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Comparative study of Wenner and Schlumberger electrical resistivity method for groundwater investigation: a case study from Dhule district (M.S.), India

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Abstract The area chosen for the present study is Dhule district, which belongs to the drought prone area of Maharashtra State, India. Dhule district suffers from water problem, and therefore, there is no extra water available to supply for the agricultural and industrial growth. To understand the lithological characters in terms of its hydrogeological conditions, it is necessary to understand the geology of the area. It is now established fact that the geophysical method gives a better information of subsurface geology. Geophysical electrical surveys with four electrodes configuration, i.e., Wenner and Schlumberger method, were carried out at the same selected sites to observe the similarity and compared both the applications in terms of its use and handling in the field. A total 54 VES soundings were carried out spread over the Dhule district and representing different lithological units. The VES curves are drawn using inverse slope method for Wenner configuration, IPI2 win Software, and curve matching techniques were used for Schlumberger configuration. Regionwise lithologs are prepared based on the obtained resistivity and thickness for Wenner method. Regionwise curves were prepared based on resistivity layers for Schlumberger method. Comparing the two methods, it is observed that Wenner and Schlumberger methods have merits or demerits. Considering merits and demerits from the field point of view, it is suggested that Wenner inverse slope method is more handy for calculation and interpretation, but requires lateral length which is a constrain. Similarly, Schlumberger method is easy in application but unwieldy for their interpretation. The work amply proves the applicability of geophysical techniques in the water resource evaluation procedure. This technique is found to be suitable for the areas with similar geological setup elsewhere.

Keywords Geophysics · Groundwater · Exploration · Vertical electrical sounding · Wenner and Schlumberger

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Introduction

Long years ago, humanity existed in groups and rarely in larger numbers. Therefore, there was a type of absorbance within the community if any natural or anthropogenic changes took place. However, over a period of time, the human race has seen explosion in technology and population obviously for both categories: the rich out of greed and poor out of need. This has definitely placed pressure on whatever natural resources we have, which includes environment and space. The world population has increased sharply in a very short period of time and death has been prolonged due to the lowering of death rate. Urbanization rules the divide between rural and urban populations. The impact of urbanization and industrial development is being seen as a negative stress put on atmosphere, hydrosphere,

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lithosphere, and on human beings in general, life in particular. The rate at which the development is taking place is going to lead to no where and has bearing on water resources. One such impact is now being seen on water resource more than other natural resources as water is now being considered as an important natural resource.

Many researchers have studied the area from different point of views. The Geological Survey of India published report on the Geology of Dhule district (Geological Survey of India 1976). Some aspects of hydrogeology of Maharashtra have been attempted by earlier researchers (Adhyalkar and Mani 1972; Adhyalkar 1975; Aurangabadkar 1990; Aurangabadkar and Waldhe 2001). The Deccan Volcanic activity and their characteristics are studied by Krishnan (1982). Startigraphic study has been carried out by few researchers (Powar 1987; Sethna et al. 1996; Vaidyanadhan and Ramakrishnan 2008).

Geophysics plays an important role in groundwater exploration. It is necessary to locate groundwater potential zones using cost-effective methods. As urban, agricultural, and industrial development, the volume and proportion of water required will also increase and water supplies that were obtained from shallow unconfined aquifers may not be sufficient, because the availability of the resources becomes confined. The water resources required will have to be tapped from deeper aquifers or, more often, can be drawn from aquifers or surface water bodies and reservoirs. Thus, importing of water becomes necessary for urban, agricultural, and industrial development. If this does not happen, then the development may get hampered. It is observed that very little work has been done in the area of studies with respect to correlation between Vertical Electrical Sounding studies (Erram et al. 2010).

The authors have made an attempt to correlate the VES methods of Wenner and Schlumberger in understanding the scientific principles. This will help the academicians to understand to practical importance of these methods.

Study area

The area chosen for the present study is Dhule district, which belongs to the drought prone area of Maharashtra state, India. Dhule district covers an area of 8063 km². This is about 2.6% of the total land of the state (Fig. 1). According to 2011 census, the population of Dhule district is about 2050862. The population density of the Dhule district is about 254 per km². The density needs to be critically reviewed as compared to the state's density. This indicates that increase in density will put pressure on the limits of urban cities and they will increase in size. This will give cumulative stress especially on water.

Physiographically, Dhule district is covered in Upper Tapi basin which forms the northern part of Maharashtra state. It is bounded by 20° 38″–21° 60″ North latitude and 73° 50″–75° 11″ East longitudes. Dhule district is bounded by Jalgaon district in the east, Nasik district forms the southern end, on the northern part is the Nemad district in Madhya Pradesh, and western side forms the Nandurbar district boundary. Dhule district is drained by rivers, such as Tapi, Panzra, Burai, Arunavati, Aner, Bori, Kan, and Amravati. These rivers are the major source for surface and groundwater in the district. The district is divided into three regions based on the type of soils which is low, medium, and black cotton soil. Low fertile land is about 60%, medium fertile land is 25%, and black cotton soil covers 15% of the area (Central Ground Water Board 2009).

The soils of the district are derived from weathering of basalt and from the river system. The alluvium is present along the rivers and along hill slope streams. These are light soils, dark brown to yellowish brown, and loamy-to-clay loamy texture with sub-angular grains. The presence of clayey soil is towards south of Tapi valley (CGWB).

The climatic condition of Dhule district is hot and dry, arid to semi-arid type. Temperature is maximum 45 °C and minimum of 06 °C in the months of May and October, respectively, with relative humidity 75% (Aurangabadkar 1990). In the district, June, July, August, and September are the rainfall months. The rainfall statistics for Dhule district shows that average rainfall is 771.0 mm.

Scope of the work

There is need to understand the two important concepts with respect to water as: (1) sustainability and (2) management. To achieve sustainability, there is a need for rethinking of our basic needs. If our basic need is considered to be water on priority, then water as a resource must be valued as to how much of water do we really require and how much do we use. The need of water for ecosystem and the animal life too require water, and therefore, the basic needs to preserve and use water judiciously as a resource becomes our greatest challenge and to adopt sustainable practices. For managing this resource, information regarding the availability of subsurface water is important. With right information, effective communication using modern scientific knowledge and dialogue between individuals and institutes, water as a source can be understood and managed in a sustainable manner and, therefore, needs to focus on productive water by managing water in rain fed zones and sustainable use of groundwater through exploration method.

Aims and objectives

In the present study, geophysical approach has been adopted to investigate the subsurface lithology of the Dhule

Fig. 1 Geological map of Dhule district (Source: GSDA 2001)
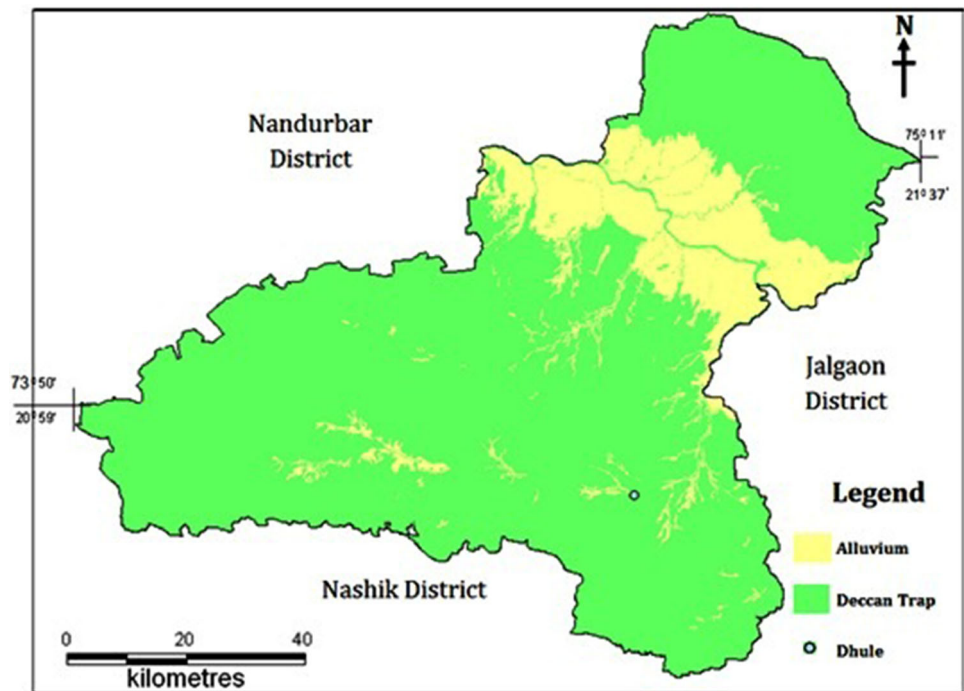
District located in Maharashtra state (India), with an aim to differentiate the aquifers and delineate the depth of aquifers and comparison between Wenner's and Schlumberger method.

Geological setting

Geology, topography, relief, climate, soils, temperature, rainfall, and other natural factors govern the development of groundwater. It is necessary to understand the basics of the terrain and river dynamics besides other factors in relation to groundwater occurrence and movement in the area.

Regional geology

Nearly, 65 million years ago, large amount of outpouring of molten lava took place through fractured Western India. The eruption is intermittent giving rise to Large Volcanic Province called Deccan Volcanic Province (Krishnan 1982; West 1988). It is most extensive lava eruption and formation in the Peninsular India. It is recognized as Deccan Trap and also called as Large Igneous Province (LIP). The term Deccan Trap is suggested by Sykes, meaning 'south' (Sykes 1833). The topography is typical step like.

The extent of DVP spreads over an area of about 5,00,000 km^2 extending over large parts of Madhya Pradesh, Maharashtra, Gujarat, and some parts of Andhra Pradesh and Karnataka and also large part of the DVP is

concealed under the Arabian Sea (Powar 1987). They are exposed along Sahyadri Mountains or Western Ghats with steep escarpments in west coast of India. The Ghat is a result of faulting to produce an Atlantic type of continental margin (Erram et al. 2010). The composite thickness may be about 3000 m. Deccan Traps exhibit horizontal lava flows, development of flat-topped hills, and step-like terraces. The horizontal basaltic lava flows are inferred to be due to fissure eruptions (Vaidyanadhan and Ramakrishnan 2008; Bondre et al. 2006).

Earlier pioneer workers who studied DVP are stated that the basalts from the Deccan Province are vesicular with or without secondary zeolite material. The rock also shows a variety of joints and fractures. These fracture zones have become the path for drainage development and undulating topography (Blanford 1869; West 1972). The Deccan lavas are traversed by the number of dykes along Narmada-Tapi tectonic zones with ENE-WSW trend. Concentration of dyke is more in Nandurbar district and Konkan region. Some of the dykes form linear ridges for a long distance. Some dykes are eroded faster forming linear depressions. Geological map of Dhule district has depicted in Fig. 1.

Lineaments and dyke intrusive from the study area

The large number of dolerite dykes intrudes the basaltic lava flows in the study area. Dykes can act as pathways or as barriers to the groundwater flow depending upon the intensity of fracturing in the dyke rock (Babiker and Gudmundsson 2004; Gurugnanam et al. 2008). Whether

the dykes act as water conduits or as barriers their structure, location and orientation with respect to the groundwater flow are important parameters (Gurugnanam et al. 2008; Singh and Jamal 2002). Dhule district of Maharashtra is known for the occurrence of dykes and dyke swarms (Geological Survey of India 2001). However, attempt to study the area from hydro-geological point of view has been done by few researchers (Duraiswami 2005; Pawar 2006; Gupta et al. 2012; GSDA 2001).

The trend of the majority of the lineaments is in the E–W direction, and some of the lineaments show N–S, NNW–SSE, and NNE–SSW trend. The lineaments are the major fractures and dykes. The fractures are related to shears and the dykes appear to occupy dilatory tensional fractures. Dykes are vertical intrusions showing linear ridges due to differential weathering. They are simple and undifferentiated. The dykes trending E–W and ENE–WSW directions are parallel to the Narmada–Tapi–Satpura zones. These dykes extend for kilometers with varying thickness. The dykes belonging to these sets are generally coarse grained, gabbroic. The jointing pattern produces larger blocks. Dykes belonging to the north–south swarm are few in number and are exposed in the southern and western parts of the Panzra river (Sheth and Chandrasekharam 1997). Some of the dykes exhibit a negative relief at higher elevations but stand out as low elevation in the low lying areas. These are compact fine grained and exhibit closely spaced joints. Some of the dykes are partly concealed, while some are exposed in stream cuttings, dug well section, and road cuts. Dykes from the study area are in part responsible for controlling the topography of the basin. Systematic studies by adopting hydro-geological and geophysical (electrical resistivity and magnetic) approaches have not yet been attempted to indicate the status, occurrence, and movement of groundwater except by a few as already referred above.

Figure 2 shows that the presence of dykes, lineaments, and the drainage in Dhule district. It is observed that dykes trending east–west show branching and sharp cross-cutting relationship. Dykes show sharp contrast with the country rocks. Dykes trending E–W are generally dense, dark, less fractured, and moderately compact, whereas north–south trending dykes are moderately weathered and fractured. In the district EW trending, dykes run more or less parallel to the drainage and sometimes follow surface divides and act as barriers of ground water, while north–south trending dykes cut across the drainage and behave like conduits of groundwater (Sheth and Chandrasekharam 1997). The Flood Basalt is fissure-type volcanic activity, and therefore, dykes in large number are exposed in the Nandurbar and Dhule. In Dhule area, basalts show a thick sequence of about 870 m in Toranmal. It is dominated by columnar jointing simple flows, which are similar to that of Western

Ghat (Sheth and Pande 2004; Ray et al. 2007; Sant and Karanth 1990). Tertiary and quaternary alluvium is exposed along the major rivers. The lava flows are horizontal around Dhule and Dondaicha and Dips towards north at 5°–10° near Shahada and Kondaibari.

The dyke controlling local groundwater table in Sakri taluka has been reported by earlier researcher (Pawar 2006). The Narmada–Satpuda–Tapi dyke swarm is a liner ENE–WSW trending Giant dykes (Melluso et al. 1999). The petrographic and geochemical studies of dykes in Nandurbar Dhule area have been carried out by earlier researchers (Sheth 2005; Bhattacharji et al. 2004; Das Balaram Maity and Tarafdar 2007). Since the dykes are not emplaced along faults or fracture, it suggests regional horizontal compressive stress along north–south as a region for the emplacement of dyke (Sant and Karanth 1990).

Alluvium

Patches of alluvium are exposed along the Panzra river and its tributaries near villages Samode and Kasare, Dhadne, Morane, and Kundane-War. Small patches of alluvium are also found between Dahivel, Surpan, and Ashtane along the Kan river (GSDA 2001). The thick sequence of alluvium is found in the low lying areas between Sukwad and Vadali and at Bhadne. Primary sedimentary structures, such as parallel bedding, trough cross bedding, tabular cross bedding, and cut-and-fill structures, are seen in the litho-sections. Alluvial deposits of Tapi river valley occurs in long narrow basin, which are probably caused by faulting. About 15% of the district is occupied by alluvium consisting of clays, silt, and sand. The beds of sand and gravels are discontinuous and lenticular and pinch out laterally within short distance. They are mixed with large proportions of clayey material. Sections show the presence of more or less nodular calcrete material associated with alluvium. The deposit consisting of talus and scree locally known as Bazada zone forms colluvial deposits which have developed along foothills that overlie alluvium along stream banks. This zone consisting of poorly sorted unconsolidated large boulders, pebbles, and cobbles with sand is porous and has a capacity to accept higher quantity of water as recharge. The maximum thickness of this formation ranges from 35 to 40 m.

Black cotton soil is the ultimate product of decomposition and weathering of basalt. The lava flows are covered by black clayey to loamy soil. The thickness of the soil is less than meter. However, in some part of Tapi river and Burai river, the thickness of soil ranges from 2 to 3 m admixed with local alluvium. The soil in the alluvial part along the Burai river is gray in color and at places unsuitable for irrigation due to their high sodium content. Light types of soil are good for cultivation in kharif crops

Fig. 2 Map showing rivers, dykes, and lineaments in Dhule district [Source, GSDA]
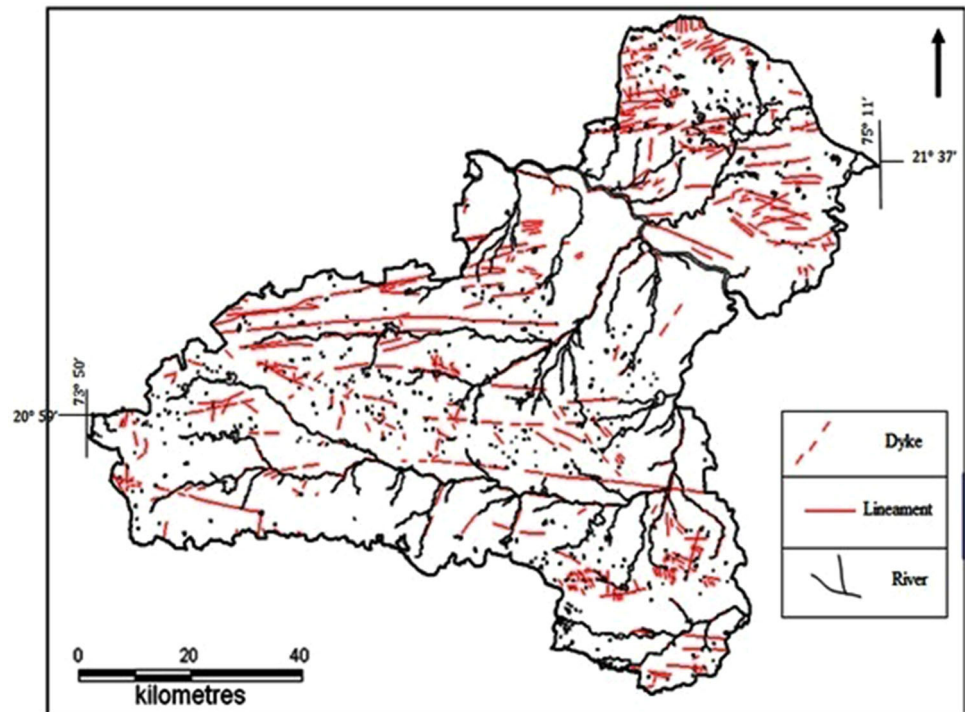
and occur in parts of Sakri and Dhule talukas. Medium type of soil is well suited for irrigation and cover parts of Sindhkheda, Sakri, and Dhule talukas. The weathered part of Deccan trap is called murum and covers a thickness of meter or 2 m between the soil and the lower hard rock.

Nearly, 75% of the total area of Shirpur taluka is covered by Tapi alluvium. This area is almost plain topographic expression with gentle slope towards south. The maximum thickness of this alluvium in Shirpur taluka is 65 m. Similarly, northern portion of Sindhkheda taluka is also covered by Tapi alluvium which is saline with thickness 30–35 m.

Hydrogeology of the study area

The well and bore-hole logs for Sakri taluka suggest that the upper layer consists of highly fractured basalt, a thin layer of soil/murum and highly weathered basalt, less fractured basalt, and compact basalt, but very thin layer of soil present in many of the sites is not reflected in the values obtained from VES. There are more dug wells present in this taluka. The water table is encountered at the depth of 10–12 m for dug wells and bore wells are rare because of the kind of lithology that does not support groundwater. However, few bore wells show the presence of water table at 100–120 m.

The general lithology in Shindkheda taluka shows a top layer of black cotton soil or soil. The thickness is less. It is followed by weathered basalt or murum, highly fractured basalt, weakly fractured basalt, and compact basalt. In this area, the groundwater is obtained from a depth of 16.5–18 m for dug wells. The dug wells over the period of time have become dry, and therefore, many farmers have taken bore in these wells (dug–cum–bore wells). The water is found at 137–152 m. About 4000 L/h is obtained.

The general lithology in Shirpur taluka is predominantly composed of alluvium. The bore-hole log shows upper layer of black cotton soil followed by sandy alluvium with clay lenses. Earlier, the water table was found at 27–30 m with sufficient water. Later on with time, the depth of water table increased. At present, it is tapped at 60–76 m. The quantity of water is about 5000 L/h. It is observed that in Shindkheda, the groundwater was not available in sufficient quantity as compared to that of Shirpur. However, after incidents of Killari earthquake (September 1993), the situation has changed. Now, the Shindkheda taluka has a better quantity of water than Shirpur.

In Dhule taluka, the general lithology observed shows soil as the top layer with murum, jointed basalt, highly weathered and jointed basalt, weakly jointed basalt and compact basalt. There were more dug wells in the earlier times, but with lowering of the water table, the depth has increased, and therefore, bore holes are constructed. The water table encountered for dug wells is at 18–20 m, and for bore wells, it is 137–152 m with 3000 L/h quantity of water.

Methodology

Exploration techniques

Geophysical methods were developed in the early 1900, and are still being used extensively for groundwater investigations by several workers who have also used the method for defining and delineating other structures and pollution. This method is considered as the most suitable for investigating geological structures. Das Balaram Maity and Tarafdar (2007) used a combination of resistivity—cum—IP sounding with Schlumberger and concluded that this can help to detect fluoride contamination (Todd 1959). Integrating groundwater data from electrical resistivity survey is employed using Wenner and Schlumberger electrode configuration to identify the subsurface features and location of water (Gurugnanam et al. 2008; Zohdy et al. 1974; Ayolabi 2005; Bhattacharya and Patra 1968; Deshpande 2008; Ojelabi et al. 2001; Alisiobi and Ako 2012; Ariyo et al. 2011; Patangay et al. 2002).

The resistivity survey is generally carried out across the slope, where conductivity varies with depth without lateral variation (Srinivasamoorthy et al. 2009). The application of resistivity is also used in coal and mineral exploration, but commonly, the method is used for groundwater exploration (Zohdy et al. 1974; Ayolabi 2005; Krishnamurthy et al. 2009; Kumar et al. 2011; Swartz 1937; Udaya Laxmi and Ramadass 2009). Studies on dykes have been carried out to classify the dykes as carrier or barrier for groundwater flow (Erram et al. 2010; Singh and Jamal 2002; GSDA 2001). Andrade (2011) and Golekar et al. (2014) have been established that VES method and 2D resistivity can be a better tool in understanding the hydro-geological problems (Andrade 2011; Golekar et al. 2014). In the area under study, electrical resistivity method is carried out and favorable groundwater zones are identified. It is now established fact that geophysical method gives a better information of subsurface geology.

The apparent resistivity using four probe electrodes configuration of Wenner and Schlumberger method is carried out on the same selected sites to observe the similarity and compared both the applications in terms of its use and handling in the field. The VES was carried out by Wenner and Schlumberger methods. For Wenner, data are plotted on respective graphs and values calculated. For Schlumberger, the IPI2 Win software was used. A total of 54 VES were carried out spread over the district and representing different lithological units (Table 1). The VES locations are shown in Fig. 3. The instrument used is resistivity meter MINITRONIX model AQUA II and AQUA II PLUS. In resistivity meter, AC voltage input is used (100/200 V).

Wenner method (Wenner 1969)

It is based on equal distance spacing 4 probe methods which is carried out by inverse slope method suggested by Narayan and Ramanujachary (1967). The objective of VES is to record the changes in resistivity with depth and to correlate it with the available geological information to infer the depths and resistivity of the layers present. The resistivity of the strata is determined by passing an electric current between two electrodes on the surface. As the distance between electrodes increases, the depth of penetration also increases. The penetration of current below the surface is proportional to 1/3rd distance between two current electrodes on the surface.

The resistivity meter is placed at the exploration site which is suitable for lateral spreading of the cable in either direction. The non polarizing electrodes needed for measuring the potential differences are placed at predetermined distances on either side of chosen center near to the measuring equipment. PVC covered cable is connected to the potential electrodes as also the current electrodes are connected to the proper terminals on the equipment. The power supply pack (100 V) is also connected to the instrument.

The current electrodes are driven into the ground 10 cm deep each on either side of the center. These current electrodes are connected to the instrument by PVC cable. The working of the instrument begins and is operated as per the principles used in the instrument. Current is passed through the two extreme electrodes; the potential difference measured between the two inner electrodes gives a measure of the resistivity of the ground. Due to its constant and extensive use, the Wenner's 4 probes method is used as this method provides a simple resistivity formula and the field procedure is easier.

In Wenner method, the array spacing "a" is increased by steps, keeping the midpoint fixed, the four electrodes with a definite array spacing "a" is moved as a whole in suitable steps, four electrodes are moving after each measurement, and the values from the instrument is recorded as R with depth d. The reading R is then divided by unit value to get the inverse values as 1/R.

Vertical electrical sounding (Wenner's method) carried out for 54 sites representing soil, weathered rock, and hard rock aquifers is presented in Table 1. The talukawise sample site distribution is 14 VES which were taken in Sakri taluka, 12 VES in Shindkheda taluka, 8 VES in Shirpur taluka, and 20 VES in Dhule taluka.

In the meantime, Narayan and Ramanujachary (1967) showed that it is possible to solve the field equation directly to get resistivity and thicknesses of the subsurface layers from the field data by inverse slope method (Narayan and

Table 1 VES locations in Dhule district, India

VES no.	Village	Taluka	VES no.	Village	Taluka	VES no.	Village	Taluka
1	Nimgvhan	Sakri	19	Sulvade	Sindhkheda	37	Vinchur	Dhule
2	Chinchkeda	Sakri	20	Sarve	Sindhkheda	38	Ankvadi	Dhule
3	Kirvade	Sakri	21	Bhadne	Sindhkheda	39	Purmepada	Dhule
4	Akkalpada	Sakri	22	Babhale	Sindhkheda	40	Mukti	Dhule
5	Malpur	Sakri	23	Dattane	Sindhkheda	41	Kalkheda	Dhule
6	Pimpalner	Sakri	24	Bamhane	Sindhkheda	42	Aarvi	Dhule
7	Dahivel	Sakri	25	Pimprad	Sindhkheda	43	Ner	Dhule
8	Varsus	Sakri	26	Chimthane	Sindhkheda	44	Junnar	Dhule
9	Mhasdi	Sakri	27	Thalner	Shirpur	45	Tamsvadi	Dhule
10	Surpan	Sakri	28	Manjrod	Shirpur	46	Nimgul	Dhule
11	Sakri	Sakri	29	Kharde-Patharde	Shirpur	47	Babhulvadi	Dhule
12	Chadvel-Korde	Sakri	30	Palasner	Shirpur	48	Kulthe	Dhule
13	Kavthe	Sakri	31	Nimzari	Shirpur	49	Chaugaon	Dhule
14	Perejpur	Sakri	32	Ahilyapur	Shirpur	50	Dhamangaon	Dhule
15	Dhavde	Sindhkheda	33	Shirpur	Shirpur	51	Devbhane	Dhule
16	Varshi	Sindhkheda	34	Vikharan	Shirpur	52	Khedi	Dhule
17	Dondaicha	Sindhkheda	35	Borkund	Dhule	53	Morane	Dhule
18	Dhamane	Sindhkheda	36	Nhyahalod	Dhule	54	Dhanur	Dhule

Fig. 3 VES location map along with geo-electric section and resistivity geo-electric section along NE–SW and NW–SE from Dhule district
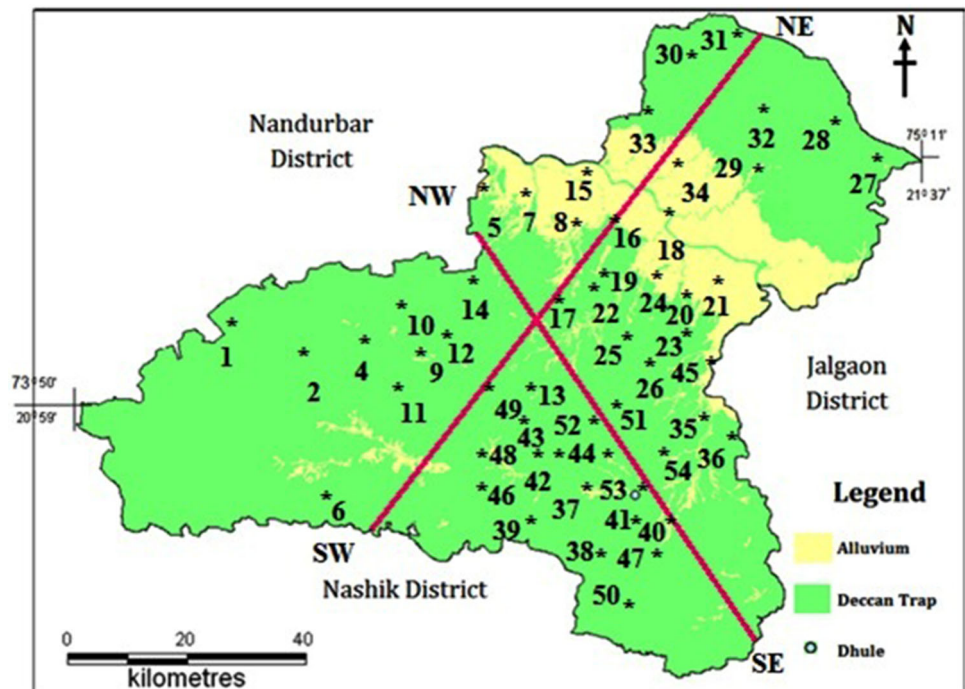
Ramanujachary 1967). The inverse slope vertical electrical resistivity (VES) method as suggested by these two authors works very well in engineering geology and also in groundwater exploration for 2–5 layered. This method assumes considerable importance in the field of ground-water exploration because of its ease of operation, low cost, and its capability. This method was tested widely in India, using it in different geological situations. It was found to give good results correlating well with bore-hole data. This method is simple and gives resistivities and depths directly from the plot of the field data on a linear graph. Interpretation by the inverse slope method has been used to

calculate the values of $\frac{1}{R}$, where $R = \frac{V}{I}$ are plotted against the Wenner's electrode spacing.

The values of resistivity p are determined by the formula, $\rho = \frac{V}{I} 2\pi a$, where V is the potential in volts measured between the two current electrodes, and I is the current in amperes passes into the ground, and a is the distance between the successive electrodes and 2π, a constant. Since $\frac{V}{I} = R$, the resistance (in ohms), the formula, may be expressed as: $p = 2\pi a \, R.$, (in Ω m). The resistivity data were plotted in excel sheet, depth plotted on X axis, and inverse $1/R$ on Y axis (Vaidyanadhan and Ramakrishnan 2008). The obtained resistivity value of each layer was compared with the standard values of different strata. Thereafter, a standard resistivity table prepared for the study area.

Schlumberger method

This method differs from Wenner arrangement in placing the two current electrodes with much larger interval than that between the two (inner) potential electrodes. Vertical electrical sounding (Schlumberger method) carried out for the same site, whereas VES was conducted through Wenner's method (Table 1). The obtained data from the instrument were key into the software for further calculations. The preliminary interpretation of the VES curves was carried out by the curve matching technique of Orellana and Mooney (1972, 1966) in which the field curves are matched with the theoretical master curve (Orellana and Mooney 1972, 1966). The VES curves plotted using the IPI2WIN Geoscientific Software (Babachev 1994).

Two-dimensional (2D) geo-electrical cross section has been drawn using the IPI2 win software along chosen profiles passing through different VES locations to understand the aquifer geometry in the study area.

Result and discussion

Wenner method

The generalized range of resistivity values for different litho units were proposed based on the resistivity sounding results which match with lithology of dug wells (Table 2). Figures 4, 5, 6, and 7 show talukawise representative inverse slope curve (Wenner's method) of Sakri, Shindkheda, Shirpur, and Dhule, respectively, regarding the present study area. The ranges of resistivity values of the subsurface strata obtained through Wenner method are presented in supplementary material (Appendix 1).

Type of aquifer, depth of water bearing rock formation, and suggested exploration of subsurface water through

Table 2 Ranges of resistivity values of different lithounits

Sr. no.	Range of resistivity	Lithounits
1	4–6 Ω m	Black cotton soil with sand
2	6–10 Ω m	Black cotton soil with calcified soil/murum
3	10–12 Ω m	Black cotton soil/murum
4	12–26 Ω m	Black cotton soil with murum
5	26–60 Ω m	Highly weathered and fractured basalt
6	6 0–100 Ω m	Highly fractured basalt
7	100–250 Ω m	Weakly fractured basalts
8	>250 Ω m	Hard compact basalts

In some occasion, black cotton soil may show higher resistivity due to the impervious nature (Zambre and Thigale 1980)
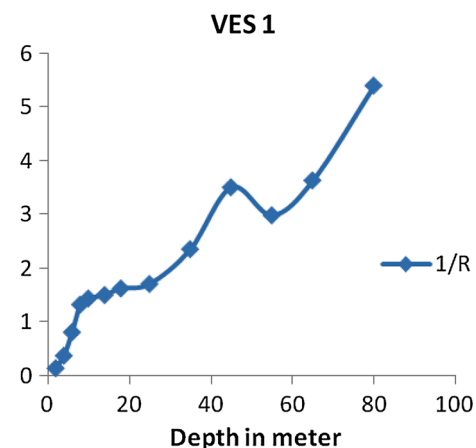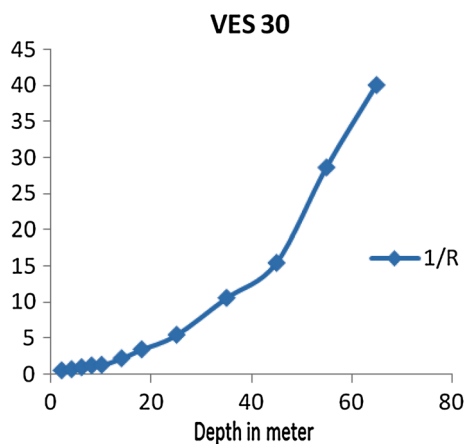

Fig. 4 Representative resistivity curve obtained by the inverse slope method from Sakri taluka
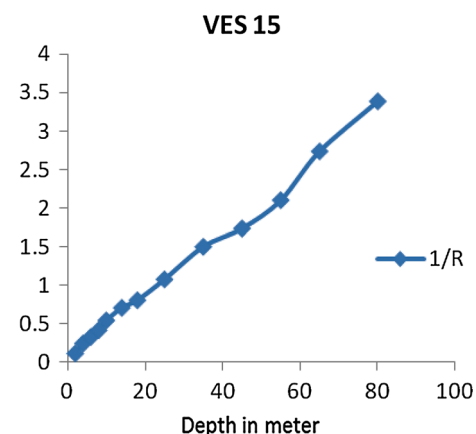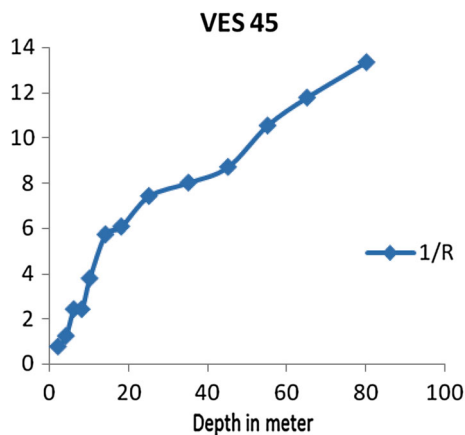

Fig. 5 Representative resistivity curve obtained by the inverse slope method from Shindkheda taluka

different types of wells are depicted in Table 3. However, certain points may be located, where there is a chance for occurrence of groundwater and feasibility for digging dug wells and bore wells. Based on the resistivity data, 37 sites

VES 30

Fig. 6 Representative resistivity curve obtained by the inverse slope method from Shirpur taluka

VES 45

Fig. 7 Representative resistivity curve obtained by the inverse slope method from Dhule taluka

are feasible for exploration of dugwell out of 54 locations which have given a good indication of water bearing zones at shallow depth (Table 3). The remaining 17 sites are not feasible for the exploration of dugwell because of depth of water bearing rock formation at deep. Therefore, these sites are only suitable for exploration of bore wells. Resistivity result showed that the ten sites are suitable for exploration of bore wells and seven sites not feasible for exploration of borewell due to the presence of thick alluvium, hence these sites only suitable for drilling the tube wells (Table 3). Subsurface lithology indicates that the 43 sites belong to unconfined aquifer and 11 show under confined condition.

Schlumberger method

Figures 8, 9, 10, and 11 indicate that talukawise sounding curves are interpreted as per Orellana and Mooney (Schlumberger method) for Sakri, Shindkheda, Shirpur, and Dhule, respectively, regarding the present study area.

Resistivity values and thickness of different layers at all VES locations from Dhule district are presented Table 4. The Schlumberger sounding data are used for creating comprehensive pictures on horizontal scale along two different sections such as NW–SE and NE–SW over the Dhule district. NW–SE passing through VES 6, 12, 11, 17, 16, 33, and 31 NW–SE trends covered near about 90 km. NE–SW passing through VES 5, 17, 40, and 53 NE–SW trends covered near about 75 km.

Pseudo cross sections

Figures 12 show the pseudo cross sections of VES 6, 12, 11, 17, 16, 33, and 31 in the study area. In Fig. 12, at VES 11, the feasible zone is from 9.0 to 14 m (shallow aquifer) and 26 to 37 m (deep aquifer) indicating highly weathered and fractured basalts, while, at VES 16, 33, and 31, anomaly constantly increasing (<13.3–100 Ω m). This indicates a sudden change from black cotton soil, highly weathered and fractured basalts, and weakly fractured basalts to hard and compact basalts, which are less productive from groundwater point of view. Figures 13 show the pseudo cross sections of VES 5, 17, 40, and 55 in the study area. In Fig. 13, all VES stations show that the resistivity anomaly constantly increased. This indicates a sudden change from black cotton soil, highly weathered and fractured, highly fractured basalts, and weakly fractured basalts to hard and compact basalts, which are less productive from groundwater point of view.

Resistivity cross sections

The geo-electrical section along NW–SE includes sites VES 6, 12, 11, 17, 16, 33, and 31 (Fig. 12). The geo-electrical section along NE–SW includes sites VES 5, 17, 40, and 53 (Fig. 13). In Fig. 12, at VES 6 below soil layer, resistivity trend increases up to 360 Ω m indicative of hard and massive basaltic layer. At VES, 12 increases resistivity with increasing depth indicating poor aquifer zone. Afterward, below VES 11, resistivity anomaly abruptly decreases with increasing depth 0.362 Ω m (30 m below) and may serve as groundwater potential zone. At VES 16 and 33 below soil layer, resistivity anomaly decreases downward up to 95 and 11.4 Ω m suggestive of highly fractured basalt and highly weathered and fractured basalt, respectively. At VES 31, trend first increases (6648 Ω m) and then gradually decreases (249 Ω m) exhibiting hard compact basalts and weakly fractured basalts, respectively. This indicates less productive zone of groundwater.

In Fig. 13, at all VES in this cross section, resistivity trend is very less at the top (<2 Ω m). Then, below VES 5, resistivity anomaly increases up to 129–423 Ω m and this

Table 3 Type of aquifer, depth of water bearing rock formation, and recommendation for exploration through wells

VES	Depth of favorable water bearing rock formation	Yield	Type of aquifer	Recommendation for exploration through wells
1	35–45 m	Medium	Unconfined	Bore well
2	10–14 m	Medium	Unconfined	Dug well
3	14–18 m	Medium	Confined	Dug well
4	6–16 m	High	Unconfined	Dug well
5	Below 18 m	High	Unconfined	Dug well
6	18–25 m	Low	Confined	Dug well
7	Below 35	Medium	Unconfined	Bore well
8	14–18 m	Medium	Confined	Dug well
9	4–14 m	High	Unconfined	Dug well
10	55–80 m	Low	Unconfined	Bore well
11	4–25 m	High	Unconfined	Dug well
12	Up to 10 m	Low	Unconfined	Dug well
13	Up to 6 m; 25–65 m	Medium	Unconfined	Dug well
14	6–18 m	Medium	Confined	Dug well
15	55–65 m	Medium	Unconfined	Bore well
16	45–55 m	Medium	Unconfined	Bore well
17	Up to 18 m	Medium	Unconfined	Dug well
18	25–55 m	Medium	Unconfined	Bore well
19	10–18 m	Medium	Unconfined	Dug well
20	10–18 m	Medium	Unconfined	Dug well
21	35–45 m	Medium	Confined	Bore well
22	10–18 m	High	Unconfined	Dug well
23	10–25 m	Medium	Confined	Dug well
24	Below 4 m	High	Unconfined	Dug well
25	6–18 m	Medium	Unconfined	Dug well
26	14–18 m and below 18 m	Medium	Confined	Dug well
27	65–80 m	Medium	Unconfined	Tube well
28	45–80 m	Medium	Unconfined	Tube well
29	55–65 m	Medium	Unconfined	Tube well
30	45–65 m	Medium	Unconfined	Tube well
31	45–80 m	Medium	Unconfined	Tube well
32	55–70 m	Medium	Unconfined	Tube well
33	35–45 m	Medium	Unconfined	Tube well
34	Below 35 m	Medium	Unconfined	Bore well
35	Below 4 m	Medium	Unconfined	Dug well
36	Up to 25 m	Medium	Unconfined	Dug well
37	8–14 m	Low	Unconfined	Dug well
38	4–14 m	Low	Unconfined	Dug well
39	23–33 m and below 43 m	Medium	Unconfined	Bore well
40	6–11 m; 25–55 m and below 55 m	Low	Confined	Bore well
41	Up to 08 m	Low	Confined	Dug well
42	10–18 m	High	Confined	Dug well
43	10–18 m	Medium	Unconfined	Dug well
44	6–8 m	Low	Unconfined	Dug well
45	Below 14 m	High	Unconfined	Dug well
46	Below 45 m	Medium	Unconfined	Bore well
47	4–6 m and 8–10 m	Medium	Unconfined	Dug well
48	18–25 m	Medium	Unconfined	Dug well

Table 3 continued

VES	Depth of favorable water bearing rock formation	Yield	Type of aquifer	Recommendation for exploration through wells
49	Below 4 m	High	Unconfined	Dug well
50	25–35; 45–65 m	Medium	Unconfined	Bore well
51	18–25 m and 45–65 m	Low	Confined	Bore well
52	Below 10 m	High	Unconfined	Dug well
53	6–25 m	High	Unconfined	Dug well
54	8–15 m	High	Confined	Dug well

Fig. 8 Representative sounding curves are interpreted as per Orellana and Mooney by Schlumberger methods from Sakri taluka
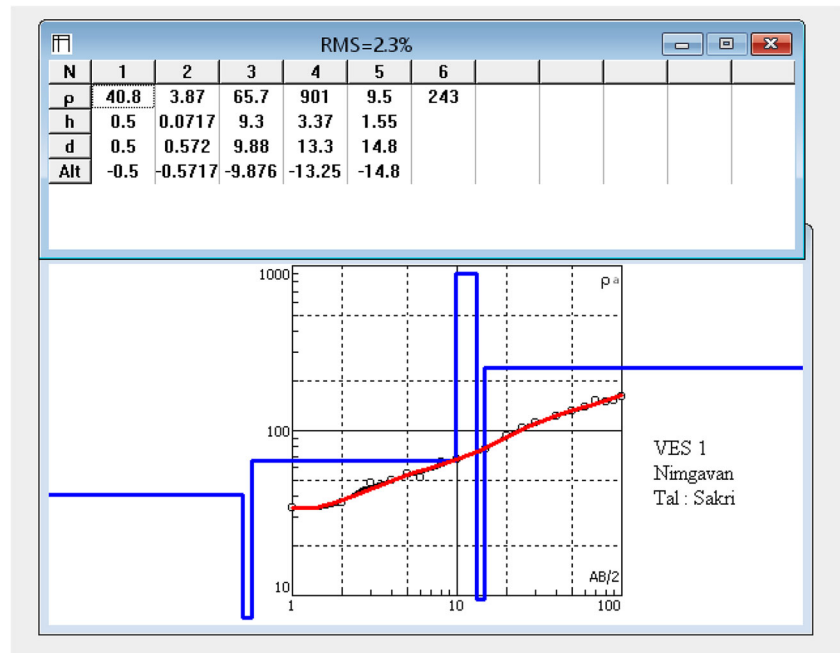
indicates the presence of weakly fractured basalts and hard compact basalt. However, at VES 17, ascending downward trend gradually increases from 18 to 30 Ω m suggesting highly weathered or fractured basalts, and again, resistivity decreases up to 10 Ω m. At VES 40, below soil layer, trend of resistivity increases up to 181 Ω m. This indicates the presence of weakly fractured basalts below 2 m. At VES 53, resistivity increases from 18 to <30 Ω m, becoming 1–10 Ω m and suggesting highly weathered/fractured jointed basalts. This indicates good aquifer zone between 1 and 5 m (shallow aquifer).

This suggests that the groundwater potential is more along the highly fractured rocks and in alluvium. The central part of the district can be considered to be potential zone for groundwater. This indicates that Sakri and Dhule taluka are prone to drought conditions in terms of availability of groundwater zone. The data corroborate with the observations of central groundwater board.

### Curves types (Schlumberger method)

The resistivity curve types A, Q, H, and K and combinations were obtained. These curves are interpreted using the curve matching technique using two and three layer master curves (Singh and Tripathi 2009). The different basic types of curves are Q type ($\rho 1 > \rho 2 > \rho 3$), H type ($\rho 1 > \rho 2 < \rho 3$), K type ($\rho 1 < \rho 2 > \rho 3$), and A type ($\rho 1 < \rho 2 < \rho 3$). A combination of the basic curves can be obtained if the model is obtained for more than three layers. Then, the combinations possible can be as HA type ($\rho 1 > \rho 2 < \rho 3 < \rho 4$), HK type ($\rho 1 > \rho 2 < \rho 3 > \rho 4$), AA type ($\rho 1 < \rho 2 < \rho 3 < \rho 4$), AK type ($\rho 1 < \rho 2 < \rho 3 > \rho 4$), KH type ($\rho 1 < \rho 2 > \rho 3 < \rho 4$), KQ type ($\rho 1 < \rho 2 > \rho 3 > \rho 4$), QH type ($\rho 1 > \rho 2 > \rho 3 < \rho 4$), and QQ type ($\rho 1 > \rho 2 > \rho 3 > \rho 4$).

In the study area, 5–6 layer model is obtained, and therefore, the curve types are identified accordingly in

Fig. 9 Representative sounding curves are interpreted as per Orellana and Mooney by Schlumberger methods from Sindhkheda taluka
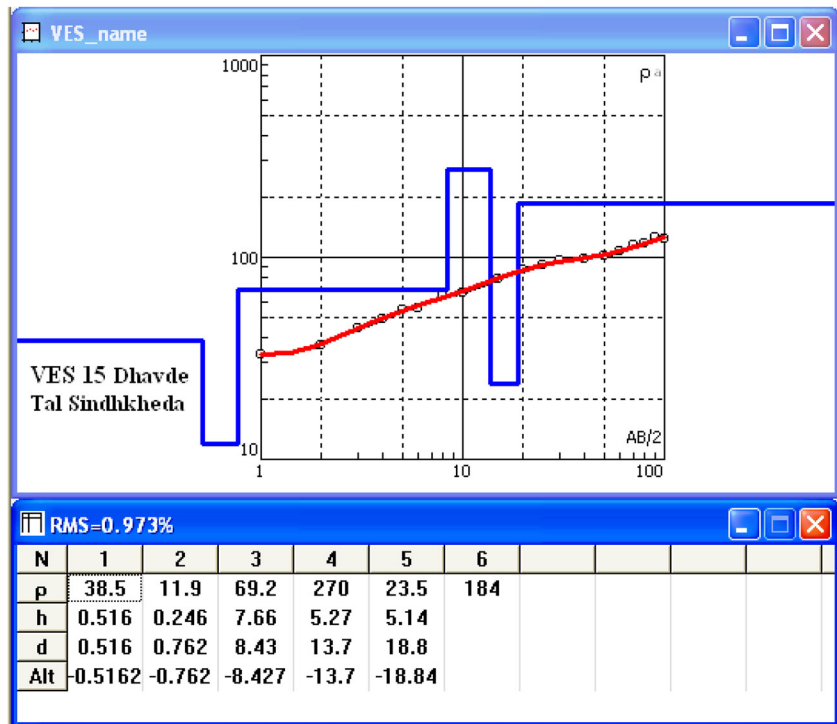
Fig. 10 Representative sounding curves are interpreted as per Orellana and Mooney by Schlumberger methods from Shirpur taluka
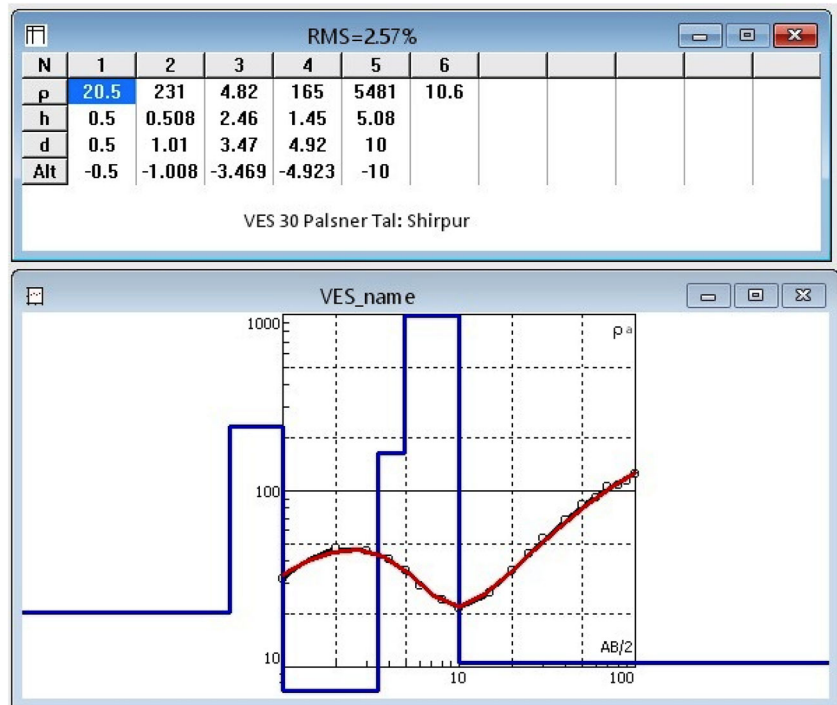

combinations with the basic types. The majority of the curve types observed in the area under study are as follows:

For Sakri taluka, the majority of curve types are HKH = AKH > KHA.

The Shindkheda taluka shows the majority of curve types are KHA > HAK > KHK;

In Shirpur taluka, the majority of curve types are KHA > KQH = KQH;

Fig. 11 Representative sounding curves are interpreted as per Orellana and Mooney by Schlumberger methods from Dhule taluka
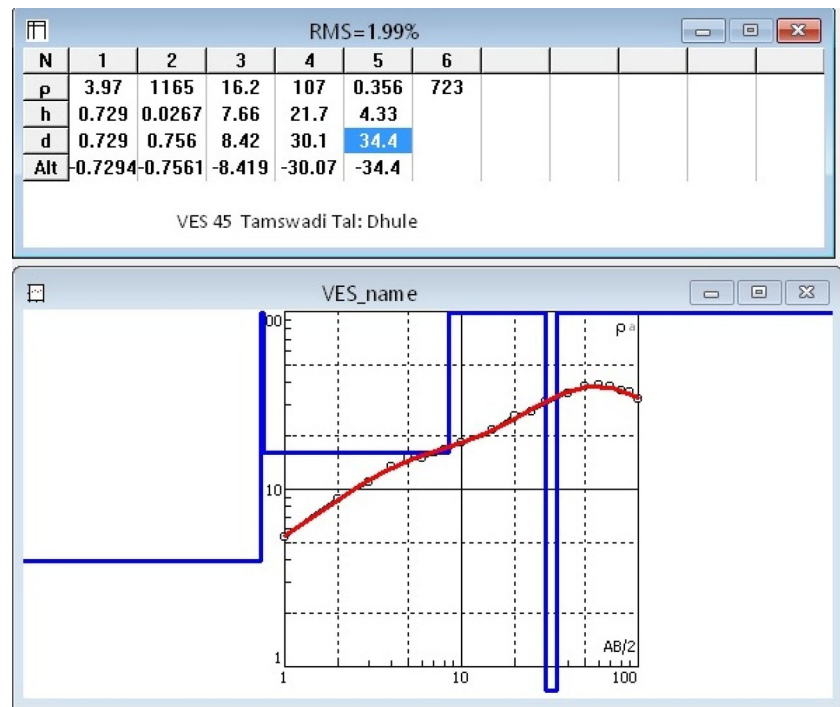
For Dhule taluka, the majority of curve types are HKH > KHK > HAK.

Talukawise lithological interpretations based on layers obtained as a result of Schlumberger method

Sakri taluka

First layer It is observed that resistivity range varies from 4.23 to 114 Ω m. The value more than 100 Ω m is observed in VES no. 9 which is weakly fractured to hard compact basalt. The values between 10 and 100 Ω m are observed in VES no. 1, 2, 3, 4, 5, 6, 7, 10, 11, 12, and 14 which shows the presence of highly weathered basalts. The values less than 10 Ω m are observed in VES no. 8 and 13 with weathered basalts or murum/black cotton soil. Thickness varies from 0.5 to 1.56 m.

Second layer The resistivity range varies from 3.87 to 665 Ω m. The value of resistance is more than 100 Ω m which was observed in VES no. 3, 5, 12, and 13 which is weakly fractured to hard compact basalts. The values between 10 and 100 Ω m are observed in VES no. 4, 7, 8, 9, 10, 11, and 14 which suggest highly weathered basalts. The resistance values less than 10 Ω m are observed in VES no. 1, 2, and 6 which indicate the presence of

weathered basalts or black cotton soil/murum. Thickness varies from 0.0717 to 11 m.

Third layer It varies from 10.9 to 3027 Ω m. The values more than 100 Ω m are observed in VES no. 1, 3, 4, 6, 7, 8, and 10. The layer is weakly fractured to hard compact basalts. The values between 10 and 100 Ω m are observed in VES no. 2, 5, 9, 11, 12, 13, and 14 which shows the presence of highly weathered basalts. Thickness varies from 0.0698 to 11.1 m.

Fourth layer The range varies between 0.498 and 2627 Ω m. The value more than 100 Ω m is observed in VES no. 2, 5, 12, 13, and 14 which is weakly fractured to hard compact basalts. The values between 10 and 100 Ω m are observed in VES no. 1, 3, 6,7, 8, 9, and 11 which are highly weathered basalts and less than 10 Ω m are observed in VES no. 4 and 10 which show weathered basalts or black cotton soil/murum. Thickness varies from 0.307 to 45.2 m.

Fifth layer The range varies between 8.66 and 1458 Ω m. The value more than 100 Ω m is observed in VES no. 1, 3, 4, 5, 6 7, 8, 9, and 12 which is weakly fractured to hard compact basalts. The values between 10 and 100 Ω m are observed in VES no. 13 and 14 which show that the presence of highly weathered basalts and values less than 10 Ω m are observed in VES no. 2 and 11 showing

Table 4 Resistivity values and thickness of different layers at all VES locations from Dhule district (Schlumberger method)

VES no.	p1	p2	p3	p4	p5	p6	h1	h2	h3	h4	h5	Type curve
1	40.8	3.87	65.7	901	9.5	243	0.5	0.0717	9.3	3.37	1.55	HAK
2	52.3	8.43	134	24	111	16.2	0.68	0.258	0.49	1.09	88.9	HKH
3	61.6	107	1048	86.3	10,401	–	0.935	2.16	4.57	45.2	–	AKH
4	29.7	28.5	3027	1.73	148	3.62	0.849	0.987	0.0698	0.307	97.4	HKH
5	25.5	220	18	196	413	1530	0.5	0.425	0.577	16.3	82.2	KHA
6	35.9	8.44	188	36.4	134	387	0.545	0.118	0.307	0.778	15.7	HKH
7	36.4	46.2	378	87	1458	95.8	0.5	3.79	0.0748	16.2	6.03	AKH
8	5.46	29.6	213	48.6	153	130	0.5	0.836	2.23	5.96	15.9	AKH
9	114	45.9	11.8	36.3	368	35.4	0.5	1.61	0.529	16.8	8.12	QHA
10	46.2	22.7	228	0.498	–	–	1.33	11	11.1	–	–	HK
11	43.2	26.2	69.9	28.7	8.66	222	0.553	0.624	0.707	8.6	7.45	HKQ
12	42.8	127	50.2	106	229	16.5	1.56	0.21	6.15	31.5	42.1	KHA
13	4.23	665	18.8	2627	21.3	1307	0.5	0.385	2.34	3.19	10.3	KHK
14	32.5	22.4	10.9	528	52.2	3155	0.5	2.33	2.09	0.571	55.4	QHK
15	38.5	11.9	69.2	270	23.5	184	0.516	0.246	7.66	5.27	5.14	HAK
16	52.8	4.05	134	725	13	101	0.968	0.639	0.399	2.54	2.29	HAK
17	28.7	30	28	30.9	148	46.6	o.882	2.25	2.54	29.5	22.3	KHA
18	23.7	3.53	76.3	10.5	71.4	5995	0.513	0.455	0.198	9.62	53	HKH
19	51.1	214	27.7	565	194	11	0.96	0.848	1.38	1.2	78.6	KHK
20	38.4	5.09	29.6	724	35.8	8.14	0.618	0.109	8.16	24	35.1	HAK
21	51.1	214	27.7	565	194	11	0.96	0.848	1.38	1.2	78.6	KHK
22	16.3	46.7	426	600	11.9	1.82	0.5	2.03	28	11.8	15	AAK
23	17.9	151	12	114	997	2.62	0.6	0.652	0.409	18.6	18.3	KHA
24	14	477	8.56	218	7186	26.4	0.5	0.252	0.978	19.3	3.01	KHA
25	23.2	56.8	15.7	66.6	11,156	9.55	1.25	8.427	4.05	11.3	1.22	KHA
26	18.4	10.3	32.6	86.9	412	3.17	0.501	0.14	2.08	23.9	12.1	HAA
27	2.9	172	0.347	8.47	133	1.1	0.5	0.396	0.0799	22.1	11.7	KQH
28	22.9	9.91	1.92	6.79	266	2.03	0.5	2.8	0.633	21.6	8.23	QHA
29	8.76	196	3.17	1077	11,317	44.1	0.5	0.326	1.62	7.09	72.5	KHA
30	20.5	231	4.82	165	5481	10.6	0.5	0.508	2.46	1.45	5.08	KHA
31	3.27	57.1	2.2	287	6648	249	0.503	678	2.19	4.62	74	KHA
32	23.1	9.43	1.74	6.85	281	2.03	0.5	2.98	0.618	20.9	7.42	QHA
33	4.83	71.9	2.09	180	7217	11.4	0.571	0.564	1.95	1.11	3.22	KHA
34	19.8	114	20.2	3.02	17.6	–	0.953	0.277	9.98	2.36	–	KQH
35	19.8	12.5	155	25.5	162	6.56	0.738	0.496	1.1	3.48	72	HKH
36	18.1	1.15	352	5.24	68,230	18.1	0.54	0.156	0.659	4.53	0.441	HKH
37	118	9.57	134	150	2572	2.99	0.521	0.157	6.36	0.402	7.8	HAA
38	144	108	2167	323	224	6.28	0.507	0.536	0.169	26.6	41	HKQ
39	64.1	2.98	1031	16.8	2143	200	0.5	0.106	0.34	3.05	2.51	HKH
40	27.5	522	28.7	181	932	–	0.645	0.848	0.407	98.1	–	KHA
41	35	3.62	124	248	41.7	2927	0.5	0.0686	14.3	9.84	22.3	HAK
42	5.86	19.6	10.4	1424	5.09	0.957	1.81	0.164	0.607	4.93	17.9	KHK
43	116	138	578	80.9	190	302	0.508	3.38	4.5	11.8	17	AKH
44	173	706	79	2040	8.54	723	2.02	0.944	2.08	9.61	6.93	KHK
45	3.97	1165	16.2	107	0.356	723	0.729	0.0267	7.66	21.7	4.33	KHK
46	12.4	78.1	16.2	63.4	2.79	723	0.729	0.0266	1.73	29.6	1.66	KHK
47	355	115	390	27.5	497	0.916	0.517	7.34	3.01	7.38	12.2	HKH
48	5.55	67.3	5.6	34	1103	0.916	1.08	0.7448	2.49	7.88	4.08	KHA

Table 4 continued

VES no.	p1	p2	p3	p4	p5	p6	h1	h2	h3	h4	h5	Type curve
49	15.5	0.755	5701	1455	5.55	0.916	0.5	0.249	0.368	3.25	61.9	HKQ
50	299	3.84	3719	42.9	190	0.916	0.706	0.19	0.177	3.3	95.6	HKH
51	243	1.87	6606	23.8	484	0.916	0.5	0.138	0.102	3.16	42.4	HKH
52	6.47	3.29	184	675	145	19.7	0.875	0.0635	3.94	0.392	94.7	HAK
53	7.5	0.582	29.1	151	177	19.7	0.875	0.0448	3.96	0.392	94.7	HAA
54	12.3	451	16.2	4859	88.8	12	0.875	0.0296	3.71	0.198	92.9	KHK

h thickness (meter); *p* resistivity (Ω m)
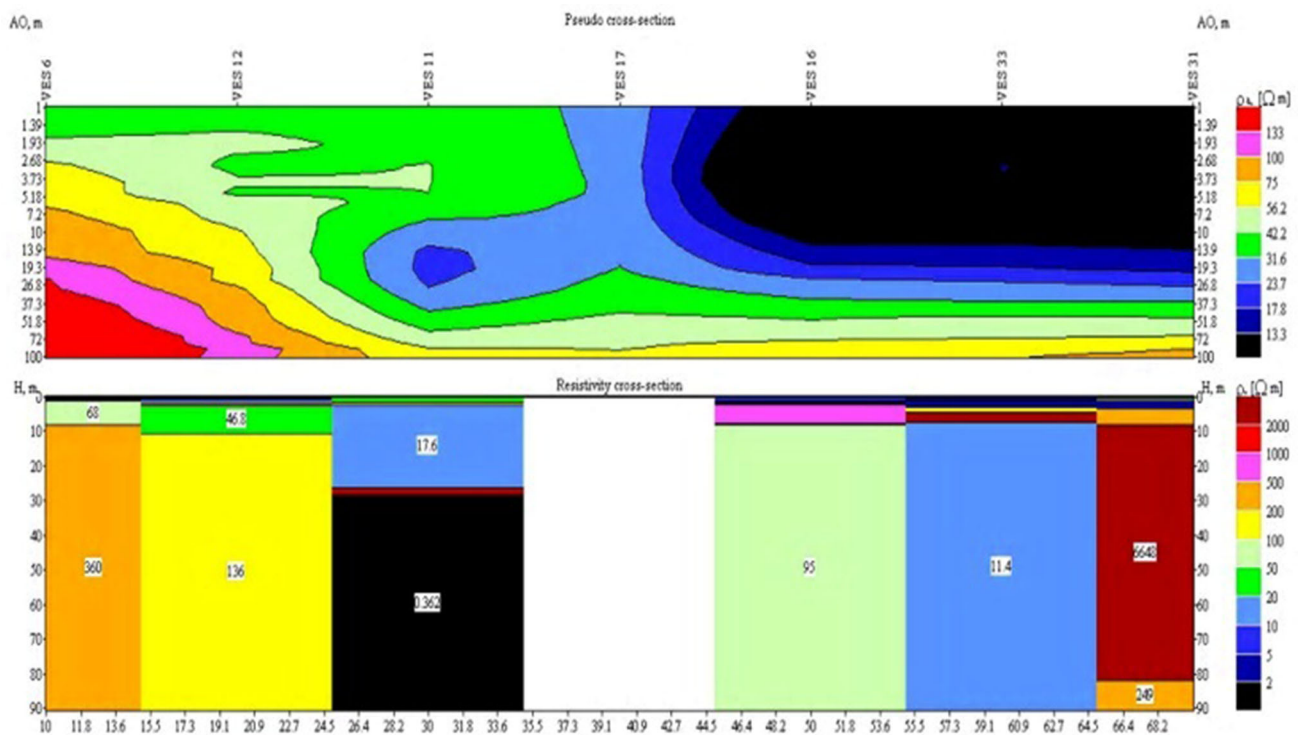
Fig. 12 Apparent and true resistivity geo-electric section along NE–SW from Dhule district

weathered basalts or black cotton soil/murum. Thickness varies from 1.55 to 97.4 m.

Shindkheda taluka

First layer The resistivity range varies from 14 to 52.8 Ω m. Value between 10 and 100 Ω m is observed in all VES of Shindkheda taluka which shows highly weathered basalts. Thickness varies from 0.5 to 1.25 m.

Second layer The resistivity range varies from 3.57 to 477 Ω m. The value more than 100 Ω m is observed in VES no. 19, 21, 23, and 24 which is weakly fractured to hard compact basalts. The values between 10 and 100 Ω m are observed in VES no. 15, 17, 22, 25, and 26 which show highly weathered basalts. The values less than 10 Ω m are observed in VES no. 16, 18, and 20 which show the presence of weathered basalts or black cotton soil/murum. Thickness varies from 0.109 to 8.427 m.
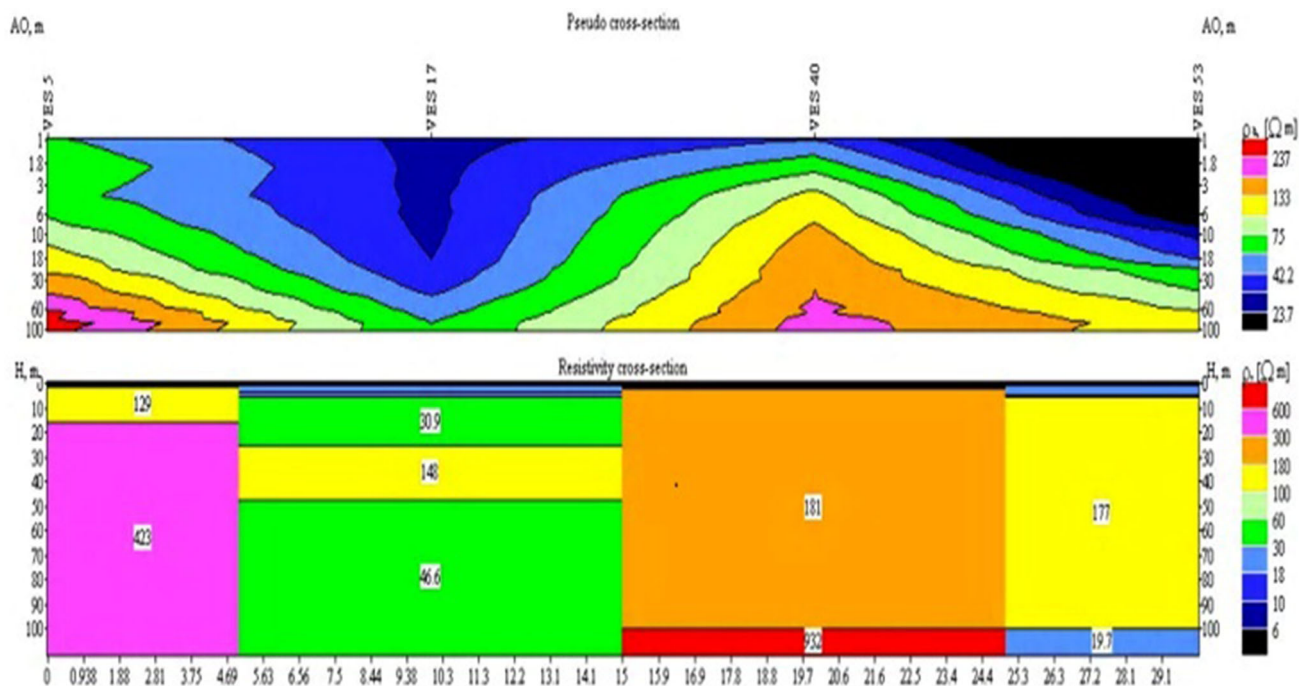
Fig. 13 Apparent and true resistivity geo-electric section along NW–SE from Dhule district

Third layer The resistivity range varies from 0.347 to 426 Ω m. More than 100 Ω m is observed in VES no. 16 and 22 which is found to be weakly fractured to hard compact basalts. The values between 10 and 100 Ω m are observed in VES no. 15, 17, 18, 19, 20 21, 23, 25, and 26 which show highly weathered basalts. The values less than 10 Ω m are observed in VES no. 24 of weathered basalts or black cotton soil/murum. Thickness varies from 0. 0799 to 28 m.

Fourth layer The resistivity range varies from 8.47 to 725 Ω m. More than 100 Ω m is observed in VES no. 15, 16, 19, 20, 21, 22, 23, and 24 showing weakly fractured to hard compact basalts. The values between 10 and 100 Ω m are observed in VES no. 17, 18, 25, and 26 which show highly weathered basalts. Thickness varies from 1.2 to 24 m.

Fifth layer The resistivity range varies from 13 to 11,156 Ω m. More than 100 Ω m is observed in VES no. 17, 19, 21, 23, 24, 25, and 26 which is weakly fractured to hard compact basalts. The values between 10 and 100 Ω m are observed in VES no. 15, 16, 18, 20, and 22 of highly weathered basalts. Thickness varies from 1.22 to 78.6 m.

Shirpur taluka

First layer The resistivity range varies from 2.9 to 23.1 Ω m. The values between 10 and 100 Ω m are observed in VES no. 28, 30, 32, and 34 which suggest cotton soil with calcified soil. The values less than 10 Ω m are observed in VES no. 27, 29, 31, and 33 which show black cotton soil with sand and occasional clays. Thickness varies from 0.5 to 0.953 m.

Second layer The resistivity range varies from 9.43 to 231 Ω m. Value more than 100 Ω m is observed in VES no. 27, 29, 30, and 34 of highly fractured basalts. The values between 10 and 100 Ω m are observed in VES no. 31 and 33 which show the presence of highly weathered basalts with murum. The values less than 10 Ω m are observed in VES no. 28 and 32 of black cotton soil with sand and clay. Thickness varies from 0.277 to 2.98 m.

Third layer The resistivity range varies from 0.347 to 20.2 Ω m. The values less than 10 Ω m are observed in all VES except VES 34 (20.2 Ω m) with black cotton soil and black cotton soil with sand. Thickness varies from 0.0799 to 9.98 m.

Fourth layer The resistivity range varies from 3.02 to 1077 Ω m. More than 100 Ω m is observed in VES no. 29, 30, 31, and 33 of weakly fractured to hard compact basalts. The values less than 10 Ω m are observed in VES no. 27, 28, 32, and 34 which show the presence of alluvium, sand, and clay. Thickness varies from 1.11 to 22.1 m.

Fifth layer The resistivity range for the fifth layer varies from 17.6 to 11,317 Ω m. Value more than 100 Ω m is observed in VES no. 27, 28, 29, 30, 31, and 32 showing weakly fractured to hard compact basalts. The values between 10 and 100 Ω m are observed in VES no. 34 of highly weathered basalts. Thickness varies from 3.22 to 72.5 m.

Dhule taluka

First layer It is observed that resistivity range for the first layer varies from 3.97 to 299 Ω m. The value more than 100 Ω m is observed in VES no. 37, 38, 43, 44, 47, 50, and 51 of weakly fractured to hard compact basalts. The values between 10 and 100 Ω m are observed in VES no. 35, 36, 39, 40, 41, 46, 49, and 54 with highly weathered basalts. The value less than 10 Ω m is observed in VES no. 42, 45, 48, 52, and 53 and it shows the presence of weathered basalts/murum. Thickness varies from 0.5 to 2.02 m.

Second layer The resistivity range varies from 0.582 to 1165 Ω m. More than 100 Ω m is observed in VES no. 38, 40, 43, 44, 45, 47, and 54 to be of weakly fractured to hard compact basalts. The values between 10 and 100 Ω m are observed in VES no. 35, 42, 46, and 48 which show highly weathered basalts. The values less than 10 Ω m are observed in VES no. 36, 37, 39, 41, 49, 50, 51, 52, and 53 with the presence of weathered basalts/murum. Thickness of this varies from 0.0296 to 7.34 m.

Third layer The resistivity range varies from 5.6 to 6606 Ω m. More than 100 Ω m is observed in VES no. 35, 36, 37, 38, 39, 41, 43, 47, 49, 50, 51, and 52 to be of weakly fractured to hard compact basalts. The values between 10 and 100 Ω m are observed in VES no. 40, 42, 44, 45, 46, 53, and 54 of highly weathered basalts. Less than 10 Ω m is observed in VES no. 48 of weathered basalts or murum. Thickness of this varies from 0.102 to 14.3 m.

Fourth layer The resistivity range varies from 5.24 to 4859 Ω m. Value more than 100 Ω m is observed in VES no. 37, 38, 40, 41, 42, 44, 45, 49, 52, 53, and 54 to be of weakly fractured to hard compact basalts. The values between 10 and 100 Ω m are observed in VES no. 35, 39, 43, 46, 47, 48, 50, and 51 which show highly weathered basalts. The values less than 10 Ω m are observed in VES

no. 36 of weathered basalts or murum. Thickness of this varies from 0.198 to 98.1 m.

Fifth layer The resistivity range varies from 0.356 to 68,230 Ω m. The value more than 100 Ω m is observed in VES no. 35, 36, 37, 38, 39, 40, 43, 47, 48, 50, 51, and 53 to be of weakly fractured to hard compact basalts. The values between 10 and 100 Ω m are observed in VES no. 41 and 54 which show highly weathered basalts. Variation in the values for different layers suggests the change in lithology in different talukas. The thickness also varies for each layer. Compared with the relief of the district, the variation in the lithologs supports the findings.

Conclusion

In Wenner configuration, it is observed that it is difficult to operate, since the depth to spread ratio is 1:3. Therefore, it is difficult or not possible to record values beyond the depth of 100 m. Since the method used is of inverse slope type, the resistivity of each layer can be calculated separately. This method when compared with the exposed well section matched with the resistivity. Therefore, it is easy to calculate and interpret manually without using the curve matching technique. This reduces the error. It is recommended to use the Wenner's inverse slope method for hard rock terrain.

In Schlumberger method, the observed value of *R* is used for calculation. The software has the option for the taking care of the errors for matching with the standard curves. In doing so, the original values of the layers may vary and the interpretation may differ depending upon the person handling it. The Schlumberger method is easy to operate, because it is less time consuming, and in short spread of current electrodes, spacing greater depth can be achieved. It is not an easy task to interpret the data by the curve matching technique as it is executed manually. Consideration of number of layers is difficult, because if more layers are demanded, then adjustment through the software during reduction in the number of curves will have an effect on the thickness of the first layer which will be automatically adjusted. Identifying different curves is also time consuming.

Both the Wenner and Schlumberger methods cannot be applied, where there is urban development as well as village community areas, because there is no space for lateral spread of the electrodes. Therefore, care should be taken while giving suitable sites. To use Schlumberger method in hard rock, terrain will still require more detailed survey. In both the cases, it is necessary to have dry surface for effective penetration of the current. If the ground is wet or enough, moisture is present in the ground and it is likely that the current will not penetrate the ground.

In all the above cases for both methods, the sites given for consideration as positive sites have been successful with respect to the strata obtained through the instrument and actual lithology observed at the site along with the amount of the water that was announced.

Some of the common problems faced during the electrical resistivity methods are loss of resolution, where saline and clarets' soil are present when using Wenner method for greater depth and to some extent lateral variations in electrical properties. Variable water quality may show variation, and limitations are seen for depth of investigation for Wenner method. The applications of resistivity techniques for VES methods of Wenner and Schlumberger are useful in determining bedrock depth. Thin layers are difficult to detect, because there is possibility of being average and merged with overlying or underlying layer.

Based on the interpretation of geo-electrical data, the following conclusions are drawn:

1. Vertical electrical sounding results give information about the subsurface strata as the resistivity obtained from different depths is indicative of the type of strata present.
2. Clay layer associated with alluvium may act as restriction. Vertical electrical sounding survey shows clay layers in Shirpur taluka, where groundwater occurs in alluvial aquifer.
3. The general litho log has a top layer of soil and black cotton soil followed by murum and weathered basalt, then a layer of highly jointed and fracture basalt with base of compact and or hard massive basalt.
4. Interpretation of the VES indicates the presence of an unconfined weathered zone aquifer, alluvial aquifer, and confined aquifer below the hard and massive basalt.
5. The unconfined aquifer is located at an average of 10.6–12.2 m in Sakri, in Dhule, it is 18.2–19.8 m, and in Shindkheda, it is 16.7–18.2 m.
6. The confined aquifer is observed to be at an average of 106.5–152.4 m except in Shirpur, where it is 61–76.2 m.
7. The Wenner and Schlumberger data suggest the similar type of layers present in the area with a little difference in the values of resistivity.

Based on the data from VES of Wenner and Schlumberger method, suggestions made are

1. Most part of the district (Sakri, Dhule, and parts of Shindkheda) is underlain by Deccan Trap basalt; therefore, only Dug wells are feasible structures.
2. Careful selection of sites for bore wells should be carried out with scientific investigation.

3. The overall stage of groundwater development is 53.55%; therefore, there is a scope for further development of groundwater particularly in Dhule, Sakri, and Shindkheda taluka. Care should be taken during planning for use of groundwater. This is important because of the fact that residing water level trends is observed periodically repeated every 8–12 years.
4. Since the stage of groundwater development has reached to a level of about 78% in Shirpur taluka; hence, future groundwater development is not feasible. Even if there is demand for more groundwater, then it is advised to take all possible measures, so that the stage does not go beyond 80%. This can be achieved by carrying out various artificial recharge methods. The same will be the case, where the groundwater is identified as semi-critical, critical, and over-exploited watersheds.
5. The structures recommended for artificial recharge in the hilly regions of Deccan Trap basalt in the central part can be contour bunds, gully plugs, nala bunds, and check dams. The dug wells can also be treated for artificial recharge with proper maintenance. For alluvial area, especially in Shirpur taluka, percolation tanks and recharge wells or shafts can be constructed.
6. Thus, the future groundwater conservation and recharge structures need to be prioritized. The fractured/weathered basement constituted the major aquifer in the area based on their thick over burden and relatively low resistivity values. The overburden thicknesses, respectively, could be a good area for groundwater exploration.

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