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Delineation and sustainable development of groundwater resources in granitic terrain using electrical resistivity tomography

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ABSTRACT

Hard rock's possess negligible primary porosity but due to inherent secondary porosity in the form of geological structures such as faults, fractures, joints etc, these rocks are rendered permeable to allow movement and storage of groundwater in limited quantity. Because of sporadic distribution of these water bearing geological structures, their delineation is a challenging task. Groundwater saturated geological formations/ structures are characterized with appreciably lower resistivity in comparison to those devoid of groundwater. Because of this, resistivity method is found to be most suitable among all the geophysical methods in delineation of groundwater bearing zones in all types of geological formations in general and hard rock terrains in particular. This paper discusses the efficacy of 2D Electrical Resistivity Tomography (ERT) to delineate groundwater bearing zones in complex hydrogeological environs like granitic terrains with the help of case studies from sites located in and around Hyderabad (Telangana state, India). ERT results have also been used to identify suitable sites for managing recharge of groundwater resources. This study has helped in establishing some criterion about the possibility of occurrence of potential groundwater resources in similar geological environs.

INTRODUCTION

A major part of southern Indian territories consisting of Telangana, Andhra Pradesh, Karnataka and Tamil Nadu states is occupied by various types of hard rock such as granites, granitic gneisses, granulites, charnokites etc. Hard rock terrains exhibit weathered formation and structural features such as fractures, joints, faults and fissures developed as secondary porosity within them. These geological formations/structures are capable of storing ground water and allow its movement through them, if these are interconnected. These geological formations/ structures are referred as aquifers in hydrological term. Acute shortage of groundwater in hard rock terrains is well known because of their limited groundwater storage capacity. In hard rock terrains, ground water occurs under phreatic condition in the top weathered formation and under semi-confined to confined conditions in fractures, faults and joints at relatively deeper level. Because of withdrawal of groundwater in excess to recharging of groundwater system to meet the ever increasing demand of water supply, groundwater level has been declining year by year beyond the recovery limit. As a result, groundwater in many areas has been almost depleted in the upper weathered formations, which happen to be the main sources of water supply to the dug wells penetrating shallower aquifers. Thus, the possibility of availability of groundwater lies in the fractures, faults, joints etc at deeper levels within the hard rock unites. Delineation of groundwater potential zones and suitable sites for managing aquifer recharge are prerequisite for the sustainable development and management of groundwater resources to ensure safe and secured water supply.

Geophysical Electrical resistivity methods with different types of electrode configurations are widely used for groundwater prospecting because of noticeable contrast in resistivity value of water saturated geological formations/ structures in comparison to those devoid of groundwater. These methods are described in detail in different text books on geophysical methods (Kirsch, 2006; Dobrin and Savit, 1988; Kearey and Brooks, 2002; Todd and Mays, 2013 etc). A 2D model of the sub-surface terrain can provide information about the distribution of different units of geological formations/structures in the vertical as well as in lateral directions below the entire spread of the survey line. This becomes possible by development of 2D electrical resistivity tomography (ERT) (Griffiths et al., 1990; Griffiths and Barker, 1993; Loke, 2000) and effective data processing softwares based on inversion techniques (Loke and Barker, 1996; Loke, 1997). The main advantages of the ERT are: (i) fast and large amount of computer controlled data acquisition, (ii) increased resolution of the computed 2D images of the resistivity variation of subsurface geological formation, and (iii) presentation of resistivity variation in vertical and horizontal directions below the entire survey line. In fact, 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 collapsing of mines, extraction of geothermal energy etc (Loke, 2000; Dutta et al., 2006; Hamzah et al., 2006; Anthony and John, 2010; Kumar et al., 2011; Rai et al., 2019). Electrical resistivity tomography has further been used in Deccan traps covered draught prone Vidarbha and Marathwada regions of Maharashtra state, India (Ratnakumari et al, 2012; Rai et al., 2015; Thiagarajan et

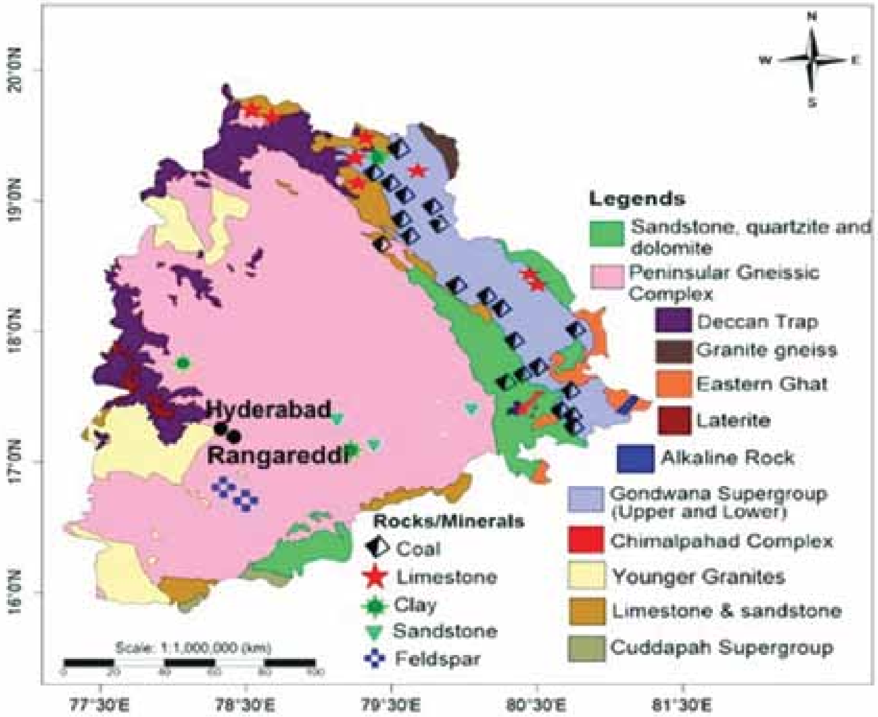

Figure 1. Geological map of Telangana (source Google).

al., 2018). The present study is aimed for delineation of aquifers and suitable sites for managing aquifer recharge using electrical resistivity tomography. The reason for failure of bore wells in short span of time and the corrective measures to overcome this problem are also discussed. The case studies presented in this paper may serve as a role model for the delineation and sustainable development of groundwater resources in other parts of hard rock terrains in order to achieve the preset objectives of management of the groundwater resources.

STUDY AREAS

The areas under investigation are located in Hyderabad city and adjoining Rangareddi district of Telangana state. Location of Hyderabad in Telagana state is shown in Figure 1. One of the investigated sites lies in the CSIR-Centre of Cellular and Micro Biology (CCMB) colony and further two sites are located in the campus of CSIR-Indian Institute of Chemical Technology (IICT). Both institutes are located in the Habshiguda area of Hyderabad. Figure 2 presents aerial view of CSIR-CCMB colony and its surroundings, together with the location of ERT profile. The colony is surrounded by Peddacheruvu (lake) from northern side, CSIR-National Geophysical Research Institute (NGRI) campus from southern side, HMT colony and CSIR-IICT colony from western side. It spreads in an area of over 14 acres. About 65% area is occupied by staff quarters. Slope of the landscape is northwards. Similarly, Indian Institute of Chemical Technology (IICT) campus is located by the side of Uppal road between Tarnaka and Habshiguda areas of Hyderabad (Figure 3). Electrical resistivity tomography is carried out along two profiles, P1 and P2, using Wenner configuration. Locations of P1 and P2 profiles are marked in figure 3. The P1 profile runs in east-west direction from staff quarter to the IICT boundary along the Uppal road through Diamond Jubilee Park (D.J. Park) and premise of Director's bungalow. The P2 profile is located in front of Lipid Science Center between IICT boundaries with Snehapuri colony in East and Nagarjunanagar colony in west. Other two ERT sites are located in a farmland under Raviryal village in Mahesharam mandal of Rangreddi district and one ERT site is located near Himayat sagar lake in the Aziz nagar under Moinabad thesil of Rangareddi district. Locations of Raviryal and Aziz nagar are shown in figures 4 and 5, respectively.

The regions under investigations are covered by the Archean granites and granite gneisses. These rocks are the major constituents of peninsular gneissic complex which occupies more than 70% surface area of Telangana state, as shown in figure 1. Gray and pink color granites are cropped out at several locations. Red soil of varying thicknesses forms top layer within the CCMB colony and IICT campus, while black soil forms top layer in the farmlands under Raviryal village and Aziz Nagar. Top soil 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

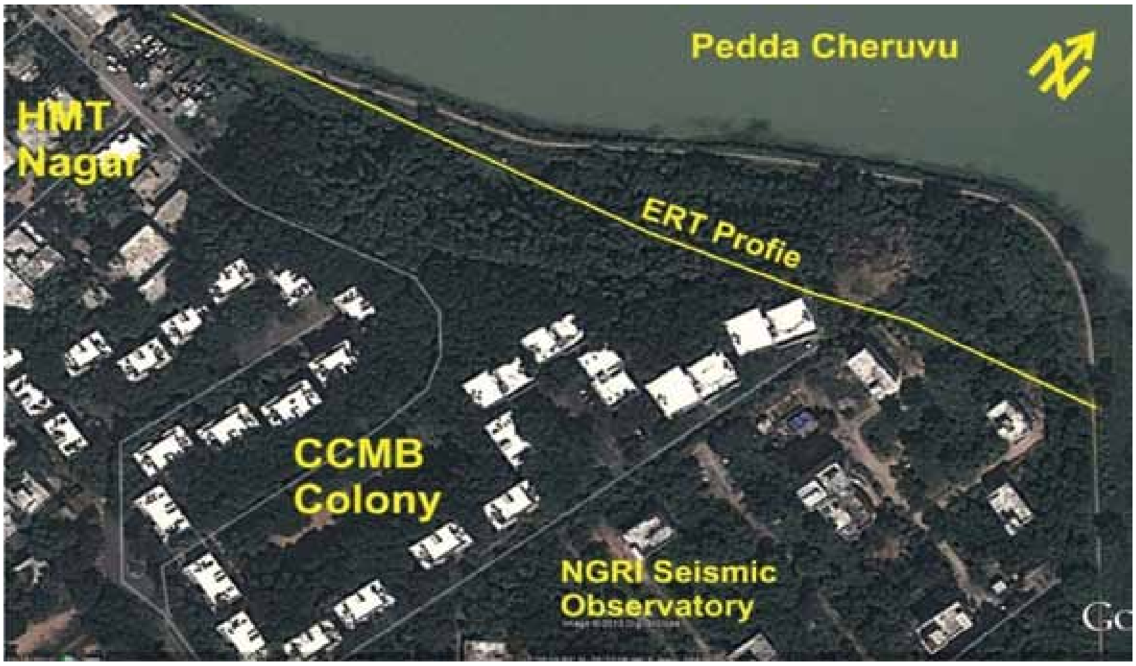

Figure 2. Aerial view of CSIR-CCMB colony along with location of ERT profile.

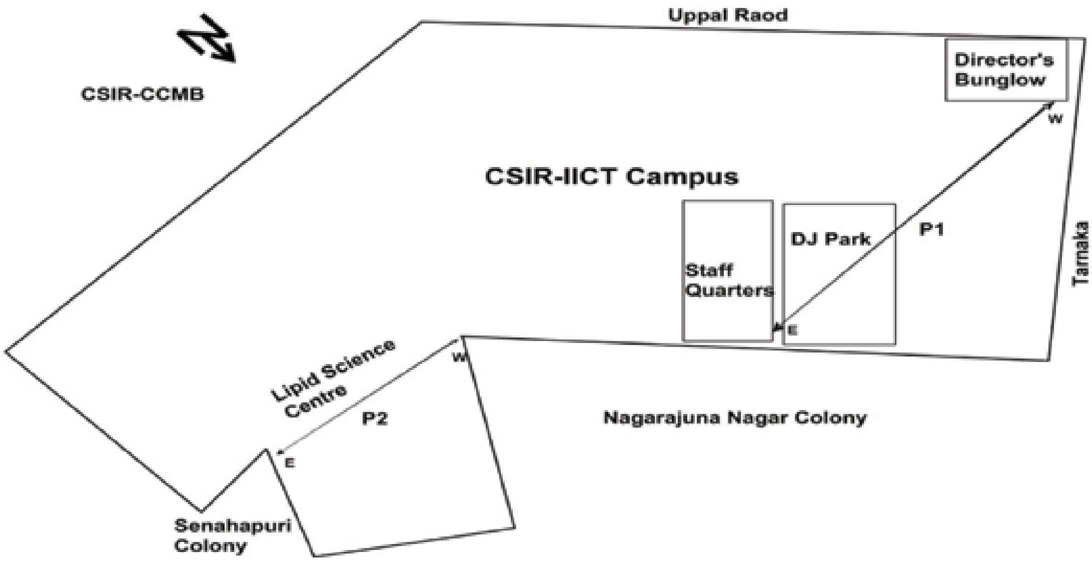

Figure 3. Location map of CSIR-IICT campus along with P1 and P2 ERT profiles

is confined mainly to the weathered and semi-weathered layers at shallower depths and in fractures and joints in massive rock units. The climatic condition in the region is of semi-arid nature. Temperature varies mostly between 16^{o}C in winter season to 44°C in peak summer season. The annual rainfall varies between 750-850 mm. The area receives more than 80% of its rainfall from the SW monsoon, mostly during rainy season from June to September. Precipitation is the main source of groundwater recharging. Estimated groundwater recharge is less than 10% of the total precipitation.

Two decades earlier, dug wells penetrating up to the depth of weathered zone were mostly used for groundwater supply. But because of exploitation of ground water resources, in excess to their recharging the groundwater level, has been continuously declining beyond its recovery limit. As a result availability of groundwater remains mostly confined to the fractured/faulted granitic rock at deeper level throughout the year, except during short period of rainy season. Thus, the possibility of availability of ground water is mainly confined to the geological structures like fractures, faults and joints at deeper level. Such water bearing geological

Figure 4. Location of Raviryal village (Source Google map)

Figure 5. Location map of Aziz Nagar (Source Google map)

structures are distributed sporadically and are of finite areal extent. Therefore, delineation of their exact locations is a challenging task. This task has now becomes possible only with the development of 2D electrical resistivity tomography (ERT) which is capable of mapping 2D images of subsurface geological formations/structures (Loke, 2000). This task is accomplished by inversion of surface measured apparent resistivity data in form of layered resistivity model, followed by its interpretation in term of geological formations. It helps in delineation of groundwater potential zones. A brief description of ERT set up used for field survey is presented below.

Electrical Resistivity Tomography

Electrical Resistivity Tomography is carried out by using multi-electrode resistivity imaging system. In this system, many electrodes are connected with multi core cables to form a multi-electrode setup. The number of electrodes differs from system to system. In the present study, the ABEM made Terrameter Lund Imaging System with 64 electrodes is used. For demonstration purpose, figure 6 shows field setup of an ERT survey with four multi-core cables. In each multi-core cable, 16 electrodes are placed at equal spacing of 10 meters. Spacing between two electrodes can be reduced during survey depending on the availability of space for ERT survey. 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. Laptop based software together with the electronic switching unit is used to select automatically four relevant electrodes (two current electrodes and two potential electrodes) for each measurement. Provision is made for resistivity survey using different electrode configurations such as Wenner, Wenner-Schlumberger, Dipole-Dipole, Pole-dipole, Pole-Pole etc. 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 into a text file which can be read by a computer program uploaded in a laptop. After reading the control file, the computer program then automatically selects the appropriate electrodes (two current electrodes and

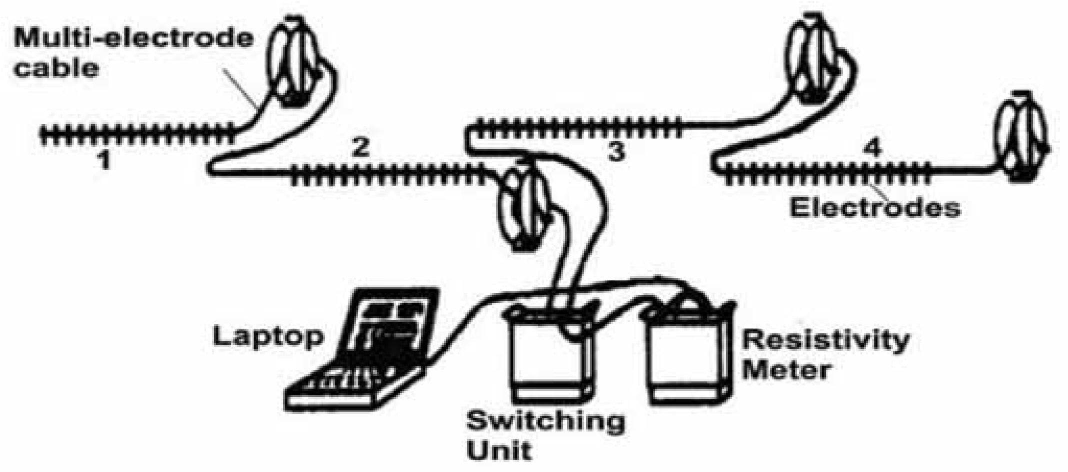

Figure 6. A sketch diagram showing field layout of ERT system

two potential electrodes) for each measurement. After that, the measurements are taken automatically and stored in the laptop. For the first measurement with 10 m electrode spacing, electrodes 1, 2, 3 and 4 are used. Electrode 1 is used as the first current electrode, electrode 2 as the first potential electrode, electrode 3 as the second potential electrode and electrode 4 as the second current electrode. For the second measurement, electrodes number 2, 3, 4 and 5 are used for first current electrode, first potential electrode, second potential electrode and second current electrode, respectively. This is repeated until electrodes 61, 62, 63 and 64 are used. After completing the sequence of measurements with 10 m spacing, the next sequence of measurements with 20 m electrode spacing is conducted. For the first measurement, electrodes 1, 3, 5 and 7 are used. For the second measurement, electrodes 2, 4, 6 and 8 are used. This process is repeated down the line until electrodes 58, 60, 62 and 64 are used for the last measurement with electrode spacing 20 m. The same process is repeated for measurements with electrode spacing 30 m, 40 m, etc. As the electrode spacing increases, the number of measurements decreases.

In ERT survey the depth of investigation is maximum below the central portion of the survey line and gradually decreases towards both ends of the survey line. Therefore, after completing the sequence of measurement for one field setup, the cable is moved along the survey profile past one of its end by several units of electrode spacing in such a way that in the next sequence of measurements, the depth coverage left over in the previous sequence of measurement is completed. By this way, it is possible to achieve the complete depth coverage of the resistivity measurements for a desired segment of the survey line. Shifting of the full length of a cable to the new position along the survey line is more convenient for this purpose. This procedure is known as roll-along (Loke, 2000; Rai et al., 2019). In present work ERT is conducted using Wenner configuration for measurement of apparent resistivity values on ground surface. The apparent resistivity value is computed by using mathematical expression $\rho_a=2\pi a\ (\Delta V / I)$ in which ρ_a is the apparent resistivity, a is the spacing between the two consecutive electrodes, ΔV is the potential difference between the two potential electrodes, and I is the current induced in to ground through current electrodes (Wenner, 1912).

The next step is to convert the measured apparent resistivity values in to a 2D true resistivity model, which can be used for geological interpretation in order to identify water bearing geological formations and structures. This task is accomplished by using inverse modeling. Inverse modeling of the measured apparent resistivity data is carried out using RES2DINV program (Loke, 1997). This program automatically creates a 2D model by dividing the subsurface into rectangular blocks. To initiate modeling, some resistivity values will be assigned to the model blocks. Thereafter, the program calculates the apparent resistivity values of the model blocks and compares them to measured apparent resistivity values. The resistivity values of model are adjusted iteratively until the calculated apparent resistivity values of the model are in close agreement with the measured apparent resistivity values. 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. RMS values should be preferably $<10\%$ or close to it. Then, the quality of field data and computed model are considered to be good. The inverse resistivity model is interpreted in terms of geological formations by correlating resistivity values with the corresponding geological formations. It helps in identifications of groundwater potential zones and suitable sites for managing aquifer recharge. Central Ground Water Board (CGWB) of the Government of India has published resistivity values of different litho units of granitic terrains in its website. These values are given in Table 1. The same

Table 1. Geological units and their respective resistivity values

Geological formations	Resistivity values in ohm m
Soil cover	< 20
Highly weathered granite saturated with water	20–50
Semi weathered granite	50–120
Moderately fractured/jointed granite	120–200
Massive granite	> 300

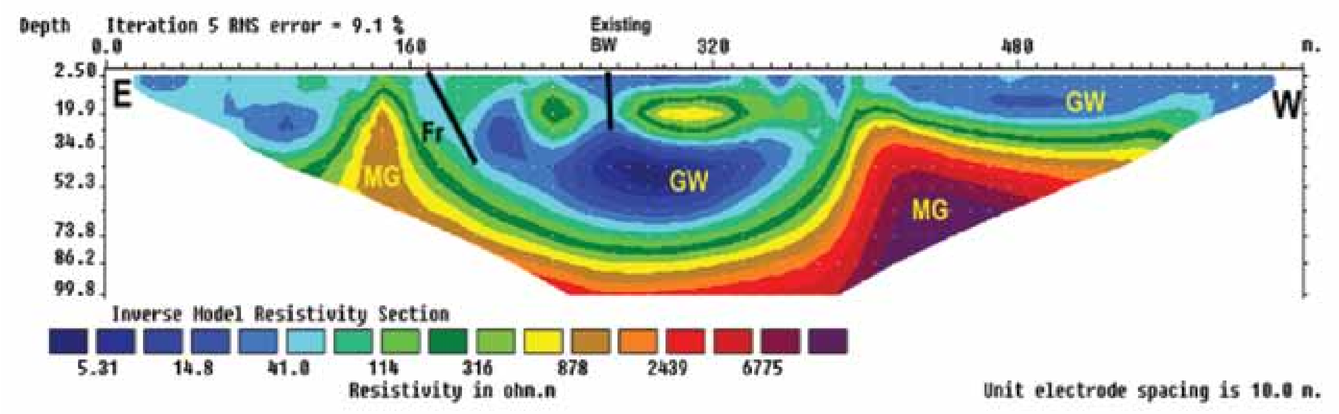

Figure 7. Resistivity model for the site in CSIR-CCMB colony; GW - groundwater zone, Fr - fracture, MG - Massive granite

values are used for interpretation of inverse resistivity models. Hereafter, inverse resistivity model will be referred as resistivity model.

RESULTS AND DISCUSSION

CSIR- CCMB Colony

Electrical Resistivity Tomography is carried out along a profile running in east to west direction along the boundary with Peddacheruvu as shown in figure 2. Profile is extended outside the boundary of CCMB Colony on both sides. Four multi-core cables each having 16 electrodes are used. Spacing between two electrodes is 10 m. For this electrode spacing, the length of this profile is 630 m. The first electrode is positioned at 78.5540°E, 17.4185°N and the last 64th electrode is positioned at 78.5499°E, 17.4219°N. Centre of the profile is located at 78.5520°E, 17.4199°N. The 2D resistivity model for the survey profile is presented in figure 7. Small vertical lines on top of the resistivity model indicate the positions of electrodes starting from 1st electrode at zero distance to the 64th electrode at 630 m. Distances are measured from E to W direction. The colored index of resistivity variation is presented below the model. The resistivity model indicates the presence of a bowl shaped set up of geological formations between 150 m and 400 m distances, which are bounded by elevated two arms of massive granites basement (> 300 Ohm). This bowl shaped set up of geological formation lies in front of CCMB colony, adjacent to the lake boundary. Within this segment of resistivity model, ~15-20 m thick two units of semi-weathered granite layer (50-120 ohm m) between 170-400 m can be seen 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 as marked by *Fr*. The semi-weathered granitic layer is underlain by water saturated semi weathered granitic 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. The resistivity model also shows the presence of a low resistivity zone (<20 ohm m) within the highly 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 water saturated zone is the main source of water supply to the CCMB colony using a bore well whose location is shown in the model. Two units of similar geological setup can also be seen towards both ends of the profile which are separated from the central unit of geological formation by both elevated arms of the massive granite. 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 remaining part of CCMB colony situated on elevated ground surface and serves as a recharge pit.

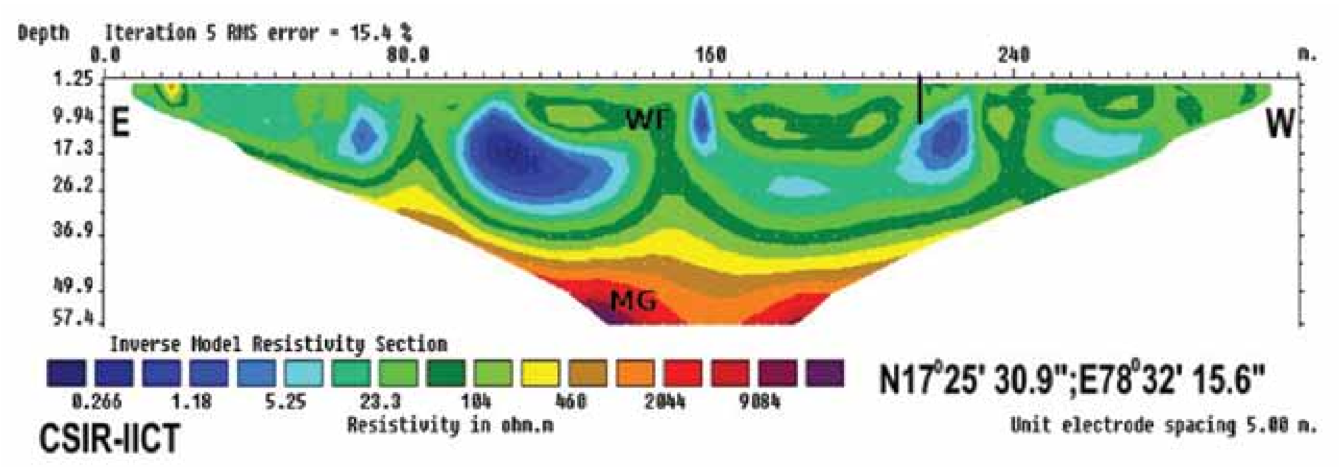

Figure 8. Inverse resistivity model along P1 profile in CSIR-IICT campus.

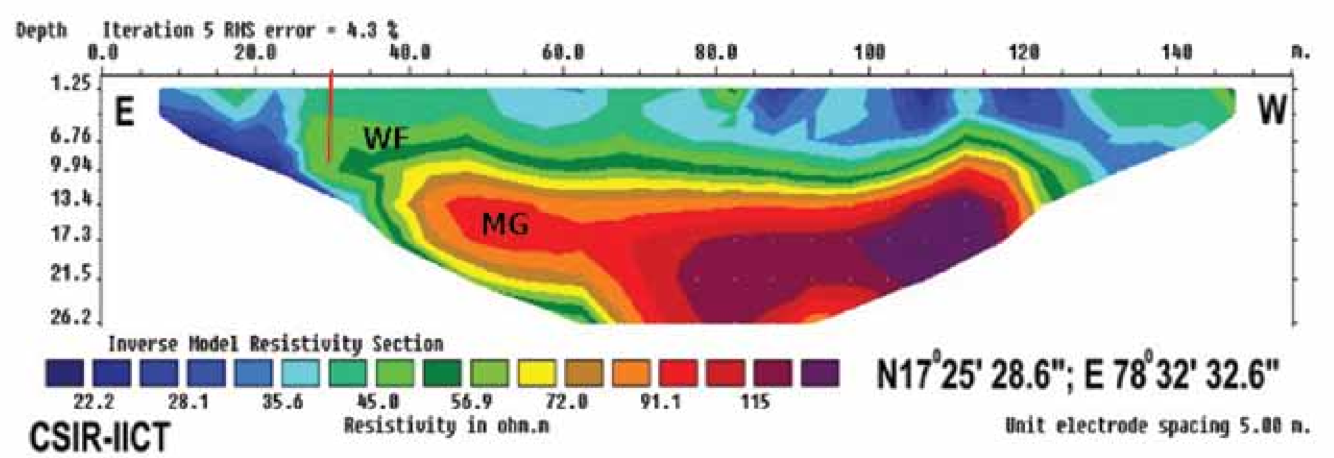

Figure 9. Inverse resistivity model along P2 profile in CSIR-IICT campus.

CSIR-IICT campus

Locations of two ERT profiles in CSIR-IICT campus marked by P1 and P2 are shown in figure 3. Profile P1 with centre at 17°25′30.9″N, 78°32′15.6″E runs in east to west direction from the corner of the staff quarter to the IICT boundary along Uppal road. This profile passes though the Diamond Jubilee Park marked as DJP in the map and the backyard of the Director's bungalow. Because of lack of space, length of this profile is restricted to 315 m only. ERT was conducted with 5m electrode spacing. Inverse resistivity model along this profile is shown in figure 8. Geological interpretation of this resistivity model suggests the presence of a composite layer of weathered and semi-weathered granitic formation (20-120 ohm m) in the depth range of ~25 to 35 m below soil cover. This layer is a water bearing. A suitable site for bore well drilling is suggested between 210 to 225 m distances where highly weathered formation is exposed on ground surface. Because of less thickness of this composite layer, its water storage capacity is too less to maintain the required demand of water supply. This resistivity model suggests the suitable site for managing aquifer recharge between 80 to 100 m distances where highly weathered granitic formation is exposed to ground surface and is low lying where run off can be diverted in to a proposed recharge structure in the form of injection well. Another suitable site for construction of injection well for groundwater recharge is between 210 to 230 m distances. Groundwater recharging from these two injection wells can increase the groundwater storage.

The second profile P2 with its centre at 17°25′28.6″ N, 78°32′32.6″ E is located in front of Lipid Science Centre. The profile is in east to west direction and lies between the two IICT boundary walls running along Snehapuri colony and Nagarjunanagar colony, as shown in figure 3. Length of the profile is only 115 m and electrode spacing used in this survey is 5 m. Resistivity model of this profile is presented in Figure 9. In this case, the depth of investigation is only 26.2 m. This resistivity model indicates the presence of highly weathered formation (<50 ohm m) on top in two units. The first unit is extended up to 25 m distance from eastern edge of the profile. The second unit is spread over in between 50 to 125 m distances. This second unit is underlain by a layer of

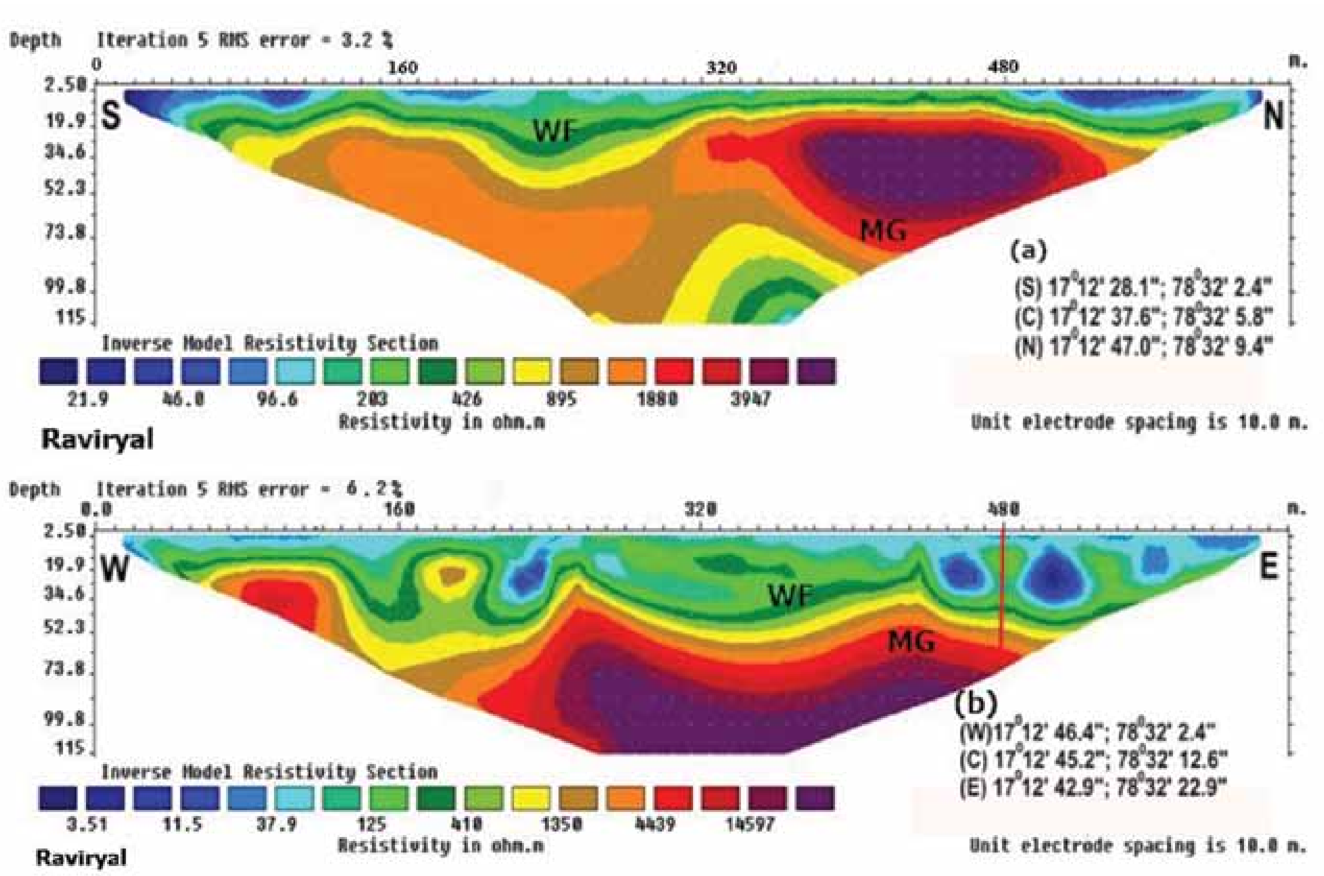

Figure 10. Resistivity models (a) and (b) in farm land under Raviryal village

semi-weathered granite which is extended up to a depth of ~ 10 m and is exposed to the ground surface between 25 m to 50m separating both units of highly weathered formation. The semi-weathered formation is underlain by massive granite unit (>300 Ohm m) between 40 m to 120 m distances. The first unit of highly weathered formation dips downwards below the massive granite unit. Similarly, the second unit of highly weathered formation is dipping downwards adjacent to the massive granite unite. Both the segments of highly weathered formations appear to be water bearing at deeper level. Suitable sites for bore well drillings are at 30 m and 130 m distances. A bore well is drilled in the first segment of the highly weathered formation and confirms the presence of groundwater. This bore well is currently in use to augment the water supply requirement of IICT. This resistivity model indicates two sites suitable for developing recharge pits for managing groundwater recharge by diverting surface runoff in to recharge pit. One site could be between eastern edge of the profile up to 20 m distance and the other one between 115 m to 130 m towards western edge of the profile. At both sites the highly weathered formation appears to be extending downwards to a greater depth.

Raviryal Village

Resistivity models presented in figures 10 (a) and (b) are along two profiles in a farm land falling under Raviryal village of Rangareddi district. This farm land is located adjacent to the Nehru outer ring road (ORR) as shown in figure 4. The profile of figure 10(a) is in south to north direction with the centre located at 17°12′45.2″N, 78°32′12.6″E. Geographical locations of the southern and northern ends of the profile are also given in the model. Length of this profile is 630 m. This model shows a thin layer of soil cover, which is underlain by massive granite unit along the entire stretch of the profile. This model does not indicate presence of any groundwater bearing zone. The profile of figure 10(b) is in west to east direction with the centre located at 17°19′51′8″ N, 78°32′12.6″ E. Geographical location of the first and last electrodes are also given in the model. Resistivity model of this profile also indicates the presence of a layer of soil on top. This is underlain by a composite layer of highly to semi-weathered granite in the depth range of 5 to 30 m. Patches of clayey formation can be seen within the soil layer which reduces its resistivity value <10 ohm m. This composite layer is

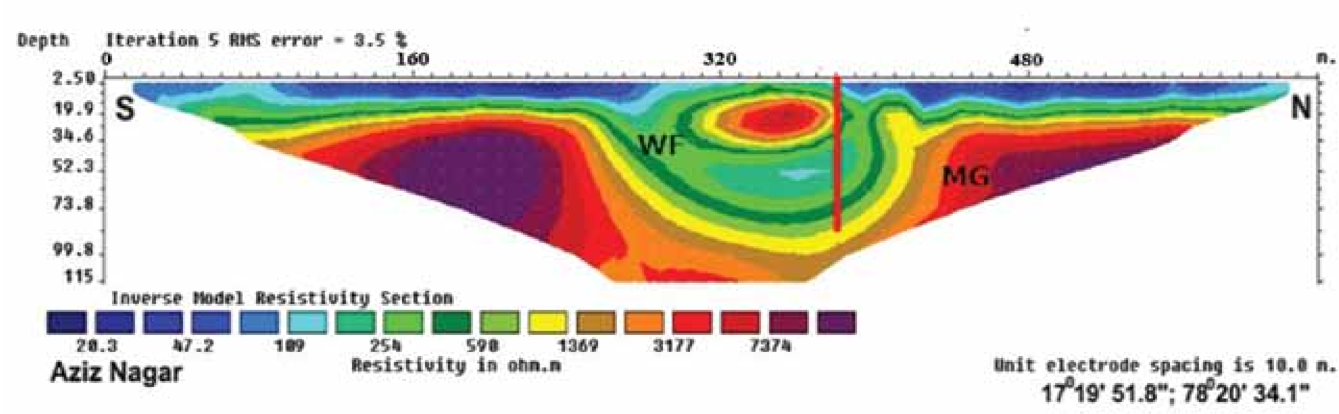

Figure 11. Inverse resistivity model in a plot in Aziz Nagar

underlain by massive granite. This profile indicates the possibility of groundwater occurrence in small quantity between 440 to the eastern edge of the profile at deeper level within the weathered granite layer. At this site development of a large diameter dug well is suggested between 480 to 550 m distances for both purposes, i.e. withdrawal of ground water for irrigation as well as managing aquifer recharge by diverting run off in to the well.

Aziz Nagar

Figure 11 presents resistivity model along a profile in a plot located near Himayat Sagar Lake in Aziz Nagar. This model indicates presence of massive granite below a thin cover of soil and weathered formation along the entire length of the profile. The massive granite unit is exposed to the ground surface between 270 m to 360 m distances. This model does not show any groundwater bearing zone.

In order to establish a criterion about the most likely possibility of occurrence of groundwater potential zones in hard rocks, in this case granitic terrain, the resistivity model of figure 9 is compared with three resistivity models obtained from ERT conducted in CSIR-NGRI campus (Rai et al., 2013). These three models are presented in figure 12. All the four models show a similar geological set up in which weathered formation is dipping downwards against the massive granite units. Presence of massive granite unit will restrict the lateral movement of groundwater beyond the interface between the massive granite and the weathered formation. In such situation the ground water will percolate down to get stored in the contact zone. Groundwater collected in the contact zone further percolate down in to fractures, faults and joints within the granite units in case if these geological structures are connected to the contact zone. In spite of less depth of investigation, occurrence of potential groundwater zones have been confirmed by bore well drilled at much deeper level in contact zone between the weathered formation and the massive granite units. This confirms more possibility of occurrence of groundwater potential zone in such geological set up.

Sustainable development

Generally in hard rock terrains, casing of bore well is done only up to the depth of weathered zone. Remaining portion of the bore well is left without casing. As a result sediment particles along with flowing groundwater water enter in to the well and get deposited around and inside the well. It leads to continuous reduction in the bore yield which ultimately resulted in to failure of bore well after few years inspite of presence of groundwater in the aquifer system. To prevent the deposition of sediments in and around the well, casing should be done for entire depth of the bore well. Slotted pipes should be used within the top layer of weathered formation to capture infiltrating rain water and within the zones of fracture, faults, joints etc of the granite unit to allow sediment free groundwater flow in to the wells as shown in figure 13. Slots of 10 to 12 cm length can be made around the periphery of pipes by pipe cutter. This measure helps in sustaining the bore yield. This is being experienced from a bore well drilled in the NGRI campus. Information about the depth of water bearing geological formations/structures beyond the depth of investigation can be obtained from the driller during drilling operation. This can be further verified by sonic log. The sonic log presents two parallel plots; one plot of travel time of an elastic wave through the geological formation and another plot of corresponding velocity of the elastic wave in that formation. If the elastic wave passes through water bearing geological formation/structures, it will be reflected in the decrease of velocity and corresponding increase in the travel time in comparison to the velocity and travel time for the same geological formations/structures devoid of water. Thus by sonic log and information collected from the driller the presence of water bearing zones delineated by interpretation of ERT data is confirmed (Rai et al., 2013).

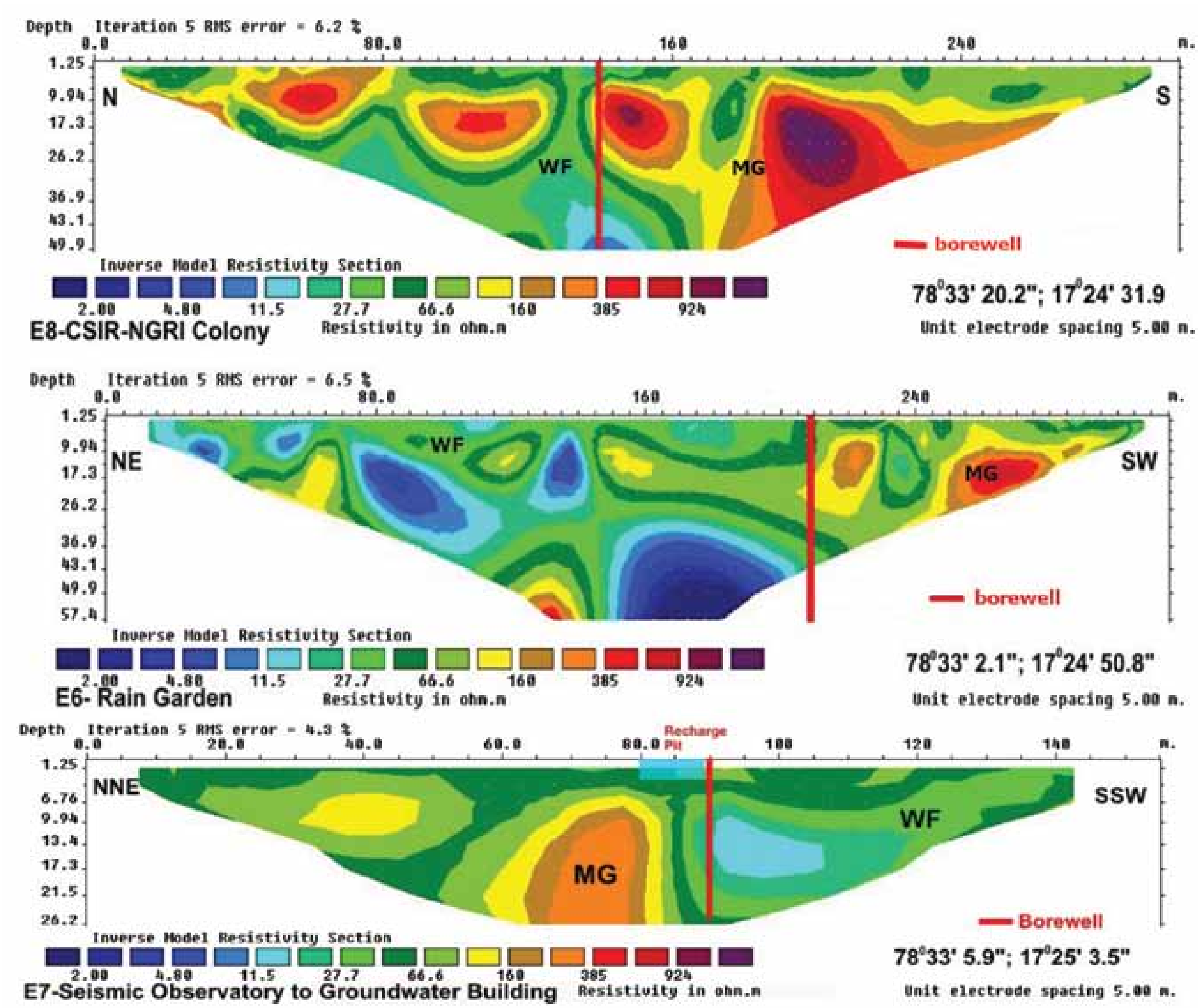

Figure12. Resistivity models from CSIR-NGRI campus. (after Rai et al., 2013)

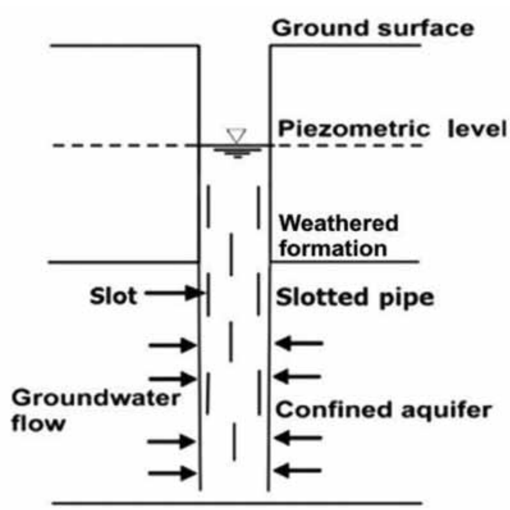

Figure 13. Bore well casing with slotted pipe within water bearing aquifers.

CONCLUSIONS

Electrical resistivity tomography has been carried out along 8 profiles, namely one in CCMB colony, two in the premise of IICT, two profiles in a farm land under Raviryal village and one profile in Aziz Nagar to delineate groundwater potential zones and sites suitable for managing groundwater recharge to increase the storage of groundwater. Interpretation of resistivity models indicates the occurrence of potential groundwater zone in CCMB colony and at the site of P2 profile in front of Lipid Science centre of IICT. One resistivity model in the farm land under Raviryal village indicates the presence of aquifer. Other resistivity models of Raviryal and Aziz Nagar do not show presence of ground water resources along the surveyed profiles. Sites for bore well drilling and for managing groundwater recharging have been also suggested. Development of one dug well at one site in the farm land of Raviryal village is also suggested, which can be used to store the groundwater. This study demonstrates the efficacy of ERT in delineation of groundwater potential zones and suitable sites for managing aquifer recharge. The use of slotted pipes for bore well casing within the weathered formation at shallower depth and in water bearing geological structures such as fracture, faults etc within the granites at deeper level is suggested to secure the bore well yield for a longer period. This work also suggests very strong possibility of occurrence of potential groundwater zone in the contact zone between weathered formation and massive hard rock unit.

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Compliance with Ethical Standards

The authors declare that they have no conflict of interest and adhere to copyright norms.

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