

Hydrogeochemical analysis and evaluation of groundwater quality in the Gadilam river basin, Tamil Nadu, India

M V PRASANNA^{1,*}, S CHIDAMBARAM², A SHAHUL HAMEED³ and K SRINIVASAMOORTHY²

¹*School of Engineering and Science, Department of Applied Geology, Curtin University, Sarawak Campus, CDT 250, 98009 Miri, Sarawak, Malaysia.*

²*Department of Earth Sciences, Annamalai University, Annamalainagar 608 002, India.*

³*Centre for Water Resources Development and Management, Kozhikode, Kerala, India.*

**e-mail: geoprasanna@rediffmail.com*

Water samples were collected from different formations of Gadilam river basin and analyzed to assess the major ion chemistry and suitability of water for domestic and drinking purposes. Chemical parameters of groundwater such as pH, electrical conductivity (EC), total dissolved solids (TDS), Sodium (Na^+), Potassium (K^+), Calcium (Ca^+), Magnesium (Mg^+), Bicarbonate (HCO_3^-), Sulphate (SO_4^-), Phosphate (PO_4^-) and Silica (H_4SiO_4) were determined. The geochemical study of the aquatic systems of the Gadilam river basin show that the groundwater is near-acidic to alkaline and mostly oxidizing in nature. Higher concentration of Sodium and Chloride indicates leaching of secondary salts and anthropogenic impact by industry and salt water intrusion. Spatial distribution of EC indicates anthropogenic impact in the downstream side of the basin. The concentration levels of trace metals such as Iron (Fe), Lead (Pb), Nickel (Ni), Bromide (Br), Iodide (I) and Aluminium (Al) have been compared with the world standard. Interpretation of data shows that some trace metals such as Al, Ni and Pb exceed the acceptable limit of world standard. Geo-physical study was carried out to identify the weathered zone in the hard rock and contaminated zone by anthropogenic impact in the downstream of river Gadilam. A few of the groundwater samples in the study area were found to be unsuitable for domestic and drinking purposes.

1. Introduction

Geochemical processes occurring within the groundwater and reactions with aquifer minerals have a profound effect on water quality. Hydrogeochemical composition of groundwater can also be indicative of its origin and history of the passage through underground materials with which water has been in contact. Groundwater contains dissolved minerals from the soil layers through which it passes. It may also contain some harmful contaminants through the process of seepage from the surface water and biological activities. On the other hand, the surface water contains a lot of organic matter,

mineral nutrients and other contaminants brought by run-off from agriculture fields, fertilizers, pesticides, soil particles, waste chemicals from industries and sewage of cities and rural areas. The water bodies are continuously subjected to a dynamic state of change with respect to lithological characteristics and geo-climatic conditions. This dynamic balance in the aquatic system is upset by human activities, resulting in pollution.

Trace element studies of groundwater have attracted researchers for a variety of reasons; their significance related to public health problems, their need in relation to plant growth and the mechanism of metal transport in aqueous environment. Trace

Keywords. Groundwater; major ions; hydrogeochemistry; trace metals; resistivity.

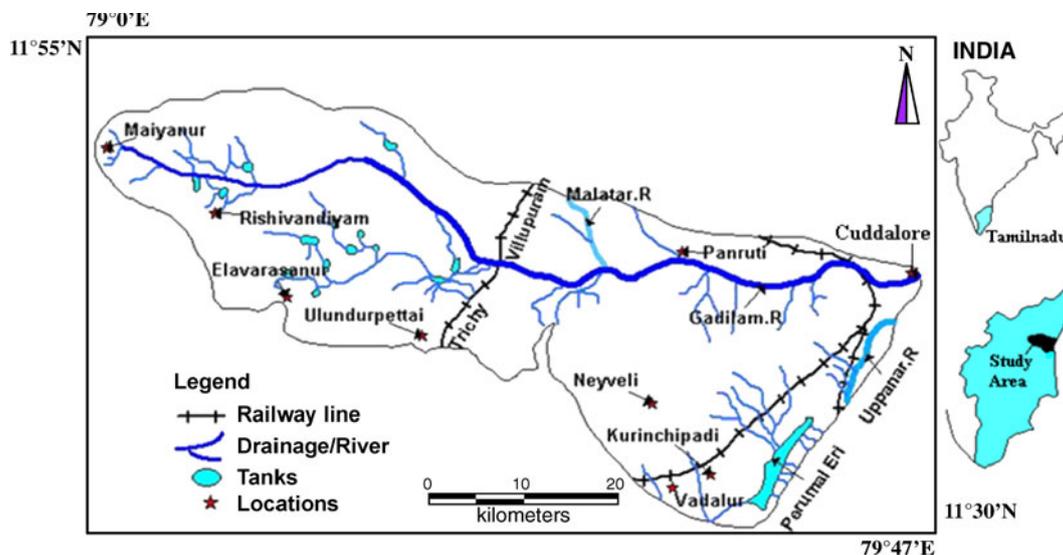


Figure 1. Location map of the study area.

elements in groundwater are defined as chemical elements dissolved in water in minute quantities, always or almost always in concentration of less than 1 mg of trace element in one liter of water (USGS 1993). The study of quantity of water alone is not sufficient to solve the water management problems because its uses for various purposes depend on its quality. Hence, the hydrogeochemical character of groundwater and groundwater quality in different aquifers over space and time have proven to be important in solving the problems (Panigrahy *et al* 1996; Atwia *et al* 1997; Ballukraya and Ravi 1999; Ramappa and Suresh 2000). Similar studies were done by Lakshmanan *et al* (2003); Mondal and Singh (2004); Rabemanana *et al* (2005); Das Brijraj and Kaur (2007); Singh Abhay *et al* (2007) and Sadashivaiah *et al* (2008).

Geophysical resistivity surveys are regularly used for studies related to groundwater investigations. Resistivity profiling delineates the lateral changes in resistivity of the formation that can be correlated with steeply dipping interfaces between two geological formations in the subsurface. Resistivity sounding determines the thickness and resistivity of different horizontal or low dipping subsurface layers, including the aquifer zone (Choudhury and Saha 2004). The electrical resistivity method is widely used in groundwater exploration studies (Todd 1959) because it is the least expensive of all the geophysical methods requiring no specially trained technicians to operate the instrument. Water barren formations can be identified based on the contrast in electrical resistivity (Zohdy *et al* 1974). Characterization of groundwater flow regime by fracture network was carried out with the help of geophysical methods by Deevashish Kumar (2002). Balaram Das *et al*

(2007) have highlighted the utility of the electrical resistivity method along with chemical data for successful delineation of contaminated/polluted groundwater zones in part of Birbhum district, West Bengal.

Earlier work carried out in the lower sub-basin of river Gadilam consists of sedimentary terrain and coastal alluvium to understand the geochemical processes using major ions and stable isotope (Prasanna *et al* 2008). There has been limited attempt to study the quality of groundwater using trace metals and geophysical data. Hence, the main objective of this study was to assess the utility of geochemical data including trace metals and geophysical data for delineating the areas suitable for groundwater development in the entire basin (including hard rock and sedimentary formation), for four different seasons.

2. Study area

Gadilam river basin is located in parts of Cuddalore and Villupuram districts of Tamil Nadu, India. It lies between 79°0'E to 79°47'E longitudes and 11°30'N to 11°55'N latitudes (figure 1). It occurs within the Survey of India toposheets of 58M/1, 2, 5, 6, 9, 13, 10 and 14, covering a total area of about 1394 km². The Gadilam river basin is bounded by Ponnaiyar river basin in the north and the Vellar river basin in the south. The total length of the river is about 112 km with a catchment area of about 900 km². The important large scale groundwater extraction sites in this basin are Neyveli Lignite Corporation (NLC) and the boreholes of New Veeranam Scheme (NVS). The open cast mining of

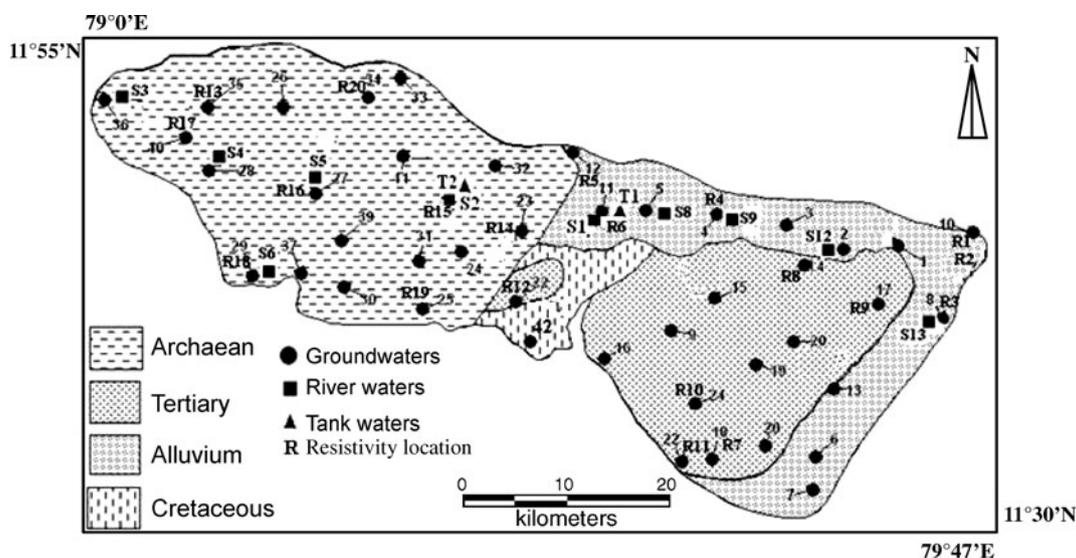


Figure 2. Geology, water sample and resistivity sounding location map.

Lignite requires heavy pumping at the rate of $9000\text{--}10,000\text{ m}^3\text{h}^{-1}$ as water table condition has to be brought down below the level of mining (Anandhan 2005). Water from the Veeranam Lake is supplied through transmission line to Chennai city. To augment the supply during summer season, 48 deep bore wells were drilled and operations are done alternatively to pump the groundwater from deep aquifer and the pumped water is supplied through the New Veeranam Scheme (NVS) pipelines. Apart from these large scale extraction features, an industrial estate SIPCOT (Small Industries Promotion Corporation of Tamil Nadu) with groups of industries, which generate multi-facet chemicals and raw materials are distributed along the downstream of the river Gadilam, near the coast at Cuddalore (Prasanna 2008). The average annual rainfall of the Cuddalore district is 1902 mm and that of Villupuram district is around 1384 mm (India Meteorological Department, 2004–2006). The water level varies from 3.10 to 48.85 bgl (below ground level) with an average of 12.37 bgl (Tamil Nadu Water and Drainage Board, 2005–2006). Gadilam river originates in the hard rock region and passes through the sedimentary terrain. Rock types of different stratigraphic units are exposed in the basin (figure 2). The charnockites, leptinites, schists and gneiss of Archaeane complex constitute the upstream area. The younger Cretaceous and Tertiary formations are found in midstream and the recent Alluvium is found in the downstream of the Gadilam basin. Lithologically, hard rocks characterize the western part of the basin with the dominance of pediments. The northern part is essentially covered by flood plain and recent Alluvium.

3. Methodology

3.1 Major ions

The water samples were collected (figure 2) during March 2005, July 2005, January 2006 and November 2006 to broadly cover seasonal variation. A total of 178 water samples were collected from bore wells (156), river (14) and tank (8) in four different seasons (November 2006 represents NE monsoon; January 2006 represents post-monsoon; March 2005 represents Summer; July 2005 represents SW monsoon). In summer (SUM) and southwest monsoon (SWM), 12 groundwater samples were collected from Alluvium, 10 groundwater samples from Tertiary, 14 groundwater samples from Archaeane and two surface water samples from tank. In northeast monsoon (NEM) and post-monsoon (POM), 12 groundwater samples were collected from Alluvium, 12 groundwater samples from Tertiary, 17 groundwater samples from Archaeane, one groundwater sample from Cretaceous, seven surface water samples from river and two surface water samples from tank. Cretaceous formation covers less than 5% of the study area. In certain locations during summer and southwest monsoon periods the wells were dry. River Gadilam is an ephemeral river, as the water flows only during NEM and POM periods.

Water samples of one litre were collected in polyethylene bottles, four times a year. The bottles were sealed, sent to the laboratory and stored properly at 4°C before analysis.

The samples collected were analyzed for major cations like, Ca and Mg by Titrimetry, Na and K by Flame photometer (CL 378); anions, Cl and

HCO₃ by Titrimetry, SO₄, PO₄ and H₄SiO₄ by Spectrophotometer (SL 171 minispec). The EC and pH were determined in the field using electrode (Eutech). The TDS was also measured *in situ* by TDS portable electrode model TDS Testr11+ (multi-range). The analyses were done by adopting standard procedures (APHA 1998). The analytical precision for the measurements of cations and anions was determined by calculating the ionic balance error that varies by about 5–10% (Domenico and Schwartz 1998; Srinivasamoorthy *et al* 2008).

3.2 Trace metals

Twenty-nine groundwater and seven surface water (river water) samples were analysed during the post-monsoon period (figure 2). Before the estimation of dissolved metals, the samples were filtered through 0.45 µm membrane filter paper using vacuum pump. The samples were then spiked with the standard solution of the metals chosen for analysis. This standard addition method was adopted to achieve greater accuracy in the analysis of trace metals such as Fe, Pb, Ni, Br, I and Al. Fe was analyzed in Atomic Adsorption Spectrophotometer (AAS), (Model – SL 176, Elico Limited, Hyderabad, India) with a spectral range of 185–930 nm and ±0.5 nm accuracy. Pb, Ni and Al were analysed in AAS (Model – Shimadzu-AA-6800), Br and I were analysed in ion electrodes (Model – CONSORT).

3.3 Geophysical survey

Resistivity sounding was carried out to cover major litho units in the study area (figure 2). The resistivity survey was done with the help of SSR-MP-AT resistivity meter (IGIS, Hyderabad, India), adopting Schlumberger electrode configuration method. The apparent resistivity of the sub-surface formation was determined and the results were manually plotted by curve matching method.

4. Results and discussion

4.1 Geochemical investigation

4.1.1 Water chemistry

The average, mean, and standard deviation values for chemical composition of the groundwater samples collected during four different seasons, viz., northeast monsoon (NEM), post-monsoon (POM), summer (SUM) and southwest monsoon (SWM) in different formations are given in tables 1 and 2. The total cations (TZ⁺) and total anions (TZ⁻) balance (Freeze and Cherry 1979) was considered to show

the charge balance error percentage. The error percentage in the samples of the present study ranged between ±1% and ±10%. Occurrence of errors in chemical analysis of groundwater is also due to the reagents employed, limitations of the methods, the instruments used and the presence of impurities in distilled water, etc. The correlation coefficient between TZ⁺ and TZ⁻ is around 0.6 to 0.9. The TDS/EC ratio was in the range of 0.5–0.9. The role played by other ions than those considered in the study for the cations and anions charge balance is less significant. The groundwater in the study area was generally odourless and colourless in most of the places.

In Alluvium formation, Cl was the dominant anion followed by HCO₃, SO₄ and PO₄ during SUM, NEM and POM seasons. But in SWM, HCO₃ was the dominant anion followed by Cl, SO₄ and PO₄. In POM, Na was the dominant cation followed by Ca, K and Mg. But in SUM, SWM and NEM, Na was the dominant cation followed by Ca, Mg and K.

In Tertiary formation, Cl was the dominant anion followed by SO₄, HCO₃ and PO₄ during SUM. In POM, Cl was the dominant anion followed by HCO₃, SO₄ and PO₄. In SWM, HCO₃ was the dominant anion followed by SO₄, Cl and PO₄. In NEM, HCO₃ was the dominant anion followed by Cl, SO₄ and PO₄. In SUM, NEM and POM, Na was the dominant cation followed by Ca, K and Mg. But in SWM, Na was the dominant cation followed by Ca, Mg and K.

In Archaean formation, HCO₃ was the dominant anion followed by Cl, SO₄ and PO₄ during SUM, SWM and NEM seasons. But in POM, Cl was the dominant anion followed by HCO₃, SO₄ and PO₄. In SUM, SWM and POM, Na was the dominant cation followed by Ca, K and Mg. But in NEM, Na was the dominant cation followed by Ca, Mg and K.

In tank water, Cl was the dominant anion followed by HCO₃, SO₄ and PO₄ irrespective of the seasons. Na was the dominant cation followed by Ca, K and Mg irrespective of the seasons. In river water, HCO₃ was the dominant anion followed by Cl, SO₄ and PO₄ irrespective of the seasons. In NEM, Na was the dominant cation followed by Ca, Mg and K. But in POM, Na was the dominant cation followed by Ca, K and Mg.

The Durov diagram was used to infer hydro-geochemical facies. Chemical data of representative samples from the study area are presented by plotting them on Durov plot for all the seasons. In NEM and POM, the samples of Alluvium formation (figure 3) were concentrated in Na–Cl type indicating saline nature in the groundwater. In SUM and SWM, cluster of samples fell in Na–Cl

Table 1. Maximum, minimum, average and standard deviation for chemical composition of groundwater (in mg/l) except EC and pH (EC in $\mu\text{s}/\text{cm}$).

	Summer				Southwest Monsoon				Northeast Monsoon				Monsoon				
	Max	Min	Avg	Std	Max	Min	Avg	Std	Max	Min	Avg	Std	Max	Min	Avg	Std	F.Avg
	Aluminium																
pH	7.30	6.60	6.99	0.21	8.65	6.40	7.29	0.65	7.83	6.01	7.17	0.61	9.20	6.83	8.15	0.91	7.40
EC	6337.31	420.18	1424.31	1605.68	6278.93	387.00	1543.82	1538.59	6728.00	468.00	1829.58	1645.38	6005.00	345.00	1652.59	1621.56	1612.58
Cl	2384.01	62.03	347.77	646.29	1994.06	26.59	357.67	526.91	2782.82	96.42	498.17	734.87	2375.15	51.00	393.60	639.42	399.30
HCO ₃	677.10	48.79	289.84	241.36	1293.20	91.50	397.77	334.67	634.39	54.30	270.75	151.37	1500.59	12.20	271.44	399.28	307.45
SO ₄	341.00	23.00	96.28	84.30	189.00	27.00	90.23	39.78	368.00	1.00	69.62	106.03	312.20	5.00	107.21	85.42	90.83
PO ₄	10.10	0.25	6.08	3.76	6.80	0.10	4.20	2.55	6.60	0.01	1.25	1.92	6.80	0.00	0.90	1.97	3.11
H ₄ SiO ₄	34.00	8.10	19.02	9.15	50.00	1.60	30.06	14.15	147.50	8.80	58.60	36.30	160.00	27.00	73.92	40.62	45.40
Ca	261.33	11.00	64.11	69.41	264.00	16.00	103.14	76.12	352.00	6.00	64.33	93.63	168.00	10.00	50.16	41.09	70.44
Mg	91.20	1.00	14.47	25.00	62.39	0.00	17.09	17.51	134.40	1.00	27.51	35.31	124.80	4.79	19.50	33.78	19.64
Na	1210.03	81.00	279.94	310.56	1400.20	49.30	267.35	365.38	1091.95	74.71	317.34	274.98	1149.43	52.00	293.71	307.29	289.59
K	42.00	3.00	11.71	11.11	48.71	3.00	13.61	12.21	36.40	1.00	15.14	10.46	108.40	1.00	25.21	32.74	16.42
TDS	4436.44	267.81	994.45	1122.35	4395.25	271.00	1080.07	1077.38	4710.00	328.00	1291.44	1149.91	4204.08	242.00	1157.33	1134.97	1130.82
Tertiary																	
pH	7.30	6.10	6.69	0.35	8.52	6.00	7.36	0.87	7.50	5.56	6.68	0.57	8.60	6.21	7.76	0.72	7.12
EC	867.00	250.00	492.93	214.50	1280.00	197.00	543.72	330.01	822.00	165.00	448.75	220.10	981.00	286.21	476.58	198.16	490.49
Cl	241.05	26.59	84.19	64.26	239.29	8.86	89.69	73.97	194.97	8.00	81.67	52.13	255.23	44.00	95.32	61.99	87.71
HCO ₃	274.50	18.30	72.51	74.60	323.30	36.60	100.65	81.60	195.19	12.20	84.36	55.25	195.10	24.40	72.52	46.72	82.51
SO ₄	171.00	28.00	89.10	52.89	247.00	18.00	98.60	66.33	196.00	0.01	50.29	63.45	141.00	7.00	46.89	38.38	71.22
PO ₄	10.10	0.07	3.92	4.69	6.40	0.15	2.36	2.40	7.45	0.09	1.83	2.57	1.40	0.00	0.30	0.42	2.10
H ₄ SiO ₄	69.00	18.10	31.62	17.51	54.00	7.30	27.16	15.29	72.40	8.00	39.37	18.93	120.00	18.00	68.38	27.02	41.63
Ca	55.99	8.00	24.90	14.18	88.00	10.00	36.00	27.36	40.00	6.00	23.16	11.83	34.00	10.00	22.08	7.78	26.54
Mg	9.00	0.00	3.40	3.13	33.60	1.00	8.48	10.03	14.40	0.00	6.51	4.35	14.40	1.00	6.40	4.20	6.20
Na	195.40	45.98	91.53	51.13	272.00	1.80	82.49	83.15	191.00	6.00	69.36	61.11	183.91	22.99	72.30	45.89	78.92
K	14.00	0.00	4.60	4.70	21.90	1.00	7.01	6.71	14.60	1.00	7.68	3.89	23.90	1.00	7.41	5.71	6.68
TDS	646.27	175.00	349.06	158.05	897.22	138.76	380.88	231.05	633.30	122.60	319.83	162.71	687.00	200.35	329.56	140.48	344.83
Archaeon																	
pH	8.10	6.73	7.14	0.33	8.00	6.80	7.14	0.32	8.60	6.78	7.46	0.41	9.20	8.10	8.52	0.32	7.56
EC	2610.32	657.13	1500.32	580.51	2725.89	618.29	1498.53	642.83	2810.00	617.00	1364.24	591.00	2574.00	490.37	1129.36	583.25	1373.11
Cl	771.03	59.03	342.01	225.96	771.03	53.17	361.46	248.08	638.10	35.44	233.55	152.64	620.37	35.45	229.38	168.76	291.60
HCO ₃	524.60	284.50	425.76	90.61	579.50	274.50	416.11	92.70	414.79	183.00	278.44	84.44	268.39	109.80	185.15	48.27	326.36
SO ₄	124.60	43.00	70.97	21.56	158.20	53.40	87.03	28.66	336.22	1.50	67.27	98.55	288.18	4.00	116.98	82.67	85.56
PO ₄	15.00	4.80	8.76	2.75	6.40	3.80	5.36	0.81	3.60	0.20	0.75	1.01	1.60	0.00	0.18	0.40	3.76
H ₄ SiO ₄	63.00	5.80	27.10	21.81	53.00	21.20	39.63	10.19	94.00	6.60	50.08	28.69	120.00	22.00	72.82	28.03	47.41
Ca	225.99	35.99	108.14	50.11	240.00	55.99	143.00	61.72	111.99	23.99	56.47	27.78	96.00	18.00	49.05	24.64	89.16
Mg	40.80	4.79	20.50	13.82	52.80	4.79	24.25	18.19	33.59	4.80	16.35	7.99	24.00	0.00	12.98	6.95	18.52
Na	405.00	55.20	231.60	90.11	491.00	50.30	188.58	122.44	581.20	69.80	192.60	129.67	551.72	54.90	188.04	128.68	200.21
K	208.00	1.00	56.11	66.48	115.30	3.30	31.24	34.95	17.40	9.40	10.12	1.93	78.00	6.60	14.95	17.78	28.11
TDS	1827.23	459.99	1050.22	406.35	1908.12	482.80	1048.97	449.98	1967.00	436.00	972.94	403.76	1802.47	343.26	795.56	409.11	966.92

Max: maximum, Min: minimum, Avg: Average, Std: Standard deviation, F.Avg: Final average.

and mixed Ca–Na–HCO₃, Ca–Mg–Cl facies. In Tertiary formation (figure 3), SUM and SWM seasons were well represented in the field of NaCl and mixed Ca–Na–HCO₃, indicating the dominance of alkaline and strong acids. In NEM and POM, cluster of samples fell in Na–Cl type and some samples also represented mixed Ca–Mg–Cl and Ca–Cl facies.

In Archaean (figure 3), most of the plots fell in the field of NaCl with less representation in mixed Ca–Na–HCO₃ and mixed Ca–Mg–Cl. In NEM and POM, alkaline and strong acid were predominant, indicating the intensive weathering action of silicate bearing minerals and secondary leaching of ions (Srinivasamoorthy 2004). In SUM and SWM, majority of samples fell in Na–Cl and mixed Ca–Mg–Cl with minor representation from mixed Ca–Na–HCO₃ and Ca–HCO₃ facies.

In Cretaceous formation (figure 3), NEM samples fell in Ca–HCO₃ facies indicating the dominance of alkali earth and weak acids. But in POM, the plot fell in Na–Cl facies indicating the predominance of alkaline and strong acid. In tank waters (figure 3), SUM and SWM samples fell in Na–Cl and mixed Ca–Mg–Cl facies. In NEM and POM, most of the samples fell in Na–Cl facies indicating the dilution of secondary salt precipitation. In river water (figure 3), cluster of samples during POM is noted in Na–Cl facies and NEM samples fell in mixed Ca–Na–HCO₃, Ca–HCO₃ and mixed Ca–Mg–Cl facies. In general, the plot shows that alkali (Na) exceeds alkaline earth (Ca and Mg) and strong acid Cl and SO₄ exceeds the weak acids (HCO₃) in all the litho units irrespective of season.

The attribute values of the specific locations were used to create a spatial data in order to obtain an overall behaviour of the electrical conductivity in the study area. The spatial data of electrical conductivity gives a general trend of the characteristics of the anions and cations present in water. This initially provides first-hand information about the geochemically active regimes (Srinivasa Rao *et al* 1997; Chidambaram 2000; Srinivasamoorthy 2004; Anandhan 2005). Spatial distribution of EC of samples was done for all four major seasons (figure 4). The study revealed that in SUM and SWM seasons, EC was higher in the regions covered by the Archaean formation in the upstream side and along the downstream side near the coastal areas. In NEM and POM seasons, higher concentration was observed in the upstream side along the lithological boundaries and near the coastal area. This indicates the leaching of secondary salts in the upstream side and anthropogenic activities in the downstream side.

Table 3 shows the range of ionic concentration in groundwater of the study area and prescribed

specifications of WHO (2004) and ISI (1995). The groundwater was generally colourless and odourless in all major litho units. Groundwater was near-acidic to alkaline (5.56 to 9.20) and mostly oxidizing. Parameters exceeding permissible limits were identified in most of the locations indicating higher ionic concentration. Na, Cl and K exceeded the permissible limit in all the litho units. Ca, Mg, HCO₃ and SO₄ also exceeded the permissible limit of WHO (2004) standard except in Tertiary formation. But HCO₃ was within the permissible limit of ISI (1995) standard except in Alluvium formation indicating the precipitation of CO₃ as scales in pipelines (Rengarajan and Balasubramanian 1990). Few of the groundwater samples in the study area were found to be unsuitable for domestic and drinking purposes.

4.1.2 Trace metals pollution

To understand the variation of trace metals such as Fe, Pb, Ni, Br, I and Al in the study area after the monsoon period, samples were collected and analysed (figure 5). Iron is an essential element in the metabolism of animals and plants. If it is present in water in excessive amounts, it forms red oxyhydroxide precipitates that stain laundry and plumbing fixtures and, therefore, is an objectionable impurity in domestic and industrial water supplies. For this reason, iron determinations are commonly included in chemical analyses of water. The recommended upper limit for iron in public water supplies is 0.3 mg/l (NAS–NAE 1972).

The Fe plays a biogeochemical role in the life cycle of plants and animals. Its presence in groundwater with high concentration is unsuitable (Ballukaraya and Ravi 1999). In Alluvium formation, Fe varied from 0.09 to 0.41 mg/l with an average of 0.17 mg/l. Higher concentration of Fe in groundwater was derived from nearby laterites capping in Cuddalore and Panruti regions of the basin (Prasanna 2008). In Tertiary formation, Fe varied from 0.02 to 0.29 mg/l with an average of 0.10 mg/l. Higher concentration of Fe in groundwater may be attributed to the weathering of marcasite and iron oxide coating in sediments which might have contributed this ion (Anandhan 2005). In Archaean formation, Fe varied from 0.03 to 0.19 mg/l with an average of 0.11 mg/l. The Fe in all of the surface water bodies (river water) exceeds the average levels in the world's rivers (Taylor and McLennan 1985) ranging from 0.11 to 0.41 mg/l with an average of 0.21 mg/l. Generally higher concentration was observed in Alluvium followed by Tertiary and Archaean formations.

Aluminium is the most abundant metallic element and constitutes about 8% of the Earth's

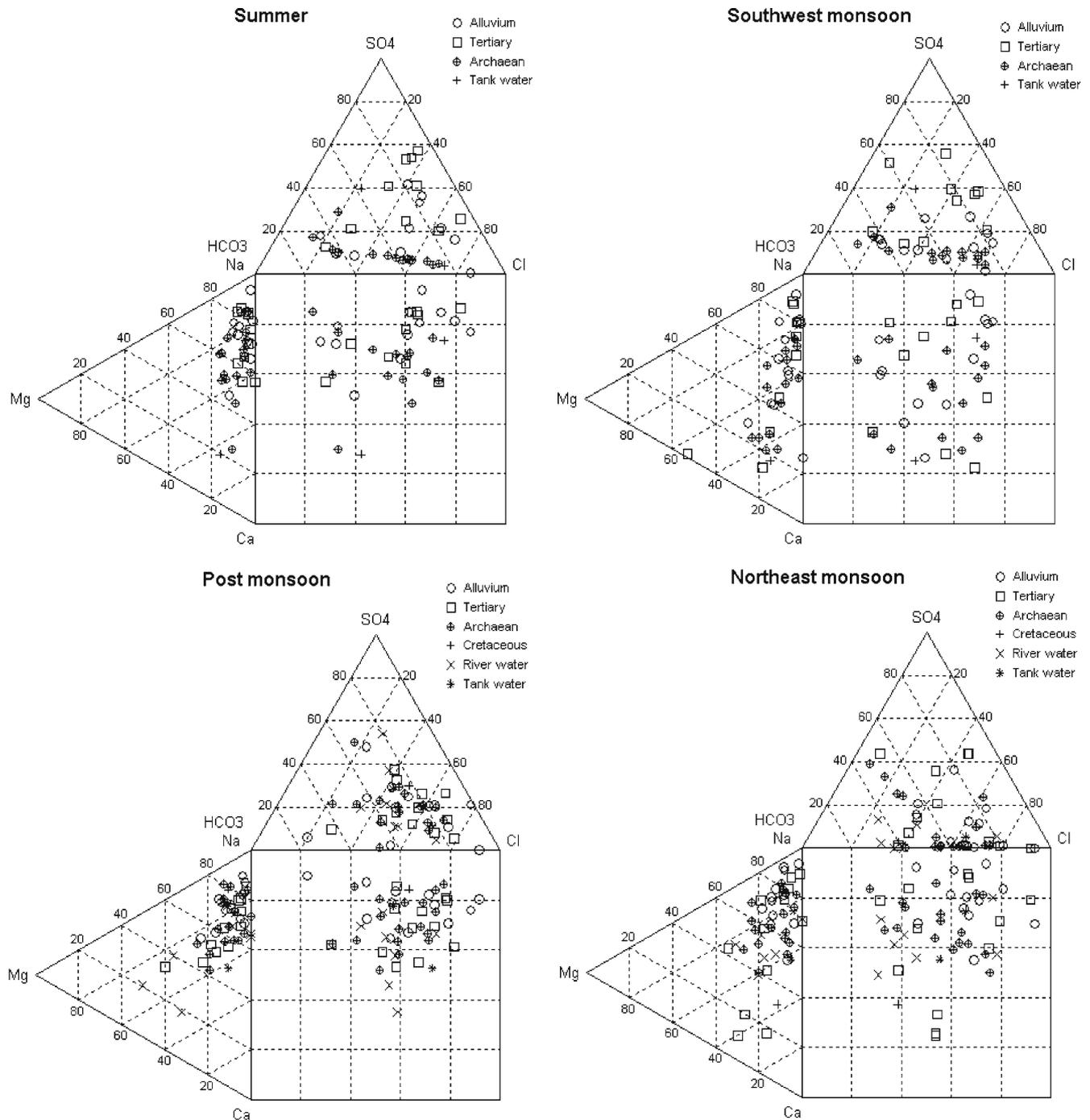


Figure 3. Durov diagram for water classification.

crust. Aluminium salts are widely used in water treatment as coagulants to reduce organic matter, colour, turbidity and micro-organism levels. Aluminium occurs in substantial amounts in many silicate igneous rock minerals such as the feldspars, the feldspathoids, the micas and many amphiboles.

In Alluvium formation, Al varied from 0.011 to 2.800 mg/l with an average of 1.054 mg/l, whereas in Tertiary formation, it varied from 0.004 to 2.300 mg/l with an average of 0.917 mg/l.

In Archaean formation, Al varied from 0.032 to 2.740 mg/l with an average 0.741 mg/l. In surface water, it varied from 0.097 to 2.380 mg/l with an average of 0.723 mg/l. Generally higher concentration was observed in Archaean followed by Alluvium and Tertiary formations.

The concentration of nickel in drinking-water is normally less than 0.02 mg/l, although nickel released from taps and fittings may contribute up to 1 mg/l. In special cases of release from natural

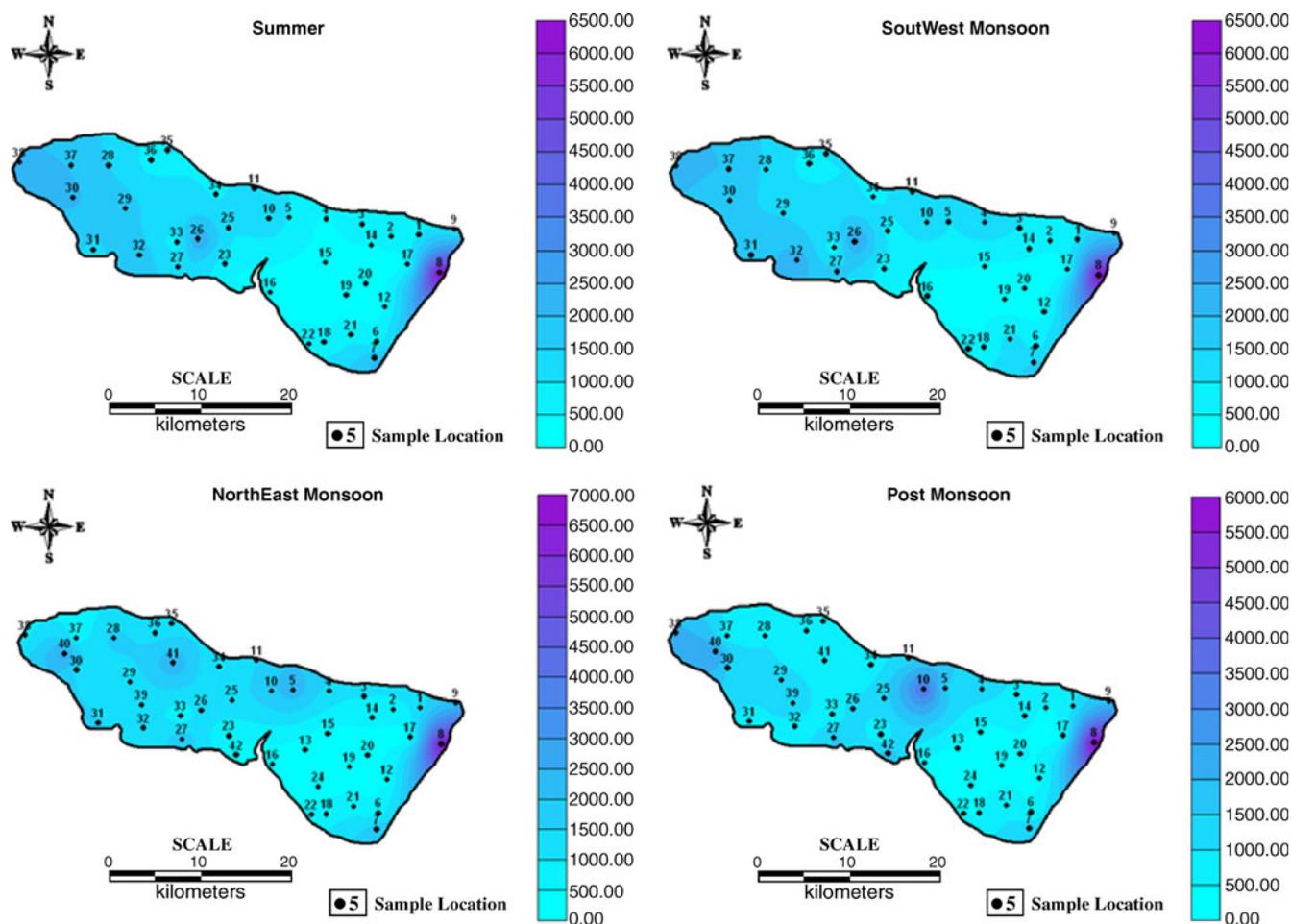


Figure 4. Spatial distribution of EC (in $\mu\text{s}/\text{cm}$).

or industrial nickel deposits to the ground, the nickel concentrations in drinking-water may be higher (WHO 2004). In Alluvium formation, Ni varied from 0.001 to 0.742 mg/l with an average of 0.130 mg/l. In Tertiary formation, Ni varied from 0.015 to 0.134 mg/l with an average of 0.089 mg/l, whereas in Archaean formation, it varied from 0.005 to 0.163 mg/l with an average of 0.072 mg/l. The Ni in all of the surface water bodies (river water) exceeds the average levels in the world's rivers (Taylor and McLennan 1985). It varied from 0.005 to 0.134 mg/l with an average of 0.066 mg/l. Generally higher concentration was observed in Alluvium followed by Archaean and Tertiary formations.

A study by Schock (1980) of the factors that might affect the corrosiveness of water towards lead pipe indicated that maintaining a tap-water lead concentration below 50 $\mu\text{g}/\text{L}$ might be possible by careful control of pH and alkalinity in water supplies. The guideline value for Pb is 0.01 mg/l (WHO 2003). In Alluvium formation, Pb varied from 0.370 to 8.519 mg/l with an average

of 3.128 mg/l, whereas in Tertiary formation, it varied from 0.001 to 5.556 mg/l with an average of 2.531 mg/l. In Archaean formation, Pb varied from 0.370 to 6.667 mg/l with an average of 3.229 mg/l. In surface water, it varied from 0.001 to 4.444 mg/l with an average of 2.328 mg/l. Generally higher concentration was observed in Alluvium followed by Archaean and Tertiary formations.

Bromine is similar in chemical behaviour to chlorine but in much less concentration. Bromine in natural water is always present as the bromide ion Br. The concentration present in sea water is 65 mg/l, an amount sufficient to make bromide an important constituent. Bromide concentrations in rainwater and snow range from about 5 to >150 $\mu\text{g}/\text{L}$, and a wider range is given for river water by Fuge (1973). Bromine is extracted commercially from sea water and brines. The presence of small amounts of the element in fresh water is not known to have any ecologic significance. Bromide is generally the most conservative constituent in waters, i.e., it is less affected by chemical reactions such as mineral precipitation or adsorption.

Table 3. Comparison of chemical composition of water with WHO (2004) and ISI (1995) in mg/l (except EC in $\mu\text{s}/\text{cm}$ and pH).

Parameters	Alluvium	Tertiary	Archaean	WHO (2004)	ISI (1995)
EC	345–6728	165–1280	490.37–2810	1400*	–
pH	6.01–9.20	5.56–8.60	6.73–9.20	6.5–8.5	6.5–9.2
TDS	242–4710	122.60–897.22	343.26–1967	500–1000	1500
Ca	6–352	6–88.00	18–240	100	200
Mg	1–134	1–33.60	4.79–52.80	50	100
Na	49.30–1400.20	1.80–272	50.30–581.20	200	–
K	1–108.40	1–23.90	1–208	20	–
HCO ₃	12.20–1500.59	12.20–323.30	109.80–579.50	125–350	600
SO ₄	1–368	0.01–247	1.50–336.22	250	400
Cl	26.59–2782.82	8–255.23	35.44–771.03	250	1000

*WHO (1996).

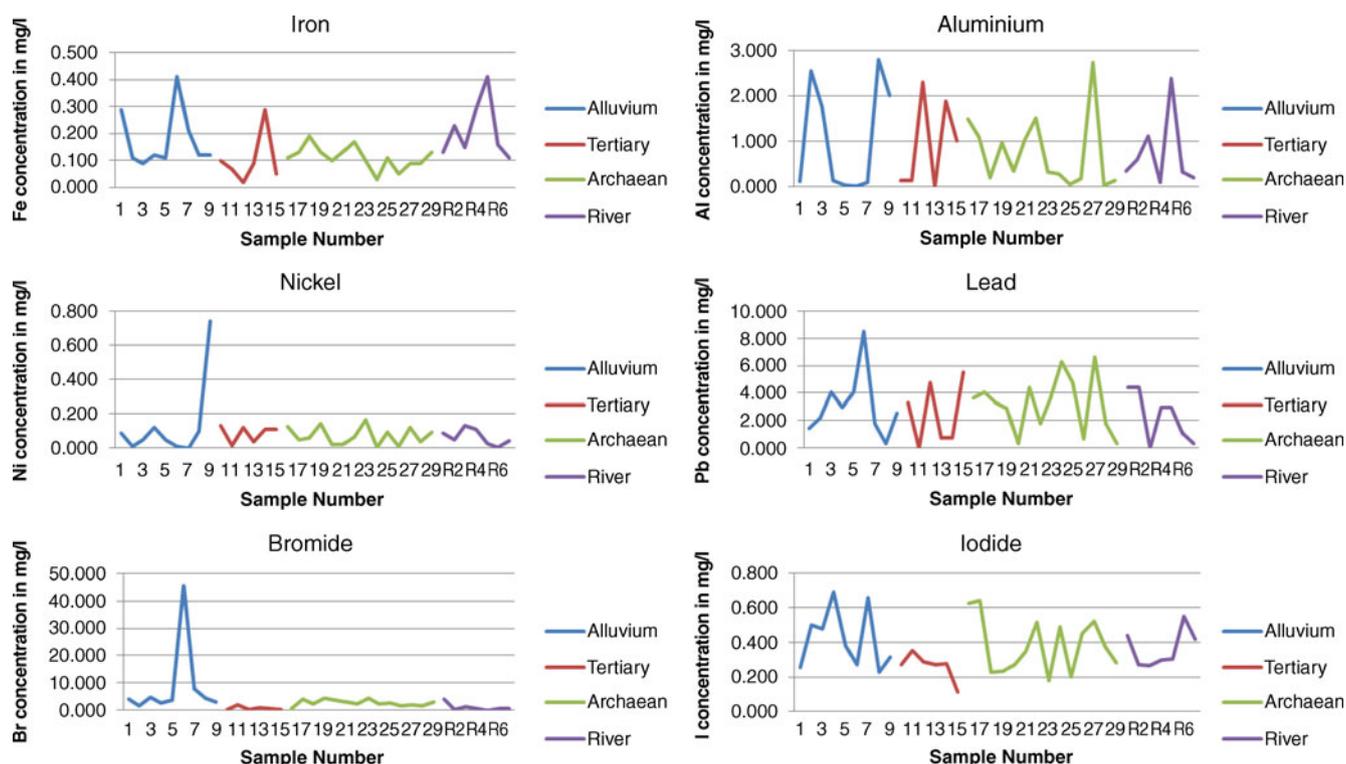


Figure 5. Trace metals concentrations in the study area.

In Alluvium formation, Br varied from 1.630 to 45.600 mg/l with an average of 8.606 mg/l. Samples showed higher concentration of Br along the coastal region. This may be attributed to the possibility of sea water intrusion or pollution from local industry. In Tertiary formation, it varied from 0.204 to 2.020 mg/l with an average of 0.761 mg/l. In Archaean formation, it varied from 0.693 to 4.580 mg/l with an average of 2.856 mg/l. In surface water, it varied from 0.118 to 4.000 mg/l with an average of 1.184 mg/l. Generally higher concentration was observed in Alluvium followed by Archaean and Tertiary formations.

Although Iodine (I) is not a particularly abundant element, it is widely distributed. It is essen-

tial in the nutrition of animals, humans and its concentrations in natural water have received considerable attention. In Alluvium formation, I value varied from 0.23 to 0.69 mg/l with an average of 0.42 mg/l. In Tertiary formation, iodide value varied from 0.11 to 0.35 mg/l with an average of 0.26 mg/l, whereas in Archaean formation, it varied from 0.18 to 0.64 mg/l with an average of 0.38 mg/l. In surface water, I varied from 0.26 to 0.55 mg/l with an average of 0.36 mg/l. Generally, higher concentration was observed in Alluvium followed by Archaean and Tertiary formations.

The concentration levels of trace metals were compared against the WHO (1993) standard (table 4). Interpretation of trace metals data shows

Table 4. Comparison of trace element with WHO (1993) standard.

Parameters	WHO (1993) standard		Alluvium (mg/l)	Tertiary (mg/l)	Archaean (mg/l)	Surface water (mg/l)
	Minimum acceptable	Maximum acceptable				
Fe	0.3	1	0.090–0.410	0.020–0.290	0.030–0.190	0.110–0.410
Al	0.3	–	0.011–2.800	0.004–2.300	0.032–2.740	0.097–2.380
Ni	0.01	–	0.001–0.742	0.015–0.134	0.005–0.163	0.005–0.134
Pb	0.05	0.1	0.370–8.519	0.001–5.556	0.370–6.667	0.001–4.444
Br	–	–	1.630–45.600	0.204–2.020	0.693–4.580	0.118–4.000
I	–	–	0.230–0.693	0.111–0.353	0.180–0.644	0.267–0.552

Table 5. Resistivity and thickness of geoelectrical sections.

Sounding no	Lithology	Location	Resistivity (Ωm)				Thickness (Ωm)				Curve type
			Layer 1	Layer 2	Layer 3	Layer 4	Layer 1	Layer 2	Layer 3	Layer 4	
R1	Alluvium	Cuddalore (NT)	50.63	50.63	18.3	–	1.36	2.04	∞		Q
R2		Cuddalore (OT)	0.411	41.96	929.6	–	1.2	1.5	∞		A
R3		Karaikadu	2894	79.22	191.6	1.33	0.73	3.4	16.63	∞	HQ
R4		Panruti	17.44	4.589	4999	–	3.89	5.89	∞		H
R5		Arasur	36.54	456.2	43.68	0.1709	1.04	2.08	16.17	∞	K
R6		Veeraperumanallur	253.8	7.311	1.52	1.371	0.62	1.93	9.84	∞	Q
R7	Tertiary	Kurinchipadi	35.78	5.57	2.717	5.543	0.85	3.03	14.73	∞	H
R8		Naduveerapattu	32.09	2621	177.4	–	7.2	26.8	∞		K
R9		Ramapuram	7156	39.74	90.83	0.4023	0.55	13.42	21.92	∞	HQ
R10		Vadakuttu	159.3	5.26	9.16	3.97	0.72	2.79	40.18	∞	HQ
R11		Vadalur	0.2272	30.33	849.5	–	1.2	1.68	∞		A
R12		K. Kallakurichi	0.5159	0.1873	0.486	–	0.6711	19.52	∞		H
R13	Archaean	Ariyur	1.625	5.14	1928	–	0.85	9.83	∞		A
R14		Gadilam	0.0309	39.06	3.41	–	1.2	22.5	∞		K
R15		Kalamaruthur	0.247	29.96	0.105	–	1.02	9.78	∞		K
R16		K. Palayam	0.5249	817	848.3	–	1.2	10.52	∞		A
R17		Pasar	25.28	3.33	2952	–	0.86	5.12	∞		H
R18		Sembimadevi	9.77	0.9	126.6	–	0.88	1.3	∞		H
R19		Ulundurpettai	0.1145	11.11	17.52	–	1.2	1.33	∞		A
R20		Villivalam	2.84	41.61	1549	–	2.4	42.12	∞		A

that some trace metals such as Al, Ni and Pb exceeded the acceptable limit of WHO (1993) standard.

4.2 Geophysical investigation

The Vertical Electrical Sounding (VES) were carried to cover different lithologies, six soundings falls in Alluvium formation, six in Tertiary and eight in Archaean formation. The interpretation was done through the following procedures and 3–4 layers were identified in this region.

The geophysical survey was conducted and the curves were manually plotted and then checked with IPI2Win software and the root mean square (RMS) error was found to be less than $\pm 2\%$ (Prasanna 2008). Most of the values of manual matched curves and that of IPI2Win v.2.0 software were the same. Thickness of weathered zone estimation and depth of bedrock studies were carried out by using inverse slope and curve matching techniques in comparison to lithology data

and the curve matching was found to give fruitful results (Sankaranarayanan and Ramanujachary 1967). Curve matching technique is adopted here with the objective to delineate the thickness of the aquifer zones. The data analyzed by curve matching techniques and IPI2Win for 20 locations were compared. The layer parameters like apparent resistivity (ρ_a) and thickness (h) of different layers were derived. Minor deviations due to subsurface discrepancies and the error in the field data were corrected by smoothening the field curve for easier interpretation. More importance was given to thickness and resistivities of various layers in hydrogeochemical studies. The values obtained by the manual curve matching were used for further studies since the deviation was lesser. A maximum of four layers were identified in few regions, but major parts of the study area have predominantly three layers (table 5).

Interpreted master curves are mostly three-layered curves, namely A type followed by H, K

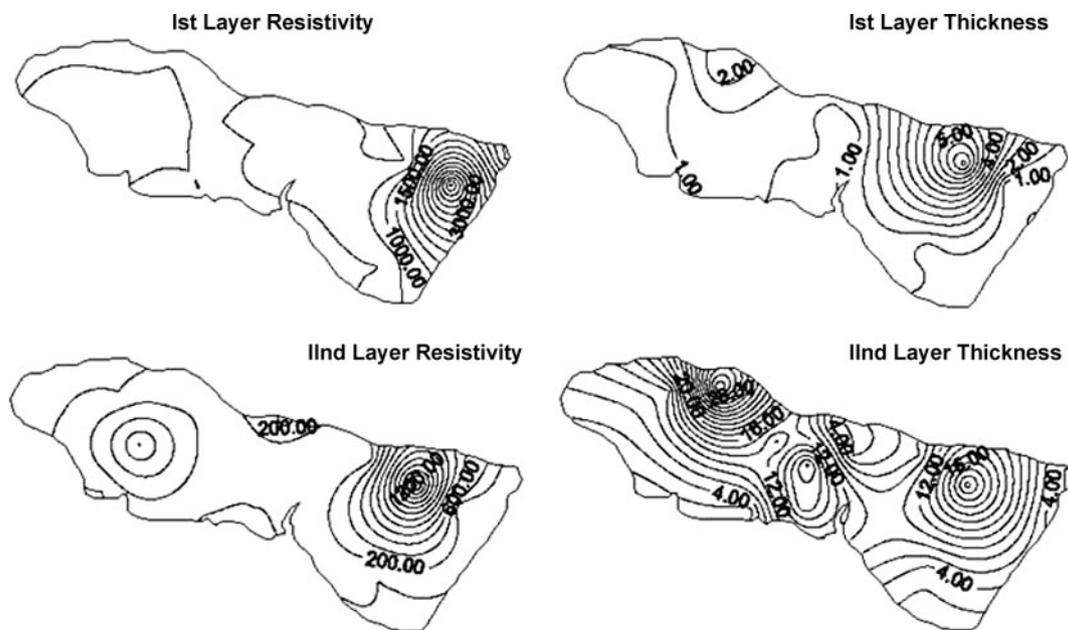


Figure 6. Spatial distribution of resistivity and thickness of first and second layers.

and Q types. VES location numbers 2, 11, 13, 16, 19 and 20 are of A type, whereas the VES no. 4, 7, 12, 17 and 18 are of H type. Four VES curves (5, 8, 14 and 15) are of K type, three belong to HQ combination type (3, 9 and 10) and two are of Q type (1 and 16). Generally, A type curve is dominant in Archaean terrain indicating gradually increased resistivity values ($\rho_1 > \rho_2 > \rho_3$). Minor representation of K and H type curves were also observed in this region indicating few weaker zones. In Tertiary formation, HQ and H are dominant curve types indicating that a low resistivity layer is sandwiched between the top soil and sand layer of high resistivity. In Alluvium formation, the aquifer consists of alternate bands of sand, clayey sand and fine sand with clay of varying thickness. Hence a specific dominant layer is not evident in this terrain.

It is observed that in Alluvium terrain, the resistivity value varied from 0.17 to 4999 Ωm with an average of 420.08 Ωm . The thickness varied from 0.62 to 16.63 m with an average of 6.16 m. In Tertiary formation, resistivity values varied from 0.18 to 7156 Ωm with an average of 468.15 Ωm . The thickness varied from 0.55 to 40.18 m with an average of 12.89 m. In Archaean terrain, resistivity varied from 0.03 to 2952 Ωm with an average of 350.55 Ωm . The thickness varied from 0.85 to 42.12 m with an average of 7 m. Generally, the thickness of the first layer shows decreasing trend from Tertiary, Alluvium and Archaean but in the second layer, decreasing trend from Archaean, Tertiary and Alluvium was also observed. The area of low apparent resistivity values indicates the occurrence of relatively good conductors while

those with high values indicate poor conductors (Srinivasamoorthy 2004).

In general, three major zones were delineated as weathered, fractured and massive in hard rock region and top soil, sandy layer and clayey layer in sedimentary region. The apparent resistivity values and the thickness have been distributed spatially to develop a resistivity map to get an overall perspective of the study area. The first two layers were selected to prepare the isoresistivity map by using Surfer software. The first layer isoresistivity map indicates that the SE side shows higher resistivity values indicating the presence of top soil and away from the coast the values get decreased (figure 6). Higher thickness was noted in Panruti of Cuddalore sandstone formation due to the deeper water level by overexploitation of groundwater in this region. In Archaean formation, both the resistivity and the thickness values are lesser. In the second layer isoresistivity map, lower resistivity values were noted along the coast indicating the influence of saline water in the coastal aquifer. The resistivity values got increased at locations that are away from the coast and a higher resistivity zone was also observed at K. Palayam of Archaean formation considered as a weathered layer of 10 m thickness. In the NW side of the Archaean formation, thickness of the second layer is around 40 m with lesser resistivity values.

The integration of resistivity sounding and geochemistry of groundwater samples was found to be a highly effective method for determining the location of fresh-water areas and the saline water or industrial effluent contaminated zones (Choudhury

and Saha 2004). All the results revealed that the second layer of low resistivity values in the coastal aquifers determines the saline water contaminated zones, which caused high Na and Cl in the groundwater. It is also noted that Na is the chief cation and Cl is the dominant anion in all the seasons and in the different formations. Trace element concentrations were also noted higher in areas of more contaminated zones. In noncontaminated zones, the apparent resistivity values were higher indicating the nonpolluted nature of the groundwater.

5. Conclusion

This research reports the characterization of ground and surface water in the Gadilam basin by a combined approach of hydrogeochemical and geophysical data. The dominant facies in the entire litho units is Na-Cl type indicating saline nature of the water. Spatial distribution of EC indicates anthropogenic impact in the downstream side of the basin. Interpretation of data shows that Na, Cl and K exceed the permissible limits in all litho units. Some trace metals such as Al, Ni and Pb also exceed the acceptable limit of world standard. Resistivity studies reveal that contaminated water from industrial effluent and saline water intrusion with higher ionic concentration was noted near the coastal region. The potable groundwater occurred away from the coastal area.

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