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Groundwater Geochemistry of Neyveli Lignite Mine-Industrial Complex, Tamil Nadu, India and Its Suitability for Irrigation

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Abstract This study was undertaken to assess the quality of groundwater for irrigation and level of trace metal concentration in the surface and groundwater bodies from Neyveli lignite mine-industrial complex which is located in Cuddalore district, Tamil Nadu, India. The hydrogeology of the Neyveli groundwater basin is extremely complex, consisting of a series of productive, confined aquifers below the lignite seam in both Mine I and II areas, while a semi-confined aquifer lies above the seam and occurs only in the Mine II area. The suitability of groundwater quality for agricultural purposes in and around Neyveli lignite mine-industrial complex was assessed by measuring physicochemical parameters, including major cation and anion compositions, pH, total dissolved solids, electrical conductivity, and trace metals. The results of the chemical analysis of the groundwater showed that concentrations of ions vary widely and the most prevalent water type is mixed $CaNaHCO_3$, followed by other water types: mixed CaMgCl types and NaCl which is in relation with their interactions with the geological formations of the basin, dissolution of feldspars and chloride and bicarbonate minerals, and anthropogenic activities. The most dominant class is C1-S1, C2-S1 (85% PRM and 74% POM) in the study area, indicating that sodicity is very low and salinity is medium, and that these waters are suitable for irrigation in almost all soils. Based on sodium absorption ratio the groundwater of the study area is suitable for all types of crops and soil except for those crops sensitive to Na and based RSC values of the groundwater, considered safe. Based on the parameters such as TDS, EC, SO_4, Cl and Wilcox diagram about 99% of samples are suitable for irrigation. The average concentration of trace metals (Fe, Mn, Cr, Zn, Pb, and Cu) in groundwater samples fall within the permissible limit, with the exception of Ni which is recorded higher than the permissible limit which may retard growth and metabolic activities while the groundwater used for irrigation.

Keywords *Hydrogeochemistry, Irrigation Suitability, Industrial Area, Lignite Mine, Neyveli, Trace Metals*

1. Introduction

Quality of water is the function of its physical, chemical, biological and geological parameters [1], which depend upon the soluble products of weathering and decomposition and the related changes that occur with respect to time and space [2-4]. All groundwater contains minerals carried in solution, the type and concentration of which depend upon the surface and subsurface environment, rate of groundwater movement and source of groundwater [5-7]. Man can also adversely alter the chemical quality of groundwater by permitting highly mineralized water to enter into fresh water through mining activity, industrial activity and by disposal of solid and liquid wastes which affects the groundwater through leaching. Pollution of groundwater due to external contaminants such as industrial, urban and agricultural activities is quite well documented [3-4, 8-13]. One of the aspects on which enough attention has not been focused is the degradation of groundwater quality caused by opencast mining activity, in that the interaction between rock, soil and water has led to increasing content of various cations, anions and trace metals in groundwater. Groundwater is of great importance for agriculture in the province of Neyveli, there is a necessary research requirement to provide improved understanding of the quality of groundwater in this region. Many studies have been undertaken in the last two decades and successfully assessed the groundwater quality for irrigation [14-21] which have been useful for agricultural management plan. Therefore, the objectives of the present study are to characterize the main hydrogeochemical features of the groundwater from Neyveli Mine-industrial complex area and its surroundings and to assess the suitability of groundwater for Irrigation purposes.

2. Study Area

The Neyveli Mine-industrial complex is located in Cuddalore district, Tamil Nadu, India (Figure 1). The area has a tropical climate with the highest and lowest temperatures recorded in June (40.3°C) and January (20.4°C), respectively. At the mine site, the average annual precipitation is 1369 mm with 55% and 45% rainfall from the NE and SW monsoons, respectively. The area gently slopes towards southeast and east, and is not drained by any major river except for a small ephemeral stream (the Paravannar River) flowing east. This carries mine water and industrial effluents instead of natural water, and discharges into the Walaza and Perumal Ponds east of the lignite mines. The study area is underlain by the Tertiary Cuddalore Formation and by recent alluvium. The Cuddalore sandstones cover mostly the northern and western parts, while the alluvium covers mostly the eastern and south-eastern parts of the study area. The lignite occurs in the Cuddalore Formation at depths ranging from 45 to 120 m below ground level (bgl).

The hydrogeology of the Neyveli Groundwater basin is extremely complex, consisting of a series of productive, confined aquifers below the lignite seam in both Mine I and II areas, while a semi-confined aquifer lies above the seam and occurs only in the Mine II area. In the Cuddalore sandstones, groundwater occurs in unconfined, semi-confined, and confined conditions; in the alluvium, it occurs in unconfined condition. In the study area, both Tertiary Cuddalore Formation and the recent alluvium form a potential aquifer system.

Around the mine, the ground is either flat or undulating with elevations ranging from 100 to 337 ft. above mean sea level with a general slope to the south and southeast. Of the mean annual rainfall of about 1080 mm, maximum rainfall is recorded between October and December during the northeast monsoon. The Gadilam and Vellar Rivers and their tributaries constitute the principal drainage. These rivers are ephemeral. The study area includes two very large (Mines I and II) and one small (Mine IA) opencast lignite mines, associated industries (two pit-head thermal power plants, a urea plant, and a briquetting and carbonization plant) that are operated by Neyveli Lignite Corporation Ltd. (NLC), and an independent power plant.

Generally, about 550,000 L/min of water are pumped from the pits in a normal season, though much more is pumped during monsoons. Huge quantities of untreated wastewater are also discharged from fly-ash ponds and associated industries into natural reservoirs (Peria, Kolakudi, Walaza and Perumal Ponds, and Paravannar River) and agricultural fields. The water in the ponds and river is severely contaminated with heavy metals, but has been used for the last several decades by nearby villages for irrigation, animal watering, bathing, and washing, etc. Today, about 8,100 ha of agricultural land are irrigated by wastewater discharged from the mine pits and associated industries.

3. Materials and Methods

Seventy seven representative ground water samples were collected in and Neyevli mine industrial complex and two surface water samples from the vicinity of the mine-industry area for trace metal analysis. Sampling was carried out in pre and post-monsoon seasons during 2006. Water samples were collected in sterile 1 L polyethylene bottles and after being filtered (pore size-0.45 μm); each sample was treated with 10 ml HNO_3 to prevent possible precipitation of heavy metals. The water samples were analyzed for water quality (Na, K, Ca, Mg, CO_3, HCO_3, Cl, PO_4, NO_2, and NO_3) and heavy metals according to international standard methods [22]. The analyses of Fe, Mn, Cr, Cu, Ni, Pb, and Zn were performed in the Department of Applied Geology, University of Madras, India using Atomic Absorption Spectrophotometer – Graphite Furnace (Perkin Elmer AAanalyst700).

4. Results and Discussion

4.1. Water Chemistry and Its Spatial Distribution

The Summary of statistical data of groundwater from Neyveli lignite mine-industrial complex is listed in Table 1. The pH of the groundwater during premonsoon (PRM) ranges from 5.7 to 8.5, with an average of 6.9 (Figure 2a), indicating the overall neutral nature of the samples. During postmonsoon (POM), the pH is ranged between 5.9 and 7.9, with a mean of 6.7 (Figure 2b). The highest value is recorded at station 37 (near Periakurichi) and station 3 (Utangalmangalam), western part in PRM and POM seasons respectively. The TDS during PRM is ranged from 19 to 986 mg/l, with an average value of 283 mg/l and during POM; it is ranged between 21 and 1,864 mg/l., (avg. 319 mg/l). The EC of the groundwater during PRM ranged from 30 to 1540 mg/l, with an average value of 441 mg/l. During POM, the EC ranged from 33 to 2,913 mg/l, with an average of 498 mg/l. The highest value of was recorded near the Andikuppam outlet in the eastern part, at Station 12, while the lowest value was recorded near Thekkruppu 9 (Station 24) and Kellakiruppu (Station 24) in the eastern part of the study area during PRM and POM seasons respectively (Figure 2 c, d).

Sodium is the most dominant cation, and the order of abundance of cations is Na^{+}> Ca^{2+}> Mg^{2+}> K^{+}. The seasonal effect does not have any impact on the order of abundance, but it does change the concentration of various ions present in the groundwater. The sodium concentration in the groundwater of the study area is ranged from 2.8 to 408 mg/l (PRM); 3.3 to 297.3 mg/l (POM), with an average value of 55.8 and 43.4 mg/l during PRM and POM seasons respectively. The highest value is recorded near the Gangaikondan outlet in the eastern part of the study area at Station 12, during both seasons while lowest value was recorded in Seduthankuppam (Station 21), and near Marugur in the western part (Station 28) during PRM and POM seasons respectively (Figure 3 a, b). Potassium concentration is recorded nil to 92.9 mg/l, (avg. 7.5 mg/l) and nil to 69.6 mg/l, (5.6 mg/l) in PRM and POM seasons respectively. The highest value is recorded near the Thandavakuppam outlet in the western part of Neyveli, (Station 19), while the lower values were recorded in the eastern part of the study area for both seasons (Figure 3 c, d). Calcium is the second dominating ion in the groundwater of the study area is ranged between 1.1 and 355 mg/l (avg.30.8), in PRM and 0.8 and 333.1 mg/l (avg.25.6), in POM respectively. The highest value is recorded near the Gangaikondan outlet (Station 12) in the eastern part of the study area, while lowest values is recorded Deviakuppam (Station 23) and near Vadakumelur (Station 2) during PRM and POM seasons respectively (Figure 3 e, f). The Mg concentration is observed as 0.6 to 61.5 mg/l, with an average value of 21.5 during PRM and 0.3 to 51.5 mg/l, (avg. 17.8 mg/l) during POM. The highest value is recorded near the Melpathi outlet in the western part of Neyveli, (Station 53), while the lowest value was recorded at near Thekkruppu (Station 27) and near Nandukuzhi (station 23) in the eastern part of the study area in PRM and POM seasons respectively (Figure 3 g, h).

During PRM, the carbonate content is recorded as nil to 30.8 mg/l (avg. 6.2 mg/l) and 0.9 to 22.5 mg/l, (avg. 4.8 mg/l) during POM. The highest value is recorded near the Vadakumelur outlet (Station 2) eastern part of the study area, and lowest values are recorded in the western part of the study area during PRM. During POM, the highest and lowest values during PRM and POM seasons are recorded near the Periakovialkuppam outlet (Station 9) in the eastern part and near Kunnakurichi (Station 2) in the western part of the study area (Figure 4 a, b). The bicarbonate content is higher in PRM as 10 to 270 mg/l, with an average of 81.7 mg/l compared to POM (4.9 to 258.1 mg/l, avg. 63.8mg/l). The highest value is recorded near the Kolagudi outlet (Station 33) in the western part of the study area, for both seasons, while the least value is recorded at Thekkruppu (Station 27) and Kellakiruppu (Station 24) in the eastern part of the study area during PRM and POM respectively (Figure 4 c, d). The sulfate concentration ranged between 1.5 and 362.6 mg/l, (avg.94.3 mg/l) during PRM while in POM, ranged from 2.4 to 330 mg/l, with an average of 78.3 mg/l. The highest value is recorded near the Vadukkuvellur outlet (Station 11) in the western part of the study area for both seasons, while the least value was recorded in the western parts near Marugur at Station 28 and near Vallam (Station 25) during PRM and POM seasons respectively (Figure 4 e, f). Chloride is the dominant anion, ranged from 8.00 to 757.2 mg/l, (avg. 79.4 mg/l) in PRM and 3.2 to 637.4 mg/l, (avg. 63.4.mg/l) in POM seasons respectively. The highest value is recorded near the Andikuppam outlet (Station 12), in the eastern part of the study area during both seasons, and the lowest value is recorded in the western part of the study area near Vallam (Station 25) during PRM and near Kellakiruppu (Station 24) in the eastern part of the study area during POM season (Figure 4 g, h).

During PRM, the phosphate content is recorded as 0.02 to 5.04 mg/l, with an average value of 0.49 mg/l and during POM; it is ranged between 0.02 and 1.2 mg/l, with an average of 0.22 mg/l. The nitrite concentrations vary between nil and 1.51 mg/l in PRM with an average of 0.07 mg/l while during POM nitrite content is observed lower (nil to 1, avg. 0.07 mg/l). The nitrate concentration in PRM is ranged from 0.2 to 89.3 mg/l, with an average of 12.8 and in POM; it is ranged from 0.07 to 68.3 mg/l, with an average of 8.1 mg/l. The relatively higher concentrations of nitrate values in many of the stations in the study area reveal that there exist intensive agricultural activities, and the fertilizers would have contributed to the nitrate values. In both seasons, there is no much change in the spatial distribution pattern of nitrate and it is almost isotropic.

***Table 1:** Summary of statistical data of groundwater from Neyveli lignite mine-industrial complex, Tamil Nadu, India*

Parameters (mg/l)	PRM					POM					R
	Min	Max	Mean	σ	Var	Min	Max	Mean	σ	Var	
pH	5.7	8.5	6.9	0.6	7	5.9	7.9	6.7	0.6	7	S
EC(mS/cm)	30	1540	441	577.0	333987	33	2913	498.0	498.0	248333	N
TDS	19.0	986.0	283.0	370.0	136801	21.0	1864.0	319.0	370.0	136932	N
Ca^{2+}	1.1	355.0	30.8	48.9	2386	0.8	333.1	25.6	44.4	1973	N
Mg^{2+}	1.0	61.5	21.5	12.4	153	0.3	51.5	17.8	15.2	230	S
Na^{+}	2.8	408.0	55.8	64.5	4156	2.3	449.5	43.4	61.0	3720	N
K+	0.0	92.9	7.5	14.6	214	0.0	69.6	5.6	10.0	100	N
CO_3^{-2}	0.0	30.8	6.2	5.3	28	0.9	22.5	4.8	3.9	5	N
HCO3-	10.0	270.0	81.7	67.1	4503	4.9	258.1	63.8	60.5	3657	N
SO_4^{2-}	1.5	362.4	94.3	109.7	12032	2.4	330.0	78.3	95.6	9130	N
Cl-	8.0	757.2	79.4	100.9	10181	3.2	637.4	63.4	86.5	7480	N
NO^{3-}	0.2	89.3	12.8	18.6	347	0.1	68.3	8.1	13.5	182	N
NO^{2-}	0.0	1.5	0.1	0.2	0	0.0	1.0	0.1	0.1	0	N
PO_4^{3-}	0.0	5.0	0.5	0.8	1	0.0	1.2	0.2	0.2	0	S

s- standard deviation Var-variance S-significant, N-non-significant, R- Result

4.2. Hydrochemical Facies

The evolution of hydrochemical parameters of groundwater can be understood by plotting the concentration of major cations and anions in the Piper diagram [23]. Figure 5a shows that most of the groundwater samples analyzed during the PRM fall in the field of mixed $CaNaHCO_3$, mixed CaMgCl and NaCl. Some of the values also fall in the field of $CaHCO_3$ and CaCl type. During POM (Figure 5b), most of the values fall in the field of mixed $CaNaHCO_3$, mixed CaMgCl, NaCl and CaCl types. Similar to PRM, some of the values fall in the field of $CaHCO_3$ and $NaHCO_3$. Water types NaCl and mixed CaMgCl suggest the mixing of high salinity water caused from surface contamination sources followed by ion exchange reactions. Some of the samples show higher content of Na coupled with low Ca content, suggesting that Ca^{2+}-Na^{+} ion exchange is an important geochemical process for the NaCl type of groundwater. From the plot, it is observed that alkalis (Na^{+} and K^{+}) exceed the alkaline earths (Ca^{2+} and Mg^{2+}), and Cl^{-} exceeds the other anions. This type of water generally creates salinity problems for the irrigation use.

4.3. Chemical Characteristics of Major Ions

The plot of equilines (Figures 6a - 6l) for both the seasons shows a marked difference. In PRM, the plot of Na+K vs. Cl (Figure 6a) shows that most of the values fall just above and below the equiline, except a few values, which suggests that most of the alkali ions are balanced by the chloride ions. Also, in the plot of Ca+Mg vs. HCO_3+SO_4, (Figure 6b) the distribution pattern of the points follows almost that of alkali vs. Cl type (Figure 6e), but with fewer points deviating from the 1:1 equiline, reflecting that HCO_3+SO_4 anions balance the alkaline earth metals in these groundwater samples (Figure 6f). During POM, the plot of Na+K vs. Cl (Figure 6g) shows that most of the values fall along and adjacent to the equiline, except a few values deviating from the line, suggesting that most of the alkali ions are balanced by the chloride ions. As observed in the PRM plot of Ca+Mg vs. HCO_3+SO_4 (Figure 6h), the balancing of these anions over the alkaline earth metals is almost complete with few values falling away from the line. Moreover, it could be seen that the alkali excess in Figure 6a, and the alkaline earth metal excess in Figure 6b are well balanced by the HCO_3+SO_4 and Cl anions, respectively. Furthermore, this pattern could be seen in the POM values, too (Figure 6g and h).

During PRM, among the alkalis, Na is dominant and the concentration of potassium is apparently low. The natural source of potassium in water usually originates from chemical weathering, and subsequent dissolution of minerals of local igneous rocks such as feldspars (orthoclase and microcline), mica and sedimentary rocks as well as silicate and clay minerals [24]. Since these minerals are not abundant in the study area, potassium concentration in these waters is only 1/10th of the concentration of sodium; also, the low contribution of K may be due to the greater resistance of K to weathering and its fixation in the formation of clay minerals [25]. The high ratio of Na+K vs. Z^+ (Fig 6c and i) suggests that silicate weathering may, to some extent, contribute to the total cations [25]. In POM, the concentration of sodium predominates over that of potassium. Cl^- ion concentration in groundwater normally arises from three sources viz., ancient seawater entrapped sediments, solution of halite and related minerals in evaporate deposits, and solution of dry fallout from the atmosphere, especially in arid regions [26]. The high concentration of chloride in the study area does not seem to arise from the above factors, but it may be caused by anthropogenic activities, and also from the leaching of saline residues of the soil by the action of rainwater during POM [27].

4.4. Suitability for Irrigation

Irrigational suitability of groundwater in the study area was evaluated by different parameters such as EC, SAR, RSC, USSL classification, Na%, and Wilcox diagram. The excessive total content of soluble salts such as Na affects the suitability of groundwater for irrigation by its exchangeable capacity to Ca and Mg. If the percentage of Na^+ to $[Ca^{2+}+(Mg^{2+}+Na^+)]$ is more than 50% in irrigation waters, calcium and magnesium exchange with sodium, thus causing deflocculation and affects the permeability of soils [2] and the texture makes the soil hard to plough and unsuitable for seedling emergence [28]. The EC and Na concentration are important to classify the irrigation water. According to Richards [29], the irrigation water is classified into four groups such as low (EC = <250 μS/cm), medium (250–750 μS/cm), high (750–2,250 μS/cm), and very high (2,250–5,000 μS/cm) salinity. High EC in water leads to formation of saline soil, whereas high Na content in water causes alkaline soil. The sodium or alkali hazard in the use of water for irrigation is expressed by determining the SAR, and it was estimated by the equation:

$$SAR = Na/ [(Ca + Mg)/2]^{0.5}$$

Units are expressed in milliequivalent per liter

The SAR values indicate the relative proportion of Na to Ca and Mg. The calculated values of SAR in the study area vary between PRM and POM as 0.35-5.58 and 0.21-4.93 respectively (Table 2). According to SAR values, all the samples in PRM and POM are suitable for most types of crops and soils. Groundwater of the study area was classified based on salinity hazard (EC) and SAR which is given in table 3. It is found that 14% (PRM) and 25% (POM) of samples are considered as very high salinity and the water class is poor. High salinity and exchange with sodium, thus causing deflocculation and impairment of the tilth and permeability of soils [2]. The irrigation suitability of the groundwater was also assessed by plotting the data on the USSL (US Salinity Laboratory of the Department of Agriculture) diagram [29]. According to USSL, low salinity water (200mg/l) may be used for all the soil types. The groundwater of the study area falls into good to moderate category (Figure 7). Overall 85% (PRM) and 74% (POM) of samples fall in C1S1 and C2S1 fields indicating of low to medium salinity and low alkalinity water, which can be used for irrigation. Moreover 15% (PRM) and 25% (POM) of samples fall in C3S1 field indicating high salinity and low alkalinity hazard, which may not have appreciable sodium hazard.

Sodium can lead to the formation of alkaline soils combined with carbonate, while forms saline soils combined with chloride. Both soils do not support for plant growth. An alkali soil has an unfavourable structure, puddles easily and restricts the aeration. Further, the high sodium saturation directly causes calcium deficiency. Na% was calculated using the following equation.

$$Na\% = (Na \times 100)/ (Ca^{2+} + Mg^{2+} + Na + K)$$

A sodium percentage more than 60% is considered unsafe for irrigation [9]. The values for the Na % in the study area range from 6–89% and 15-91% in PRM and POM seasons respectively. About 27% (PRM) and 17% (POM) of the samples are higher than 60% Na and the remaining are within the recommended limit. Calculated Na% for the groundwater of present study region is plotted against specific conductance in Wilcox diagram (Figure 8) [30]. According to this plot, 96% of samples during PRM 95% of samples during POM are classified as excellent to permissible; 2 samples during PRM and 3 during POM are permissible to doubtful; and only 1 sample located near Andikuppam outlet in the eastern part of the study area, at Station 12 is doubtful to unsuitable category during PRM and POM.

The effect of bicarbonate ion concentration on the water quality is based on the residual sodium carbonate (RSC) concept by Eaton [31], where waters having >2.5 (meq/l) RSC are unsuitable for irrigation, 1.25–2.5 are marginal and <1.25 are safe waters. The residual sodium carbonate (RSC) is obtained on computation by the following equation:

$$RSC = (CO_3 + HCO_3) - (Ca^{2+} + Mg^{2+})$$

Where, ionic concentrations are considered in milliequivalents per litre. Based on this criterion, all the samples during both seasons are considered safe for irrigation based their low RSC values.

Suitability of groundwater for irrigation purposes was also assessed using the criteria shown in table 3. A comparison of TDS values with irrigation standards shows that 76% during PRM and 71 % during POM is considered class I, which is excellent to good category, whereas 1% in PRM and 8% in POM is considered class II which are suitable for permeable soil [20]. The Cl content of water samples suggests that 17% in PRM and 5% in POM are of Class II which may be injurious to crops. As per Cl and EC comparison 0-1% of samples during PRM and 1% of samples during POM are unfit for the irrigation purpose. The overall comparison between various suitability assessments show that only one sample (E12) is highly not suitable for irrigation.

The deficiency or excess of certain trace elements in irrigation water can retard growth and metabolic activities. Hence, neither the nutrient value nor the toxicity of trace elements in irrigation water can be ignored. Average and range of heavy metals in surface water bodies around the Neyveli mine-industrial complex and groundwater were compared with the average in the world's rivers [32] and irrigation water quality standards [33-34]; all values in mg/l (Table 4). Accordingly the average concentrations of Mn, Cr, Zn and Ni in surface waters exceed the recommended limits, whereas Pb, Cu, and Fe were well within the permissible limits. The source for the maximum concentration in the surface water bodies is the coal-based thermal power plant [35]. But the average concentration of trace metals in groundwater samples fall within the permissible limit, with the exception of Nickel which is recorded higher than the permissible limit.

Table 2: *Water quality classifications of the groundwater for irrigation based on SAR, EC, and RSC values*

SAR Range	EC	Water Class	PRM - Sample Number (%)	POM - Sample Number (%)	Salinity Hazard	Irrigation Suitability
<10	250	Excellent	1, 2, 5, 8, 23-27, 30-33, 35-37, 41-43, 60, 62, 64-68, 70 (35)	1, 2, 5, 6, 8, 9, 23-27, 29-33, 35, 36, 38, 41-43, 46, 47, 49, 60, 62,64-68, 70 (43)	Low	
10-18	251-750	Good	3,4,6,7,9-11, 13,14, 16-18,20-22,28,29,34,38-40,44-47,49,51-57, 61, 63, 69, 71, 75, 76 (51)	3,4,7,10, 11, 14, 17, 20, 28, 34, 39, 40, 44, 45, 52, 54, 55, 57, 59, 61, 63, 69, 71, 77 (31)	Medium	
18-20	751-2250	Fair	12, 15,19,48,50,58-59,72-74,77 (14)	13, 15, 16, 18, 19, 21, 22, 37, 48, 50, 51, 53, 56, 58, 72-76 (25)	High	
>20	>2250	Poor	- (0)	12 (1)	Very High	
Based on SAR Only						
1-10	Excellent		1-77 (100%)	1-77 (100%)		Suitable for all types of crops and soil except for those crops sensitive to Na
11 – 18	Good		-	-		Suitable for coarse textured or organic soil with permeability
19 – 26	Fair		-	-		Harmful for almost all soil
>27	Poor		-	-		Unsuitable for irrigation
Based on RSC						
< 1.25			1-77 (100%)	1-77 (100%)		Safe
1.25-2.5			-	-		Marginal
>2.5			-	-		Unsuitable

Table 3: *Irrigation Suitability of groundwater of the study area with different constituents*

Parameters	Class of Water I			Class of Water II			Class of Water III		
	Range	No of Samples (%)		Range	No of Samples (%)		Range	No of Samples (%)	
		PRM	POM		PRM	POM		PRM	POM
TDS (ppm)	0 – 700	76 (99)	71 (92)	700 – 2000	1 (1)	6 (8)	> 2000	-	-
SO_4 (ppm)	0 – 192	63 (82)	67 (87)	192 – 480	14 (18)	10 (13)	> 480	-	-
Cl (ppm)	0 – 142	63 (82)	72 (94)	142 – 355	13 (17)	4 (5)	> 355	1 (1)	1(1)
Ec (mS)	0 – 0.75	66 (86)	57 (74)	0.75 – 2.25	11 (14)	19 (25)	> 2.25	0	1(1)
Suitability for irrigation	Excellent to good			Good to Injurious			Unfit		

Table 4: *Average values of trace metals in surface and groundwater around the Neyveli mine-industrial complex compared with the average in the world's rivers [32] and irrigation water quality standards [33-34]; all values in mg/L*

Elements	World River (avg.)	Irrigation Water Standards	Study area (Average)			
			Surface water (N=2)		Groundwater (N = 77)	
			PRM	POM	PRM	POM
Fe	0.04	5.0	4.44	4.93	1.04	1.37
Mn	0.007	0.2	0.40	0.41	0.08	0.12
Cr	0.001	0.1	0.45	0.47	0.04	0.04
Cu	0.007	0.2	0.12	0.12	0.13	0.11
Pb	0.001	5.0	1.34	1.36	0.01	0.01
Zn	0.02	2.0	0.35	0.39	0.27	0.20
Ni	0.0003	0.2	0.63	0.53	0.62	0.46

5. Conclusion

Based on this study on quality of groundwater, it was found that Na content was dominant among cations and Cl among anions for both seasons. The variation of ions is observed except for pH, Mg, and phosphate, suggesting that the effect of monsoons is minimal on these ions. The results also suggest that there is no significant pollution of groundwater, except at a few stations. The type of water that predominates in the study area is $CaNaHCO_3$ type during both seasons of the year 2006, based on hydrochemical facies. The suitability of water for irrigation is evaluated based on SAR, %Na, RSC and salinity hazards. Most of the samples in study area are in the suitable range for irrigation purpose either from SAR, % Na or RSC values. About 85% (PRM) and 74% (POM) of the samples are grouped within C1S1 and C2S1 in both pre- and post-monsoon seasons, which is more suitable for irrigation. Remaining samples of groundwater needs better drainage to overcome salinity problems. Most of the samples (~99%) in the study area fall in the suitable range for irrigation purpose from USSL diagram. Even though some of the individual samples show higher concentration of trace metal the overall average values are within permissible limit of the standards, except Nickel content in the groundwater of the study area.

Figures

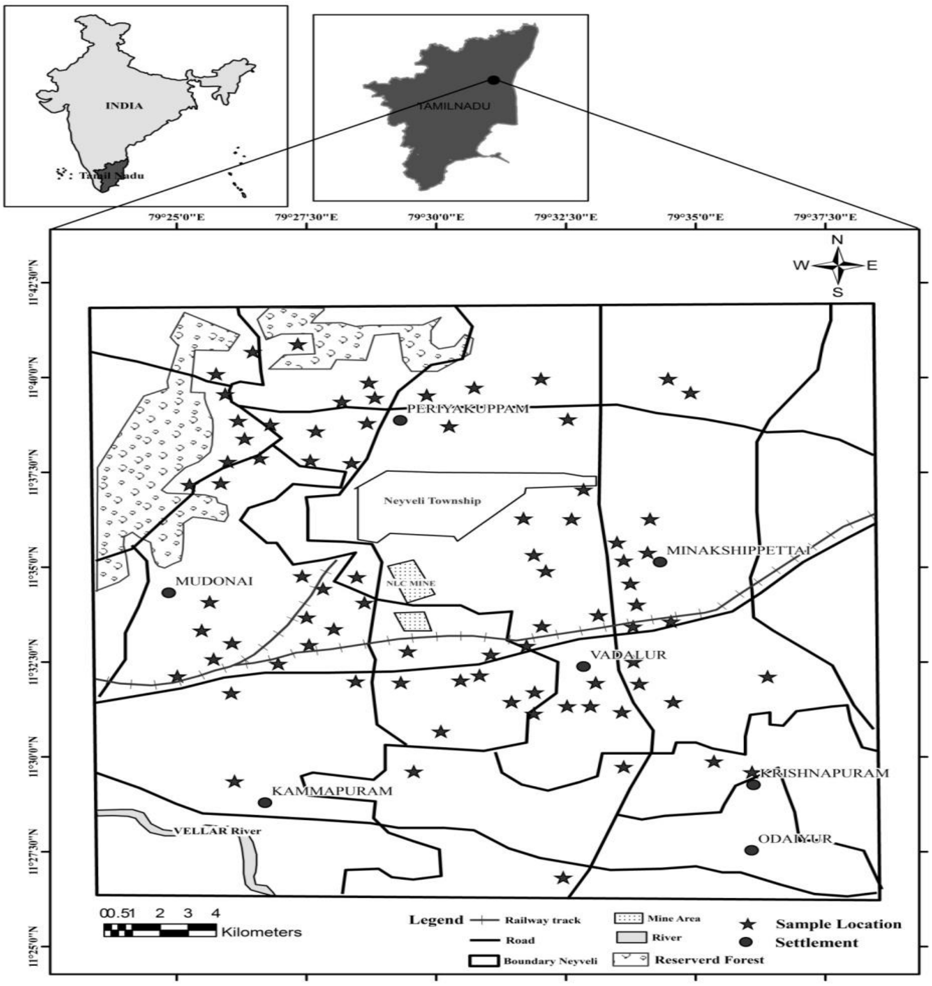

Figure 1: *Location map of the study area*

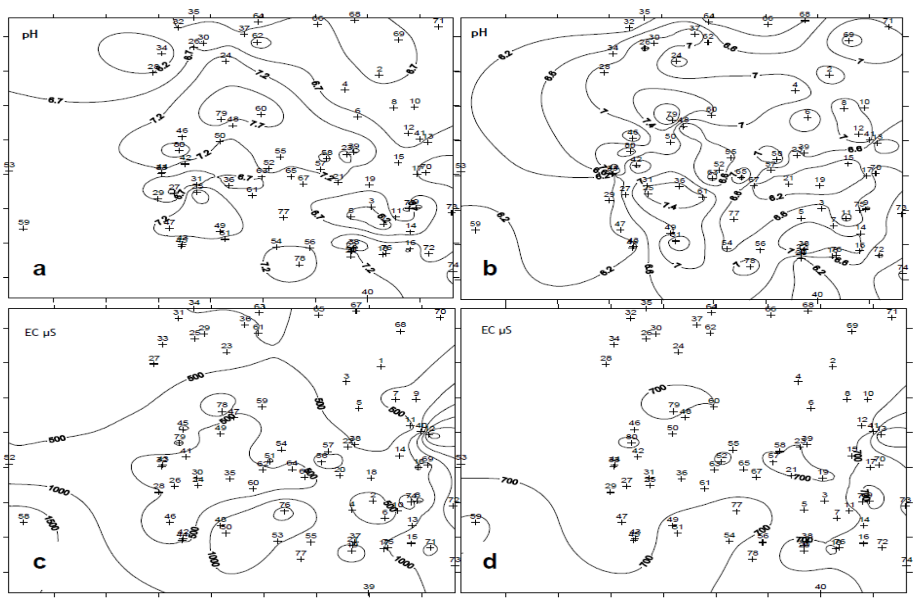

Figure 2: *Spatial distribution of pH and EC in the groundwater of the study area*

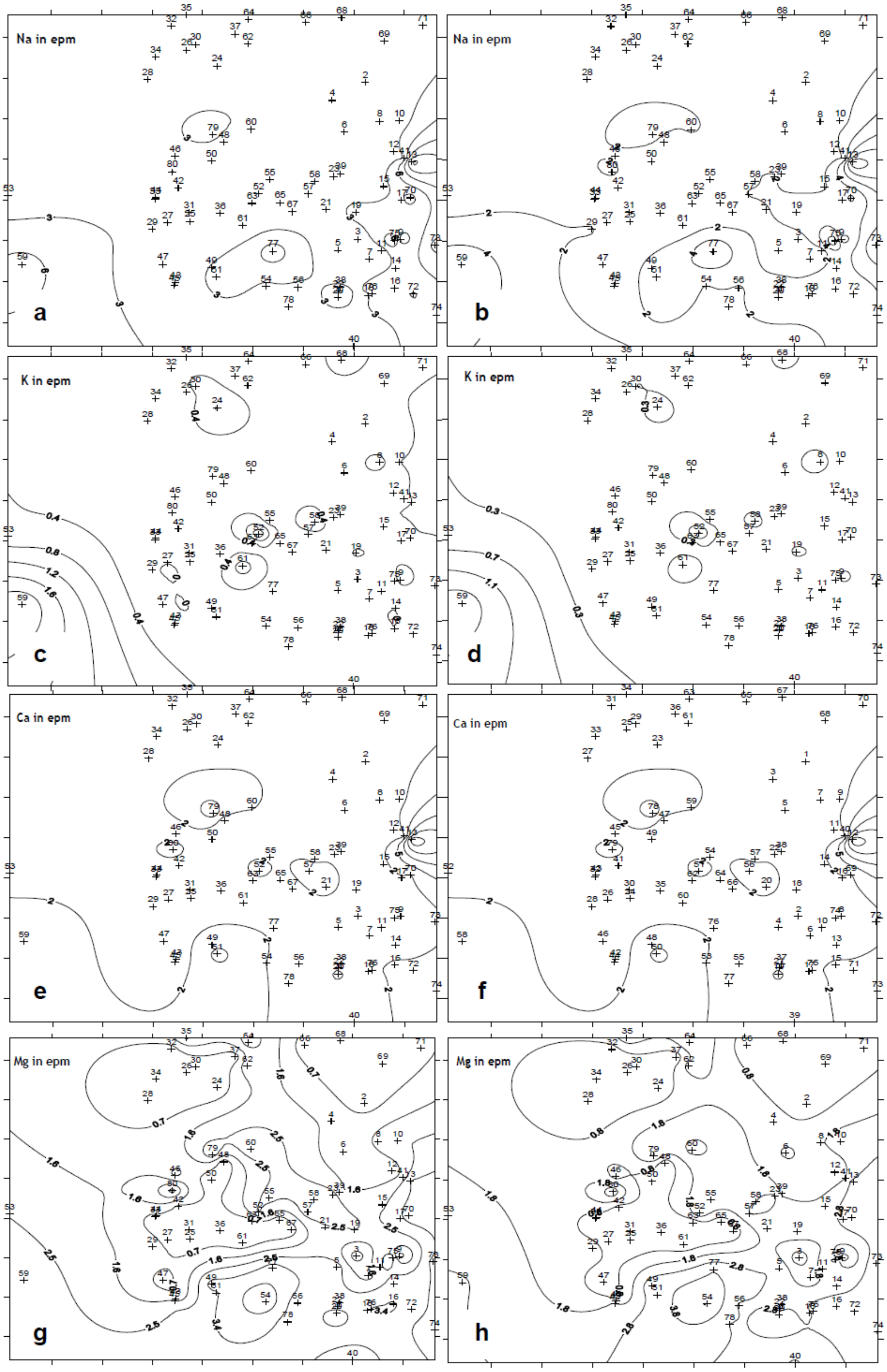

Figure 3a-h: *Spatial distribution of cations in the groundwater of the study area*

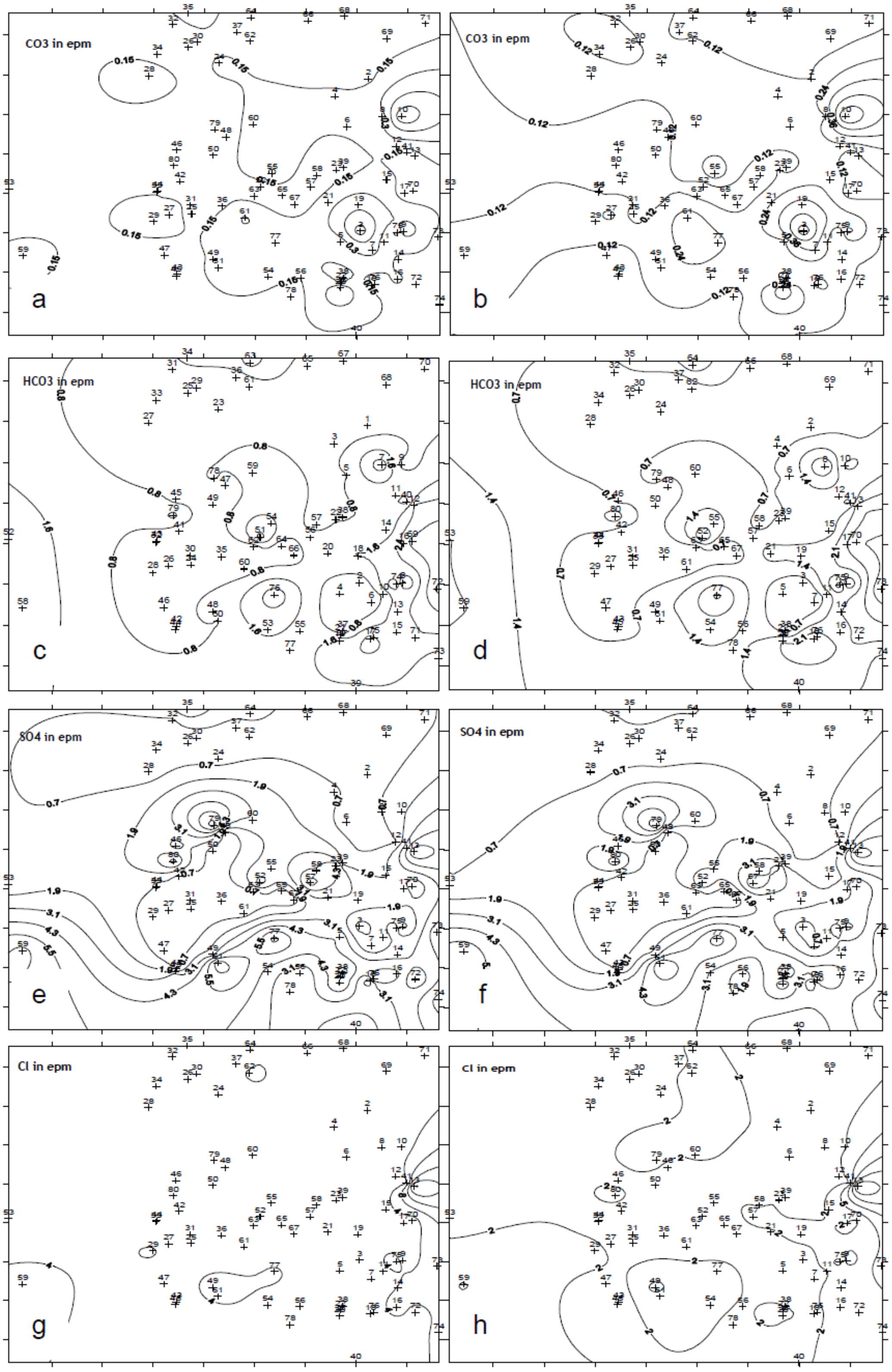

Figure 4a-h: *Spatial distribution of anions in the groundwater of the study area*

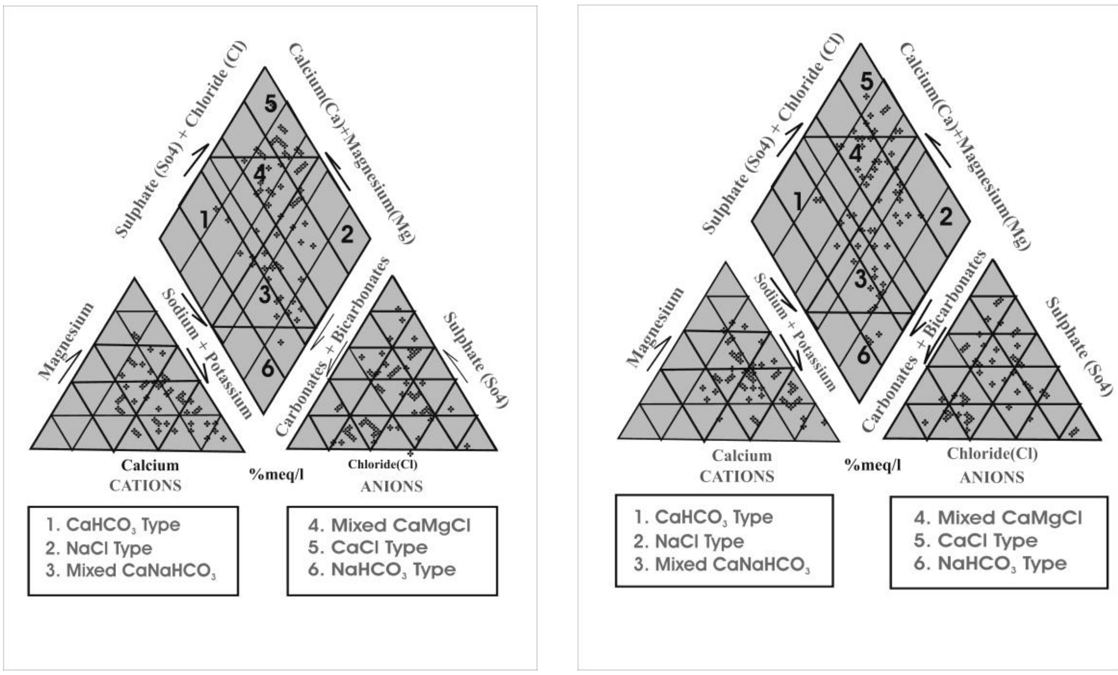

Figure 5: *Piper trilinear diagram for hydrogeochemical facies for groundwater of the study area (a.PRM; b.POM seasons)*

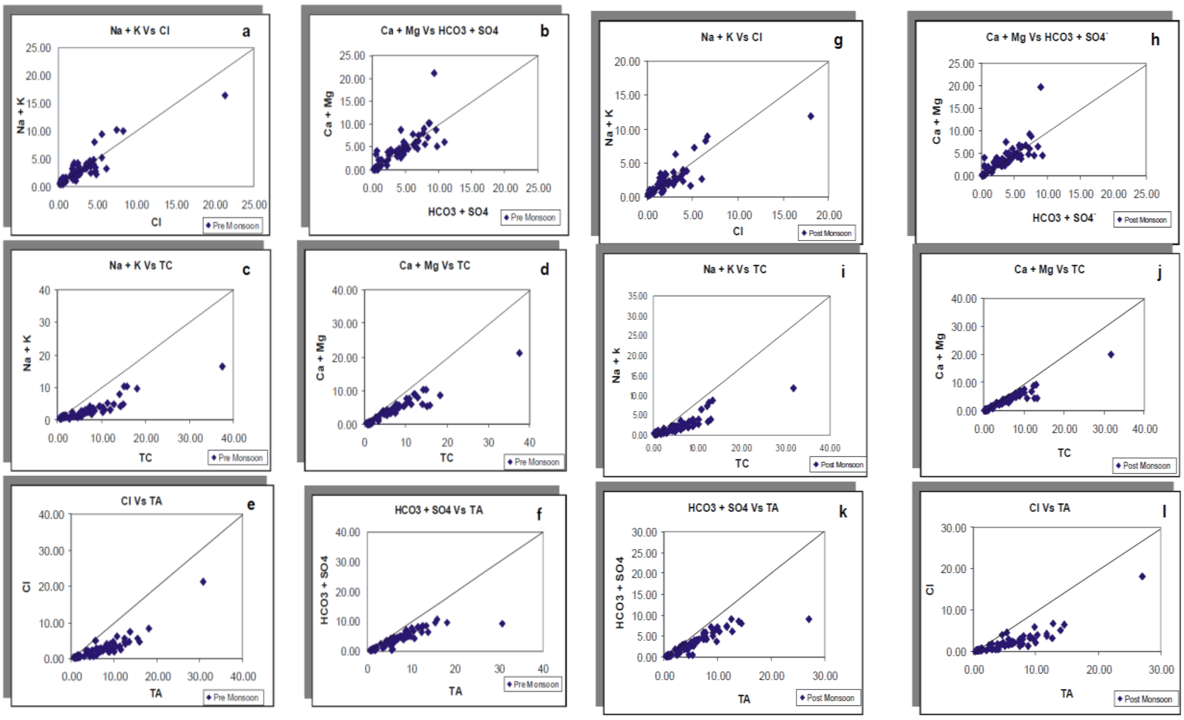

Figure 6a-l: *Equiline diagrams of the chemical parameters for the groundwater of the study area (a-f PRM; g-l POM)*

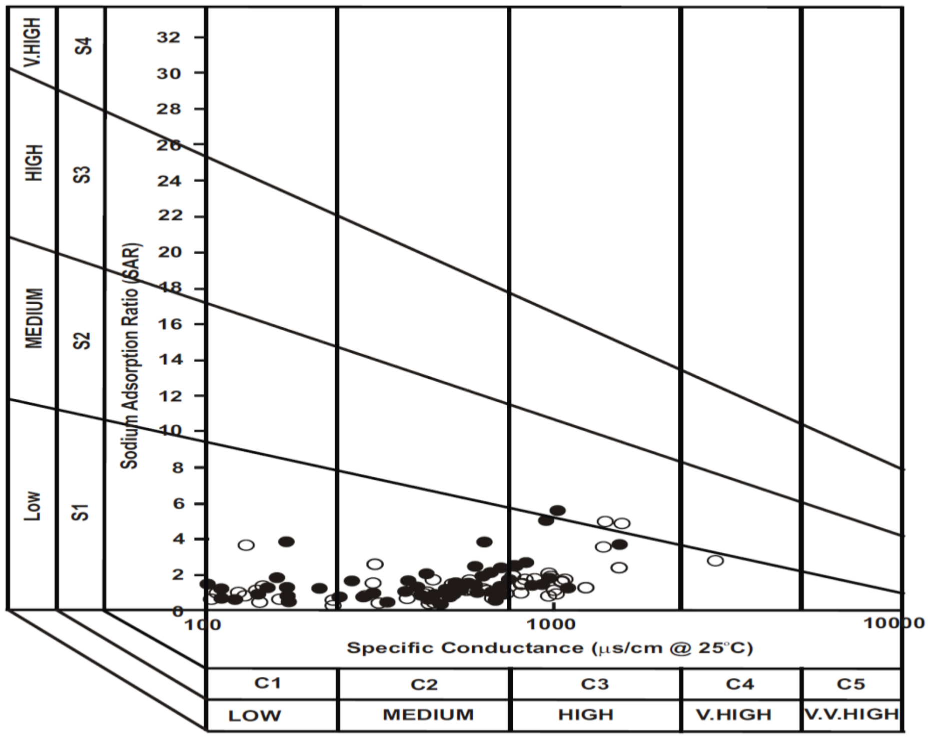

Figure 7: *USSL classification of groundwater samples (filled circle – PRM; open circle – POM)*

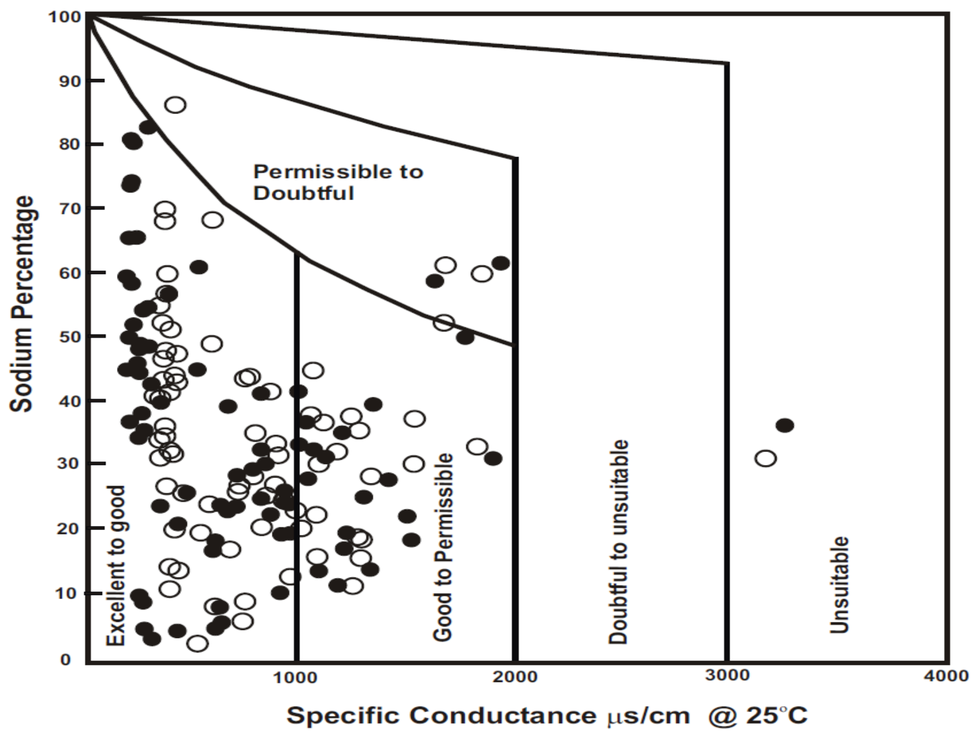

Figure 8: *Irrigational suitability of groundwater in the study area (filled circle – PRM; open circle – POM)*

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