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Integration of geophysics and petrography for identifying the aquifer and the rock type: A case study from Giddalur, Andhra Pradesh, India

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A comprehensive geophysical and petrological study was carried out at Giddalur area in Prakasam district, Andhra Pradesh, which is geologically a highly deformed area and is difficult to delineate the aquifer zone(s). The task was to find out the exact rock type in which aquifer is concealed as well as to delineate the aquifer zone, which can yield sufficient quantity of water. The resistivity models derived from geophysical dataset were interpreted in terms of hydrogeology and the results revealed substantial resistivity contrast of the geological formations within the study area. We have delineated two major groundwater potential zones based on this study. These zones were tapped at different depths in diverse rock types. Drilled hand specimens (rock cuttings) were not adequate, so these specimens were petrographically studied to reveal the exact contact zones of the rock type. On integration of the geophysical and the petrographic results, it was illustrated that two aquifer zones were struck at a depth of 92 and 122 m between shale-phyllite and phyllite-quartzite, respectively. These findings were correlated, which matched with the lithology of the drilled borehole. This integrated approach will be helpful in strategy for groundwater assessment as well as prospecting groundwater resources in different geological terrain.

Keywords. Geophysical methods; drilling; petrography; groundwater exploration; India.

1. Introduction

The geophysical method and combination of techniques for application in exploration is based on the disparity between the physical properties of the target and the neighbouring rock medium. Mostly in hard rock fractures occur up to hundreds of metres and if these fractures are saturated with groundwater, a disparity between the resistivity of fractured rocks and massive hard rocks would be pragmatic; fractured rocks showing lower resistivity than massive hard rocks (Karous and Mares 1988). An integrated geophysical surveys for groundwater exploration in hard rock areas has been attempted by Bernard and Valla (1991), Ramteke *et al.* (2001), Sharma and Baranwal (2005) and Porsani *et al.* (2005). Many researchers have developed numerous geophysical techniques

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and various configurations to conduct sounding and profiling in the resistivity surveys such as Wenner (1915), Schlumberger (1920), dipole–dipole (Al'pin 1950) and pole–dipole (Yadav 1988). Further, data obtained in this way has a drawback that the apparent resistivity exhibits deviation when each one of the electrodes crosses the boundary of inhomogeneity or contact (Keller and Frischknecht 1966). Hence, the identification of exact location of fractured zone may become difficult. Extensive discussions of the gradient array are given by Kunetz (1966), Kearey and Brooks (1984) and Telford *et al.* (1976).

Electrical resistivity tomography (ERT) and vertical electrical sounding (VES) geophysical techniques are two vital methods for groundwater exploration survey, which helps in knowing the rock physical property as well as delineation of aquifer zones (Kumar *et al.* 2014), identification of fractures, delineation of subsurface dykes, demarcation of saltwater encroachment zone, etc. ERT has an ability to scan the subsurface geological formations both in vertical and horizontal directions (Herman 2001). The acceptance of multi-electrode resistivity technique in the scientific research community is not new (Dahlin 2001). ERT produces large density and best-quality dataset, which is very helpful in geological and structural mapping as well as delineation of prospect groundwater zones (Kumar *et al.* 2016). The sensitivity of resistivity method is very high towards the inhomogeneity of earth resistivity, which helps in identifying lithological units and its variations within lithological units. These changes are usually highly notable with respect to groundwater (Owen *et al.* 2005). The ground resistivity depends on several parameters such as the mineral content, intergranular compaction, porosity, degree of water saturation in the rocks, etc. (Marescot 1995). In hard rock region, regolith act as a primary water-bearing zone. All the water, which falls on the surface and percolate through near surface layers for recharge to the water table is through regolith under a normal as well as induced conditions (Burman and Das 1990). The electrical resistivity tomography is known as the most effective method in two dimensions for groundwater exploration. While, VES is the conventional one dimensional geophysical technique, which gives the subsurface informations along a point (Mohamaden *et al.* 2017). Scientific workers have been using it for many decades and its use has proved to be very effective till date. The hydrogeological conditions of the aquifer in terms of weathered and fractured zones of sedimentary rock, which is subjected to metamorphism, viz., schist, phyllite, and quartzite have manifold potential in terms of water resources. Weathered part of schist, slate and phyllite principally produces clay, therefore, its yield capacity is not sufficient and restricted within the rock matrix. Phyllite is known as a feeble foliated rock in which the open fractures where clay is not present can proved to be a good aquifer medium (Burman and Das 1990).

The objective of this paper is to find out the definite lithological zone where groundwater is concealed, it was onerous to find out the exact zone of interest with the intact hand specimen of rock samples used for analysis. Here we have carried out petrological studies for the collected drilled rock samples in order to find out the exact water bearing zones. Our study includes integrated ERT, VES and petrological studies and their correlation, which was discussed here in detail.

2. Study area

The study area Giddalur in Prakasam district is located between 15°21′30″15°22′N latitude and 79°2′45″–79°3′E longitude and falls in the Survey of India (SOI) topographical sheet no. 57M/3. The study area is $\sim$0.5 km^2 as shown in figure 1 and lies at 269 m above mean sea level. The average annual rainfall of the district is 616 mm. The northeast and southwest monsoon both contribute significant amount of rainfall in this district. The average temperature of the study area varies from 24.08° to 33.72°C in winter and summer, respectively. The area falls in Giddalur town (census town) in Prakasam district, Andhra Pradesh, which is known for severely critical region in terms of availability of groundwater resources both for domestic and irrigation uses. There is one irrigation tank built in Cumbum is considered as a huge tank and its importance can be seen in areas around Cumbum, which lies 34 km North of Giddalur on the Giddalur–Markapur road. Detailed survey and finding shows that the tank was constructed 400 years ago during the rule of Vijayanagara Kings according to most of the past research (Census of India (AP) handbook, 2011).

Figure 1. Location map of the Gundreddypalle area with sounding and ERT location.

3. Geology and hydrogeology

Proterozoic basins in peninsular India, is predominantly more in numbers with an aggregate thickness of 8–10 km as in the Cuddapah basin occurring in the Eastern Dharwar Craton (Nagaraja Rao *et al.* 1987; Chaudhuri *et al.* 2002; Ramakrishnan and Vaidyanadhan 2008). Our study area (Giddalur) lies in Nallamalai sub-basin, which is a part of Cuddapah basin; the shape of this basin is likely to be a crescent-shaped as we can see in figure 2. This basin is known as one of the largest Proterozoic, intra-cratonic, sedimentary basins in India and it is located in the eastern part of Dharwar craton. The area of the basin is estimated around 44,500 km^2 with extreme length and breadth of 440 km and 145 km, respectively. It is believed that the northern part of the basin is unaffected by tectonic activity or it can say that the effect is very low and dipping of sedimentary rock is very gentle (10°–15°) towards east. On the other hand, eastern part of the basin is in multiple phases of folding and immensely metamorphosed during the middle to late Proterozoic (∼1.3–1.6 Ga) Eastern Ghat Orogeny (Goodwin 1996). The intensely deformed Nallamalai group has long been considered to be a part of the Cuddapah Supergroup (Meijerink *et al.* 1984). Nallamalai group is exposed at Nallamalai hills, which are further divided into Cumbum and Bairenkonda subgroup – the whole succession is highly deformed. Age of Cuddapah basin is Proterozoic and our area falls under Cumbum subgroup. The major rock type of this area is shales and phyllites. In and around the study area Giddalur, it is underlain by a different type of rocks, ranging in age from Archaean to Recent. Mainly groundwater occurs in different types of the aquifer namely crystalline aquifer system, Cuddapah aquifer system, Gondwana, alluvial and laterite aquifer (Bhaskara Rao 2013). On the basis of reconnaissance survey and drilling report, it seems that our area is comprised mainly of shales, slates, limestone, and phyllites rocks. The degree of weathering, fracturing and contact zone of different lithology play a vital role in the occurrence and movement of groundwater within the aquifer. The

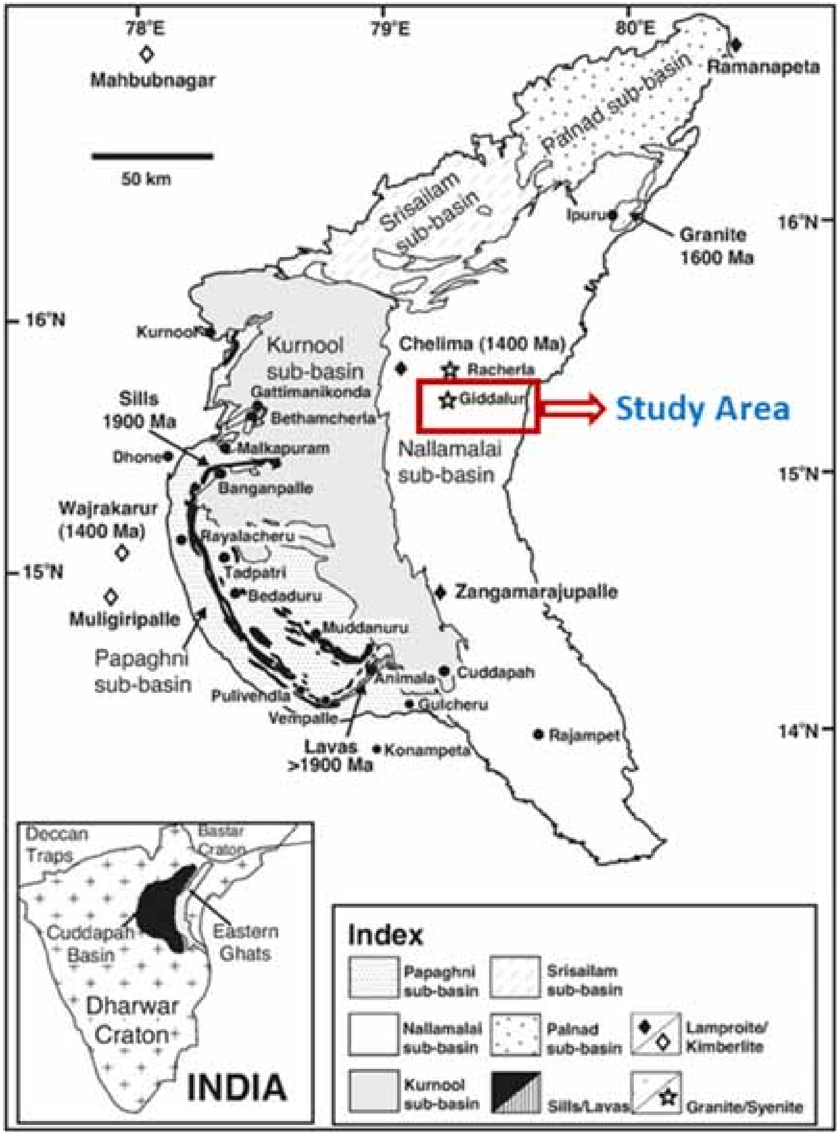

Figure 2. Geological map of study area, Cuddapah Basin, after Nagaraja Rao and Ramalingaswamy (1976).

thickness of the weathered zone varies from 3.0 to 15 m. The yielding capacity of the aquifers in different formations ranges from 20 to 120 m^3/day (Bhaskara Rao 2013).

4. Methodology

Vertical electrical sounding (VES) is one of the conventional resistivity technique most commonly used in electrical resistivity survey to determine the vertical variation of the electrical resistivity parameter below the earth's surface and the potential field generated by the current (Todd 2004). VES method is based on the assumption that the ground is uniformly stratified and homogeneous. However, practically the resistivity of the subsurface strata is inhomogeneous in nature. A graph of apparent resistivity against current electrode spacing is used to determine vertical variation in formation resistivity. Interpretation of the graph using curve matching technique (Bhattacharya and Patra 1968) gives the true resistivity and depth of the geoelectric layers and the interpreted results are used to ascertain the presence of groundwater in an aquifer in any geological medium. The parameters that affect the estimation of groundwater resources include namely the aquifer thickness, the size and degree of inter-connection of pore spaces within the aquifer material. These properties affect the ability of an aquifer to store and transmit groundwater (Tizro *et al.* 2014).

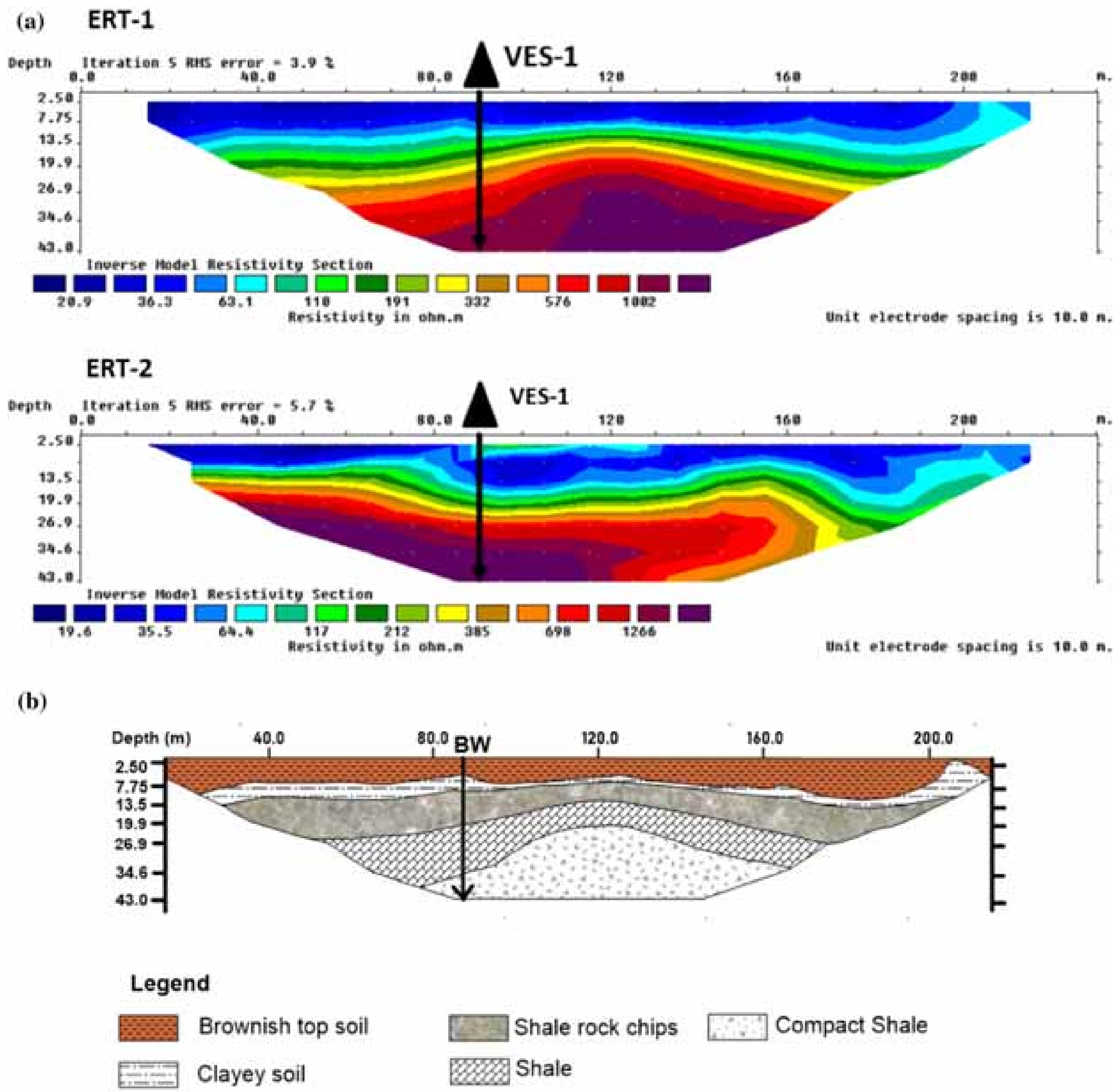

Figure 3. (**a**) Electrical resistivity tomography (ERT) model result near the foothill of the study area. ERT-1 is the inverted resistivity section of Wenner–Schlumberger array while ERT-2 represents dipole–dipole inverted resistivity section at the same location as shown in figure 3. **(b)** Conceptual geological model based on the subsurface resistivity characterization and lithology of the drilled borehole at Gundreddypalle site.

Electrical resistivity tomography (ERT) is a latest tool for groundwater exploration and management (Kumar 2012). From past several years, we could see the ascent of ERT method for solving the complexity of subsurface geology (Griffiths and Barker 1993; Loke and Barker 1996). The conventional arrays, which are used commonly are Schlumberger, Wenner, dipole–dipole, two electrodes, half-Schlumberger (Keller and Frischknecht 1996; Yadav 1988) Lee-partitioning, etc. In order to achieve a superior resolution for the subsurface geological features in both vertical as well as in horizontal directions – Wenner–Schlumberger array is very prominent (Sasaki 1992). In our study, the ERT was carried at Gundreddypalle, Giddalur with Syscal Switchpro 90 using 48 electrodes with an electrode spacing of 10 m. The configuration used was Wenner–Schlumberger and dipole–dipole array (figure 3a). The VES were carried out using DDR3 resistivity meter and its accessories using Schlumberger configuration. At the field site, total seven VES at different locations were carried out and the resistivity data was obtained and interpreted in understanding the

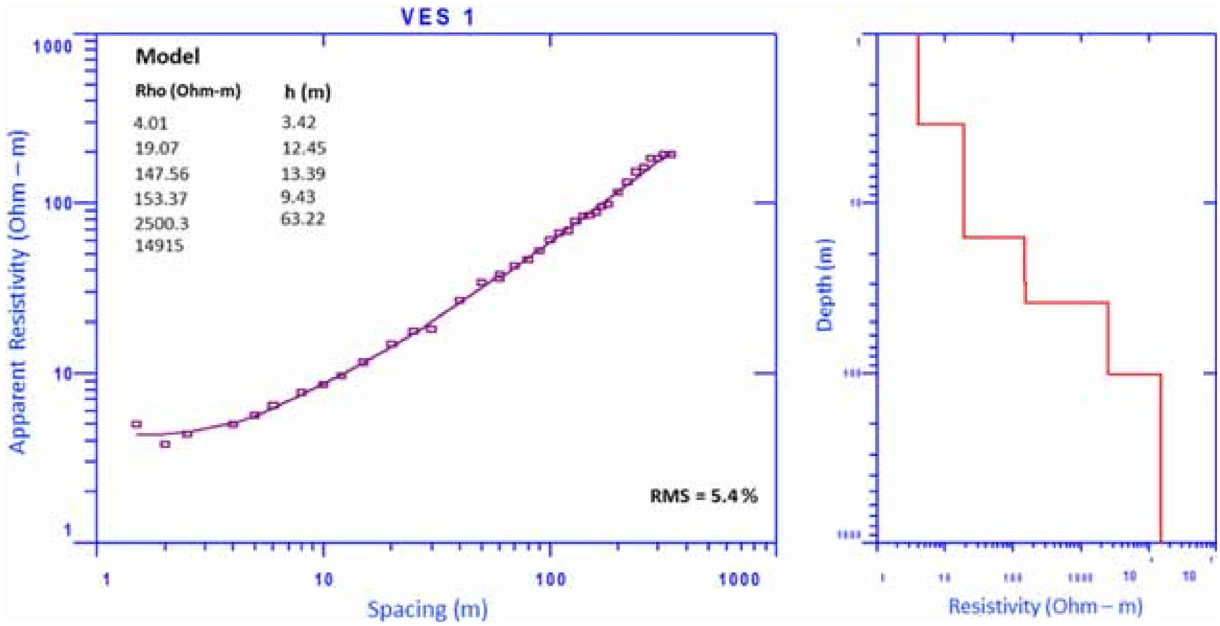

Figure 4. Shows the vertical electrical sounding (VES) model result (VES-1) where the square box is the field data and smooth line is the computed curve along with resistivity *vs.* depth model.

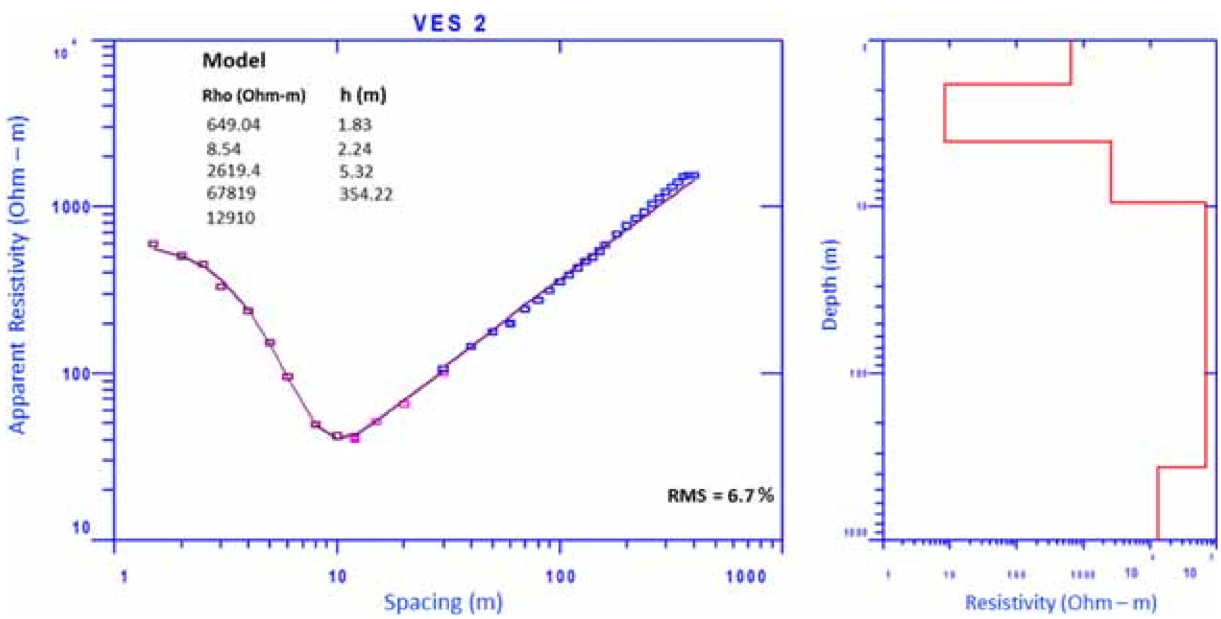

Figure 5. Shows the vertical electrical sounding (VES) model result (VES-2) where the square box is the field data and smooth line is the computed curve along with resistivity *vs.* depth model.

subsurface geoelectric layers (Kumar *et al.* 2007). At first, all the resistivity data collected in the field area were plotted at the field site to check the quality of data as well as its qualitative nature (Kumar 2004). The acquired apparent resistivity data were plotted in log–log graph sheet, subsequently traced data shows that all the curves are either A-type or H-type in nature.

In order to find out the stacked model of subsurface, we integrate all the thickness and resistivity results in such a way that the contours of resistivity fall on the same plane with their respective depth. After integration of ERT and VES, we have narrowed down our area to a single point, which was inferred to be a good potential zone for groundwater prospecting. Auger drilling is a common technique for groundwater exploration, which is commonly used for the groundwater exploitation, with the help of this technique drilling was performed at the selected point. Now the challenge was to find out the

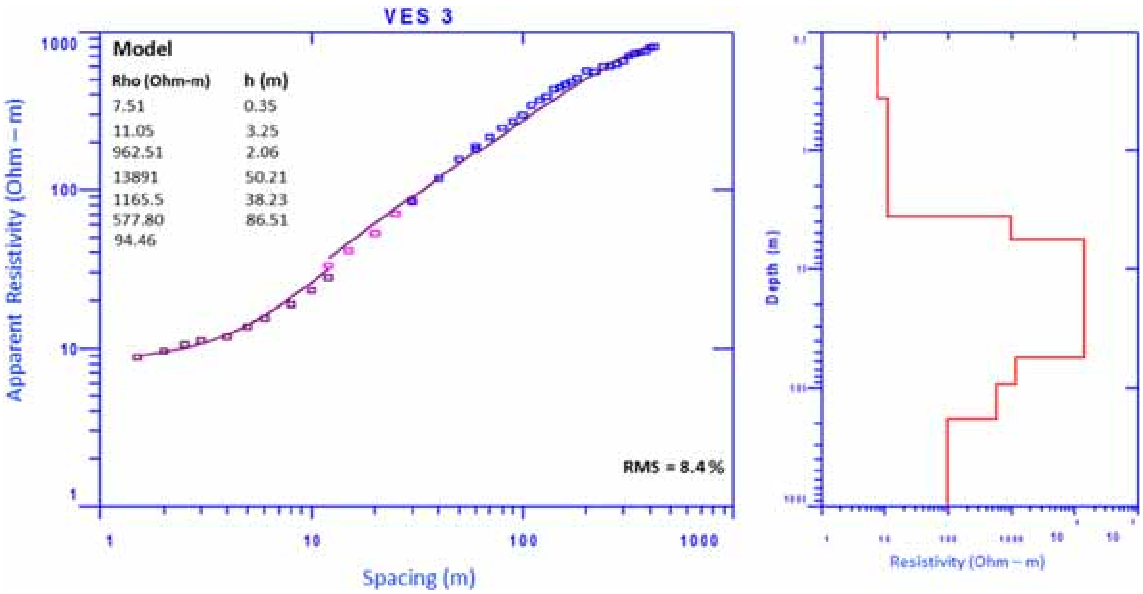

Figure 6. Shows the vertical electrical sounding (VES) model result (VES-3) where the square box is the field data and smooth line is the computed curve along with resistivity *vs.* depth model.

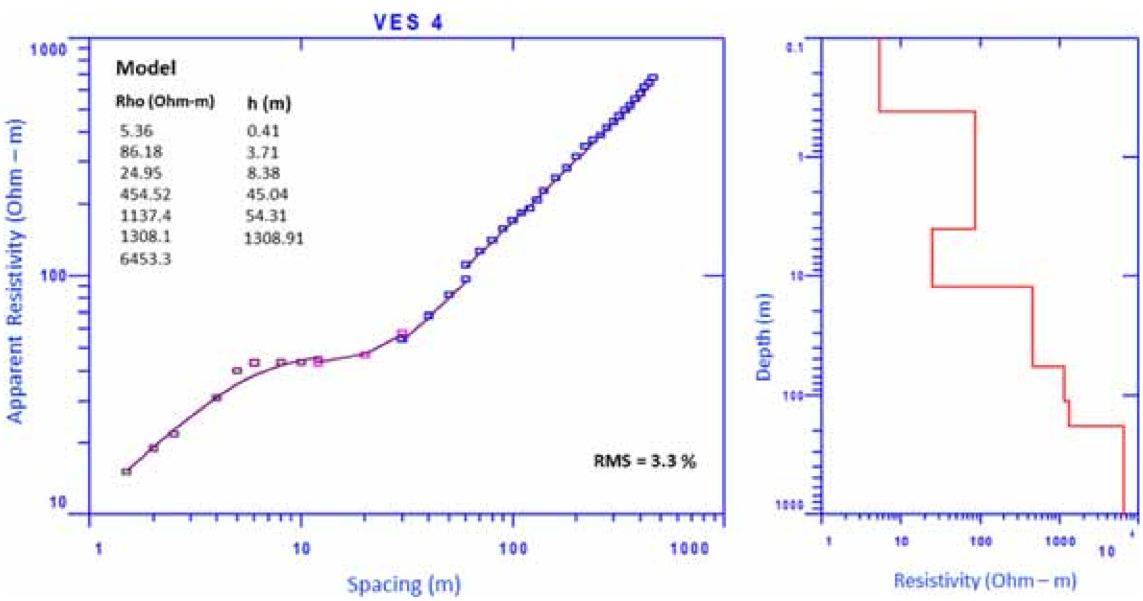

Figure 7. Shows the vertical electrical sounding (VES) model result (VES-4) where the square box is the field data and smooth line is the computed curve along with resistivity *vs.* depth model.

rock zone where the aquifer is concealed within the geological formation. The drilled hand specimen was not adequate because all the rock chips were showing almost the same physical properties, which made us difficult to find out the aquifer zone.

It was a need of the hour to incorporate an additional method to figure out the exact zone of water bearing strata, for which we have made the thin sections of rock samples. For preparing these sections, we collected several rock chips at different depth intervals and these rock samples were taken to the rock cutting laboratory where we used carborundum powder of different mesh size to rub the sample at the desired thickness. The final sample then stuck to the glass slide using Canada Balsam at the base of the sample for petrological studies using a petrological microscope (Nikon eclipse LV100P0L) where we have successfully identified the aquifer zone after a detailed study of the thin sections (figure 12).

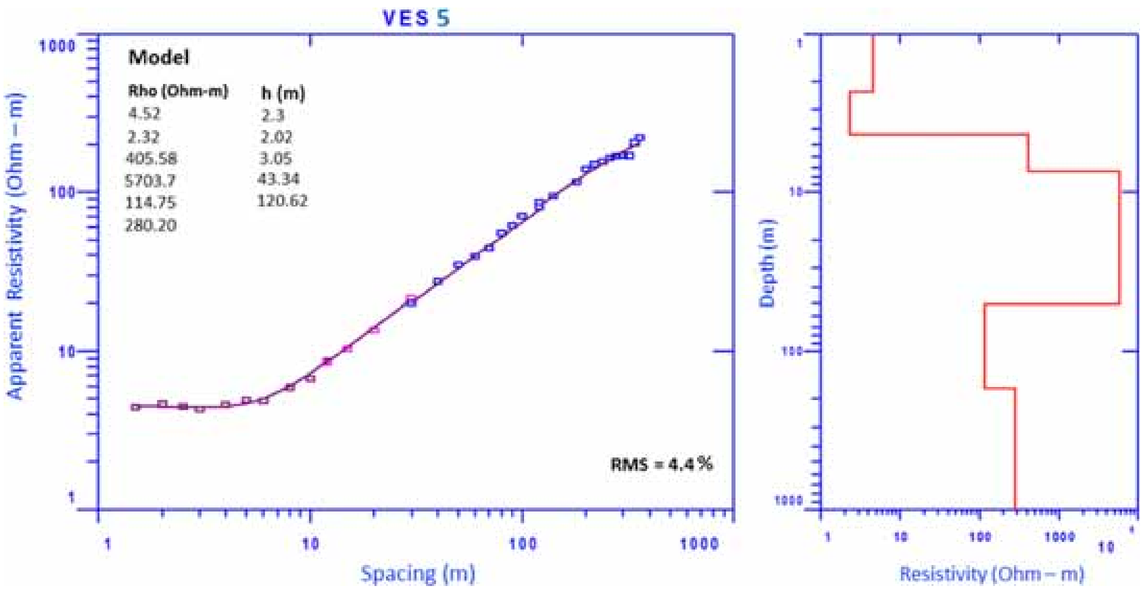

Figure 8. Shows the vertical electrical sounding (VES) model result (VES-5) where the square box is the field data and smooth line is the computed curve along with resistivity *vs.* depth model.

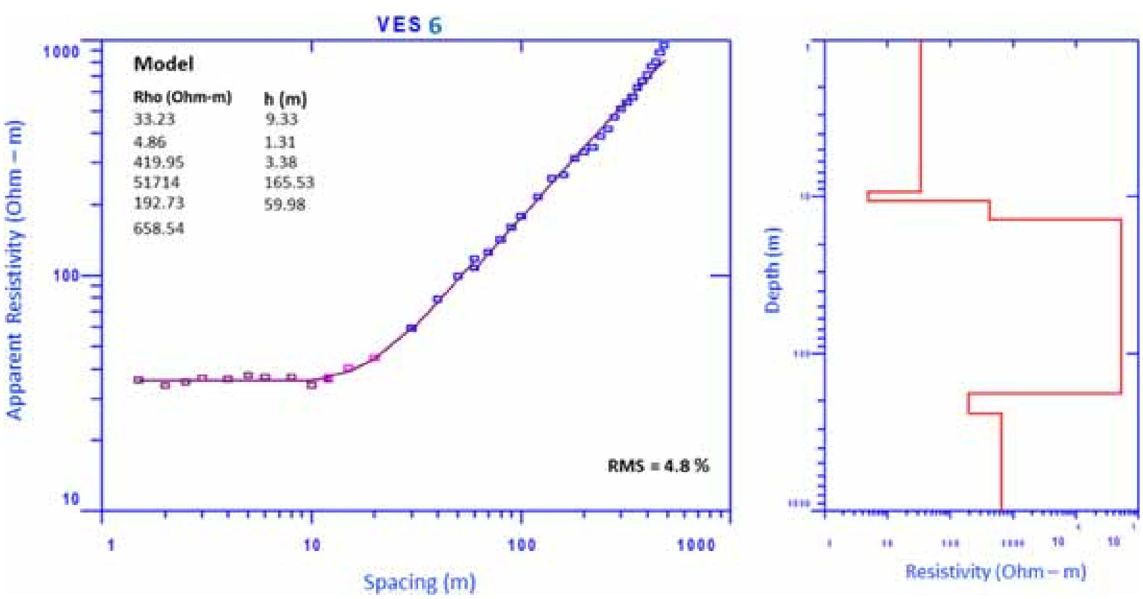

Figure 9. Shows the vertical electrical sounding (VES) model result (VES-6) where the square box is the field data and smooth line is the computed curve along with resistivity *vs.* depth model.

5. Results and discussion

In a highly deformed area geophysical studies namely ERT and VES were carried out at Gundreddypalle for mapping the shallow subsurface layers because the daily need of water is not sufficient for the resident people for the domestic and agriculture purposes due to water depletion within the study area. Geophysical technique like VES and ERT were combinedly used and is essential to select the appropriate places to do this survey because the said area was surrounded by small mounds, which made us very difficult to spread the cable in all directions.

This site is not very intricate and heterogeneous in nature as discovered from resistivity model up to a depth of 43 m (figure 3a). The inverted resistivity model at Gundreddypalle site shows a conspicuous lateral homogeneity in ERT-1 (figure 3a) with a gradual increase in resistivity with depth. The inverse model resistivity section impart us an idea about the initial deposition of rock in a horizontal way followed by metamorphism in a basin, which was confirmed by a borehole drilling up to a depth of 152 m. The interpretation of the ERT-2 (figure 3a) inverted resistivity section revealed the near-surface layer, which is characterized by a weathered rock with a resistivity 19–40 Ωm, up to 12 m depth. Further down resistivity increase to ∼1300 Ωm up to a maximum depth of 43 m (figure 3a). But the target depth achieved from ERT survey was not sufficient to reach the deeper rock strata due to limitation of space availability in the field. The conceptual geological model depicted the subsurface scenario based on resistivity characterization and borehole lithology, which corroborated with the resistivity characteristics of the various litho units up to a depth of 43 m (figure 3b). To achieve the deeper depth information, sounding (VES-1) was done at the marked point on ERT profile (refer figure 3a). The interpretation of the sounding curve (figure 4) revealed a 6-layer geological formations whose (resistivities: $\rho 1$, $\rho 2$, $\rho 3$, $\rho 4$, $\rho 5$, $\rho 6$ and thickness: h1, h2, h3, h4, h5) shows HA-type of the sounding curve (figure 4). The interpreted model results shown in the curve plot (figure 4) inferred as the prospect zone for groundwater exploration and prospecting. Whereas VES-2 and 7 (figures 5 and 10) show H-type of curve, which may indicate another prospect site for groundwater prospecting but with limited weathered rock. Whereas VES-3 and 4 show A-type of the modelled curve (figures 6 and 7), which do not indicate any major sign of prospect groundwater zones but at VES-3 (figure 6), there is one low resistivity anomaly at a depth of 180 m was seen, while VES-5 and 6 show another variety of HA-type of modelled curve with high resistivity, which are not recommended for groundwater prospect (figures 8 and 9).

With the help of geological and resistivity survey and their results, we arrived at a concrete potential zones at different depths and the final model (figure 12) gave us a clear idea about the prospect

Table 1. *Comprehensive table showing integrated results from lithology, petrography and geophysics.*

Depth (m)	Rock type	Resistivity (Ωm)	Resistivity ranges
0–14	Brownish soil	4–55	Low to moderate resistivity
14–36	Shale with rock chips	11–962	Low to high resistivity
36–67	Shaly mud	454–600	Moderate resistivity
67–92	Weathered shale (water struck point)	25–150	Low to moderate resistivity
92–110	Phyllite	1137–2500	High to very high resistivity
110–122	Weathered–fractured Phyllite (fresh and clear water)	10–150	Very low to moderate resistivity
122–152	Quartzite	>2500	Very high resistivity

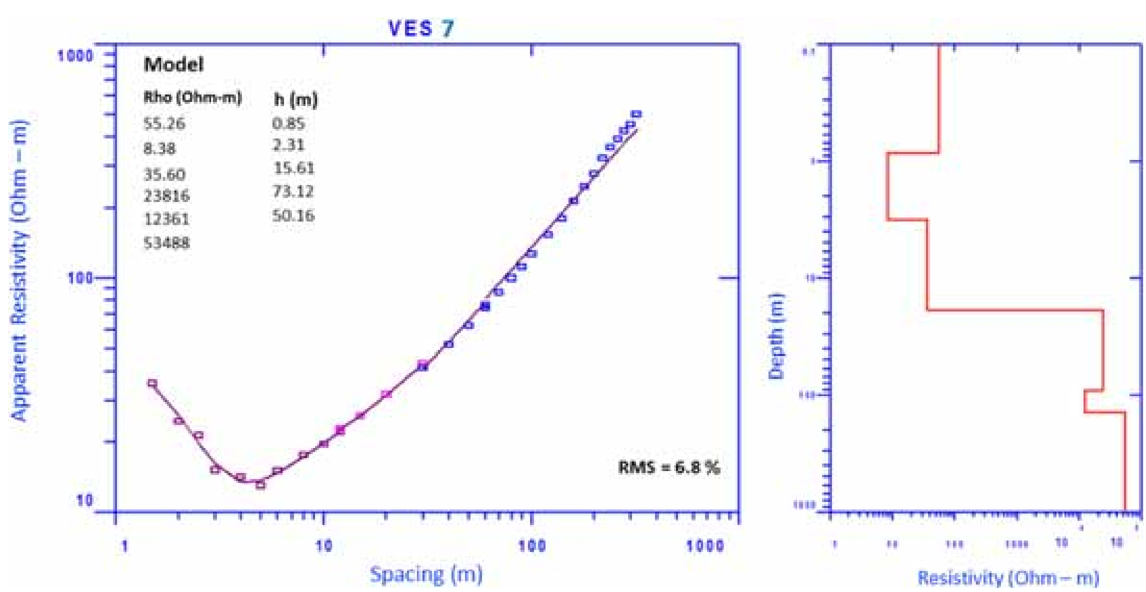

Figure 10. Shows the vertical electrical sounding (VES) model result (VES-7) where the square box is the field data and smooth line is the computed curve along with resistivity *vs.* depth model.

groundwater zone and lithology of the study area. At the same time, a comprehensive table (table 1) showing integrated results from lithology, petrography and geophysics from the integrated study is achieved, which depicted the corroboration between the lithology and hydrogeology. However, the output of inverted resistivity model shows substantial resistivity contrast between the highly weathered and massive rock strata with a definite anomaly, which is the indicator for groundwater potential zones at the marked location on the ERT profile (figure 3a). Integrated sounding data plot clearly shows the presence of two major potential zones at different depths marked by an ellipse (figure 11). This zone was confirmed by a borehole drilling up to 152 m depth. The second zone, which is below 30 m from the first layer is depicting the overall good potential zone as represented in the stacked figure (figure 11). As we move further down the depth, we can see another potentiality of groundwater towards the southern region.

Taking into consideration the results of the 2D and 1D geophysical models, drilling was confirmed at VES-1 at a lateral distance of 90 m marked on ERT model result (figure 3a). A borehole was

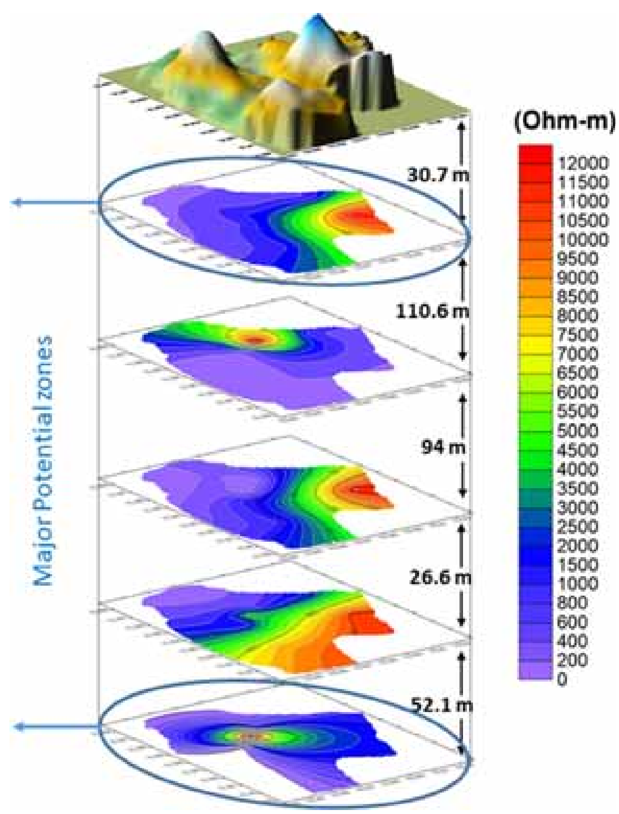

Figure 11. Shows the stacked 3D section from VES results depicting the potential layers of groundwater zones at different depth levels.

drilled up to a depth of 152 m encountering shale, phyllite and quartzite as major rock type with 1st water struck at 92 m and subsequently at a depth of 122 m, we encounter fresh water with pressure, which acts as a major aquifer zone. This finding from geophysics and drilling was also corroborated with the petrological study. While drilling at the top up to a depth of 36 m, shale encountered as it was analyzed from drill cuttings in the field followed by platy flaky rock sample, but its identity was not clear in hand specimen. It was observed that the top soil, up to a depth of 14 m was characterized as brownish soil, which was sticky in nature. As the depth increased, it was observed fine to medium-grained soil with intermediate between grey and brown in colour and it was characterized as shale from 36–67 m. Further down we noticed small sub-angular rock chips of shale, which was dark grey to black in colour with fine powder sample at a depth of 14–36 m and later from $\sim$67 to 92 m, which imparts the compactness of rock strata. When drilling bit reached 92 m, it punctured the rock formation and the water struck around 92 m depth but the exact type of rock and its identification was not clear from the rock water mixed rock cuttings at this depth. Subsequently, a sudden increase in water pressure was noticed as the drilling crosses 100 m depth with fresh and clear water rushing out of the borehole between 110 and 122 m depth. This confirms the presence of water bearing rock with saturated fractures within the phyllite–quartzite formation – is the main aquifer zone at this depth (figure 12).

In another detailed study and analysis, plane polarized light (PPL) image covers the same spot as the cross polarized light (XPL) image as seen in figure 12(i, ii). The typical yellow-green range of pleochroism of epidote and chlorite is obvious in XPL, which were made with the polarizer at two different angles, $\sim 90°$ apart. It is visible that most of the quartz grains are clustered around the margin of the section and in the same section, lower-left corner is more noticeably visible with quartz, and this is identified as shale. The thin section study clearly shows the arrangement of crystals in such a way that they follow the same trend of crystallization because of increasing efficiency of temperature and pressure as seen in figure 12(iii, iv). The visibility of micro folds in the plane-polarized image imparts an idea about the increasing trend of metamorphism, which is more visible on crossed polar image. The crossed polar image reveals that there are several minerals

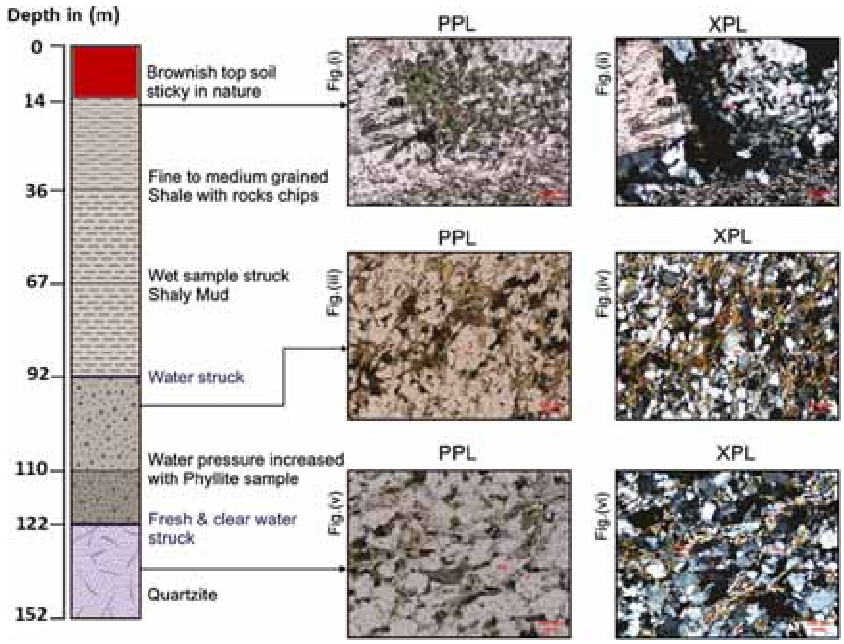

Figure 12. Shows the correlation of borehole litholog with thin sections of rock samples at different depth levels (where PPL – plane polarised light, XPL – cross polarised light).

present in the sample, e.g., quartz showing grey and white colour, micas identified with higher order colours and chlorite is in green colour under PPL as well as the alignment of the micas is clearly visible along the weak zones which is identified as phyllite. A thin section was made with rock chips below 122 m depth, which shows sutured contacts among fine to medium grained recrystallized quartz as seen in figure 12(v, vi). The sutured grain boundaries and undulose extinction of the quartz grains indicate that this rock formed under relatively low-temperature metamorphism. Most of the grains simultaneously display higher interference colours in one orientation and lower interference colours in the other orientation. This strong fabric was produced by recrystallization under directed stress, which caused all the grains to elongate in one direction figure 12(v, vi). The presence of some accessory minerals indicate that the quartzite is not completely metamorphosed and it is in transition phase, such rock we identified and named as transition quartzite. The presence of micro folds and fractures with mineralized lineament(s) within the rock matrix revealed the information about major tectonics in the study area. In response of this activity potential zones for groundwater has been created within the rock matrix. The detailed petrological study shows its advantage in identification of rocks with their micro features, which was not possible merely in hand specimen. The integration of geology, geophysics and petrography in the present studies exemplify the complete picture of aquifer zone in the prospect area.

6. Conclusions and recommendations

The study epitomizes and discloses the subsurface geological setting and structure of the hard rocks as well as availability of groundwater resources in the area of study. VES has been helpful in delineating the potential groundwater zones at a deeper depths while ERT results give the lateral and vertical variation of the resistivity up to 43 m depth. Out of the seven VES sites, the borehole drilling was accomplished at VES no. 1, which confirmed and validated the potentiality of groundwater resources between 110 and 122 m depth within the phyllite–quartzite formation. The thin sections of the rock samples were systematically and minutely analyzed through petrography study and their results with detailed identification, confirming that the rock type of the aquifer zone is at two distinct depths (figure 12), i.e., first at the depth of 92 m between shale and phyllite, the second depth is the contact zone between phyllite and quartzite rock at 122 m. In addition, the detailed thin section petrological study was one of the feasible approaches to determine the potential water bearing zones and the rock type in and around the study area.

While the detailed geophysical study and their results provided more additional groundwater zones for future prospecting of groundwater resources in the present geological setting.

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