Geoelectric investigation to delineate groundwater potential and recharge zones in Suki river basin, north Maharashtra

Gautam Gupta[1,*], S N Patil[2], S T Padmane[2,3], Vinit C Erram[1] and S H Mahajan[1]

[1]*Indian Institute of Geomagnetism, Kalamboli Highway, Navi Mumbai 410 218, India.*
[2]*School of Environment and Earth Sciences, North Maharashtra University, Jalgaon 425 001, India.*
[3]*Groundwater Surveys and Development Agency, Nagpur, Maharashtra 444 602, India.*
[*]*Corresponding author. e-mail: ggupta@iigs.iigm.res.in*

Suki river basin of Raver sub-division is located towards the northeastern part of Jalgaon district in Maharashtra State. The existing land use pattern of the region clearly shows that more than 60% of the area is utilized for agricultural sector. Groundwater is the major source of irrigation and domestic purposes. To assess the overall water resources development of Raver area for better environment in future, investigation was carried out with the help of geophysical indicators. Vertical electrical sounding studies were conducted at 17 stations in the study area using Wenner configuration. The study was aimed at characterizing the aquifer in the area as well as assessing its potential risk to contaminant seepage in terms of protective capacity of the overburden rock materials using Dar-Zarrouk (D-Z) parameters, viz., the transverse resistance (T), longitudinal conductance (S), transverse resistivity (ρ_t) and longitudinal resistivity (ρ_l). These were computed to generate the resistivity regime of freshwater-bearing formations and its movement. The central-western part of the study area reflects very good to good protective capacity rating as can be seen from the high longitudinal conductance values. The low value of the protective capacity in the eastern part is making the aquifer system in the area highly vulnerable to surface contamination. This indicates that the ground water quality may have been deteriorated in the area and borehole water samples should be randomly sampled for contaminant loads based on this analysis.

1. Introduction

Water is a prime necessity of life and has been fundamental for the development of civilization from the ancient period. The beginning of our civilization was confined to river basins and early settlements were associated with proximity of surface water such as springs, running streams and rivers. Many civilizations came into existence around perennial water resources. The need to prospect for additional groundwater sources in a typically hard-rock terrain like Raver sub-division in Jalgaon district, Maharashtra, became inevitable in order to to cope with the ever increasing population, basic amenities and rapid development for utilizing the water resources for their increasing needs.

The vertical electrical sounding (VES) technique has been effectively used by many researchers in diverse fields of application including groundwater investigations (Devi *et al.* 2001; Lenkey *et al.* 2005; Hamzah *et al.* 2007; Gupta *et al.* 2012), groundwater contamination studies (Karlik and Kaya 2001; Park *et al.* 2007; Frohlich *et al.* 2008; Kundu and Mandal 2009; Maiti *et al.* 2013a; Mondal *et al.*

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2013), saltwater intrusion problems (Edet and Okereke 2001; Hodlur *et al.* 2006; Song *et al.* 2007; Adeoti *et al.* 2010; Hermans *et al.* 2012; Maiti *et al.* 2013b; Gupta *et al.* 2014), and geothermal explorations (El-Qady *et al.* 2000; Majumdar *et al.* 2000; Kumar *et al.* 2011).

Several researchers have carried out systematic hydrogeological and geophysical studies in the Deccan trap region (Bose and Ramakrishna 1978; Singhal 1997; Pawar *et al.* 2009; Rai *et al.* 2011; Ratnakumari *et al.* 2012; Rai *et al.* 2013) to delineate aquifers and the 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.

With the available database in the northern part of Deccan Volcanic Province (DVP), Central Groundwater Board (CGWB) (http://cgwb.gov.in/CR/achi_geo_stu.html) has established standardized resistivity ranges for different litho units in respect of water bearing zones in the Deccan basalts. These studies have reported that for weathered/fractured vesicular basalt saturated with water, the resistivity values are of the order of 20–45 Ω-m. The moderately weathered/fractured basalt/vesicular basalt saturated with water has a resistivity range of 40–70 Ω-m, whereas, hard, compact and massive basalts have been assigned resistivity values of >70 Ω-m.

The study was aimed at characterizing the aquifers, to delineate the depth of the aquifer and its lateral extent and to estimate the aquifer protective capacity in the area as well as assessing its recharge capability using Dar-Zarrouk (D-Z) parameters in the Raver area of Jalgaon district, Maharashtra (figure 1a).

2. Physiography and geology of the region

The Suki river basin is located in the northeastern part of Jalgaon district of Maharashtra State (figure 1a). It is a tributary of the Tapi River and originates in Madhya Pradesh and enters into Maharashtra at north of the village Pal in Raver sub-division and meets river Tapi at village Hatnur. The total area covered under study is about 328 km^2. The area is included in Survey of India toposheet nos. 46 O/11, O/12, O/15, O/16 and 55 C/4 and lies between 75°44′00″–75°56′02″ east longitude and 21°04′25″–21°21′43″ north latitude. The mean sea level (MSL) ranges from 180 to 1074 m. The study area experiences a semi-arid climate. The average annual rainfall of the area is about 742 mm. The maximum temperature ranges from 29 to 48°C, while the minimum temperature ranges from 12 to 24°C.

The area includes the undulating piedmont plains along southern fringe of Satpuda hills and the flood plains of Tapi River. The general gradient is southwards. The topography in combination with the nature of soil and sediments is largely responsible for the high surface run-off, poor infiltration and its impact on consequent scarcity of ground/surface water resources. Many streams originate from Satpuda ranges, flow towards south and ultimately discharge into the Tapi River. The dendrites and parallel drainage pattern is clearly seen in the study area. Hatnur Right Bank Canal is also passing from the southern part of the area which helps in replenishment of groundwater (Chavan and Nile 2012). The regional geology (figure 1b) of the region is described by Lamsoge (2009) and is given in table 1.

The entire region is covered by a thin layer of alluvial soil of varying thicknesses. This soil cover is underlain by a composite layer of younger and older alluvium. This layer is further underlain by weathered and highly fractured basalts (Deshpande 1998). The location map and general geology of the study area is shown in figure 1(a and b). Groundwater in Deccan Trap Basalt occurs mostly in the upper weathered and fractured parts down to 20–25 m depth. Potential groundwater zones are encountered at deeper levels in parts of Raver in the form of fractures and in intertrappean zones, which are sedimentary formations deposited during the interval of two consecutive lava flows. Intertrappeans together with the vesicular basalt units form groundwater potential zones between two compact basalt layers (Rai *et al.* 2011) If the intertrappean bed is clay rich, then it is not a likely source of groundwater. Such beds are termed as bole beds (Ghosh *et al.* 2006). The upper weathered and fractured parts form phreatic aquifer and groundwater occurs under water table (unconfined) conditions. At deeper levels, the groundwater occurs under semi-confined conditions.

The yield of dug wells, tapping upper phreatic aquifer, ranges between 21 and 337 m^3/day, which have a depth range of 5–15 m bgl. Bore wells drilled down to 60–150 m depths, tapping weathered and vesicular basalt are found to yield 1.8–52 m^3/day. On the other hand, groundwater in alluvium occurs under water table, semi-confined and confined conditions (Lamsoge 2009). The average thickness of aquifer ranges from 4 to 9 m. The pre-monsoon static water level ranges from 5 to 11.60 m, while the post-monsoon static water level ranges from 2 to 8.35 m.

Presently, groundwater withdrawal in the study area for irrigation and domestic uses are from dug wells penetrating approximately 5–15 m depths up to the bottom of weathered/fractured mantle.

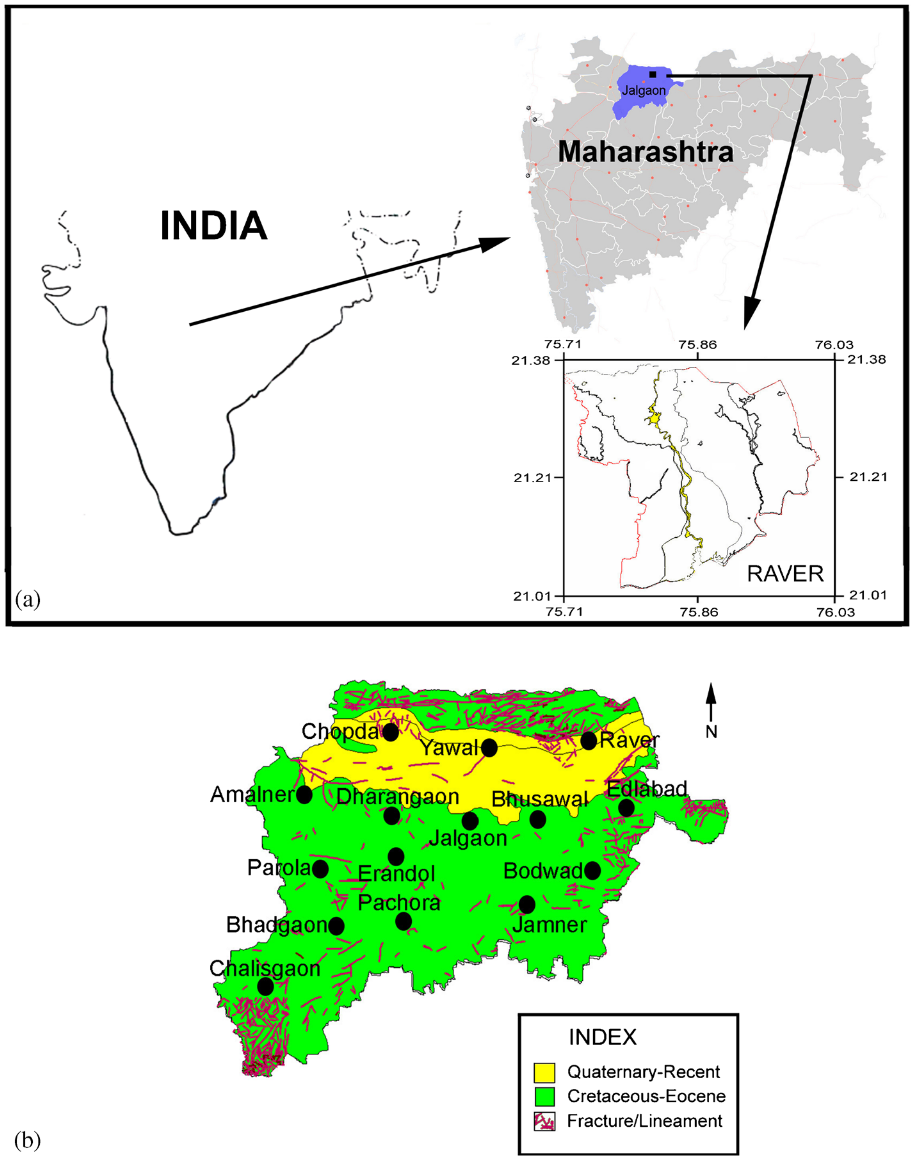


Figure 1. Map depicting (**a**) the location of the study area in Raver sub-division of north Maharashtra and (**b**) the general geology of Jalgaon district. Also shown are the lineaments present in the region.

Table 1. *Regional geology of the study area.*

Recent	Alluvium
Quaternary to Recent	Bazada (Talus and Scree), younger alluvium and older alluvium
Upper Cretaceous–Lower Eocene	Basalt (Deccan Traps)

Most of the dug wells go dry during summer season. Thus, availability of water in these dug wells is inadequate to meet the present demand of water supply. The unpredictable fluctuation in rainfall tends to aggravate the problem. Excessive pumping of groundwater resources for cash crop like banana has also caused depletion in water table.

3. Survey design

In the DC resistivity method, current is introduced directly into the ground through a pair of current electrodes and the resulting voltage difference is measured between a pair of potential electrodes. This method provides the apparent resistivity distribution against depth. The depth of penetration of electrical signal is generally found to be approximately one-third of the distance between the electrode separations (Dahlin 2000; Maiti *et al.* 2011). This method is carried out to decipher problems of aquifer in hard formation such as the Deccan Trap region.

A total of 17 resistivity soundings were carried out in the study area using Aqua-II plus D.C. resistivity meter manufactured by Minitronics, Pune. The general hydrological conditions were ascertained on the basis of geomorphologic setting and lithological characteristics of different alluvial beds exposed in dug wells. Representative areas of different hydrological environments were then selected for resistivity survey. The Wenner configuration of equally spaced electrode distribution was employed in the present survey. The current electrodes were placed 300 m apart to obtain information up to a depth of approximately 100 m. The data obtained from the field was processed and modelled using IPI2WIN software, version 3.0.1.a7.01.03 (Bobachev 2003) for interactive semi-automated interpretation. It is observed that most of the sounding curves in the area reflect much variation in the curve type and suggests 4–5 layered structure in the study area. The layer resistivity, layer thickness, total thickness (H) and the RMS error for all the 17 VES stations are shown in table 2.

4. Analysis of VES data

Maillet (1947) termed the Dar-Zarrouk (D-Z) parameters (T, transverse resistance and S, longitudinal conductance). T is the resistance normal to the face and S is the conductance parallel to the face for a unit cross-section area, which plays an important role in resistivity soundings. D-Z parameters are sufficient for computing the distribution of surface potential and hence electrical resistivity graphs (Henriet 1976). Later on, many other workers (Niwas and Singhal 1981, 1985; Shahid and Nath 2002; Singh *et al.* 2004; Khalil 2006; Mondal *et al.* 2013) studied the significance of D-Z parameters for obtaining hydrological properties of the aquifers.

In the present study, the D-Z parameters (Singh and Singh 1970; Henriet 1976; Salem 1999; Ayolabi *et al.* 2010) namely longitudinal unit conductance (S), transverse unit resistance (T), transverse resistivity (ρ_t), longitudinal resistivity (ρ_l), coefficient of anisotropy (λ) and root mean square resistivity (ρ_m), have been adopted to analyze the data.

Let us consider a prism of unit cross-section which is characterized by its thickness 'h' and resistivity 'ρ'. Then the resistance (T) perpendicular to

Table 2. *Geoelectrical layers and Dar-Zarrouk parameters in and around Raver sub-division.*

VES	Layer resistivity (Ω-m)					Thickness (m)					RMS						
no.	$\rho 1$	$\rho 2$	$\rho 3$	$\rho 4$	$\rho 5$	h1	h2	h3	h4	H (m)	error (%)	S	T	ρ_l	ρ_t	λ	ρ_m
VES 1	5.41	60.7	13.1	85.3	–	0.5	2.98	7.2	–	10.68	0.34	0.69	277.9	15.47	26.02	1.68	20.06
VES 2	3.77	90.4	6.01	96.4	–	0.544	0.972	55.0	–	56.51	0.31	9.30	420.4	6.07	7.43	1.22	6.70
VES 3	29.9	118	8.38	29.2	0.345	1.3	6.81	5.93	54.4	68.44	0.48	2.67	2480.6	25.63	36.24	1.41	30.47
VES 4	13.4	39.3	24.6	–	–	2.3	21.0	–	–	23.3	0.32	0.7	856	33.28	36.73	1.10	34.96
VES 5	7.11	11.7	3.15	–	–	0.504	64.0	–	–	64.5	0.26	5.54	752.3	11.64	11.66	1.00	11.65
VES 6	16.8	9.99	21.8	0.137	–	1.15	2.55	58.9	–	62.6	0.43	3.02	1328.1	20.72	21.21	1.02	20.96
VES 7	20	10.3	17.8	–	–	2.0	23.1	–	–	25.1	0.33	2.34	277.9	10.72	11.07	1.03	10.89
VES 8	24.3	12.9	27.2	11.1	–	0.572	5.91	16.9	–	23.38	0.12	1.10	549.8	21.25	23.51	1.10	22.35
VES 9	12.1	18.5	4.91	–	–	1.66	39.2	–	–	40.86	0.28	2.25	745.2	18.16	18.23	1.00	18.19
VES 10	84.6	13.7	29.6	0.119	–	4.41	5.74	43.6	–	53.75	0.31	1.94	1742.2	27.70	32.41	1.17	29.96
VES 11	19.9	10.6	24.9	3.97	24	0.973	3.65	2.57	2.99	10.18	0.32	2.36	133.9	4.31	13.14	3.04	7.52
VES 12	5.05	8.1	172	–	–	0.5	77.3	–	–	77.8	0.23	9.64	628.6	8.07	8.07	1.00	8.07
VES 13	12.4	16.2	31.8	0.838	–	1.05	5.76	59.7	–	66.51	0.28	2.31	2004.7	28.79	30.14	1.04	29.45
VES 14	5.08	8.01	8.26	–	–	0.5	4.24	–	–	4.74	0.16	0.62	36.5	7.64	7.70	1.00	7.67
VES 15	12.1	18.5	5.02	–	–	1.67	38.7	–	–	40.37	0.47	2.23	736.1	18.1	18.23	1.00	18.16
VES 16	20.3	7.84	28.7	9.12	–	1.5	2.02	1.87	–	5.39	0.29	0.39	99.9	13.82	18.53	1.34	16.0
VES 17	10.5	25.1	12.2	0.528	–	0.5	3.01	56.1	–	59.61	0.39	2.40	765.2	24.83	12.82	0.51	17.84

the face of the prism and the conductance (S) parallel to the face of prism (Mondal *et al.* 2013) can be written as:

$$T = h \times \rho, \tag{1}$$

and

$$S = \frac{h}{\rho}. \tag{2}$$

It is considered that the prism consists of n-geoelectrical layers and is completely characterized by its thickness $h_1, h_2, \ldots, h_n$ and resistivities $\rho_1, \rho_2, \ldots, \rho_n$, respectively. Then, the total resistance of the current flowing perpendicular to the layers will be the sum of resistance offered by each layer and can be expressed as follows:

$$T = h_1\rho_1 + h_2\rho_2 + \cdots + h_n\rho_n, \tag{3}$$

or

$$S = \sum_{i=1}^{n} h_i * \rho_i. \tag{4}$$

This is 'transverse resistance'.

The transverse resistivity to the current flowing perpendicular to the layers is given by:

$$\rho_t = \frac{T}{H}, \tag{5}$$

where $H = \sum h_i$ and H being the depth to the bottommost geoelectric layer.

Similarly, the total conductance of the current flowing parallel to the layers can be expressed as:

$$S = \frac{h_1}{\rho_1} + \frac{h_2}{\rho_2} + \cdots + \frac{h_n}{\rho_n}, \tag{6}$$

or

$$S = \sum_{i=1}^{n} \frac{h_i}{\rho_i}. \tag{7}$$

This is 'longitudinal conductance'.

The longitudinal resistivity of the current flowing parallel to the layers is given by:

$$\rho_l = \frac{H}{S}. \tag{8}$$

The coefficient of pseudo-anisotropy (λ) is given by:

$$\lambda = \sqrt{(\rho_t/\rho_l)}. \tag{9}$$

The root mean square resistivity, also known as effective resistivity, is given as:

$$\rho_m = \sqrt{(\rho_t * \rho_l)}. \tag{10}$$

The above parameters were used for delineating the sub-surface freshwater zones in the study region and to determine the aquifer protective capacity. As mentioned earlier, 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 and for the evaluation of hydrologic properties of aquifer. The protective capacity is considered to be proportional to the longitudinal unit conductance (S) (Oladapo *et al.* 2004; Ayolabi 2005; Atakpo and Ayolabi 2008; Atakpo 2013). Thus, the overburden protective capacity was evaluated using the total longitudinal unit conductance (S) values (Henriet 1976; Oladapo *et al.* 2004; Atakpo and Ayolabi 2008; Atakpo 2013).

5. Results and discussion

5.1 *Estimation of Dar-Zarrouk parameters*

As mentioned earlier, a total of 17 VES were carried out using Wenner configuration in the study region (figure 2). The data were acquired between the latitudes 21.10°–21.30° and longitudes 75.82°–76.06° in the Raver sub-division of Jalgaon district, northern Maharashtra. In order to characterize the aquifers, to delineate the depth to the aquifer and its lateral extent and to estimate the aquifer protective capacity in the area as well as assessing its recharge capability, contour maps for longitudinal conductance (S), transverse resistance (T), transverse resistivity (ρ_t), longitudinal resistivity (ρ_l), anisotropy (λ) and root mean square resistivity (ρ_m) were generated. This will aid in understanding the spatial variation of these parameters to demarcate the fresh water bodies, to envisage effect of saline water ingress, if any, and to delineate the groundwater potential zones. The D-Z parameters in the study area are given in table 2.

5.1.1 *Longitudinal unit conductance*

The longitudinal conductance (S) varies from 0.39 to 9.64 in the study area with a contour interval of 0.5 (figure 3a). It can be clearly seen that there is a distinct boundary at the central part of the study area. The eastern part is infested with low S values (0.39–1), encompassing VES stations 1, 4 and 14, whereas the central part is characterized by S values greater than 3 at VES stations 3, 6 and 11. Very high S values (>6) are observed at VES stations 2, 5 and 12. Elsewhere, the S value is moderate. It can be envisaged that the VES stations with low to moderate S value (0.39–5) represents freshwater region.

The longitudinal conductance (S) gives information about the variation of the highly resistive fresh basement topography as depth to the basement

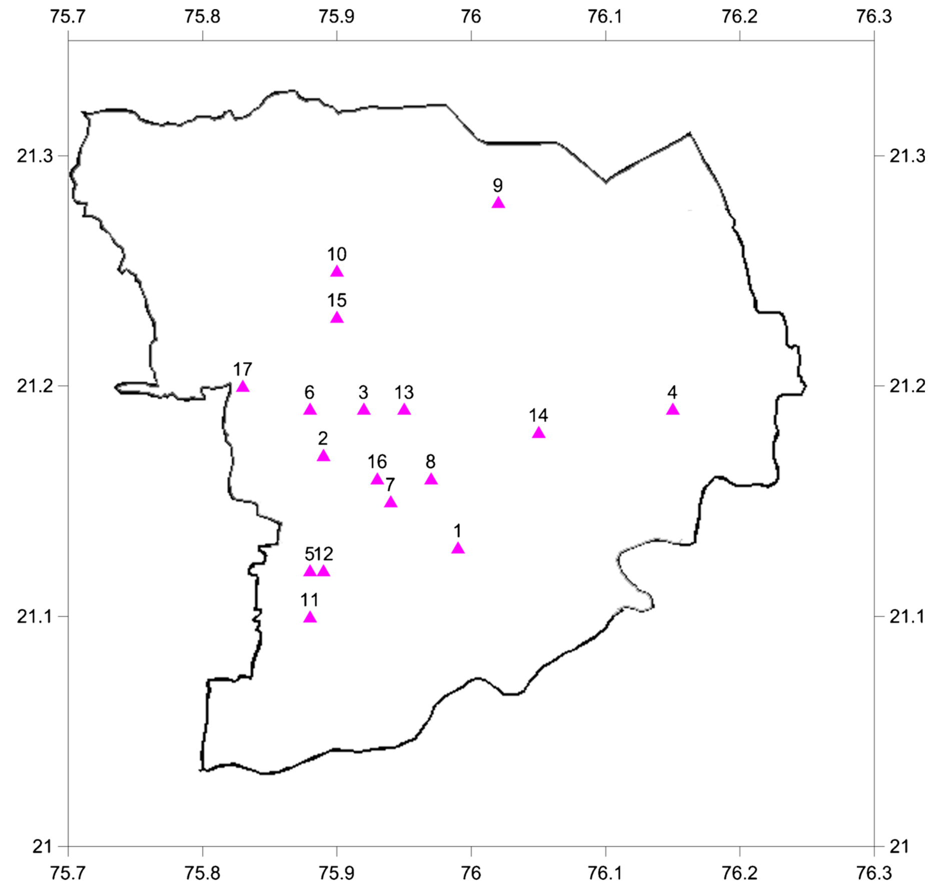
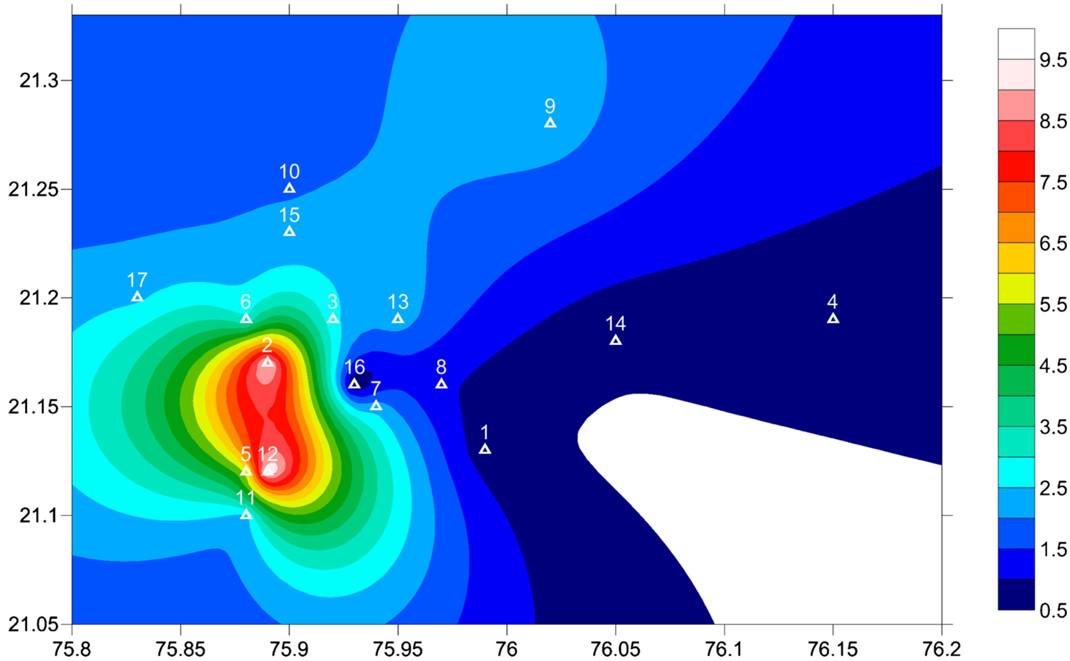


Figure 2. Location map of vertical electrical sounding points in the study area.

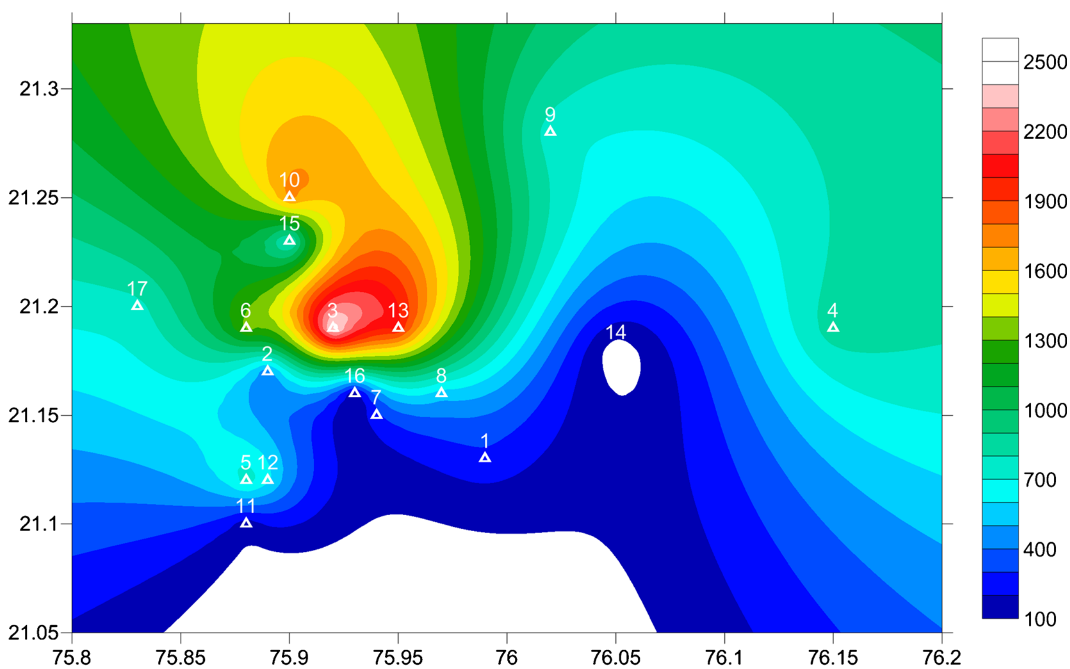
relates to S (Ayolabi *et al.* 2010). It has also been reported that in an area where geoelectric environments are uniform, resistivity will not vary much and thus, S will be proportional to H, which means that large S values are indicative of deeper basement and *vice versa* (Murali and Patangay 2006). In the present study, very high S values (9.64 and 9.3) are obtained at VES stations 12 and 2 and the corresponding depth to the bottom-most geoelectric layer is about 77 and 56 m having a resistivity of 172 and 96 Ω-m, respectively, which might be the fractured basement in this area.

Clayey overburden, which is characterized by relatively high longitudinal conductance, offers protection to the underlying aquifer. According to the classification of Oladapo and Akintorinwa (2007), Atakpo (2013), the longitudinal unit conductance values facilitate to classify the area into poor, weak, moderate, good, very good and excellent protective capacity zones. Where the conductance is greater than 10, they are considered as zones of excellent protective capacity. The part having conductance values ranging from 5 to 10 was classified as zone of very good protective capacity; areas with S values ranging from 0.7 to 4.9 were classified as exhibiting good protective capacity; the region where the conductance value is between 0.2 and 0.69 is considered as moderate protective capacity and the section having a conductance value in the range of 0.1–0.19 exhibits weak protective capacity, while the zones where the conductance value is less than 0.1 were considered to have poor protective capacity.

The S-map (figure 3a) revealed that about 18% of the area falls within the 'very good' protective capacity, while about 64% constitutes the 'good' protective capacity rating and the remaining 18% exhibits moderate/weak protective capacity. This suggests that the entire study area, which is characterized by relatively moderate to high longitudinal conductance, envisages good aquifer protective capacity rating. Clayey/silty overburden in this part, which is characterized by relatively high longitudinal conductance, offers protection to the underlying aquifers. Oteri (1981) reported that a marked increase in S value may correspond to an average increase in the clay content and therefore, a decrease in the transmissivity of the aquifer. In the present study, one borehole lithology at VES 17 (figure 6) suggests that the 60 m litholog encountered clayey overburden with lenses of sand, pebbles, etc. The longitudinal conductance value at VES 17 is 2.4 and falls under good protective



(a)



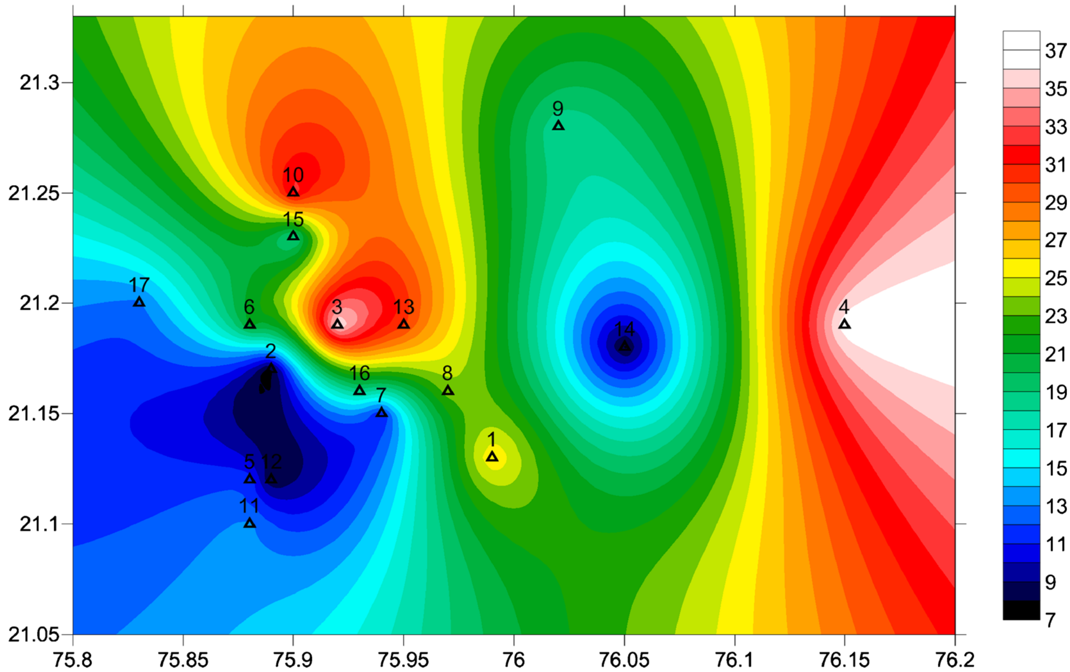
(b)

Figure 3. Spatial distribution of (**a**) longitudinal conductance (S) in Seimens, (**b**) transverse resistance (T) in Ω-m^2, (**c**) transverse resistivity (ρ_t) in Ω-m, (**d**) longitudinal resistivity (ρ_l) in Ω-m, and (**e**) electrical anisotropy (λ) in the study area.

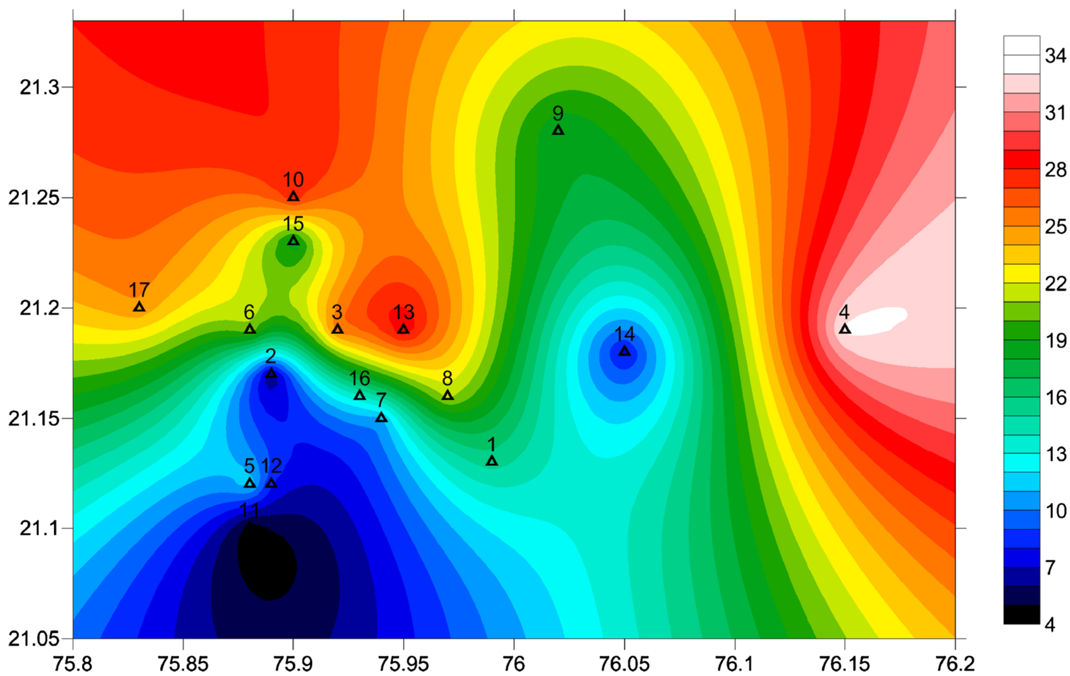
capacity rating. Further from figure 3(a), it can be surmised that the central-western part of the study area reflects very good to good protective capacity rating as can be envisaged from the high longitudinal conductance values. The low value of the protective capacity is a consequence of the absence of significant amount of clay as an overburden impermeable material in the eastern part (VES stations 1, 4 and 14), thereby enhancing the percolation of contaminants into the aquifer. The aquifers here may be prone to contaminations such as industrial and agricultural wastes, septic tanks and landfills, if located close to the sounding points.

5.1.2 *Transverse unit resistance*

The transverse resistance (T) contour map with a contour interval of 100 Ω-m^2 is shown in



(c)



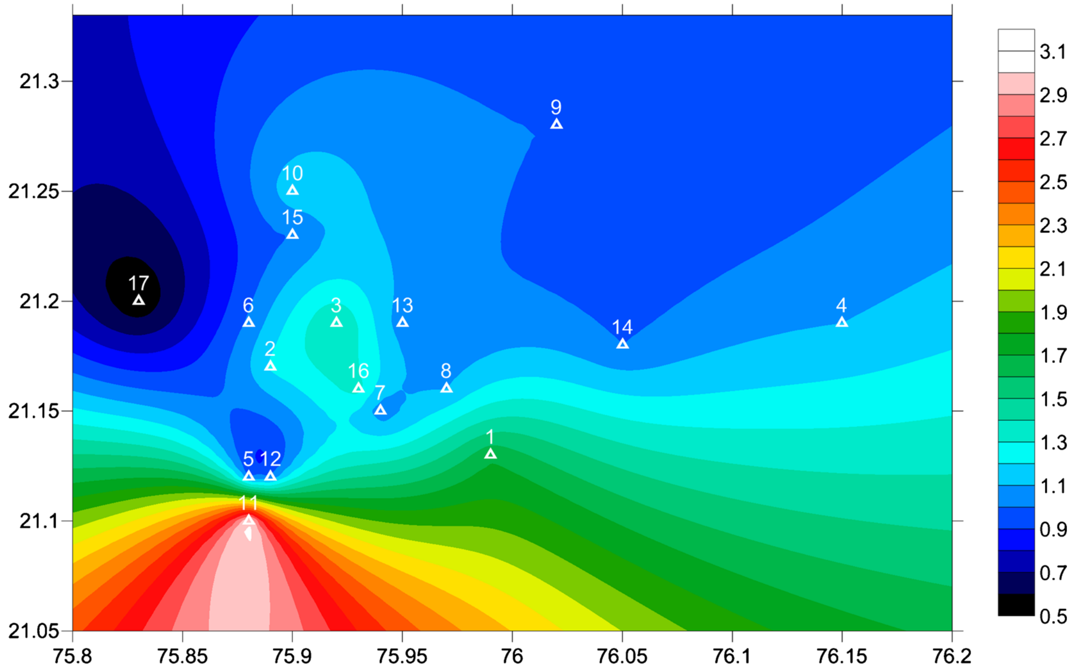
(d)

Figure 3. (*Continued.*)

figure 3(b). The T value varies from a minimum of 36.5 Ω-m^2 at VES 14 to a maximum of 2480 Ω-m^2 at VES 3. It is evident from figure 3(b) that high T values (>700 Ω-m^2) are encompassing VES stations 3, 4, 6, 9, 10, 13, 15 and 17 in the study area, signaling fresh water zone. Increasing T values indicate high transmissivity of aquifers. The south-eastern and southern part of the study area are characterized by low T values (<700 Ω-m^2).

5.1.3 *Transverse resistivity*

Figure 3(c) depicts the contour map for transverse resistivity (ρ_t) with a contour interval of 1 Ω-m. This map has a certain resemblance with the T contour map (figure 3b). The northern part shows a broad feature with resistivities in excess of 25 Ω-m and is governed by the VES stations 3, 10 and 13. The southern part encompassing VES points 2, 5,



(e)

Figure 3. (*Continued.*)

7, 11 and 12 is characterized by resistivities of the order of 7–15 Ω-m. The central part of the study region is encompassed by resistivity values of about 16–24 Ω-m indicating freshwater zone. The pockets of very low resistivity observed at VES 12 and 14 are probably due to contaminant waters caused by agricultural and domestic wastes. There is no effect of saline water intrusion in the transverse resistivity map.

5.1.4 *Longitudinal resistivity*

The contour map (contour interval of 1 Ω-m) of longitudinal or horizontal component (ρ_l) of resistivity values is shown in figure (3d). The entire study region shows the resistivity value of 4–33 Ω-m. The northern part of the study region encompassing VES stations 3, 10 and 13 is characterized by resistivities in excess of 25 Ω-m. VES station 4 in the extreme eastern part of the study area indicates resistivity value in excess of 30 Ω-m. Low resistivities in the range of 4–12 Ω-m is observed at VES stations 2, 5, 7, 11–12 in the southern part. The central and northwestern part of the map depicts moderate resistivity of the order of 13–22 Ω-m.

The longitudinal resistivity (ρ_l), in general, is less than the transverse resistivity (ρ_t), unless the medium is uniform (Flathe 1955), which is observed in the present study also. This suggests that the current flow and average hydraulic conduction along the lithology boundary (longitudinal) are greater than those normal to the boundary plane (Ayolabi *et al.* 2010). Further, Keller (1982) opined that ρ_l is dominated by the more conductive layers (in the present case, clay and weathered layers), whereas ρ_t increases rapidly even if a small fraction of resistive layers are present.

5.1.5 *Electrical anisotropy*

The above-mentioned parameters introduce the concept of anisotropy (λ), where the block of layers as one unit behaves like an anisotropic medium characterized by the longitudinal and transverse resistivities (Maillet 1947; Khalil 2009). The values of electrical anisotropy (λ), as shown in table 2, ranges from 0.5 (VES 17) to 3.0 (VES 11) with an average of 1.21 in the study area and its distribution is shown in figure 3(e). 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 value <1 and up to 1.5 is considered to be a potential zone for groundwater (Singh and Singh 1970). As can be seen from figure 3(e), entire study area depicts a λ value of around 1–1.5, except at VES point 11. It can thus be suggested that the areas having lowest water table fluctuation is related with low λ values and higher water table fluctuation regions are associated with high λ values. Mondal *et al.* (2013) reported that the anisotropy in a hard rock area could be due to different geological layers in such a semi-arid region.

5.1.6 *Root mean square resistivity*

The root mean square resistivity (ρ_m), also known as effective resistivity, in the study region, as shown in table 2, ranges between 6.7 (VES station 2) and 34.96 Ω-m (VES station 4). Khalil (2009) observed that when the longitudinal, transverse and mean resistivities differ, then the change in resistivity is dependent on the direction of groundwater flow and the influence of lithological variation. These three types of resistivity values are different in layered anisotropic sediments (Mazac *et al.* 1985; Ayolabi *et al.* 2010). In the present case, it is observed that the three resistivity values are different (except at VES 12) which reflect the fact that heterogeneous anisotropic lithology is encountered here.

5.2 *Geoelectrical modelling*

The 2-D geoelectrical section has been generated over four selected profiles in order to understand the geometry of the aquifer developed in and around the study area. The profiles are marked as Profile AB, Profile CD, Profile EF and Profile GH for the sake of discussion (figure 4). The 2-D longitudinal geoelectrical model is shown in figures 5(a–d).

5.2.1 *Profile AB*

The profile AB is trending E–W and encompassing VES points 17, 6, 3, 13, 14 and 4. It can be seen from figure 5(a) that the top 2 m is saturated with water below VES sites 17 and 6 on the western part. An aquifer zone is delineated up to depths of 10 m below VES 6, having a resistivity of less than 16 Ω-m. This low resistive zone extends further down and the direction of groundwater flow seems to be beneath VES 17 at depths of 40 m. VES 17 and 6 are both potential zones for groundwater recharge. The dug well lithological cross-section at VES 17 is shown in figure 6. The litholog suggests that the aquifer zone lies at depths of about 47 m. The VES study defines a resistivity value of about 12–16 Ω-m at depths of about 40 m and below for this zone. Thus, there is a clear correlation between resistivity data and litholog section at VES 17. As mentioned earlier, the longitudinal conductance (S) at VES 17 is 2.4 and falls under good aquifer protective capacity rating.

VES 3 is characterized by a 30-m thick high resistive (>40 Ω-m) oval-shaped body. This is due to weathered/fractured basalt. Further east of the profile below VES 13, 14 and 4, an expansive low resistive zone is encountered having resistivity of less than 15 Ω-m. The thickness of this zone is thicker (30 m) beneath VES 14, while it thins down to about 3 m beneath VES 4. Below this conductive zone, the entire stretch is moderately resistive (25–30 Ω-m) at depths below 30 m representing weathered/fractured basalt saturated with water.

5.2.2 *Profile CD*

Profile CD trending N–S comprises of VES stations 10, 15, 6, 2, 5, 12 and 11. The longitudinal cross-section (figure 5b) reveals that beneath VES 10, the top layer is resistive (>18 Ω-m), indicating

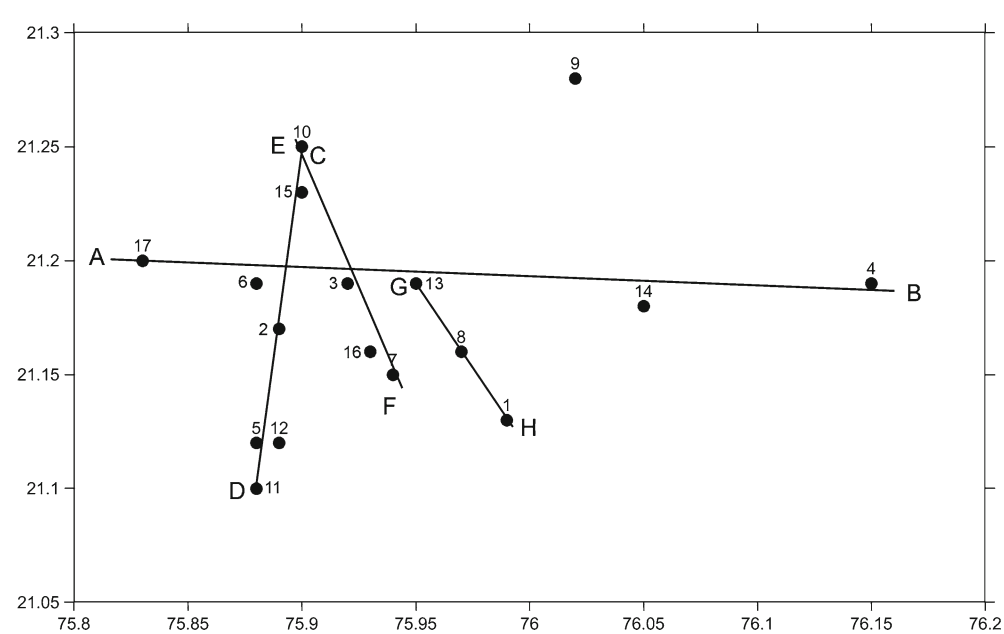


Figure 4. Location map of VES profiles (AB, CD, EF and GH).

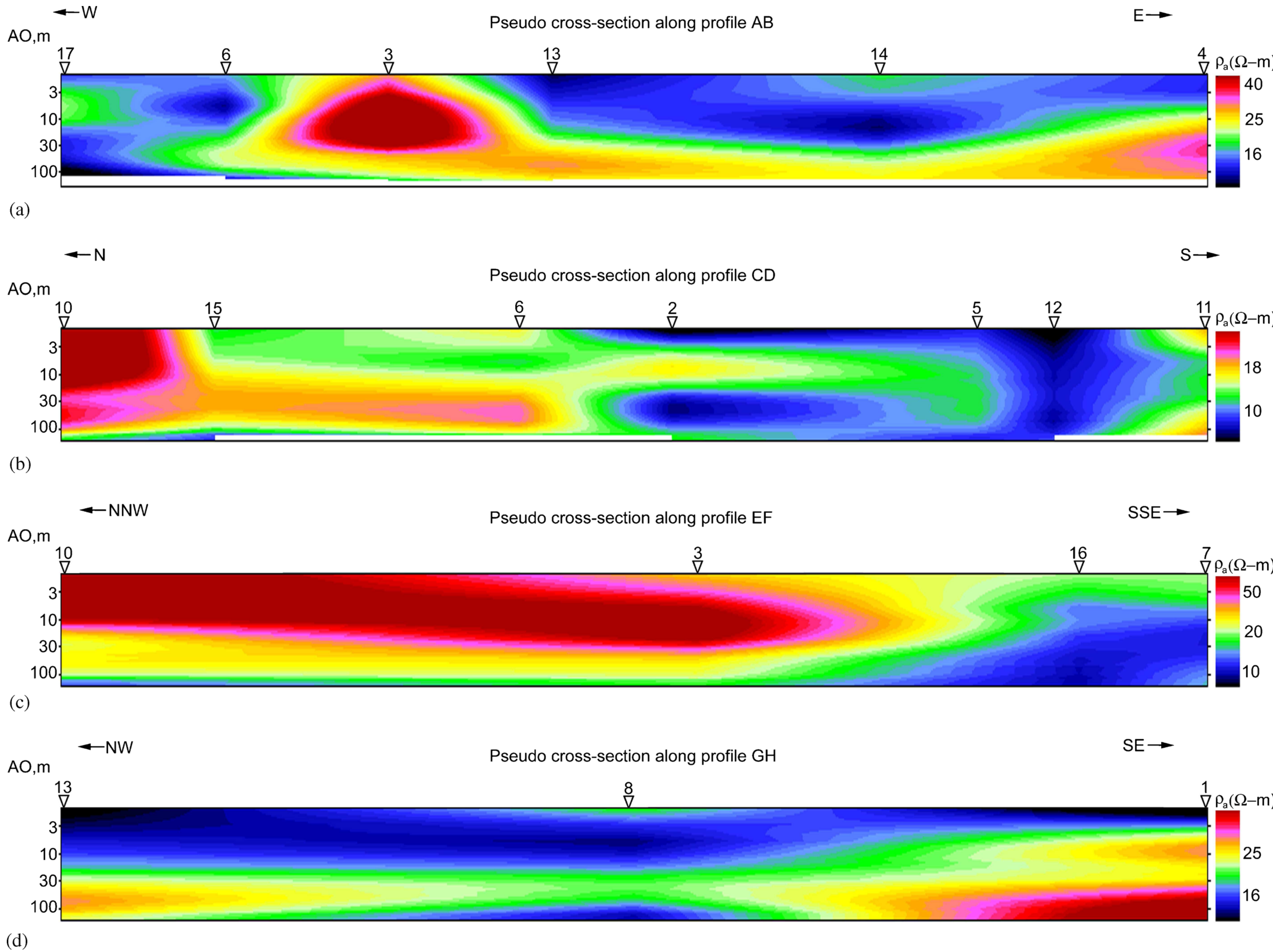


Figure 5. Longitudinal geoelectrical cross-section over profile (**a**) AB, (**b**) CD, (**c**) EF and (**d**) GH.

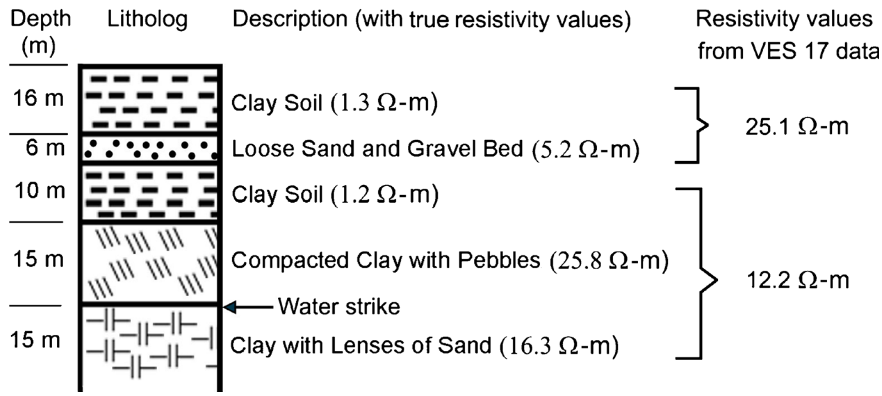


Figure 6. Correlation of one-dimensional inversion of Schlumberger vertical electrical sounding of station 17 along with the dug well lithology of the study area.

hard and compact rock at the top and seems to continue up to depth of penetration. The top 3–5 m below VES 15 and 6 is conductive (about 15 Ω-m) underneath which a resistive (>18 Ω-m) layer is delineated. The top layer in longitudinal geoelectric section beneath VES 2 and 5 depicts a thin conductive (<10 Ω-m) layer, below which a moderately resistive (about 15 Ω-m) layer is observed. Below this, a conductive layer at depths of 30 m is revealed having resistivities in the range of 5–10 Ω-m. Further south, a wide low resistive (5–10 Ω-m) feature is demarcated beneath VES 12. This low resistive feature extends from shallow depths up to depths of investigation. This is a potential aquifer zone and the groundwater flow is both in south (below VES 11) and north (beneath VES 5 and 2) directions. VES sites 2, 5 and 12 and potential aquifer zones are over this profile.

5.2.3 *Profile EF*

This profile, as presented in figure 5(c), consists of VES stations 10, 3, 16 and 7 from NNW–SSE. Below VES stations 10 and 3 towards north, a 20-m thick high resistive (>50 Ω-m) layer is encountered, which is representative of hard and compact rock. Below this, moderate resistive (25 Ω-m) layer is observed which is inferred as clay with lenses of sand. Further south, the top 10 m below VES stations 16 and 7 is conductive (about 20 Ω-m), beneath which a very conductive (5–10 Ω-m) zone is encountered up to depths of investigation. Both VES 16 and 7 are conducive for groundwater exploration.

5.2.4 *Profile GH*

This profile, as shown in figure 5(d), is trending NW–SE and comprises of VES stations 13, 8 and 1. The top layer over the entire stretch of the profile is highly conductive (<10 Ω-m) suggesting clayey layer saturated with water. This layer is 10 m thick beneath VES 13 and 8 and thins down to about 3 m beneath VES 1. Beneath this layer a moderately resistive (>25 Ω-m) zone is delineated throughout the profile.

6. Discussion

From the above-mentioned analysis and results, it is seen that the Dar-Zarrouk (D-Z) parameters are highly useful to comprehend the spatial distribution of groundwater in addition to the geometry of the sub-surface litho units and provide an indication to aquifer prospective zones in the study area. The advantage of using D-Z parameters to estimate protective capacity is that the non-uniqueness of interpreting resistivity data is minimized. These parameters provide a positive solution as they reflect very clear, conspicuous and widely varying ranges of sub-surface resistivities. They also do not possess an overlapping character and in turn facilitate easy resolution. These results also give a useful first approximation of the D-Z parameter variation and could be used to site exploratory boreholes.

The aquiferous zones are clearly reflected in the longitudinal conductance (S) and transverse resistance (T) maps. The longitudinal conductance values reveal about 18% of the area, falls within the 'very good' protective capacity, about 64% constitutes the 'good' protective capacity rating, while 18% exhibits moderate to weak protective capacity suggesting that the entire study area, which is characterized by relatively moderate-to-high longitudinal conductance, envisages good aquifer protective capacity rating. Clayey/silty overburden in this part, which is characterized by relatively high longitudinal conductance, offers protection to the underlying aquifers.

As mentioned earlier, the entire area is exhibiting moderate-to-high S values (0.39–9.64), thus indicating that clayey overburden is dominant in this region. Due to an increase in clay content, a decrease in transmissivity of aquifer is expected. However, the protective capacity rating of the aquifer is good at most of the sites. The low values of protective capacities at some stations in the eastern part of the study area indicate that the overburden material has no clayey overlying strata, which is a risk to groundwater contamination. Figure 6 shows the correlation between a borehole log at VES 17, which consists of five different types of geological formations together with their depths and true resistivity values. However, the disagreement in the number of layers obtained from the borehole log and VES 17 data is due to the large contrast in the resistivity between bedrock and regolith which often masks the presence of suppressed layers of intermediate resistivity, representing fractured bedrock that often contains significant quantities of water, encountered in drilling (Maiti *et al.* 2013b).

High T values (above 700 Ω-m^2) are evident at VES stations 3, 4, 6, 9, 10, 13, 15 and 17, mostly in the central part of the study area indicating freshwater regime. High T values are related with zones of high transmissivity and thus are highly porous to water movement. Such zones suggest that the groundwater aquifers have a high tendency of being contaminated, a fact which can be envisaged from VES 4, which has very low S and high T values. The low protective capacities of the overburden material and the high aquifer transmissivities will help the leaching of contaminants and migration within the aquifer system. Deolankar (1980) reported that the weathered basalt shows highest aggregate porosity (34%) in Deccan Volcanic Province (DVP), 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. This may be caused due to the presence of clay minerals in the weathered basalt which has higher water retention capacity.

It is also seen from the longitudinal geoelectric sections that the central-western part of the study area has high potential of fresh water aquifers at average depths of about 40 m. Potential aquifer zones are VES sites 17, 6, 13, 14 and 4 over Profile AB. The dug well lithological cross-section along with the true resistivities of different formations at VES 17 is shown in figure 6. The aquifer zone in the dug well lies at depths of about 47 m, whereas the VES 17 data defines a resistivity value of about 12–16 Ω-m at depths of about 40 m and below for this zone. Thus, there is a clear corroboration between resistivity data and litholog section at VES 17. Over profile CD, potential aquifer zones are revealed at VES sites 2, 5 and 12. VES sites 16 and 7 over Profile EF are ideal aquifer zones. However, a few VES points further south of VES 7 would have given the complete picture of the low resistivity zone. VES point 8 over Profile GH is a potential aquifer zone.

7. Conclusion

Geophysical mapping of Suki river basin in Raver sub-division of Jalgaon district, Maharashtra was carried out using Wenner electrical soundings. The interpreted result of the 17 VES points reveal aquifers are made of clay, weathered and fractured rocks. Combination of sounding results, borehole lithology and geoelectric (Dar-Zarrouk) parameters signify potential aquifer zones at VES stations 2, 5, 6, 7, 12, 13, 14 and 17. The central-southern part of the study area has high groundwater potential due to the backwaters of Hatnur dam.

The overburden protective capacity in the area was evaluated using the longitudinal unit conductance values. This is due to the fact that the earth medium acts as a natural filter to percolating fluid and that its ability to retard and filter percolating fluid is a measure of its protective capacity. High clay content which impeded fluid movement is generally characterized by low resistivity values and low hydraulic conductivities and thus, low longitudinal unit conductance, enabling classification of the study area into weak, moderate and good protective capacity zones. The longitudinal conductance map suggests good aquifer protective capacity rating in most parts of the study area. The D-Z parameters also reveal heterogeneous anisotropic lithology in the study area.

It is seen that the estimation of D-Z parameters for evaluation of aquifer protection studies is of considerable significance in terms of societal issues like groundwater exploration and protection from pollution. Further, this result will be useful to gain a better understanding of the complex geology of the area and should provide basis for future detailed water resource study using electrical resistivity tomography (ERT) and very low frequency (VLF) techniques.

Due to the change from normal cropping pattern to cash crops, especially those which require more water, there is over-exploitation of water resources in Raver sub-division. Though the surface water resources are available in the area and all the surface/groundwater resources are rain-dependent, a need to cultivate the habit of resource conservation has become a must for the community of this area. Thus, change in cropping pattern with low water requirement crops should be encouraged. The disused dug wells along Hatnur dam can be recharged by canal water in monsoon season, mostly in central and southern parts of the area.

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