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G. Shailaja
Indian Institute of Geomagnetism

Mukkera Laxminarayana
Indian Institute of Geomagnetism

Vinit C. Erram
Indian Institute of Geomagnetism

Suryawanshi Ravindranath Anandrao
Yashwantrao Chavan College Of Science Karad

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Efficacy of anisotropic properties in groundwater exploration from geoelectric sounding over trap covered terrain

G. Shailaja[1], M. Laxminarayana[1], J.D. Patil[2], V.C. Erram[1], R.A. Suryawanshi[3] and Gautam Gupta[*1]

[1]Indian Institute of Geomagnetism, New Panvel (W), Navi Mumbai 410218, India
[2]D.Y. Patil College of Engineering & Technology, Kasaba Bawada, Kolhapur 416006, India
[3]Yashwantrao Chavan College of Science, Karad-Masur Road, Karad 415124, India
*Corresponding Author: gupta_gautam1966@yahoo.co.in

ABSTRACT

Electrical resistivity study assumes a special significance for mapping aquifer in hard rock area and is also widely used in delineating the lateral and vertical distribution of sub-surface. 23 Vertical electrical soundings (VES) with Wenner electrode configuration were carried out over Chikotra basin, located in the southern part of Kolhapur district in the Deccan Volcanic Province (DVP) of Maharashtra to delineate the groundwater potential zones and anisotropic properties of fractures for sustainable groundwater development within the study area. The results illustrate that the secondary geophysical indices provide a constructive solution in delineating the fresh water aquifers in the trap covered area. The longitudinal conductance (S) value vary from 0.016 to 5.44 Ω^{-1}, suggesting that the entire study area reveals good to weak aquifer protective capacity rating. The low value of the protective capacity in the northern and central part of the basin is due to the absence of significant amount of clay as an overburden impermeable material, thereby enhancing the percolation of contaminants into the aquifer. The large variation in the coefficient of anisotropy from 1 to 6.18 at the 23 VES data sites, suggests the anisotropic disposition of the aquifers in basaltic region. The fracture porosity inferred from the geophysical parameters and specific conductance of groundwater varies from 0.0001% to 0.556% in the study area, signifying different degrees of water saturation within the basaltic layers. The high-porosity zones corroborate with the high anisotropy values, indicating significant reserves of exploitable groundwater. This practice of analyzing VES data provided the direct solution to resolve problems in different hard rock terrains with a severe scarcity of groundwater, which has a great social impact.

Key words: Electrical resistivity, Chikotra basin, anisotropy, porosity, groundwater, Deccan Volcanic Province

INTRODUCTION

Investigation of groundwater resources in hard rock terrain (HRT) has always remained a topic of debate and exigent task for hydrogeologists as the potential groundwater zones/recharge pockets in HRT are restricted to localized weathered, fractured and fissured backgrounds. The groundwater potential in such an environment depends upon the thickness of the weathered/fractured layer overlying the compact basement rocks (Kumar et al., 2014). It is complex to identify and map such layers in the HRT subsurface; equally obscure is to perceive the infiltration, flow, accumulation and storage of groundwater. The availability of groundwater in such areas is largely due to the development of secondary porosity and permeability resulting from weathering and fracturing (Rai et al., 2015). The chronic scarcity of potable water, increased frequency of drought years and growing population led to the need for locating auxiliary sources of groundwater almost all over the HRT of the Deccan Volcanic Province (DVP) of Maharashtra.

Of all the non-invasive geophysical techniques, the electrical resistivity profiling and vertical electrical sounding (VES) are most widely deployed to demarcate different layers such as top soil, weathered, fractured and bedrock zone for construction of suitable groundwater structures (Gupta et al., 2015), groundwater contamination studies (Mondal et al., 2013), saline water incursion studies (Maiti et al., 2013), and geothermal explorations (Kumar et al., 2011). Hydrogeological and geophysical studies carried out in the Deccan trap region (Rai et al., 2015) delineated aquifers and reported occurrence and movement of groundwater in intertrappeans/vesicular and fractured zones within the trap sequence and sedimentary formations below the traps, which are considered to be a potential source of groundwater.

In the present study, resistivity method has been adopted to investigate the subsurface litho environment in Chikotra basin located in southern Maharashtra, with an aim to characterize the aquifers, to find out the depth to the aquifer and its lateral extent and to estimate the aquifer protective capacity in the area as well as the fracture geometry using secondary geophysical indices (Dar Zarrouk parameters): (i) the total longitudinal unit conductance (S), and (ii) total transverse unit resistance (T). These parameters assume an important role in geoelectrical soundings, and are related to different combinations of thickness and resistivity for each medium

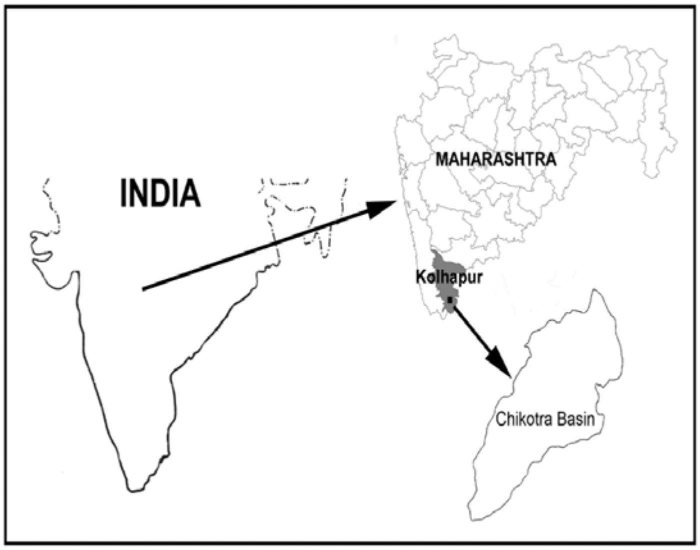

Figure 1. Location map of Chikotra basin in Kolhapur district.

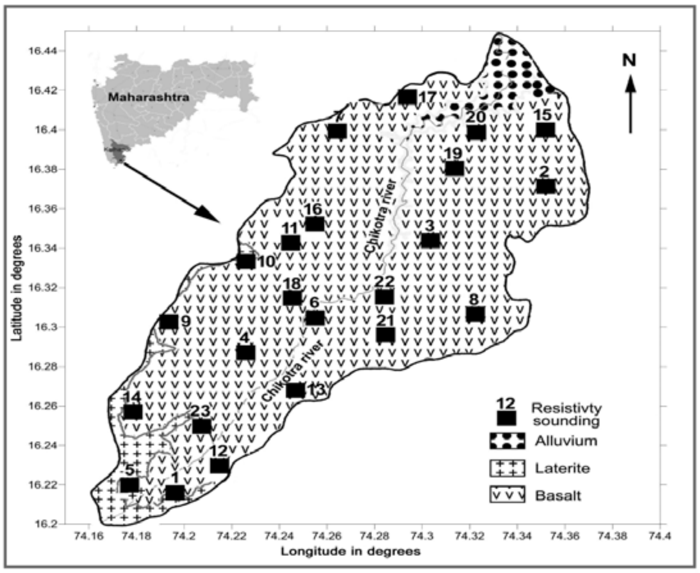

Figure 2. Geological map of the study area showing the location of vertical electrical sounding points.

and applied to define different groundwater characteristics and geological conditions (Batayneh, 2013). This type of studies has been carried out for the first time over Chikotra basin.

Geologic and hydrologic settings

The region selected for the present study is Chikotra basin of Kolhapur district (Figure 1) covering parts of Bhudargad, Kagal and Ajara sub-divisions of Kolhapur district. The basin comprises hills on the southwestern side with steep slopes characterizing relatively high altitude source area (700 m to 960 m) above mean sea level. The central part of the basin depicts moderate slopes and altitude, while the plain area on the northeastern side shows gentle slopes at altitudes 540-600 m above mean sea level, thus forming an uneven and diverse nature of topography.

The Chikotra basin typifies the basaltic formations of DVP which are of simple type with trap thickness up to about 100 m. The flows have been separated by thin (<1-2.5 m thick) veneer of red beds. In the source part, the topographic highs are covered with lateritic formation and in the downstream part by a thin layer of alluvium along the banks of the river and streams. The laterites occur at an elevation of about 905 m as capping the flat basaltic hillocks. The laterites form potential aquifers due to their cavernous or vesicular nature. These are generally formed by the process of residual weathering which occurs near

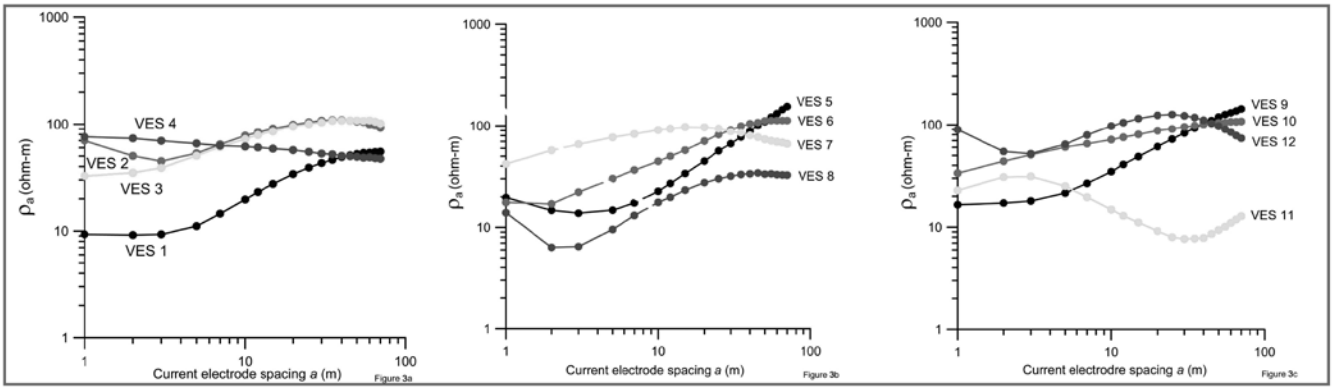

Figure 3. (a, b and c). Interpreted VES 1, 2, 3, 4 curves, VES 5, 6, 7, 8 curves and VES 9, 10, 11, 12 curves.

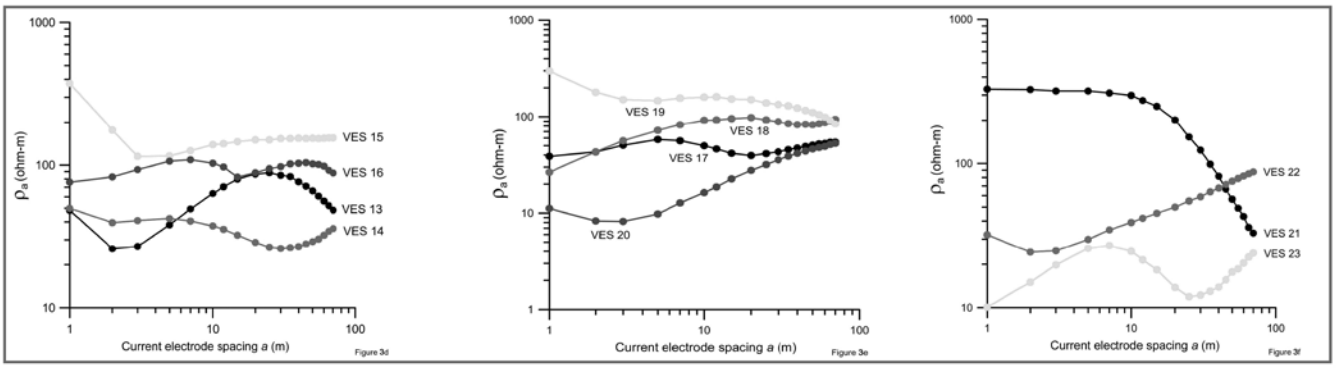

Figure 3. (d, e and f). Interpreted VES 13, 14, 15, 16 curves, VES 17, 18, 19, 20 and VES 21, 22, 23 curves.

the surface and is rich is iron and/or aluminium oxides (Banerji, 1982). The basaltic formations are highly jointed and fractured all over the basin. These joints provide secondary porosity to the basalts making them potential aquifers (Deolankar, 1980).

The drainage pattern is inconsistent in the basin. It is dendritic and fine to coarse textured in the basin. The annual rainfall in the basin ranges from 1000 mm to about 2800 mm, primarily from south-west monsoon. The maximum temperature is about 40°C in the month of May, while minimum of 10°C to15°C is recorded in the month of November (Gupta, 2013). The discharge values from the wells in the study region vary from 135 l/s to 5890 l/s due to the hydraulic and morphologic characteristics of the tributaries of Chikotra River (Gupta et al., 2015). The static water level from well inventory in the study area varied from 2.6 m (VES 12) to 10.25 m (VES 15) during pre-monsoon of 2013, while it varied from 1.85 m (VES 2) to 9.2 m (VES 21) during the post-monsoon period of 2013. A set of standardized resistivity ranges has been reported by Rai et al., (2015) for different litho units in respect of water bearing zones in the Deccan basalts viz., 5-10 Ω-m for black cotton soil, bole beds and clay, 10-20 Ωm for sand with clay, 20-45 Ω-m for weathered/fractured vesicular basalt saturated with water, 40-70 Ω-m for moderately weathered/fractured basalt/vesicular basalt saturated with water and, > 70 Ω-m for compact and massive basalts. These ranges may however vary to some extent on either side from place to place depending on the proportion of clay, joints/fractures etc.

Materials and methods

A total of 23 vertical electrical soundings (VES) were carried out within the study area (Figure 2), employing the Wenner electrode configuration in sounding mode with a constant electrode separation of 70 m. All the soundings were carried out in east-west direction because the basin is composed of both shallow and deep structural units oriented in NW-SE and NE-SW directions (Anand et al., 2016).

The initial interpretation of the VES data was accomplished using the conventional partial curve matching technique, with two-layer master curves in conjunction with auxiliary point diagrams (Orellana and Mooney, 1966). The layer resistivities and thickness thus obtained, served as the initial parameters for computer-based interpretation using IPI2WIN software, version 3.0.1, a 7.01.03 (Bobachev, 2003) for interactive semi-automated interpretation. The sounding curves suggest two to five layered structures as shown in Figure 3a-f.

Anisotropy of the sub-surface layers might introduce ambiguity in the interpretation of true resistivity and depths as in any formation which is anisotropic due to the presence of fractures, the apparent resistivity measured normal to its strike direction is greater than apparent resistivity measured along the strike direction. The secondary geophysical indices (viz. Dar Zarrouk parameters) are thus very useful to comprehend the spatial distribution of groundwater in addition to the geometry of the sub-surface litho units and provide a clue to aquifer prospective zones in the study area. Maillet (1947) termed the Dar Zarrouk (D-Z) parameters: T, as the resistance normal to the face (transverse resistance) and S, as the conductance parallel to the face (longitudinal conductance) for a unit cross section area, which plays an important role in resistivity soundings.

A geo-electric layer is described by two basic parameters, resistivity (ρi) and thickness (hi), where the subscript i indicates the position of the layer in the section. Other geoelectric parameters like average transverse resistivity (ρ_t), average longitudinal resistivity (ρ_l) and coefficient of anisotropy (λ) can be derived from its resistivity and thickness (Henriet, 1976). For i = 1, 2 ... n-layer, these parameters are:

Total longitudinal conductance (S) is defined as,

$$S = \sum_{i=1}^{n} \frac{h_i}{\rho_i} \tag{1}$$

Similarly, the total transverse unit resistance (T) is defined as,

$$T = \sum_{i=1}^{n} h_i \, \rho_i \tag{2}$$

Using eq. (1), the longitudinal resistivity due to the current flowing parallel to the layers is given by,

$$\rho_l = \frac{H}{S} = \frac{\sum_{i=1}^{n} h_i}{\sum_{i=1}^{n} \frac{h_i}{\rho_i}} \tag{3}$$

H is the depth to the bottom most geoelectric layer.

Similarly, the transverse resistivity due to the current flowing perpendicular to the layers is expressed using eq. (2) as,

$$\rho_t = \frac{T}{H} = \frac{\sum_{i=1}^{n} h_i \, \rho_i}{\sum_{i=1}^{n} h_i} \tag{4}$$

Combining eq. (3) and (4), the coefficient of anisotropy (λ) is given by,

$$\lambda = \sqrt{\rho_t / \rho_l} \tag{5}$$

Fracture porosities associated with tectonic fracturing of rocks were estimated using the expression derived by Lane et al., (1995) and Kumar et al., (2014),

$$\varphi_f = \frac{3.41 \times 10^4 (N-1)(N^2-1)}{N^2 C(\rho_{max} - \rho_{min})} \tag{6}$$

where ϕ_f is the fracture porosity; N is the vertical anisotropy related to the coefficient of anisotropy λ, in this case, the vertical anisotropy is equal to the coefficient of anisotropy (λ) since for Schlumberger 1-D data, both (λ) and N are equal; ρ_{max} is the maximum apparent resistivity (Ω-m); ρ_{min} is the minimum apparent resistivity (Ω-m) and C is the specific conductance of groundwater in μS/cm. The specific conductance of groundwater from bore wells and dug wells in the study area were averaged to 666 μS/cm.

Henriet (1976) showed that the combination of layer resistivity and thickness in the D-Z parameters S (longitudinal conductance) and T (transverse resistance) may be of direct use in aquifer protection studies to signify the percolation of contaminants into the aquifer, and for the evaluation of hydrologic properties of aquifer. The protective capacity is considered to be proportional to the longitudinal unit conductance (S). Accordingly the overburden protective capacity was evaluated using the total longitudinal unit conductance (S) values.

RESULTS AND DISCUSSION

Longitudinal conductance (S)

The longitudinal conductance (S) value varying from 0.016 to 5.44 Ω^{-1} in the study area (Figure 4a) helps us to differentiate the variations in the total thickness of low resistivity materials. The southern and central parts are characterized by S values greater than 1 Ω^{-1} at VES stations 11, 14 and 23, coinciding with the hilly terrain. Between these two highs, low S values (0.1 to 0.35 Ω^{-1}) are observed encompassing VES stations 9, 4, 13, 21, 6 and 10. Another low S zone varying from 0.016 to 0.39 Ω^{-1}, is seen in the northern part of the basin at VES stations 7, 16, 19, 17, 2 and 15. It can be envisaged that the VES stations with low to moderate S value (0.01 to <2 Ω^{-1}) represent freshwater region.

The longitudinal conductance (S) provides information on the variation of the resistive basement topography, as depth to the basement relates to S. It may however be noted that the resistivity of a layer depends more on the saturation of the layers and not necessarily on the thickness of the aquifer, hence higher resistivities may not correlate with areas of thicker aquifer as in the case of VES 11 and 23 in the present study.

Relatively thick geologic succession and clayey overburden are usually characterized by reasonably high longitudinal conductance and offer protection to the underlying aquifer from contaminants. However, the earth acts as a natural filter to these percolating contaminants and its ability to retard the infiltrating contaminants is a measure of its protective capacity. According to the classification of Oladapo and Akintorinwa (2007), the S-map (Figure 4a) suggests that about 4% of the area falls

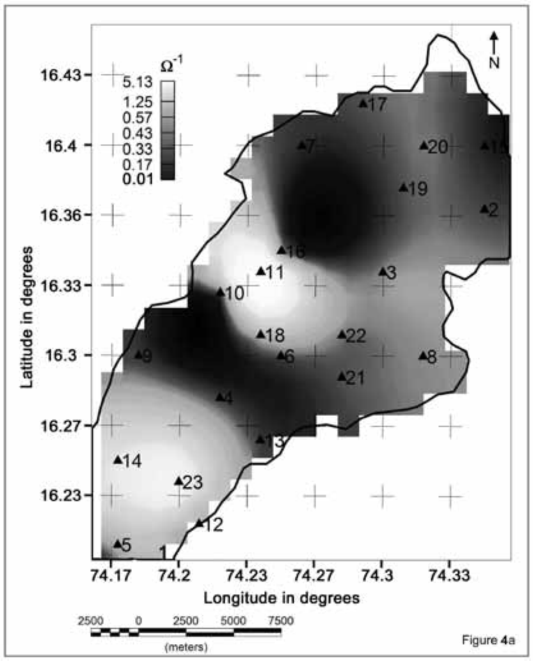

Figure 4a. Spatial distribution of longitudinal conductance (S) in the study area.

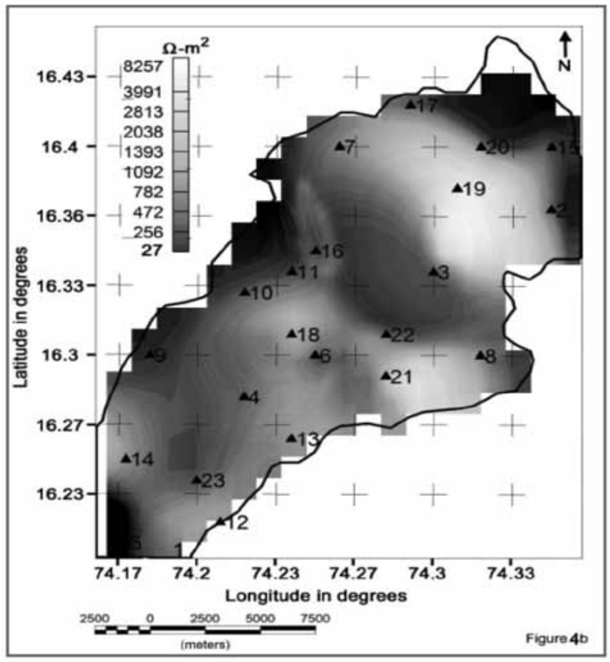

Figure 4b. Spatial distribution of transverse resistance (T) in the study area.

within the "very good" protective capacity, while about 17% constitutes the "good" protective capacity rating. About 49% exhibits "moderate" protective capacity and 17% is having "weak" protective capacity rating. Remaining 13% falls in the poor protective capacity category. This implies that the entire study area, which is characterized by relatively low to moderate longitudinal conductance, envisages good to weak aquifer protective capacity rating. Clayey/silty overburden in this part, which is characterized by relatively high longitudinal conductance, offers protection to the underlying aquifers (George et al., 2014). A noticeable increase in S value may correspond to an average increase in the clay content and therefore, a decrease in the transmissivity of the aquifer (Oteri, 1981). In the present case, the longitudinal conductance value at VES 11, 1, 14, 18 and 23 falls under very good to good protective capacity rating. Further from Figure 4a, it is observed that the southern and central parts of the study area reveal good protective capacity rating as can be envisaged from the high longitudinal conductance values. The low value of the protective capacity is a consequence of the absence of significant amount of clay as an overburden impermeable material in the northern and central part of the basin (VES 4, 10, 12, 13,7, 15 and 16), leading to the percolation of contaminants such as agricultural wastes and anthropogenic activities.

Transverse resistance (T)

The transverse resistance (T) contour map with a contour interval of 100 Ωm^2 is shown in Figure 4b. The T value varies from a minimum of 27.95 Ωm^2 at VES 20 to a maximum of 8387 Ωm^2 at VES 3. It is obvious from Figure 4b that high T values (> 1000 Ωm^2) encompassing VES stations 1, 3, 7, 12, 13, 14, 16, 18, 19 and 21 in the study area, indicate fresh water zone. Increasing T values are associated with zones of high transmissivity and, hence highly permeable to fluid movement (Braga et al., 2006). The southern, south-western and northern parts of the study area are characterized by low T values < 700 Ωm^2.

Electrical anisotropy (λ)

The concept of anisotropy (λ) is derived from the parameters transverse resistivity (ρt) and longitudinal resistivity (ρl), where the block of layers as one unit behaves like an anisotropic medium characterized by the longitudinal and transverse resistivities (Maillet, 1947). The values of electrical anisotropy (λ) ranges from 1 (VES 4, 6, 9 and 10) to a maximum value of 6 (VES 1) with an average of 1.69 in the study area and its distribution is shown in Figure 4c. The coefficient of anisotropy is generally 1 and seldom exceeds 2 in most of the geological conditions (Zohdy et al., 1974). As the hardness and compaction of rocks increases, λ also increases (Keller and Frischknecht, 1966). These areas can thus be associated with low porosity and permeability.

An area with λ <1 and up to 1.5 is considered to be a potential zone for groundwater. As can be seen from Figure 4c, the entire study area portrays a λ value of around 1-1.4, except at VES point 1, 2, 8, 15, 17 and 23. It can thus

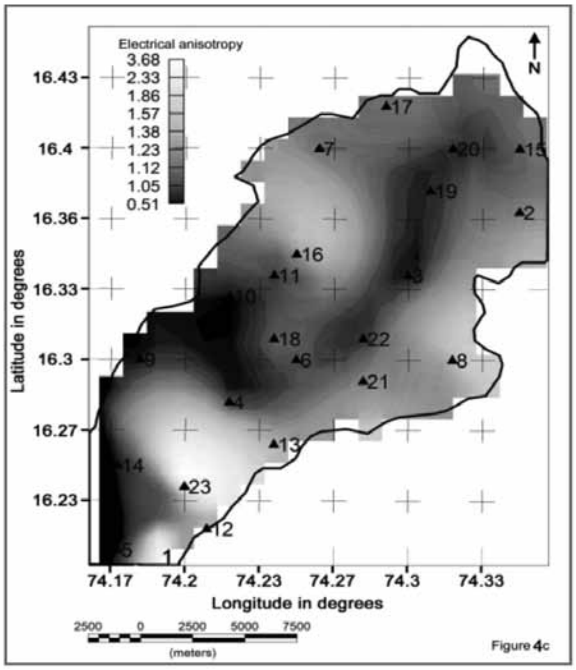

Figure 4c. Spatial distribution of electrical anisotropy (λ) in the study area.

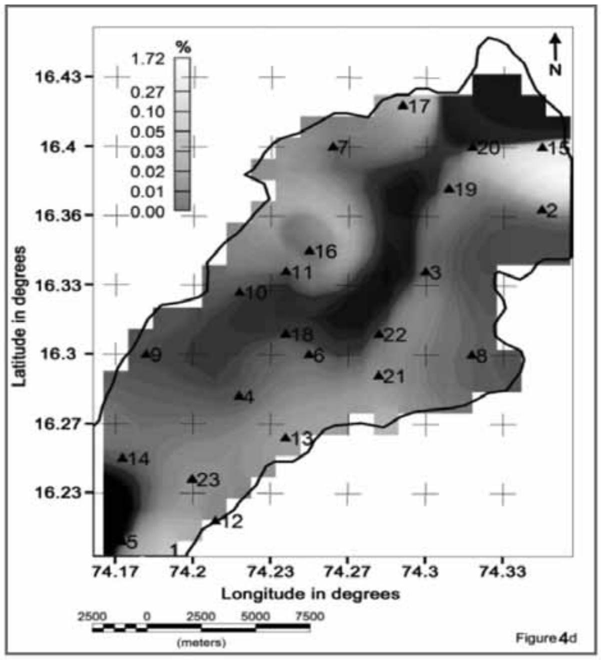

Figure 4d. Map showing the fracture porosity (ϕ_f) variation in the study area.

be surmised that the areas having minimum water table fluctuation is related with low λ values and higher water table fluctuation regions are associated with high λ values.

Fracture porosity (ϕ_f)

The estimated fracture porosity (ϕ_f) reveals that porosity values are higher on the south-eastern and eastern (VES 1, 8, 2 and 15) and in north (VES 17) part of the basin compared to the south-western and central part of the study area (Figure 4d).

A maximum porosity value of 0.55 was observed in the eastern sector at VES 8, while minimum value of 0.0001-0.002 were obtained at a few stations in the south, central and northern part. The fracture porosity values correlate well with the high and low values of anisotropy (λ) suggesting a positive correlation, as can be seen in Figure 4c. This suggests that the fracturing due to the anisotropy trending NE-SW is predominantly developed in the eastern part and is likely to possess varying water retention ability.

It is worthwhile to mention that the resistivity of aquifer layer is largely influenced by porosity and fluid resistivity in the pores. Also, the resistivity value of each layer is an average value, constructed from all of the small scale heterogeneities within that layer. Thus, the calculated porosity value of an aquifer, using an average resistivity, results in an averaged porosity value (Niwas and Celik, 2012). As mentioned earlier, very prominent joints and fractures revealed in the study area enhances secondary porosity. The bore wells in the study area essentially tap the fractured basaltic aquifer. The litho logs suggest that the top layer consists of alluvium/laterite/black cotton soil followed by weathered/jointed fractured basalt, which are often good aquifers, provided they have low clay content. The bottom layer is essentially the jointed/compact basalt (Gupta et al., 2015). It is noted that most of the porosity values are in reasonable agreement with aquifer resistivity values. However at some VES points, the resistivity value of aquifer layer is very low and there is a mismatch with the porosity values. This is presumably because of high concentration of saturated clay matrix in the aquifer zone.

Generally, porosity values may range from zero or near zero to 70%, depending on the geological formation and rock matrix. Very high porosity value is indicative of recently deposited sediments, while a zero or near zero value reflects dense crystalline rocks or highly compacted rocks. The zero porosity values observed is perhaps, due to the compact basalts encountered at different depths. In the Deccan Volcanic Province of Maharashtra, the porosity values of weathered basalt, fractured jointed basalt and fresh amygdaloidal basalt varies from 10-34%, 5-15% and 0-3% respectively. The hard and compact basalts are however non porous (Deolankar, 1980).

As mentioned earlier, the electrical anisotropy (λ) ranges from 1 to 6, portraying a large variation in the study area, suggesting the nature of anisotropy of the geoelectrical parameters. Kumar et al. (2014) observed that if λ exceeds 1, the subsurface basaltic formation is more fractured; however if the value of λ is about 1, then probably the overburden thickness (H) is more. In the

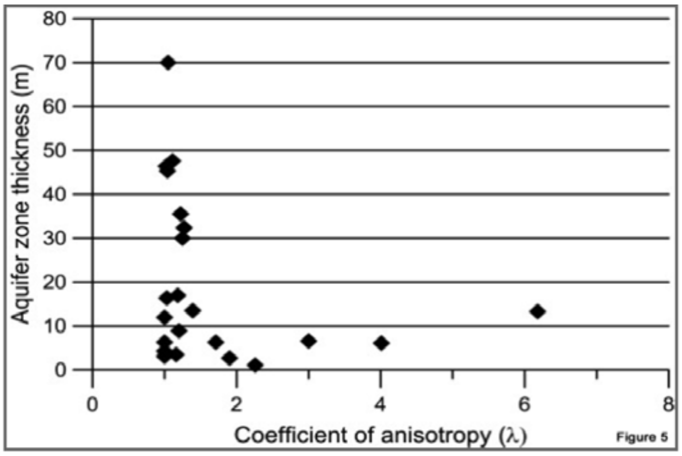

Figure 5. Plot of aquifer zone thickness and coefficient of anisotropy with maximum tendency of anisotropic behaviour of rock.

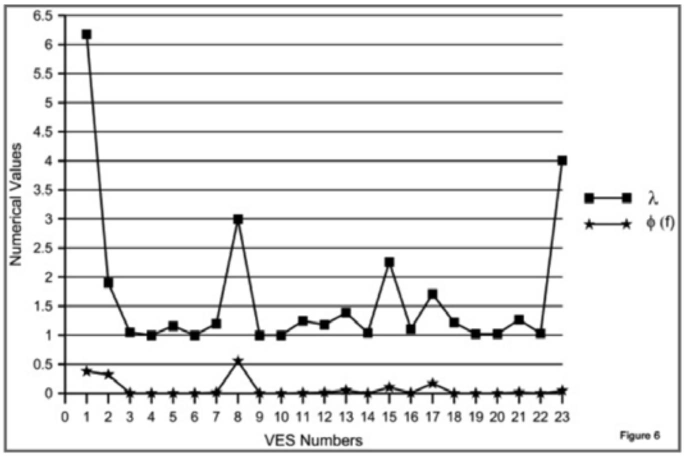

Figure 6. Plot of coefficient of anisotropy (λ) and fracture porosity (ϕ_f) with VES number.

present study, the plot of electrical anisotropy and aquifer zone thickness (Figure 5) suggests that the VES stations with relatively thick overburden is hovering around the λ value of 1. It can also be seen in Figure 4c that the λ values are high in NE-SW direction and around the northern part, with major highs at VES 23, 8 and 15. This reveals that the fractures in the subsurface are more conspicuous in the NE-SW direction. The fracture porosity (ϕ_f) values suggests similar trend as that of electrical anisotropy (λ) thereby corroborating with the porous zones (Figure 4d) in the NE-SW part of the study area.

The plot of the electrical anisotropy (λ) and fracture porosity (ϕ_f) with the VES stations (Figure 6) depicts that λ is greater than 1 at most of the VES stations, while ϕ_f varies from 0.0001% to 0.55% at all the VES points, suggesting differing degrees of water saturation within the fractured and vesicular basaltic rock formation. As mentioned earlier, Deolankar (1980) reported that the weathered basalt shows highest aggregate porosity of about 34% in Deccan Volcanic Province, whereas the specific yield is less (around 7%). Though the porosity is high, the specific yield is very small signifying higher specific retention of the weathered basalt which may be due to the presence of clay minerals.

CONCLUSIONS

The vertical electrical sounding studies facilitated delineation of aquifer zones and characterized the conditions of the underground flow in terms of fracture porosities of the aquifers and the protective capacities of the overburden rock materials.

The longitudinal conductance map reveals that the protective capacity rating of Chikotra basin falls in the moderate to poor category. VES 11, 1, 14, 18 and 23 falls under very good to good protective capacity rating indicating thick clayey/silty layer thus offering protection to the underlying aquifers. VES 4, 10, 12, 13, 7, 15 and 16 reveals low value of the protective capacities of the overburden rock materials which make the aquifer system in the area highly vulnerable to contamination. The high T values are related to zones of high transmissivity aquifer materials and thus highly permeable, thereby enhancing the migration of contaminants within the groundwater system over large areas. These revelations are indications that the groundwater quality may have been impaired in the area and borehole water should be randomly sampled for contaminant loads based on this analysis.

Higher values of fracture porosity are observed on the south-eastern and eastern (VES 1, 8, 2 and 15) and in northern (VES 17) parts compared to the south-western and central parts of the study area. This implies that the fracturing due to the anisotropy trending NE-SW is mainly developed in the eastern part and that the fractured rocks are expected to hold water with differing water retention ability. A positive correlation is observed between the fracture porosity values and the values of anisotropy (λ), corroborating the porous zones in the NE-SW part of the study area. The present study helps in characterizing the aquifers of the hard rock terrain (HRT) in Deccan Volcanic Province (DVP) of Maharashtra and to estimate the aquifer protective capacity as well as the fracture geometry using secondary geophysical indices.

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Compliance with Ethical Standards

The authors declare that they have no conflict of interest and adhere to copyright norms.

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