Estimation of aquifer parameters from surfacial resistivity measurement in a granitic area in Tamil Nadu

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This article aims to establish an empirical relationship among geoelectrical properties of aquifer and hydrogeological parameters to estimate its hydraulic properties, and reduce the processes of pumping test, which are costly and time consuming. A total of 19 Vertical Electrical Sounding (VES) data were collected using Schlumberger configuration in a granitic terrain in Tamil Nadu. The geographical parameters were analysed with IX1-D v.3 Interprex software. The pumping test conducted on nearby open wells was also used. A cross-correlation test was ascertained between hydraulic conductivity (K) and aquifer resistivity (ρ). It was found that hydraulic conductivity is best defined as an exponential function of aquifer resistivity. The field parameters, $A = 20.235$ and $B = 0.012$, of the function were optimized by using 'Solver', with the least SSQ (=7.82) and MARE (=0.816). It helped to estimate hydraulic parameters along with an empirical equation without pumping test data. The results emphasized the potential of surfacial resistivity survey in granitic area to determine aquifer properties where well information is not available.

Keywords: Field parameters, granitic terrain, geoelectrical properties, hydraulic conductivity, shallow aquifer.

WATER, a renewable natural resource, occurs in three forms – liquid, solid and gas. It is essential for irrigation, industry and domestic purpose. Groundwater is the main source for potable water supply, domestic, industrial and agricultural uses in most countries[1]. But its scarcity is increasing due to rapid population, urbanization, industrial and agricultural related activities, with devastating effects on humans and ecosystems. Groundwater is more beneficial than surface water, because there is no scope to conjunctively use two resources in some areas which have remote chances of surface water availability. This scarcity not only affects human life, but also other living things. To meet the demand for water, people depend more on deeper aquifers[2]. The aquifer characteristics are important for both groundwater and land vulnerability assessment. A well known technique called 'pumping test' for determining hydraulic conductivity, and grain size analyses for parameter estimation is available, but it is relatively expensive. They are either integrated over a large volume, or only provide information at the bore-hole vicinity[3]. By exploring a possible application of surfacial geoelectrical data, these pitfalls could be circumvented and the information/cost ratio optimized, to estimate aquifer properties.

Many researchers have studied the relationship between aquifer characteristics and geoelectrical parameters[4–14]. It has been hypothesized that the geology and quality of groundwater remain fairly constant within the interested area, and aquifer and geophysical parameters are interrelated[4]. For saturated and unsaturated zones of aquifers, the correlation has also been established[15]. An analytical relationship was developed between hydraulic conductivity and electrical resistivity, through Darcy's law of lateral flow of groundwater and Ohm's law of current flow in clean porous media[4]. These results provide a physical and mathematical basis for statistically established relations[4].

Electrical measurements through geoelectrical methods are mainly influenced by porosity and fluid resistivity. This is because the rock matrices are porous, insulated and electrical currents pass easily through water or moisture present in the pores. Therefore, resistivity data collected on the surface restrain useful information about the subsurface, including aquifers which could be deciphered by experienced hydrogeophysicists. A good estimation of hydraulic conductivity and transmissivity from surface geoelectrical measurements could provide important complementary information. The hydraulic flow is mainly controlled by porosity and it helps reduce the cost of hydrogeological studies.

It is common practice to characterize the aquifer along with its resistivity and thickness obtained from surfacial resistivity data. But it is essential to transform aquifer resistivity in terms of aquifer parameters. A meaningful relationship between resistivity and hydraulic conductivity of the aquifer could be derived either theoretically or

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empirically. Theoretical relations are advisable if the model is based on the real world. Now, the empirical relationships are flourishing due to obvious limitations of the mathematical model.

Thus, the objectives of this article are to (1) estimate geoelectrical layers through vertical electrical soundings; (2) establish relationship between geoelectrical properties and hydraulic parameters; and (3) refine the transmissivity map using the model parameters (depend on the field conditions) in a hard granitic terrain in Tamil Nadu.

Study area

The study was carried out in an area of 2250 sq. km, between long. 77°53′08″–78°01′24″E and lat. 10°13′44″–10°26′47″N in Tamil Nadu (Figure 1). Topography varies from 360 m above mean sea level (amsl) in the southern part to 120 m amsl in the northern part in plain areas, sloping towards north and northeast[16,17]. There is no perennial river, but the main river Kodaganar, originates from the Pantrimalai hill along with its short distance streams. These streams encompassed second and third order drainages and flow towards its confluence with Amaravati River in the north[18–20]. There are two surface water reservoirs. One at Attur in the southern corner, upstream and another at Alagapuri, in the downstream. The annual average rainfall is about 875.8 mm in the upper basin and about 607.6 mm in the lower basin, as recorded at Dindigul and Vedasandur rain gauge stations respectively. The mean of maximum temperature ranges from 36.5°C to 41.8°C, whereas the mean of minimum temperature varies from 17.4°C to 24°C.

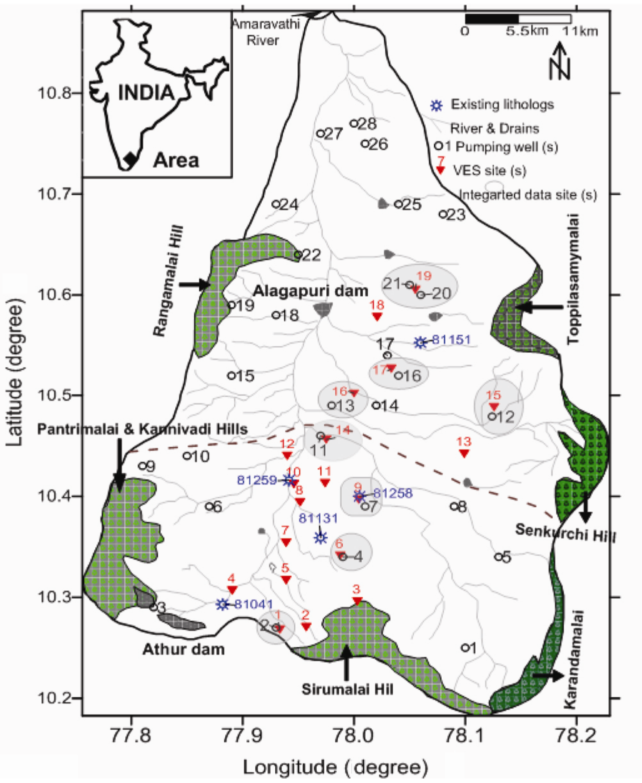

Figure 1. Location of the study area showing VES points, pumping wells and available lithologs sites.

Geologically, granite and gneisses occupy most of the parts except in hilly areas where charnockite exists[21]. The larger part is occupied by highly folded, fractured and jointed metamorphic crystalline rocks[22]. Quartzite and pyroxenite also occur in patches. Lineaments are limited in the entire area. They are mainly oriented in the NNE–SSW, NEE–SWW and NW–SE directions[20]. The denudational terrain surrounded by structural hills occur in the form of pediments. Both shallow and buried pediments are major geomorphic units in the study area[23]. Groundwater is moderate in the shallow pediment[16]. The areas of low relief constituting buried pediments are the most favourable regions for groundwater potential. Groundwater occurs in weathered portions in unconfined condition whereas in deeper joints and fractures, it is in unconfined, semi-confined and confined conditions[24]. Local people exploit groundwater through dug, bore and dug-cum-bore wells. The shallow weathered part facilitates the movement and storage of groundwater, through a network of joints, faults and lineaments in the study area. The depth in groundwater level varies from 3.90 to 24.00 m bgl. Aquifer parameters, namely, transmissivity (T) and storage coefficient (S) vary from 4 and 1166 m^2/day and 0.00001 to 0.099, respectively[16].

Database and methods

Vertical electrical sounding survey

Vertical electrical resistivity (VES) survey using Schlumberger configuration[25] has been adapted in 19 locations (Figure 1) to deduce weathered and fractured zones in the study area. In the Schlumberger array, apparent resistivity (ρ_a) is given as

$$\rho_a = 2\pi R\left(\frac{L^2}{2l} - \frac{l^2}{2l}\right), \quad (1)$$

where L = half current electrode separation, l = half potential electrode spacing and R = resistance.

The collected data were interpreted using IX1D (v3) Interprex software keeping the idea of depth investigation equal to one third (1/3) of the current electrode spacing (2L), at the point of inflection[26]. This yielded electrical resistivities (ρ) and thicknesses (h) of the various subsurface layers. Then these parameters were standardized based on existing lithologs[23].

Pumping test data

Aquifer performance tests were conducted[16] with constant discharge rates at 28 existing dug wells (Figure 1). The data were analysed using an easy and versatile numerical method, which was proposed by Singh and Gupta[27]. Both, the pumping and recovery phases, had been considered for estimating aquifer parameters used for the analysis.

Evaluation of field parameters

For performance evaluation of any model there are many criteria[28]. The sum of squares of deviation (SSQ) and mean absolute relative error (MARE) are the two objective functions to obtain optimal solutions corresponding to minimum deviation and least error. It helps to obtain the computed hydraulic conductivity (K_c) for any model, which should be close to the observed hydraulic conductivity (K_0). Alternatively, the performance evaluation criteria parameters lead to the required modifications (field parameters, A and B) in the model of hydraulic conductivity and the efficiency of the model to obtain the desired results. Therefore in this study the performance evaluation criteria parameters are used as objective functions. It includes SSQ (L^1T^{-1}, in eq. (2)), to verify the accuracy of the procedure adopted for model calibration. The MARE (L^0T^0, in eq. (3)) is also used to verify the mean absolute error between observed and calculated hydraulic conductivity

$$\text{SSQ} = \sum_{i=1}^{N} (K_0 - K_c)^2, \quad (2)$$

$$\text{MARE} = \frac{1}{N} \sum_{i-1}^{N} \frac{K_0 - K_c}{K_0}, \quad (3)$$

where N is the number of observation points, K_0 the observed hydraulic conductivity (L^1T^{-1}) and K_c the calculated hydraulic conductivity (L^1T^{-1}).

The main objective of our model was to compute the required hydraulic conductivity corresponding to the input resistivity value. To calibrate this model, the field parameters that include the values of A, and B were estimated. Optimization (minimization) was carried out by using the add-in tool Microsoft Excel Solver, which uses known data set values. These datasets included aquifer resistivity and the corresponding hydraulic conductivity at a particular VES location. The optimal values of model parameters were calculated using these data. These values were then utilized to calibrate the mathematical model. Optimization involve steps for finding an alternative with the highest achievable performance under given constraints by maximizing desired factors and minimizing undesired ones. SSQ (eq. (5)) and MARE (eq. (6)) were used to estimate optimal values of the model parameters. Here the objective was to minimize the SSQ (or MARE) value, such that the least value of SSQ (or MARE) would correspond to the optimal field values for A and B. The following steps were used to estimate field parameters for the nonlinear structure, and consequently, for computation of hydraulic conductivity:

- Any suitable first trial values were assumed for the field parameters for A and B.
- Computation of hydraulic conductivity regarding aquifer resistivity with corresponding VES location:

$$K = A\mathrm{e}^{-B\rho}. \quad (4)$$

- Then the first objective function

$$\text{SSQ} = \sum_{i=1}^{N} (K_0 - K_c)^2, \quad (5)$$

- and second objective function

$$\text{MARE} = \frac{1}{N} \sum_{i-1}^{N} \frac{K_0 - K_c}{K_0}, \quad (6)$$

were utilized for optimization (minimization). The Microsoft Excel tool (Solver) was used to estimate field parameters, as it is easy and user-friendly and does not require any programing language.

Results and discussion

Geoelectrical parameters

Vertical electrical sounding (VES) data with Schlumberger array were collected with the current electrode spreading (AB) of 80–120 m at 19 sites (Figure 1) to estimate geoelectrical parameters. These data were plotted on double log sheet (Figure 2) to generate field curves. It indirectly indicates that the apparent resistivity values increase with depth in the experimental area. Initially the sounding curves were interpreted through the curve-matching techniques[29] to generate initial model parameters and then entered in the IX1-D Interprex software for interpreting layer parameters. It yields about 3–7 geoelectrical layers up to the explored depth of 37 m (Tables 1 and 2). Typical outputs of interpreted VES data (at VES_17) are presented in Figure 2. The details of subsurface lithology as observed from nearby existing lithologs and well cuttings were considered during interpretation.

Table 1. Geoelectrical layer parameters along with inferred lithology from a hard rock area in Tamil Nadu

				Geoelectrical parameters				
				Depth (m)				
VES No.	Village	Longitude (°)	Latitude (°)	From	To	Resistivity (Ω-m)	Inferred lithology	Depth to water level (m bgl)
1	Ambathrai	77.9333	10.2679	0.00	0.31	48.5	Top soil	24.00
				0.31	2.13	17.9	Clay with kanker	
				2.13	4.52	43.0	Weathered granite	
				4.52	23.90	250.0	Fractured weathered granite	
				23.90	–	3028.0	Fresh granite	
2	Ellapatti	77.9570	10.2704	0.00	0.41	8.7	Top soil	20.95
				0.41	1.77	4.9	Clay with kanker	
				1.77	8.00	13.3	Clay with kanker	
				8.00	20.82	336.1	Semi weathered/fractured granite	
				20.82	–	8636.0	Fresh granite	
3	Malaikovilur	78.0030	10.2960	0.00	0.78	3328.0	Top soil	16.05
				0.78	2.06	387.0	Semi weathered/fractured granite	
				2.06	4.34	1454.0	Granite	
				4.34	9.82	473.0	Hard rock	
				9.82	18.30	709.0	Granite	
				18.30	37.17	345.0	Semi weathered/fractured granite	
				37.17	–	689.3	Fresh rock	
5	Ratanagiri	77.9390	10.3170	0.00	0.37	56.3	Top soil	8.10
				0.37	0.86	81.8	Weathered granite/saline aquifer	
				0.86	3.12	58.0	Weathered granite	
				3.12	11.71	316.8	Semi weathered/fractured granite	
				11.71	33.44	176.7	Weathered gneiss	
				33.44	–	702.0	Fresh rock	
7	Paraipatti	77.9390	10.3540	0.00	0.39	40.3	Top soil	3.90
				0.39	0.39	106.4	Weathered gneiss/saline aquifer	
				1.17	2.70	30.8	Clay with kanker	
				2.70	5.66	102.0	Weathered granite/saline aquifer	
				5.66	5.66	11.2	Clay with kanker	
				13.55	24.38	164.7	Weathered granite	
				24.38	–	614.5	Fresh rock	
8	Chinnamanyakkapatti	77.9515	10.3940	0.00	0.38	101.0	Top soil	5.50
				0.38	0.38	53.8	Weathered granite/saline aquifer	
				1.74	15.18	260.3	Semi weathered/fractured granite	
				15.18	–	2386.0	Hard rock	
10	Budipuram	77.9460	10.4120	0.00	2.83	4.2	Top soil	5.70
				2.83	6.99	24.9	Partially weathered mica gneiss	
				6.99	35.92	430.0	Fresh rock	
				35.92	–	720.0	Fresh rock	
11	Alkkuvarpatti	77.9740	10.4130	0.00	0.74	19.1	Top soil	5.80
				0.74	1.94	56.1	Partially weathered mica gneiss	
				1.94	4.12	45.0	Partially weathered gneiss	
				4.12	10.28	368.0	Semi weathered granite	
				10.28	–	772.0	Hard rock	
12	Ulagapatti	77.9400	10.4400	0.00	0.97	9.2	Top soil	12.90
				0.97	7.96	40.3	Weathered granite	
				7.96	16.57	378.5	Semi weathered gneiss	
				16.57	–	324.5	Semi weathered granite	
13	Vadamadurai	78.0990	10.4420	0.00	0.73	4.3	Top soil	5.80
				0.73	2.36	65.5	Weathered granite	
				2.36	8.50	21.9	Clay with kanker	
				8.50	–	14896.0	Hard rock	
14	Undarpatti	77.9750	10.4561	0.00	0.43	12.3	Top soil	4.90
				0.43	3.38	26.3	Partially weathered mica gneiss	
				3.38	8.16	7.3	Clay with kanker	
				8.16	16.06	107.9	Weathered granite	
				16.05	–	3134.0	Hard rock	

(*Contd*)

Table 1. (*Contd*)

VES No.	Village	Longitude (°)	Latitude (°)	Geoelectrical parameters: Depth (m) From	To	Resistivity (Ω-m)	Inferred lithology	Depth to water level (m bgl)
15	Pallakkurichchi	78.1258	10.4882	0.00	1.47	28.5	Top soil	9.50
				1.47	4.12	96.1	Weathered granite	
				4.12	18.91	78.6	Weathered granite/saline aquifer	
				18.91	–	1536.8	Hard rock	
16	Mathinipatti	78.0000	10.5020	0.00	1.71	115.0	Top soil	14.25
				1.71	13.27	73.0	Weathered granite	
				13.27	17.77	47.0	Saline aquifer	
				17.77	23.72	336.7	Semi weathered granite	
				23.72	–	11902.0	Hard rock	
17	Erioydu	78.0334	10.5268	0.00	0.43	26.3	Top soil	7.90
				0.43	1.83	83.3	Weathered granite	
				1.83	7.56	43.5	Weathered gneiss/saline aquifer	
				7.56	31.44	590.6	Hard rock	
				31.44	–	2094.0	Hard rock	
18	Usilampatti	78.0208	10.5780	0.00	1.17	52.1	Top soil	10.00
				1.17	2.07	80.6	Weathered granite	
				2.07	13.10	62.6	Weathered granite/saline aquifer	
				13.10	–	641.5	Hard rock	
19	Kovilur	78.0551	10.6051	0.00	0.40	102.0	Top soil	6.25
				0.40	1.00	24.0	Clay with kanker	
				1.00	2.20	90.0	Weathered granite	
				2.20	4.40	24.3	Clay with kanker	
				4.40	8.30	102.0	Weathered gneiss/saline aquifer	
				8.30	–	8723.0	Hard rock	

Table 2. Geoelectrical layer parameters along with inferred lithology at the selected sites from a hard rock area in Tamil Nadu

Litholog ID	Depth (m bgl) From	To	Existing lithology	Geoelectrical layer: Depth (m bgl) From	To	Resistivity (Ω-m)	Hydrogeological inferences
81041 (near at VES_4 site)	0.00	2.00	Red sandy	0.00	4.47	15.7	Top soil
	2.00	13.00	Weathered granite	4.47	18.80	36.8	Weathered granite
	13.00	22.00	Partially weathered granite	18.80	–	408.0	Fresh rock
	22.00	35.00	Fissured mica gneiss	–	–	–	–
	35.00	38.00	Fissured mica gneiss pegmetite intrusion	–	–	–	–
	38.00	43.00	Pegmetite intrusion	–	–	–	–
	43.00	48.00	Fissured mica gneiss with pegmetite intrusion	–	–	–	–
	48.00	50.00	Fissured mica gneiss	–	–	–	–
	50.00	55.00	Fresh mica gneiss	–	–	–	–
81131 (near at VES_6 site)	0.00	3.00	Top soil	0.00	0.23	7.5	Top soil
	3.00	14.00	Weathered biotite gneiss	0.23	11.45	32.6	Weathered gneiss
	14.00	29.00	Partially weathered biotite gneiss	11.45	–	7076.0	Fresh rock
	29.00	40.00	Fresh granite gneiss	–	–	–	–
81258 (near at VES_9 site)	0.00	1.00	Top soil	0.00	2.08	247.0	Topsoil
	1.00	7.00	Kankar	2.08	24.08	140.0	Weathered granite
	7.00	8.00	Pegmatite intrusion	24.08	27.37	415.0	Semi weathered/ fractured granite
	8.00	17.00	Weathered granite gneiss	27.37	–	7194.0	Fresh rock
	17.00	22.00	Weathered biotite gneiss	–	–	–	–
	22.00	38.00	Fissured sheared granite gneiss	–	–	–	–

Standardization: The interpreted layer parameters were standardized and discussed in collaboration with nearby selected existing lithologs and/open well cut (Table 2). The comparison of interpreted geoelectrical attributes at VES_4 (village: Sivalsragu) shows that the geoelectrical section consists of a succession of top soil, weathered gneiss and fresh granite rock. The weathered gneiss granite (resistivity: 36.8 Ω-m) serves as a shallow aquifer where groundwater level is measured at a depth of 13 m bgl (Figure 3). At Thottumattu (VES_6) the first geoelectrical layer consists of clay kankar soil with resistivity value of 7.5 Ω-m. The second layer consists of partly weathered biotite gneiss with resistivity of 32.6 Ω-m.

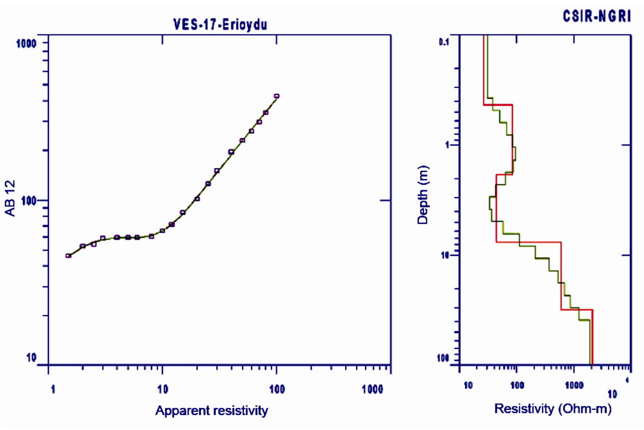

Figure 2. *a*, Logarithm plot between electrode spacing and apparent resistivity (circle indicates field data and continuous line indicates field curve). *b*, VES interpreted smooth (green line) and layered curves (red line) through the computer 1X1-D Interpex software.

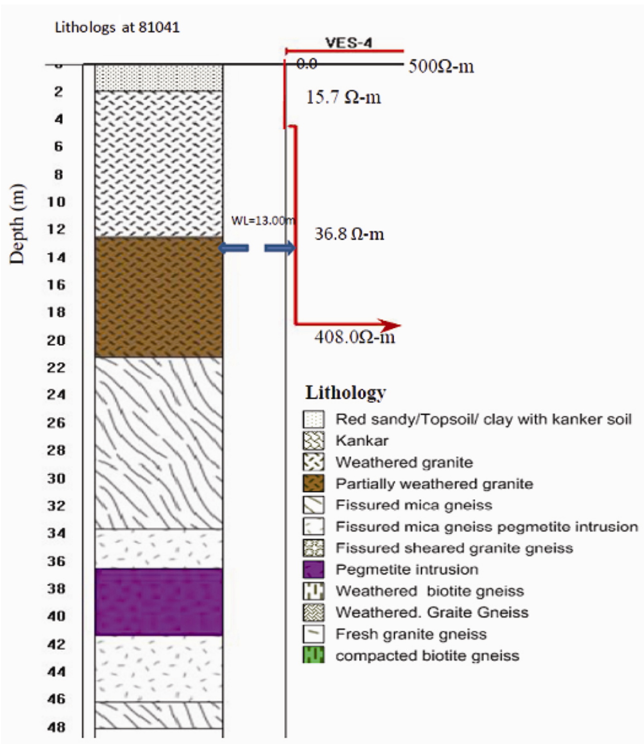

Figure 3. Comparison of geoelectrical parameters (at VES_4) with the existing borehole lithologs (81041) at Sivalsragu village.

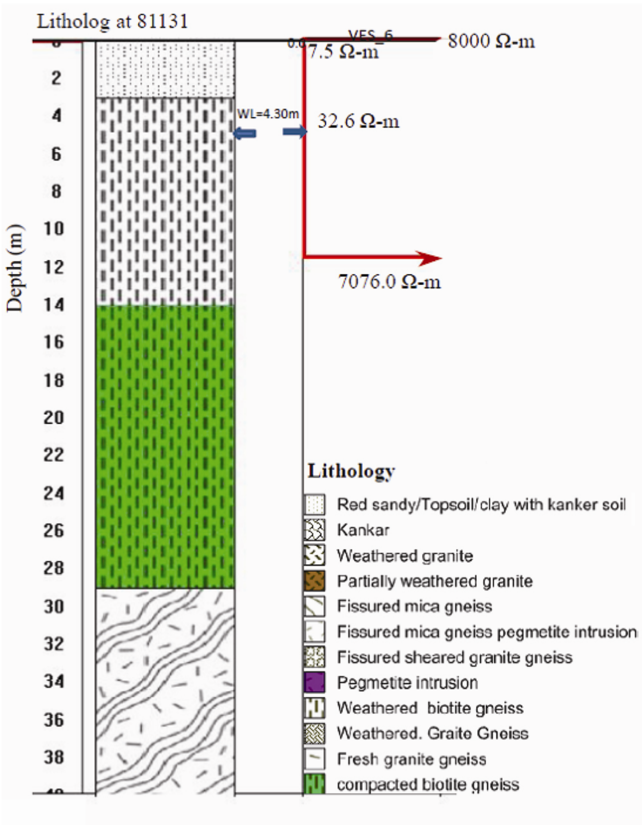

Figure 4. Comparison of geoelectrical parameters (at VES_6) with the existing borehole lithologs (81131) along with water level at Thottumattu village in the study area.

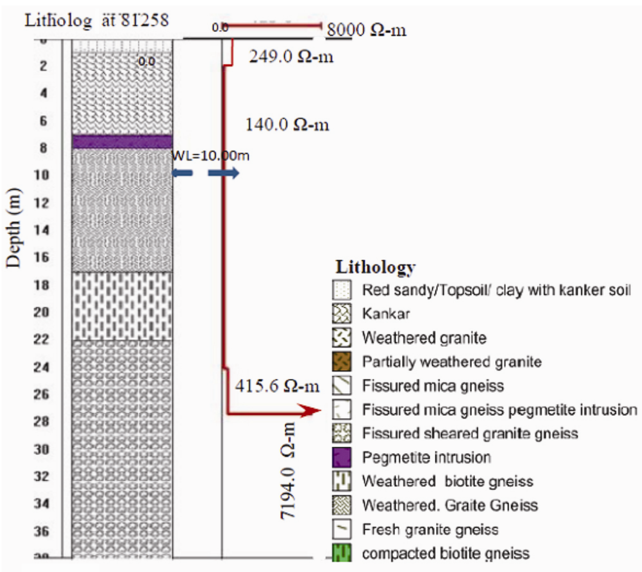

Figure 5. Bore hole lithologs (81258) compared with geoelectrical layer parameters and groundwater level at VES_9 (Mullipadi village in Tamil Nadu)

Table 3. Aquifer parameters both hydraulic properties (*T* and *K*) along with geoelectrical attributes at the selected locations in the study area

VES No.	Village	Aquifer resistivity, ρ (Ω-m)	Aquifer thickness (m)	Depth to water level (m bgl)	Transmissivity, T (m^2/d)	Hydraulic conductivity, K (m/day)
1	Ambathrai	250.0	19.39	24.00	15	0.77
6	Thottumattu	32.6	11.22	4.30	200	17.83
9	Mullipadi	140.0	22.00	10.00	96	4.36
14	Undarpatti	107.0	7.90	4.90	53	6.71
15	Pallakkurichchi	78.6	14.79	9.50	84	5.68
16	Mathinipatti	47.0	4.50	14.25	25	5.56
17	Eriodu	43.5	5.73	7.90	70	12.21
19	Kovilur	102.0	4.10	6.25	32	7.80

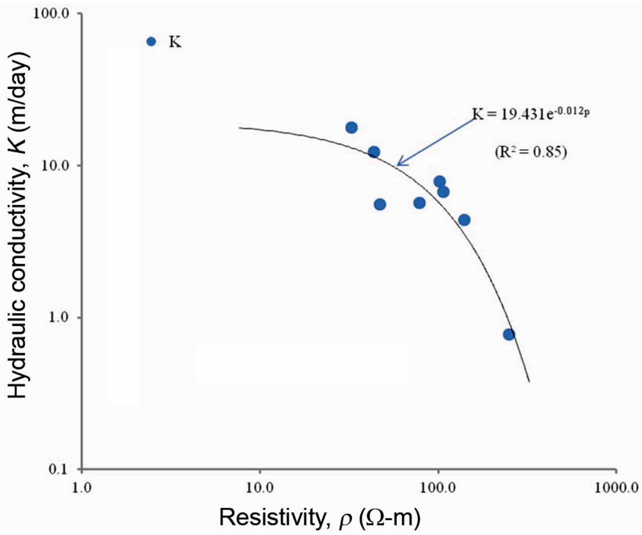

Figure 6. Relation between hydraulic conductivity (*K*, in m/day) and electrical resistivity (*p*, in Ω-m).

It acts as shallow aquifer where groundwater level is encountered at a depth of 4.30 m bgl. This layer is underlain by fresh granite gneiss with resistivity of 7076.0 Ω-m (Figure 4). The VES_9 (village: Mullipadi) is explored up to depth of 27.37 m with 4-geolectrical layers. The first geoelectrical layer at VES_9 encountered kankar soil with resistivity value of 249.0 Ω-m and thickness of 2.08 m. Partly weathered biotitic gneiss has a second layer of resistivity of 140.0 Ω-m with thickness of 22.00 m, acting as a shallow aquifer. The groundwater level of this aquifer is measured as 10 m bgl. This layer is underlain by layer fissured granite gneiss with resistivity 415.6 Ω-m and fresh granite (bed rock) of 7194.0 Ω-m resistivity respectively (Figure 5).

The sounding results obtained from the computer-aided interpretation are presented in Tables 1 and 2. The results of the VES, when compared with existing litholog data[23] and cross-sections of nearby open wells (water table: 3.90 to 24.00 m bgl) confirmed the resistivity ranges of different subsurface geoelectrical layers.

4.2–3328 Ω-m: Top soil cover/clay with kankar,
21.9–399.0 Ω-m: Weathered formation/saturated or saline aquifers,
23.7–384.0 Ω-m: Semi-weathered/fractured granite and gneissic granite,
>400.0 Ω-m: Hard rock (gneissic granite and gneisses).

In the study area the aquifer resistivity ranges from 21.9 to 399.0 Ω-m with thickness varying from 2.96 to 22.00 m.

Pumping test data

Singh *et al.*[16] carried out pumping test at 28 wells in the study area. Transmissivities (*T*) vary from 4 to 1166 m^2/day with an average 117 m^2/day whereas storativities (*S*) vary from 0.00001 to 0.09. Of these, eight sites available near the conducted VES stations (Figure 1) were feasible for establishing an empirical relationship between geoelectrical attributes and aquifer characters (Table 3). This shows that the shallow aquifer thicknesses vary from 4.10 to 22.00 m, with resistivity range of 32.6 to 250.0 Ω-m.

Establishment of empirical relationship between geoelectrical and aquifer parameters

Geoelectrical attributes ascertained from the 8 VES data using Schlumberger configuration and aquifer parameters (i.e. conductivity and transmissivity) were obtained for the pumping tests carried out at the open wells in the vicinity of VES points[16]. These parameters were considered for correlation studies. Electrical resistivity of aquifer (in Ω-m) and hydraulic conductivity (in m/day) of the corresponding location (at the eight sites) were correlated (Figure 6). It was observed that the data points were distributed exponentially. The best nonlinear regression line was presented ($K = A\exp(-B\rho)$), using eight data points, where both hydraulic and geoelectrical parameters were available. The curve shows negative correlation between hydraulic conductivity and electrical resistivity of the aquifers. Here *A* and *B* are called 'field parameters'

Table 4. Results of sensitivity analysis for the VES_1 site

VES No.	Sl. No.	K (m/day)	ρ (Ω-m)	A	B	R^2	Remarks	Final values of	
1	1	1.01	325.0	14.77	0.008	0.85	30% (+ve)	A	B
	2	0.94	300.0	15.97	0.009	0.86	20% (+ve)	17.47	0.011
	3	0.86	275.0	17.47	0.011	0.86	10% (+ve)		
	4	0.78	250.0	19.43	0.012	0.85	Original		
	5	0.70	225.0	21.67	0.014	0.83	10% (–ve)		
	6	0.62	200.0	24.30	0.016	0.78	20% (–ve)		
	7	0.55	175.0	26.67	0.017	0.71	30% (–ve)		

(+ve), increasing; (–ve), decreasing.

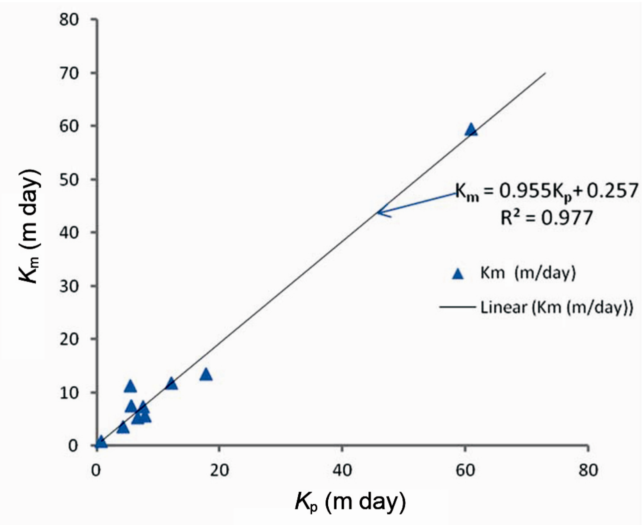

Figure 7. Cross plot of model and observed hydraulic conductivity values in a granitic area in Tamil Nadu.

and depend on the local hydrogeology of the field. A nonlinear equation was fitted and it was well correlated to each other with cross-correlation coefficient $R^2 = 0.85$. This equation was fitted with the values of $A = 19.431$ and $B = 0.012$. These parameters were optimized using Solver with minimum SSQ (= 7.82) and least mean absolute relative error MARE (= 0.08377). The values for the overall study were estimated as $A = 20.235$ and $B = 0.012$. Then the standardized empirical equation for the study area is

$$K = 20.235 \exp(-0.012\rho) \quad (7)$$

Sensitivity analysis: The field parameters (A and B) are site-specific. In order to estimate them for individual VES sites sensitivity analysis was carried out. The alternating changes (±10%, ±20% and ±30%) of the inputs like aquifer resistivity and K value at VES_1 site, keeping other parameters constant at other VES sites, the field parameters were estimated. The maximum R^2 was observed and considered as the field parameter at that specific location. The field parameters estimated at the location VES_1 are shown in Table 4. The same was done for other seven VES sites. Table 5 gives the variation of field parameters, where A value varied from 17.47 to 22.19 and B was almost constant for all VES locations as 0.012. The variation of field parameters is associated with landscape, land use, soil types, measurement devices and methods, climate and environment conditions, etc. We observe that A-values are more sensitive among all the locations at VES_15 (Pallakkurichchi) and VES 16 (Mithinipatti).

Validation: Using eq. (7) and contour maps of field-parameter distribution (A and B), the aquifer hydraulic conductivity (K_m) and transmissivity (T) was computed at each well site, where the pumping test was carried out. The computed and field-measured aquifer parameters match closely with each other within a standard mean error of 7.82 m/day. It is due to stratigraphy of the hydrogeological inferences in the sites of the granite area. The unconfined aquifer condition was shallower with higher resistivity. A cross plot between modelled and observed hydraulic conductivities is shown in Figure 7.

The aquifer parameters in the 19 VES sites are shown in Table 6. It provides aquifer hydraulic conductivities, calculated using areal distribution maps of the known field parameters (A and B, in Table 5). The unknown field parameters in 11 VES sites were also estimated based on their locations. Equations (5) and (6) were utilized for determining aquifer parameter, K, using aquifer resistivity and its thickness obtained from the interpreted VES data. Aquifer hydraulic conductivities were obtained using the standardized eq. (7) with the help of constant field parameters ($A = 20.235$ and $B = 0.012$) at all VES sites. The deviation of estimated K (m/day) between the two methods is also shown. It varies from –0.53 to 1.75 m/day with an average of 0.30 m/day. It indicates that the first method has less potential than the second and could be adopted for aquifer parameter estimation from the surface geophysical electrical method. This is because the second method provided comparatively less deviation from the actual field parameter than the first method. In the present study area the transmissivity values were also estimated at VES sites and they vary from 0.1 m^2/day to 168 m^2/day with an average of 47 m^2/day.

Table 5. Field parameters for individual VES location

VES	Village	Longitude	Latitude	*A*-value	*B*-value	SSQ value
1	Ambathrai	77.9333	10.2679	17.47	0.011	8.35
6	Thottumattu	77.9876	10.3413	17.64	0.012	8.84
9	Mullipadi	78.0042	10.3967	19.28	0.012	7.92
14	Undarpatti	77.9750	10.4561	18.90	0.012	8.04
15	Pallakkurichchi	78.1258	10.4882	20.72	0.012	7.92
16	Mathinipatti	78.0000	10.5020	22.19	0.013	8.03
17	Eriodu	78.0334	10.5268	19.36	0.012	7.90
19	Kovilur	78.0551	10.6051	18.21	0.012	8.41

SSQ, Mean of sum square deviation.

Table 6. Aquifer parameters at the 19 VES sites in shallow granite aquifers in Tamil Nadu

VES No.	*K*-value (m/day) obtained from the field experiment	*A*-values	*B*-values	Aquifer resistivity (Ω-m)	Aquifer thickness (m)	Hydraulic conductivity, *K* (m/day)	Model hydraulic conductivity, K_m (m/day) obtained from eq. (7)	Deviation, column (8–7)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
1	0.77	17.47	0.011	250.0	19.39	1.12	1.01	–0.11
2	–	17.52	0.011	336.1	12.82	0.43	0.36	–0.08
3	–	17.79	0.011	399.0	8.48	0.22	0.17	–0.05
4	–	17.57	0.011	36.8	14.33	11.72	13.01	1.29
5	–	17.58	0.011	316.8	8.59	0.54	0.45	–0.09
6	17.83	17.64	0.012	32.6	11.20	11.93	13.68	1.75
7	–	17.82	0.012	102.0	2.96	5.24	5.95	0.71
8	–	18.36	0.012	260.3	13.44	0.81	0.89	0.08
9	4.36	19.28	0.012	140.0	22.00	3.59	3.77	0.18
10	–	18.55	0.012	24.9	4.16	13.76	15.01	1.25
11	–	18.74	0.012	386.7	6.17	0.18	0.20	0.01
12	–	18.70	0.012	378.5	12.90	0.20	0.22	0.02
13	–	20.28	0.012	21.9	6.14	15.59	15.56	–0.03
14	6.71	18.90	0.012	107.9	7.90	5.18	5.54	0.36
15	5.68	20.72	0.012	78.6	14.80	8.07	7.88	–0.19
16	5.56	22.19	0.013	47.0	4.50	12.04	11.51	–0.53
17	12.21	19.36	0.012	43.5	5.70	11.49	12.01	0.52
18	–	18.90	0.12	62.6	11.03	0.01	0.02	0.01
19	7.80	18.21	0.012	102.0	4.10	5.36	5.95	0.59

Refined transmissivity distribution map

The estimated aquifer transmissivity was contoured with the help of Surfer software using the kriging method (Figure 8). It indicates that *T*-values vary from 4 to 1166 m^2/day with an average of 117 m^2/day in the pumping test data; whereas the combined *T*-distribution obtained from both the pumping test and surface geophysical method vary from 0.1 to 1166 m^2/day with an average 89 m^2/day in the study area. The distribution of *T*-values was not altered in the northern part, in the absence of additional VES data. But it was refined in the central, southern and eastern parts due to inflow of additional information from the surface geophysical data where pumping test was sparse. It indicates that the contour map of *T* is not so smooth for the heterogeneous hydrogeological system which was obtained from the sparse pumping test data. It could be refined through the surface geophysical method and used as an input for groundwater modelling.

Conclusions

A hydrogeophysical model in granitic aquifer from Tamil Nadu is deduced from the results of Vertical Electrical Sounding (VES) conducted near open wells, along with available pumping test information. It is observed that estimation of hydraulic conductivity (*K*) and other properties of aquifer is feasible due to surface resistivity measurement. A cross-correlation test is ascertained between hydraulic parameter and aquifer geoelectrical property (ρ). It is found that for shallow aquifers in the hard rock area, hydraulic conductivity is best-fitted as an exponential function of aquifer resistivity. However, the

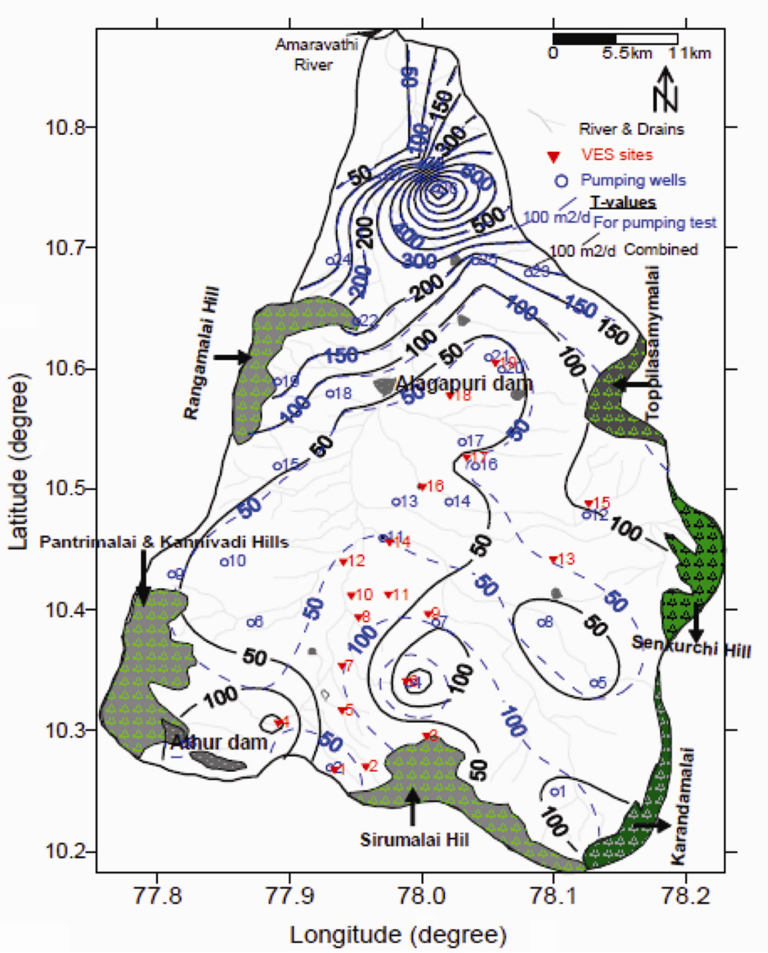

Figure 8. Distribution of *T*-values obtained from the pumping test as well as refined values from the surface geophysical method.

sensitivity analysis of the empirical relation between aquifer hydraulic conductivity and its resistivity shows that field parameters (*A* and *B*) depend on local hydrogeology at individual VES sites where the pumping test data is available. Thus, the estimated field parameters at each VES site are to be considered for preparing contour maps using a standard kriging. Then the aquifer hydraulic parameter could be extracted with the help of the contour map and aquifer resistivity along with an empirical equation without the pumping test data. The results emphasize the potential of surfacial resistivity survey to determine aquifer properties in granitic area and used for optimal assessment of groundwater resources.

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