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Nonlinear estimation of aquifer parameters from surficial resistivity measurements

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Abstract

The present study is focused on an examination of the correlation relationships for hydraulic permeability and transmissivity with electrical resistivity in a range of fractured and alluvial aquifers. The observed permeability data for fractured rock aquifers at some locations is correlated nonlinearly with electrical resistivity of the aquifers estimated from resistivity sounding data and it is found that the permeability of the aquifer in this region exponentially decreases with increase in resistivity. Permeability of the hard rock aquifer within the weathered zone and alluvium aquifers increases exponentially with increase in resistivity, and transmissivity decreases exponentially. However, in case of fracture rock and sandwiched aquifers, transmissivity increases exponentially with increase in resistivity. An attempt has been made to find general functional relationship between hydraulic parameters and resistivity of the aquifer, and therefore, published and observed data from India and other parts of the world has been taken under consideration. It is found that for fracture rock and alluvium aquifers, permeability and the transmissivity are best defined as the exponential functions of aquifer resistivity. The application of electrical parameters obtained from resistivity data for evaluation of hydraulic parameters has been demonstrated in detail within the Osmania University Campus, Hyderabad (India). The empirical relations between aquifer parameters and resistivity are established for transforming resistivity distribution into permeability and transmissivity of the aquifer. The information thus obtained from resistivity data on permeability of the aquifer and transmissivity distribution in the study area can be used for optimal use and assessment of water resources.

1. Introduction

The hydraulic characteristics of subsurface aquifers are important properties for both groundwater and contaminated land assessments, and also for safe construction of civil engineering structures. Hydraulic conductivity/permeability (K), Transmissivity (T), and Storativity (S) are all commonly applied hydraulic parameters in groundwater flow modelling (Freeze and Cherry, 1979; Fitts, 2002). Application of field hydrogeological methods of assessment is a standard technique for evaluating these aquifer properties, however estimating K, T, and S values from field pumping tests and downhole well-log data can be very expensive and time-consuming. In this context, surface geophysical methods may provide rapid and effective techniques for groundwater exploration and aquifer evaluation. Application of geophysical methods generally is proving very effective for water content estimation, water quality assessment and mapping of the depth to the water table and bedrock (Hubbard and Rubin, 2002). Although various geophysical techniques currently are being applied to explore and assess water resources, the DC electrical resistivity method still proves the most powerful and cost-effective. Use of Wenner and Schlumberger array vertical electrical sounding (VES), profiling, and also electrical tomography techniques have become very common in groundwater exploration and contamination studies, and there are standard, published direct and indirect interpretation techniques specifically for VES data (cf. Jupp and Vozoff, 1975; Koefoed, 1979). Recently, attempts have been made by researchers also to obtain such hydraulic parameter estimates from resistivity measurements (e.g. Brace, 1977; Biella et al., 1983; Bussian, 1983),

In porous media and alluvial aquifers per se, transmissivities, formation factors and permeability can be estimated using empirical/semi-empirical correlations, often using simple linear relations (Kelly, 1977a, b; Heigold et al., 1979; Schimschal, 1981; Urish, 1981; Chen and Hubbard et al., 2001). In the present study, Schlumberger resistivity soundings have been assessed in both alluvial (porous medium) and fractured hard rock aquifers for possible relationships with hydraulic parameters. Particularly in fractured and fissured hard rock regions delineation of aquifer properties by geophysical methods can be a very difficult task. For example, if the conductive aquifer is thin and sandwiched between two electrically resistive layers then no indication of its presence will be observed in a resistivity sounding curve (Singh, 2003a). Moreover, groundwater flow in fractured aquifers is very complicated, and accuracy in estimation of the hydraulic parameters depends on the hydraulic behavior in particular fractures, which is site specific. In such situations, non-conventional methods may be useful to detect a hidden aquifer (Singh, 2003a).

2. Theoretical foundations

The theory of and mathematical expressions used for exploration of groundwater by geoelectrical methods are well established (e.g. Bhattacharya and Patra, 1968; Koefoed, 1979; Keller and Frischknecht, 1966). The Schlumberger array method of Vertical Electric Sounding (VES) has been applied both for obtaining the electrical resistivity structure of the shallow earth and for exploring for groundwater (Fig. 1). The depth of investigation in a Schlumberger sounding configuration typically varies between 0.25 AB to 0.5 AB (Roy and Elliot, 1981).

Mathematically, electrical current flow (J) in a conducting medium is governed by Ohm's law and groundwater flow in a porous medium Darcy's law, both having similar forms of equation:

$$J = -\sigma \frac{dV}{dr} \tag{1}$$

$$q = -K \frac{dh}{dr}, \tag{2}$$

where J, σ, V, r, q, K, h are respectively the current density (amps per unit area), electrical conductivity (Siemens/m = reciprocal resistivity, ρ ohm.m or Ω.m), electrical potential (volts), distance (metres), specific discharge (discharge per unit area), hydraulic conductivity (or permeability; m/s) and hydraulic head (m). The analogy between these two macroscopic phenomenona is widely accepted (Freeze and Cherry, 1979; Fitts, 2002). Thus, the electrical method provides a powerful analogue and tool for groundwater exploration and modelling, and may be useful e.g. in generating analytic flow nets.

For homogeneous and isotropic medium, electric current and groundwater flow both satisfy the Laplace equation: for electrical flow,

$$\frac{d^2V}{dr^2} + \frac{2}{r}\frac{dV}{dr} = 0 \tag{3}$$

and for groundwater flow,

$$\frac{d^2h}{dr^2} + \frac{1}{r}\frac{dh}{dr} = 0\,. \tag{4}$$

For a point current source, the solution of Eq. (3) in a semi-infinite, homogeneous medium for (hemispherical earth) electrical flow can be written as

$$V = \frac{\rho I}{2\pi}\frac{1}{r} \tag{5}$$

and for hydraulic flow a similar equation can be written as:

$$h = \frac{Q}{2\pi T}\ln r\,. \tag{6}$$

Transmissivity of an aquifer of saturated thickness b then is expressed by

$$T = Kb \tag{7}$$

such, Eq. (4) becomes:

$$h = \frac{Q}{2\pi Kb}\ln r\,. \tag{8}$$

In general terms, since larger connected pores make for better flow characteristics for both water and electric currents it is expected that at the very least there should be some relationship between electrical and hydraulic parameters. Although the previous equations relate to flow in homogeneous earth media, in the present study nevertheless an attempt is made firstly to identify (site-specific) empirical relations in two particular aquifer types (alluvial, fissured), and secondly then to identify more general aquifer relations. Moreover, hydrogeological properties of the aquifers in fractured aquifers generally vary rapidly. As a result, directly linear relations between resistivity and hydraulic parameters (K and T) do not readily exist. Therefore, in present study, nonlinear relations between resistivity and transmissivity and permeability have been fit.

2.1. Methodology

A nonlinear empirical correlation analysis of field hydraulic parameters (K and T) with resistivity (ρ) has been performed for a range of published data from aquifer studies in central Japan and Rhode Island (USA), along with observed data from India. The empirical relation between K and ρ obtained in the present study for Osmania University Campus, Hyderabad (India) particularly may be used to compute permeability estimates at other VES locations where K data from pumping tests is not directly available. However, it is potentially a very difficult task to generalise the relationships both to alluvial and fractured aquifers. Transmissivity evaluations based on permeability estimates in the former case may be particularly erroneous if the saturated thickness and electrical resistivity of the aquifer are not interpreted accurately. Thus accuracy in estimation of thickness and resistivity of the aquifer must be adequately maintained while interpreting the VES data, rms error<5%. Information on thickness of the aquifer is extracted here using a non-conventional method proposed by Singh (2003a) along with other available information on depth to the water table from existing dug wells in the area. Thickness and resistivity of the aquifer at various observation points are obtained by inversion of VES data. The a priori information available on hydrological parameters and depth of water table from dug wells and bore well is used to constrain and minimize the ambiguity of interpretation. The root mean square (rms) error between observed and computed VES data is maintained less than 5% while computing the resistivity and thickness of the aquifer by employing inversion scheme proposed by Jupp and Vozoff (1975).

3. Results and discussions

Interestingly, in all cases permeability and transmissivity prove best correlated with resistivity if a nonlinear, exponential curve is fitted.

3.1. Alluvium aquifers

Published data on alluvial aquifers from U.P., India (Sriniwas and Singhal, 1985), and Beaver River aquifer and Chipuxet aquifer of the Pawcatuck River basin, Rhode Island, USA (Kosineski and Kelly, 1981) have been used here to examine the empirical relationship between permeability (K) and electrical resistivity (ρ) in these aquifers (Table 1). Permeability is calculated from the published pumping test data for the sites shown in Table 1 (Sriniwas and Singhal, 1985). Subsequently, various functions were tried in the present study to fit the pumping test data by the cited authors for the site-specific K and ρ values for the alluvial aquifer studies. For the published data on alluvial aquifers, it is found generally that an exponential fit of K on ρ is reasonable. The levels of confidence (standard deviation = SD for all data fits is found to be >90% (Figs. 2a–2c). The empirical relations obtained in the different aquifers are:

U.P. India alluvial aquifer data:

Banda Area: $K = 2.0345\, e^{-0.2458\rho}$ (9)

Varanasi Area: $K = 0.0538\, e^{0.0072\rho}$ (10)

Saharanpur Area: $K = 0.0002\, e^{0.0897\rho}$ (11)

USA alluvial aquifer data:

Rhode Island, USA: $K = 0.0192\, e^{0.003}$ (12)

Most of the examples of alluvial aquifers show K increases with ρ, excepting the Banda Area (Fig. 2a). In the Banda area, the presence of granitic hillocks exposed

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at the surface in some locations (Sriniwas and Singhal, 1985) may give rise to a significantly different subsurface geological setting in comparison with the other alluvial aquifers looked at. The presence of hard rock lithologies in the area may be the cause the negative correlation of the variation in permeability with resistivity. This type of behavior typically is found in hard rock aquifers (see below). Nevertheless, it is noted that for all of the alluvial aquifers the permeability-electrical resistivity relationship can be fit generally with an exponential function.

3.2. Hard rock aquifers

In the present analysis, the permeability (K) and resistivity (ρ) data from published laboratory and borehole measurements at Mount Tsukuba, Central Japan (Sudo et al., 2004) are considered, along with observed data recently measured by the author at the Osmania University Campus (OUC), Hyderabad, A.P., India (Table 2). Both regions are located in granitic host media, and have different climatic condtions/geograhic locations but in both case similar relation between permeability and electrical resistivity of the aquifer is found. The Osmania University Campus (OUC) is a granitic hard rock region of Hyderabad, A.P., India (Fig. 4). Granitic soils and rocks of Archaean age cover the area and the topography follows a gentle slope. Twenty-five VES were conducted at accessible locations across the campus (Fig. 4).

In hard rock aquifer of Central Japan, aquifer permeability exponentially decreases with resistivity in the intact rock cases but increases with increasing resistivity in the weathered rock cases (Figs. 3a and 3b). The following two expressions are obtained for weathered (SD=0.982) and intact rock aquifers (SD=0.980) with excellent fit.

For weathered rock aquifers: $K = 5E - 08\, e^{0.0045\rho}$. (13)

In hard rock aquifer of Central Japan, aquifer permeability exponentially decreases with resistivity in the intact rock cases but increases with increasing resistivity in the weathered rock cases (Figs. 3a and 3b). The following two expressions are obtained for weathered (SD=0.982) and intact rock aquifers (SD=0.980) with excellent fit:

For weathered rock aquifers: $K = 5E - 08\, e^{0.0045\rho}$ (14)

and for intact aquifers: $K = 1945.6\, e^{-0.0055\rho}$ (15)

The OUC study (India) also shows a decreasing K with increasing ρ values. From in situ measurements, it is observed that the shallow (weathered rock) aquifers in the OUC, India are dry and no pumping test data is available for them. Thus, correlation analysis of ρ and K directly of the shallow aquifers in weathered zone could not be performed as for the central Japan study. However, ρ and K data of an identified aquifer sandwiched between resistive or less permeable layers within depth range 10–30 m do correlate nonlinearly, and K exponentially decreases with increasing ρ (Fig. 3c) and the expression for this dependency is given by:

OUC granitic aquifer: $K = 8 \times 10^{-6}\, e\, -^{0.0013\rho}$ (16)

Generally, the aquifer in the OUC is found to be sandwiched between two resistive layers (Singh, 2003b). The transmissivity of the homogeneous aquifer then can be expressed as the product of the saturated thickness of the aquifer and permeability, such that:

$$T = 8 \times 10^{-6} e\, -^{0.0013\rho}\, b \quad (17)$$

Equations (15) and (13) then are used to convert resistivity distribution of the aquifer to transmissivity estimates for the OUC, India.

In more general terms, using a nonlinear, exponential fit there is the possibility of identifying generalised equation for the variation of K with ρ.

$$K = Ae^{B\rho} \quad (18)$$

For intact, unweathered aquifers, $A>0$, $B<0$; and $B>0$ for alluvium or weathered rock aquifers, for which A and B are site dependent constants. This nonlinear correlation study also reveals that the permeability decreases exponentially if an aquifer is sandwiched between two highly resistive layer, but increases with increase in resistivity of the aquifer, if the aquifer is just underlying or within weathered rock.

An empirical relation is obtained by correlating observed permeability and resistivity of the aquifer that are estimated from VES data. This equation is used to transform resistivity into permeability of the aquifer in OUC. Equation (13) can be rewritten in general form as given below:

$$T = Ae^{-B\rho} . \quad (19)$$

Where A (=8×10^{-6} h) and B are the site dependent constants for a particular aquifer, and can be determined by using available information of permeability and resistivity of the particular area.

The results obtained from the interpretation of VES data reveal that the depth of potential aquifers varies from 10 to 30 m in OUC (Singh, 2003b). The resistivity distribution of aquifers shown in Fig. 5 shows high values (160–360 ohm-m) around TA (Tagore Auditorium) and LIB (library). These high ρ value(s) are observed close to the sandwiched aquifer and where the overlying resistive layer has considerable thickness (>5 m). Such aquifers are found however to be high yielding at the time of drilling and some bore well subsequently have dried after some time after drilling; such aquifers are not adequately recharged due the presence of high resistive (less permeable) layer.

The yield of the bore well can be computed from derived geoelectrical parameters like Dar Zarrouk parameters (Singh, 2003b, 2004). The resistivity data is transformed into transmissivity (T) using Eq. (17). The transmissivity image of the aquifer within depth range 5–30 m is shown in Fig. 4.

The transmissivity varies from 10^{-3} to 10^{-2} cm^2/s. Dried bore wells are found in the low transmissivity (~10^{-3} cm^2/s) parts of OUC near VCL, TA and south-west of LIB. The yield of the existing bore wells at some locations nearby VES (Table 3) can be compared with resistivity data by Singh (2003b). The yielding wells are found in the areas of high transmissivity (9×10^{-3} to 2.1×10^{-2} cm^2/s) near NCC office (6.95 m^3/h) and Landscape garden (7.27 m^3/h). Thus, the site observations support the computed estimation of transmissivity distribution of the aquifer from the OUC data.

4. Conclusions

The present study reveals that the permeabilities of hard rock and alluvium aquifers vary exponentially with resistivity. From the field examples of India and other parts of the world discussed in present study, it is concluded that the permeability increases in weathered hard rock and alluvium aquifers and decreases as the aquifer resistivity increases within intact rock aquifers. In present area, the resistivity distribution of the aquifer is converted into transmissivity using Eq. (17). In present study the uncertainity is minimized using nonconventional method of interpretation of VES data. This approach can be applied in other parts of the hard rock and alluvium aquifers of India and other parts of the world. This transformation can be used to convert electrical resistivity imaging/tomography data into permeability/transmissivity. This will provide valuable information for flow modeling and recharge of groundwater, and in finding suitable sites for construction of safe civil engineering structures in the study area where less permeability or transmissivity zone are of the interest. However, before generalizing this approach as described in Eqs. (17) and (18), geophysical and hydrogeological study should be carried out at large scale. The study of permeability and transmissivity of near surface unsaturated weathered rock would be very helpful for finding suitable sites for studies of recharge, contamination and dewatering of aquifers.

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Table 1. The resistivity and pumping test data of alluvium aquifers U.P. (after Sriniwas and Singhal, 1985) and Rhode Island, USA (after Kosinsky and Kelly, 1981).

Area	**Alluvium Aquifers**		
	S.N.	ρ (Ohm-m)	K (cm/s)
1. Banda Area, U.P., India	1.	19.9906	0.01346
	2.	15.2497	0.04612
	3.	18.7243	0.02112
	4.	18.7243	0.02269
2. Varanasi Area, U.P., India	1.	42.7221	0.06424
	2.	62.0974	0.08704
	3.	183.095	0.18738
	4.	96.5639	0.1265
3. Saharanpur Area, U.P., India	1.	51.6808	0.02431
	2.	60.5518	0.05903
	3.	60.6832	0.05787
	4.	44.3255	0.01215
	5.	66.3742	0.08183
4. Rhode Island, USA	1.	403.86	0.04932
	2.	176.784	0.02511
	3.	304.8	0.06143
	4.	114.3	0.03297
	5.	693.42	0.1653

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Table 2. The resistivity and pumping test data of hard rock aquifers of Central Japan from weathered rock and intact rock aquifers (after Sudo et al., 2004), and Osmania University Campus, Hyderabad (India).

Area	Hard rock Aquifers		
	S.N.	ρ (Ohm-m)	K (cm/s)
1. Mt. Tsukuba, Central Japan			
(a) Weathered rock aquifers	1.	2561	0.00468
	2.	1511	3.4E-05
	3.	1275	3.9E-05
	4.	1061	3.2E-06
	5.	2300	0.00135
(b) Intact rock aquifers	1.	2561	0.00468
	2.	2110	0.0115
	3.	4575	1E-08
	4.	4000	1E-07
	5.	2850	0.00057
2. OUC, Hyderabad, A.P. (India)	1.	92	0.02431
	2.	252	0.05903
	3.	496	0.05787
	4.	1061	0.01215
	5.	3500	0.08183
	6.	5100	1E-08

Table 3. Yield of the existing bore wells near some VES sites in OUC, Hyderabad (India).

S.N.	VES No.	Yield (m^3/h)
1.	S1	6.13724
2.	S5	6.81915
3.	S7	6.9328
4.	S11	7.27376
5.	S14	6.95553

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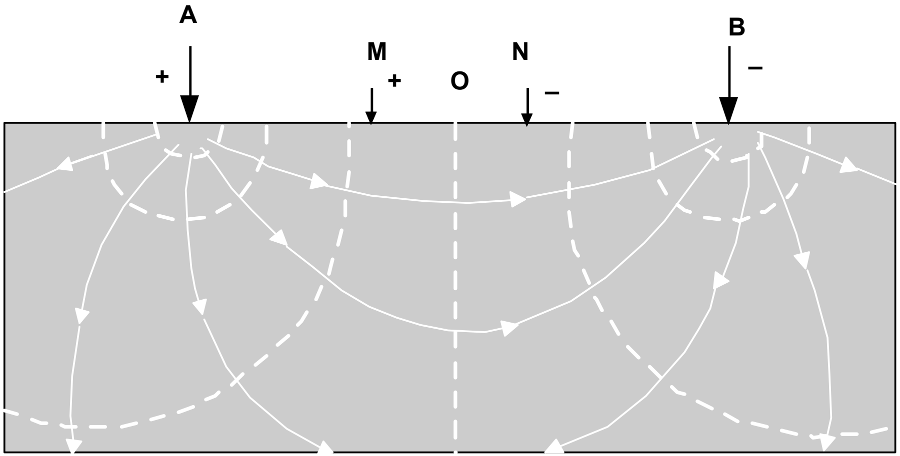

Fig. 1. Schematic diagram of Schlumberger resistivity sounding electrode configuration and principle of current flow in subsurface. The dotted lines (. . .) represent the equipotent surfaces and solid lines (—) direct currents. A and B are the current electrodes, and M and N are the potential electrodes.

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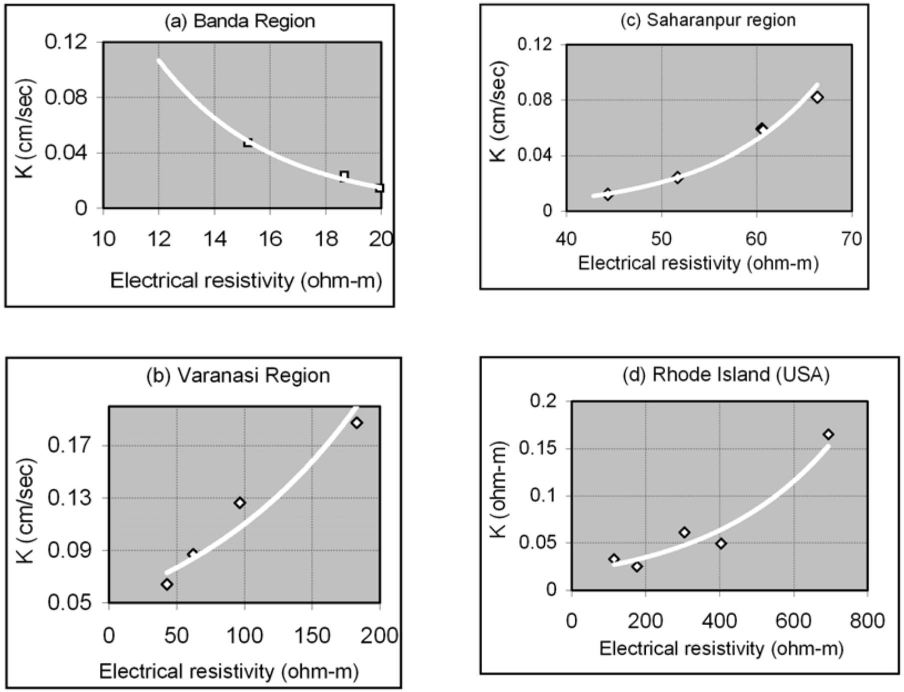

Fig. 2. Nonlinear correlation analysis of alluvium aquifers. Permeability (K) **(a)** decreases with increasing electrical resistivity in Banda Area of U.P., India but increases with increase in resistivity in **(b)** Varanasi area, U.P. (India), **(c)** Saharanpur area, U.P., India and **(d)** Rhode Island, USA.

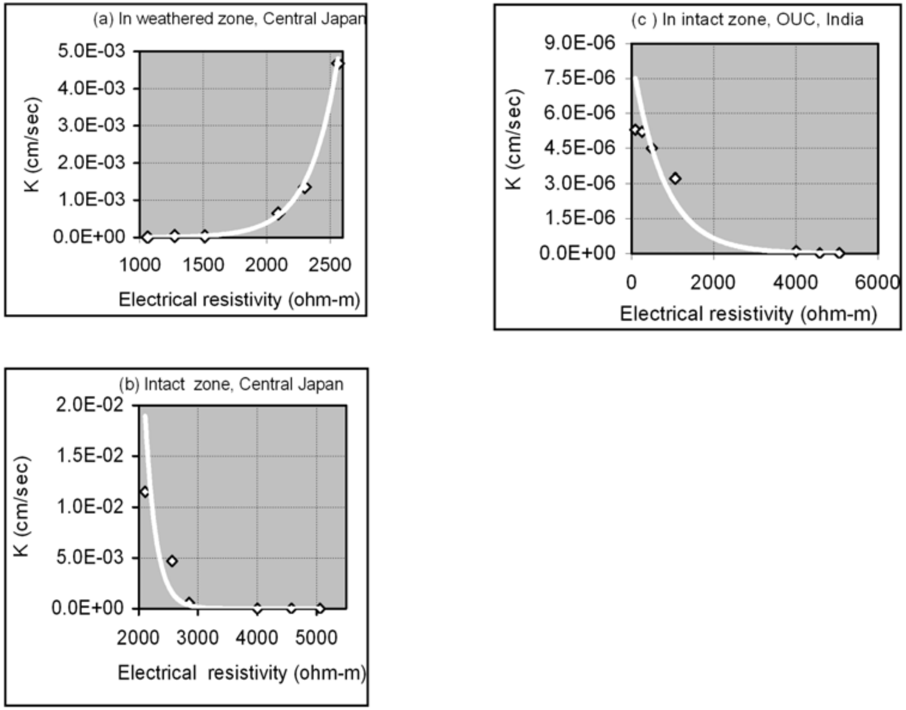

Fig. 3. Correlation analysis of hard rock aquifers. Aquifer permeability **(a)** increases for weathered rock, but decreases in unweathered, intact aquifers with increasing resistivity both for **(b)** Central Japan, and **(c)** OUC, Hyderabad, A. P. (India) data.

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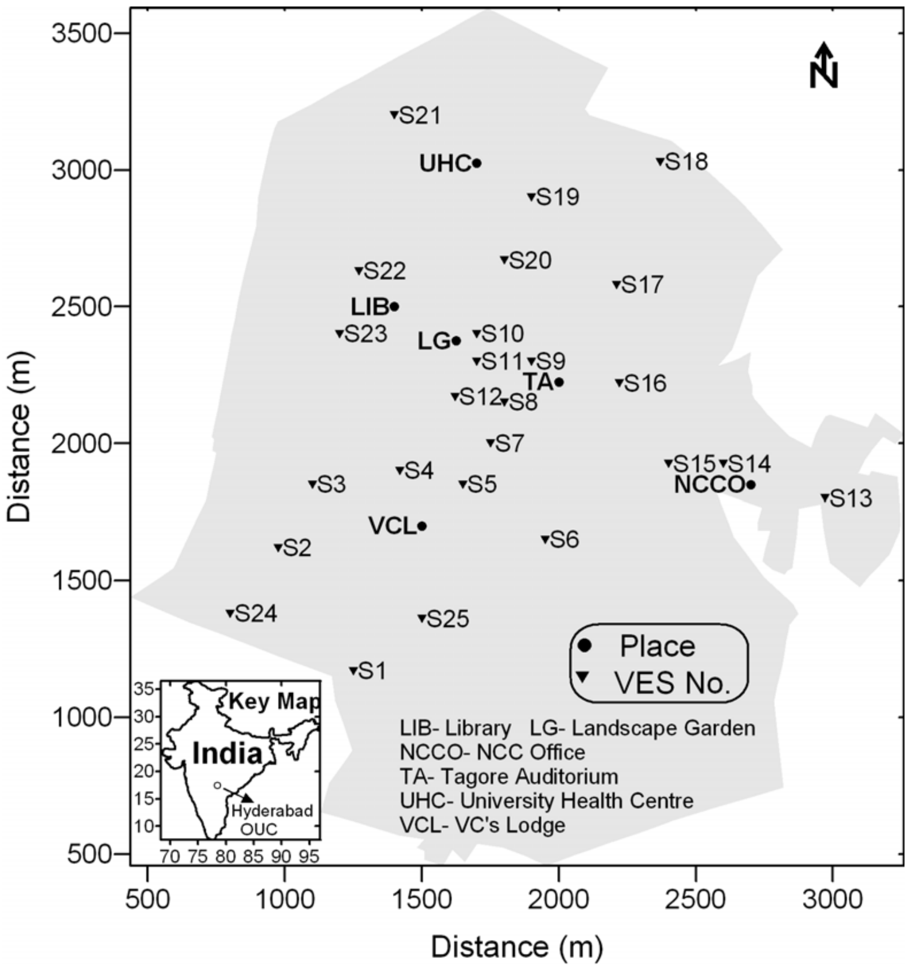

Fig. 4. Location map of OUC, Hyderabad showing VES and important places.

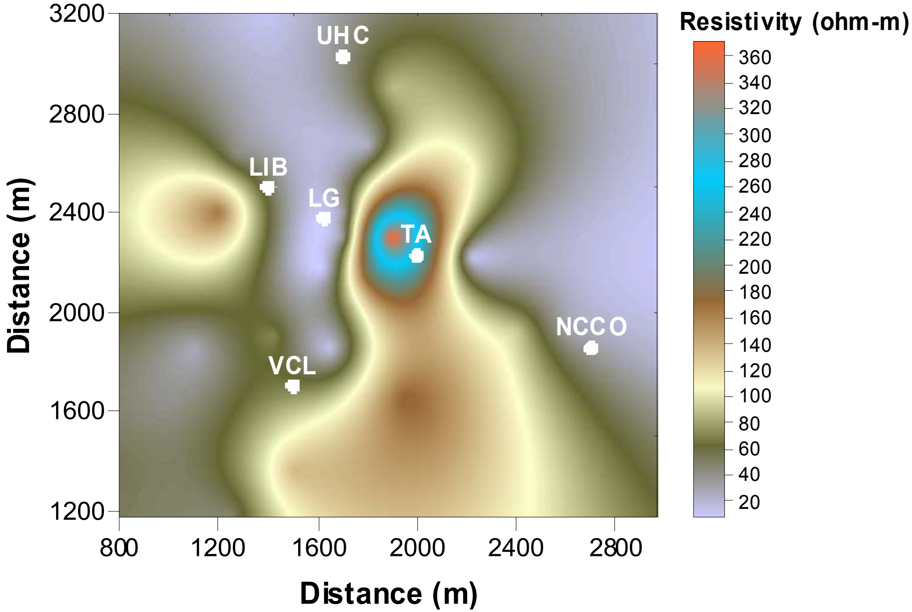

Fig. 5. Resistivity map of the aquifer obtained from interpretation of VES data.

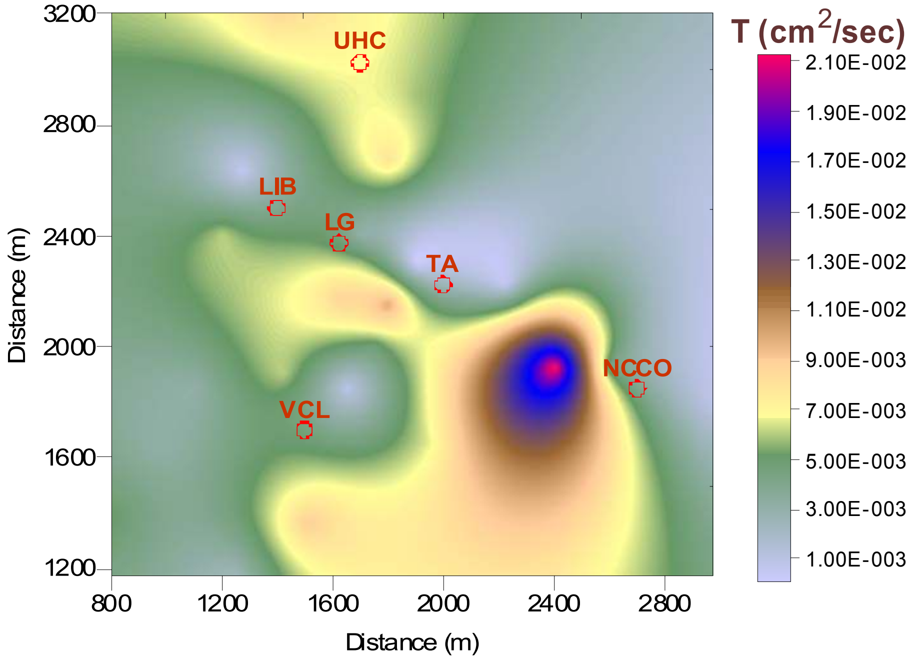

Fig. 6. Transmissivity distribution map of the aquifer in OUC, Hyderabad.

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