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Groundwater prospecting in Deccan traps covered Tawarja basin using Electrical Resistivity Tomography

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ABSTRACT

Acute shortage of water supply for domestic and irrigation purposes in hard rock area is accentuated by occurrence of groundwater in limited quantity within sparsely distributed aquifers characterised with secondary porosity of finite areal extent. Tawarja river basin is in drought prone Latur district of India falling in basaltic Deccan Volcanic Province (DVP). which occupies half a million square km area. Because of availability of limited quantity of groundwater in the shallower aquifers, ever increasing withdrawal of groundwater in excess to recharge is resulting in continuous declining of water table. As a result bore wells/ dug wells used for groundwater pumping from shallower aquifers often go dry, with the onset of summer season. Locating of groundwater potential zones by bore well drilling, in the absence of scientific investigations, is fraught with high percentage of failure. Therefore, delineation of deeper sources of groundwater with certainty based on scientific investigations is urgently needed to meet the ever increasing demand for water supply. This paper presents results of 2-D Electrical Resistivity Tomography carried out in part of Tawarja basin, a complex geo-environ, to demonstrate its efficacy in delineation of groundwater potential zones and sites of aquifer recharging. Several sites suitable for bore well drilling have been identified, which can be developed to meet the water supply demand in the investigated region.

INTRODUCTION

Deccan traps occupy about 80% of the surface area of Maharashtra state, India. It is pile up of multiple layers of lava flows below a cover of soil and weathered mantle of varying thicknesses. Each lava flow can be divided into upper vesicular and lower massive units. In the vesicular unit, ground water occurs in intra-granular porous space. In the massive basalt unit, ground water occurs in fractures, faults and joints. These geological structures serve as reservoir and conduits for the movement of groundwater. The lower massive basalt unit may or may not be fractured / faulted. Two consecutive lava flows are separated by sedimentary formation called intertrappeans. These intertrappeans together with underlying vesicular basalt layers form good aquifers. Because of limited areal extent and sporadic nature of distribution, accurate location of groundwater bearing zones in basaltic terrain is a challenging task.

Electrical resistivity survey is widely used for groundwater prospecting because of noticeable contrast in resistivity values between water saturated geological formations/structures and dry geological formations/ structures. This contrast is more prominent in hard rock terrains. In early works mostly vertical electrical sounding (VES) technique with four electrodes configurations was used for delineation of deeper resources of groundwater (Bose and Ramkrishna, 1978; Rai et al. 2011, 2012, 2013). The limitation of such a survey is that it provides only 1-D model of resistivity variation below the centre of the survey profile which provides information about the litho units below the centre of the survey line and does not provide any information about the lithological sequence falling on either side of central point of the profile. Therefore, delineation of water bearing geological formations or structures by 1-D model is only possible if these formations/structures coincidently lie below the centre of the profile. A more accurate model of the subsurface litho units would be a 2-D model, which provides information about the resistivity variations in the vertical as well as lateral direction below the entire spread of the survey line. This will lead to the possibility of delineation of groundwater bearing geological formations/structures below the entire spread of the survey line. Development of 2-D resistivity models becomes possible with the development of Electrical Resistivity Tomography (ERT) technique (Griffiths and Barker, 1993). ERT is now being used worldwide for different purposes including groundwater exploration. Owen et al. (2005) have conducted ERT survey over metasedimentary strata and metavolcanics in the Harare greenstone belt in northeastern Zimbabwe for delineation of groundwater resources. The ERT was conducted to map thickness of aquifer and bedrock in Banting, Selangor in Malaysia (Hamzah, et al. 2006) and at the periphery of the impounding reservoir of the Ahmadu Bello University farm dam in northern Nigeria to delineate possible weak zone that could serve as seepage paths in the vicinity of the dam (Osazuwa and Chii, 2010). ERT was

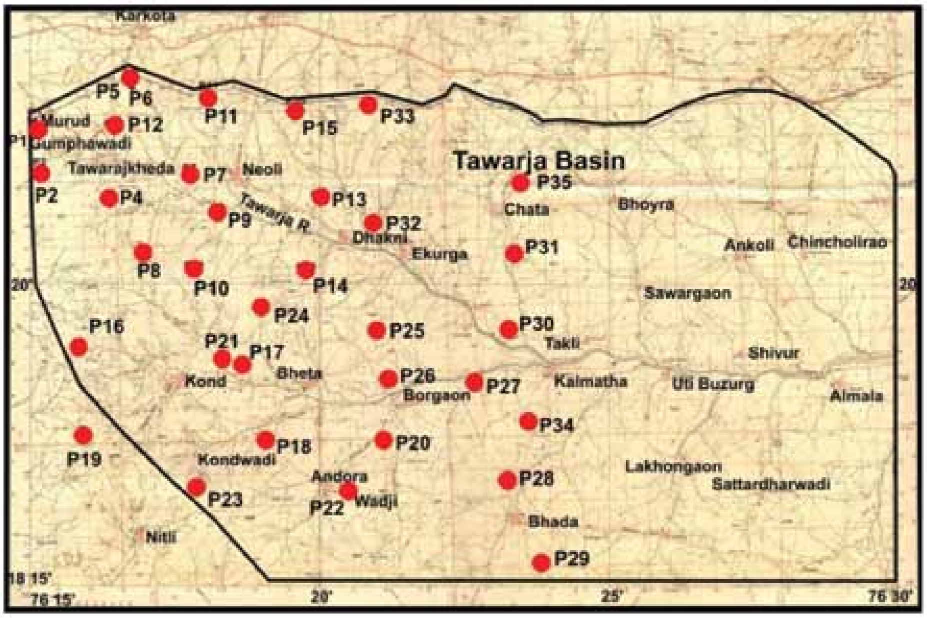

Figure 1. Location map of Twarja river basin, Latur district with the locations of Electrical Resistivity Tomography sites represented by Pn (n=1-35) (modified after SOI topo sheet nos. 56B/3, 56B/7 and 56B/11)).

Table 1: Regional Stratigraphy

Age	**Lithology**
Recent to Quaternary	Black cotton soil, silt and clay
Lower Eocene to upper Cretaceous	Highly to moderately weathered/fractured basalt underlain by vesicular and Massive units of basaltic Lava flows with intervening intertrappean sediments
Permian	Infra-Trappean sedimentary formations
Archaeans	Granite gneisses basement

carried out in Pagoh and Johor, in Malaysia (Kadri and Nawawi, 2010) and in parts of Kumbani River Basin, Zaria, in Nigeria (Anthony and John, 2010) to explore ground water potential zones for irrigation and drinking purposes. Kumar et al (2011) have conducted Electrical Resistivity Tomography in the Chiplun taluk of Ratnagiri district of Maharashtra to delineate aquifers in search for geothermal reservoir and potential zones of groundwater with normal temperature. The ERT survey was carried out in Deccan traps occupied Chandrabhaga basin in Nagpur district for delineation of groundwater bearing geological formations/ structures within and below the traps (Ratnakumari et al., 2012). Bore wells were drilled at some locations to verify the interpreted ERT results. Some of these bores are being used by farmers for irrigation. Abdullahi and Iheakanwa (2013) have carried out ERT survey at the Kaduna Polytechnic Demonstration Secondary School in Kaduna state of Nigeria for groundwater detection in basement complex. The Electrical Resistivity Tomography has been conducted to decipher groundwater resources in north Badra area located in eastern Iraq (Thabit and Al-Hameedawie, 2014). In a recent paper Kumar et al (2014) have used ERT for delineation of deeper groundwater resources in quartzite hard rock ridge region within the campus of Jamia Hamdard University, New Delhi. This paper presents results of ERT surveys carried out in parts of Tawarja basin for the delineation of groundwater potential zones in order to meet the ever increasing demand of water supply for drinking and irrigation purposes.

STUDY AREA:

The present ERT study has been carried out in Tawarja river basin located in Latur district of Maharashtra. This river originates near Murud railway station and is about 50 km long. The Tawarja river flows eastwardly till it joins Manjira river and covers an area of 642. 40 km^2 between 18°12′16″ to 18°24′15″ north latitudes and 76°15′ to 76°41′35″ east longitudes (Babar and Shah, 2012). The entire basin is covered by thin soil cover, which is underlain by basaltic Deccan traps. At many places Deccan traps are exposed. Deccan traps consist of a number of nearly horizontal lava

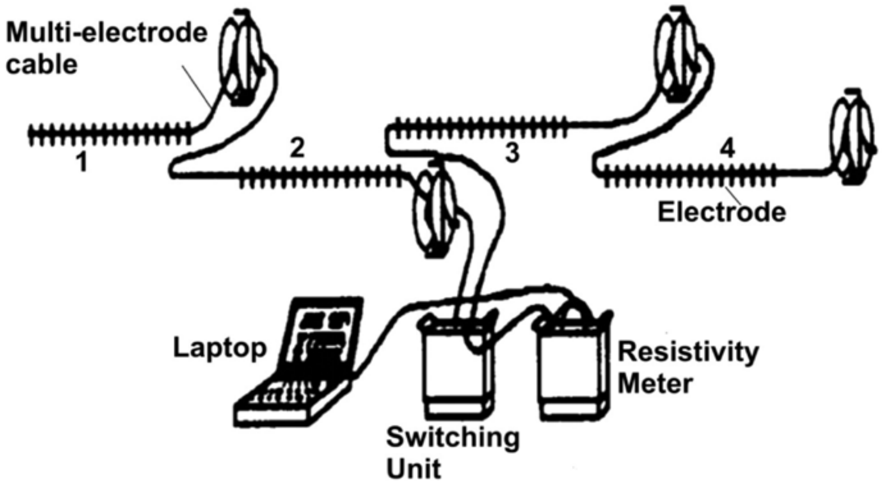

Figure 2. Field arrangements of ERT survey with 4 multi-core cables

flows of late Cretaceous to early Eocene. Lava flows are separated from each other by inter trapped ash beds and ancient buried soil called red bole beds (Singhal, 1997). These sedimentary formations lying between two layers of lava flows are known as intertrappeans. The regional stratigraphy is given in table-1.

Sugarcane is mainly grown in this region. It requires plenty of groundwater for irrigation round the year. Because of this groundwater is being pumped out in this region in excess to replenishment by precipitation. This led to the continuous declining of the water table. As a result shallower unconfined aquifers have become almost dry with the onset of summer and could not sustain the required demand of water supply for irrigation and for domestic purposes. The basin area is also being drained by dense network of streams of various orders (Fig. 1). The network of the streams shows dendritic to sub-dendritic and sub-parallel drainage pattern (Babar and Shah, 2011). This also adds to the already prevailing conditions of water scarcity. The climatic condition of the basin is semi-arid with average annual rainfall of 880 mm. The aim of the present study is to delineate groundwater potential zones at relatively deeper level using advanced technique of ERT. In the present study only western part of the basin lying between 18º15′ to 18º20′30″ north latitudes and 76º15′ to 76º25′ east longitudes has been considered for ERT survey, in order to delineate potential zones of groundwater for the development. The region under investigation and the ERT sites marked with red circles are shown in fig. 1. The ERT survey has been conducted at 35 locations. The sites are numbered as Pn (n=1,2…35) in figure 1.

Electrical Resistivity Tomography

In Electrical Resistivity Tomography survey, multi core cables with many electrodes take outs are connected together to form a multi-electrode setup, where selection of any four electrodes (two for current injection and two for potential measurements) out of these electrodes is possible. The number of electrodes differs from system to system. In the present study the ABEM made Terrameter LUND Imaging System SAS 4000 with 64 electrodes is used. Figure 2 shows typical field arrangement of an ERT survey with four multi-core cables. In each multi-core cable, 16 electrodes are placed at equal spacing. Multi-core cables are connected to an electronic switching unit. The switching unit is connected to a resistivity meter and the resistivity meter is connected to a laptop. Information regarding the sequence of measurements to take, the type of array to be used and other survey parameters such as the intensity of current to be used is entered in to a text file, which can be read by a computer program uploaded in the laptop. After reading the control file, the computer program then automatically selects appropriate two current electrodes and two potential electrodes for each measurement. After that, measurements are taken automatically and stored in the laptop (Loke 2000). Provision is made for resistivity survey using different electrode configurations. In the present study Electrical Resistivity Tomography is carried out using Wenner configuration with four multi-core cables each having 16 electrodes. 10m spacing between two consecutive electrodes is maintained. In the next step the measured apparent resistivity values are converted in to a 2-D sub-surface true resistivity model. This task is accomplished by using inverse modelling. Inverse modeling of the measured apparent resistivity data is carried out using RES2DINV program (Loke 1997). The final output is a 2-D inverse model of true resistivity variation below the entire stretch of the survey line. By using this approach 2-D inverse model of true resistivity variation for all 33 investigated sites have been computed. The inverse model of true resistivity variation is referred as resistivity model in the following section.

Table 2: Resistivity values of different rock type in the study area (Source: CGWB website: http:// cgwb.gov.in/CR/ achi_geo_stu. html).

Geological Formation	
Alluvial, Black cotton, bole bed	5-10
Weathered/fractured/ vesicular basalt saturated with water	20-40
Moderately weathered/fractured/vesicular basalt with water	40-70
Massive basalt	> 70

INTERPRETATION

Hydrogeological interpretation of these resistivity models is needed to identify groundwater potential zones suitable for bore well drilling and also for the identification of suitable sites for managing aquifer recharge. Based on the resistivity surveys carried out in parts of Nagpur, Amaravati, Akola and Jalgaon districts, resistivity values for the different litho units of Deccan traps are suggested by the Central Ground Water Board (CGWB) of India, which are presented in table-2.

In general the values of resistivity suggested by CGWB are taken as guidelines for the interpretation of 2-D images of resistivity models. As stated above, ERT was conducted at 33 locations in the study area (figure 1). 2-D resistivity models for profiles P1 to P35 are presented in figures 3a & 3b, 4, 5, 6 and 7. ERT was carried out at different times at different locations. Accordingly profiles are numbered. Each resistivity model is presented along with the profile number denoted by Pn (n=1 to 35), nearby village name, coordinates of the centre of the profile, color index of the resistivity values, electrode spacing and root mean square (RMS) value. If the value of the RMS error is preferably <10% or close to it, then it is considered as the realistic subsurface model for a good quality data. It is related to the data quality. In the present study electrode spacing is maintained as 10 m. Geological interpretation of these resistivity models is used for identification of groundwater potential zones. Except a few, majority of the profiles are in the west to east direction. Resistivity models are presented based on their locations from north to south, to explore the possible extension of geological formations from the site of one profile to the adjacent profile. Profile wise hydrogeological interpretation of the resistivity models are discussed below.

PROFILES P1, P2, P3, P5, P6, P12, P4, P8, P16 and P19

Resistivity models for Profiles P1, P2, P3, P5, P6, P12, P4, P8, P16 and P19 are presented in figures 3a and 3b. Location of each electrode is indicated by small vertical spikes on horizontal axis representing survey line. Depths of the resistivity variations are marked on the vertical axis and restricted to depth of 115 m which is the maximum depth of investigation for a spread length. Position of the 1st electrode is marked at 0.0 and 64th at 630 m distance. Resistivity model of P1 profile indicates a composite layer of soil/weathered/fractured basalt up to ~5- 8 m depth. This is underlain by a stratum of massive basalt (> 70m Ohm m). Below it lies two units of moderately weathered/ fractured basalt (~45-70 Ohm m) separated by a massive basalt unit, whose tip can be seen in the central part of the profile (between 320 to 380 m). This model does not indicate presence of any potential zone of groundwater. Resistivity model of profile P2 shows a moderately weathered/ fractured basalt layer sandwiched between two layers of massive basalt from top and bottom. Three small units of water saturated formation (< 40 Ohm m) are visible within the middle layer. Because of their small size these units are not suitable for groundwater extrication. Resistivity model of P5 profile presents water saturated composite layer of weathered/fractured/vesicular basalt (< 40 Ohm m) sandwiched between two layers of massive basalt. This water bearing geological formation is extended up to ~ 80 m depth and appears to be suitable for groundwater exploitation. A suitable site for bore well drilling could be at 180 m distance where aquifer appears to attain maximum thickness. Resistivity model of profile P6 shows the sequence of the geological formations, similar to that of profile P5. A water saturated composite layer of weathered/fractured/ vesicular basalt (<40 Ohm m) of varying thicknesses in the range of ~35 m to 80 m is found sandwiched between massive basalt layers from top and bottom. This water bearing formation is extended up to 440 m distance. Beyond 440 m distance, presence of moderately fractured basalt layer (45-70 Ohm m) is seen. In order to check the presence of groundwater in the middle layer of weathered/fractured/vesicular basalt, a bore well was drilled at 16.7 m distance west of the centre of profile P6. This bore well confirmed the presence of water, within the entire depth section of the middle layer of weathered/ fractured/vesicular basalt.

Resistivity model of profile P12 shows a massive basalt layer from top to bottom up to 430 m distance with two small patches of low resistivity formations, which may have small quantity of water. Another low resistivity formation (<10 Ohm m) is visible between 430 m and 530m, which could be clayey bole bed. This site also does not indicate any potential zone of groundwater. Resistivity model of

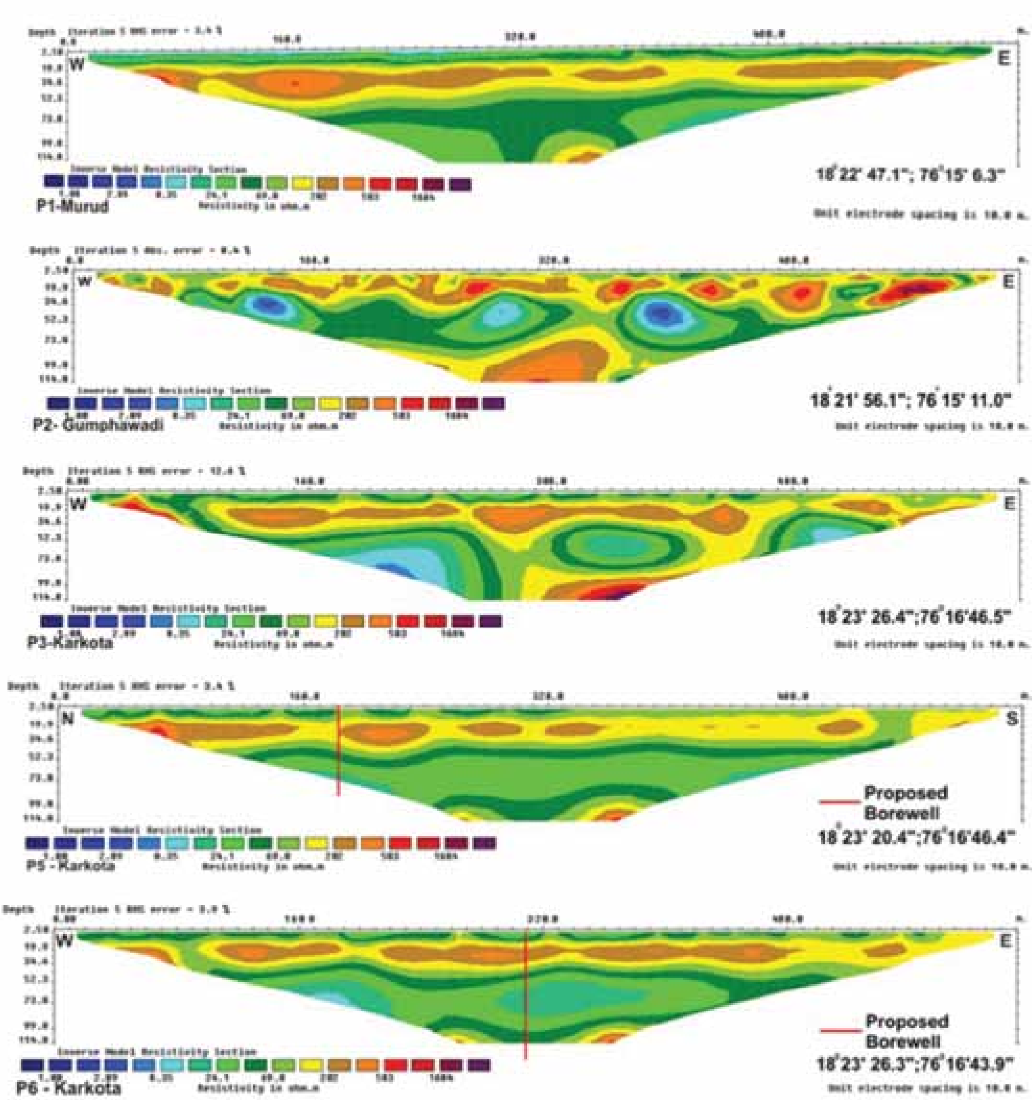

Figure 3a. Resistivity models for profiles P1, P2, P3, P5 and P6

profile P4 shows the exposure of water bearing weathered/ fractured basalt between 70 m to 130 m distances, which is extending downward. This formation is characterized by < 40 ohm m resistivity value, indicating presence of ground water. This zone appears to be suitable for groundwater exploitation. The remaining part of the profile toward east is covered with the massive basalt layer of ~20 m thickness. This massive basalt layer is underlain by moderately fractured basalt followed by again massive basalt unit between 160 and 360 m distance. Beyond 360 m distance another unit of weathered/ fractured basalt characterized by < 40 Ohm m resistivity value is seen, which can be another potential zone of groundwater suitable for exploitation. A bore well site at 460 m distance is suggested.

Resistivity model of profile P8 shows two groundwater potential zones. One zone can be seen between 170 and 340 m distance, at 40 m depth below massive basalt unit. This zone appears to be extending beyond 114 m depth in the central part of the profile. It is suitable for groundwater exploitation. Another zone is exposed on the ground surface between 360 m and 420 m. Beyond it, this zone is covered by massive basalt. Its downward extension beyond ~60 m depth is not established from the resistivity model and appears to be underlain by adjoining massive basalt unit from eastern side. So, this zone is not suitable for groundwater exploitation. Resistivity model of profile P16 indicates the presence of massive basalt on top, which is extended up to ~35 m depth. Below it lies a composite layer of weathered/ fractured /vesicular basalt. This water bearing formation appears to be extending further downward in the central part of the profile, in between two units of massive basalt whose exposures are visible at the bottom of the resistivity model. Groundwater from this

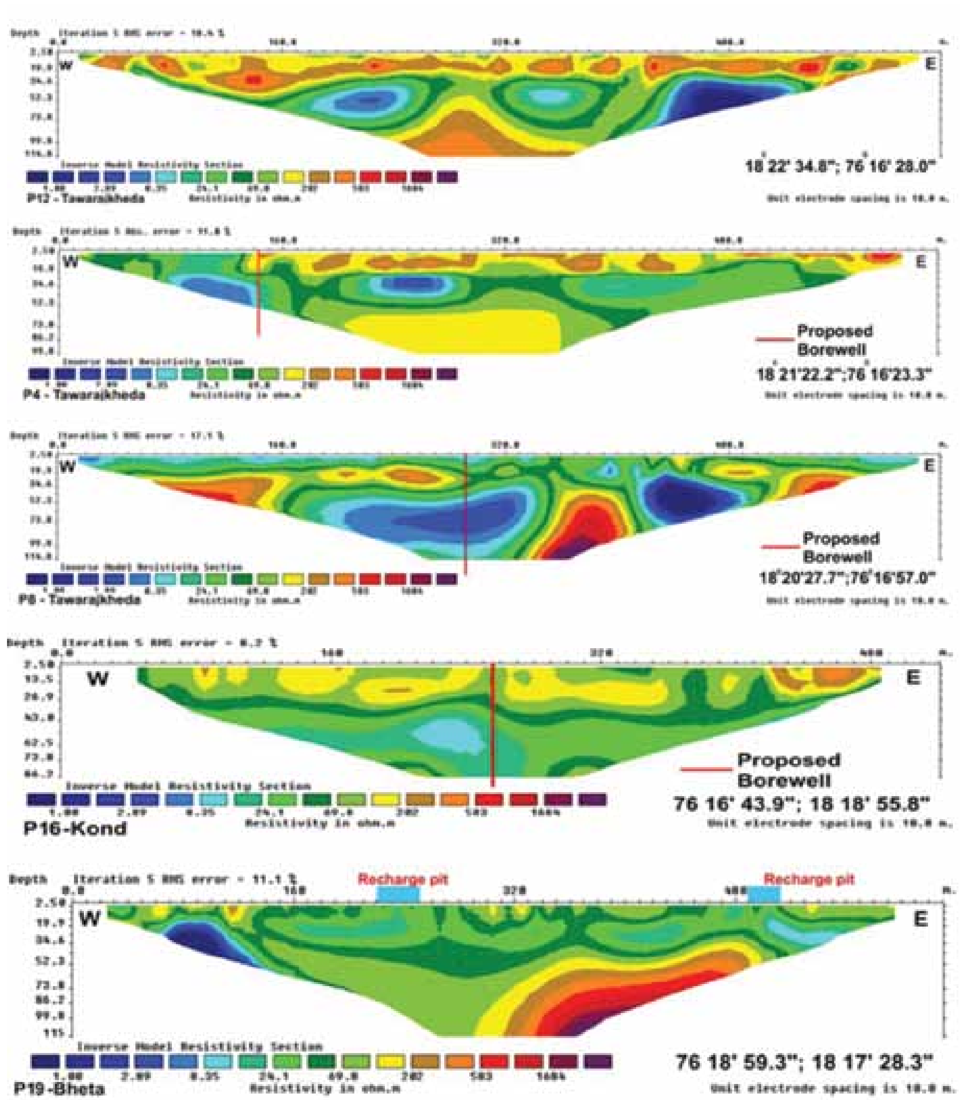

Figure 3b. Resistivity models for profiles P12, P4, P8, P16 and P19

zone can be exploited by drilling bore well between 230 and 280 m distance. Profile P19 is close to the western boundary of Tawarja river basin. Resistivity model of this profile indicates presence of a composite layer of weathered /fractured /vesicular basalt from 140 m to beyond the eastern edge of the profile. This layer is exposed on the ground surface between 200 to 280 m and between 460 to 510 m. These two segments of the profile appear to be the recharge sites of this layer. This layer can be exploited by large diameter dug well. Probable site of dug well (DW) is shown in the model. From 140 m onwards this layer is underlain by massive basalt. Exposures of two zones indicating low resistivity values (20 Ohm m) can be seen near western and eastern edges of the profile. They seem to be extending downwards. These zones may be suitable for groundwater exploitation.

PROFILES P11, P7, P9, P10, P23

The respective resistivity models of profiles P11, P7, P9, P10 and P23 are presented in figure 4. Profiles P11, P7, P9 and P10 are located within the administrative unit of Neoli village. Resistivity model of P11 presents two potential groundwater zones below 35 to 50 m thick cover of massive basalt. Both zones are separated by a massive basalt unit, which is vertically connected to the top layer of the massive basalt. One water saturated zone is visible between 130 m and 250 m and extending downward beyond 100 m depth. Suitable sites for bore well drilling could be at 220 and 315 m, as shown in the model. Both the water bearing zones are vertically separated by massive basalt. As such, pumping from one zone is not going to affect the groundwater storativity of other zone even though

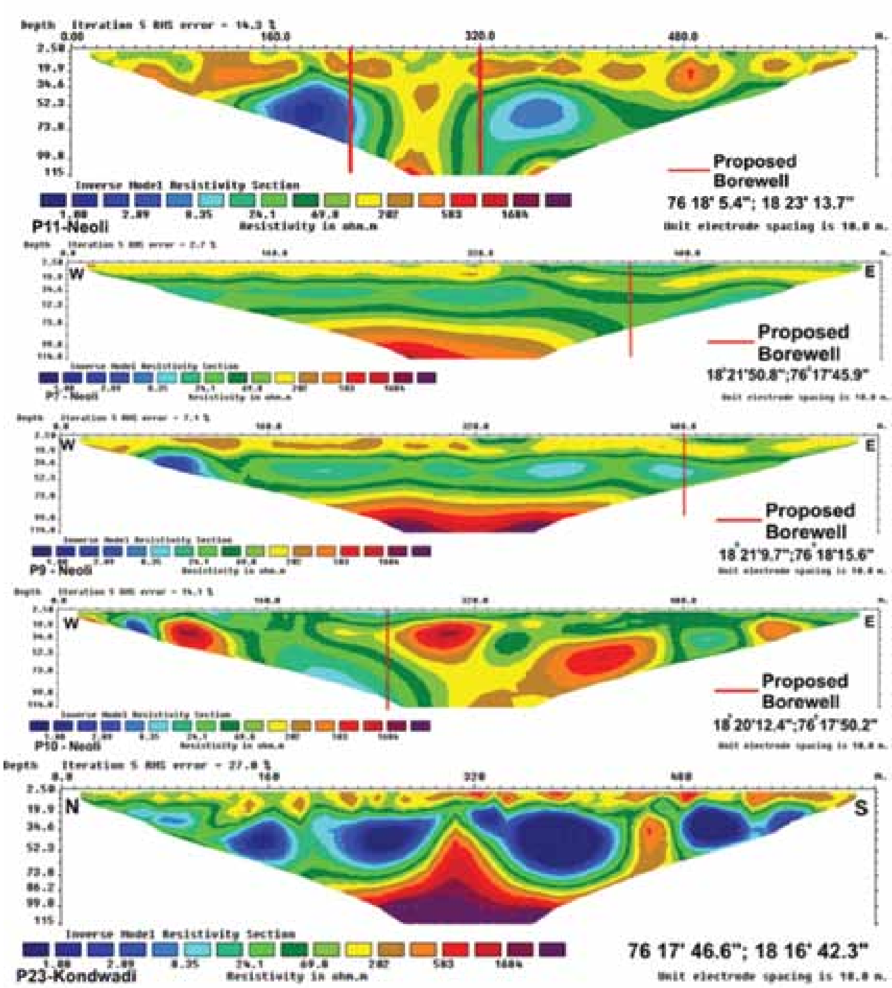

Figure 4. Resistivity models for profiles P11, P7, P9, P10, and P23.

the distance between two bore wells will be <100 m. In general, to avoid interference, minimum distance between two bore wells should be 300 m, if bore wells are drawing water from the same aquifer.

Resistivity model of P7 profile indicates a ~20 to 25 m thick massive basalt layer on the top. Below it lies a stratum of water bearing weathered/fractured/vesicular basalt extending up to a depth of ~40-45 m. Depth of this water bearing stratum appears to be extending further downwards beyond 430 m, towards eastern boundary of the profile. A suitable site for drilling bore well could be at 440 m distance, as shown in the model. This water bearing formation is underlain by another massive basalt unit, which is visible between 180 and 450 m. Resistivity model of profile P9 shows sequence of litho units exactly similar to that of profile P7, as both the profiles are closely located. Hence, the geological setup of profile P11 is extended to the site of P7. A ~20 to 25 m thick layer of massive basalt on top is covering entire length of the survey line. Below it lies a layer of weathered/fractured /vesicular basalt extending up to 40 to 45 m depth. Its thickness appears to be extending further downward beyond 460 m. A suitable site for bore well drilling would be in the vicinity of 480 m, as shown in the model. The water bearing formation is being underlain by a massive basalt layer, which is visible between 180 m and 450 m. Resistivity model of profile P10 shows three fracture zones, exposed on the ground surface. The first zone of small dimension is exposed between 50 and 70 m distance, near the western edge of the profile. The second one of larger size is exposed between 110 and 160 m. This fracture zone has inclination towards east and extending downwards beyond 140 m distance, as shown in the resistivity model. This fracture zone is suitable for groundwater exploitation, by drilling bore well at 240 m, which will penetrate the water bearing formation outside the clayey red bole zone of low resistivity formation (<10 Ohm m). The third unit of fracture zone can be seen between 480 and 520 m. Because of smaller sizes of first and third zones, located near the western and eastern edges of profile, drilling of bore wells in these zones is

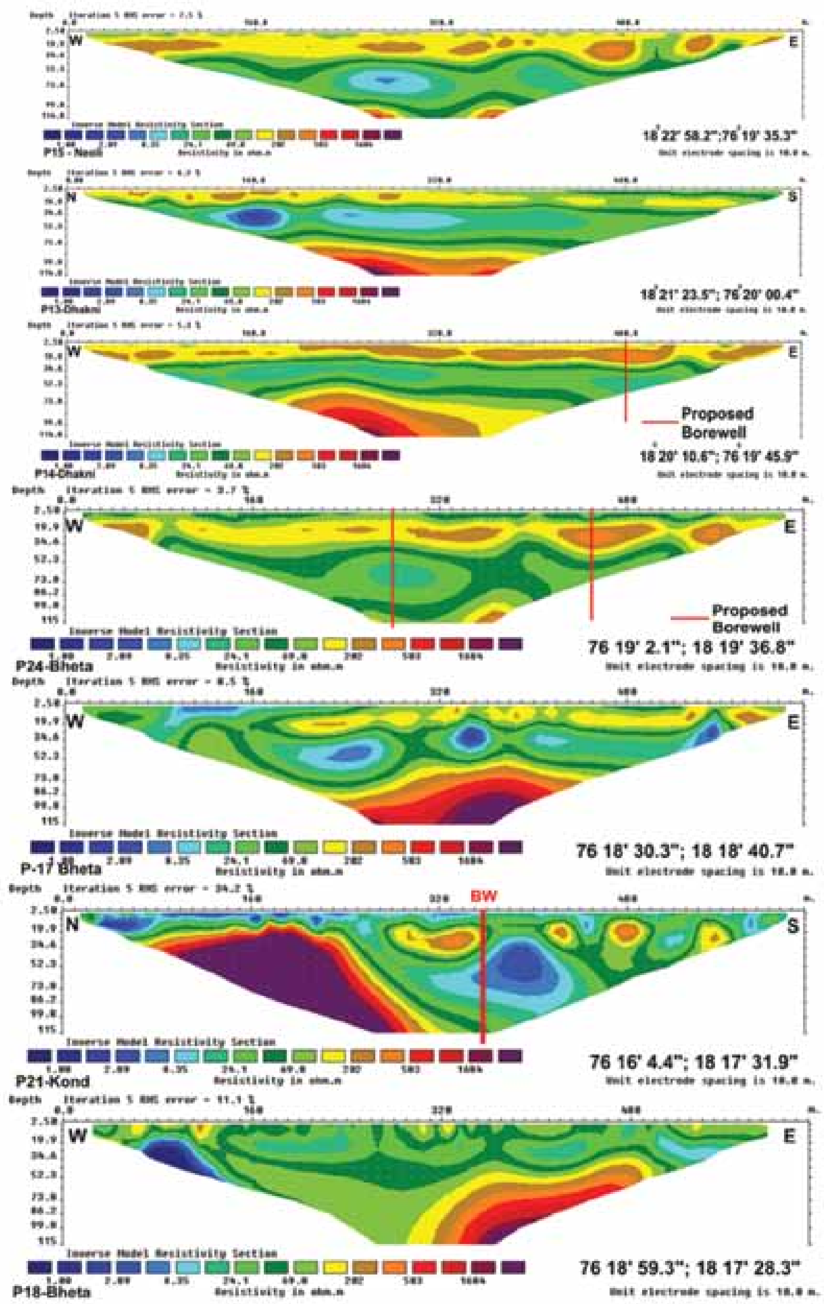

Figure 5. Resistivity models for profiles P15, P13, P14, P24, P17, P21 and P18.

not recommended. Resistivity model of P23 profile shows presence of a thin layer of massive basalt. This is underlain by a layer of weathered/fractured/vesicular basalt of varying thicknesses. This layer is having 4 patches of clayey red bole characterized with < 10 Ohm m resistivity values. Groundwater can be pumped out from this zone by drilling a bore well at 180 m, as shown in the model, in order to avoid penetration of bore well through clayey bole zones. Depth of the bore well should be restricted to ~70 to 80 m. At the bottom massive basalt unit is present with ridge like structures below 310 and 460 m.

PROFILES P15, P13, P14, P24, P17, P18, P21

Profile P15 also belongs to Neoli, while P 13 and P14 belong to Dhanki village. Resistivity models for profiles P15, P13 and P14 are presented in figure. 5. The resistivity models of P15, P13 and P14 also show three layered structure, almost similar to those of profiles P7 and P9, i.e. a thin layer of massive basalt on top followed by a water saturated layer of weathered/ fractured/ vesicular basalt and a layer of massive basalt at the bottom. It is noticed that the geological settings of the region covered by profiles P7,

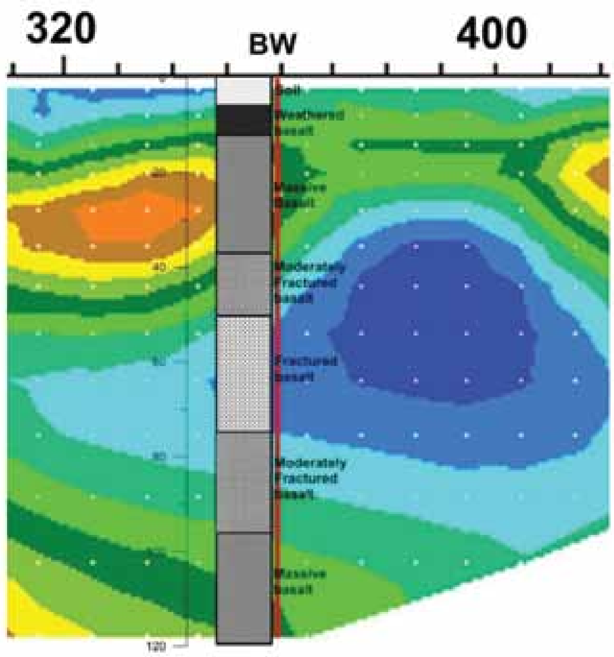

Figure 6. Comparison of geological stratigraphy obtained from resistivity model for Profile P21 with the stratigraphy obtained from the exploratory bore well.

P9, P15, P13 and P14 are similar. Due to less thickness of aquifers and absence of any recharge site, probable water bearing formations associated with profiles P15 and P13 are not suitable for groundwater exploitation. Suitable site for bore well drilling for profile P14 would be at 480 m, as beyond 480 m distance, thickness of the water bearing formation appears to be increasing downward.

Profiles P24, P17 and P18 belong to Bheta village, while profile P21 belongs to Kond village. Resistivity models for all these profiles are also presented in figure 5. In case of profile P24, resistivity model indicates a thin layer of soil, spread over the entire length of the profile. This is followed by in sequence a layer of massive basalt extending up to 30 to 35 m depth, and a water saturated layer of weathered/fractured/vesicular basalt (< 40 Ohm m) in the depth range of ~40 to 90 m. At the bottom is massive basalt unit, whose surface exposure is visible between 270 and 370 m. The water saturated stratum of weathered/ fractured/ vesicular basalt is bisected in to two units by the presence of moderately fractured basalt between 340 and 400 m. Two bore well sites are suggested. One is between 250 and 320 m and another between 430 and 480m, for to exploit both the units. The resistivity model of profile P17 indicates presence of massive basalt up to a depth of 20 to 25 m. This is followed by water bearing weathered/ fractured/ vesicular basalt layer extending up to 45 -55 m depth. There after massive basalt exists, beyond 115 m depth. The water bearing formation seems to be connected to the ground surface through a fracture located at 160 m distance. This could probably be the site of its recharging. However, because of smaller thickness of the water bearing formation, drilling of bore well is not suggested.

Profile P21 is in north-south direction and passing through an existing bore well located at 360 m distance. Location of the bore well on the resistivity model is marked by BW. This bore is being used for irrigation. Resistivity model of profile P21 shows a compact massive basalt unit extending almost parallel to the ground surface up to 240 m distance under a thin cover of soil. Beyond this distance the massive basalt unit is dipping southward below a fractured zone consisting of moderately fractured basalt on top (45 -70 Ohm m) and water bearing weathered/fractured basalt (< 40 Ohm m) at the bottom. This zone is exposed to the ground surface between 240 and 400 m. Beyond this it is again bounded by massive basalt unit. The massive basalt unit on the northern side of the profile appears to be extending beyond 115m depths. But water saturated weathered/fractured basalt unit seems to be extending up to ~100 m depth and is underlain by moderately fractured basalt, as shown in the resistivity model. A comparison between the litho units obtained from the interpretation of resistivity model with those obtained from bore well is presented in figure 6. On top is a thin layer of soil. This is followed by in sequence weathered/fractured basalt, massive basalt, moderately fractured basalt, water saturated weathered/fractured basalt, another unit of moderately fractured basalt followed by massive basalt at the bottom. Both the sequences of litho units are in good agreement. This validates the ERT results.

Resistivity model of profile P18 indicates presence of a

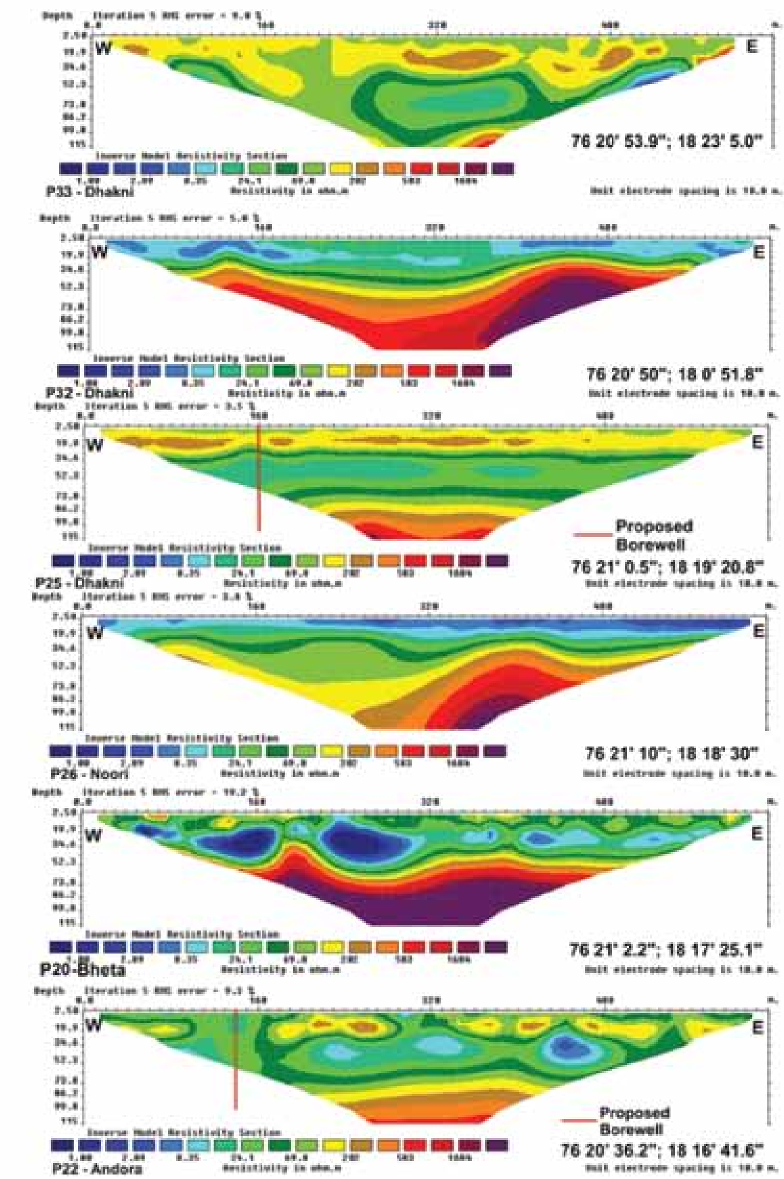

Figure 7. Resistivity models for profiles P33, P32, P25, P26, P20, and P22.

water bearing layer of weathered/ fractured basalt extending from 140 m distance to the eastern edge of the profile. This layer is extended up to ~ 30 m depth and is exposed to the ground surface between 210 to 280 m distance and between 460 to 510 m distance. In the remaining segment of the profile, this layer is covered by moderately fractured/ massive basalt. This water bearing formation is underlain by massive basalt, which appears to be extending beyond 115 m depth. Presence of another zone of low resistivity formation (<10 Ohm m) is visible near the western edge of the profile, which appears to be extending downwards below the massive basalt. This zone is characterized by < 10 Ohm m resistivity. This, as such, could be clayey red bole, and not suitable for drilling a bore well.

PROFILES P33, P32, P25, P26, P20 AND P22

Profiles P33, P32 and P25 are falling within the administrative unit of village Dhanki, while the other three profiles, namely P26, P20 and P22 fall in Noori, Bheta and Andora villages, respectively. Resistivity models for these profiles are presented in fig. 7. Resistivity model for P33 profile indicates presence of massive basalt in its entire cross section, except two small zones of low resistivity formation (<40 Ohm m) indicating presence of water. The first zone in elliptical shape can be seen between 260 and 400 m at ~ 50 m depth. This is enveloped by massive basalt. The other water bearing zone appears between 500 m and 550 m, below the massive basalt. Because of smaller sizes, both units are not suitable for groundwater exploitation. Thus the site of this profile does not show any potential zone of groundwater. Resistivity models of profile P32 shows a layer of weathered/fractured formation with the thickness between 20 to 40 m on the top. This is underlain by compact massive basalt extending beyond 115 m depth. The top layer of weathered/ fractured formation may have small quantity of water as a result of return flow from irrigation; otherwise this profile does not show presence of any potential zone suitable for groundwater exploitation. Resistivity model for P25 profile indicates three layered structure; a ~ 20 to 25 m thick layer of massive basalt on top, underlain by a layer of weathered/fractured/vesicular basalt extending up to 60 m depth, followed by a separate unit of massive basalt at the bottom. The middle layer may be exploited for groundwater by drilling bore well at 160 m, distance where this layer appears to be attaining maximum thickness. Only one bore well is suggested because the same aquifer is stretched in the entire length of the survey line. Resistivity model of profile P26 shows a 5 m to 8 m thick layer of soil (<15 Ohm m) on top. This is followed by water bearing weathered/moderately weathered basalt (<40 Ohm m) extending up to 20 to 25 m depth and thereafter massive basalt. For this profile only large diameter dug well at 160 m or 320 m or at 480 m penetrating up to the upper boundary of the massive basalt unit is suggested. Only one dug well is suggested because the same water bearing formation is stretched over the entire length of the profile.

Resistivity model for profile P20 indicates a thin layer of moderately fractured/massive basalt layer (> 50 Ohm m) on the top. Below it lies water bearing/fractured basalt in the depth range between 30 to 60 m. This formation is connected to a fracture zone, which is exposed to the ground surface between 230 and 250 m. This zone could be recharge site for the under lying water bearing formation. This water bearing formation contains clayey red bole zones, west of the centre of the profile. A suitable site for bore well drilling would be at 300m distance up to a depth of 60 m to 70 m in order to avoid penetration through clayey red bole formation. This water bearing formation is underlain by compact massive basalt. Resistivity model for profile P22 shows a layer of massive basalt (> 70 Ohm m) on top beyond 160 m distance. Below it lies a water bearing formation up to ~ 45 m, between 170 and 490 m distance. This is underlain by moderately fractured basalt, followed by massive basalt. The middle water bearing formation is connected to a fracture zone between 280 to 310 m, which could be recharge site for this aquifer. Because of smaller size of potential zone this site is not suitable for groundwater exploitation through a bore well. Another fracture zone is seen between 90 and 160 m, which appears to be extending downwards below a thin layer of massive basalt seen up to 90 m distance. This zone appears to be a potential zone, which can be exploited by locating a bore well between 90 m and 140m distance.

PROFILES P35, P31, P30, P34, P28 AND P29

Profiles P35 and P31 are located near Chatta village, P 30 near Bopla village and P34, 28 and P29 near Bhada village. Their corresponding resistivity models are presented in figure 8. Resistivity model of profile P35 indicates a layer of massive basalt extending up to 25 to 30 m depth, below a thin soil cover. The massive basalt layer is underlain by water bearing weathered/ fractured/ vesicular basalt extending up to 70 m depth. This layer is bisected by the presence of a vertical column of moderately fractured basalt (45-70 Ohm m) between 160 and 190 m. This water bearing formation is showing a trend of downward expansion beyond 430 m. For this profile a bore well site is suggested at 450 m distance. This water bearing formation is underlain by a massive basalt unit, which is visible between 210m to 380m and appears to be extending on both sides. Resistivity model of profile P31 indicates the presence of moderately fractured basalt (45 to 70 Ohm m) up to 130 m distance and beyond it a composite layer of water bearing soil/weathered/fractured/vesicular basalt (<40 Ohm m) on the top. This is a overlying compact massive basalt unit. which is seen from 160 m distance onward to the eastern edge of the profile. Because of small thickness of the water bearing soil/weathered/fractured/vesicular basalt this model site is not suitable for bore well drilling. Resistivity model of profile P30 also presents a compact massive basalt unit below a thin soil cove. This site also not favorable bore well drilling.

Profile P34 comes under Bhada village. It's resistivity model presents three layered sub-surface structure. On top is massive basalt layer in the depth range of 5 m to 20m. This is underlain by water bearing weathered/fractured/ vesicular basalt extending up to ~40 to 50 m depth. At the bottom is massive basalt. The middle water bearing formation, because of less thickness and absence of its connectivity to any fracture zone for recharging, is not considered for groundwater exploitation. Resistivity model of profile P28, which is located near Bhada village also presents three layered structure. On top is massive basalt unit, in the middle water bearing weathered/ fractured/vesicular basalt and at the bottom massive basalt unit (visible only in the central segment of the profile). Thickness of the middle water bearing formation is increasing towards western edge of the profile. A suitable site for bore well drilling would be at 140 m distance, where the water bearing formation appears to be relatively thicker. Resistivity model of profile P29 presents heterogeneous geological set up. On top is massive basalt layer, whose thickness is increasing westward from the

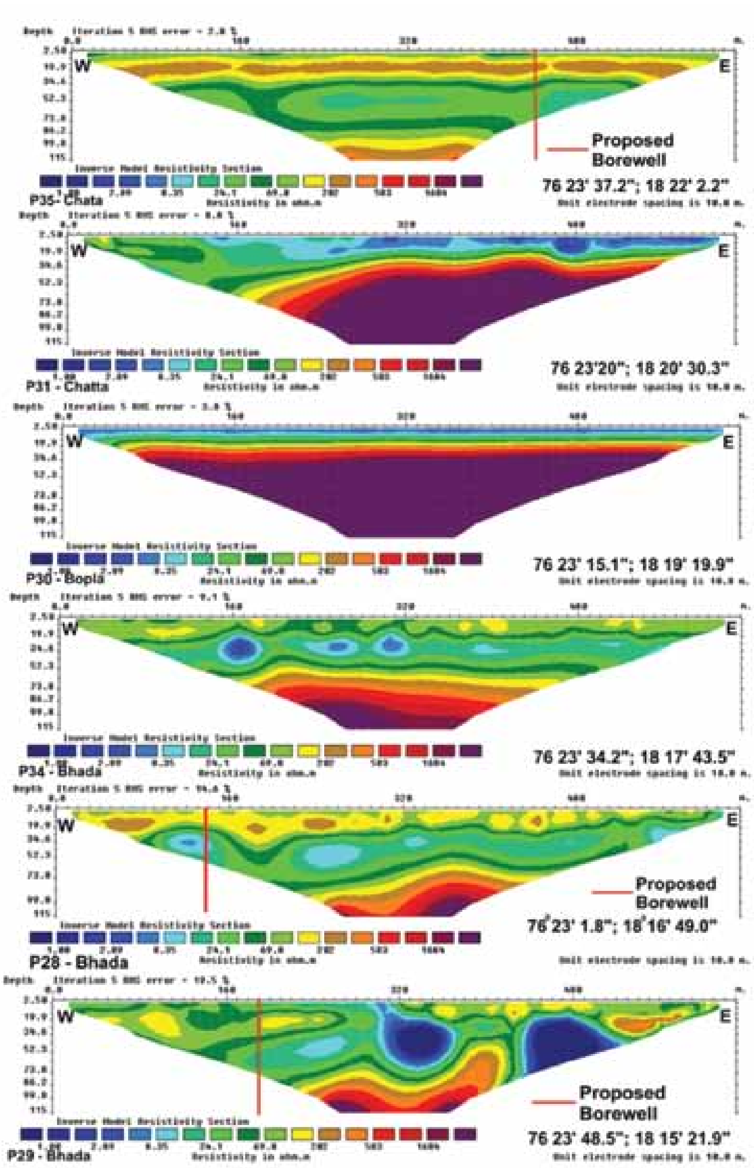

Figure 8. Resistivity models for profiles P35, P31, P30, P34, P28, P29.

center of the profile. This massive basalt unit is bisected by a fracture zone exposed on the ground surface between 270 m to 310 m. This fracture zone is connected to water bearing weathered/fractured /vesicular basalt unit, which extends below the massive basalt unit on both sides of the centre of the profile between 160 and 430 m. This is underlain by a massive basalt unit, which is visible in the central portion of the profile. A suitable site for bore well drilling would be at 200 m. Another water bearing formation can be seen below the top layer of massive basalt between 430 and 530 m. This appears to be filled with clayey red bole characterized with low resistivity value (<10 Ohm m) and as such not suitable for groundwater exploitation.

CONCLUSIONS:

Electrical Resistivity Tomography has been carried out at 33 sites. Out of 33 sites groundwater potential zones suitable for groundwater exploitation have been identified at 17 sites related to profiles P5, P6, P4, P8, P16, P11, P7, P9, P10, P14, P24, P21, P25, P22, P35, P28, and P29. Remaining profiles sites are not showing presence of groundwater potential zones. Suggested suitable sites for bore well drilling are marked by "Proposed bore well" on the respective resistivity models. Selection of sites for bore well drilling is based on the experience of previous works carried out in Chandrabhaga river basin (Ratna Kumari et al, 2012). Interpreted results of the resistivity models for the profiles P5, P6 and P21 are verified by bore well drilling results. Water supply from bore wells drilled at the suggested location may help in meeting the ever increasing demand of water supply. Electrical Resistivity Tomography results have identified several sites of aquifer recharging related to profiles P4, P8, P19, P10, P21, P18, P22 and P29. These recharge sites should be suitably modified to increase the recharge rate. This study demonstrates the efficacy of ERT survey in delineation of groundwater potential zones in complex geological environ of hard rock regions and should be taken as a role model for development and management of groundwater resources in other hard rock terrains. In some cases delineated water bearing geological formations may not be having adequate water for the purpose of pumping. In this region casing of bore well is done only for 15 to 20 m depth. Remaining portion of the bore well is left without casing. As a result sediments along with water may flow in to well sealing the interface of the bore well facing the water bearing formations/structures. This leads to the failure of bore well after 4-5 years. To avoid this situation casing of the bore wells through entire depth, with perforated casing through water bearing formations/ structures is recommended.

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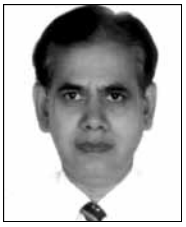

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