Bulletin of Pure and Applied Sciences. *Print version ISSN 0970 4639*
Vol.39F, Geology (Geological Science), No.2, *Online version ISSN 2320 3234*
July-December 2020: P.264-273 *DOI: 10.5958/2320-3234.2020.00023.2*
Original Article *Available online at www.bpasjournals.com*

Electrical Resistivity Investigation for Groundwater Potential in Lateritic Plateau of Bamnoli Range, Satara District, Maharashtra

[1]Rajesh V. Desai, [2]Khan Tahama, [3]Gautam Gupta, [4]R.A. Suryawanshi, [5]Vinit C. Erram

Author's Affiliations:
[1,4]Department of Geology, Yashwantrao Chavan College of Science, Karad, Maharashtra 415124, India
[2,3]Indian Institute of Geomagnetism, New Panvel (W), Navi Mumbai, Maharashtra 410218, India
[5]Indian Institute of Geomagnetism, MF Radar Facility, Shivaji Univ. Campus, Kolhapur, Maharashtra 416004, India

***Corresponding Author: Gautam Gupta,** Indian Institute of Geomagnetism, New Panvel (W), Navi Mumbai, Maharashtra 410218, India

E-mail: gupta_gautam1966@yahoo.co.in

(Received on 16.05.2020, **Accepted on 06.11.2020**)

ABSTRACT

The Bamnoli range in Satara district of Maharashtra is a lateritic plateau in India. The aim of this study is to measure the thickness of lateritic plateau so as to understand the groundwater potential zones beneath the surface in this region. In the studied region, lateritic formation is dominant and is underlain by weathered and fractured rocks followed by hard and massive basalt. To achieve the desired objective, resistivity studies are conducted in the region and a total of 10 vertical electrical soundings (VES) were carried out by using Schlumberger configuration with maximum electrode spacing of 200 m. Isoresistivity contour maps at 1 m, 2 m, 5 m, 10 m, 20 m, 35 m, 50 m, 70 m and 100 m depths are generated to decipher the resistivity distribution over eight horizons of Bamnoli lateritic plateau. Geoelectric pseudo sections are generated to study the vertical variation in geology and groundwater depth. The results reveal that a thin soil cover is present on the top of laterites. The laterites are exposed from surface up to about 40 m depth, beneath which weathered and fractured basalts and fresh basaltic basement are present. It can be inferred that potential aquifer zones are observed in weathered/ fractured environs of the study area.

KEYWORDS: *Isoresistivity contour maps, Geoelectric pseudo sections, aquifer, Laterite, Bamnoli range, Satara*

INTRODUCTION

The electrical resistivity method is a widely used tool for mineral and groundwater exploration, for mapping of basement configuration and for engineering, environmental and military purposes. This technique has been effectively used by several researchers for various fields of applications including groundwater studies (Gupta et al., 2012; Kumar et al., 2014), groundwater contamination studies (Karlik and Kaya 2001; Mondal et al., 2013), saltwater intrusion (Maiti et al., 2013) and geothermal explorations (Kumar et al., 2011). Several hydrogeological and geophysical studies have been undertaken in the past over the Deccan Volcanic Province (DVP) of Maharashtra to delineate aquifers and the occurrence of groundwater in intertrappeans/ vesicular and fractured zones within the trap succession and sedimentary formations underneath the traps, which are supposed to be potential for groundwater (Bose and Ramkrishna 1978; Singhal 1997; Pawar et al., 2009; Rai et al., 2013). However, not much information is available on the occurrence and movement of groundwater in lateritic environment of the DVP.

The study area chosen for the present work is the Bamnoli range in Satara district, Maharashtra, located in between latitude 17⁰20' N and 17⁰45' N and longitude 73⁰45' E and 74⁰01' E, having an area of about 1175 km^2, which is included in the Survey of India topographic sheet nos. 47 G/14 and 47G/15. The region is composed of hard duricrust laterite underlain by Deccan basalt. The monsoon period is from mid June to October in this region. The area receives an annual average rainfall of about 1500 mm. Average temperature recorded in this area is 14ºC (in winter) to 35ºC (in summer). Due to steep slopes, rainwater is drained away in the form of various small streams which contribute to different major river basins of Krishna and Koyna. The areas where sufficient amount of surface water is not available (such as habitations), which atop the lateritic plateaus of Bamnoli range, face the problem of water scarcity after the month of November. The populace mostly depends on groundwater for domestic and agricultural needs.

Thus, the principal aim of the present investigation is to find out the thickness of the duricrust lateritic plateau and to locate various lithological contacts in the study area like laterite-lithomarge clay, lithomarge clay- weathered basalt, which is likely to possess exploitable water. In this study, non-invasive resistivity technique has been employed to acquire data over Bamnoli range of Satara district in Maharashtra state, India (Fig. 1). The study area covers the western part of Satara, Javali and Patan sub-divisions and lies parallel to the Koyna reservoir.

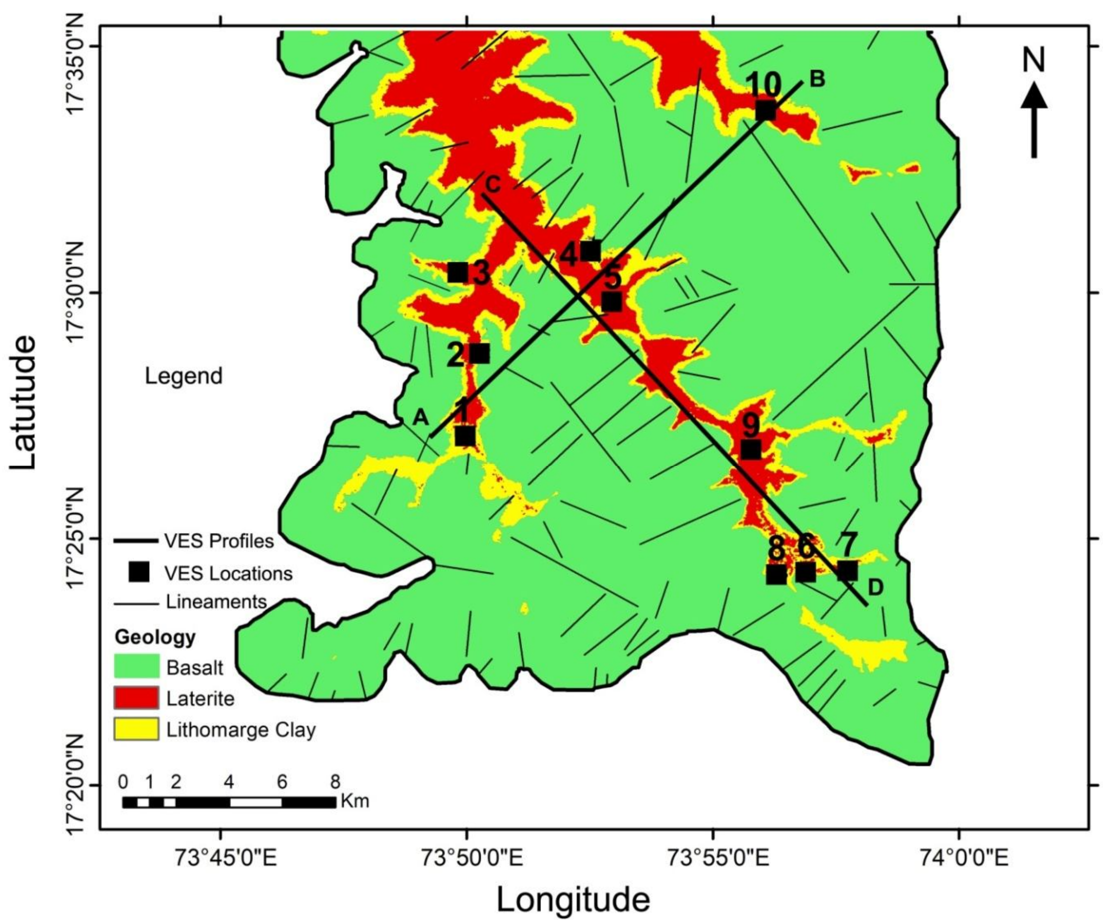


Figure 1: Location map of VES stations at Bamnoli Range in Satara district of Maharashtra, India.

GEOLOGY OF THE AREA

The study area comprises of plain and flat topped lateritic plateaus, valleys and floodplains formed after deposition by streams. Bamnoli range is characterized with basaltic lava flow units as a principal geological component. Deccan trap basalt is overlain by hard duricrust of laterite above 950 m, which are referred to as high level laterites (Sahasrabudhe and Deshmukh 1981; Widdowson and Cox, 1996; Widdowson, 1997). Earlier study of Tarale- Thoseghar plateau laterites reveal that they are formed due to in-situ chemical weathering of parent basalt rock (Desai et al., 2018). Laterites of this area is iron rich with Fe_2O_3, ranges in between 35-51% and hematite as major mineral present with goethite, maghemite, gibbsite and kaolinite as other major minerals (Desai et al., 2018). Reddish brown coloured laterites are of pisolitic/oolitic, vesicular, mottled, vermicular, compact/massive, and brecciated types. Pockets of bauxitic laterite are located at a few places. Lithomarge clay, which is reddish, yellowish red to yellow in colour, is present below hard laterite. The thickness of this clayey formation varies from 12-30 m. Vertical profile consisting of hard duricrust followed by lithomarge clay, weathered basalt and fresh basalt at the bottom is best developed and exposed near places like Doni and Jalav Khind (Fig. 2). Laterites contain unlimited store of water and prolific amount of water is supplied from such lateritic aquifers to the wells. As per observations made by Tandale (1987), permeability of laterite is higher when disposition of vesicles is horizontal than vertical.

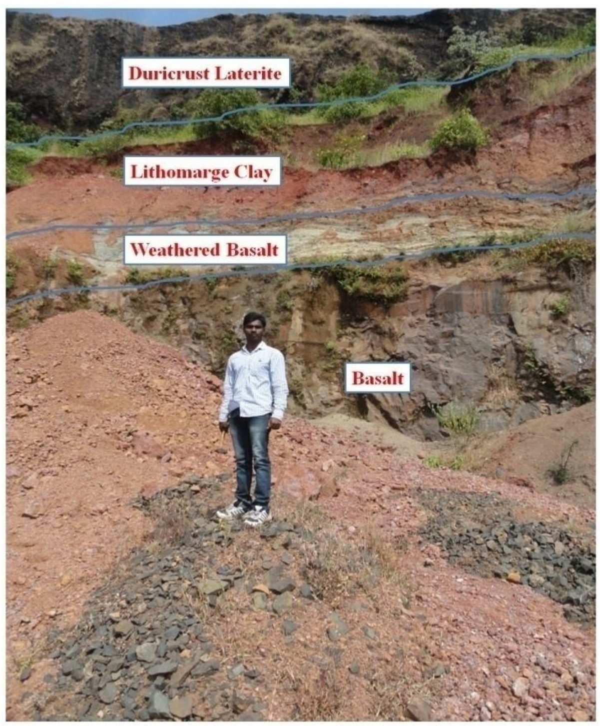


Figure 2: Vertical profile showing lithology at Doni village of Bamnoli range.

Deccan Trap Basalt of the study area belongs to Ambenali and Mahableshwar formation and composed of mostly simple 'Aa-Aa' type. Basalts in study area are mostly fine to medium grained (Deolankar, 1980). Colour of basalt is mostly grey, dark grey to green. In the exposed section of the Koyana River, 27 basaltic flows have been identified with thickness varying between 10-60 m. The main units of each flow consist of 1) lower massive unit, which constitutes 60-85% of the main trap, and 2) upper vesicular/ amygdaloidal unit which constitutes 15-40% of the flows. Flows in some cases are porphyritic in nature where laths of greyish white plagioclase feldspar are surrounded by fine grain matrix. Shape and size of the phenocrysts vary greatly in different flows and also in same flows. Plagioclase laths are elongated and tubular in form with few mm to 2 cm in size. During field work, 10 lava flows was ascertained in various ghat sections in the study area. These flows were dissociable in the field by either intermittent red bole horizon in between two consecutive lava flows or by vesicular unit present between two massive units. Secondary minerals like calcite, agate, opal, chalcedony and zeolites were deposited in the vesicles, cavities and joints present in the basalt. Basalt flows of Bamnoli range are highly jointed and fractured, with prominent vertical and horizontal sets of jointing pattern. Spheroidal weathering is common feature observed in basalt throughout in the study area and size of spheroids varies from few centimeters to about meter in diameter. A columnar joint is also observed at places like Tarale-Thoseghar and Satara-Thoseghar ghat sections. Vertical columnar joints are common all over in the study area whereas inclined, twinned and horizontal columnar jointing pattern is also observed in the field area. Primary porosity of hard basaltic rock is very poor but weathering, fracturing and jointing creates secondary porosity (Pawar et al., 2008). Massive zone of each flow is devoid of any openings which affect the porosity and permeability, while vesicular part is having abundant vesicles and opening thereby increasing the porosity and permeability (Adyalkar et al., 1975). Weathered and vesicular basalt have higher transmissivities and therefore forms better aquifer (Deolankar, 1980).

At many places successive lava flows were separated by red coloured marker horizon called as “red bole”. These intermittent beds can be easily identified by its red or reddish orange colour in the field which made up of friable earthy clay material. Thickness of the bole bed varies from place to place but not more than 3 m. Two types of contact of bole bed and basalt was observed as sharp and gradational. When red bole is completely composed of thin clayey material then mostly sharp contact is present while bole bed containing pyroclastic boulder and clay mixture exhibit gradational contact. Polygonal columnar structure is observed in few outcrops (Satara-Thoseghar and Patan-Sadawaghapur ghat section). This type of shrinkage feature in red bole is developed due to loss of fluid after deposition (Sarkar et al., 2000). At Patan-Sadawaghapur Ghat section and Tarale-Thoseghar ghat section, 8 red boles were marked and along Chaphal-Sadadadholi ghat section, 7 red boles were marked while 6 red boles were observed during Satara-Kaas traverses. Pyroclastic boulders are mostly vesicular in nature and now filled by white and yellow colour secondary minerals. Vertical profile of laterite consisting of hard duricrust followed by lithomarge clay and weathered and altered basalt followed by unaltered basalt at the bottom is best developed and best exposed near village Doni and Jalav khind (Fig. 2).

METHODOLOGY

Resistivity technique has been adopted for delineating groundwater potential zones in the study area. A total of 10 vertical electrical soundings (VES) were carried out using the Schlumberger electrode configuration with a maximum current electrode separation (AB) of 200 m (Fig. 1). Being a highly rugged terrain, systematic coverage of VES points were not possible. In this technique the potentials between one electrodes pair is measured while transmitting the current between another electrode pair. The depth of penetration is directly proportional to the separation between the electrodes, and changing the electrodes separation provides subsurface geoelectrical information (Dahlin, 2000).

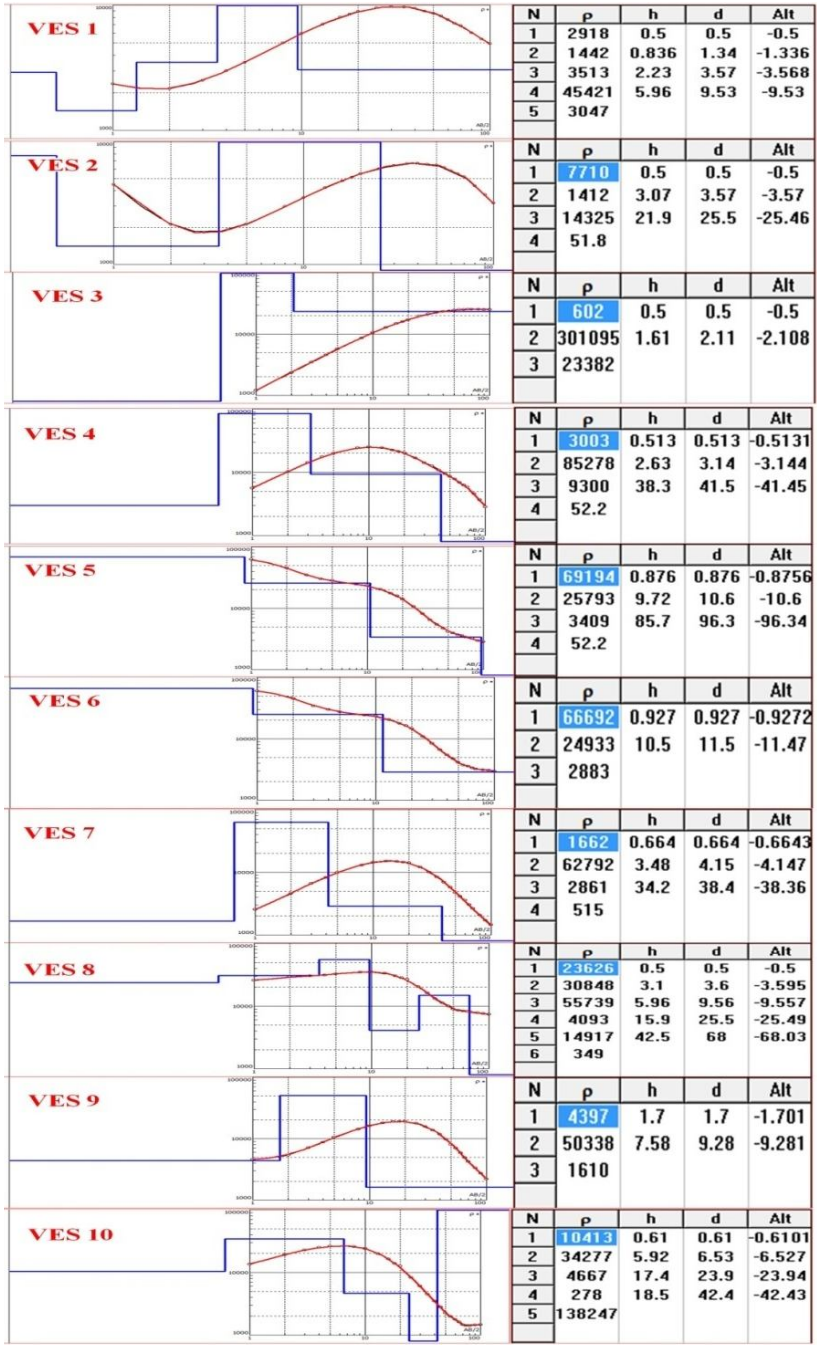
The instrument used for data acquisition is IGIS (Hyderabad) made resistivity meter (model SSR-MP-AT). The data thus acquired was processed and interpreted by IPI2WIN software (version 3.0.1.a7.01.03) developed by Moscow State University (Bobachev, 2003) after slightly modifying the manually interpreted results, keeping in view the local geology. Employing Schlumberger electrode configuration, the apparent resistivity (ρ_a) is calculated (Kearey and Brooks, 1988) as,

$$\rho a = \frac{(AB/2)^2 - (MN/2)^2}{MN} \times \frac{\pi \Delta V}{I}$$

Where,

AB	=	Current electrode spacing in meter
MN	=	Potential electrode spacing in meter
I	=	Current in ampere
ΔV	=	Potential difference in mV

The apparent resistivity vs. half of the current electrode separation (AB/2) on log-log graph suggests 3-6 layered structure in the study area (Fig. 3).



VES 1

N	ρ	h	d	Alt
1	2918	0.5	0.5	-0.5
2	1442	0.836	1.34	-1.336
3	3513	2.23	3.57	-3.568
4	45421	5.96	9.53	-9.53
5	3047			

VES 2

N	ρ	h	d	Alt
1	7710	0.5	0.5	-0.5
2	1412	3.07	3.57	-3.57
3	14325	21.9	25.5	-25.46
4	51.8			

VES 3

N	ρ	h	d	Alt
1	602	0.5	0.5	-0.5
2	301095	1.61	2.11	-2.108
3	23382			

VES 4

N	ρ	h	d	Alt
1	3003	0.513	0.513	-0.5131
2	85278	2.63	3.14	-3.144
3	9300	38.3	41.5	-41.45
4	52.2			

VES 5

N	ρ	h	d	Alt
1	69194	0.876	0.876	-0.8756
2	25793	9.72	10.6	-10.6
3	3409	85.7	96.3	-96.34
4	52.2			

VES 6

N	ρ	h	d	Alt
1	66692	0.927	0.927	-0.9272
2	24933	10.5	11.5	-11.47
3	2883			

VES 7

N	ρ	h	d	Alt
1	1662	0.664	0.664	-0.6643
2	62792	3.48	4.15	-4.147
3	2861	34.2	38.4	-38.36
4	515			

VES 8

N	ρ	h	d	Alt
1	23626	0.5	0.5	-0.5
2	30848	3.1	3.6	-3.595
3	55739	5.96	9.56	-9.557
4	4093	15.9	25.5	-25.49
5	14917	42.5	68	-68.03
6	349			

VES 9

N	ρ	h	d	Alt
1	4397	1.7	1.7	-1.701
2	50338	7.58	9.28	-9.281
3	1610			

VES 10

N	ρ	h	d	Alt
1	10413	0.61	0.61	-0.6101
2	34277	5.92	6.53	-6.527
3	4667	17.4	23.9	-23.94
4	278	18.5	42.4	-42.43
5	138247			

Figure 3: Vertical electrical sounding curve of stations 1-10.

Gupta et al. (2010) is of the view that in hard rock terrain, where 2-D coverage of soundings spread over the area has been made, the resistivity variation over an entire area would correspond to changes in the resistivity at different depths. This is achieved by increasing electrode spacing; more the electrode spacing, deeper is the current penetration which could be used to establish depth-wise lithological correlation. Bearing this in mind, resistivity contouring has been carried out for different electrode spacing i.e. AB/2 = 1 m, 2 m, 10 m, 20 m, 35 m, 50 m, 70 m and 100 m which provides the variation of resistivity over eight horizons. The spatial distribution of the apparent resistivity over the entire region is plotted (Fig. 4) by the krigging method using SURFER software. Further, geoelectric sections have been prepared over two profiles in the study region in order to understand the vertical variation in geology and to elucidate the groundwater potential zones (Figs. 5a, b).

RESULTS AND DISCUSSION

Spatial distribution of apparent resistivity:

Apparent resistivity distribution at different depths from 1m to 100 m (i.e. AB/2 = 1 m to 100 m) is shown in Fig. (4 a-d, e-h). Study of this figure reveals the layer-wise change in lithology of Bamnoli range. This change in lithology reflects an increase or decrease of apparent resistivity values from top to bottom i.e. from duricrust laterites to basalts. Resistivity of lateritic terrain is studied by Beauvais (2004) and according to his observations clayey layer has low resistivities of about 140-1120 Ωm and resistivity values more than 4480 Ωm correspond to the hard ferruginous laterites. Beauvais (2004) further noticed soft ferruginous horizon with 1120-4480 Ωm resistivity. McNeill (1980) also observed such high resistivity values over hard laterites.

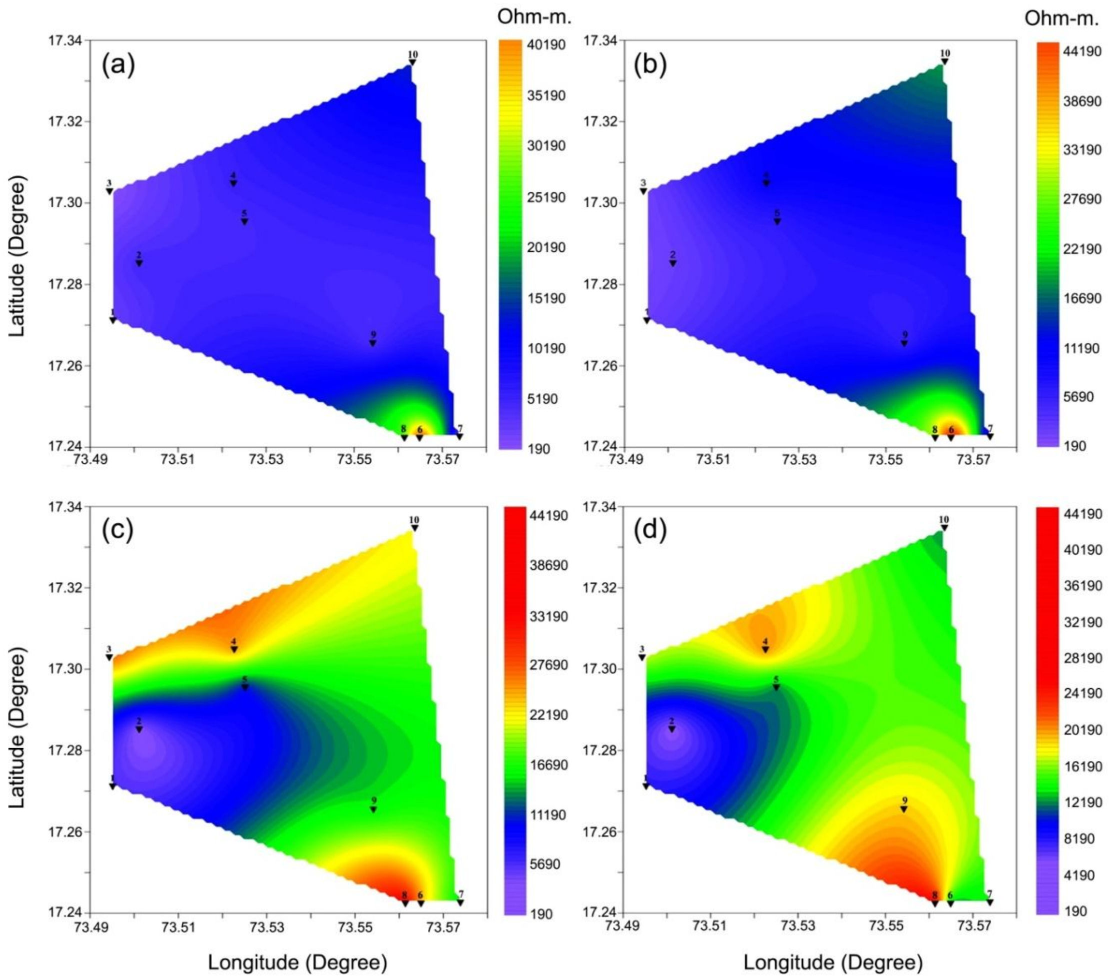


Figure 4 (a-d): Apparent resistivity distribution at various depths (a- 1m, b-2m, c-10m, d-20m).

The figures 4 (a) and 4 (b) show similar pattern of resistivity distribution from surface to 2 m depth. Overall impression of these two figures indicates presence of unconsolidated lateritic sandy soil with low resistivity less than 1000 Ωm except at south eastern part of the study region, where very high resistivity (> 20000 Ωm) is observed. As seen during field visit, this region is at higher elevation and comprises of hard laterites. In the western side of the study area, VES 1, 2 and 3 is showing low resistivity values in the range of 200-500 Ωm, which could be the signature of saturated lithomarge clay present there.

Resistivity values at 10 m and 20 m depth is contoured and shown in Figs. 4 (c) and 4 (d). High resistivity values (> 12000 Ωm) are observed over the maximum study area, indicating hard ferruginous laterite. The western part of the region showing less resistivity values (< 5000 Ωm), is due to lineament crossing over VES 1 and 2 (Fig. 1), which are likely to be potential aquifer zones. Trend of high resistivity values in Figs. 4 (c) and 4 (d) continues up to Fig. 4 (e) at 35 m depth from surface, corresponding to hard laterites at central part and weathered and fractured rocks at western, south eastern and north eastern part of the region.

At 50 m depth (Fig. 4f), resistivity around 10000 Ωm is observed all over the region except in the north western part of the study area. A low resistivity feature, particularly at VES 10 (resistivity around 200 Ωm) is indicative of weathered and fractured basalts which may contain potential groundwater pockets. Increasing resistivity (ranging from 12000- 20000 Ωm) at north western part indicates decreasing intensity of weathering and fracturing of rocks. Fresh basalts are expected beneath VES 3, at 50 m depth (Fig. 4f) which is evident from the resistivity value of the order of 40000 Ωm.

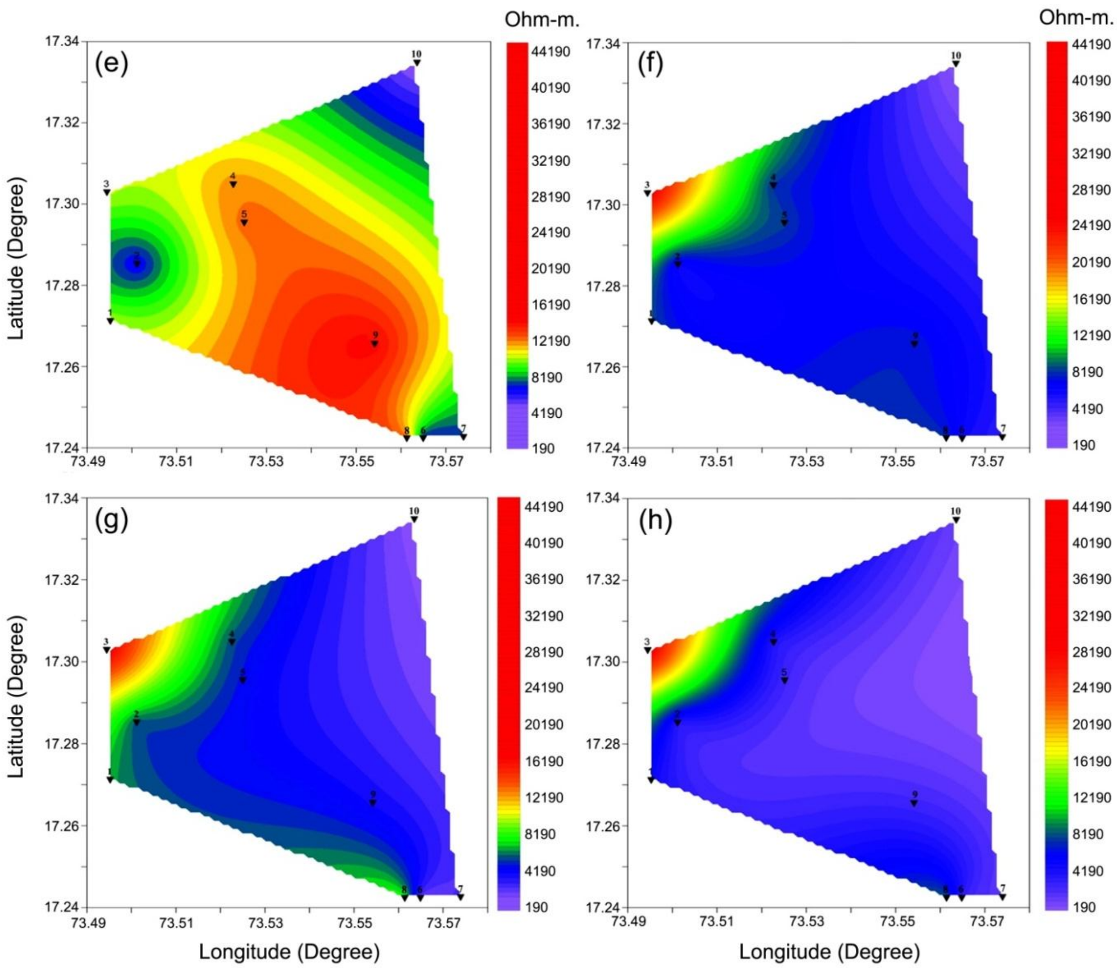


Figure 4 (e-h): Apparent resistivity distribution at various depths (e- 35m, f-50m, g-70m, h-100m).

Figure 4 (g, h) reveals low to moderate resistivity values (200-5000 Ωm) over the northern, eastern, central and southern parts of the study area except at VES 9, which is showing resistivity around 10000 Ωm. The low values (around 200 Ωm) are indicative of potential groundwater zones encountered at deeper levels 70 and 100 m in the form of jointed, weathered and fractured basalt and in intertrappean zones, which are sedimentary formations deposited during the interval of two consecutive lava flows (Rai et al., 2011). Nevertheless if the intertrappeans bed is clay rich, then it is an unlikely source of groundwater. Such beds are termed as bole beds (Ghosh et al., 2006). At deeper levels, the groundwater occurs under semi-confined conditions. However the fresh basaltic basement is continued to be observed beneath VES 3 revealing very high resistivity values (Fig. 4g, h).

Geo-electric cross-section:

In order to study the sub-surface features and to decipher the underlying aquifer bodies, two geoelectric cross-sections were generated in the study area. The two profiles, each having five VES points is marked as AB and CD (Fig. 5a, b) oriented in NE-SW and NW-SE directions.

Profile AB covers the VES stations 1, 2, 5, 4 and 10 (Fig. 5a). A shallow low resistive (200 Ωm) feature is evident beneath VES 1 and VES 2 having thickness of about 2 m. This effect is due to the presence of lithomarge clay there which may contain groundwater. Below this at VES 1, resistivity value of 3000 Ωm up to the depth of observation is seen. This may be the laterites present in the dominant lithomarge clay zone. A high resistivity feature (14000 Ωm) up to 25 m depth is observed at VES 2, followed by very low resistivity (around 50 Ωm) up to the depth of observation. The high resistivity is indicative of lateritic formations and the low resistivity is likely to be a potential zone for groundwater, as a lineament is reported near VES 2 (Fig. 1). Similar low resistive feature is witnessed in NE direction beneath VES 4 and VES 5, albeit at greater depths of about 40 m and 80 m respectively. It is pertinent to mention here that VES 2, 4 and 5 are in the vicinity of several lineaments as shown in Fig. (1). Hence these sites are suitable for groundwater exploration.

At VES 5, the top 80 m is revealing resistivity value of around 3000 Ωm, indicative of a rather thick lateritic formation in lithomarge clay-prone zone. At VES 4, a thin lateritic layer is evident beneath which resistivity value of the order of 10,000 Ωm is recorded up to the depth of 40 m which is the hard and compact basalt. Further north east, the top couple of meters at VES 10 reveals hard laterites, underlain by the same formation with resistivity values of about 4,600 Ωm. The last layer beneath this station suggests a resistivity value in excess of 1, 00,000 Ωm indicating massive basalts. However, low resistivity feature of 270 Ωm is observed from 30 m to 40 m depth in between the laterites at the top and the basalts at the bottom. This low resistive layer can be intertrappean clay sandwiched between laterites and basalts respectively.

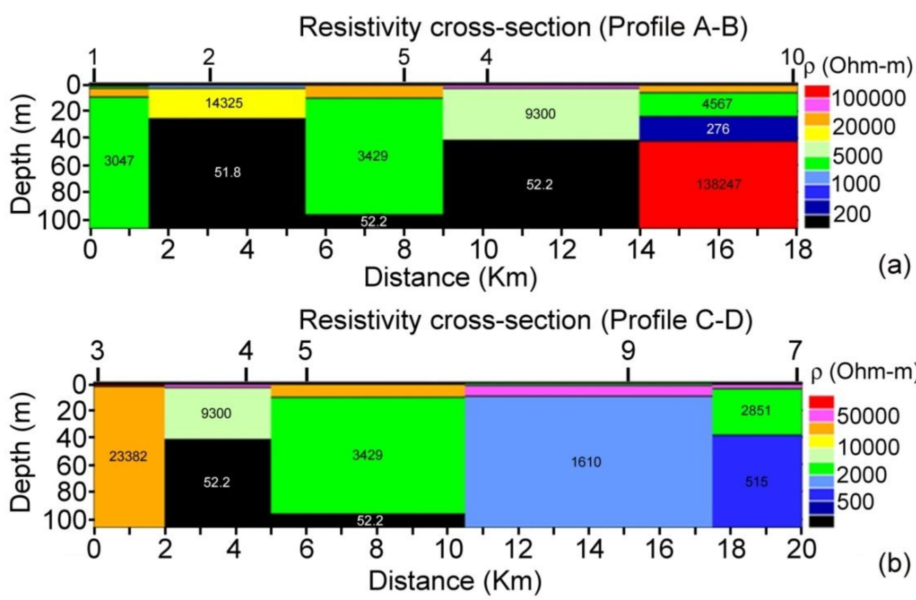


Figure 5 (a-b): Geo-electric cross-section of two profiles (a- A-B profile, b- C-D profile).

The profile CD comprises of VES stations 3, 4, 5, 9 and 7 trending in NW-SE direction (Fig. 5b). A thin veneer of dry and hard soil is characterized at the top surface all along the profile. VES 3 is composed of massive basalts giving the resistivity in excess of 20,000 Ωm up to the depth of investigation. As discussed earlier, VES 4 and VES 5 are in the environs of lineaments hence having very low resistivity of the order of 50 Ωm at depths of 40 m and 80 m respectively. This low resistivity reveals the information about saturated groundwater potential zones. Further south east, VES 9 is under the vicinity of mega lineament hence showing moderately low resistivity around 1,600 Ωm. This may be due to fractured basalt beneath dry and hard lateritic soil at the top. VES 7 is in the environs of lithomarge clay, patches of laterites and the lineaments passing all around the region. It is showing resistivity around 2,800 Ωm up to 30 m depth. This is the lateritic layer present in the lithomarge clay zone. Underlying this layer, resistivity value of 515 Ωm is observed up to the depth of investigation. It can be presumed that fractured basalts are giving rise to such low resistivity in an otherwise high resistivity terrain. Such fracture zones are likely to be potential aquifers.

CONCLUSION

The vertical electrical sounding data were acquired in Bamnoli Range of Satara district, in the southern part of the Maharashtra, to delineate the thickness of the lateritic formation and to assess the potential groundwater aquifer zones beneath the laterites. Groundwater generally occurs in vesicular basalt, intertrappeans as well as in weathered mantle and fractured zones. From the foregoing, it can be advocated that the thickness of the lateritic formation varies from surface to about 40 m over most of the VES stations. It is also deciphered that potential aquifer zones are located beneath the laterites, and is observed within the traps and beneath it. It is pertinent to mention here that Deccan Traps form an important water-bearing formation in the district. The secondary porosity due to cooling joints, fractures and fissures play an important role in groundwater circulation, especially in the highly porous 'pahoehoe' flows. In the Deccan Volcanic Province, degree of weathering and physical setting plays a vital role in respect of groundwater storativity.

Acknowledgements
The authors are grateful to Director, IIG, Navi Mumbai, for kind permission and support during field survey and allowing publishing the same. Authors are thankful to Dr. M. Laxminarayana for the contribution in data acquisition. Thanks are also due to Shri B.I. Panchal for drafting few figures.

REFERENCES

1. Adyalkar, P.G., Rane, V.V., Mani, V.V.S. and Dias, J.P. (1975). Evaluation of the aquifer characteristics of the basaltic terrain of Maharashtra in India. Proc. Indian Acad. Sci., 81A, 108-117.
2. Beauvais, A, Ritz, M., Parisot, J-C., Bantsimba, C. and Dukhan, M. (2004). Combined ERT and GPR methods for investigating two-stepped lateritic weathering systems. Geoderma, 119, 121-132.
3. Bobachev, A. (2003). Resistivity soundings interpretation. IPI2WIN: Version 3.0.1.a7.01.03. Moscow State University.
4. Bose, R.N. and Ramkrishna, T.S. (1978). Electrical resistivity surveys for ground water in the Deccan trap country of Sangli district, Maharashtra. Jour. Hydrol., 38(3-4), 209-221.
5. Dahlin, T. (2000). Electrode charge-up effects in DC resistivity data acquisition using multi electrode arrays. Geophys. Prospect. 48(1), 181-187.
6. Deolankar, S.B. (1980). The Deccan basalts of Maharashtra, India – their potential as aquifers. Ground Water, 18, 434- 437.
7. Desai, R.V., Khanapurkar, J.V. and Suryawanshi, R.A. (2018). Geochemistry of Upland laterites of Tarale- Thoseghar plateau of Bamnoli range of Satara district of Maharashtra, India. Jour. Appl. Geochem., 20(4), 432- 442.
8. Ghosh, P., Sayeed, M.R.G., Islam, R. and Hundekari, S.M. (2006). Inter-basaltic clay (bole-bed) horizons from Deccan traps of India: Implications for palaeo-climate during Deccan trap volcanism. Palaeogeography, Palaeoclimatology, Palaeoecology, 242, 90-109.

9. Gupta, G., Erram, V. C. and Kumar, S. (2012). Temporal geoelectric behavior of dyke aquifers in northern Deccan Volcanic Province, India. Jour. Earth Syst. Sci., 121(3), 723-732.
10. Gupta, G., Kachate, N.R., Erram, V.C., Maiti, S. and Patil, S.N. (2010) Geoelectrical studies for delineating seawater intrusion in parts of Konkan coast, western Maharashtra. Inter. J. Environ. Earth Sci., 1(1), 62-79, 2010.
11. Karlik, G. and Kaya, M.A. (2001). Investigation of groundwater contamination using electric and electromagnetic methods at an open waste-disposal site: a case study from Isparta, Turkey. Environ. Geol., 40, 725-731.
12. Kearey, P. and Brooks, M. (1988). An Introduction to Geophysical Exploration, ELBS, Blackwell Scientific Publication, Oxford, 296.
13. Kumar, D., Thiagarajan, S. and Rai, S. N. (2011). Deciphering geothermal resources in Deccan Trap region using electrical resistivity tomography technique. Jour. Geol. Soc. India, 78, 541-548.
14. Kumar, D., Rai, S. N., Thiagarajan, S. and Ratnakumari, Y. (2014). Evaluation of heterogeneous aquifers in hard rocks from resistivity sounding data in parts of Kalmeshwar Taluk of Nagpur district, India. Curr. Sci., 107(7), 1137-1145.
15. McNeill, J.D. (1980). Electromagnetic Terrain Conductivity Measurement at Low Induction Numbers. Geonics Ltd., Technical Note TN-6.
16. Maiti, S., Gupta, G., Erram, V. C. and Tiwari, R. K. (2013). Delineation of shallow resistivity structure around Malvan, Konkan region, Maharashtra by neural network inversion of vertical electrical sounding measurements. Environ. Earth Sci., 68, 779-794; doi: 10.1007/s12665-012-1779-8.
17. Mondal, N.C., Singh, V.P. and Ahmed, S., (2013). Delineating shallow saline groundwater zones from Southern India using geophysical indicators. Environ. Monit. Assess., 185, 4869-4886.
18. Pawar, N.J., Pawar, J.B., Kumar, S. and Supekar, A. (2008). Geochemical eccentricity of ground water allied to weathering of basalts from the Deccan volcanic Province, India: Insinuation on CO_2 consumption. Aquat. Geochem., 14, 41-71.
19. Pawar, N.J., Pawar, J.B., Supekar, A., Karmalkar, N.R., Kumar, S. and Erram, V.C. (2009). Deccan dykes as discrete and prospective aquifers in parts of Narmada-Tapi zone, Dhule District, Maharashtra. In Indian Dykes (eds Srivastava, R. K., Sivaji, Ch. and Chalapathi Rao, N. V.), Narosa Publishing House Pvt Ltd, New Delhi, pp. 189-198.
20. Rai, S.N., Thiagarajan, S., Ratnakumari, Y., Anand Rao, V. and Manglik, A. (2013). Delineation of aquifers in basaltic hard rock terrain using vertical electrical soundings data. Jour. Earth Syst. Sci., 122(1), 29-41.
21. Rai, S.N., Thiagarajan, S., Ratnakumari, Y. (2011). Exploration for groundwater in the basaltic Deccan Traps terrain in Katol taluk, Nagpur district, Maharashtra. Curr. Science, 101(9), 1198-1205.
22. Sahasrabudhe, Y.S. and Deshmukh, S.S. (1981). The Laterites of the Maharashtra State. In: Proceedings of the International Seminar on Lateritisation Process. IGCP 129 and IAGC Trivandrum, India, Oxford and IBH Publishing Company, New Delhi, 209-220.
23. Sarkar, P.K., Chakranaryan, A.B., Deshwandikar, A.K., Fernandes, M.R., Rau, S.D. (2000). Development of pencil joints in a red bole bed at Dighi, Raigad district, Maharashtra, India. Curr. Sci., 79, 1422-1423.
24. Singhal, B.B.S. (1997). Hydrogeological characteristics of Deccan trap formations of India. In Hard Rock Hydrosystems, IAHS Publ. No. 241, 75-80.
25. Tandale, T.D., (1987). Geotechnical studies of laterites of western Maharashtra. Ph.D. thesis, Unpublished, Univ. of Pune.
26. Widdowson, M. and Cox, K.G. (1996). Uplift and erosional history of the Deccan Traps, India: evidence from laterites and drainage patterns of the Western Ghats and Konkan Coast. Earth and Planet. Sci. Lett., 137, 57-69.
27. Widdowson, M. (1997). Tertiary palaeo-surfaces of the SW Deccan, Western India: implications for passive margin uplift. In: Widdowson, M. (Ed.) Palaeo-surfaces: Recognition, Reconstruction and Palaeoenvironmental Interpretation. Bath: Geol. Soc. London, 120, 221-248.