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Geoelectrical Investigations in a Hard Rock Area Containing Pockets of Saline Groundwater

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Areas of fresh and brackish groundwaters have been delineated in an area underlain by granulitic rocks using electrical resistivity method. A sharp boundary between fresh and brackish waters has been identified on one side of the area. Sedimentological studies have indicated that the area having brackish to saline groundwaters of chloride-/sulphate type is covered by clays of marine origin. A hydrogeological boundary with limited permeability has been identified, which seems to help the fresh water area from getting contaminated by the saline waters. The study shows that the saline groundwaters may be the result of marine environment that may have existed in the area during the geological past. It is observed that the aquifer resistivity pattern of the area compares well with the electrical conductivity pattern of the groundwater.

Introduction

Groundwater in areas underlain by crystalline rocks – particularly those away from saline water bodies – is generally of acceptable quality except that occasionally it may have considerable bicarbonate hardness. Owing to a general uniformity in hydrogeological conditions in such areas, the spatial variation in the chemical quality of groundwater is not very sharp, unless there are some local sources of contamination. Among the dissolved solids, bicarbonate is the most dominant ion (Freeze and Cherry 1979). A few instances of saline groundwaters have been reported from areas underlain by crystalline rocks, but from relatively deep seated aquifers (Edmunds

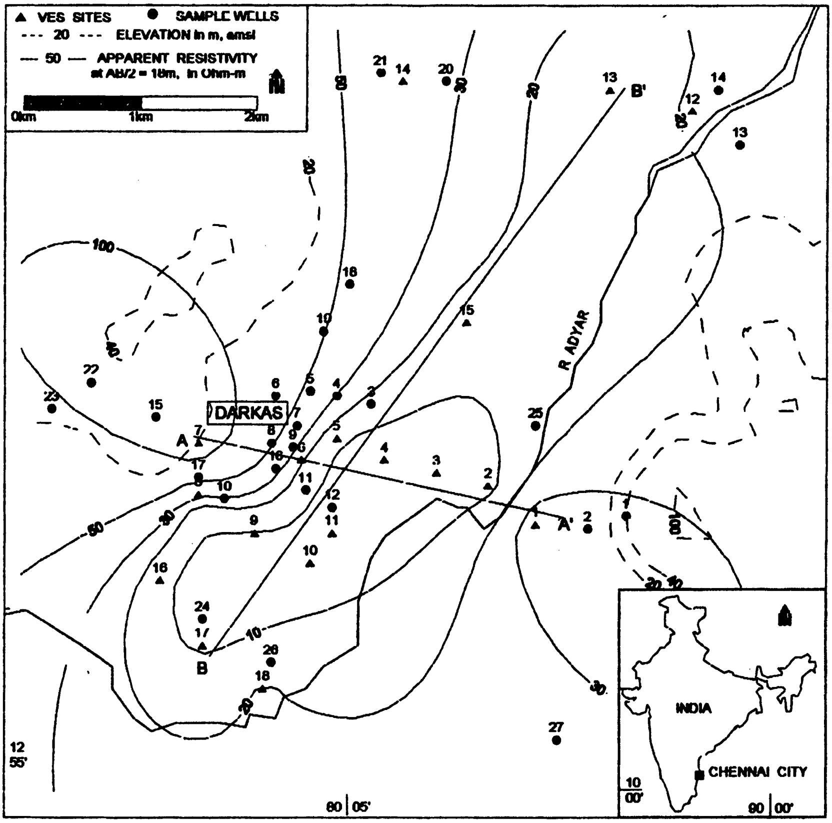

Fig. 1. Location map showing VES sites, sample wells, apparent resistivity pattern and surface Elevation.

and Savage 1991; Coutre *et al.* 1983). The Chebotarev (1955) hydrochemical evolution of groundwater, leading to the enrichment of chloride ions, is not generally applicable to shallow aquifers in crystalline rock areas. This forms a helpful premise in characterizing groundwaters of sedimentary rocks and those of crystalline rocks.

A very unusual hydrogeochemical environment was observed in village Darkas (12°55' 30" N. & 80(05' 10" E.), about 25 km west of the city of Chennai in southern India. The area is underlain by Precambrian granulitic rocks, and three borewells drilled here to provide water supply to an amusement park (Kishkinda) yielded brackish waters with EC values ranging from 6,000 to 12,000 µS/cm (Baratan 1991), although fresh groundwater was being pumped from shallow dug wells within a distance of few hundred metres from these borewells. The presence of such a brackish water pocket in a crystalline rock area, away from sea coast or other sources of contamination was quite intriguing and this was the reason for the present investigations.

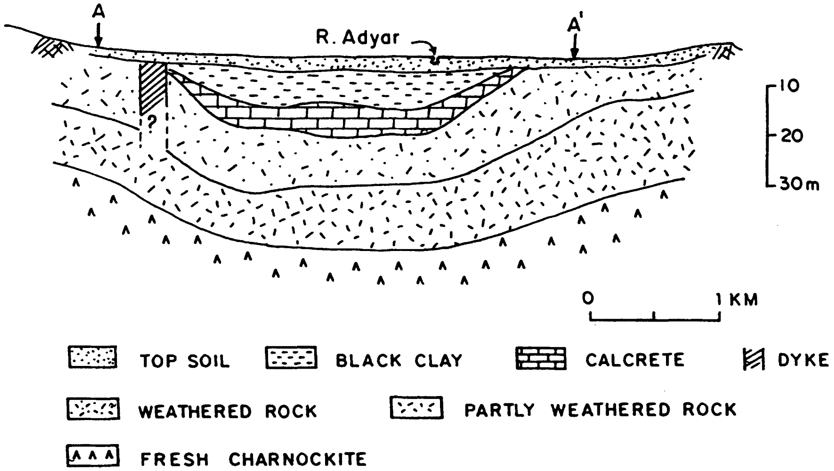

Fig. 2. Geological section along AA'.

The area of study is along the flood plains of a minor stream (river Adyar), which is mostly a storm water channel in the area (Fig. 1) of present investigations. The region is underlain by charnockitic rocks, often garnetiferous, and is exposed as prominent structural hills to the south and north. The highly sheared nature of rocks, presence of fault scarps, slicken sides *etc.* suggest that the river valley may be a structural depression. The subsurface lithology, as reconstructed from borehole and dug well lithologs, is shown in Fig. 2. It can be seen that the central part of the basin has black clay at the top, underlain by a layer of calcrete (area-1). This is followed by the regolith or weathered rock zone which forms the surface layer on the southern as well as northern parts (area-2) of the area. Partly weathered and intensely jointed charnockite of a few metres thickness underlies this and fresh bed rock is encountered at about 30 m depth below ground level (bgl). Bouldery exposures of dolerite dyke rock are noticed in a dug well section (No. 16, Fig. 1) on the northern side of the area.

The groundwater in the area is generally under unconfined conditions, except probably in the fractures and joints below wherein it is likely to be under semi-confined pressure. Depth to groundwater levels fluctuate between ground level just after the recharge season (December-January) to about 9 m (bgl) in the summer months (June-July). The dominant hydraulic gradient is towards the basin from the north as well as south. On an average, the yields from borewells drilled here vary from 0.5 to 6.0 m^3/hr, with most of the groundwater coming from the jointed and partly weathered rock zone.

Groundwater samples from eight borewells (average depth:40 m) and 19 dug wells (average depth: 8 m) were analyzed for their major ion concentrations and the results are shown in the Piper diagram (Piper 1944) of Fig. 3. It is seen that the sam-

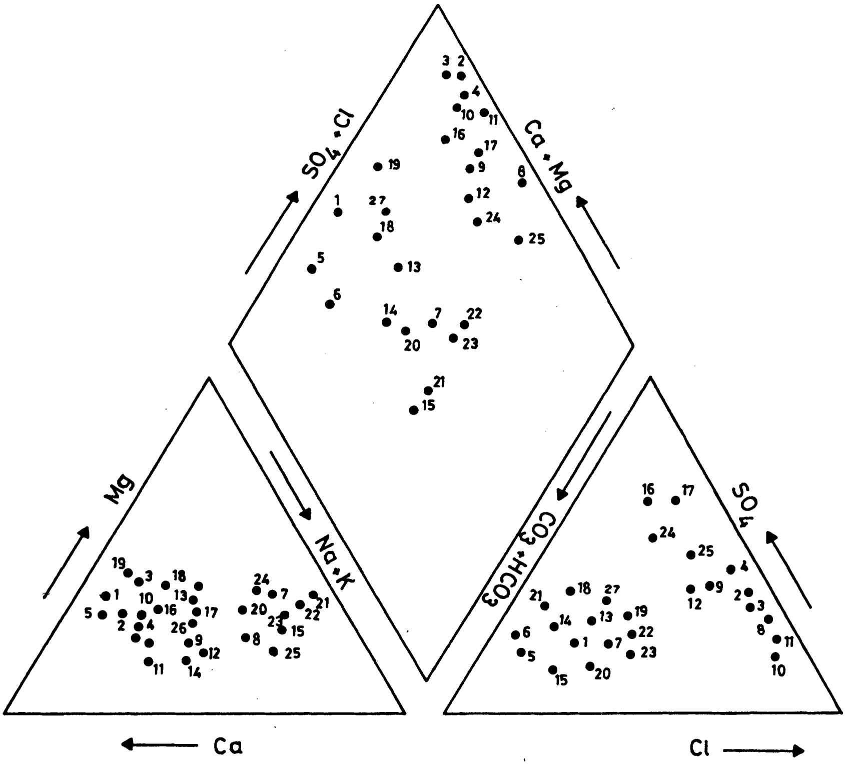

Fig. 3. Piper Hill diagram showing groundwater quality.

ples fall into two broad categories, based on the classification suggested by Back and Hanshaw (1965), namely: Bicarbonate type (wells 1,5,6,7,13,14,15, 18 to 23 and 27) and chloride type (wells 2,3,4 and 8 to 12). The Bicarbonate type waters are typically from areas devoid of clay and calcrete layers, *i.e.* from areas where the weathered rock or regolith forms the surface layer (area-2). The pattern of electrical conductivity of groundwaters prevailing in the area during September 1994 is shown in Fig.4. The conductivity is seen to increase to the middle of the area from the south as well as north. On the northern side of the basin, close to a group of abstraction wells, the southerly increase in electrical conductivity is relatively sharp – from about 1,500 μS/cm to 5,000 μS/cm over a distance of about 400 m. This close proximity of fresh groundwater to brackish groundwater suggests the existence of a barrier, with only a limited hydraulic continuity between the two.

Fig.5 is a plot of Cl versus CO_3+HCO_3 as percentage of cations. Water samples were grouped into two – based on a threshold limit of EC = 3,500 μS/cm. A very clear demarcation is observed with water from area-1 being rich in Chloride and low in bicarbonate while the groundwaters from area-2 are high in bicarbonates and low in chloride.

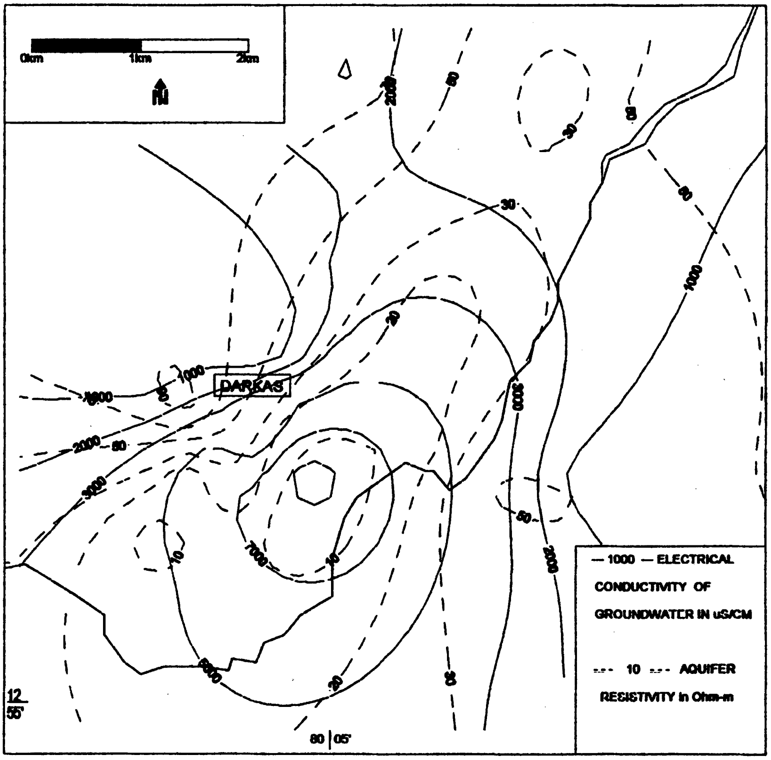

Fig. 4. Pattern of aquifer resistivity and groundwater conductivity in the area.

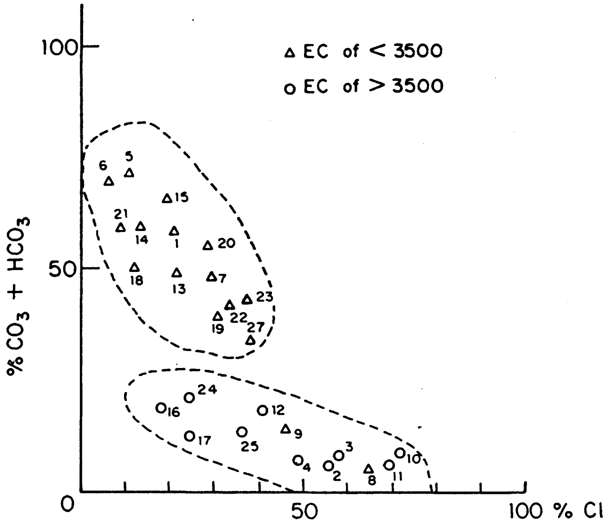

Fig. 5. Chloride versus bicarbonate plot.

Table 1 – VES Data.

MN/2	AB/2	VES No.						Apparent Resistivity in Ohm – metres											
(m)	(m)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
0.3	1.5	5.5	3.7	2.9	8.9	6.3	12.6	79.4	7.2	9.5	9.7	6.0	7.9	6.5	7.2	7.6	8.5	9.2	7.8
	3	8.5	1.6	1.5	2.9	3.6	13.3	64.2	6.5	4.3	6.2	3.6	6.8	5.1	10.7	4.3	5.0	4.0	9.6
	6	15.4	2.2	1.9	2.4	5.6	17.0	59.4	8.2	3.9	4.9	3.2	9.5	6.1	19.7	5.7	5.4	4.6	14.2
	9	20.7	3.1	2.3	2.8	6.9	16.3	66.0	10.4	5.2	5.0	3.6	12.7	7.6	23.2	7.9	7.1	5.9	15.9
1.5	9	21.1	3.0	2.3	3.0	7.2	17.0	69.5	10.6	4.9	5.1	3.6	13.1	7.2	24.1	8.1	7.2	5.4	16.0
	12	25.6	4.0	2.7	3.5	8.3	21.6	91.0	13.4	6.4	5.5	4.2	16.1	9.0	29.0	10.3	9.0	6.6	17.1
	15	32.0	4.8	3.3	4.3	9.5	19.6	119	16.7	7.8	6.2	4.9	18.9	10.1	33.7	12.6	10.90	7.6	19.0
	18	38.0	5.7	3.9	4.9	10.8	21.1	141	20.3	9.3	7.4	5.6	22.0	10.8	39.0	14.6	12.8	8.4	21.2
3	18	37.6	5.8	4.1	5.1	10.2	20.8	138	21.1	9.7	7.2	6.0	22.6	10.3	41.1	15.3	13.3	8.6	21.6
	24	49.0	7.3	5.2	6.3	13.2	21.4	141	26.1	12.2	9.0	7.1	27.9	12.2	51.1	18.8	17.1	10.9	25.5
	30	60.0	8.7	6.5	7.9	15.7	26.5	223	32.7	14.9	10.5	8.2	35.3	15.0	63.6	23.0	21.3	13.8	24.1
	36	72.9	10.6	8.0	9.3	17.9	30.3	276.7	41.5	17.5	12.7		42.5	17.0	74.0	27.0	25.0	16.0	29.0
	42	81.1	12.1	9.4	10.9	20.2	32.6	313	47.5	18.9	13.8		50.0	19.0	82.0	31.0	28.0	19.5	31.0
	48	88.7	13.7	10.6	12.5	23.1	35.4	350	54.4	21.2	15.5		56.9	21.0	92.0	35.0	32.0	23.0	33.0
10	48	89.3	13.7	10.7	12.6	23.0	34.7	354	52.3	20.9	15.8		56.1	21.0	91.3	34.3	32.1	22.8	33.1
	54	98.7	15.3	12.4	14.2	25.3	37.7	406	56.0	23.2	17.1		63.0	23.0	100.0	37.0	36.0	26.0	35.0
	60	114	16.6	13.7	15.7	27.8	41.3	484	69.2	27.1	18.8		67.6	25.4	108	39.7	43.9	29.1	37.3
	75	135	20.7	16.5	19.0	32.5	48.0	620	88.6	33.1	24.1		82.1	30.5	128	38.6	54.7	37.2	42.3
	90	160	24.8	20.0	23.0	37.0	54.3	780	118	37.0	30.0		96.2	36.9	148	48.4	64.2	42.9	48.8
	105	175	29.7	23.0	26.0	42.0	60.0	940	145	42.5	30.4		115	43.0	170	51.0	73.5	48.0	55.5
	120	190	33.4	27.0	30.0	46.0	70.0	1100	180	47.0	35.2		130	48.0	190	53.0	81.3	54.0	60.0

Table 2 – Interpreted results of VES data.

VES	LAYER RESISTIVITY IN Ohm-m					LAYER THICKNESS in m			
No.	ρ_1	ρ_2	ρ_3	ρ_4	ρ_5	h_1	h_2	h_3	h_4
1	4.5	28.6	53.8	1395.0	---	1.3	1.2	9.0	---
2	4.0	0.4	4.0	25.1	high	0.9	0.7	4.6	3.6
3	4.1	0.3	6.7	high	1.0	0.7	12.2	---	
4	16.5	0.6	2.0	9.5	high	0.8	0.2	5.1	10.7
5	10.3	1.2	14.4	65.6	high	0.8	0.9	15.1	21.7
6	12.0	17.9	36.2	high	---	1.5	9.4	32.8	---
7	88.5	38.8	101	high	---	1.2	2.7	4.8	---
8	7.3	4.2	16.5	94.8	high	1.5	1.6	4.4	3.8
9	14.7	0.6	3.1	26.8	high	0.9	0.2	3.1	21.0
10	11.3	2.7	4.0	13.2	high	1.2	0.3	6.1	17.0
11	7.5	1.7	3.0	7.5	high	1.0	0.8	3.9	15.4
12	8.4	5.3	52.6	high	---	1.0	2.6	14.5	---
13	7.5	3.5	18.5	high	---	1.0	2.4	27.1	---
14	6.0	28.2	78.2	high	---	1.3	2.4	20.9	---
15	11.5	1.5	13.1	high	---	0.8	0.9	8.8	---
16	11.8	2.0	6.0	54.4	high	0.9	0.8	4.6	10.5
17	16.3	0.6	6.0	13.5	high	0.8	0.3	3.9	11.2
18	7.1	15.9	41.3	high	---	1.3	6.0	65.6	---

Note: VES 6 interpretation inaccurate due to effects of lateral inhomogeneity on the measured values.

Geoelectrical Investigations

Eighteen vertical electrical soundings (VES) were carried out for studying the resistivity pattern of the area at locations shown in Fig.1. The electrode spread azimuth was kept approximately north – south for all the soundings, in order to avoid variations in measured resistivity due to formation anisotropy. The measurements at VES site-6 seem to have been affected by the presence of a lateral inhomogeneity, probably the sub-surface dyke exposed in the nearby well. A direct current resistivity meter was used and measurements were made adopting the Schlumberger electrode configuration. Current electrode separations were expanded in steps of 3 m (AB/2 = 1.5, 3, 6, 9, 12 m ....) upto AB/2 = 60 m and then in steps of 6 m upto a maximum of AB/2 = 120 m, with appropriate MN separations. A fairly large current (about 1 ampere) was impressed on the ground for increasing accuracy of measurements. The apparent resistivity values (for selected AB/2 separations) for all the soundings are given in Table 1. The sounding data was interpreted first by using the auxiliary point chart method (Bhattacharya and Patra 1968) and later refined by computer simulation using the software developed by Vander Velpen (1988). The interpreted results are given in Table 2. The spatial variation in the resistivity of the unconfined aquifer formation (7 to 10 m depth) is shown in Fig.4 in the form of iso-resistivity contours.

The pseudo-electric sections drawn, using apparent resistivity values for various current electrode separations, along two profiles, AA' (across the valley) and BB' (along the valley) is shown in Fig.6 (A and B). The figures show that the sub-surface lithology is clearly reflected by the resistivity pattern of the area in that a very pronounced resistivity-low in the middle part of the basin coincides with the zone underlain by thick clay and clacrete formations. It also incidentally coincides with the zone of high electrical conductivity of groundwaters. The geoelectric section along the two profiles AA' and BB', are shown in Fig.7 (A and B). It is noticed that geoelectrically, the calcrete layer and the weathered rock layer are indistinguishable from each other, probably due to identical resistivities. The geoelectric section clearly indicates the existence of a valley at the centre and reflects the subsurface geology as seen in Fig.2 adequately.

Sediment Analysis

Sedimentological studies often help in understanding the nature and origin of the aquifer which may throw light on the quality of groundwater present in it. Sieve analyses of samples from the area showed clear cut differences in particle size as well as grain shapes of the sediments from the area having brackish water and fresh water. In the case of the regolith material present at the surface in the northern part of the basin, the clay content (> 4 on phi scale) is as high as 97% by weight while it is only about 80% in the case of the black clay occurring in the central part. The black clay is further characterized by substantial quantities of concretionary materials as well as gypsum crystals which together make up as much as 7% of the sample. It also contains about 6% fine sand and well rounded, spherical particles of sandstone rock indicating transportation over long distances. The black clay is also totally unfossiliferous and X-Ray difraction studies have revealed that illite is the main clay mineral in it. The regolith material characteristically contains less than 1% fine sand, appreciable amounts of garnet and magnetite crystals.

Discussion

The basin-like structure of the study area suggested by the lithologs points to the possibility of the existence of a depositional basin wherein the black clay was deposited. Presence of calcrete above the weathered bed rock (below the clay) indicates a period of arid climate prior to the period of deposition. The angular nature of the particles and presence of garnet and magnetite in the regolith indicate that the material is a weathered *in situ* product of the charnockite basement. On the other hand, the well developed sphericity and roundness of sand particles in the illite-rich black clay points to the possibility that the black clay is made up of re-worked sediments derived from the Gondwana shales/clays exposed a few kilometres to the west and north of the area.

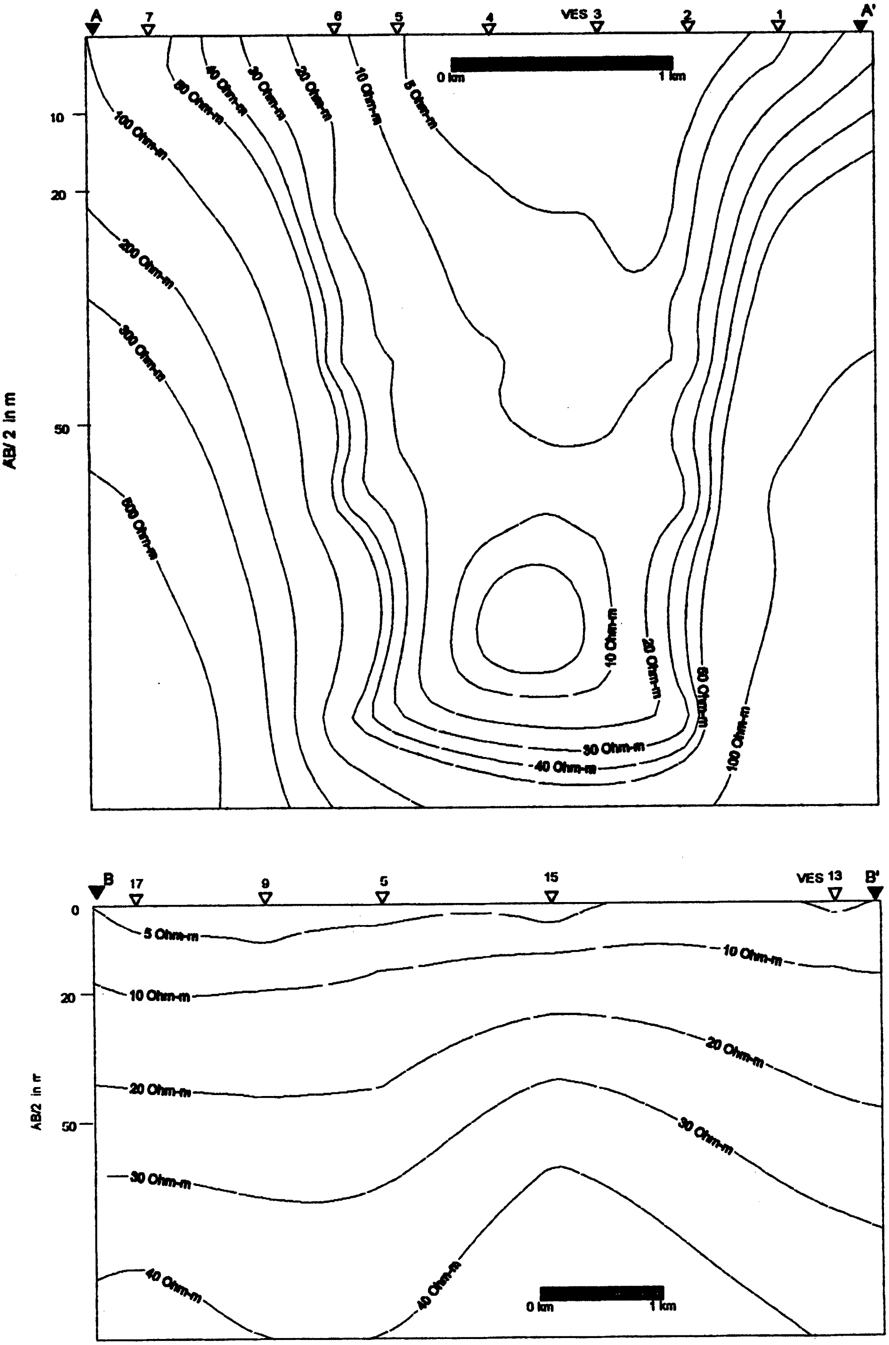

Fig. 6. Apparent resistivity sections along profiles AA' and BB'.

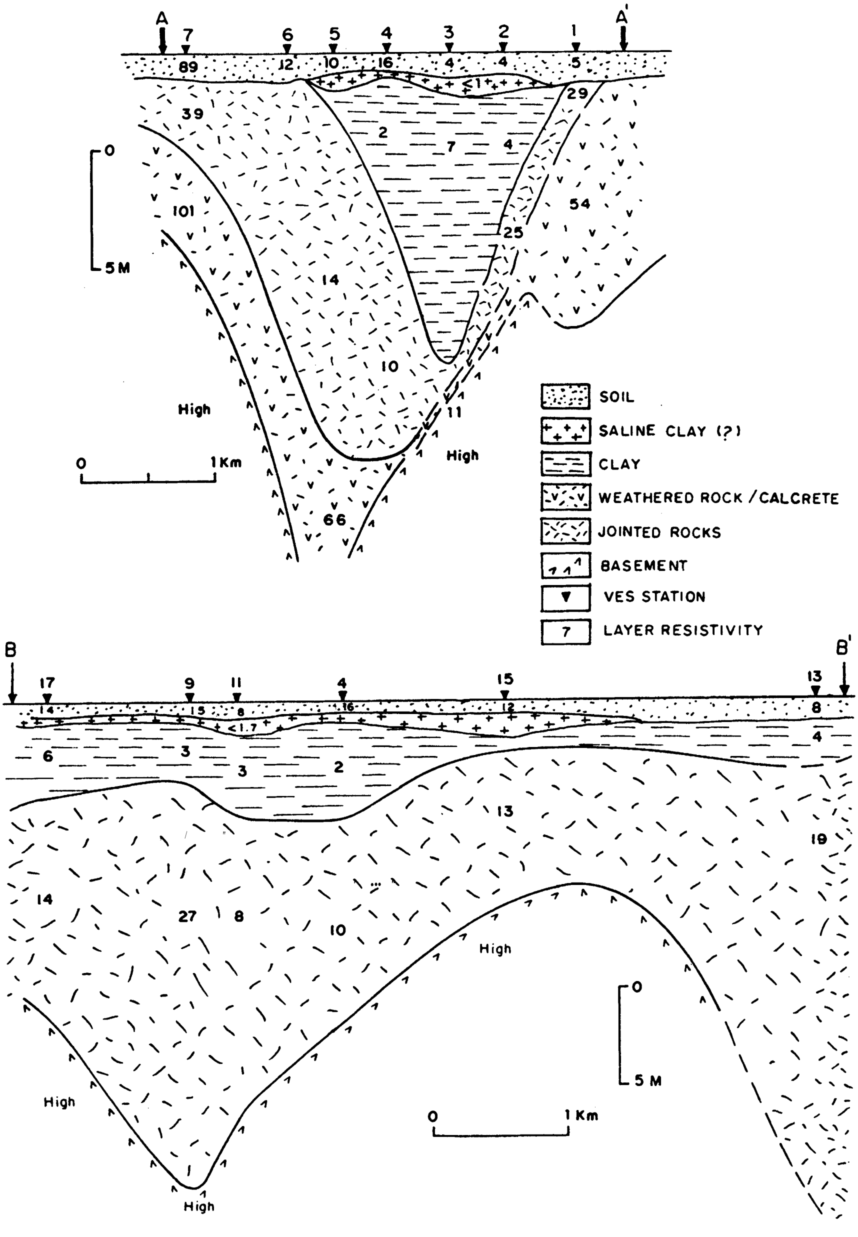

Fig. 7. Geoelectric sections along profiles AA' and BB'.

The high salinity of the groundwater in the aquifers underlying the black clay probably indicates a period of marine/estuarine conditions during which the clays were deposited. Absence of fossil remains indicates a shallow, highly brackish environment and arid climate. The sharp differences in groundwater quality – chloride type in area-1 and bicarbonate type in area II – also points to this possibility.

Several cases of occurrence of saline groundwaters in crystalline rocks have been reported (Edmunds and Savage 1991). However, most of them are related to groundwater in deep aquifers – 500 m or more. Rock-water interaction, leaching of overlying sediments and marine transgression have been cited as possible reasons for the presence of saline waters in the crystalline rocks. In the study area however, it appears that the salinity of the groundwaters is wholly due to marine environment. This is indicated from the fact that fresh water exists in the same bed rock on either side of the basin containing saline waters at relatively the same depths. The presence of brackish groundwater in a well in area-2 (with no clay/calcrete layer on top) on the southern side of the basin rules out the possibility of leaching as a source of brackishness.

The groundwater in the area falls into two distinct types namely 1) chloride (+ sulphate) and 2) bicarbonate waters. These two classes can be almost exactly correlated with the near surface lithology : areas with black clay and calcrete having type-1 groundwaters while areas with regolith on the surface having type-2 waters, excepting one or two zones like that of well No. 2. The brackishness of groundwater in the area of well No. 2 is obviously caused by the mixing of the fresh and saline waters of the area in the contact zone due to good hydraulic continuity between the two waters. Fig. 5 highlights these two classes of groundwaters and shows that groundwaters having an EC of less than 3,500 µS/cm have uniformly high bicarbonate (+ carbonate) concentration compared to chloride concentration. All these wells are also located in area-2 which do not contain any black clay and/ or calcrete near the surface as compared to those having an EC of more than 3,500 µS/cm which are rich in (CO_3+HCO_3) concentration and poor in Cl.

The abrupt change in the salinity of groundwaters over a few hundred metres in the northern side of the basin is a fortuitous circumstance, brought about by the probable existence of a subsurface dolerite dyke with an approximately east-west trend. This is supported by the presence of boulders of this rock, found exposed in well No.16. This dyke may be acting as a semi-impermeable barrier, separating the fresh groundwaters in the northern side from the saline groundwaters of the basin. Such a contrast in the quality of groundwater is not observed in the southern margin of the basin and in fact well No. 2, which was under construction when the investigations were on, was found to contain brackish groundwater. This is despite the fact that no sustained groundwater abstraction is taking place on the southern side unlike in the northern side, where several dug wells have been in use supplying water for irrigation over a number of years. However, with the commissioning of a few deep borewells for industrial purposes in the year 1992-93, the groundwater quality in the

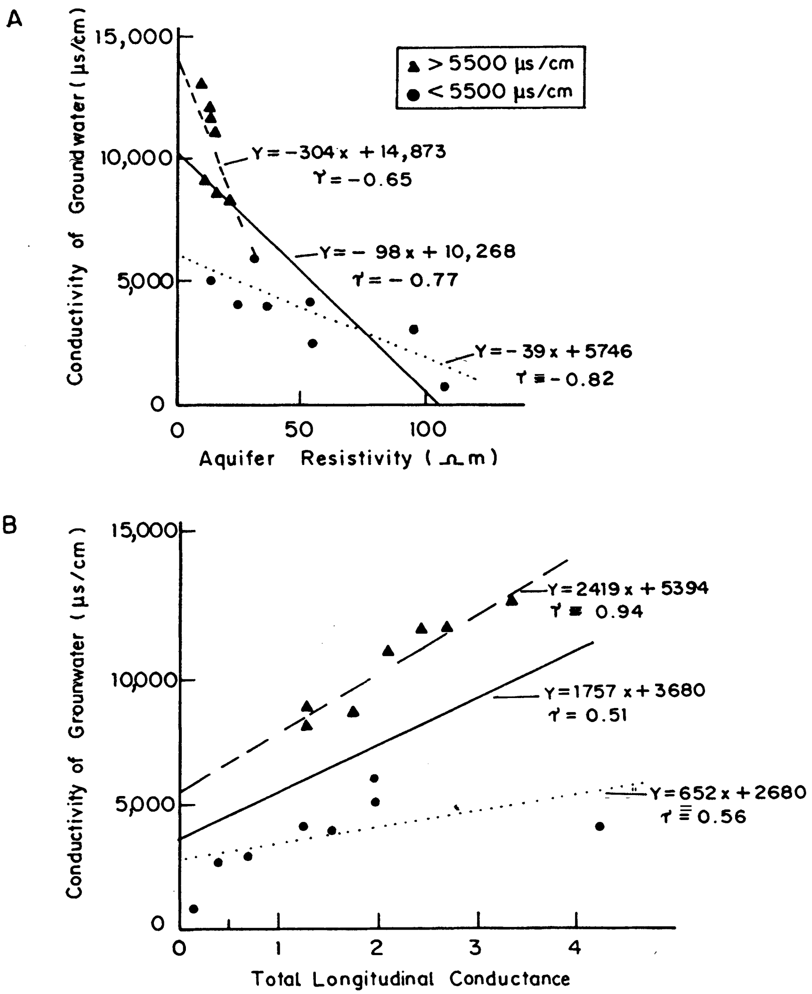

Fig. 8. Correlation plots – (A): Aquifer resistivity vs Groundwater conductivity and (B): Total longitudinal conductance *vs* Groundwater conductivity.

northern side also has started showing signs of contamination with the brackish waters. This is apparent from the fact that the EC of groundwater from borewells 7 and 8, on the northern side of the dyke, was about 1,000 µS/cm in 1991 (Baratan 1991) but by 1994 it had reached a value of about 3,500 µS/cm, though the EC of groundwater in the shallow wells close by continued to be less than 1,000 µS/cm. The sharp increase in salinity of the groundwater of these two borewells is obviously caused by large scale abstraction by the industry, resulting in the development of a steep hydraulic gradient northwards. The brackish water from the south had not migrated northwards prior to 1992 because of the presence of the dyke, relatively gentle hydraulic gradient as well as recharge from the northern side. The significant increase in groundwater abstraction since 1992 has considerably steepened the northward hydraulic gradient leading to increased flow of brackish water, resulting in greater salinity in the borewells to the north of the dyke.

A comparison of aquifer formation resistivity with groundwater conductivity (Fig.4) shows excellent correlation. A similar correlation is observed between apparent resistivity (Fig.1) and groundwater conductivity as well, which is mainly due to the fact that the area of highly brackish groundwater has a cover of conductive clay layer while the area with fresh water is underlain with more resistive regolith. Statistical analysis of data on groundwater conductivity and aquifer resistivity and also total longitudinal conductance was carried out to study the correlation factors (Fig.8). It is seen that while the correlation coefficient between aquifer resistivity and groundwater conductivity for all the samples is -0.77, it is slightly higher (-0.82) for those samples having a conductivity of less than 5,500 µS/cm. A much better picture emerges in the case of total longitudinal conductance ($h_1/\rho_1+h_2/\rho_2+ \ldots h_n/\rho_n$, where h is the layer thick ness and ρ is the layer resistivity). While the correlation coefficient for all the samples is 0.51, in the case of areas having groundwaters with EC of more than 5,500 µS/cm (wholly from area-I) the correlation coefficient is 0.94 as compared to 0.56 for areas where the groundwater conductivity is less than 5,500 µS/cm. It is possible that the low coefficient of correlation is caused, to some extent, by the likely inaccuracies in the determination of the formation resistivities due to the principle of equivalence (Mailet 1947).

Conclusions

The presence of brackish to saline groundwater along a narrow part of Adyar river basin, flanked by fresh water on either side suggests that the area must have experienced marine environment and was probably an extended arm of the near by Gondwana sedimentary basin in its terminal stages. The presence of fresh water close to brackish groundwater is most probably due to the presence of a sub-surface barrier which apparently restricts the movement between the two groundwater regimes. An excellent correlation between geoelectric parameters and groundwater salinity is seen in the area. However, as the brackish to saline groundwaters are in areas having more clayey material, the formation resistivity is likely to influence the overall aquifer resistivity to a significant extent. This underscores the fact that any attempt to correlate aquifer resistivity with groundwater quality should necessarily consider the variation in lithology that may be present in the area of investigation. The fact that the correlation coefficient is quite low in the case of partly weathered/jointed rock aquifers indicates that the aquifer resistivity in case of crystalline rock aquifers is controlled more by formation resistivity than formation water resistivity. This has important implications in the application of geoelectrical parameters for groundwater quality studies in areas underlain by more than one rock type. The study also shows the usefulness of sedimentological analysis in understanding the geochemical evolution of groundwater. The study further illustrates the usefulness of geoelectrical investigations in mapping sub-surface geology and delineating fresh water – saline water bearing zones in an area.

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