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https://doi.org/10.47884/jweam.v1i2pp01-15

Journal of Water Engg. and Management

ISSN 2582 6298
Volume-01
Number- 02

Jr. of Water Engg. and Mgt.
2020,1(2) : 01-15

Author's personal copy

Journal of Water Engg. and Management, 2020, 1(2) : 01-15
https://doi.org/10.47884/jweam.v1i2pp01-15

Research Paper

Electrical Resistivity Tomography for Mapping Groundwater Resources in Different Environ

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Received August 13, 2020, Revised on September 8, 2020, Accepted on September 10, 2020

ABSTRACT

A major share of water supply to meet the ever increasing demands for domestic, industrial and irrigation usages is derived from groundwater resources which are distributed over the entire globe. These resources are invisible from ground surface. The need for their delineation with high precision has led to the continuous advancement in the geophysical survey techniques and interpretation theory. Electrical resistivity tomography (ERT) is an outcome of such advancement in the conventional electrical resistivity methods used for exploration of this sub-surface natural resource on the basis of distinctive reduction in the electrical resistivity value of groundwater bearing geological formations/structure in comparison to their host environs devoid of water. Objective of this paper is to present an overview of the application of ERT in delineation of groundwater resources in complex geological setup of problematic areas, sources of geothermal water, and delineation of groundwater pockets in mining areas in order to prevent natural disasters such as landslide in open cast mines with the help of related case studies. This kind of knowledge about the occurrence of groundwater/geothermal resources is essential to achieve the preset objectives of their management.

Keyword - Groundwater, Electrical resistivity tomography, Mapping, Deccan Traps.

INTRODUCTION

Geophysical investigations of subsurface involve taking measurements at ground surface that are influenced by the internal distribution of physical properties such as resistivity, conductivity, density, magnetic susceptibility of the geological formations and structures under prevailing physical conditions. Analysis of these measurements can reveal how the physical properties of the Earth's interior vary vertically and laterally. There is a broad division of geophysical surveying methods into those that make use of natural fields of the Earth and those that require induction of artificially generated field into the ground. The natural field based methods utilize the gravitational, magnetic, electrical and electromagnetic fields of the Earth for searching local perturbations in these naturally occurring fields that may be caused by concealed geological features of economic or of other interest. Artificial source based methods involve the generation of local fields such as electrical or electromagnetic fields that may be used similar to natural fields for measuring physical properties of the subsurface geological formations/structures. Geophysical methods are named after physical properties which are being measured by them. For example the method used for measurement of density variation is named as gravity method, the method used for measurement of magnetic susceptibility is known as magnetic method, the method used for measuring seismic velocity is called seismic method, the method used for measuring conductivity is named as electromagnetic method, and the method used for measuring electrical resistivity is named as electrical resistivity method. The local variation in a measured parameter relative to some normal background value is known as a geophysical anomaly. The primary interest of the geophysical survey is to map the geometrical shape, size and depth of occurrence of the targets which are the sources of geophysical anomalies.

Dynamics of groundwater plays an important role in many geological processes such as evolution of groundwater resources, hydrothermal circulation between source of heat at deeper level to the ground surface, land slide in open cast mines, flash flood in underground mines, genesis of mineral deposits etc. This paper is aimed to describe the use of electrical resistivity tomography in study of some of the geological problems related to the groundwater movement and occurrence such as delineation of groundwater potential zone for exploration, geothermal reservoir for harnessing geothermal energy and groundwater pockets in mines essential to prevent landslides/ flash floods by reviewing related case studies. Though the analysis is confined to the case studies of regions under consideration but the solutions to address the associated problems are applicable to any of the problematic regions.

Electrical Resistivity Tomography (ERT)

Occurrence and movement of groundwater is controlled by primary porosity in sedimentary formations and by secondary porosity in hard rock terrains in the form weathered mantle, faults, fractures, joints etc. Therefore, there is always a need for locating the geological formations and structures favorable for groundwater occurrence to meet the ever increasing demand of water supply for domestic, irrigation and industrial usages. Electrical resistivity method is the most suitable method among all other geophysical methods for groundwater exploration in hard rock terrains because of good contrast between the electrical resistivity of water saturated geological formations and structures like weathered/fractured formations, faults, joints etc and their surrounding environ devoid of water. Geophysical electrical resistivity surveys with four electrodes array have been in use since more than five decades for aquifer mapping in different geological provinces all over the world. The greatest limitation of electrical survey with four electrodes arrays is that it provides only 1-D model of resistivity variation with depth below the center of the survey profile and does not provide any information about changes in the resistivity value on either sides of the center of the profile due to the presence of geological formations and structures such as faults, fractures, joint, etc. which may be groundwater resources. Therefore, mapping of groundwater bearing geological formations/structures by 1-D modeling is not always possible unless these formations/ structures coincidently lie below the center of the spread of the profile.

In hard rock terrains water bearing geological formations/structures are of small dimension and located sporadically. Therefore, a more accurate subsurface model would be the 2-D model where resistivity changes in the vertical as well as in the horizontal direction are being mapped. This problem is overcome by the development of 2-D electrical resistivity tomography (ERT) technique (also known as electrical resistivity imaging (ERI)) using multi electrode sub-surface imaging systems and effective data processing software based on the inversion techniques (Griffiths and Barker, 1993; Loke and Barker, 1996; Loke, 1997, 2000). Electrical resistivity tomography is now being used worldwide for delineation of groundwater resources for various purposes such as groundwater exploration to meet water supply demand, dewatering of mines to prevents land slide and flood flash in mines, extraction of geothermal energy etc. (Krisnamurthy et al., 2006; Hamzah et al., 2006; Anthony and John, 2010; Kumar et al., 2011, 2016; Ratnakumari et al., 2012; Rai et al., 2013, 2015, 2019a, 2019b; Gupta et al., 2016; Thiagarajan et al., 2018; Singh et al., 2019). The main advantages of geophysical electrical survey using multi-electrode ERT systems are: (1) fast computer controlled data acquisition for a single layout of multi- electrodes along the survey line; (2) simultaneous mapping of the geological formation in both vertical as well as lateral directions; and (3) increased resolution of the computed images of the sub-surface geological formations due to processing of large amount of acquired data.

Electrical Resistivity Tomography (ERT) is carried out using multi-electrode resistivity imaging systems and laptop. Multi-core cables with many electrode takeouts are connected together to form a multi-electrode set-up where selection of any four (two for current injection and two for potential measurement) of those electrodes is possible. The number of electrodes differs from system to system. Some systems carry 64 electrodes, some carry 72 electrodes and so on. Spacing between two electrodes remains the same. It is mostly 5 m or 10 m. Figure 1 shows the field layout of an ERT system with four multi-core cables, each fitted with 16 electrodes placed at an equal distance of 10 m. Selection of spacing between electrodes can be made based on the nature of survey. For subsurface images of high resolution, smaller spacing is used.

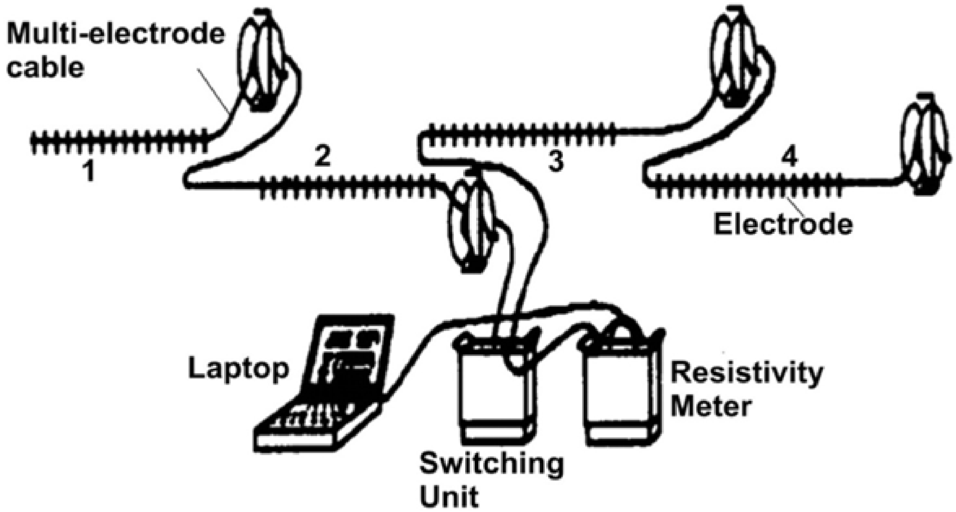

Fig. 1. Field layout of ERT units with 4 multi-core cables.

Multi-core cables are connected to an electronic switching unit that is connected to a laptop computer and a resistivity meter. Provision is made to conduct ERT using different arrays such as Wenner, Schlumberger, Wenner-Schlumberger, Dipole-dipole, etc. Information regarding the sequence of measurements, type of array to be used and other survey parameters such as the intensity of current are entered in a text file which can be read through a computer program loaded in the laptop. After reading the control file, the computer program automatically selects the appropriate electrodes (two current electrodes and two potential electrodes) for each measurement. Details about ERT survey using different electrode arrays is presented in Loke (2000) and Rai (2017).

The ABEM made Terrameter with 64 electrodes is used for ERT survey in the areas of case studies under investigation. The measurements of resistivity are taken automatically for Wenner configuration and the calculated apparent resistivity values from the ratio of induced current and corresponding potential difference between two potential electrodes are stored in the laptop. The apparent resistivity value for Wenner configuration is calculated by using the expression $\rho_a = k\,(\Delta V/I)$ in which ρ_a is apparent resistivity, k is geometric factor, I is the current induced into ground and ΔV is the corresponding potential difference. The expression of geometric factor is different for different electrode configurations (Loke, 2000). Geometric factor for Wenner electrode configuration is given by $k=2\pi a$ in which a is the spacing between two consecutive electrodes. The next step is to convert the measured apparent resistivity values in to a 2D true resistivity model which provides distribution of each litho units which falls below the profile in terms of their true resistivity values. This task is accomplished by using inverse modeling. Inverse modeling of the measured apparent resistivity data is carried out using RES2DINV program (Loke, 1997). The final output is a 2D inverse resistivity model in the form of 2D distribution of true resistivity values and thicknesses of respective geological formations. The model also presents root mean square (RMS) error value. The inverse resistivity model is interpreted in terms of geological formations by correlating resistivity values with the corresponding geological formations as given in Table 1. It helps in identifications of groundwater potential zones and suitable sites for managing aquifer recharge.

Table 1: Resistivity values of different geological formations (CGWB website)

Geological formations	Resistivity values (Ohm-m)
Alluvial, black cotton soil	< 20
Weathered/fractured/vesicular basalt saturated with water	20-45
Moderately weathered /fractured/vesicular basalt with water	40-70
Massive basalt	>70
Highly weathered granite saturated with water	20-50
Semi weathered granite	50-120
Moderately fractured/jointed granite	120-200
Massive granite	>200

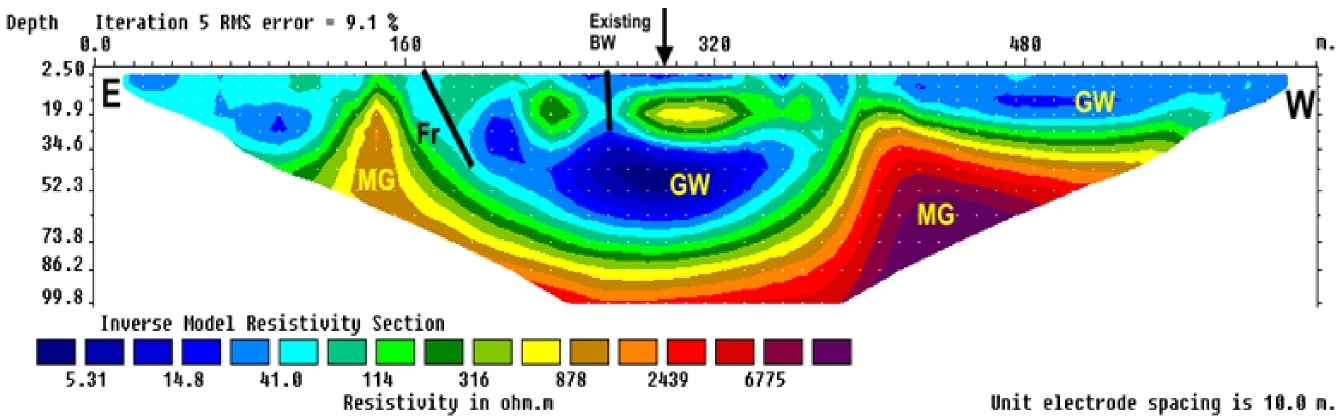

Fig. 2. 2D resistivity model along a profile located in CSIR-CCMB colony; GW- aquifer, MG-massive granite, Fr-fracture zone (Rai and Thiagarajan, 2019b)

RESULTS AND DISCUSSION

Case-1: Delineation of groundwater potential zones in granitic terrain

This case study deals with the ERT survey conducted in granitic terrain falling within residential colony of the CSIR-Centre for Cellular and Microbiology (CCMB) at Hyderabad. At the investigation site red soil of varying thicknesses forms top layer. This layer is underlain by weathered granitic formation of considerable thickness followed by massive granite units which may or may not be fractured/ faulted. In granitic terrain, the groundwater is confined mainly to the weathered and semi-weathered layers at shallower depths and in fractures and joints in massive rock units. Issues related to this case study are two folds: to map the aquifer which is the source of water supply and to find out the ways and means to increase the yield of bore well. To get satisfactory answers to these issues ERT survey was conducted.

Length of the profile is 630 m with. The profile is in east-west direction with center located at 78.5520^{0} E, 17.4199^{o} N. Spacing between two electrodes is 10 m. The 2D resistivity model obtained from the modeling of measured apparent resistivity data is presented in Fig. 2. On top of the resistivity model, small vertical lines indicate the positions of electrodes. The colored index of resistivity values is presented below the model. The resistivity model indicates the presence of a bowl shape unit of massive granite (>300 Ohm m) with two elevated arms below 150 m and 400 m distances, respectively. Within this bowled structure ~15 to 20 m thick two units of semi-weathered granite layer (50-120 ohm m) can be seen between 170-400 m below a thin soil cover (<20 Ohm m). Both the units are separated by a fracture zone located at 250 m. The model indicates another fracture zone near 160 m distance. Fracture zones are marked by *Fr*. The semi-weathered granitic layer is underlain by water saturated weathered to semi-weathered formation (20-120 Ohm m) which is extended to a maximum depth of 80 m in the centre of the bowl structure. It's thickness decreases with the distance away from the centre of the profile towards both elevated arms of the massive granite. This water saturated aquifer is the main source of water supply to the CCMB colony using a bore well whose location is shown in the model. The resistivity model also shows the presence of a low resistivity zone (<20 ohm m) within weathered formations. This indicates the leaching of the clay minerals from the host granite. This is a common feature in the granitic terrain due to alteration of alkali feldspar which is chief constituent of clay. This drastically lowers the resistivity values. This is the answer to the first posed problem related to the mapping of the aquifer system. The entire area in front of CCMB colony is a low lying area and is bounded by a bund from the lake side. This area receives run off from the CCMB colony situated on elevated ground surface and serves as a recharge pit. Recharging of the aquifer is through the both fracture zones. Answer to the second problem related to maintaining the initial yield of the bore well is described at the end of this section by taking in to consideration of remaining case studies.

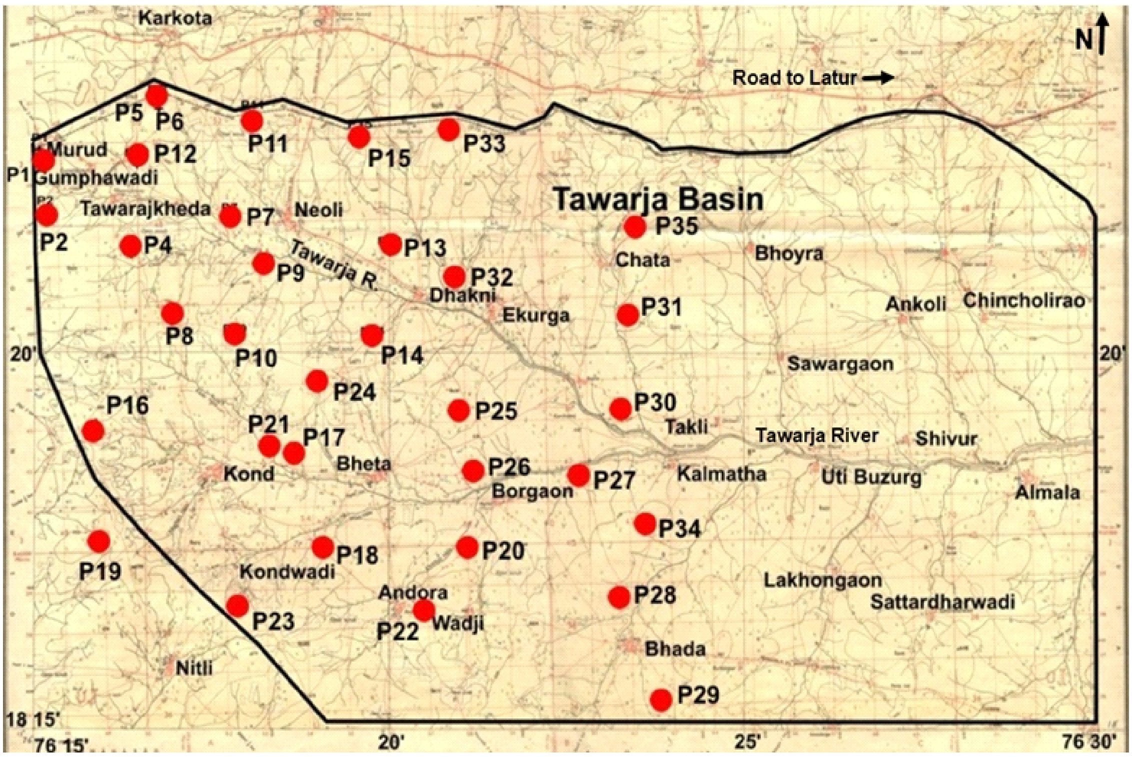

Fig. 3. Map of Tawarja basin with ERT sites marked as Pn (n =1 to 35) (modified after Rai et al., 2015)

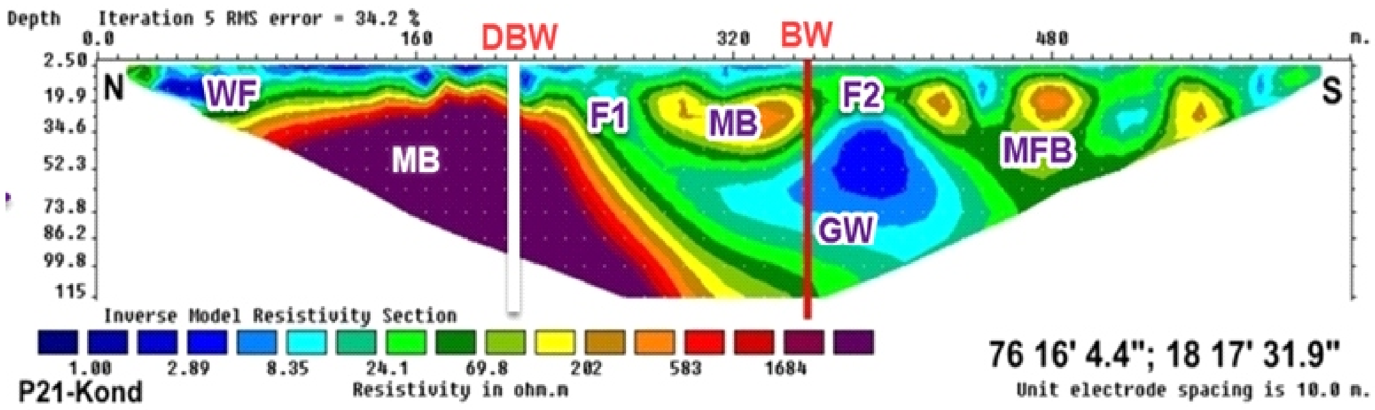

Fig. 4. 2D Resistivity model at P21 site near Kond village located within Tawarja basin; MB-massive basalt, MFB-moderately fractured basalt, GW-Groundwater zone, WF-weathered formation, DBW-dry bore well, BW-water yielding bore well, F1 and F2-fracture zone (modified after Rai et al., 2015).

Case 2: Delineation of ground water resources in basaltic Deccan volcanic province

The Deccan volcanic province (DVP) occupies half a million km^2 area spread over in parts of Gujarat, Madhya Pradesh, Telangana, Karnataka, and Maharashtra. More than 80% of the total surface area of Maharashtra extending from Mumbai in west to Nagpur in the east is covered by Deccan traps. Scarcity of groundwater availability to supply for drinking and irrigation in the region of DVP is well known. Especially Marthwada and Vidarbha regions of Maharashtra are infamous for acute shortage of water supply. Unlike other hard rock terrains, Deccan traps are compilation of several layers of lava flows alternately separated by sedimentary formations. These sedimentary formations are known as intertrappeans and are the markers of the interval time of eruption of lava flows. Each lava flows consists of two units. The top unit is vesicular basalt which is followed by massive basalt unit at the bottom. Vesicular basalt unit together with overlying sedimentary intertrappean forms good aquifers at middle and deeper levels in the region of Deccan traps. Top weathered mantle together with highly fractured basaltic layer forms unconfined aquifers at shallower depths which is the main sources of water supply in dug wells.

The ERT site for this case study is located near Kond village falling within the Deccan trap covered Tawarja basin in Latur district of Marathwada region. Northern boundary of the basin coincides with railway track which passes through Murad railway station located on the north-western corner of the basin.The origin of Tawarja river is near the Murad railway station as shown in Fig. 3. The ERT survey is conducted at 35 sites which are marked as Pn (n=1to 35) in Fig 2. The ERT site for this case study is marked as P21. At this site two bore wells are drilled. Spacing between both the bore wells is about 140m. One bore well is totally dry while yield of the other bore well is very good and is used for irrigation. In order to understand the difference in hydrogeological environ at sites of both bore wells, ERT survey was conducted along a 630 m long profile which passes through the locations of both the bore wells. The centre of the profile is at 76^0 $16'4.4''$ E longitude and $18^0 17'31.9''$ N latitude. The 2D resistivity model along the profile running in north-south direction is presented in Fig. 4. Location of the water yielding bore well is marked by the vertical red line at 360 m distance while the dry bore well is located at 210 m distance. Distance is measured from north to south. The interpretation of the resistivity model shows the presence of a thin layer of black cotton soil (<10 Ohm m) on top. This is followed by another thin layer of weathered formation up to 230 m distance. Up to this distance the weathered formation is underlain by massive basalt unit beyond the 115 m depth which is the maximum depth of investigation.

Beyond 230 m, the massive basalt unit is dipping down ward below the weathered formation (< 40 Ohm-m). The surface projection of this weathered zone is between 230 m to 400 m. Beyond 400 m distance this weathered zone is dipping downward below moderately weathered formation (~70 Ohm m) and appears to be extending beyond 115 depth between 320 m to 450 m. This weathered formation is saturated with water which is being confirmed by the yield of the bore well positioned at 320 m by 360 m distance. This water saturated weathered zone is overlain by a oval shape small unit of massive basalt between 270 m to 360 m and is connected to the ground surface through two fracture zones which are exposed between 240 m to 270 m and between 350m to 400 m. These two fracture zones facilitate vertical recharging of the weathered formation. A small patch of the clayey formation (<10 Ohm-m) can be also seen within the water saturated weathered formation. This water saturated weathered zone is expected to be extended in the orthogonal direction to this profile. At the location of dry bore well presence of massive basalt unit can be seen below a thin composite layer of black cotton 'and weathered formation'. Several thousands of dry bore wells have been drilled at such site in the absence of any information about the presence of groundwater resources. This leads to huge economic loss to the farmers. This kind of loss can be avoided by suggesting suitable site for bore well drilling on the basis of scientific investigation using ERT survey alone as well as sites suitable for managing aquifer recharge which is needed for increasing groundwater storage.

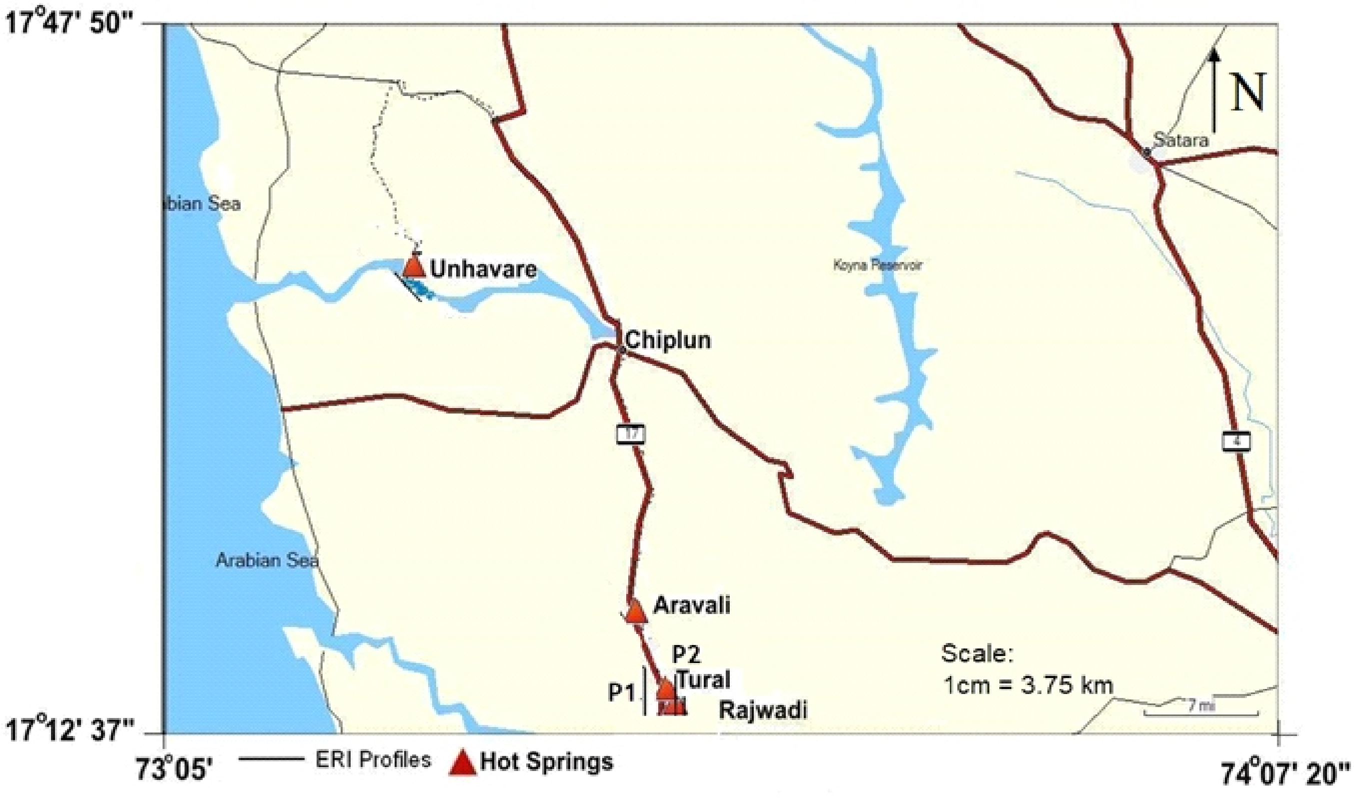

Fig. 5. Location map of hot springs in Deccan trap region of Chiplun Taluk (modified after Kumar et al., 2011)

Case-3: Delineation of source of geothermal water

Geothermal energy is one of the cleaner sources of energy. More than 20 countries generate electricity from geothermal resources and about 60 countries make direct use of geothermal energy (Gupta and Roy, 2007). Western margin of Deccan traps is characterized with the presence of many hot springs which extends for a distance of about 300 km from Koknere (north of Mumbai) in the north to Rajapur in the south and occupies the central part of the Thane, Raigad and

Ratnagiri districts of Maharashtra (Pitale et al., 1986). This geothermal belt is comprised of about 1000 m thick sequence of near horizontal lava flow overlying Precambrian sedimentary and meta-sedimentary (Kaladgi and Dharwar) rocks and Archaean igneous complex. Kumar et al. (2011) have conducted electrical resistivity tomography at four hot spring sites located at Unhavare (Khed), Tural, Rajwadi and Aravali villages of Chiplun taluk in Ratnagiri district of Maharashtra for delineation of the geothermal reservoirs. Surface temperatures measured at Unhavre, Tural, Rajwadi and Aravali hot springs are 69°C, 62°C, 48-51°C and 44°C, respectively. Conventional geothermometry indicates that the reservoir-temperature for hot springs belt would be around 120°C±10°C. It suggests that, there is interplay of reservoir water with shallow ground water and surface water which brings down temperature of reservoir water by the time of its emergence from hot springs. The resistivity contrast for the geothermal reservoir rock and the surrounding host rock is significantly high in volcanic terrains which is the case of present study. In such cases the resistivity associated with geothermal reservoirs usually varies from <5 to 15 Ohm-m regardless of how high resistivity is outside the reservoir zone.

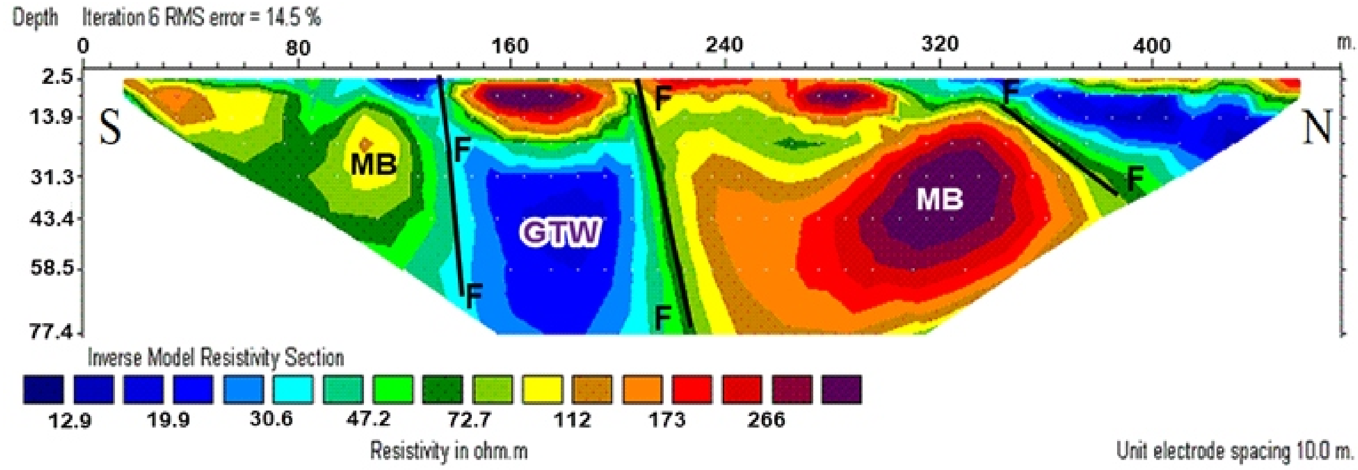

Fig. 6. 2D resistivity model along P1 profile of Tural hot spring (modified after Kumar et al., 2011)

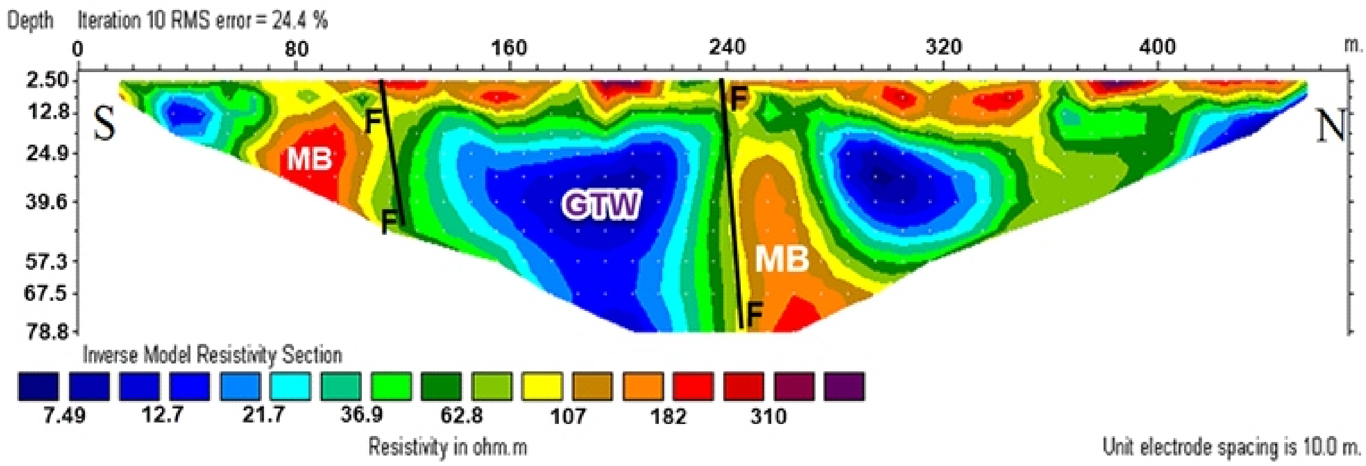

Fig. 7. 2D resistivity model along P2 profile of Tural hot spring; MB-massive basalt, GTW- Geothermal water zone, FF-fault plane (modified after Kumar et al., 2011).

In this case study two 2D resistivity models obtained from ERT survey carried out along two profiles on both sides of Tural hot spring are considered to demonstrate the application of ERT in delineation of source of geothermal water with the purpose of harnessing geothermal energy and for irrigation and industrial usages. Both profiles are running parallel in south to north direction. Profile P1 is located on the western side of the hot spring with centre at 17°15'0.9" N latitude and 73°33'18.1" E longitude while the other profile P2 with centre at 17°15'0.7"N latitude and 73°33'12.4" E longitude is located on the eastern side of the hot spring. Spacing between both the profiles is 150 m. Resistivity models for the profiles P1 and P2 are shown in Figs. 5 and 6, respectively. The resistivity model of Fig. 5 shows the presence of a fault plane at 210 m almost in E-W direction. This fault plane is separating highly conducting zone (<20 Ohm-m) from a highly resistive zone (>140 Ohm-m) with a sharp resistivity contrast of <40 Ohm-m. This zone of geothermal water towards its southern boundary seems to be separated from another massive basalt unit (>70 Ohm-m) by other fault plane whose surface exposure is at 130 m. This fault appears to be the site from where geothermal water is ejecting on the ground surface. This zone is at a depth of ~25 m and is trending vertically downward beyond 77 m depth which is the maximum depth of investigation for the present profile. It suggests that this zone of geothermal water is connected to a deeper heat source which is energizing this zone of geothermal water which is the cause of lowering of its resistivity value to the extent of <13 Ohm m in its central part. This zone of geothermal water is overlain by a massive basalt unit (112-266 Ohm-m) which is visible from 150 m to 310m. Surface exposure of another reservoir of geothermal water with value <13 Ohm-m resistivity is between 320m to 360 m. This zone of geothermal water is separated from the massive basalt unit by another fault dipping towards NEE-SWW direction. Presence of sharp resistivity contrast of ~30-40 Ohm-m between massive basalt and water reservoir body can be seen across this fault plane.

The resistivity model of figure 6 along the profile P2 on east of the hot spring shows a zone of geothermal water with low resistivity (~8-20 Ohm-m) at a depth of ~25 m between 110 m and 240 m. This zone is extending downward beyond 78 m depth. It suggests that the source of this geothermal water zone is extending towards deeper level similar to that visible in the resistivity model of profile P1. This zone of geothermal water is separated from massive basalt (> 70 Ohm-m) by a fault on its northern boundary whose surface projection is at 240 m. This zone of geothermal water is also separated from another high resistivity zone of massive basalt by a fault plane on its southern boundary whose surface projection is at 110 m. A comparison between resistivity models of P1 and P2 profiles suggests that the fault with the surface projection at ~210 m on the profile P1 appear to be the eastward extension of the fault having surface projection at ~240 m on the profile P2. Similarly, the fault with the surface projection at 130 m on profile P1appears to be the eastward extension of fault having surface projection at 110 m on the profile P2. In other words the geothermal water zone bounded by almost two vertical faults appearing on P1 profile is the extension of the geothermal water zone appearing on profile P2 between two almost vertical faults. This zone of geothermal water is suitable for exploration to harness geothermal energy. It is worth to mention here that after harnessing geothermal energy, the temperature of geothermal water is reduced to level of temperature of normal groundwater. This water can be available to meet the demand of water supply for irrigation and industrial uses.

Case-4: Delineation of groundwater bearing formation in mining areas

Land slide in an opencast mine obstruct not only mining operation but also incurs heavy economic losses as a cost of the removal of debris to facilitate further mining work. The cause of land slide is mainly due to occurrence and movement of groundwater. Solution to this problem lies in the delineation of water bearing geological formation/structures for dewatering to keep them in almost dry state. Tadkeshwar lignite mine, located in Surat district of Gujarat state, India is one such mine which is facing recurrence of land slide problem because of movement of groundwater in a segment of the mine. The total mine lease area is about 965 hectare area spread over between 73.06° to73.08° E longitude and

21.345° to 21.385° N latitude. The mine is located in south-west of Tadkeshwar village. The Kim river flows in north and Tapi river flows south of the mine lease area. Kakadapar right bank canal runs along the south-eastern, southern and western boundaries and Ukai right bank canal runs along a part of western boundary of the mine lease area as shown in figure 7.Because of dumping of excavated over burden over the drains, there is no escape route for runoff of the rain water outside the mining area. Therefore most of the rain falling within mine lease area is percolated downward to recharge the aquifer system. The mine lease area exhibits geological formations ranging in age from lower Tertiary to Quaternary. It is mostly covered by Quaternary alluvium. Scattered exposures of laterite can be seen on the ground surface. Lignite seams are occurring as inter bedded deposits within Tertiary formations. The core logging data indicates that the surface alluvium is found up to a maximum depth of 12 m which is followed by alternate beds of sand, clay, sandy clay, limestone and conglomerate belonging to Tertiary period. Lignite seams are occurring in a depth range of 30 to 110 m. Thickness of impervious clay beds ranges from 1 to 30 m occurring at different depths. Thickness of pervious layers of sand and conglomerate range from 1 to 3 meter occurring in between the clay beds (GMDC, 2010).

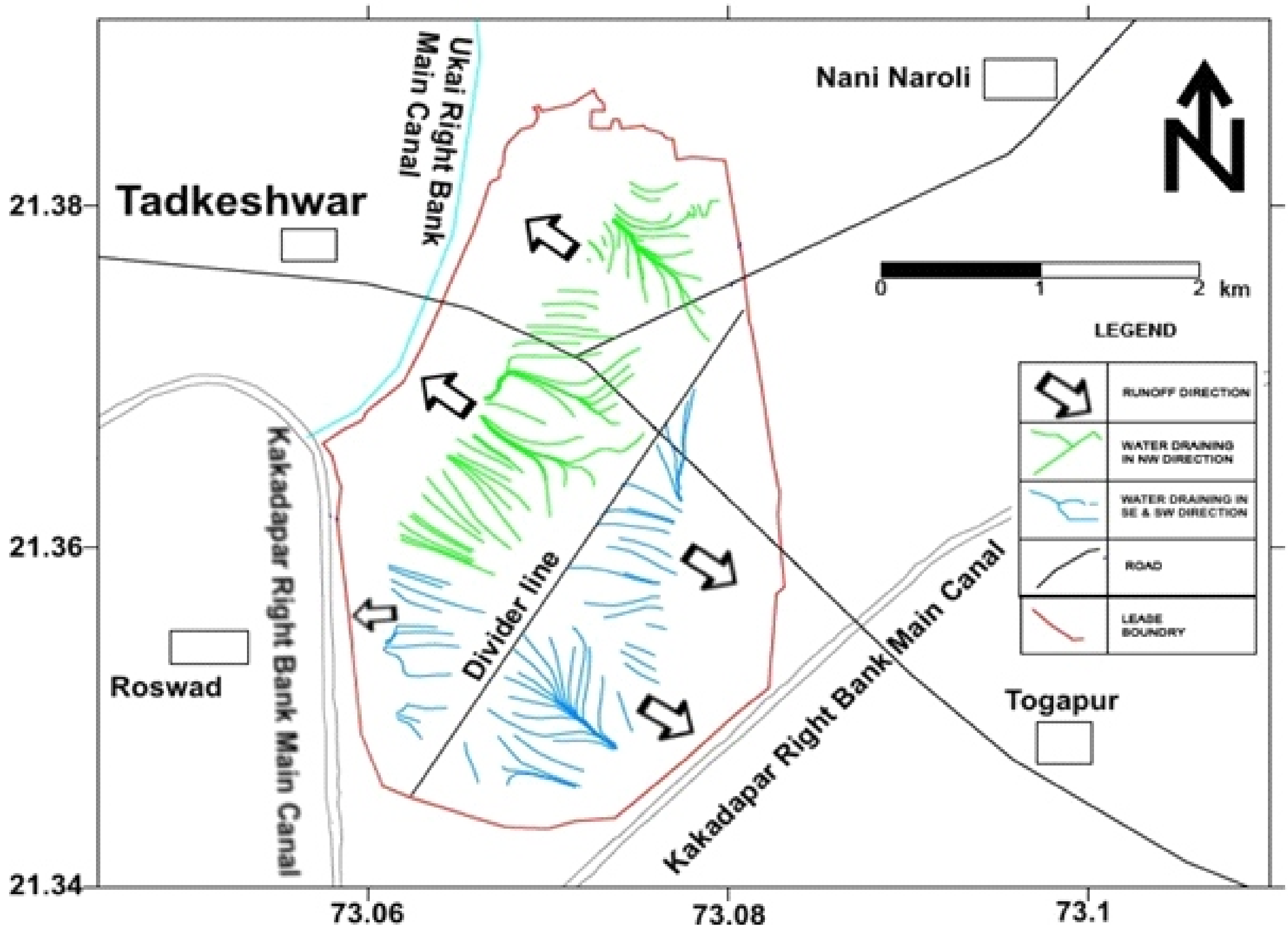

Fig. 8. Map of the Tadkeshwar lignite mine area (GMDC, 2010)

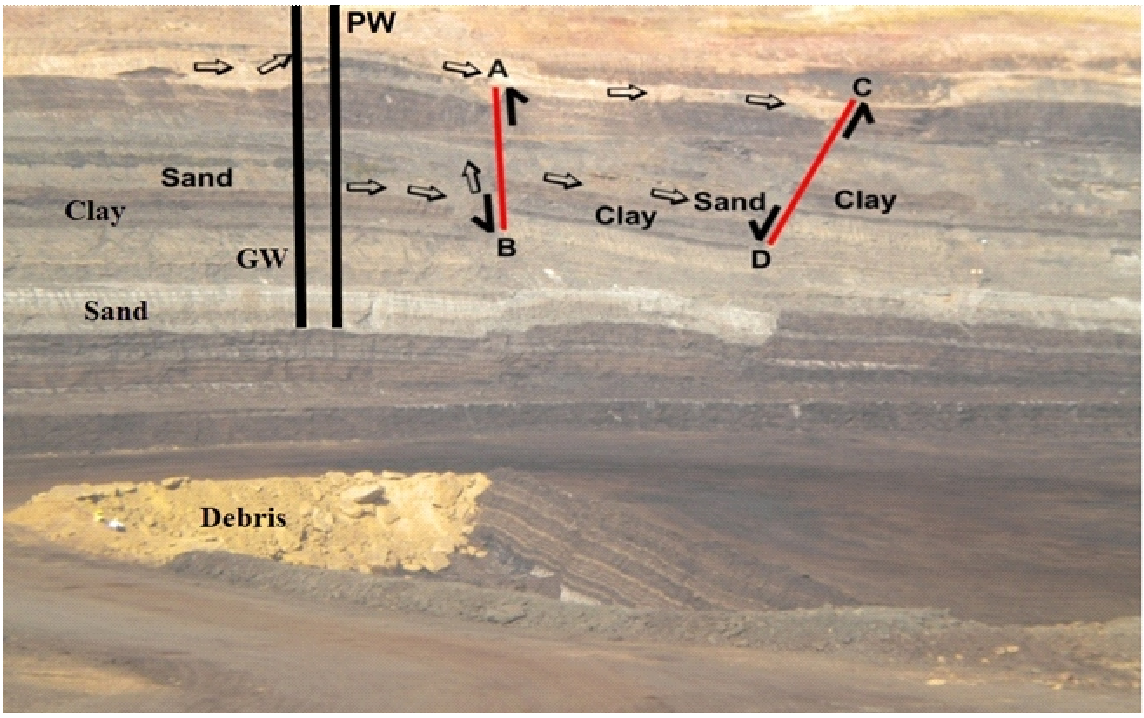

Fig. 9. A vertical cross section of geological set up with faults in the zone of land slide; AB, CD- fault planes, GW- Groundwater zone, PW-proposed well for dewatering mine, Arrow indicates direction of groundwater movement (Rai et al., 2019a).

Figure 9 presents a vertical cross section of the stratigraphy in a portion of mine which is being affected by land slide. An alternate sequence of sand, clay, clayey sand and clay beds gently dipping northward below soil cover can be seen in the figure. Sandy formations facilitate the movement of groundwater towards dip direction. Continuous extension of these water bearing sandy beds is being disrupted due to presence of two faults marked by *AB* and *CD* in the figure. Water bearing sand /clayey sandy beds on one side of AB fault plane abuts the clay beds positioned on other side of the fault plane. At this location of fault, the groundwater flow in horizontal direction is obstructed due to presence of clay beds facing the sandy formation on other side of the fault. As a result groundwater flows upward along the fault plane up to the upper edge of the fault denoted by *A*. Thereafter ground water enters into the zone lying between both the faults through another sand layer overlying *AB* fault plane. The same situation also prevails on either side of the *CD* fault plane. Because of low permeability of clay beds, accumulation of groundwater takes place in the vicinity of fault planes. As a result, geological formations in this part of mines remain always wet and get softened. Under the weight of overburden, wet geological formations bulged out which resulted in land slide. It is speculated that these faults are further extended west ward, where mining will be taken up in near future. The most suitable way to prevent land slide is to keep the sub-surface geological formations nearby both faults almost in a dry state.

Electrical Resistivity Tomography is conducted at 16 locations to delineate water bearing geological formations/structures in that portion of the mine lease area where mining is planned in future (Rai et al., 2019a). For this case study a resistivity model along a profile nearest to the site of land slide on its eastern side is considered and the same is presented in Fig 9. This profile with the center at 73^0 4' 10.4" E longitude and N 21^0 21' 10.7" N latitude is in north-south direction. This profile passes nearby a bore well drilled by GMDC to confirm the presence of lignite before the start of mining. Location of this bore well is marked as BH in the resistivity model.

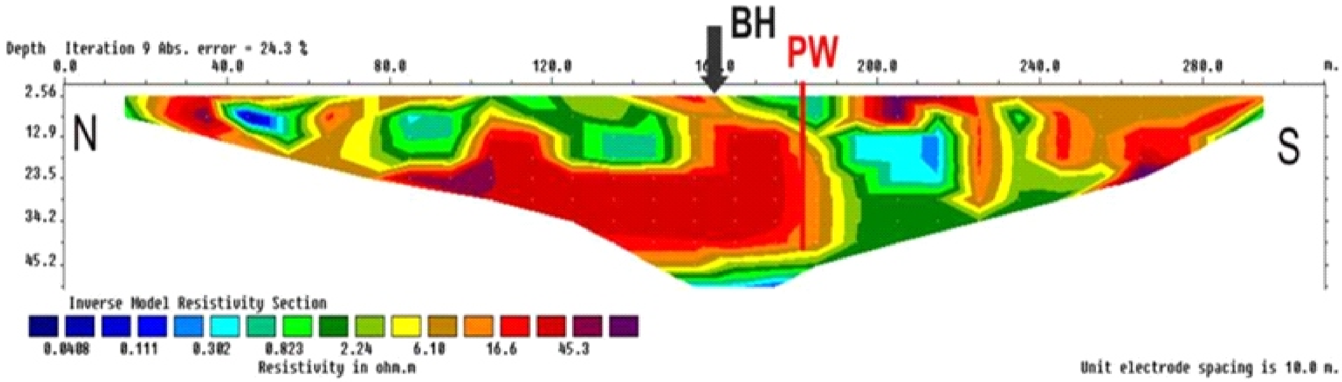

Fig. 10. Resistivity model characterizing different geological formations (Rai et al., 2019a)

Table 2. Resistivity values of geological formations of Tadkeshwar lignite mine (GMDC, 2010).

Geological formation	Resistivity values (in Ohm-m)
Top soil	10-20
Water saturated clay	< 10
Water saturated clayey sand	10-30
Water saturated sand	20-40
Limestone	21-40
Laterite (dry)	>70

The geological interpretation of the resistivity model is based on the assigned resistivity values for the corresponding geological formations as given in Table 2. Resistivity model shows the presence of soil cover (< 10 Ohm m) between 40 m to 140 m and 160 m to190 m. This soil cover is underlain by sand (20-50 Ohm m) which is exposed to ground surface at three locations, namely between 20 m to 40m, between 140 m to 160 m and 190 m to southern end of the profile . These zones of exposed sandy formation appear to be the recharge sites. Beyond 190 m, the sand bed is underlain by clayey formation. The pseudo section of land slide region presented in figure 8 also shows the presence of alternate beds of water bearing sand and clay formations below the soil cover. This sequence of geological formation is almost in agreement with the sequence of interpreted geological formations of the resistivity model. This validates the interpretation of resistivity model. The site for drilling bore well for the purpose of dewatering of the zone of landslide is suggested at 185 m distance which penetrates through the beds of water bearing sandy formation. Position of this bore well is marked as PW on the profile. Pumped water from the mine can be diverted in to nearby canal for irrigation and industrial purposes as per demand.

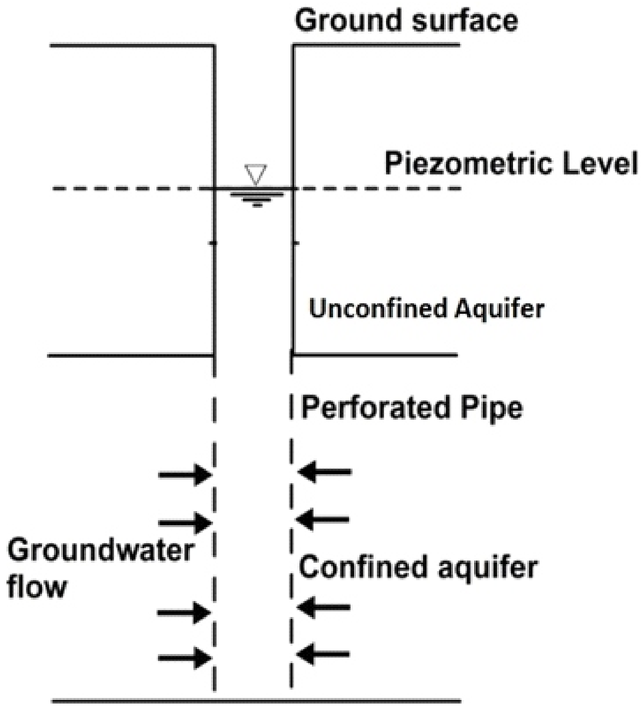

Fig. 11. Bore well design to sustain the yield for a longer period.

Bore well design

A proper bore well design is essential to sustain the economic yield of a bore well for a longer period. Unlike in the region of sedimentary formations, in hard rock regions in general and in basaltic Deccan volcanic province in particular casing of a bore well is done only for 5 to 6 m up to the depth of weathered formation. Remaining portion of the bore well is left without casing. As mentioned above groundwater in Deccan trap regions occurs in sedimentary inter-trappeans. In the absence of casing sediment particles also flow in to well along with water and choke the bore well. This gradually reduces the yield of bore well. This finally leads to the failure of bore well after 4-5 years even in the presence of groundwater. There are examples of several thousands of such bore wells in hard rock terrain. To avoid this situation casing of the bore wells for its entire depth is recommended. Perforated pipes should be used for casing within the water bearing formation as shown in Fig. 11. This arrangement allows the sediment free flow of groundwater in to well, thus maintaining its yield for a longer period.

CONCLUSIONS

Delineation of groundwater resources and identification of suitable sites for managing aquifer recharge are essential components of water management for different purposes such as for augmenting water supply to meet the ever increasing demand for domestic, irrigation and industrial usages. Similarly delineation of source of geothermal water is useful for harnessing geothermal energy to generate electricity. Delineation of groundwater resources in mining areas is needed to prevent land slide etc. The four case studies described in the paper highlight the efficacy of ERT in mapping groundwater resources under different physical conditions. The investigated studies suggest that if bore well drilling is conducted after analyzing the ERT results and casing is done in a proper manner by making use of perforated pipe within the groundwater bearing zones, then several crores of rupees and precious human lives can be saved by avoiding drilling dry bore well. After harnessing geothermal energy, the groundwater attains it natural temperature which can be used to meet the demand of water supply. Similarly groundwater pumped out from mines can be also used for irrigation and industrial purposes. This study also suggests that if data collection and its interpretation are carried out properly, then ERT alone is capable to delineate ground water resources even in complex geological environs. There is no need of data collection and interpretation by using other methods along with ERT.

ACKNOWLEDGMENTS

Mr G. B. K. Shankar, Dr. S. Thiagarajan and Dr. Dewashis Kumar participated in the field work to collect data used in this paper. They also helped in ground water modeling. Mr. Shashank Rai carried out some modification in the figures in their present form to make them more explanatory.

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