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GEOELECTRICAL INVESTIGATIONS FOR POTENTIAL GROUNDWATER IN PARTS OF RATNAGIRI AND KOLHAPUR DISTRICTS, MAHARASHTRA

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Abstract
Electrical resistivity is one of the most effective geophysical methods for investigating the presence of groundwater. In a hard rock terrain like the Kolhapur, Ratnagiri and adjoining regions in the Deccan Volcanic Province of Maharashtra, the nature and extent of weathering may vary significantly, depending mostly on the presence of fractures and lineaments at depth and the geomorphological features at the surface. Hence, electrical resistivity studies are vital in a hard rock terrain for identification and analysis of concealed lineaments and fractures zones. An attempt is made here to understand the tectonic framework of over Devrukh-Ganapatipule region and Malkapur-Sakarpa-Ratnagiri region and its relation to the movement of groundwater. A total of 43 vertical electrical soundings were conducted in Devrukh-Ganapatipule and Malkapur-Sakarpa-Ratnagiri region. The profile over the Malkapur-Ratnagiri area was divided into two profiles. It is observed from the two dimensional geoelectric cross-section that this region has more potential groundwater aquifers than the previous profile. The resistivity ranges are also less than the Devrukh-Ganapatipule profile. A couple of lineaments were also identified over this profile.
Keywords: Deccan volcanic province, electrical resistivity, geoelectrical sections, groundwater potential zones.

1 Introduction

The electrical resistivity method is widely used tool for mineral and groundwater exploration, for mapping of basement configuration and for engineering and military purposes. Self potential was the first parameter to be observed some time in 1836 by Fox. However, Schlumberger and Wenner developed their schemes during 1912 and 1915 respectively. The resistivity sounding method was first applied by Conrad Schlumberger in 1912. The electrical resistivity method involves measuring the apparent resistivity of soils and rock as a function of depth or position (Alfano, 1959). The resistivity of soil is a complicated function of porosity, permeability, ionic content of the pore fluids and clay mineralization. The most common electrical methods used in hydrogeological and environmental investigations are vertical electrical soundings (VES) and resistivity profiling (Baride et. al., 2017; Golekar et. al., 2014)).

The idea of resistivity sounding is to explore the presence of anomalous conductivity in various forms, such as lumped (three dimensional) bodies, dykes, faults and vertical or horizontal contacts between two strata. To accomplish this purpose it is necessary to arrange the measurements in such a manner that at different measurement point, the value of the measured potential difference is affected by the formation resistivities at differing depth ranges (Telford, 1990). This may be accomplished by changing the distance between the current electrodes, so that the depth range to which the current penetrates is changed. However, the distance between the potential measuring electrodes and their positions with respect to current electrodes also affect the depth range from which information on the formation resistivity is obtained. In this method, most commonly used are the four electrodes positioned on a straight line, the two current electrodes on the outside and the two potential measuring electrodes on the inside.

During a resistivity survey, current is injected into the earth through a pair of current electrodes, and the potential difference is measured between a pair of potential electrodes. The current and potential electrodes are generally arranged in a linear array. Common arrays include the Schlumberger array, Wenner array, dipole-dipole array and pole-pole array. The apparent resistivity is the bulk average resistivity of all soil and rock influencing the current. It is calculated by dividing the measured potential difference by the input current and multiplying by a geometric factor specific to the array used and electrode spacing.

In a resistivity sounding, the distance between the current electrodes and the potential electrodes is systematically increased, thereby yielding information on subsurface resistivity from successively greater depths (Mc Neil, 1990). The variation of resistivity with depth is modeled using forward and inverse modeling computer software.

Direct current (DC) resistivity methods use artificial source of current to produce an electrical potential field in the ground (Seidel and

Lange 2007). In almost all resistivity methods, a current is introduced into the ground through point electrodes (C1, C2) and the potential field is measured using two other electrodes (the potential electrodes P1, P2), as shown in Fig. 1. The source current can be direct current or low frequency (0.1 – 30 Hz) alternating current. The aim of generating and measuring the electrical potential field is to determine the spatial resistivity distribution (or its reciprocal conductivity) in the ground. As the potential between P1 and P2, the current introduced through C1 and C2, and the electrode configuration are known, the resistivity of the ground can be determined; this is referred to as the "apparent resistivity".

1.1 Objective of the present study

The purpose of this study is to demonstrate potential applicability of electrical resistivity surveys, especially vertical electrical sounding (VES) to delineate the potential zones of fresh water aquifers in a hard rock terrain.

1.2 The study area

Ratnagiri is one of the coastal districts of Maharashtra and forms part of the Konkan region. It is situated in between the Western Ghats and the Arabian Sea and lies between north latitudes 16°30' and 18°04' and east longitude 73°20' and 73°52'. The present study region is located in Ratnagiri and adjoining Kolhapur districts. Two regions have been surveyed in this area. The first region Devrukh to Ganapatipule lies in between 17.00 to 17.20 N and 73.30 to 73.70 E. The second region Malkapur to Ratnagiri lies in between 16.90 to 17.04 N and 73.40 to 73.95 E.

1.3 Geology of the study area

Geology of Kolhapur district

Kolhapur District located in Western Maharashtra Region between latitude 16° 5' 29" and longitude 74°14'23''. The district is bounded in north and east by Sangali district, west by Ratnagiri and Sindhudurg district and south by Karnataka state. In the Kolhapur District two distinct trends in the hill ranges are seen, one runs north-south pointing wild and hill slopes and valleys and the other trend stretching east ward and merging gradually into plains. The geological formations in the area in descending order of their continuity are as below.

Soil and Laterite	-Recent and sub Recent
Deccan trap	-Lower Eocene
Lower Kaladgi series	-Cuddapah
Granite gneiss Dharwars	- Archaean

Geology of Ratnagiri district

Ratnagiri district is located in the Konkan region and covers a geographical area and 8326 sq. km. The district lies in the survey of India degree sheets 47 F, 47 G and 47H. The district is located between north latitudes 16°30' and 18°04' and east longitude 73°20' and 73°52'. The district is bounded in the north by Raigad District, west by Arabian Sea in the east by Satara, Sangali, Kolhapur district and in the south by Sindhudurg District. The geological formations in the area (Deshpande 1998) which in descending order of their antiquity are as below.

Alluvium, beach sand- Recent and Sub-Recent
Pleistocene- Laterite and Lateritic spread
Miocene- Shale with peat and Pyrite nodules
Cretaceous to Eocene- Deccan trap Basalt lava flow
Upper pre Cambrian - Kaladgi series - quartzite, Sandstone, shale and associated limestone

1.4 Hydrogeology of the Ratnagiri Region

Deccan Trap lava flows (upper cretaceous to lower Eocene age) Kaladgi sandstone (Precambrian), Laterite (Pleistocene) and Alluvial deposit (Recent) is the water bearing formations observed in Ratnagiri district. However Kaladgi formation occurs in very limited patches and does not form potential aquifer in the district. The Alluviums also has limited areal extent found mainly along the coast. Central ground water Board periodically monitors 48 National Hydrograph Network stations (NHNS) stations in Ratnagiri district, four times a year i.e. in January, May (Pre monsoon) August and November (Post monsoon). The depth to water levels in the district during May 2007 ranges between 2.25 (Shringartali) and 19.05 (Jaigad) mbgl. The shallow water levels within 10 mbgl are seen in almost entire district. The deeper water levels in the range of 10-20 mbgl are observed in isolated patches in parts and Rajapur, Lanja, Guhagar and Dapoli Taluka.

2 DATA ACQUISITION AND ANALYSIS

2.1 Survey instrumentation

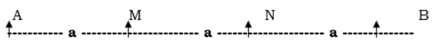
Model SSR-MP-AT

The IGIS signal stacking based signal enhancement resistivity meter model SSR-MP-AT is a state of art microprocessor based data acquisition system (Fig. 2). The instrument design incorporates several innovative features and advanced techniques of digital circuitry to make it a reliable geophysical tool providing high quality data useful for mineral and groundwater exploration and any other geophysical applications.

The SSR-MP-AT sends the entire current into the ground without wasting power for constant current generation thus increasing the signal strength to probe deeper layers. It achieves excellent depth penetration with relatively low power inputs. It utilizes the signal stacking up to 16 successive reading to achieve good signal enhancement. In the presence of random (non-coherent) earth noises, the signal to noise ratio of the SSR-MP-AT measurement will be enhanced by N where N is the number of stacks. Hence SSR-MP-AT Resistivity Meter can be used for depths of up to 600 m under favorable geological field.

2.2 Survey design with Schlumberger configuration

Schlumberger electrode configuration has been adopted in the present study. In the Schlumberger configuration the potential and current electrodes are arranged in the straight line, where potential electrode spacing is smaller than the current electrodes.



Mid point of current electrodes (AB) and potential electrodes (MN) coincide. The formula used to calculate the apparent resistivity is as follows:

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

Where,	AB	=	Current electrode spacing in meter
	MN	=	Potential electrode spacing in meter
	I	=	Current in amp.

There is large difference in the length between AB and MN, it is AB >> MN but, for getting good results the length difference must be AB ≥ 5MN (Kearey and Brooks, 1988).

2.3 The spacing factor

Spacing factor for four electrodes situated on the surface of the earth is briefly obtained as follows. If at the surface of the ground, an electric current I is introduced by means of two point electrodes A and B, when the current flows from A to B; potential at any point P on the surface is given by

$Vp = 1/2\pi\sigma \ (1/r1 - 1/r2)$

Where r1 and r2 are distances of the point P from A and B, respectively. Potential difference between two points P and Q, which are at distances r1, r2 and R1, R2 respectively from the electrodes A and B is given by

$VP\text{-}VQ = V = 1/ 2\pi\sigma \ (1/r1 - 1/r2 - 1/ R1 + 1/ R2)$

Hence the resistivity is

$\rho = 1/\sigma = 2\pi \ V/I \ [1/ (1/ r1 - 1/ r2 - 1/ R1 + 1/ R2)]$

Thus the factor $2 \pi / [1 / r1 - 1 / r2 - 1/R1 + 1/R2]$ represents the spacing factor. This factor holds good for all dispositions of the current and potential electrodes and does not change with an interchange of current and potential electrodes. Difference in disposition of current and potential electrodes gives rise to the various exploration techniques in the resistivity method of prospecting.

2.4 Data analysis

IPI2WIN is designed for automated and interactive semi automated interpreting of vertical electrical sounding and induced polarization data obtained with any of a variety of the most popular arrays used in the electrical prospecting (Bobachev, 2003). It is presumed that a user is an experienced interpreter willing to solve the geological problem posed as well as to fit the sounding curves. Targeting at the geological result is the specific feature distinguishing IPI2WIN among other popular programs of automatic inversion. Due to handy controls the interpreter is able to choose from a set of equivalent solutions the one best fitting both geophysical data (i.e. providing the least fitting error) and geological data (i.e. geologically sensible resistivity cross section). Comparing various concepts of the geological structure along the surveyed observation line rather than independent formal sounding curves, inversion is the approach implemented in IPI2WIN. This approach provides the opportunity to use a priory geological data and extract information to the greatest possible extent in the complicated geological situations. For viewing curves and models, the pseudo cross- section of a specified value and resistivity cross section are displayed (VES-IP mode: or chargeability cross section) in the pseudo cross section and resistivity cross section window, which can be used for interpretation.

2.5 Interpretation techniques

The concept of apparent resistivity is the key to the interpretation of the resistivity field data. While the interpretation of the profile data is often qualitative, the quantitative interpretation of the sounding field data has been facilitated by the publication of resistivity master curves CGG (1955) for Schlumberger array and Orellena and Mooney (1966) for Wenner configuration. The curve matching technique was successfully used till Koefoed (1979) revolutionized the computation of resistivity master curves by the application of linear digital filter after which computer-aided interpretation and inversion technique came more and more into picture.

The curve matching technique is still being used as the first step which provides values of layer parameters from computer aided interpretation. In the interpretation of resistivity sounding data the geological formations are assumed to be horizontal or near horizontal (dip up to 15^o). The ground could have two layers, three or multi layers, with different resistivity and thickness. In sedimentary basins there are layers of sandstone, shale, limestone etc., whereas in hard rock terrains soil and weathered rock formations overlie fresh rocks approximating a three-layer section. If the top soil lies directly over the fresh rock, there are dominantly two layers. Detailed description of type curves and their interpretation techniques have been provided by Bhattacharya and Patra (1968), CGG (1955). They have also provided computed master curves for two and three-layer earth sections for different resistivity and variable thickness. The field curves are matched to yield layer resistivity and thickness values, which in turn are interpreted in terms of geology of the survey area. Computer aided and inversion techniques (Das and Ghosh, 1974; Ghosh, 1971; Inman, 1975; Koefoed, 1979) for the interpretation of the resistivity sounding data have made rapid strides during the past 30 years. Often the assumption of horizontal layers is not valid. Two-dimensional structures or even at times three dimensional structures need to be considered. In such cases numerical techniques suggested by (Mufti, 1980) have to be resorted to. In the present study, the concept of the profile interpretation is carried out using IPI2Win. It means that data for a profile are treated as a unity representing the geological structure of the survey area as a whole, rather than a set of independent objects dealt separately. The concept is implemented mainly by using the interactive semi-interactive mode rather than the automated interpreting the model.

IPI2Win is capable of solving resistivity electrical prospecting 1 D forward and inverse problems for a variety of commonly used arrays for the cross section with resistivity contrast within the range of 0.001 to 10000 ohm-m (Fig. 3).

The forward problem is solved using the linear filtering. These thoroughly tested filters and filtering algorithm implementation provide fast and accurate direct problem solution for a wide range of models, covering all reasonable geological situations.

The inverse problem is solved using a variant of the Newton algorithm of the least number of layers or the regularized fitting minimizing algorithm using Tikhonov's approach to solving incorrect problems. A-priory information on layer depths and resistivites can be used for regularizing the process of the fitting error minimizing. The inverse problem is solved separately for each sounding curve.

3 RESULTS AND DISCUSSIONS

The 2-D geoelectrical section has been generated over five selected profiles (3 over Devrukh and 2 over Sakarpa) in the study region in order to understand the geometry of the aquifers developed in this region (Fig. 4).

3.1 Devrukh area

In Devrukh to Ganapatipule region, three profiles (AB, CD and EF) are presented.

A-B Profile

AB profiles covers the stations VES 19, 21, 20, 18, 17, 16, 22, 23 and 3 from west to east. Fig. 5 a showed that below stations 19 to 22 hard and compact rocks are encountered from shallow to depths of about 20 m. This layer is having resistivities in the range of 400 to more than 2000 Ω.m. Further below stations 23 and 3, an aquifer body is developed from depths of 2 m up to 100 m having resistivities of about 60-150 Ω.m. Also at lower levels this feature is trending towards west and is seen at depths of 50 m below the entire profile. It is also seen that below station 22 and below stations 21, 20 and 18, very low resistivities (below 50 Ω.m) is demarcated at depths of 50 m. It is possible that the aquifers developed are due to basalts or lateritic formation. In basaltic terrain, the groundwater occurs in vesicular zone as well as interflow zones in weathered and fractured zones. Laterite has better porosity due to intricate network of sinuous conduits making it a porous formation.

C-D Profile

The CD profile lies in the central part of the study region encompassing the VES stations 15, 14, 13, 12, 11, 10 and 9 from west to east (Fig. 5 b). It is observed that below stations 15 and 14, the top layer is not so resistive (130-250 Ω.m) up to depths of about 5 m. Below this layer a conductive zone is encountered having resistivities of about 60-130 Ω.m extending up to depths of 100 m. This conductive zone extends towards east below all the VES points at depth of 50 m. Very low resistivity (less than 50 Ω.m) is seen below stations 14 and 13 in the depth range 50-100 m. The top 10 m below stations 13-9 is having very high resistivity (more than 400 Ω.m). This region is highly infested with lateritic formation. It is possible that the fractures and fissures present in the lateritic terrain have enabled the formation of groundwater zone at depths of 50 m and below. This profile is at a lower elevation than the profile AB. Below station 9, an incomplete aquifer body is seen at depths of about 80 m.

E-F Profile

Profile EF is in continuation of profile CD. This profile is encompassed with VES stations 9, 8, 7, 6, 5, 4, 1 and 2. The station 9 is overlapping in both CD and EF profiles for the sake of continuity. It can be seen from Fig. 5 c that the low resistive zone seen in profile CD is continuing at depths of 40 m and below. However below station 6, an aquifer body is developed at shallow depths of 1 m extending up to more than 100 m.

Elsewhere in the profile, the top layer up to 20 m is encompassed with hard rock reflecting laterites. Towards VES 2, an incomplete aquifer seems to develop from depths of 2 m and below. Further stations towards east of VES 2 would have brought out the complete picture of the aquifer.

3.2 Sakarpa area

A total of 17 VES points have been sounded in Sakarpa region from Malkapur (Kolhapur) to Ratnagiri. The entire profile is divided into two parts (AB and CD) for the sake of discussion (Fig. 6).

A-B Profile

The profile AB contains the VES stations 1, 11, 5, 6, 7, 8, 9, 10, 12 and 13 (Fig. 6 a). It can be seen from this figure that below VES stations 1 and 11, hard rocks having resistivities of about 100 to more than 400 Ω.m is encountered at depths extending from 1 m up to 50 m. At VES station 5, a clear groundwater aquifer zone is delineated from shallow depths up to about 30 m. This feature is extending further down and trending towards western side below stations 11 and 1. This feature is very conductive having resistivities less than 10 Ω.m. Towards east of station 5, a high resistivity block is encountered below VES stations 6, 7 and 8. This block with resistivities of 190-400 Ω.m is extending from shallow depth up to about 50 m. Another aquifer zone to the east of this resistive block is observed below VES stations 9, 10 and 12. This feature is oval in shape having resistivities in the range of 10-50 Ω.m with depth extent from 1-20 m. Further below VES station 13, a small aquifer seems to develop at shallow and deeper levels.

From Fig. 6 a it can be proposed that the low conductivity zone sandwiched between two high resistive zones could be due to the presence of some lineaments. Many north-south and east-west lineaments in this region have been identified using satellite data (CGWB, 2009). From the foregoing it can be seen that there are well developed aquifer bodies over this profile with good potential for groundwater.

C-D Profile

The sounding stations over profile CD are 14, 15, 16, 17, 18, 20 and 19 (Fig. 6 b). This profile is in continuation of profile AB. However, due to the Sahyadri mountain range and thus non availability of sites, a large gap of about 20 km exists between VES stations 13 and 14. The features reflected below VES station 13 (Profile AB) continues below station 14 and 15 (Profile CD). It can be seen that an aquifer body is developed below station 15 from depths of 2 m and continues down up to 100 m. This low resistive zone (20-50 Ω.m) is observed below stations 14, 16, 17, 18 and 20 at depths of 20 m and below. A high resistive feature (more than 150 Ω.m) is delineated below stations 17 and 18. Further east high resistivity (more than 170 Ω.m) is obtained below station 19. In between stations 18 and 19, a low resistivity (60-120 Ω.m) patch is observed. Perhaps the lineaments observed in this region divide the low resistive station 20 from the high resistive station 18 and 19.

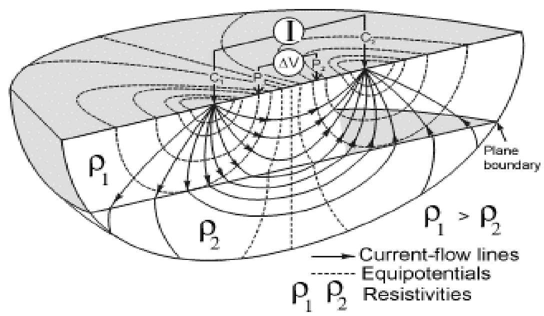


Figure 1. Resistivity measurements of four electrodes

Figure 2. SSR-MP-AT Resistivity meter

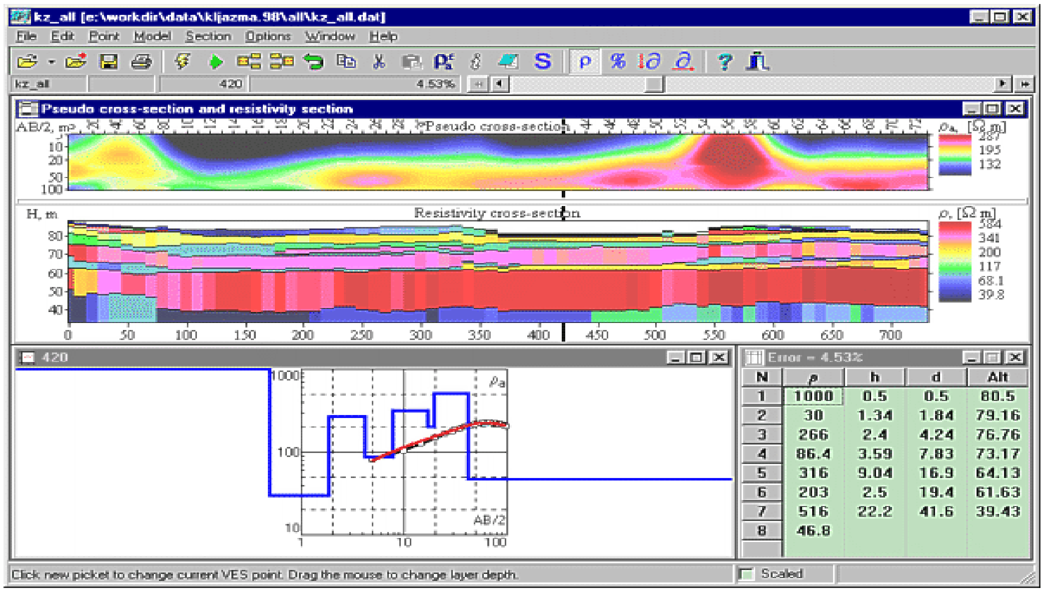


Figure 3. Typical geoelectric cross-section

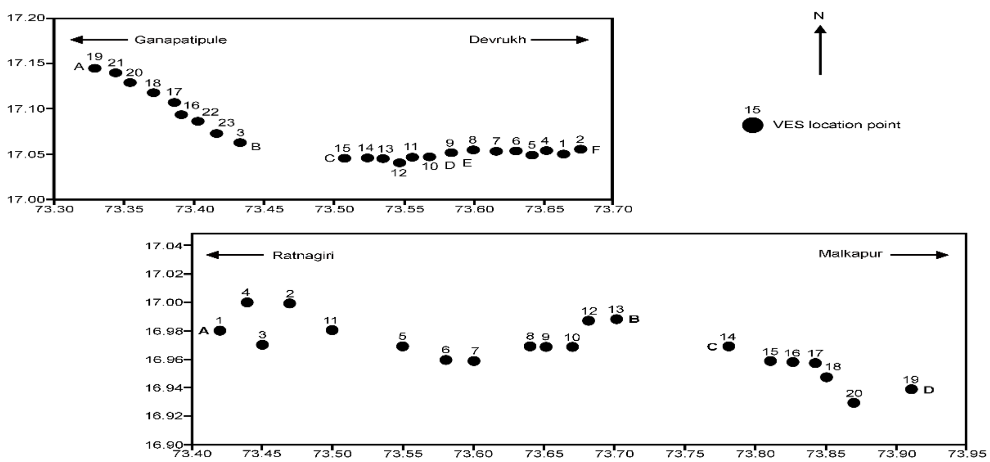


Figure 4. Location of VES sounding points over Devrukh and Sakarpa

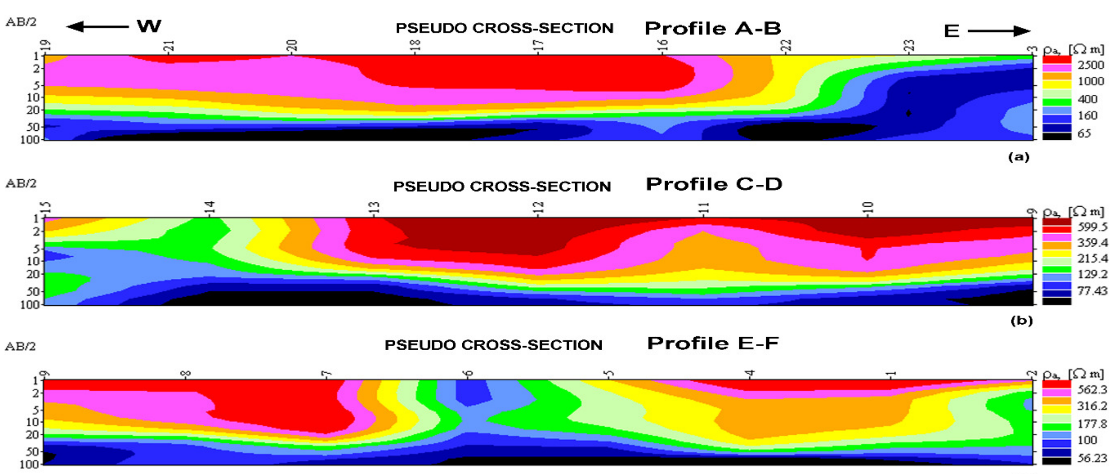


Figure 5. Geoelectrical model in Devrukh-Ganapatipule region

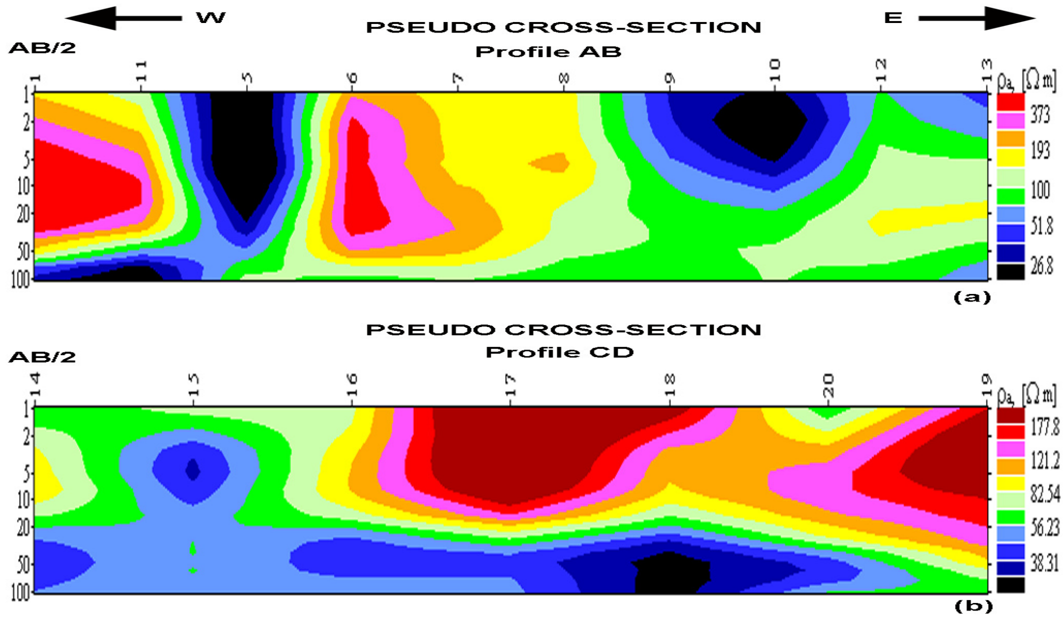


Figure 6. Geoelectrical model in Malkapur-Ratnagiri profile

4 CONCLUSIONS

The resistivity technique is used to study the horizontal and vertical discontinuities in the electrical properties of the ground. In the present work Schlumberger array configuration was adopted to categorize potential groundwater zones in the western part of Maharashtra. Two linear profiles were sounded in the districts of Ratnagiri and Kolhapur. The first profile was from Devrukh to Ganapatipule and the second profile was from Malkapur to Ratnagiri.

Two dimensional modeling was carried out in this region. The Devrukh-Ganapatipule profile was divided into three parts for the sake of clarity. It is observed that the western part of the profile is dominated by very high resistivity top layer up to depths of about 10 m. The eastern part is conductive and is potential for groundwater exploitation. The causative factor for high resistivity is the presence of laterites in this region. However, several lineaments are cris-crossing this region and hence these lineaments are also playing a significant role in the movement of groundwater.

The profile over the Malkapur-Ratnagiri area was divided into two profiles. It is observed from the two dimensional geoelectric cross-section that this region has more potential groundwater aquifers than the previous profile. The resistivity ranges are also less than the Devrukh-Ganapatipule profile. A couple of lineaments were also identified over this profile.

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REFERENCES

Alfano, L. Introduction to the interpretation of resistivity measurements for complicated structural conditions. Geophys. Prosp, 7, 311-66, 1959.

Baride Mukund Vasantrao, Patil Jitendra Bhaskarrao, Baride Aarti Mukund, Golekar Rushikesh Baburao, Patil Sanjaykumar Narayan. Comparative study of Wenner and Schlumberger electrical resistivity method for groundwater investigation: a case study from Dhule district (MS), India Applied Water Science pp 1-20, 2017). https://doi.org/10.1007/s13201-017-0576-7

Bhattacharya, P.K. and Patra, H. P. Direct current Geoelectric. Elsevier, Amsterdam, 135 p., 1968.

Bobachev, A. Resistivity Sounding Interpretation. IPI2WIN: Version 3.0.1, a 7.01.03. Moscow State University, 2003.

CGG, 1955. Abaquer de Sondage Electripue. Geophy. Prosp. 3 Suppliment 3, The Netherland. Central Ground Water Board (CGWB) Groundwater Information, Ratnagiri district, Maharashtra; Technical report No. 1616/DBR/2009.

Das, U.C. and Ghosh, D.P. The determination of filter coefficients for computation of standard curves for dipole resistivity soundings over layered earth by linear digital filter. Geophys. Prosp. 22(4), 765 – 780, 1974.

Deshpande, G.G. Geology of Maharashtra, Geological society of India, Bangalore, 1998.

Ghosh, D. P. The application of linear filter theory to the direct interpretation and geophysical resistivity sounding measurements. Geophys. Prosp., 19(2), pp. 192 – 217, 1971.

R B Golekar, M V Baride, S N Patil. 1D resistivity sounding geophysical survey by using Schlumberger electrode configuration method for groundwater explorations in catchment area of Anjani and Jhiri river, Northern Maharashtra (India). Journal of Spatial Hydrology pp 22-36, Vol.12, No.1 Fall. 2014.

Inman, J. R. Resistivity inversion with ridge regression. Geophysics, 40 (5), 798-817, 1975.

Jones, H.C. Mineral resources of Kolhapur State, Rec. Geol. Surv. India, LTV, part 4, 1923.

Kearey, P. and Brooks, M. An Introduction to Geophysical Exploration. ELBS, Blackwell Scientific Publication, Oxford, pp.296, 1988.

Koefoed, O. Geo sounding principles, Resistivity sounding measurements. Elsevier, Amsterdam, pp.300, 1979.

Li, Y. and Oldenburg, D.W. Approximate inverse mappings in DC resistivity problems. Geophysical Journal International, 109, 343-362, 1992.

Mc Neil, J. D. Use of electromagnetic methods for groundwater studies. In: geotechnical and environmental geophysics volume 1; Review and tutorial ed. Stanely H. Ward, 1990.

Mufti, I.R. Finite-difference evaluation of apparent resistivity curves. Geophy. Prosp. 28 (1) pp. 146-174, 1980.

Orellana, F., and Mooney, H.M. Master tables and Curves for vertical electrical sounding over layered structures. Inter science Madrid, 1966.

Sasaki, Y. Resolution of resistivity tomography inferred from numerical simulation. Geophysical Prospecting, 40, 453-464, 1992.

Seidel K, Lange G. Direct Current Resistivity Methods. In: Environmental Geology Handbook of Field Methods and Case Studies, Knodel KG, Lange and H. Voigt (Eds.). Springer, USA., pp. 205-237, 2008.