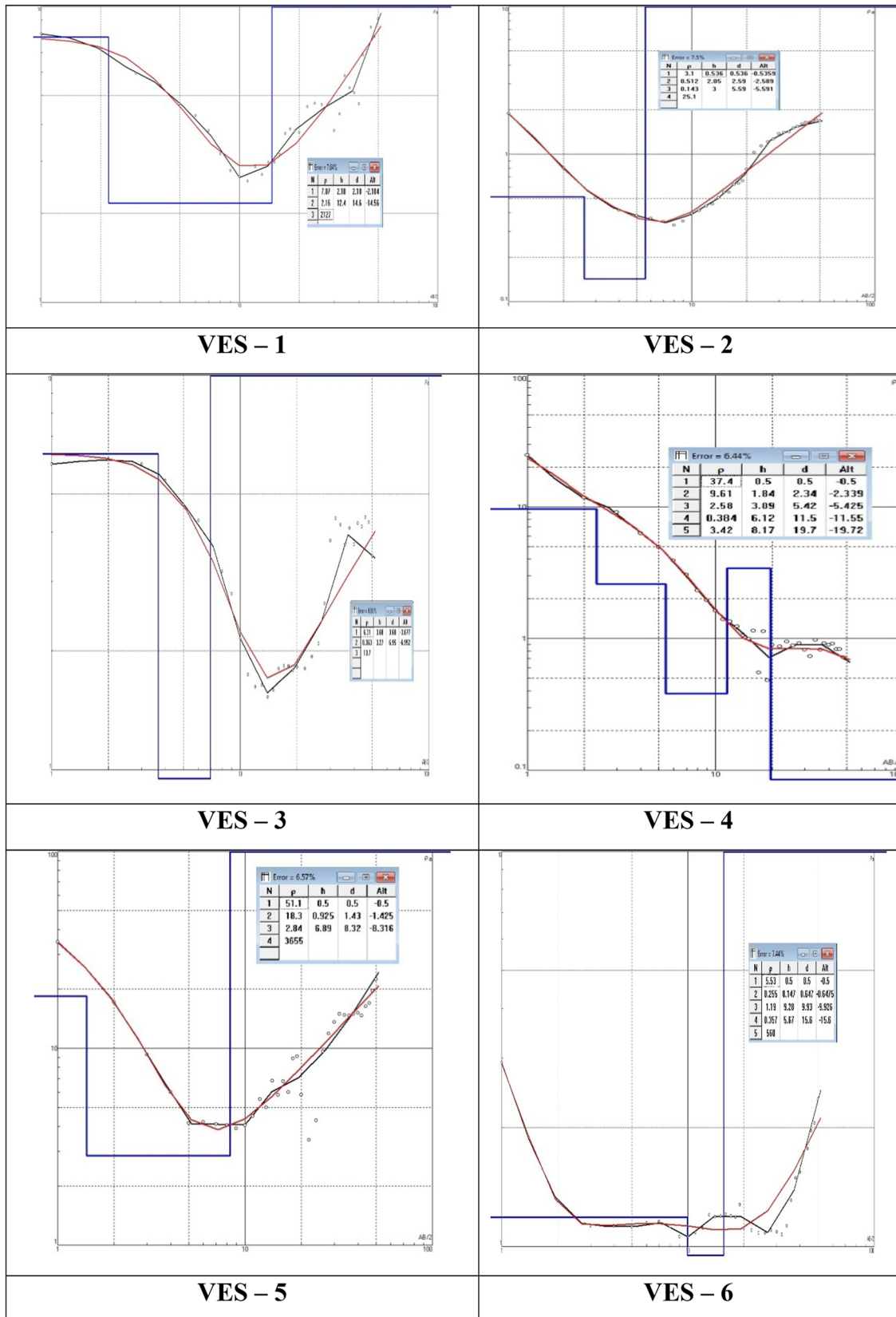


Fig. 3 Curve types of VES model

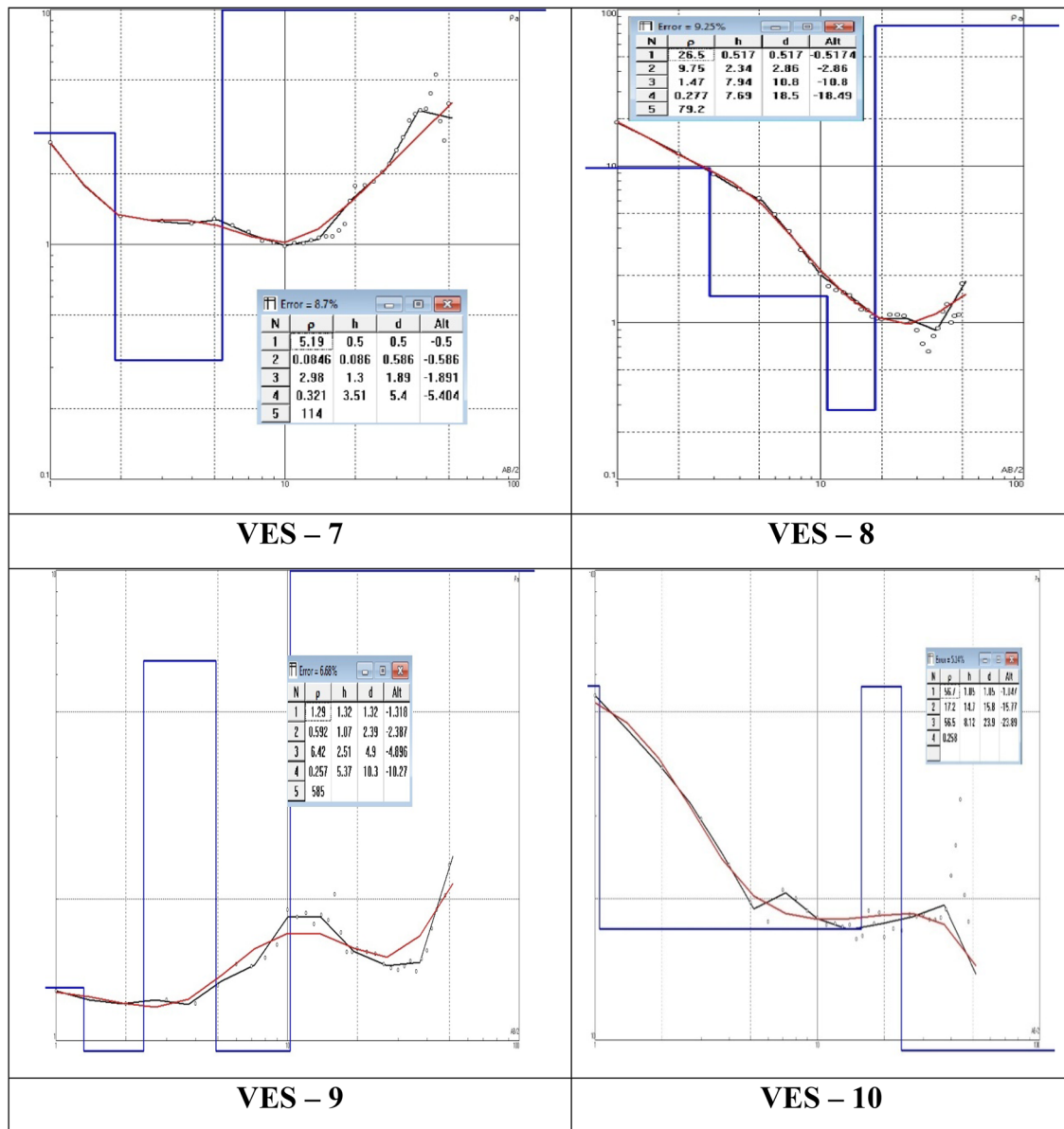


Fig. 3 (continued)

in VES-3, and high resistivity of 2127 Ω -m was found in VES-2.

The third layer thickness is varied from 1.3 to 9.28 m, and less thickness is found in VES-8, and high thickness is found in VES-7. In the fourth layer, low resistivity of 0.25 Ω -m was found in VES-10, and high resistivity of 3655 Ω -m was found in VES-6. The fourth layer thickness is varied from 3.51 to 7.69 m, and less thickness is found in VES-8, and high thickness is found in VES-9 (Table 1). This low resistivity area might be because of the coastal aquifer; there is a chance of saltwater interruption in this spring, or there is a chance of a blend of these two impacts. It is construed that the seawater has encroached to

a significant region connecting the coast due to over-abuse of groundwater at more profound springs (Senthilkumar et al. 2012). There is a thin layer of mud isolating these layers of low resistivity.

The nature of the VES curve depends on the geological and hydrogeological situation, and the maximum electrode spread is employed. Qualitative interpretation is also attempted by preparing a spatial variation map showing the types of curves encountered. Such maps can indicate the disposition of different resistivity zones with depths. In the study area, HKH type curve is found dominant by 30% indicates $\rho_1 > \rho_2 < \rho_3 > \rho_4 < \rho_5$ and the locations falling in this type of curve are Ambalathadikuppam, Melamoongiladi

Table 1 Interpreted electrical resistivity, layer thickness and curve type of the study area (ρ in Ω -m, h in m)

VES no	Village	ρ_1	ρ_2	ρ_3	ρ_4	ρ_5	h1	h2	h3	h4	Curve Type
1	Keerapalayam	6.3	0.363	13.7	–	–	3.68	3.27	–	–	H
2	Tiruppaninathan	7.87	2.16	2127	–	–	2.18	12.4	–	–	H
3	Ennagaram	3.1	0.512	0.143	25.1	–	0.536	2.05	3	–	QH
4	Vayalur	56.7	17.2	56.5	0.258	–	1.05	14.7	8.12	–	HK
5	C.Melvanniyur	37.4	9.61	2.58	0.384	3.42	0.5	1.84	3.09	6.12	QQH
6	Sluvai Puram	51.1	18.3	2.84	3655	–	0.5	0.925	6.89	–	QH
7	Melamoongiladi	5.53	0.255	1.19	0.357	560	0.5	0.147	9.28	5.67	HKH
8	Ambalathadikuppam	5.19	0.084	2.98	0.321	114	0.5	0.086	1.3	3.51	HKH
9	Melchokkonathapettai	26.5	9.75	1.47	0.277	79.2	0.517	2.34	7.94	7.69	QQH
10	Lalpuram	1.29	0.592	6.42	0.25	585	1.32	1.07	2.51	5.37	HKH
	Minimum	1.29	0.084	0.143	0.25	3.42	0.5	0.086	1.3	3.51	
	Maximum	56.7	18.3	2127	3655	585	3.68	14.7	9.28	7.69	
	Average	21.58	6.43	361.83	733.72	275.72	1.29	4.47	5.27	5.65	

and Lalpuram. 20% of the study area falls in three types of curves: H, QH, and QQH representing $\rho_1 > \rho_2 < \rho_3$; $\rho_1 > \rho_2 > \rho_3 < \rho_4$ and $\rho_1 > \rho_2 > \rho_3 > \rho_4 < \rho_5$. Keerapalayam and Tiruppaninatham are the areas coming under the H-type curve. Ennagaram and Siluvai Puram are the locations coming under the QH curve. Melavanniyur and Melachokkanathanpettai are the locations coming under the QQH curve type. In Vayalur, HK ($\rho_1 > \rho_2 < \rho_3 > \rho_4$) curve type is found dominant by 10% (Table 1 and Fig. 3). The curve types indicate various alternate layers of conductive, reflective, and resistive layer formations composed of sands and clay (Omosuyi et al. 1999; Gopinath and Srinivasamoorthy 2015; Gopinath et al. 2019a, b, c).

ISO resistivity spatial distribution analysis

The depth-wise depictions of iso-resistivity spatial plots were done using Arc GIS for five different layers. According to the resistivity values, the layers were classified into seven classes: < 5, 5–10, 10–15, 15–20, 20–25, 25–30 and > 30 Ω -m (Fig. 4). Lower than 5 Ω -m resistivity was observed in Lalpuram and Ennagaram due to clay formation in that soil. The range of 5 and 10 Ω -m resistivities is found in Ambalathadikuppam, Lalpuram, Melamoongiladi, Ennagaram, Keerapalayam, and Tiruppaninatham, which indicates the presence of mixed clayey sand. The 10–15 Ω -m resistivity range was found in Ambalathadikuppam, Melamoongiladi, Lalpuram, Tiruppaninatham, Keerapalayam, and Ennagaram along the study area, might be due to the presence of silty sand. Resistivity range of 15–20 Ω -m was recorded in Lalpuram, Ennagaram, Tiruppaninatham, Keerapalayam, Melamoongiladi and Ambalathadikuppam are found in the center of the study area. Resistivity range of > 30 Ω -m values was noted in Vayalure, C. Melavanniyur, and Siluvai Puram. This

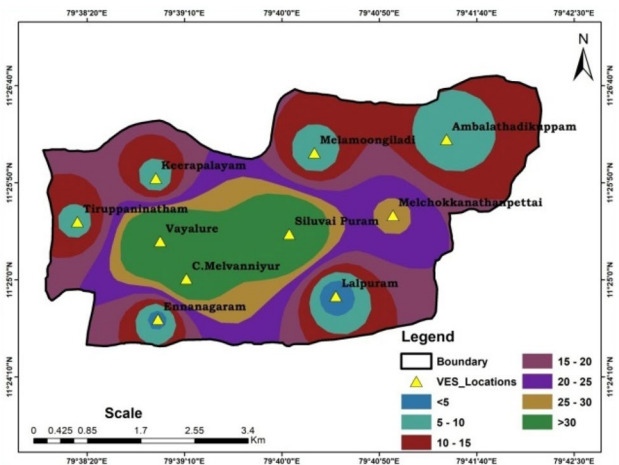


Fig. 4 Resistivity spatial plot for the first layer

area might be having fresh water-saturated sand formations. From the result, it is noted that the resistivity values change from coast to land. The resistivity decreases when away from the coast due to the saline water intrusion and vice versa. The findings of the 2nd layer iso-resistivity shown in (Fig. 5) suggest that the importance of resistivity decreases towards backwater. In the central part of our study area, higher resistivity of 10–12 Ω -m and > 15 Ω -m values are present in some locations, such as Siluvai Puram and Vayalur. The change in resistivity generally depends on the soil type and water-saturated zone. The clay formation might be the reason for the lower resistivity, and the coarse sandy mixture might be the reason for the higher resistivity. In the study area, < 5 Ω -m resistivity is found in the northern and southern parts. The third layer resistivity plot (Fig. 6) shows < 5 Ω -m, a lesser resistivity value found maximum in the study area and the central

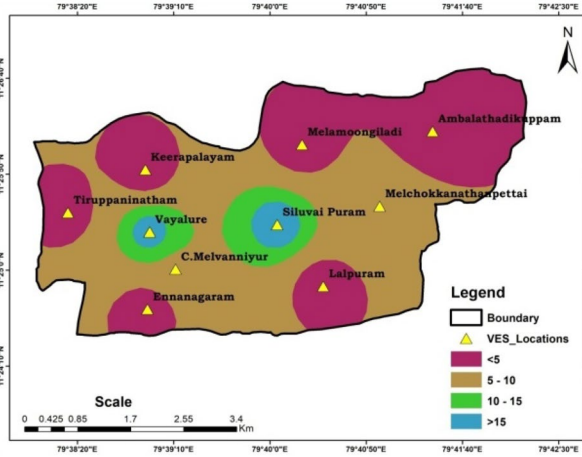


Fig. 5 Resistivity spatial plot for the second layer

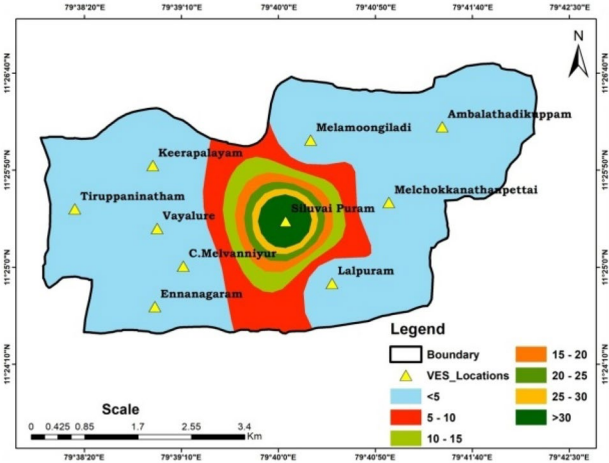


Fig. 7 Resistivity spatial plot for the fourth layer

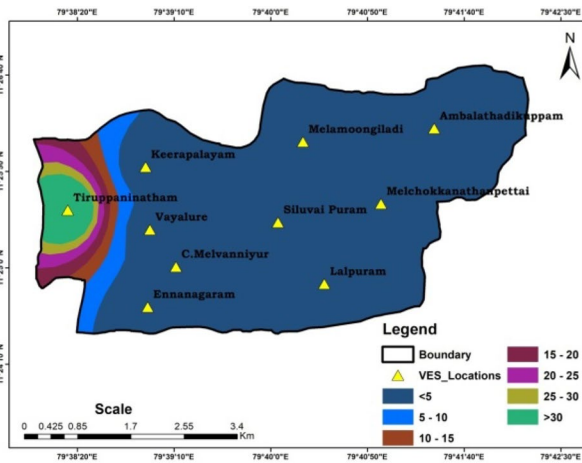


Fig. 6 Resistivity spatial plot for the third layer

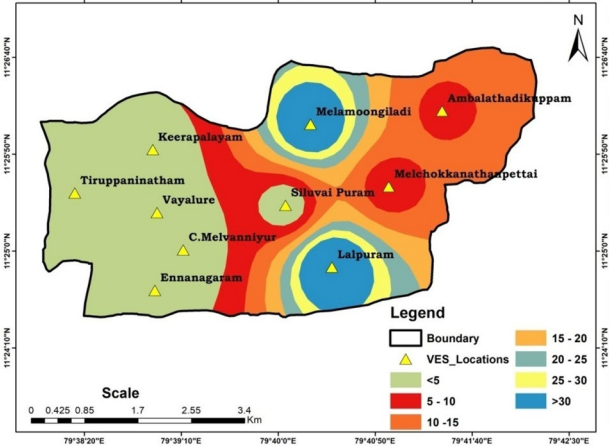


Fig. 8 Resistivity spatial plot for the fifth layer

part. The resulted resistivity in this region might be due to the presence of fresh water in that area. The saline intrusion is not found in the third layer resistivity spatial plot, and it signifies there is no intrusion in that area. The fourth layer resistivity plot (Fig. 7) indicates saltwater intrusion, which is depicted in the spatial map in the class of <5 . The areas under lower resistivity zones are Ennagaram, Melvanniyur, Vayalur, Tiruppaninatham, Keerapalayam, Melamoongiladi, Ambalathadikuppam, Melchokkanathanpettai, and Lalpuram. The Siluvaipuram shows the highest resistivity in the study area, classified from 5–10 to >30 . The fifth layer resistivity map (Fig. 8) isolates resistivity ranges from 5–10 to >30 confined to locations such as Siluvaipuram and Lalpuram Melchokkanathanpettai, Melamoongiladi, and Ambalathadikuppam noticed along with the central and northern parts of the study area indicating

the saline water intrusion at great depth. Keerapalayam, Tiruppaninatham, Vayalur, Melvanniyur, and Ennagaram are recorded as lower resistivity values of <5 , signifying the freshwater.

Pseudo-section model analysis

The pseudo-section analysis is used the subsurface lithological variation and to find out the potential aquifer zone. Two profiles were constructed from the East to West direction for making the pseudo-section. Locations bearing the maximum number of electrical resistivity were considered for initiating a better pseudo-section. For constructing pseudo-section shown in (Fig. 9) for the first profile, three vertical electrical sounding locations of VES 5, 8, and 9 were selected in which overall resistivity ranges from 22.1 to 452 Ω -m. It is noted that resistivity is moderately increased from the top

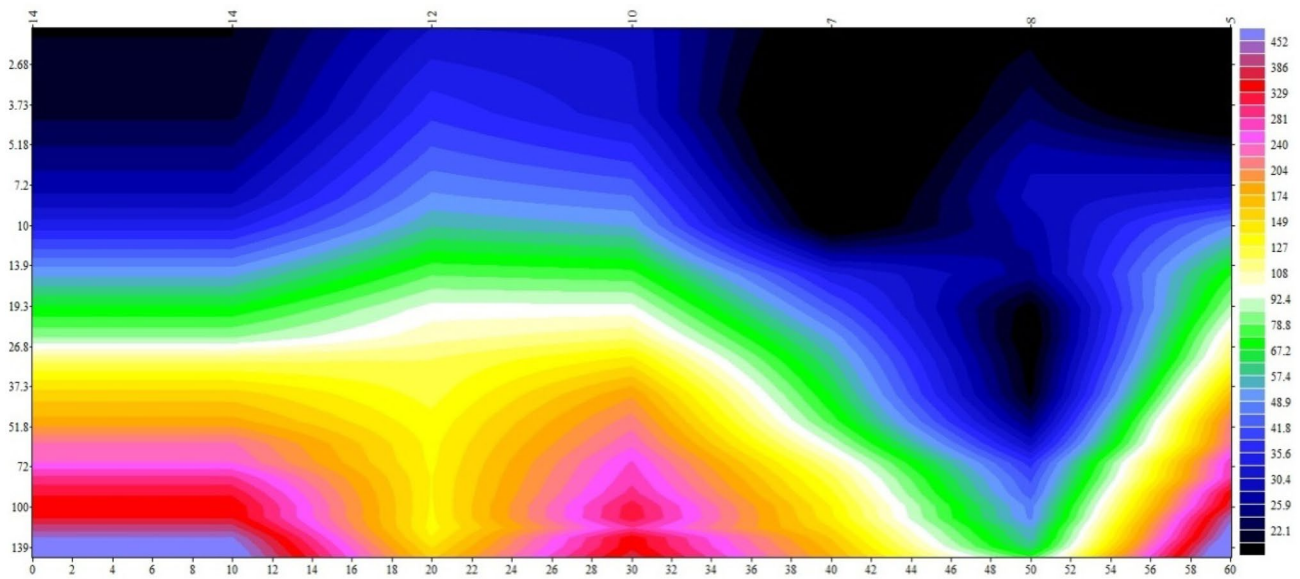


Fig. 9 Pseudo-section of profile I

layer to the bottom layer. In the top layer, resistivity range from 0.2 of 0.390 to 0.367 Ω -m is observed. The second and third layers have the resistivity range of 0.293–0.271 Ω -m. The pseudo-section’s result exposes that the top layer of low resistivity gradually decreases from west to east and is high on the eastern side.

For constructing the pseudo-section (Fig. 10) for the second profile, four vertical electrical sounding locations of VES 1, 3, 6, and 7 were selected. Overall resistivity

ranges from 0.268 to 6.63 Ω -m. The low resistivity range of 0.268–0.316 is found in the Middle Western part. The higher resistivity zone is varied from 2 to 4.2 m from the surface. Below the low resistivity zone, a resistivity range of 0.405 to 0.562 Ω -m was noticed and observed at the middle part of the study area. The resistivity could be $< 10 \Omega$ -m consider as saline coastal zone sand (Sedimentary). $< 1 \Omega$ -m will be the clay layer saturated with salt water, and 3–6 Ω -m might be red clay.

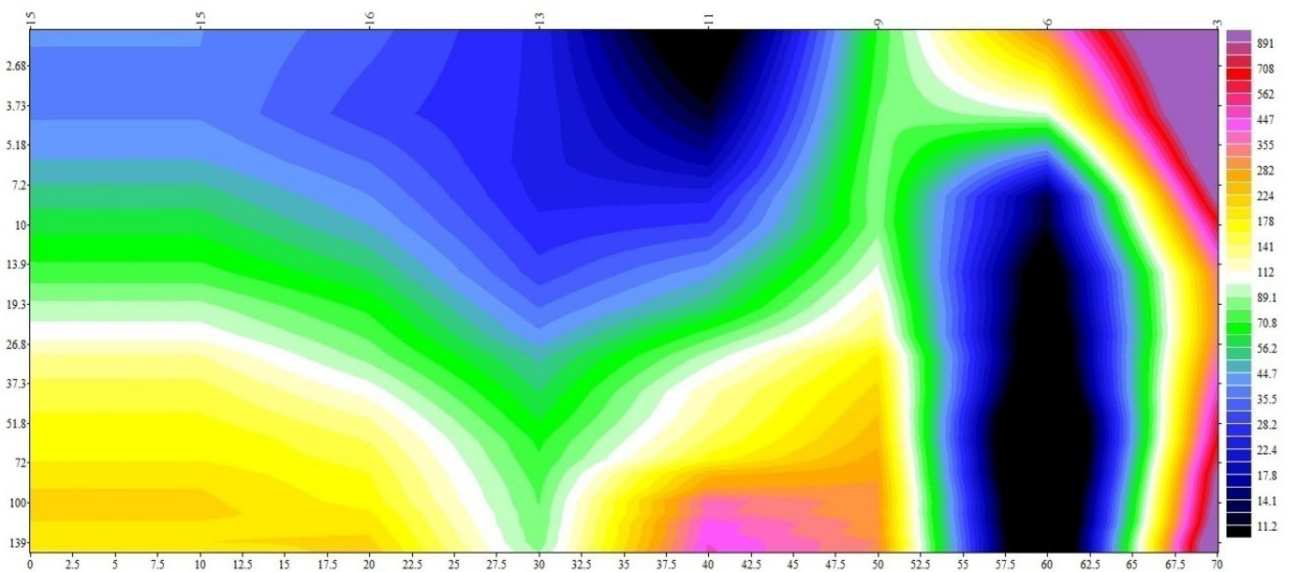


Fig. 10 Pseudo-section of profile II

Hydrochemistry and water quality

Power of hydrogen (pH)

pH is used to identify the solution, whether it is acidic or basic. If the pH resulted is less than 7, it is an acidic solution, and if the pH results are greater than 7, it is basic or alkaline. Measurements of pH are crucial in various fields of science applications. The pH of the sample is also based on the various relative quantities such as calcium, carbonates, and bicarbonates. Under the acidic condition, there occurs an enhancement of iron in sediment while pH decreases. Also, in alkaline conditions, it gets increased with pH. While comparing to the alkaline condition, the amount of iron released from sediment having (pH 56-0) is found higher (Qinghui Huang et al. 2005). From pH 6 to 8, a lower amount of iron sediments was found. The elevated pH values resulted from the development of Ca-P solids, which were the concomitants of calcium carbonate precipitate (Brown 1980; Olila and Reddy 1995), which would deduce PO_4^{3-} concentrations. The pH level varied from 6.96 to 8.02, with an average of 7.659 in the study area (Table. 2). Class 7.5–8 is found dominant in the various locations of the study area, such as Tiruppaninatham, Keerapalayam, Siluvai Puram, Melamoongiladi, Melchokkanathanpettai, Lalpuram, and Ambalathadikuppam. The lowest value is found in the regions of Vayalur, Melvanniyur, and Ennagaram, classified between the range of < 7.5 and 8 (Fig. 11). Most of the samples signifying alkaline nature, and it is due to cases of the amount of dissolved CO_2 , carbonate, and bicarbonate in groundwater (Senthilkumar et al. 2017).

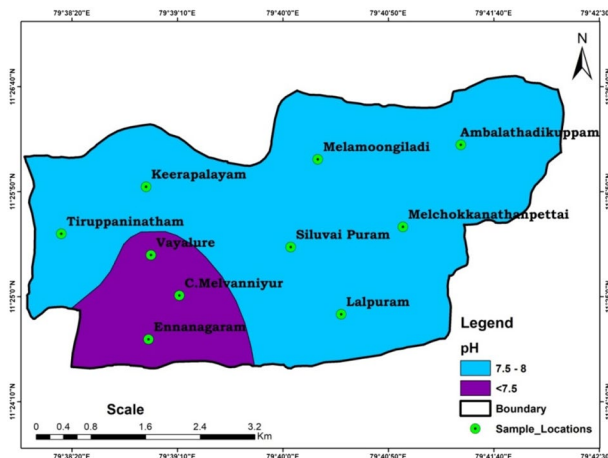


Fig. 11 The spatial distribution of pH

EC Concentration

Measurement of electrical conductivity indicates ionic concentration. If the concentration of dissolved salts increases, conductivity will also increase. EC concentration also depends upon temperature, concentration, and types of ions present (Hem 1985). Semiconfined aquifers will tend to have Na-SO₄ and Ca-Mg-SO₄ water types. Suppose an increase in EC is positively correlated with an increase in Na/Cl ratio. In that case, it usually means that fluids in the well are derived from more than one aquifer source and that the mixing ratio in the water will be susceptible to change. In the study area, EC values range between 291 and 5870 μS/cm with an average of 2892.5 μS/cm (Table. 2). The highest value of 5870 μS/cm was observed in the Ennagaram location. The minimum value is found at Lalpuram (291 μS/cm) and the maximum at Ennagaram (5870 μS/cm). The high

Table 2 Geochemical data of the study area

S. no	Location	Ca ²⁺	Mg ²⁺	HCO ₃ ⁻	Cl ⁻	Na ⁺	K ⁺	SO ₄ ²⁻	NO ₃ ⁻	pH	EC	TDS
1	Keerapalayam	58	91.2	884.5	904.0	131.2	32	2.47	146.04	8.02	1826	1290
2	Melamoongiladi	126	82.8	982.1	762.2	120.9	36.2	3.44	107.42	7.76	1980	1400
3	Melchokkanathanpettai	72	81.6	1671.4	1799.1	222.3	38.8	3.23	224.09	7.75	3680	2560
4	Lalpuram	14	14.4	384.3	132.9	25.2	4.7	0.39	-34.55	7.82	291	204
5	C. Melvanniyur	142	154.8	1659.2	3093.0	291.4	33.4	5.98	20.68	7.57	5180	3630
6	Tiruppaninatham	78	84	878.4	1081.2	158.3	53.9	4.64	31.64	7.98	2400	1690
7	Ennagaram	224	150	1793.4	2942.4	287.8	32.3	7.34	39.45	6.96	5870	4100
8	Vayalur	114	20.4	1781.2	1329.4	165.5	21	4.99	-24.22	7.42	2980	2080
9	Siluvaiapuram	68	76.8	1982.5	1223.0	206.3	49.8	1.47	4.59	7.64	3210	2270
10	Ambalathadikuppam	36	237.6	963.8	531.8	109.4	18.1	3.565	13.71	7.67	1508	1060
	Minimum	14	14.4	384.3	132.9	25.2	4.7	0.39	-34.55	6.96	291	204
	Maximum	224	237.6	1982.5	3093.0	291.4	53.9	7.34	224.09	8.02	5870	4100
	Average	93.2	99.36	1298.9	1379.9	171.83	32.02	3.7515	52.885	7.659	2892.5	2028

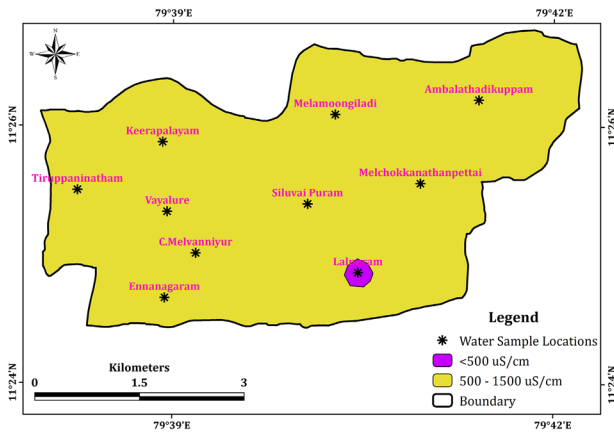


Fig. 12 The spatial distribution of EC

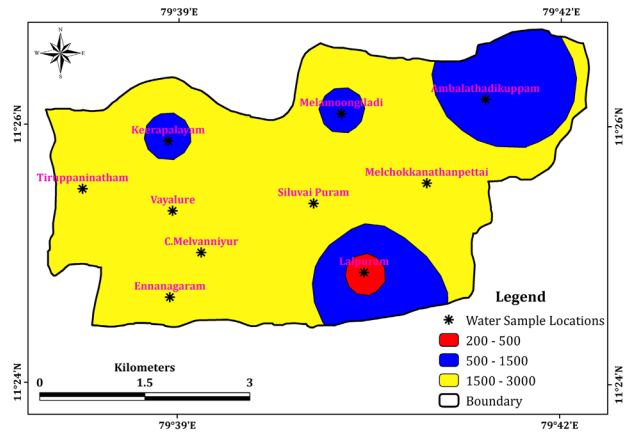


Fig. 13 The spatial distribution of TDS

Table 3 TDS classification (USSL 1954)

TDS range (ppm)	Characterization	No. of samples
< 200	Fresh	0
200–500	Slightly saline	1
500–1500	Moderately saline	3
1500–3000	Very saline	6

conduction was observed due to higher chloride concentration in the sample (Davis et al. 1998). The spatial distribution of EC is represented in (Fig. 12). A low concentration of EC values is observed in Lalpura (291 $\mu\text{S/cm}$) due to infiltration of rainwater or recharge zone.

Total Dissolved Solids (TDS)

In many groundwater investigations, the recharge zone is characterized by a lower TDS than the water discharge zone (Freeze and Cherry 1979). The TDS value of the samples ranges from 204 to 4100 mg/l with an average of 2028 mg/l (Table 2). The TDS divergence indicates a low concentration in Lalpura and a higher level at Ennanagaram.

Besides, the TDS has been classified depending on the variations in salinity degrees and different countries. The worldwide criterion (USSL, 1954) for classifying the TDS based on the degree of salinity is less than 200 to fresh; 200–500 slightly saline, 500–1500 moderately saline, 1500–3000 very saline, and greater than 35,000 is brine. The study area is classified into four categories based on the categories mentioned in Table 3.

The study area TDS classification showed that about 10% of the sample locations are in the slightly saline water, 30%

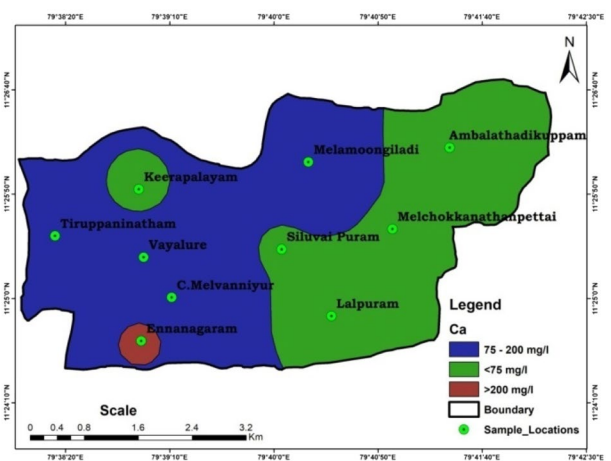


Fig. 14 The spatial distribution of Ca

are moderately saline, and 40% are in the very saline category. The spatial distribution was shown in (Fig. 13).

Major cations

Since calcium is abundantly found in most rocks and having higher solubility, it is dissolved easily in groundwater. The Ca ionic concentration was found low as 14 mg/l in Lalpura; however, it is found higher with 224 mg/l in Ennanagaram village with an average of 93.2 mg/l (Table 2). The allowable limit of Ca for drinking water is mentioned as 200 mg/l (WHO 2011). From the result, it is clear that all the samples were falling under the allowable limit. However, a minor amount of groundwater samples was observed below the desirable limit. The spatial distribution of Ca is represented in (Fig. 14). The amount of magnesium in groundwater is comparatively less than calcium since; it is hardly dissolved in water. The Magnesium concentration varied from

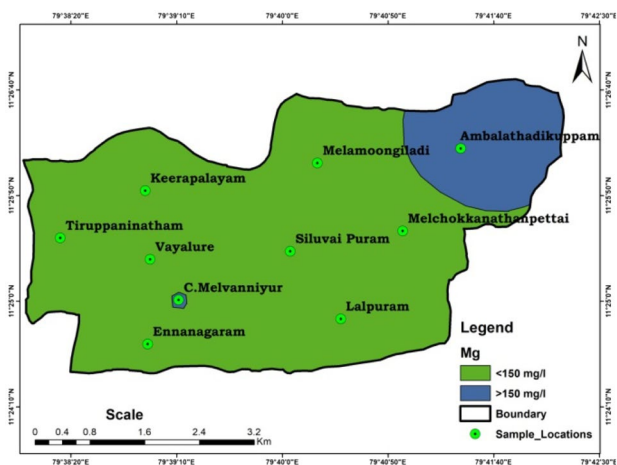


Fig. 15 The spatial distribution of Mg

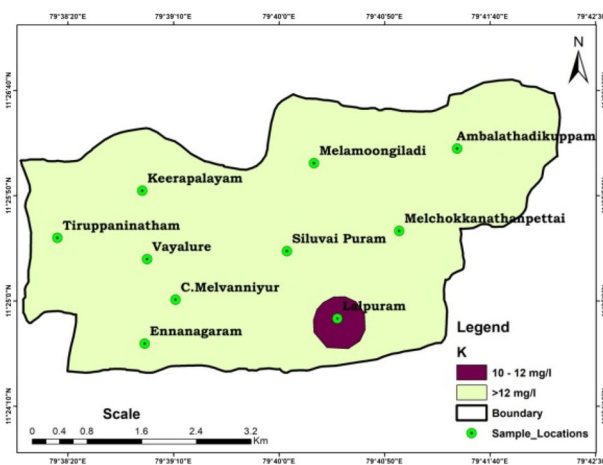


Fig. 17 The spatial distribution of K

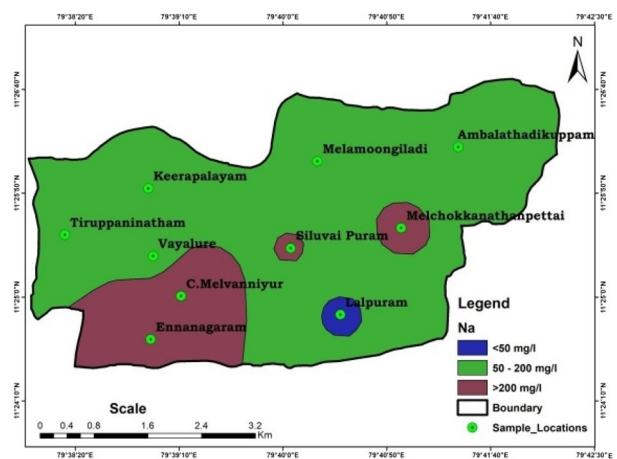


Fig. 16 The spatial distribution of Na

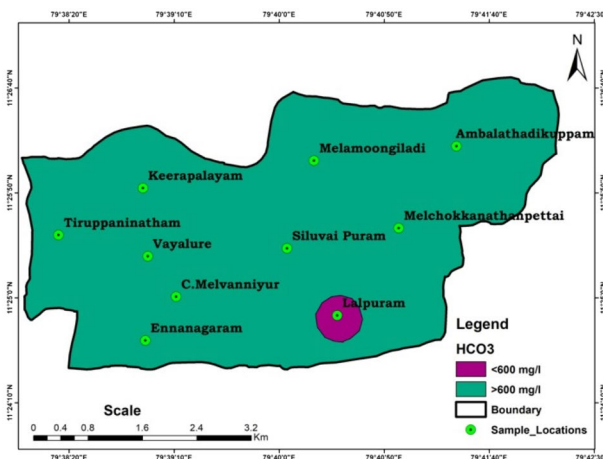


Fig. 18 The spatial distribution of HCO₃

14.4 to 237.6 mg/l with an average of 99.36 mg/l (Table 2). The lower value is found at Lalpuram and the higher value at Ambalathadikuppam as shown in (Fig. 15). The allowable limit of magnesium for drinking water is 150 mg/l (WHO 2011).

The sodium concentration ranges from 25.2 to 291.4 mg/l, having an average of 171.83 mg/l. The minimum and maximum concentration levels are found at Lalpuram and Melavanniyur, respectively (Table 2 and Fig. 16). The allowable value for drinking water is mentioned as 200 mg/l (WHO 2011). The sodium content in the sample has resulted from the feldspar minerals like halite and silicate through various weathering processes (Khan et al. 2014; Mostafa et al. 2017). The sodium content in the study area might be due to agricultural by-products such as sodium-rich fertilizers (Hem 1989; Sultana 2009). The potassium concentration ranges from 4.7 to 53.9 mg/l, having an average of

32.02 mg/l (Table 2). Lalpuram shows low concentration, and Tiruppaninatham has shown a high concentration of potassium. The allowable limitation for potassium in drinking water is mentioned as 12 mg/l (WHO 2011). The spatial distribution is represented in (Fig. 17).

Major anions

The bicarbonate concentration ranges from 384.3 to 1982.5 mg/l having an average of 1298.9 mg/l (Table 2). The high concentration was noticed at the Siluvaipuram station, and similarly, low concentration is found at Lalpuram, respectively shown in (Fig. 18). Chloride concentration ranges from 132.9 to 3093 mg/l, having an average of 1379.9 mg/l (Table 2). Low concentration is noticed at Vayalur, and high concentration is noticed at C.Melvanniyur as shown in the spatial diagram (Fig. 19). The allowable

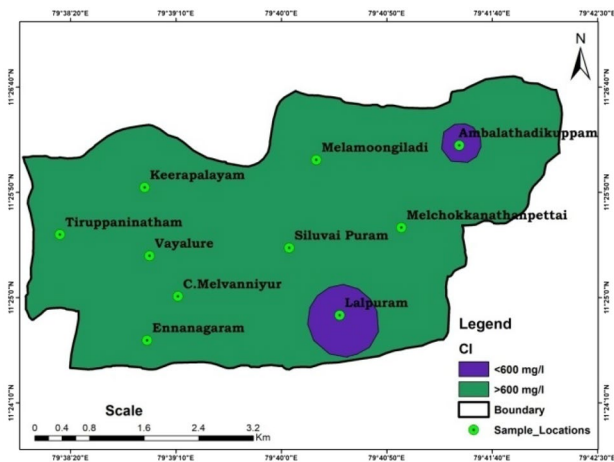


Fig. 19 The spatial distribution is shown in Cl

limitation of chloride concentration for drinking water is 600 mg/l (WHO 2011).

Sulfate (SO_4^{2-}) is the naturally occurring element on earth and is also generated by anthropogenic sources. Weathering and volcanic eruption are the major natural sources of sulfate. Dry fallout and industrial runoff are some of the main anthropogenic activities which increase sulfate content. The concentration of SO_4 ranges from 0.39 to 7.34 mg/l, having an average of 3.7515 mg/l (Table 2). Low concentration is noticed in Lalpuram, and high concentration is noticed in Ennagaram (Fig. 20). During agricultural activities, nitrogenous fertilizers will leach out the roots and enable the nitrogen to get mixed with the groundwater through percolation.

The concentration of nitrate found in the groundwater samples ranges from -34.55 to 224.09 mg/l, having an average of 52.885 mg/l (Table 2), and it was found low at

Lalpuram and higher concentration at Melchokkanathanpettai as shown in (Fig. 21). The allowable limitation of nitrate concentration for drinking water is 45 mg/l (WHO 2011). The present amount of nitrogen is mainly due to agricultural activities (Sravathi and Sudarshan 1998).

Hydrogeochemical facies

The concept of hydrochemical facies is to get a clear understanding of the chemical characteristics of groundwater also studied by various researchers such as Back (1960), Seaber (1962), Morgan and Winner (1962), Hanshaw et al. (1965a, b, c), Walton (1970) and others. The hydrochemical facies classification is usually done by practicing and following the trilinear piper diagram (1944). Nevertheless, the classification of hydrogeochemical facies and environment has been widely used by the reconstructed diamond field. The normal trilinear pattern has been reconstructed into the diamond field by Lawrence and Balasubramanian and Sastri 1994. The interpretations of the samples are shown in (Fig. 22). The diagram indicates that the majority of the samples were falling under the 1 and 2 subfields. Only one sample falls in subfield 1 representing high Ca + Mg and $\text{SO}_4 + \text{Cl}$. All other samples fall in 2 subfields representing high Ca + Mg and $\text{SO}_4 + \text{Cl}$, water contaminant with Gypsum static and disco-ordinated regimes and Ca + Mg, $\text{SO}_4 + \text{Cl}$ and $\text{HCO}_3 + \text{CO}_3$. The gypsum contamination may be due to calcium leaching or capillary movement of groundwater.

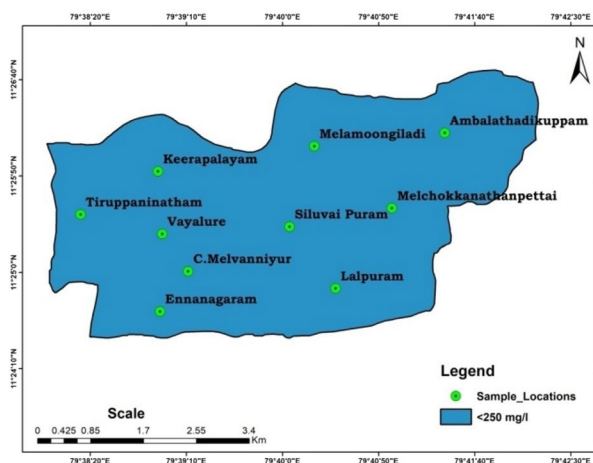


Fig. 20 The spatial distribution of sulfate (SO_4^{2-})

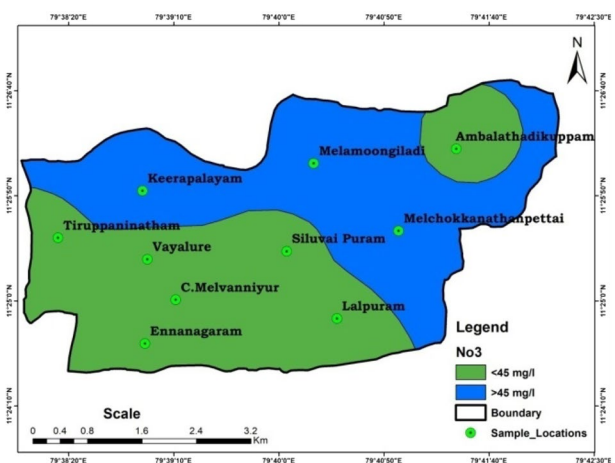
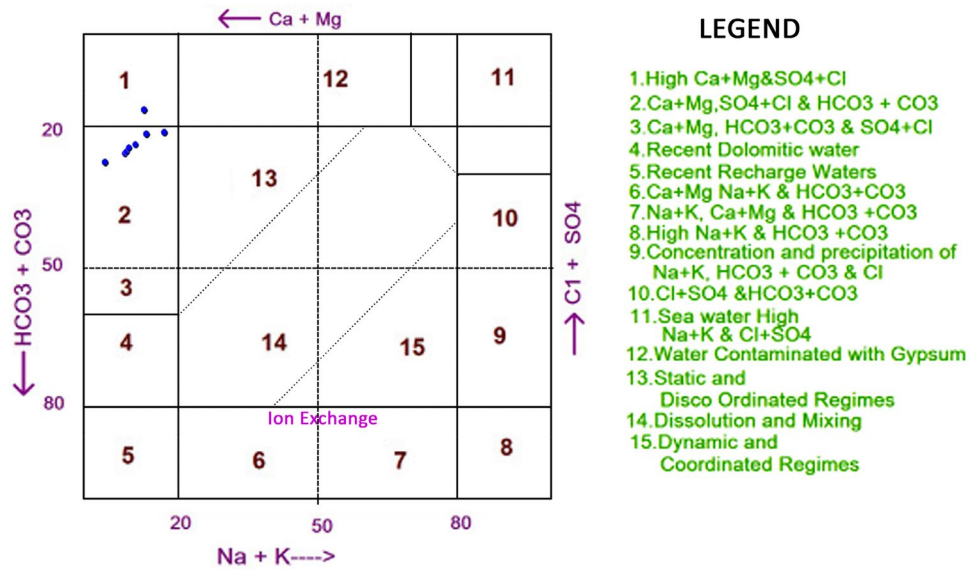


Fig. 21 The spatial distribution of nitrate (NO_3^-)

Fig. 22 Reconstructed diamond field of Piper diagram of the study area

Classification of Hydrogeochemical facies & Environment

Reconstructed Diamond Field of Piper, Lawrence and Balasubramanian, 1994



Sodium absorption ratio

Sodium absorption ratio (SAR) is used to delineate the suitability of groundwater for irrigation. Parameter such as EC and sodium % is also used to find out the suitability of the groundwater. The U.S Salinity Laboratory shows a more refined way of expressing the alkali hazard in irrigational water (USSL 1954), expressed as SAR, explaining the sodium exchange between the soils. The USSL diagram is useful in understanding the level of alkali hazard present in a groundwater sample. It is also adopted to interpret whether the groundwater is safe for agricultural activities (Todd 1980a, b). The USSL diagram prepared for the groundwater sample is shown in (Fig. 23), in which the sodium adsorption ratio is plotted with specific conductance. The following diagram is classified into 16 classes which indicates the salinity level of water that can affect the soil as (low) C1, (Medium) C2, (high) C3, and (very high) C4 and similarly sodium hazard as (low) S1, (medium) S2, (High) S3 and (very high) S4.

The SAR is computed as

$$SAR = [Na^+] / \{ ([Ca^{2+}] + [Mg^{2+}]) / 2 \}^{1/2}$$

All the ionic concentrations are expressed in meq/l. The USSL diagram can be done by plotting the known values of SAR and specific conductance of water to determine the suitable water for irrigation.

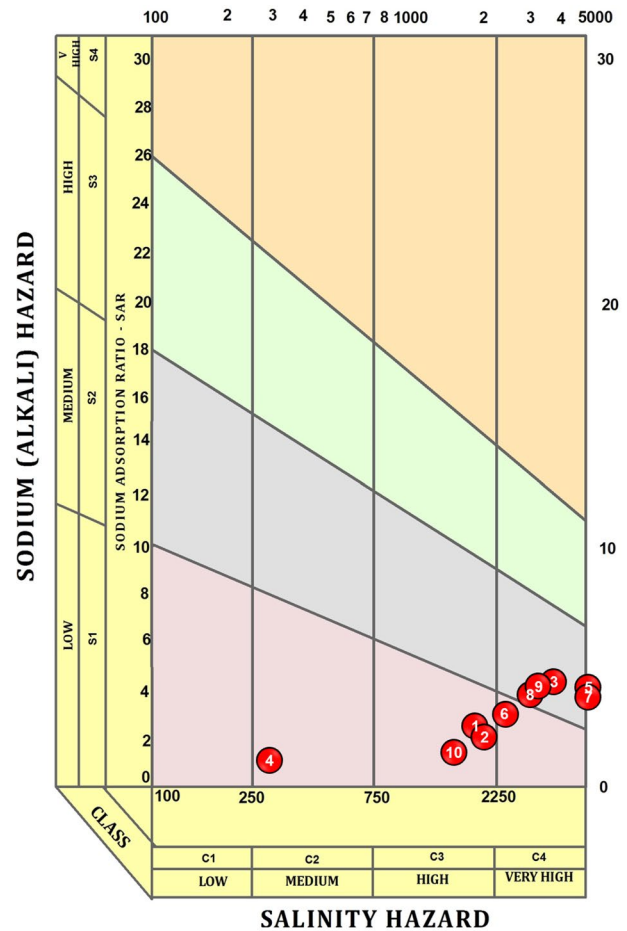


Fig. 23 USSL diagram

Gibb's ratio

In water quality, the reaction between groundwater and aquifer has a significant role. This study is also effective in understanding the source of groundwater. (Gupta et al. 2008; Subramani et al. 2009). These diagrams are usually employed to delineate the chemical components and other constituents from rocks by weathering and other phenomena (Viswanathaiah 1978). Similar research is done by (Nagaraju et al. 2014) to study the methodology involved in controlling and determining groundwater's chemical constituents in the Gomuki sub-basin. The following formula carries out the Gibbs ratio:

$$\text{Gibbs Ratio for Anion} = \text{Cl}^- / (\text{Cl}^- + \text{HCO}_3^-), \tag{1}$$

$$\text{Gibbs Ratio for Cation} = (\text{Na}^+ + \text{K}^+) / (\text{Na}^+ + \text{K}^+ + \text{Ca}^{2+}). \tag{2}$$

The samples collected from the study area are plotted similarly to the diagram (Fig. 24). Most of them fall under the rock dominance category in the study area, and only one sample fell under the Evaporation field.

Permeability Index (PI)

A term called permeability index has been developed from experiments that account for total salt concentration, sodium, and carbonate content. The permeability of soil is influenced using the longer-term irrigation water consisting of sodium and bicarbonate contents. Doneen (1964) has studied and mentioned the significance of the permeability index for determining suitable water for irrigation. Permeability index is obtained from the following equation:

$$\frac{\text{Na} + \sqrt{\text{HCO}_3}}{\text{Ca} + \text{Mg} + \text{Na}} \times 100. \tag{3}$$

The permeability index value varied from 33.5 to 121. The values plotted are shown in Fig. 25. The index is classified as soils of low, medium, and high permeability.

Stuyfzand chloride classification

The quality of groundwater can be acquired following the procedure given by Stuyfzand (1989). Based on this classification, the water quality can be classified into eight

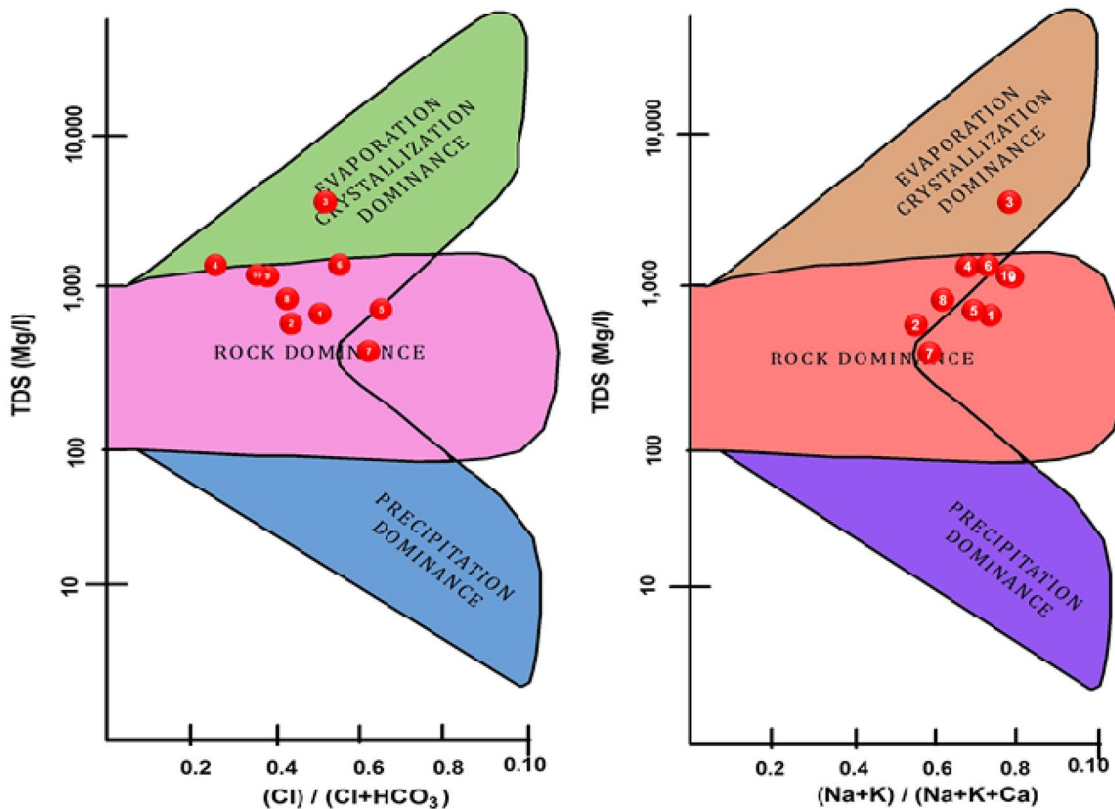


Fig. 24 Gibbs's diagram of the study area

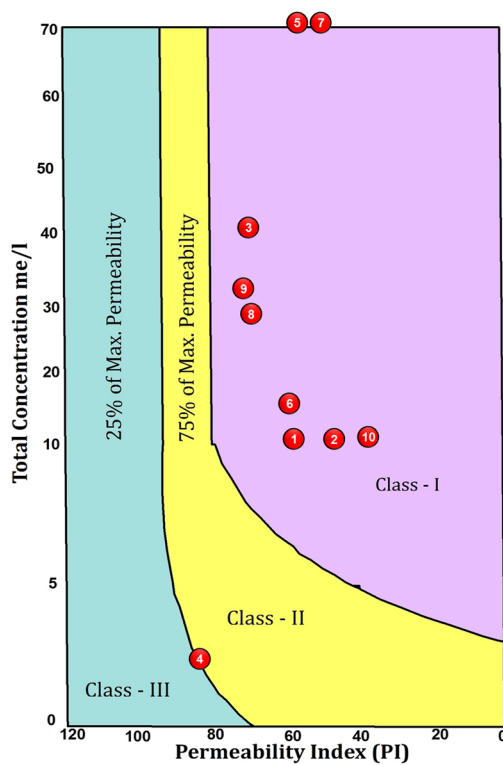


Fig. 25 Doneen diagram

Table 4 Stuyfzand (1989) classification based on chloride

Chloride type	Cl mg/l	
Extreme fresh	<0.141	Nil
Very fresh	0.141–0.846	Nil
Fresh	0.846–4.231	1
Fresh–Brackish	4.231–8.462	Nil
Brackish	8.462–28.206	3
Brackish–Salt	28.206–282.064	6
Salt	282.064–564.127	Nil
Hyper-saline	> 564.127	Nil

main types: extreme fresh, very fresh, fresh, fresh brackish, brackish, brackish salt, salt, and hypersaline. The chloride concentration study area is classified and given in the table below (Table 4).

The present classification shows that about 10% of the samples have been identified with the fresh type based on chloride concentration. Further, brackish chloride types are observed with the variation of 30%, and 60% of samples are brackish salt. It is observed that it does not show the very low chloride type, salt type, and hypersaline category. In general, the degree of brackishness of water appears to be controlled by the differing hydrogeological situations. Munn (1936) has found that the black cotton soils contain

a considerable quantity of ingredients, while the chlorides being more soluble are transported down in solution to the groundwater.

Conclusion

The present study is to determine the groundwater quality and quantity of Chidambaram taluk, Cuddalore district. The lithological variations and potential groundwater zones are the main factors in determining the results of our work.

- From the obtained spatial and vertical electrical distribution, 30% of the study area HKH type curve and other was submissive with a lower percentage. The iso-resistivity spatial plot reveals that the northern part of the study area shows saline intrusion.
- The Geophysical data show that the VES-4, -8, and -10 have been observed in high saline water zones due to estuary impact.
- The higher resistivity value obtained at the top layer and shallow depths in certain areas are mainly due to dry loosened sand at the top layer, alluvium, and sandy clay formations. The low resistivity value obtained indicates the presence of wet clay and clayey sand formations. Abnormal high resistivity in specific locations could be due to alluvial deposits saturated with the groundwater of low ionic strength could be the significant factor for high resistivity in the study area.
- The hydrogeochemical study reveals that most samples come under the permissible groundwater limit for WHO (2011). The TDS analysis confirms that 40% of the study area falls under the same saline category. However, in geochemical studies, most of the samples are in saline water.
- In the Piper plot, only one sample falls in subfield 1 representing high Ca + Mg and SO₄ + Cl. All other samples fall in 2 subfields representing high Ca + Mg and SO₄ + Cl, water contaminant with Gypsum, Static and Disco-ordinated regimes and Ca + Mg, SO₄ + Cl and HCO₃ + CO₃. The gypsum contamination may be due to calcium leaching or capillary movement of groundwater.
- According to Gibb’s plot, the majority of the samples falls under the evaporation field. The index is classified as soils of low, medium, and high permeability.
- The USSL diagram can be done by plotting the known values of SAR and specific water conductance to determine the suitable water for irrigation.
- Chloride classification observed that it does not show the very low chloride, salt, and hypersaline categories.

The hydrochemical study reveals that most of the samples are suitable for drinking. From observing geophysical and

geochemical studies, the study area is suitable for agricultural activity and unsuitable for potable drinking water.

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