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ORIGINAL PAPER

Two-dimensional electrical resistivity tomography (ERT) and time-domain-induced polarization (TDIP) study in hard rock for groundwater investigation: a case study at Choutuppal Telangana, India

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Abstract Groundwater investigation in a crystalline rock is a crucial task. A study was carried out at Choutuppal Telangana, India, under the pivotal research project of societal relevance. High-resolution electrical resistivity tomography (ERT) and time-domain-induced polarization (TDIP) dataset were collected in a granitic terrain to solve the groundwater problem as people are facing acute shortage of drinking water in the study area. The interpreted results derived from two-dimensional (2D) inverted resistivity models revealed substantial resistivity contrast between the weathered and massive granite and delineated three groundwater prospects zones, where the degree of weathering of fractured granite decreases with depth. On the other hand, the induced polarization (IP) results reflect marginal chargeability contrast, which indicates groundwater prospect zone. The basement of the hard rock aquifer system is clearly delineated showing very high resistivity with a range from 5000 to ~4×10^5 Ohm.m, which is confirmed by drilling at two places. Both the wells are drilled during the month of April and June, 2013, which are productive with a yield varying from 82.14 to 105 l/min. This study may help in future planning for groundwater exploration strategy and development for groundwater resources.

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Keywords Electrical resistivity · Induced polarization · Granitic hard rock aquifer · Groundwater exploration · India

Introduction

The study area falls in Choutuppal mandal of Nalgonda district, Telangana, India, which is considered as one of the semi-critical regions in terms of groundwater availability for the people and their daily requirements (CGWB 2007). The area is underlain by granitic rocks. Groundwater is the main source on which the local people are dependent for their need for both domestic and agriculture purposes. A detailed geophysical investigation is prerequisite to understand the geology, hydrogeological condition, geological structure(s) and the groundwater prospect zones in Choutuppal mandal, Nalgonda district, Telangana. A model study for watershed management is under implementation by CSIR-NGRI Hyderabad, India. Mandollagudem Gram Panchayat within this mandal is demonstrated as a prototype to village communities and government agencies for effective implementation of watershed management programme. During the field survey, no major tectonic fracture(s) in Choutuppal and surrounding area was observed. But, the thin/sparse fracture(s) concealed within the granitic rock, which when connected in hard rock aquifer system is only responsible for productive yield of borewells (Leveinen et al. 1998; Marechal et al. 2004). Two-dimensional electrical resistivity tomography technique along with induced polarization was applied in the study area for mapping subsurface geology and structure, the rock physical property for groundwater prospecting and development. The conventional direct current (DC) electrical surveys are designed to discriminate between anomalies reflecting subsurface electrical resistivity contrasts associated

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with lithology and/or hydrological characteristics. The interpretation of the resistivity sounding data is usually made assuming a homogeneous stratified earth (Keller and Frischknecht 1966; Koefoed 1979) and can only provide the parameters of a horizontally layered model with limited resolution of the subsurface formations. The spatial variations of earth materials or topographic effects, however, invalidate such assumptions. Hence, the highly heterogeneous nature of the overburden rock materials suggests that situations could arise in which the 1D layered earth models do not account for the realistic geological subsurface structures. This implies that at least two-dimensional (2D) information is utmost required in hard rock terrain where inherent heterogeneity and anisotropy play a major role (Ritz et al. 1999). The application of the electrical resistivity tomography (ERT) proved useful to investigate the complex geology and poorly stratified lateritic overburden rock mass (Griffiths and Barker 1993; Ritz et al. 1999). Two-dimensional large data density resistivity models resulted from ERT applications are more appropriate and reliable to investigate the deep weathered mantle in detail since they are able to map both the vertical and lateral variations of the resistivity, whereas the 1D resistivity models are based on limited measurements of the apparent resistivity dataset and thus resulted in poor geoelectric contrast and information of the subsurface formations (Beauvais et al. 1999, 2004). The main advantage of the multielectrode resistivity tomography is its efficacy for distinct view of the geoelectrical changes within the regolith (a layer of loose, heterogeneous material covering solid rock), which is readily related to the changes in the porosity and permeability values in a typical vertical profile in crystalline rocks (Owen et al. 2005; Kumar et al. 2013). The work by Kumar (2012) had shown the efficacy of the resistivity tomography technique in mapping shallow subsurface anomaly including deeper groundwater resources in different geological terrain of hard rock system in various parts of the country. ERT—an active source resistivity technique applied in quartzitic hard rock formation in a highly tectonically disturbed ridge region—indicated clear and distinct resistivity anomalies in terms of groundwater potential zones for exploration (Kumar et al. 2014a). In another work, the 2D resistivity model results deciphered potential groundwater zones within and below the Deccan traps in the Lameta/Gondwana formations as well as deeper groundwater resources (between 115 and 120 m) are delineated in Nagpur district, Maharashtra (Ratna Kumari et al. 2012). In addition, the application of ERT and time-domain-induced polarization (TDIP) techniques was used both for the groundwater exploration, mapping the lithology and delineation of the water-saturated fractured zones in various parts of the world in different geological terrains (Owen et al. 2005; Robert et al. 2011; Gazoty et al. 2012). Hard rock is devoid of primary porosity, and the secondary porosity like the joints and fractures developed within the hard rock is the main source of groundwater, and these joints and fracture(s) are acting as a conduit for groundwater flow and movement through the network of fracture system in hard rock. The weathered rock material is also responsible for the development of the secondary porosity within the hard rock aquifer system (Babar 2005; CGWB 2013; Singh and Verma 2015).

In another study, Venkateswara Rao et al. (2013) had shown the advantage of 2D resistivity and induced polarization (IP) imaging results for the identification of kaolinized layer and depth of kaolinization in a typical Khondalitic terrain—a type of hard rock. They showed that the resistivity and IP results provided a clear view of the thickness of the highly weathered zone at both the successful and failed wells in the Khondalite hard rock region. Revil et al. (2012) in their work had explained about low-frequency electrical methods for subsurface characterization and monitoring groundwater in the unsaturated zone. The main objective of the present study is to delineate the potential groundwater zones for exploration and development in the area of investigation using high-resolution geophysical results, drilling and the validation of the model results. In addition, another objective is to develop the conceptual geological model based on the integrated work for sustainable groundwater development in the area of study.

Study area

The study area is situated in Choutuppal mandal, Nalgonda district, Telangana, India (Fig. 1) and is located at about 60 km from CSIR-NGRI, Hyderabad, towards east direction on the way to Vijayawada National highway. It lies between 17° 17′ 45″ N to 17° 19′ 15″ N latitude and 78° 54′ 45″ E to 78° 56′ 15″ E longitude (Fig. 2) and forms a part of the Survey of India toposheet no. 56K/15. It belongs to semi-arid to arid region. The general elevation ranges from 346 to 359 m above mean sea level. Around 95 % of irrigation is utilizing direct use of groundwater. Paddy, cotton, red gram and castor are the main crops grown in this area. The large-diameter dug wells are noticed in and around the study area whose depth ranging between 5 and 15 m below ground level (bgl) having little or no water. In earlier days, these dug wells which were considered as a major dependable source of water supply to the villagers are now almost in defunct state. At present day, groundwater is being exploited mainly from the deep weathered, fractured/fissured part of saturated granite and is the main aquifer in this region. The two major lineaments in EW and NW-SE directions control the direction of all the three river courses namely Krishna, Peddavagu and Paler. All other streams and nallas of lower order are controlled by minor lineaments. The major river Krishna is perennial, and all other rivers are seasonal and ephemeral. The overall drainage pattern in the district is dendritic to sub-dendritic and rectangular (CGWB 2007) in nature.

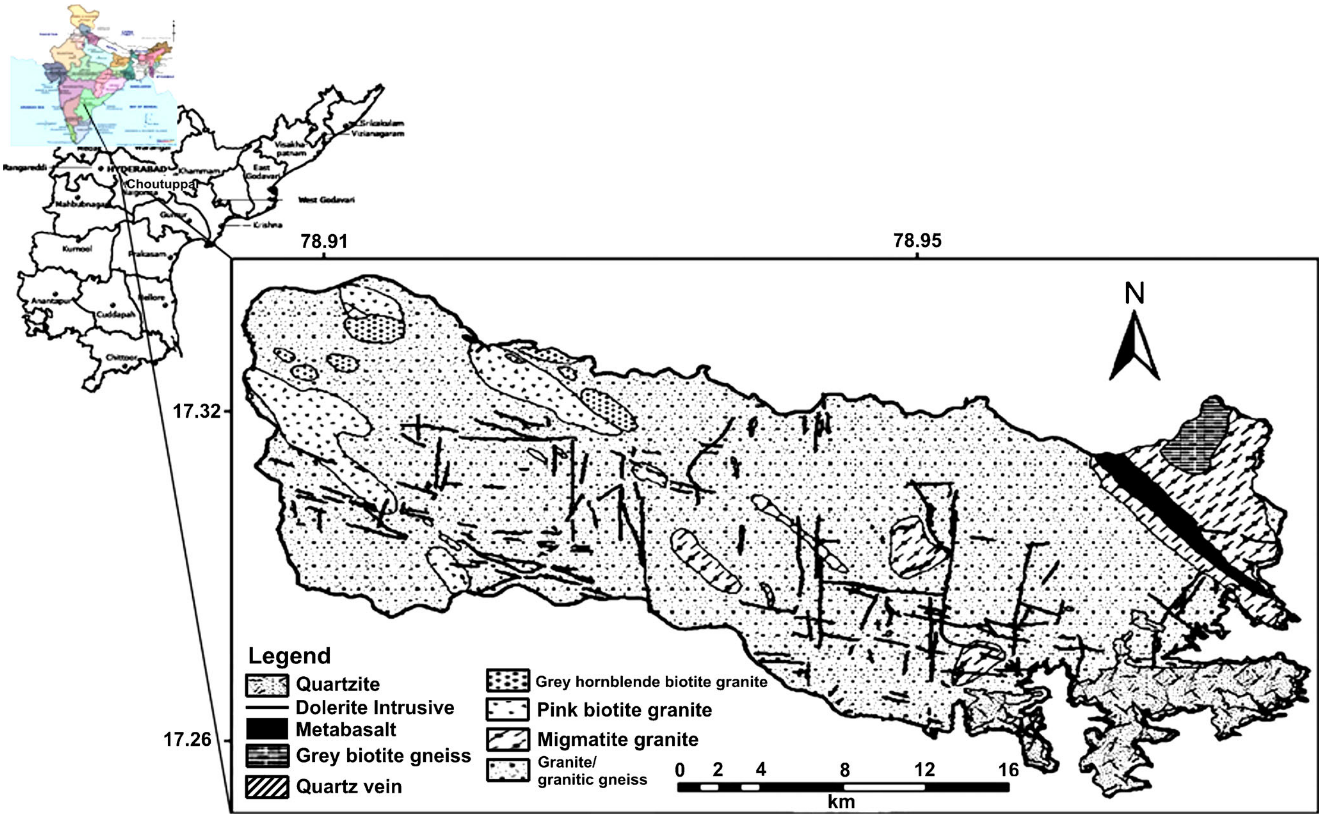


Fig. 1 Geological map of study area showing all the major rock units, structure and type of granitic rocks (*after* GSI 1995), Nalgonda district, India

Geology and hydrogeology

The geology of the Choutuppal mandal, Nalgonda district, is mainly underlain by granites. The basement rock is composed of granite, which is traversed by numerous geological structures like dolerite dykes and quartz veins (Fig. 1). Generally, granites are medium- to coarse-grained rock, and in major parts of the study area, pink and grey granites are common. We have also come across the exposures of granitic/granitic gneisses rock, which belongs to Archaean group. The Cuddapah Supergroup, which is the youngest member of the Srisailam Formation, directly overlies the basement granite with distinct unconformity. The southeastern part of the district area is mostly exposed by metamorphic sediments of Srisailam Formation. The sediments of Srisailam Formation are mainly arenaceous and include pebbly-gritty quartzite shale with dolomitic limestone, intercalated sequence of shale-quartzite and massive quartzites. The detailed stratigraphy sequence of the rock is depicted below:

The stratigraphic sequence of the study area (after GSI, 1995)

Cuddapah Supergroup	Massive quartzite
Srisailam Formation	Upper shale
	Quartzite with shale intercalation
	Lower shale with limestone intercalation
	Pebbly and gritty quartzite/ arenite

---------------------------------------Eparchean Unconformity----------------------------

Late Archaean/ Lower Proterozoic	Granite/granitic gneiss intrusion of dolerite dykes and quartz veins

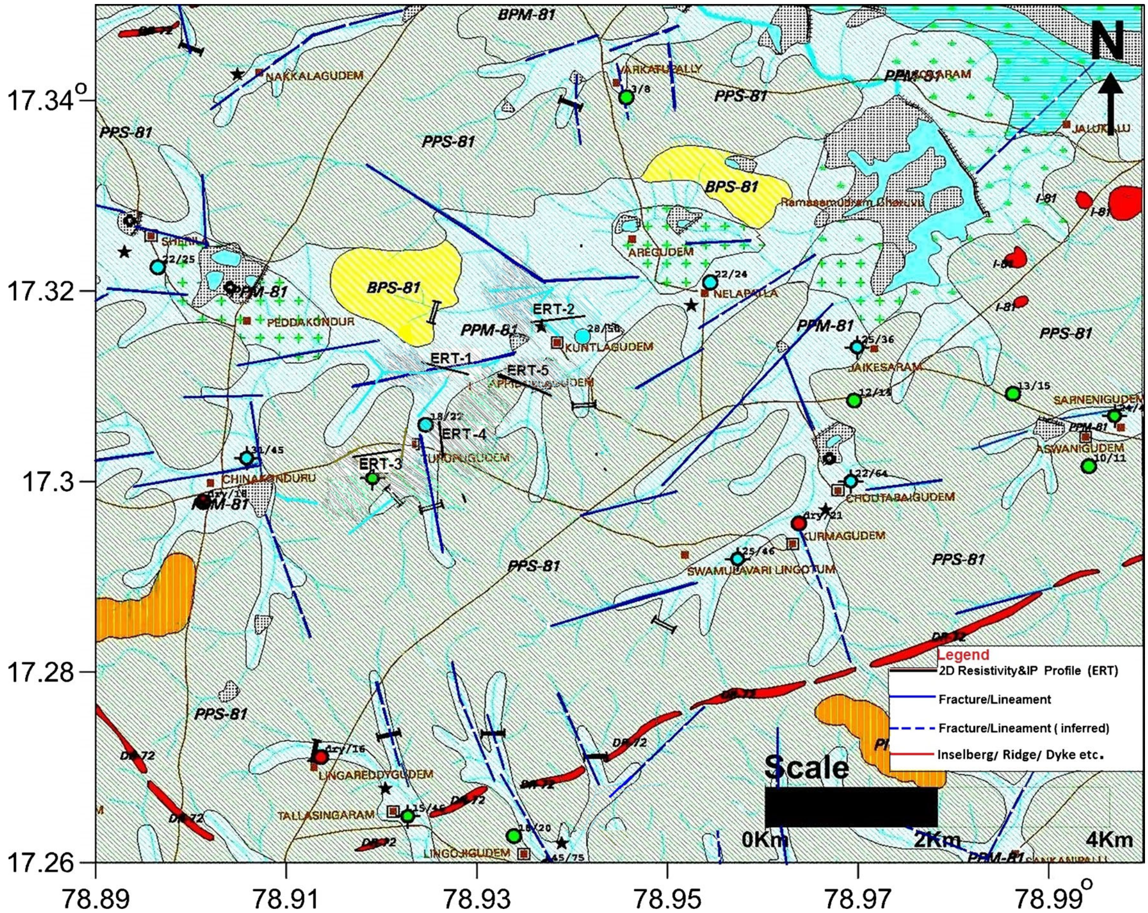


Fig. 2 Geological and geomorphological map with the location of 2D resistivity profiles (ERT-1 to ERT-5) in the study area

Almost 90 % of the district area comprises granites, gneisses, schist and intrusive, which are the crystalline rocks, and 9 % of the southern part of the area is underlain by consolidated metasedimentary rocks of Cuddapah and Kurnool system comprising limestones, quartzites and shales. The Choutuppal mandal is underlain by granite, and the basement granitic rock is exposed in some part of the study area. The secondary porosity in these hard rocks is formed due to dynamic process of the weathering in which rock undergoes fracturing, fissuring and joints over a period of time, which forms the repository for groundwater accumulation and movement. Groundwater occurs in semi-confined to confined condition in the fractured/fissured part of the granitic hard rock aquifer, where the availability of groundwater in the weathered granitic zone is very limited. The near-surface zone is characterized as soils, which are mainly black cotton, alkaline and alluvial soils of which red soils constitute 85 % of the area. Black soil is found over the limestone area in the south-eastern part of the district. The static water levels varied from 8 to 15 m bgl during 1999 (Source: 1998, Groundwater prospects map, Satellite Imagery NRSA, Govt. of India). But, during the geophysical field work accomplished in the month of January, 2013, the measured water levels vary between 20 to 28 m bgl at the studied sites of the area. While during the hydrogeological field work, the static water levels measured using light and sound water level indicator in April, 2013, are found quite deep—the maximum measured level is 33.55 m bgl, and the minimum recorded is 4.5 m bgl in the same area. This shows a large variation of the water levels within the area of study. The deep weathered and the saturated fractured/fissured granite constitutes the main part of the aquifer zone in this region, which yields the groundwater and is the main source of groundwater availability. The yield of the wells is more only when they encounter well-developed and interconnected saturated fracture/fissured zone(s). The major tectonic fracture is absent within the subsurface host rock, which is also directly visible from the near-surface exposed rocks – looks totally fresh and hard.

Groundwater prospects of Choutuppal

Choutuppal area belongs to a peninsular gneissic complex and constitutes granites and gneisses hard rock terrain (CGWB 2007). The average annual rainfall of the area is 690 mm (CGWB 2007). The yield of the wells ranges from 200 to

400 l/min (lpm), and their depth ranges from 30 to 80 m (Source 1998. Groundwater prospects map, Satellite Imagery NRSA, Govt. of India). The area is underlain by minor fracture/lineament, and the natural recharge is moderate to good. Geomorphic and landform is pediplain, which is moderately weathered. During the years 2011–2012, the groundwater prospects are not good, either the levels of water in the existing borewells are depleted or the existing source of water is totally dry. This makes the local people more concern about the availability of groundwater and is forced to depend on the alternative source of packed water from local market especially for drinking purposes or buying it from the municipal water tankers. Ironically, in the year 2011, the annual rainfall is comparatively less and it is only 258 mm. The net natural recharge to the aquifer is less due to less and sporadic rainfall during the monsoon period. Especially during the summer month, the villagers face a severe water crisis. The study shows that only the saturated part of the deep weathered, fractured granitic rock is acting as an aquifer and is productive, but the yield is relatively moderate to less and is linked to the connectivity of the fracture(s) and their distribution as well as the recharge source, which is feeding the aquifer.

Methodology

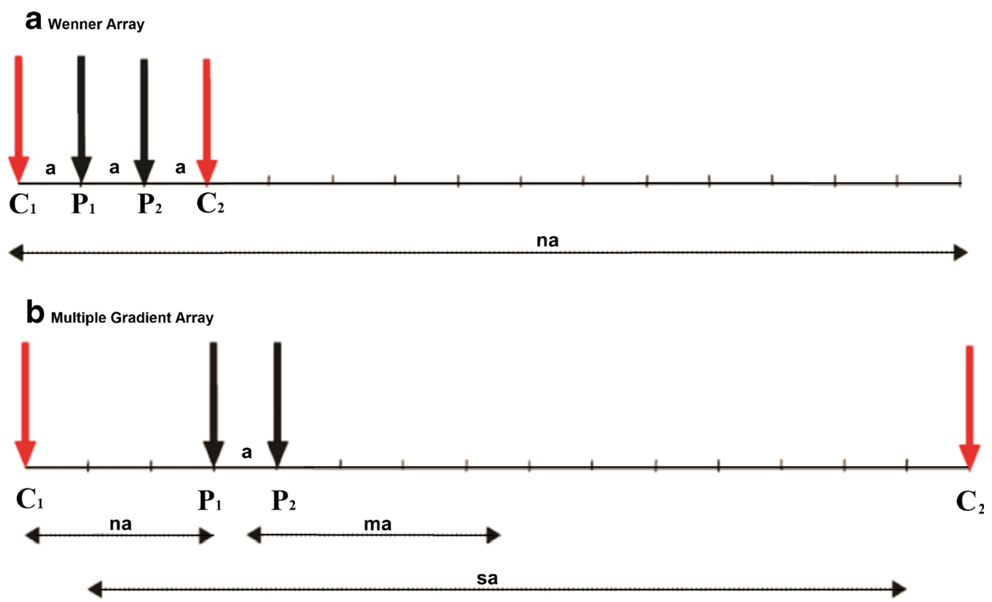
A full waveform electrical resistivity tomography (ERT) in conjunction with a TDIP good-quality dataset was collected in a granitic hard rock terrain along a 4.1 km line at five sites (Fig. 2, ERT-1 to ERT-5) in four water scarce villages in Choutuppal mandal Nalgonda district, Telangana, India. The main idea is to map the geological structure, hydrogeological features and delineating prospect groundwater zone(s) for exploration and development of groundwater resource within the surrounding villages in the study area.

ERT is widely used in groundwater prospecting and other geoscientific studies (Griffiths and Turnbull 1985; Griffiths et al. 1990; Barker 1992; Griffiths and Barker 1993; Dahlin 1996; Hossain 2000; Batayneh Awni 2001; Daily et al. 2004; Kumar 2012, 2004; Adepelumi et al. 2006; Krishnamurthy et al. 2009; Kumar et al. 2010; Shamaun Kabir et al. 2011; Andrade 2011; Robert et al. 2011; Abdulaziz et al. 2012 and Kumar et al. 2014a, b). A recent evaluation of inverse modelling has pointed out the importance of dense data sampling (Dahlin and Loke 1998). The true resistivity of subsurface geological formations and structure was estimated using a least-squares smoothness constrained inversion algorithm, RES2DINV version *3.71* Loke and Dahlin (2002). In the 2D inversion of resistivity data, Dahlin and Loke (1998) have found that in areas with a large resistivity contrasts, the Gauss-Newton least-squares inversion method leads to significantly more accurate results than the quasi-Newton method (Loke and Barker 1996). Dahlin and Zhou (2006) in their work based on the field comparisons concluded that the gradient array gives the best imaging resolution than the conventionally used arrays namely Wenner, Schlumberger, dipole-dipole and pole-dipole (Dahlin and Zhou 2006). The results supported earlier numerical modelling studies (Lu et al. 1999; Dahlin and Zhou 2004), which concluded that the gradient array using multiple current electrode combinations offers a good lateral and vertical resolution as good as or better than the commonly used Wenner array (Sketch 1). It resulted due to stable field dataset and good signal to noise ratio. In our present work, we need both the large data density coverage as well as better resolution in order to delineate even the minor hydrogeological prospecting zone(s) for groundwater exploration and development. Taking this as a consideration, idea and the geological field set-up of the area, we carried out ERT using gradient array for acquiring the field apparent resistivity along with a TDIP dataset. This gradient array is well suited for multichannel data acquisition and can significantly increase the speed of data acquisition in the field and, at the same time, provide higher data density coverage with improved resolution of subsurface formations. It offers a lower sensitivity to noise, which may be a major advantage in real-time data acquisition (Dahlin and Zhou 2006). Nevertheless, the gradient array measurements cover wider data coverage especially at the deeper level with better accuracy, which gives additional valuable information related to deeper rock strata and in terms of taking meaningful decision for groundwater exploration of the heterogeneous hard rock aquifer system. In the present investigation at each site, a total of 1072 apparent resistivity full waveform data points were collected in both resistivity and IP mode using state-of-the art four-channel ABEM Terrameter LS system (ABEM 2012).

Interpretation

Site 1: Mandollagudem

The 2D inverted subsurface resistivity model in a granitic hard rock region at Mandollagudem ERT-1 is shown in Fig. 3a. This profile is located as in Fig. 2 near the village in a plain ground at an elevation of 347 m above mean sea level (amsl) in W-E direction. The interpretation of the resistivity model shows that near-surface layer is a soil cover showing resistivity of the order of 10–30 Ohm.m followed by weathered granite, which shows a resistivity value of ~40–80 Ohm.m at a depth of 18 m. It is underlain by a low-resistivity zone showing that resistivity ~160–200 Ohm.m is revealed at a lateral distance between 320 and 370 m indicating weathered/fractured granite saturated with water but at a shallow depth up to 50 m while IP data reflects marginal contrast around this depth (Fig. 3b). On the western side at a depth from 30 to 100 m and right below 160-m lateral distance, it appears a



Sketch 1. Electrode configurations used for data measurement, C_1 and C_2 are the injecting current electrodes while P_1 and P_2 are the potential electrodes. **a** Wenner array—both the current and potential electrodes are moved concurrently for each data measurement at an interval of the minimum electrode spacing 'a'. **b** Multiple-gradient array—the current electrodes are kept fixed at the end of the survey line or other specified electrode positions while the potential measuring electrodes are progressively moved within the current electrodes for each data measurement at an interval of the minimum electrode spacing '*a*'. Where the separation factor '*s*', an integer is defined as the maximum number of potential measurements that can be measured for a given current injection. The factor '*n*' is defined as the relative spacing between the potential dipole and the closest current electrode, while the factor '*m*' is the position of the midpoint of the potential dipole relative to the midpoint of the two current electrodes (*after* Aizebeokhai and Oyeyemi 2014)

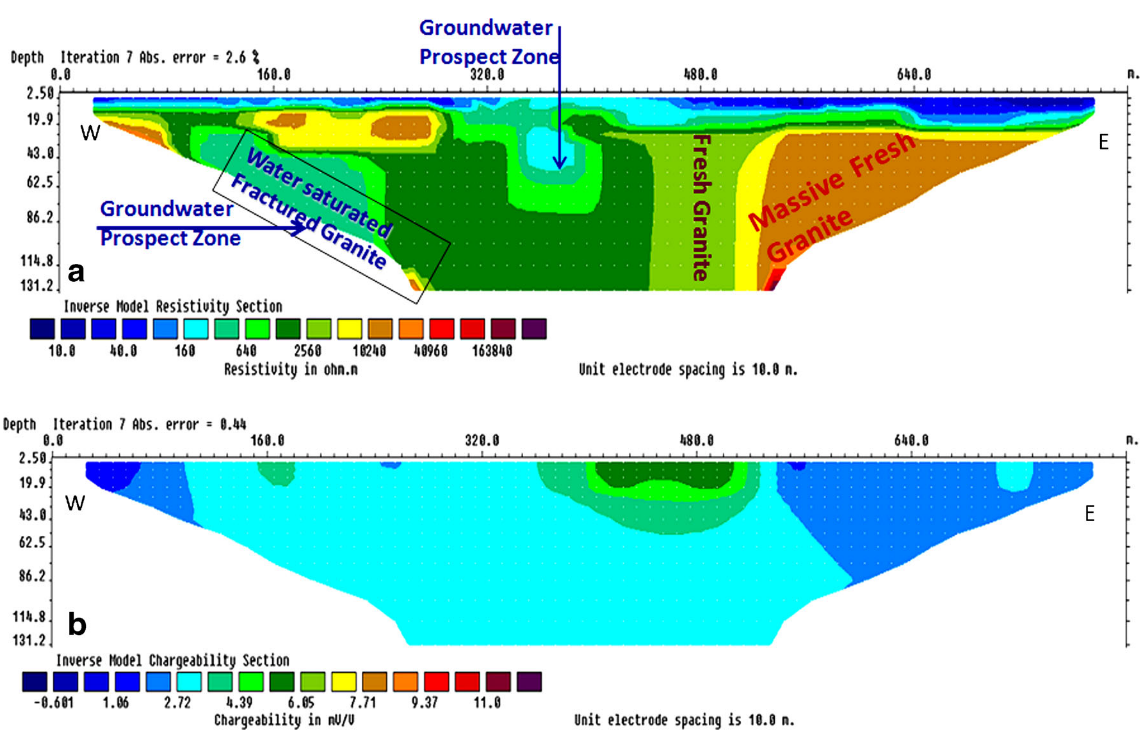


Fig. 3 **a** 2D inverted resistivity section at Mandollagudem site in a granitic hard rock region with sharp resistivity contrast between water-saturated fractured granite and massive fresh granite and with a localized groundwater pocket. **b** Depicts 2D inverted chargeability section showing no major anomaly throughout the profile, and only minor anomaly around 480-m distance is visible due to clayey soil near the surface

productive aquifer zone in the western side (Fig. 3a). The IP model reveals the change in chargeability, which favours for groundwater reserve (Fig. 3b). This aquifer zone reveals a resistivity anomaly between ~200 and 450 Ohm.m, which is interpreted as the saturated fractured granite and is extending in SW direction (Fig. 3a) to a deeper depth. While towards the eastern side, the scenario is quite different and the model resistivity shows an increase in resistivity with depth and here is no any productive groundwater zone. In the eastern side, a thick block of massive fresh granite is revealed with a very high resistivity value 10,000—~10^5 Ohm.m showing no sign of prospect groundwater zone towards eastern side both in lateral and in vertical directions.

Site 2: between Singarayacheruvu and Kuntlagudem

The subsurface 2D resistivity inverted model is shown between Singarayacheruvu and Kuntlagudem village (Fig. 4). This resistivity profile is located as in Fig. 2 in a plain ground at an elevation of 346 m amsl in NE to SW direction. It is showing a layered structure with undulating nature of granite and an increase in resistivity with depths right from ~20 m down to a depth of 110 m (Fig. 4). The near-surface layer appears as conducting and is indicative of soil mixed with clay whose resistivity is <10 to 20 Ohm.m up to a depth of 15 m. Later, it is followed by an increase in resistivity with depth. Beyond 70 m depth, the high resistivity values indicate massive granitic rock (Fig. 4), which indicates no tectonic fracture showing no sign of prospect hydrogeological condition. Such area in hard crystalline rock is totally devoid of water.

Site 3: Toorpugudem

This site is still very complex and heterogeneous in nature as revealed from the resistivity model. The inverted resistivity model at Toorpugudem site is showing a prominent lateral heterogeneity from NE to SW direction (Fig. 5). The 2D resistivity model is located as in Fig. 2 at an elevation of 357 m amsl, which is slightly more elevated than the previous two studied sites. The near-surface layer is characterized by weathered granite with a resistivity of 40–100 Ohm.m, and this layer is growing thicker in SW direction. A comparatively low-resistivity 300–500 Ohm.m zone revealed up to 35–40-m depth below 360 m lateral distance (Fig. 5) indicating saturated fractured granite surrounded by unfractured granite with a resistivity of the order of 600–1500 Ohm.m. This low-resistivity zone surrounded by high resistivity suggests a prospect groundwater target but is limited to a depth up to 45 m only (Fig. 5). Below 45 m depth, it shows the resistive granite formation all along NE-SW section (Fig. 5) showing no major sign of groundwater resource at a deeper level.

Site 4: between Mandollagudem and Toorpugudem village

The 2D inverted subsurface resistivity model between Mandollagudem and Toorpugudem village is depicted in Fig. 6a. This profile is located near the primary school and is situated in the low-lying area as shown in location map (Fig. 2) at an elevation of 357 m amsl near to the Mandollagudem village in S-N direction. The inverted resistivity model shows a smooth variation of resistivity for the subsurface geological formations but with a large resistivity contrast varying from ~10 to 1.6 × 10^5 Ohm.m from south to north end of the profile as shown in Fig. 6a. The near-surface zone indicates a soil layer followed by weathered granite up to a depth of ~30 m. The weathered granite is more prominent between 160 and 480 m lateral distance as clearly revealed from the model resistivity section (Fig. 6a). At a 240 m distance, the downward deepening of the geological bed indicates prominent weathered and highly weathered granite showing resistivity of the order of 450–750 Ohm.m. The resistivity modelled data lying below 160 to 480 m (Fig. 6a) is inferred as the prospect and potential groundwater zone due to intense weathering/fracturing of rock strata is a significant repository for groundwater reserve, which can be exploited even up to a depth of 200 m. The IP data shows low chargeability contrast below 160 to 480 m, which indicates groundwater prospect zone (Fig. 6b). The geological setting

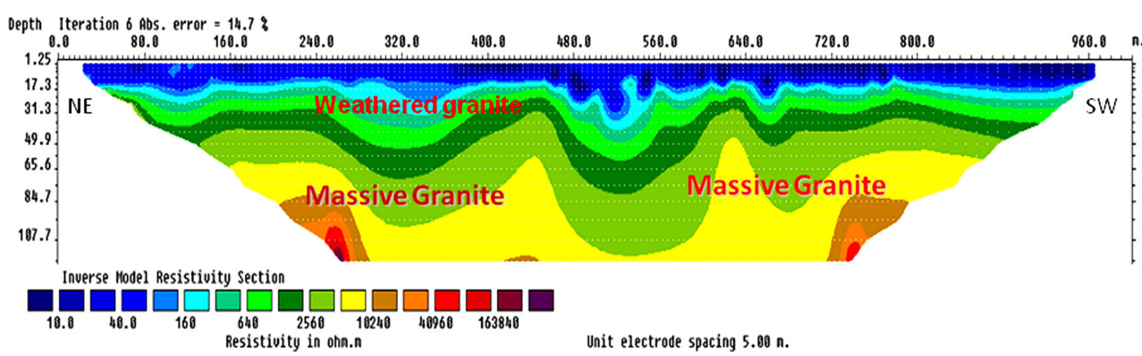


Fig. 4 2D inverted resistivity section between Singarayacheruvu and Kuntlagudem village in a granitic hard rock region indicating sharp boundary between low and high resistivity in shallower part and distinct variation between weathered and massive granite with a large resistivity contrast at deeper depth

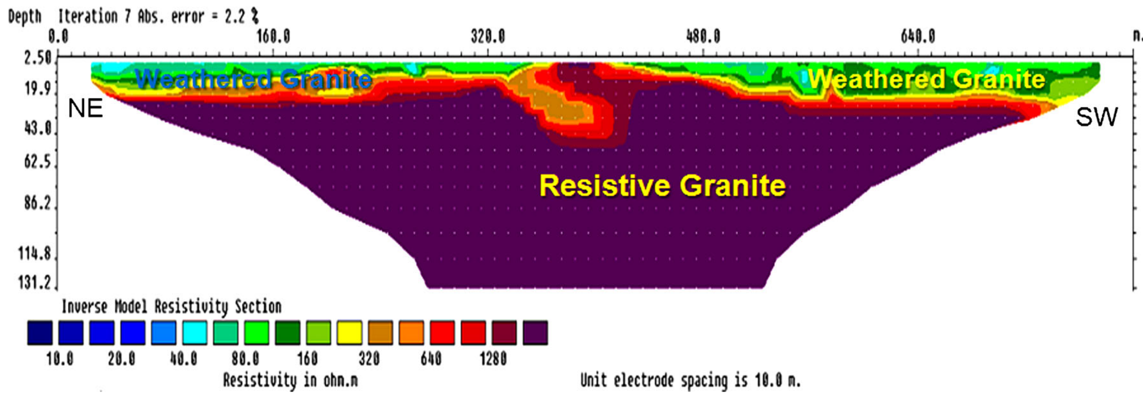


Fig. 5 2D inverted resistivity model at Toorpugudem site in a granitic hard rock terrain, which reflects heterogeneity along the profile with high resistivity at deeper level and no sign of prospect groundwater zone

and hydrogeological condition are highly favourable for groundwater exploration at this site. On the other hand, there is a clear-cut indication of massive granite with increase in resistivity with depth in the northern part. Here, the high resistivity mapped is of the order of ~1.6 × 10^5 Ohm.m from ~50 m down to a depth of 131 m (Fig. 6a), and such high resistivity area is totally devoid of water and should be avoided for groundwater exploration. In general, the southern side is more favourable in terms of groundwater prospects and exploration rather than northern side: the recharge is comparatively more around such region, which leads to rich hydrogeological condition for groundwater exploration and development as revealed in Fig. 6a.

Site 5: near Mandollagudem village

The 2D inverted resistivity model at another site near Mandollagudem village is depicted in Fig. 7. This profile is laid towards NE direction with respect to site 1 (location map, Fig. 2) near the village in a plain ground at an elevation of 359 m amsl in NE-SW direction. The resistivity model shows the weathered/fractured granite with a resistivity between 40 and 100 Ohm.m at a shallow depth up to ~25 m throughout the profile (Fig. 7). The weathered granite is more prominent from NE direction towards the centre of the resistivity profile and up to a depth of 30 m with a resistivity ~150–1000 Ohm.m. Below 35 m depth, the model shows a resistive granite with a

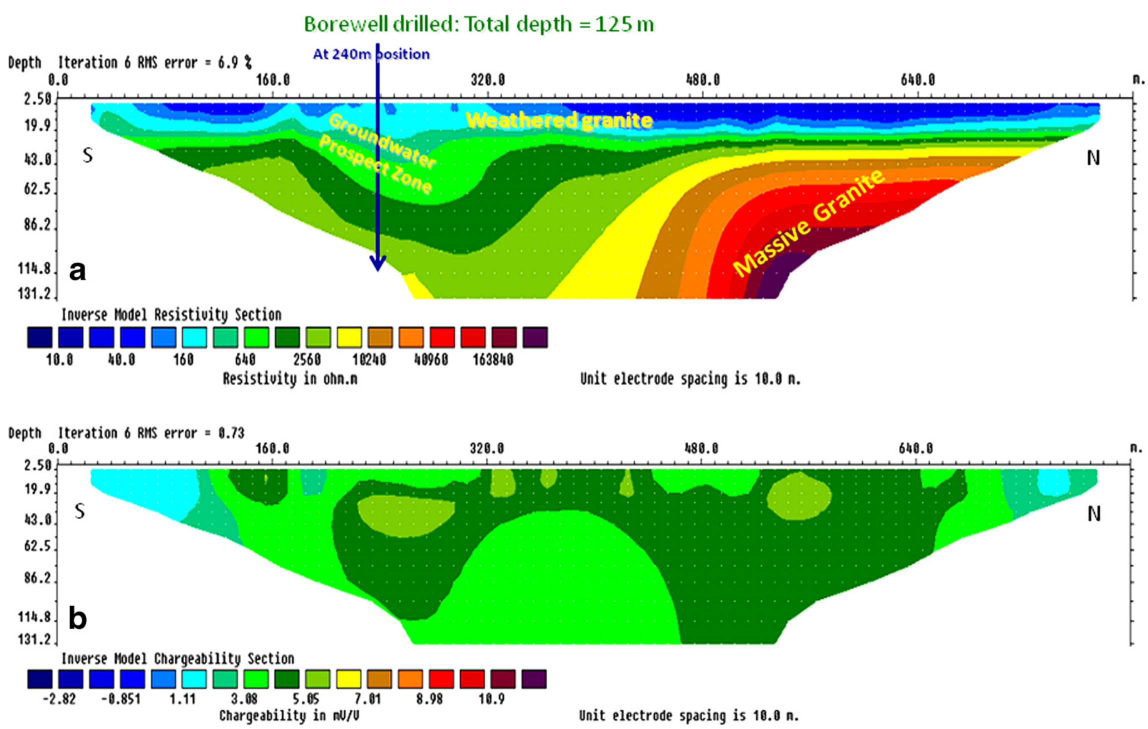


Fig. 6 **a** 2D inverted resistivity model between Mandollagudem and Toorpugudem village in a granitic hard rock region showing smooth variation of resistivity with deepening of the geological bed towards southern side. The model resistivity section shows clear-cut potential groundwater zone. **b** Depicts the inverted chargeability section showing minor variation of chargeability all along the section

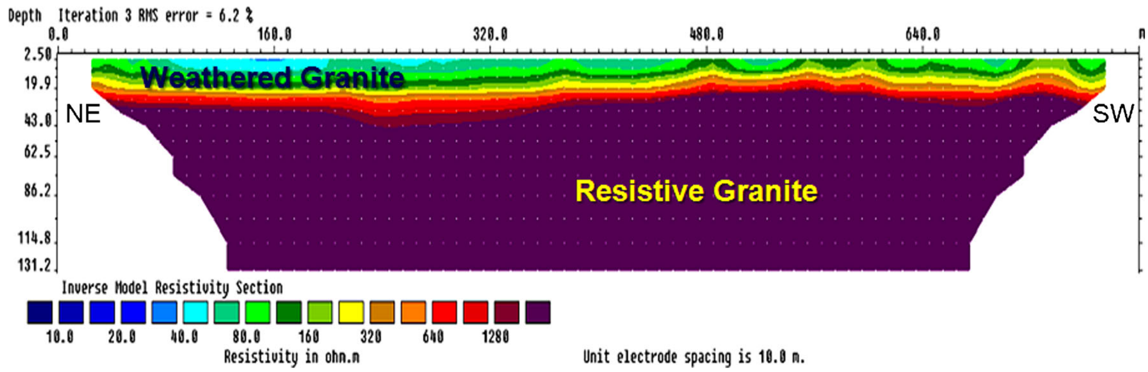


Fig. 7 2D inverted resistivity section near Mandollagudem village in a granitic hard rock region revealed sharp resistivity contrast between near-surface weathered layer and underlying hard basement rock

resistivity >2500 Ohm.m and is interpreted as the fresh crystalline rock with no fracture, which is mapped up to 131-m depth and is even continuing beyond the model's total depth of investigation (Fig. 7). Such fresh rock area should not be the target for groundwater exploration and development. In fact, the model does not revealed any prospect favourable groundwater zone at this site right from ~40 m till 131 m depth (Fig. 7).

Drilling and validation of model results

It is decided to verify the interpreted 2D resistivity model results and the major and favourable anomaly based on the 2D resistivity dataset, hydrogeological interpretation and significance. The drilling is confirmed at site 4 (Fig. 6a) exactly at a lateral distance 240 m position from south side of the profile direction at the highly anomalous zone (Fig. 6a). A borehole is drilled up to a depth of 125 m encountering a soil layer, weathered granite, highly weathered granite, semi-weathered granite, saturated fractured granite and later hard granite as incurred from the litholog of the well (Fig. 8), which is in good agreement with the model resistivity values and the interpretation (Kumar et al. 2013). The scientific basis of drilling up to a depth of 125 m is to substantiate the 2D resistivity model result at site 4 (Fig. 6a). If we look carefully the resistivity result, it is quite clear that there is a substantial formation of weathered granite towards the southern side (Fig. 6a). The resistivity contrast is much significant up to a depth of 65 m down below 240 m lateral distance—the actual drilling point. But, further down until 114 m depth, the change in resistivity contrast is less and the hardness of the rock increases, and this is inferred as the fresh granite. This fresh granite is encountered, confirmed and verified from this drilling result, thus validated the resistivity model result. A 5HP submersible motor pump is fitted and is installed in the well at a depth 54.86 m, which lies below the saturated fractured granite (Fig. 8). Based on the discharge and head calculation at the time of drilling, the yield of the well is estimated to be 2.5 in. which is equal to 1302 gal/h = 82.14 l/min under the extreme hot climatic condition during the month of April, 2013. It is considered as a good aquifer. The water first struck at 27.74 m bgl, which is under confined condition in weathered/fractured saturated granite. But, the aquifer zone is tapped in the saturated fractured granite at a depth of 46 m. The static water level under normal condition after drilling is at 23.62 m bgl on 22 April 2013, which is under normal atmospheric pressure. The water from this well is being exploited daily for 6–7 h of nonstop pumping to fulfil the need and demand of water. Seeing the hydrogeological condition of the drilled site, it is predicted that after the post monsoon season, the water level will again rise up once the water will rush in the drilled well through the interconnected fracture(s) network system within the present geological setting.

The another drilling is conducted at the extension of the 2D resistivity 800 m long profile (site 4), and it lies in front of the primary school campus in the Mandollagudem village separated by a distance of about 600 m. It is also drilled up to a depth of 125 m, and the geological formations encounter the weathered, hard, weathered/fractured, fractured, highly fractured and saturated fractured granite as seen from the drill cuttings (Fig. 9). Geologically, the main rock strata are same, but their depths and thickness ranges are varying as well as the hydrogeological situation and the aquifer depth is quite different from the first drilled well. The second well encounters the aquifer in highly fractured and fractured granite between 80- and 100 m depth (Fig. 9). The water in this well struck at two different depths at 54.9 and 80.7 m, respectively (Fig. 9). The static water level measured is at 19.27 m bgl on 29 June 2013, which clearly states a different hydrogeological situation with variant confining condition and a different amount of water storage of the aquifer. This confirms that the aquifer at the second well is under much higher pressure as compared to the situation at first well. A 7HP submersible pump is fitted and is installed at a depth 103.63 m, which is placed below the saturated fractured granite and is now pumped for 10 h daily and exploiting groundwater for domestic need of the people.

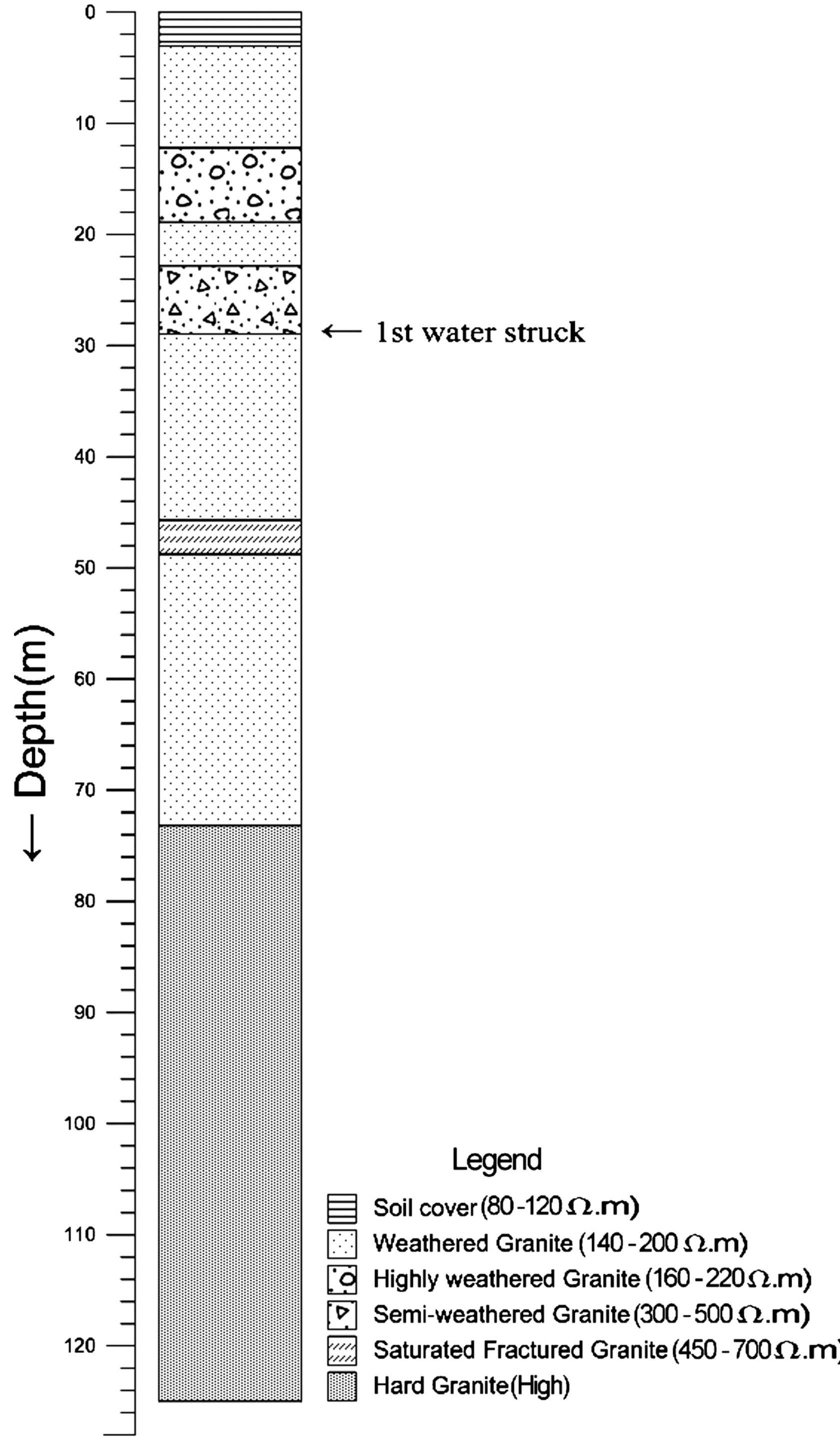


Fig. 8 Detailed litholog down to a depth of 125 m revealing various geological litho units at site 4. The aquifer zone is tapped in the saturated fractured granite at a depth of 46 m

Geological model

The conceptual geological model at Choutuppal area highlights the geological and hydrogeological significance in the present geological context. The profile view of the model as evolved along NE-SW direction based on location of 2D ERT profiles is shown in Fig. 10. This conceptual model revealed overall a natural beehive type of geological structure. The top 1–2 m thickness at the near-surface layer is the soil cover all along the section of the model in NE-SW direction. The weathered and highly weathered granite layer is varying gently from NE to SW direction with its thickness in the range 11–18 m bgl, and it is more towards the NE corner and from the centre to SW side (Fig. 10). Subsequently follows the semi-weathered granite, which is varying in an upside-down pattern, and its thickness is varying of the order of 8–25 m bgl in

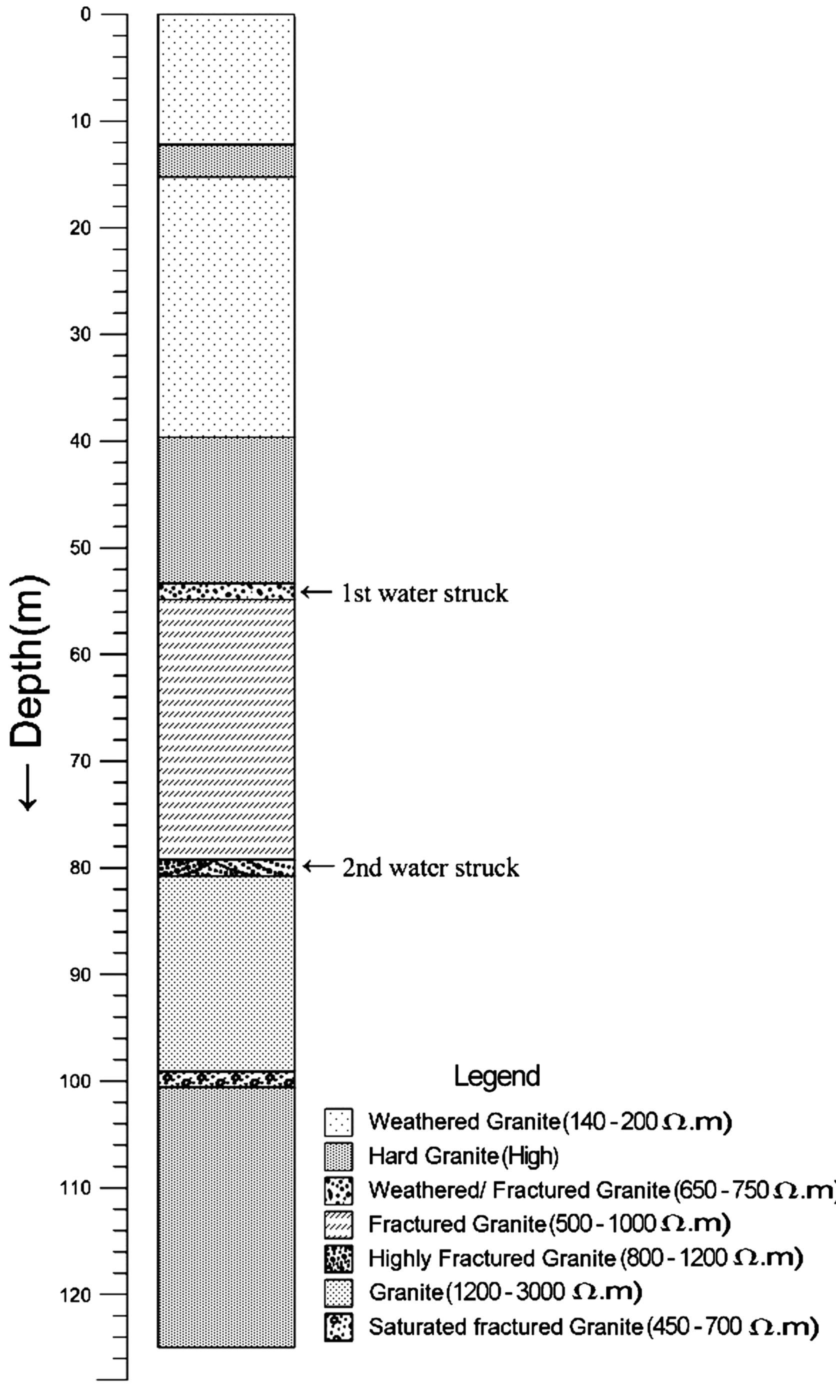


Fig. 9 Lithologic log down to a depth of 125 m depicting various geological litho units at the extension of the 2D resistivity profile (site 4) and in front of the primary school. Here, the aquifer is tapped in highly fractured and fractured granite between 80 and 100 m depth

the present geological set-up. Later further in downward direction, the model shows the weathered/fractured granite layer, which is varying in an irregular pattern as viewed from the profile section. The magnitude of its thickness is changing from 4 to 43 m bgl within the present geological set-up. The most important hydrogeological part of this geological model is the saturated fractured granite—an aquifer zone, which is varying abruptly as seen from the model (Fig. 10). Its thickness is changing from 2 to 29 m bgl showing high variability of the saturated fractured zone within the granitic rock set-up. It shows the large variation in the thickness of the aquifer zone. The model shows that its thickness is increasing from NE side towards the centre, and then later, it is decreasing gradually and is diminishing in the SW direction (Fig. 10). It means that the aquifer zone thickness is maximum near NE side and in central part and is the least in the SW corner. At the basement, the massive fresh granite is well delineated based on the high-resolution 2D resistivity tomography results and its interpretation as is shown in Fig. 10. The massive fresh granite evolved from 28 m depth down to 130 m depth in

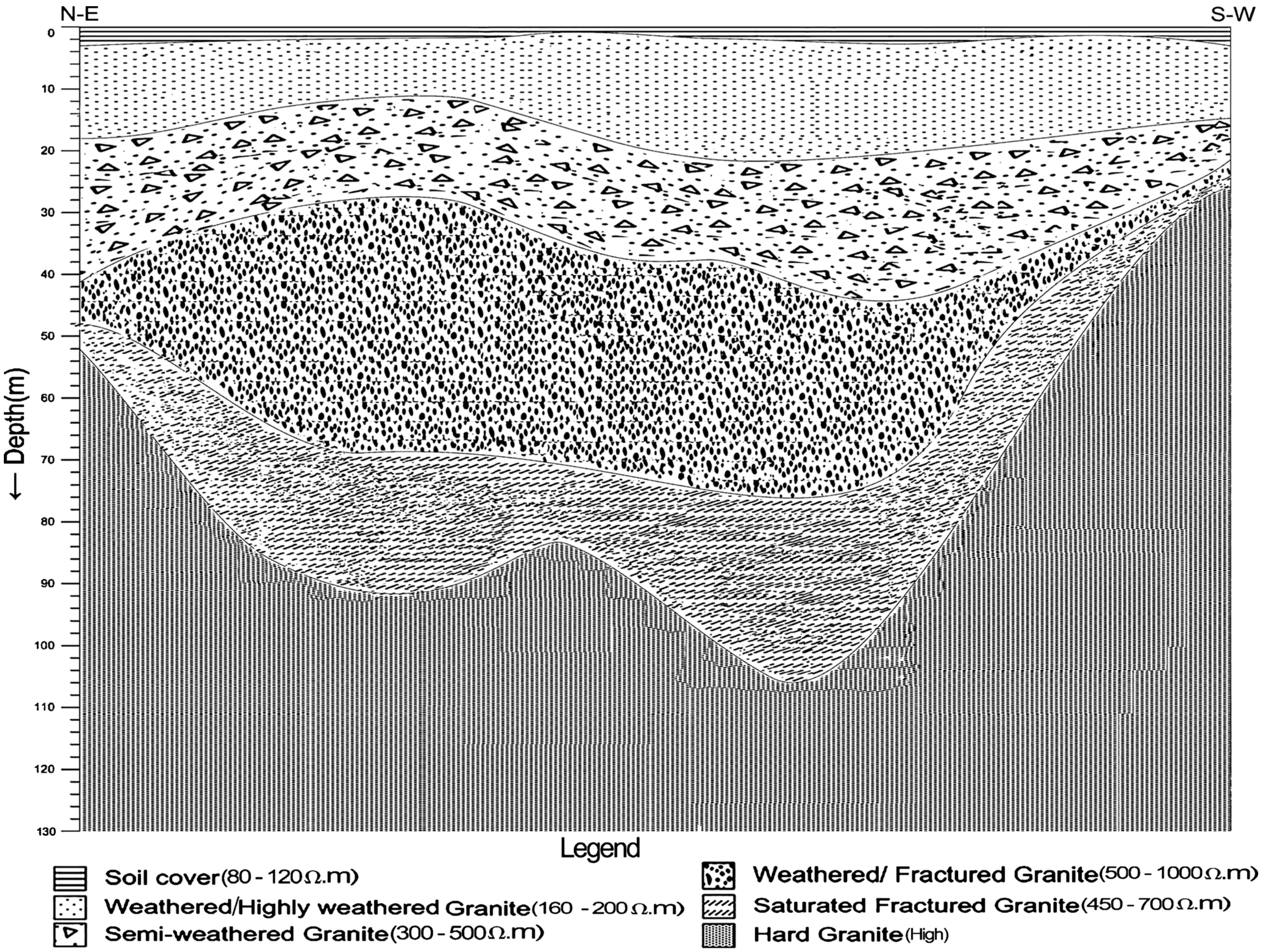


Fig. 10 Profile view of the conceptual subsurface realistic geological model of Choutuppal area, Nalgonda district, Telangana, India. It is evolved from the interpretation and results of the high-resolution 2D electrical resistivity tomography models including drilling and validation

the SW direction, and it is quite thick around SW part, but it lies at 106-m deeper depth almost near to the centre of the profile section (Fig. 10) while the thickness of this fresh granite is again increasing in the NE direction as seen from the geological model (Fig. 10). Thus, it suggests that the basement rock is also changing in an irregular fashion from NE to SW direction and is highly undulating in nature.

Discussion

The basic water requirement is not sufficient for the people and the villagers both for domestic and agriculture purposes due to water scarcity in the study area. The results and findings from the resistivity models had shown clear visibility of groundwater status, prospect scenario at few specific locations, where the exploration and future development can be taken up. However, the derived inverted resistivity models show substantial resistivity contrast with clear anomaly for groundwater zones while IP models (Figs. 3b and 6b) show marginal chargeability contrast, which helps in locating the prospect groundwater zones. At Mandollagudem (site 1), the favourable zone below 160 m towards north side of the profile is a productive groundwater zone (Fig. 3) as inferred from the inverted model resistivity and the hydrogeological interpretation. The groundwater could be exploited to a deeper depth of up to 150 m or even more at this site. The hydrogeological scenario is totally different at site 2, where the crystalline rock with no any tectonic fracture revealed from the resistivity model and the geological strata are showing an increase in resistivity with depth. The basement rock is shallow, and it is sitting right from ~40 m depth and shows no any major groundwater prospect zone. Similar is the situation at site 3, with no major fracture within the formation, which serves as a conduit for water, and the resistivity is of the order 1280 to 2560 Ohm.m, which indicates the basement granitic rock. The hydrogeological interpretation suggests that there is no any favourable location for groundwater exploration all along this site. The results and findings at site 4 located between Mandollagudem and Toorpugudem village are interesting and encouraging. Hydrogeologically, the site below 240-m distance is favourable; the deepening of the geological bed in downward vertical direction indicates highly weathered granite showing resistivity ≤150 Ohm.m up to a depth of <20 m, followed by weathered and semi-weathered granite with a resistivity 450–550 Ohm.m between 20 and 40 m depth, and again down to a depth of 70 m, it is inferred as weathered and saturated fractured granite with resistivity value 600–1500 Ohm.m. These results are corroborated with the litholog (Fig. 8) of the drilled well at this site exactly at 240 m distance (Fig. 6a). The hydrogeological scenario lying below 160 to 480 m lateral distance (site 4, Fig. 6a) indicated potential groundwater zone, and such area can be explored for exploiting groundwater resource even to a deeper depth of 200 m or beyond for long-term sustainability of the resource. The resistivity contrast between the geological weathered and highly weathered granite and along with fracture(s) within the host rock system is clearly visible from the model result (site 4, Fig. 6a), and this suggests a prospect and a productive aquifer zone. The subsurface resistivity structure is quite different at site 5 as compared to site 1 in the same Mandollagudem village, which is also correlating with the geology-geomorphology map (Fig. 2); i.e. site 1 falls on the fracture/lineament while site 5 is away from it. If we look carefully resistivity models at both the sites, this is quite clear and, hence, the results (Figs. 3 and 7). The basement rock is undulating in nature with comparatively low resistivity between ~1280 and 2560 Ohm.m at site 5, which is not the case at site 1. It is inferred that the huge chunk of rock is sitting at a depth ~40 m down to a depth of 131 m and extending laterally along the resistivity profile (site 5, Fig. 7). In the present study, it is inferred that shallow groundwater zones are meagre and only the deeper source of groundwater is resourceful for exploration and exploitation. The presence of near-surface clayey soil impedes sufficient recharge to the water table and subsequently to the aquifer in the present hard rock aquifer system. The major recharge to the aquifer is possible through the thick weathered/fractured granite and the overlying weathered granite, which are the major sources of conduit for carrying the recharge water from surface to the aquifer in the present geological setting.

Conclusions and recommendations

The study exemplifies and revealed the subsurface geological setting and structure of the crystalline rocks and the status of the groundwater scenario in the study area. The findings from the large density and best-quality dataset of ERT models are significant for both geological mapping and delineation of prospect groundwater zone(s). It clearly mapped and resolved the near-surface unsaturated layer with a clear resistivity contrast, weathered/highly weathered and saturated fractured zones and the massive fresh crystalline granitic bedrock. The resistivity contrast helped in identifying and delineating the lithological rock layers and boundaries much precisely. The true resistivity models generated using inversion in conjunction with the measured apparent resistivity dataset had been helpful in resolving geological formations, structures, basement topography, depth to bedrock and the potential groundwater resource in the present geological setting. In the present study, it is concluded that the shallow (<30 m) groundwater zones are meagre and the best productive groundwater zones lie between 45 and 100 m depth. Here, resistivity tomography method is well suited to map the hard inner structure of a granitic rock as it gives not only the resistivity values and the contrast based on the physical, chemical and hydrological parameters of the different layers; nevertheless, it also provides information on heterogeneity of the lithological variations of the rock. The lithological changes and identification of formations were confirmed and validated by drilling at the two sites. The conceptual geological model helped in logical planning for exploitation of the groundwater resource in the present geological set-up.

Based on our present study and understanding, it is recommended to build recharge structures towards the downstream side of the area in order to arrest excess rainwater during the heavy monsoon season, which is necessary due to lack of surface water storage system. The present existing recharge structure has to be revived in order to have surplus recharge of rainwater to the aquifer. This will enhance the water table depth of the groundwater in the present aquifer system - increases its storativity for its long-term sustainability. The present scientific study in the typical granitic terrain helped in solving and minimizes the groundwater problem at a local scale by providing the daily requirements of water to the villagers, and the knowledge gained from the study will further help in future development of groundwater resources in the similar geological setting.

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