Geo-electrical exploration for groundwater in a hard rock region of Hyderabad, India

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Introduction

Geo-electrical methods are employed very commonly in geohydrological investigations, as they are more economical and effective than other geophysical techniques. The direct current resistivity (DCR) method is an effective tool in groundwater exploration, geothermal studies, civil engineering applications, and in monitoring water pollution and contamination. To achieve these objectives, conventional Schlumberger and Wenner soundings and electrical resistivity tomography (ERT) are currently used worldwide. Like other geophysical methods, interpretation of DCR data provides a non-unique solution of a real geological model. In recent years, two types of technique have been developed to interpret DCR sounding data. The first is the 'direct method' that requires no information on the number of layers, and the apparent resistivities are assumed to be true resistivities (Koefoed 1979; Zhody 1989). In the second method, known as the 'indirect method', an initial-guess model is required for initialization of the inversion of observed data (Jupp & Vozoff 1975). Non-uniqueness of the interpretation makes it difficult to select the best model that is closest to the real geological model. Results of interpretation of DCR sounding data become more ambiguous with increasing depth. It is very difficult to interpret layer resistivity and thickness with sufficient accuracy, and both synthetic and field examples show that the resolution of thin layers (having thicknesses less than one-tenth of their depth) is particularly difficult (Singh 2003). The properties of a thin conducting layer can be determined in terms of longitudinal conductance, and those of a resistive layer by transverse resistance (Yungul 1996).

In the present study, layer models have been obtained using a stable iterative algorithm proposed by Jupp and Vozoff (1975). The effectiveness of the resistivity method in the determination of aquifer parameters was demonstrated by Rijo *et al*. (1977). Several factors that create problems in the detection of an aquifer/conducting layer, like the presence of a conducting surface layer, effects of anisotropy, and the screening effect of overlying layers, have been discussed in detail by Singh (1998a). It is a well-established fact that ambiguity in interpretation of resistivity data increases very rapidly with increase in depth (Singh 1998b). Singh (2003) suggested a new approach to the detection of hidden aquifers in hard-rock regions based on resistivity data transforms.

The resistivity method is applied to determine the groundwater potential of an area and to study the relationship between geophysical parameters and the yield of existing wells. 3D maps of depth and thickness of the aquifer in Osmania University Campus (OUC) were prepared in order to study the variation in the level of the water table. The role of the thickness of the aquifer in water resources management, and the natural/ artificial recharge of the aquifer, has been studied in detail.

The main objective of the present study was to delineate the subsurface distribution of groundwater in the OUC. In addition to this, the relationships between the surface/subsurface layer parameters and the yield of existing boreholes and the recharge of the water table were examined. This study has also proved very useful in identifying new sites that are suitable for groundwater exploitation.

Location and geology of the area

The study area is located between latitudes 17º 24' 30" and 17º 25' 30" north, and longitudes 78º 27' and 78º 29' east (Fig. 1). It is an area of 3.1x 2.9 km^2 covering the entire OUC. It is a typical hard-rock region where water is found in small pockets within fractures. The whole area is covered by granitic soil, and granitic rocks are also exposed at several locations. Known as the Hyderabad granites, the rocks exposed in this area of slightly elevated topography are of Archæan age.

Field data acquisition

It is very difficult to detect aquifers in hard-rock terrains using only one geophysical method. In hard-rock regions, integrated geophysical approaches are found to be more effective, but expensive. Since the resistivity sounding method is more effective and cheaper than other geophysical techniques, it has been adopted in the present study.

25 vertical electric sounding (VES) surveys were conducted to delineate the depth and thickness of the aquifers, so that the entire area was covered. Eight of these surveys were conducted near existing boreholes to try to determine some correlation between geophysical parameters and the yield of the boreholes. Schlumberger resistivity soundings with max-

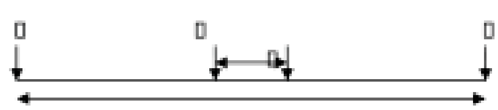

Figure 1 *Schematic diagram of Schlumberger electrode configuration. A, B and M, N are current and potential electrodes, respectively (MN=l and AB=L).*

imum current electrode spacing (*AB*/2) of 100 m were carried out for delineation of shallow aquifers. VES data are interpreted using a stable iterative procedure to delineate subsurface structure. The VES data also suggested that a half-current electrode separation (*AB*/2) of 100 m would give useful information regarding the water-saturated zone down to 50 m.

The yield of eight boreholes, converted to cubic metres per hour (m^3/hr), and the geophysical parameters of the associated aquifers near them are shown in Table 1.

Sl. No.	Geophysical Parameters of the Aquifers				Resistivity of the Overlying Layer (ohm-m)	RMS Error (%)	Yield m^3/hr
	VES No.	Depth (m)	Thickness (m)	Resistivity (ohm-m)			
1	S1	3.6	1.8	45.67	250.0	5.21	8.13724
2	S2	0.74	4.12	39.44	129.0	3.18	7.04046
3	S3	0.73	1.30	13.23	142.0	3.09	8.87915
4	S7	4.19	6.56	89.22	165.0	3.41	8.60260
5	S11	2.73	7.54	29.57	77.6	4.58	7.27376
6	S14	3.42	5.56	22.37	38.5	3.62	6.86553
7	S18	3.16	4.78	44.80	546.0	3.68	7.27376
8	S21	3.43	10.62	11.52	947.0	2.07	8.18298

Table 1 *Geophysical parameters of the aquifers, resistivity of the layers overlying the aquifers, yield of the existing boreholes near VES sites, and root-mean-square (RMS) error in the estimation of these parameters*

Brief mathematical theory

DC resistivity method

The acquisition and interpretation of VES data are based on assumptions that the earth is composed of a finite number of horizontally stratified, homogeneous and isotropic layers. In the application of VES to groundwater exploration, water resources management and water pollution studies, the concept of an isotropic, homogeneous and stratified earth holds good. The theory and practice of VES is well documented in the literature (Keller & Frischknecht 1966; Bhattacharya & Patra 1968; Zhdanov & Keller 1994). The apparent resistivity for various electrode configurations can be computed from the expression for surface potential,

$$V = \frac{I\rho_1}{2\pi}\left[\frac{1}{r} + \int_0^{\infty} k(\lambda) J_0(\lambda r)\,d\lambda\right], \quad (1)$$

where r, ρ_1, $k(\lambda)$, $J_0(\lambda r)$ and λ are, respectively,

- the distance of the measuring point from the current source,
- the resistivity of the surface layer,
- the Stefanesco kernel function determined by thicknesses and resistivities of subsurface layers,
- a zero-order Bessel function of the first kind,
- an integration variable: a real number with dimensions of inverse length.

The apparent resistivity can be computed by measuring the potential difference between potential electrodes and the current injected into the ground through current electrodes using the expression,

$$\rho_a = K\frac{\Delta V}{I}, \quad (2)$$

$$K = \frac{\pi\left(L^2 - l^2\right)}{4l}, \quad (3)$$

where ρ_a, K, ΔV and I are, respectively,

- the apparent resistivity (observed in surface measurements),
- a geometric factor that depends on electrode array,
- the potential difference between measuring electrodes,
- the current.

The geometric factor for the Schlumberger array can be expressed in terms of current electrode spacing (L), and potential electrode spacing (l), and is defined in equation (3). A schematic diagram of the Schlumberger array is shown in Fig. 2. The depth of investigation in the Schlumberger sounding configuration varies between 0.25L and 0.5L (Roy & Elliot 1981).

Correlation study between yield and geo-electrical parameters of the aquifer

Lima *et al.* (2001) found that, in the case of a highly resistive substratum, electric current flow is characterized by longitudinal conductance (C_l), whereas in the presence of a highly conductive substratum, current flow is governed by transverse resistance (R_t). Sri Niwas & Singal (1981) derived ana-

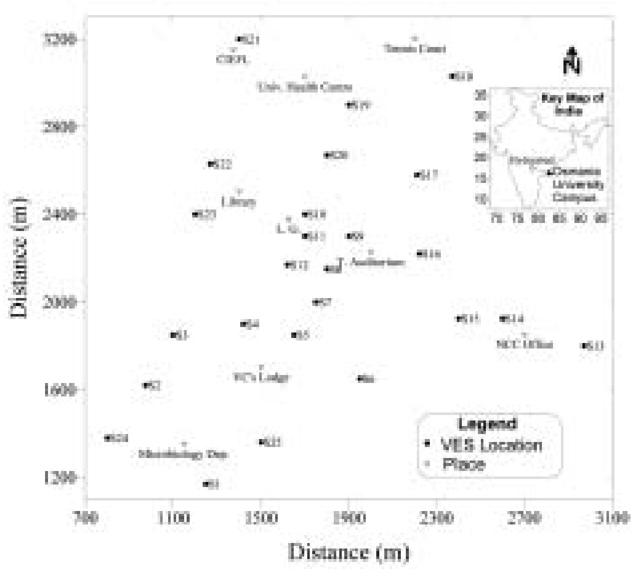

Figure 2 *Map showing VES locations and some sites near the observation points in the Osmania University Campus, Hyderabad (India).*

lytic expressions that relate transmissivity T, hydraulic conductivity K, C_l and R_t, and obtained the following equation for a highly resistive substratum:

$$T = K\rho_b C_l, \tag{4}$$

where T, K ρ_b and C_l are the transmissivity, hydraulic conductivity, bulk resistivity and longitudinal conductance of the aquifer, respectively.

The longitudinal conductance is defined as the ratio of thickness (h_{aq}) to resistivity of the aquifer (ρ_{aq}). Thus, the expression for longitudinal conductance can be written as $C_l = \frac{h_{aq}}{\rho_{aq}}$. Substituting the value of C_l in equation (4), the expression for T becomes

$$T = K\rho_b \frac{h_{aq}}{\rho_{aq}}. \tag{5}$$

Equation (5) implies that transmissivity will be proportional to the thickness and inversely proportional to the resistivity of the aquifer.

Transverse resistance will characterize electric current flow if the substratum is highly conductive. Thus, the equation for the transmissivity of the aquifer will involve R_t, and equation (4) will become

$$T = \frac{K}{\rho_b} R_t \ . \tag{6}$$

Substituting $R_t = h_{aq}\,\rho_{aq}$ in equation (6), it can be rewritten as

$$T = \frac{K}{\rho_b} h_{aq}\rho_{aq} \ . \tag{7}$$

Equations (5) and (7) show that transmissivity is either proportional or inversely proportional to ρ_{aq} and proportional to h_{aq}. Freeze & Cherry (1979) showed that transmissivity is proportional to storativity and the specific yield of an aquifer. There should, therefore, be some linear relationship between yield and the geo-electrical parameters such as ρ_{aq} and h_{aq} . On this basis, therefore, linear regression analysis has been attempted in this study.

Results and discussion

1 Interpretation of VES data

25 surveys were conducted to study the variation of the depth (water table) and thickness of the aquifer/water-saturated layer. Qualitative analysis of the sounding curves indicates that the area is a typical hard-rock region. In general, ascending or 'A-type' and 'A-K-H-type' curves are observed. 'H-type' (convex downwards) curves have also been

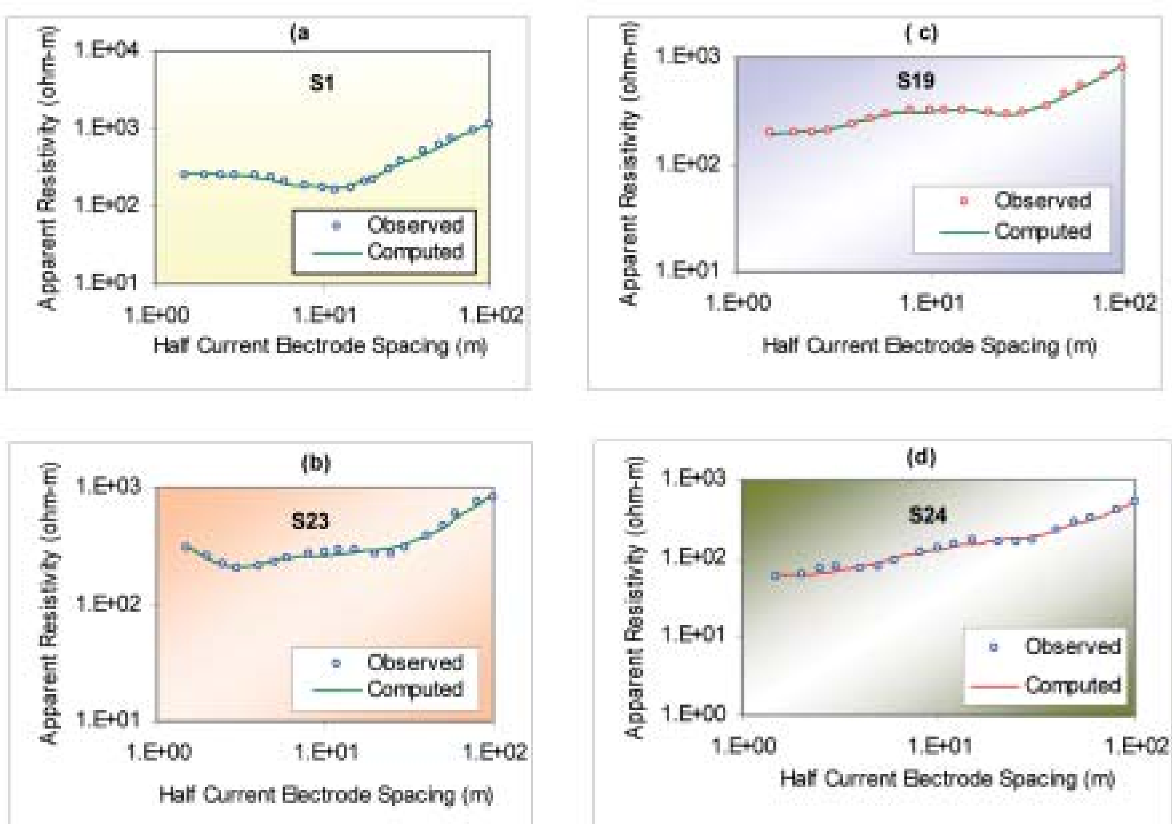

Figure 3 *Some typical observed and computed VES curves obtained after inversion of field data.*

observed at some locations. Four typical sounding curves are shown in Fig.3. The following deductions can be made from qualitative analysis of the VES curves:

1 The H-type curve observed in the south-western part of the area indicates that the aquifer underlies moderately resistive or weathered granite (Fig. 3a).
2 Some H-K-H-type curves (near the Campus Library) reflect the presence of two aquifers; one close to weathered rock, and the other at a relatively greater depth (Fig. 3b).
3 From the A-K-H-type curves (near the University Health Centre), it can be deduced that the aquifer is sandwiched between two resistive layers (Fig. 3c).
4. The A-type curve (on the west side of the Microbiology Department) shows some indication of the presence of a deep aquifer (Fig. 3d).

A-K-H- or H-K-H-type curves are observed near dry boreholes, possibly due to the presence of a highly resistive (less permeable) layer overlying the water-saturated layer. The resistivity and thickness of the first layer have been determined as 185.1 Ωm and 2.51 m, respectively. The layer immediately overlying the aquifer has a thickness of 2.74 m and a relatively high resistivity (947.2 Ωm). The aquifer has a resistivity of 86.4 Ωm and a thickness of 8.2 m at a depth of 5.25 m. The basement resistivity at this location is also found to be very high (10 010 Ωm). The presence of a resistive (less permeable) overlying layer restricts adequate natural recharge of the aquifer. Thus, at such locations aquifers should be recharged by using appropriate artificial techniques. The VES curve S24 is a typical example that reflects the presence of a shallow aquifer and a deep-seated aquifer (Fig. 3d). A six-layer model has been obtained to fit the observed and computed data with sufficient accuracy. The shallow aquifer is located beneath a relatively thick (2.8 m) weathered layer that is moderately conductive (58.8 Ωm), and the deep aquifer underlies a resistive layer (1064 Ωm) at a depth of 18.97 m. The first weathered/conductive layer (more permeable) permits adequate recharge of the shallow aquifer. From *in situ* observations, it is noted that all boreholes give a good yield throughout the year. However, where the overlying layer is fairly thick and resistive, the boreholes are found to be dry. Therefore, the depth of the boreholes should be increased to exploit the deep-seated aquifers.

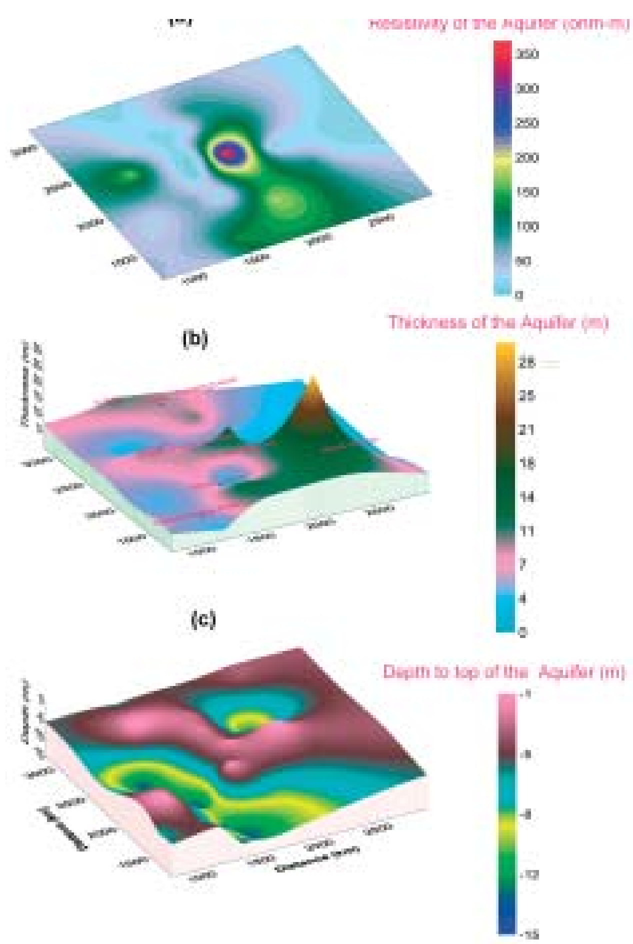

Figure 4 *3D maps prepared after interpretation of the VES data: (a) true resistivity contour map; (b) thickness; (c) depth to the top of the aquifer.*

It is essential to know the thickness and depth of the aquifers in order to locate new aquifers, to exploit existing aquifers, and to study natural/artificial recharge. Although VES data have not been collected at a uniform spacing, a regular grid has been generated using the kriging method. Three-dimensional maps showing variation in thickness and depth to top of the aquifer are shown in Fig. 4. These maps are very helpful in identifying potential zones for future prospects of producible groundwater.

Potential aquifers underlying the moderately conductive layer have greater thicknesses. It has been found that potential aquifers are at greater depths on the northern and western sides of the VC's Lodge, Tennis Court Centre and Tagore Auditorium. The aquifers are shallower near the Landscape Garden (>5 m). The high resistivity zones of the aquifer are located in the western and central parts of the area (Fig. 4a). Aquifers sandwiched between two thick, resistive layers are found to have relatively high resistivities.

In general, it has been found that the deep aquifers are thicker than the shallow ones. The thickest aquifers (~20–30 m) are estimated to lie in the northern and south-eastern parts of the study area. The aquifer becomes thicker near the University Health centre, west of the Library and CIEFL. The map of depth to the top of the aquifer shows the topography of the water table (5–15m). It is clear that artificial recharge could be achieved by means of pits and shafts, in combination with percolation tanks. Importantly, waste material should be dumped deeper than 15–50 m to avoid groundwater pollution.

2 Correlation study of yield with geophysical parameters

Fundamentally, the resistivity survey of the area was conducted to determine groundwater potential. However, for the first time an attempt was made to correlate borehole yield with thickness, resistivity, depth of the aquifer, and resistivity of its overlying layer. Eight VESs were conducted near producing boreholes. The yield and the geophysical parameters obtained from surface observations are shown in Table 1. A good correlation (correlation coefficient R=0.872) between the thickness of the aquifer (in m) and the yield (in m^3/hr) is shown in Fig. 5(a), implying a linear relationship.

The depth to the top of the aquifer correlates poorly with the yield (R=0.486, Fig. 5b). Correlation analysis of yield with resistivity of the aquifer results in very poor correlation (R=0.357, Fig. 5d). A high-yielding aquifer underlying a resistive and thick layer may show high resistivity. Similarly, a low-yielding aquifer underlying a weathered layer may have high or low resistivity, depending on the resistivities of the overlying and underlying layers. The resistivity of the layer immediately overlying the aquifer is found to be higher in areas of high yield, and very good correlation is found between these two parameters (R= 0.697, Fig. 5c). A possible reason for this relationship may be the high pressure of the water in the aquifer, sandwiched between two less permeable layers.

Apart from exploration for groundwater, the present study emphasizes the probable relationship between geophysical parameters of the subsurface and the yield of existing boreholes. Although it is true that yield depends ultimately on the available water in the aquifer/seal system, a thick aquifer (weathered/porous material) will hold more water than a thin one. Thus, yield should be proportional to aquifer thickness, and this should apply in the case of confined or unconfined aquifers.

However, in the case of a confined, or artesian, aquifer, the pressure on the water underlying an impervious or less permeable layer (in this case a granitic layer) will be very high. In such a situation, a thin aquifer can yield more for a short period. Thus, in such a situation, yield can be characterized by geophysical parameters of the layers overlying and underlying (impervious basement) the aquifer. In hard-rock regions, a granitic layer with high resistivity is considered less permeable. Therefore, a very good correlation can be found

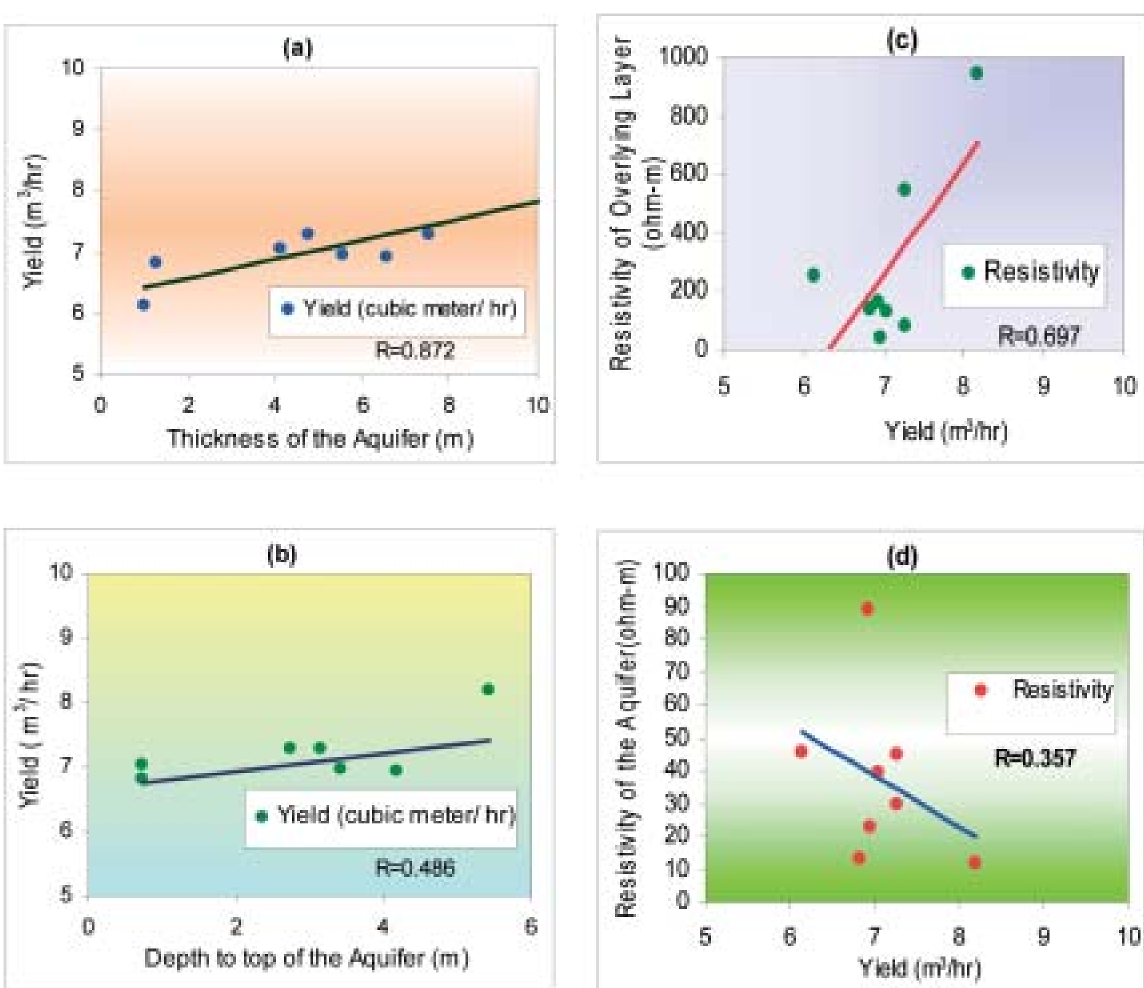

Figure 5 *Correlation study of the yield of the aquifers with (a) thickness, (b) depth to the top, (c) resistivity of the overlying layer and (d) resistivity of the aquifer.*

between the resistivity of the layer immediately overlying the aquifer and the yield of the borehole. The geophysical parameters of such an overlying layer also play a very important role in studies of recharge potential.

Conclusions

The maps of thickness and depth to the top of the shallow aquifer/water table provide insight into future prospects for groundwater. The depth of the top of the aquifer in the study area varies from 1 to 15 m, and the thicker aquifers (10–30 m) are located in the south-eastern and north-western parts of the area.

In general, aquifers are found to be sandwiched between two resistive (i.e. less permeable) layers. As a result, the aquifers are not adequately recharged to meet the increasing demand for water, and boreholes dry up (e.g. boreholes near the VC's Lodge, Landscape Garden and N.C.C. Office). It is concluded that the aquifers should be artificially recharged.

An attempt has been made to study the relationship between borehole yield and the geophysical parameters of the aquifers. Some significant linear relationships have been found, including yield versus thickness of the aquifer, and yield versus resistivity of the overlying layer. Thick water-saturated layers contain more water. Thus, boreholes at such locations will be high yielding. High-yielding boreholes are also found near VES locations where the aquifer is sandwiched between a fairly thick and resistive overlying layer (>250 Ωm) and highly resistive basement (10 000 Ωm). If the aquifer is sandwiched between two less permeable/impervious layers the water will be under the influence of high pressure. Thus, when a borehole is drilled at such a location it gives a high yield. However, it may dry up after some time, because in such a situation natural recharge will not be adequate.

This study was based on surveys made at locations accessible in this area. Although linear relationships between borehole yield and certain geophysical parameters have been observed, more work is required both in terms of closely spaced VES surveys at OUC, and geo-electrical surveys of aquifers from other hard-rock regions of India.

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