Identification of potential groundwater zones by using Dar-zarrouk parameters– A case study of Maredumilli mandal, East Godavari district, Andhra Pradesh, India

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Research Highlights:

- The present study area comprises hard crystalline rocks of the Eastern Ghats Mobile Belt. For a long period, residents in this area have been suffering from a severe water crisis. To overcome this problem, for the first time we attempted to identify the groundwater potential zones in the current study area.
- To explore groundwater, hydrogeological studies and remote sensing were combined.
- In order to determine the optimal locations to drill boreholes in the research region, the vertical electrical sounding (VES) technique is utilised in this study to locate and delineate subsurface water structures, evaluate the aquifer's capacity protection, and then estimate the groundwater potential.
- Based on the computed transmissivity statistics, four groundwater potential zones (moderate, low, very low, and negligible) have been identified for the research region.

Abstract

Finding the groundwater in sedimentary rocks is not difficult until a region is covered in thick clay but identifying the fracture zones in hard rock terrain is always incredibly difficult. To solve this issue in the Maredumilli mandal in the East Godavari district of Andhra Pradesh. In this work, the vertical electrical sounding (VES) technique is used to find and delineate subsurface water structures, assess the aquifer's capacity protection, hence estimate the groundwater potential,to find the best locations to drill boreholes in the research area. In order to do that, we used resistivity data from 108 vertical electrical soundings (conducted with a Schlumberger array) in the hard rock terrains of the Eastern Ghat Mobile Belt (EGMB) of the study area. The data were analysed and interpreted using IPI2win software to ascertain the true resistivities and thicknesses of the underlying strata.. Khondalites and Charnockites are the local geology. A serious water problem affects the local population. .The major goal of this research is to locate prospective sources of groundwater using aquifer characteristics derived from secondary geophysical parameters (Dar-zarouk parameters), which might be used to meet human needs for sustenance.

To achieve this, we chose four villages in the mandal to conduct detailed geo-electrical surveys, and the data were interpreted to determine the subsurface layers. The Dar-zarrouk (DZ) parameters were determined using the layer parameters. These properties of the Dar-Zarouk (DZ) parameters have been utilised to investigate the hydrodynamic parameters (hydraulic conductivity and transmissivity) that identify an area's potential aquifer. The results shows that three to five lithological layers were observed in the study area.Based on the findings, the resistivity and thickness of the topsoil layer ranged from 0.75 – 6.48 m and 16-2761 Ωm, second layer starting with 1.81- 47.7 m and 16.7-1855 Ωm, third layer ranging from 4.38 – 88.6 m and 6.56 – 3609 Ωm, and fourthlayer ranging from 13.4-33 m and 26.1 - 8500 Ωm finally fifth layer resistivity range is 231- 8265 Ωm. The average depth to basement is 30.98 m. Four classifications of groundwater potential zones (moderate, low, very low, and negligible) have been assigned to the research region based on the computed transmittivity data.

Keywords: Vertical Electrical Soundings, Resisitivity, Geo electrical section, Aquifer transmissivity.

Introduction

One of the most essential elements for life, water has played a crucial role in the advancement of civilisation from the prehistoric era. Due to the world's population's rapid growth, there is an increased need to locate and establish a source of safe drinking water.Groundwater is majorly derived from air moisture that has precipitated and seeped into the soil and subsurface layers (Kwami *et al.* 2018). The occurrence and movement of groundwater is influenced by hydrological factors such as the porosity and permeability of rocks, which are inturn controlled by the size, shape, and arrangement of the rock's grain (D.K.Todd 2005).

Finding possible drill sites for groundwater exploration in hard rock areas is a difficult issue that can be handled using electrical imaging techniques, remote sensing, and geographic information systems approaches.

Hard rocks and alluvial aquifers dominate the semi-arid regions of the Indian subcontinent, and it is crucial to comprehend the nature of the aquifer systems in these areas (Jha and Sinha 2009). Finding the groundwater in sedimentary rocks is not a tough task until an area is covered with thick clay but in hard rock terrain, it is always an incredible challenge to locate the fracture zones. Due to the lack of primary intergranular porosity in aquifers of hard rock regime, secondary porosity is primarily responsible for controlling groundwater movement (Das, 2017). Secondary porosity is produced when lineament intersection, fracturing, and faulting of the underlying rocks.The indigenous people that inhabit this region struggle with access to water for drinking, domestic use, and agricultural purposes. To fetch a pot of water to drink, they must walk for miles.By locating groundwater potential zones, they can obtain potable drinking water necessary for their existence. However,Groundwater investigation is challenging in these places.

Different Geophysical research investigations are there for prospecting, evaluation and management of groundwater resources. The electrical resistivity survey, which includes Transient Electro Magnetic (TEM), Very Low Frequency (VLF), Electrical Resistivity Tomography (ERT), and Ground Penetrating Radar (GPR), these methods were used to locate possible bore holes in hard rock regions (B.V. Rao and Y.S. Prasad 2021; A. Iswahyudi *et al.* 2021; balakrishna *et al.* 2014; B.B.babu *et al.* 2022). When compared to other geophysical survey methods Vertical Electrical Sounding (VES) is one of the most most reliable geophysical techniques for groundwater investigation (Chambers et al. 2013). Finding feasible aquifers for a consistent and sustainable water supply has shown to be a reliable and effective use of the geophysical survey technique known as electrical resistivity survey (Adeniji *et al.* 2013). Numerous scholars have applied this technique in various regions of India and abroad (Adepelumi *et al.* 2006; Kshetrimayum and Bajpai 2011; Kumar 2012; Sinha *et al.* 2013; Aizebeokhai and Oyeyemi 2013; Atwia and Masoud 2013; Galazoulas *et al.* 2015; Aluko *et al.* 2017; Greggio *et al.* 2018; Gao *et al.* 2018 etc.)

This research's primary goal is to determining the ground water potential zones by using Dar-Zarrouk (D-Z) characteristics to determine the aquifer transmissivity and hydraulic conductivity in Maredumilli mandal of East Godavari district, Andhra Pradesh state, India. The rocks of the present study region are Khondalites and Charnockites.The people living this region are mostly tribal people and are facing acute shortage of drinking water. Therefore, it is crucial to accurately estimate and predict groundwater recharge before drilling a bore well in the area.This research work may be helpful in future to their sustainable development of the community.

Study area and Problem

Maredumilli Mandal is located in a geographic intersection of latitudes 17.462 and 17.863 in the north and longitudes 81.512 and 81.865 in the east. The Mandal is bordered by the North Chintur Mandal and the State of Orissa, on the south and west by the West Godavari and Khammam districts, and on the east by the Y. Ramavaram Mandal. In the East Godavari district, Maredumilli Mandal is one of the largest places with a forest cover. It covers an area of 951.7 sq km and receives an average rainfall of 153.33 cm/year It is characterized by typical hard rock terrain of East Ghat Mobile Belt (EGMB) and the intersected structural ineament are the principle source for groundwater occurrence.

. The altitude of the region ranges between 14 to 1367 meters Above Mean Sea Level (AMSL). About 93.94 % of the region is covered by mountainous landforms with valleys. The Khondalite and Charnockite group of rocks completely cover the research area (Figure. 1) khondalites are not as hard as Charnockites and have a medium to coarse grain(N.subba Rao 2012). Due to their medium to coarse-grained texture and higher feldspar composition than quartz, they are readily weathered and fractured. They are capable of transporting and storing water. The Charnockites are fine to medium-grained, massive, hard, and compact rocks. Due to their higher quartz content than feldspar, they are not easily weathered and fractured and cannot transfer or store water(N.subba Rao 2012).

For groundwater exploration study, we have used four villages in Maredumilli Mandal namely Devarapalli, Kundada, Pujaripakalu, and Vetukuru have been selected for geoelectrical survey. The criteria to choose these villages are accessibility (transport facility) to reach the villages, population of each village (number of people living in the villages) and their water demand. Though there are 71 villages in the Mandal, as per the 2011 senses, major percentage of the population of the Mandal was found in and around these four villages. There are 158 lineaments altogether in the study region (Figure 1). The nature of every lineament is structural. In the direction of alignment of lineaments, only the spread of the soundings is laid.

Data and Methodology

In and around four villages the study area, 108 vertical electrical soundings were performed. out of them 48 soundings have been collected from the Andhra Pradesh State Groundwater and Water Audit Department (APGWAD) and the remaining 60 locations, the first author has conducted the survey with DDR3 Resistivity meter. Out of 108 soundings, 18 soundings were conducted in and around Devarapalli, and another 18 soundings in Kundada, 15 soundings in Pujaripakalu, and 30 soundings in Vetukuru villages were conducted (Figure 1). The remaining soundings were conducted near villages namely Sunnampadu, Mosuru, and Maredumilli. All the soundings were conducted with Schlumberger configuration and the maximum current electrode spacing varies from 120 to 200 meters. IPI2Win GUI based software was used to interpret all the VES curves due to its effectiveness (Rao *et al.* 2019).

The resultant primary geoelectrical parameters (resistivity and thicknesses of layers) to determine the secondary (Dar-zarrouk) parameters.Then, these parameters were utilized in the calculation of aquifer parameters like hydraulic conductivity and transmissivity. Finally, the potential groundwater locations in each village have been identified based on the resultant aquifer transmissivity values and the thickness of the aquifer

Based on the total longitudinal conductance values, the aquifer protection capacity (APC) is determined (Obiora et al. 2015; Adeniji et al. 2014).) that can be derived from the primary layer parameters using the following equation (Equation. 1)

$$S=\sum_{i=1}^{n}\frac{h_i}{\rho_i}, \text{where i indicates layer number} \tag{1}$$

Using equation 2, the total transverse resistance (T) was computed.

$$T=\sum_{i=1}^{n}h_i \times \rho_i \tag{2}$$

The longitudinal resistivity (ρ_L) and transverse resistivity (ρ_T) values were calculated from the derived values of S and T using equations 3 and 4.

$$\rho_L = H/S \tag{3}$$

$$\rho_T = T/H \tag{4}$$

Where H = Σ hi, H is the depth to the lowest geoelectrical layer and hi is the height

In compacted rocks, weathering and fracturing increase porosity and permeability; this leads to inhomogeneity in the basement, which is quantified by the coefficient of anisotropy (Equation 5) (Ayuk et al. 2013).

$$\lambda=\sqrt{\frac{\rho_T}{\rho_L}} \tag{5}$$

From the Dar-zarrouk parameters, the aquifer parameters, such as hydraulic conductivity (K) and aquifer transmissivity (Tr), were calculated. According to Todd (1980), equation 6 illustrates the connection between the aquifer transmissivity (Tr) and hydraulic conductivity (K).

$$T_r = K\sigma T. \tag{6}$$

The hydraulic conductivity (K) was estimated using the equation presented below, where "σ" represents electrical conductivity (which is reciprocal of resistivity), and T represents transverse resistance (Heigold et al. 1979).

$$K = 386.40 R_{rw}^{-0.93283} . \tag{7}$$

Where Rrw = Aquifer resistivity (Resistivity of the assumed aquiferous layer based on the interpreted curves). Higher values of transmissivity (Tr) are a sign of productive groundwater aquifers, According to table 2 (Offodile 1983), aquifers are divided into five categories based on their transmissivity (Tr) values,

A total of 8 geo-electrical sections were drawn at favorable locations to view the subsurface aquifer in 2 D (Dimension). The nearest neighborhood methodology was used for the generation of these 2D sections.

Results:

Based on the computed results, 3 to 5 lithological layers are noticed in the study area. The three layer curve, which encompassed the research area, was classified by the H(31), A(10), and Q(3) curve types.. The study region was covered by the four layer cases HA(16), KH(16), QH(26) HK(1) and KQ(1) curve types. Five layer curves QHA(2), KHA(1) and HKH(1). The topsoil layer thickness and resistivity values range from 0.75 – 6.48 m and 16-2761 Ωm, range of the second layer 1.81- 47.7 m and 16.7-1855 Ωm, third layer ranging from 4.38 – 88.6 m and 6.56 – 3609 Ωm, and fourthlayer ranging from 13.4-33 m and 26.1 - 8500 Ωm finally fifth layer resistivity range is 231- 8265 Ωm.

The lithological layers with varying resistivity from 10 – 150 Ωm are inferred as aquifer formations in the area and the aquifer thickness maps for each village have been prepared. The interpreted outcomes of sounding data were also used to construct the spatial distribution maps of depth to the bottom-most layer (bedrock) (Fig. 6). According to Table 1, total longitudinal conductance ranges from a minimum of 0.02 Siemens to a maximum of 3.69 Siemens. The transverse resistance (T) values vary from 209.6 to 68246.2 ohm-m^2 (Table 1). The longitudinal resistivity ($\rho_{L)}$ values vary in the range from 15.5942 to 1788.71 ohm-m and The range of the transverse resistivity (T) values is 17.22 to 1844 ohm-m. Table 1 shows that the coefficient of anisotropy ranges from 1.0 to 2.23 based on the results of the VES data that have been interpreted.

Discussion

From the interpreted results of sounding data, the layers obtained with resistivity range from 10 to 200 Ωm have been considered as the groundwater aquifers (Rao et al. 2019) then the aquifer thickness has been calculated at each sounding location. The spatial distribution maps of aquifer thickness were prepared for the selected four villages (Figure 2). From these spatial distribution maps, it is observed that in Devarapalli village (Figure 2a), the moderate aquifer thickness (21.8 – 36.6 m) is obtained in the Easten parts of the village. This may be due to the presence of two structural lineaments passing through the village. These two intersected lineaments are the sources of rock weathering or fracturing in this region. Whereas on the Western side, the aquifer thickness is less than 21.8 m and it is reduced to 6.79 m westward. (Figure 2b) shows that 3/4th of Kundada village is found as good aquiferous zones (Aquifer thickness 30.7 – 52.9 m) which are formed due to intense weathering or fracturing along the existing structural lineaments (Faults) in the village. The Western side of the village is having less (<23.1 m) aquifer thickness due to the N-S extended ridge in these regions.

In Pujaripakalu village (Figure 2c), the good to moderate aquifer thickness (20.9 – 41.6 m) is found in the northern region of the village. This high thickness is obtained due to the deposition of sediments transported from the nearby hill and weathering of underground rock along the fracture zones found in the village. Whereas, in the southern region, the aquifer thickness is found less than 20.8 m and it reduces to zero southward near a hill. The aquifer thickness map of Vetukuru village (Figure 2d) shows that the village is covered with moderate to good thickness (22.4– 51.6 m) except for a small patch in the southernmost regions. The high aquifer thickness in this village is obtained due to weathering of fracturing of rocks along existing faults (Structural lineaments) in the village. The lower thickness values are obtained near hilly terrain in the southern region.

The depth to the basement has been calculated from the results of VES data and respective spatial distribution maps have been prepared for the above-selected four villages (Figure 3). It is clear from all the spatial distribution maps of basement depth that the shallow depth (<20 m) is found near hilly terrain and deep basement depth (20 – 61.3 m) is observed in pediment-pediplain complex zones. The deep basement depth in both Devarapalli and Kundada villages is obtained in the Eastern regions of the villages (Figures 3a and 3b). It is also observed from figures 3c and 3d that the northern regions of both Pujaripakalu and Vetukuru villages are found to be deeper basement zones. These deeper basement zones in selected four villages may be the zones of groundwater recharge as the above layers from the basement are characterized by weathering or fracturing. It is also observed from the results of VES curves as the resultant resistivity of overlying layers is below 200 Ωm.

The 2D subsurface sections are very useful to have an idea of lateral extent of aquifers in the study area. Based on the interpreted resistivity values, and major geology of the area (khondalites group of rocks), the lithology of subsurface is classified broadly into weathered, semi weathered, highly weathered, and hard khondalites. Table 3 displays the resistivity ranges of various formations. With the exception of a relatively small number of curves with a high second layer resistivity, the majority of curves initially display a declining tendency. The details discussion of the generated 2D geoelectrical sections has been presented below.

The geo-electric section AA` was drawn by joining 8 soundings (VES-4, 9, 11, 13, 14, 15 ,16, and 18) conducted in Devarapalli village. This section AA` passes in the direction of NW-SE with a length of 2.25 km. This section's elevation varies from 284 to 329 meters above mean sea level (msl) (Figure 4). The variation of the aquifer's resistivity is varying from 27.9 to 145 Ωm. Along this section, the aquifer is formed with weathered and semi-weathered khondalites. The aquifer thickness is ranging from 13.8 to 36.6 m. The good aquifer with better thickness is extending from a distance of 600 m to 2300 m. Hence, a well can be recommended for drilling anywhere along this section from 600 m to 2300 m.

Section BB"s topography ranges from 316 to 319 meters above mean sea level (msl) (Figure 5). This section runs along the direction of SW-NE with a length of 1.3 km. It was prepared by combining the soundings of VES-3, 5, 7 and 14 in Devrapalli village. The formations identified along this section are topsoil followed by weathered khondalite which is overlain by semi-weathered khondalite. The bottom-most layer is hard khondalite of high resistivity (more than 326 Ωm). The weathered and semi-weathered khondalite formations collectively form the aquifer along this section. The resistivity and thicknesses of the aquifer are ranging from 37 to 112.4 Ωm and from 16.9 to 28.6 m respectively. VES locations VES-3 and VES-14 can be recommended for drilling in this section.

The length of the CC` section is 3.7 km and it runs along the E-W direction. The altitude ranges from 547 to 581 meters above mean sea level (Figure 6). Seven vertical electrical soundings (VES-19, 20, 21, 23, 25, 33 & 36) in Kundada village were used to draw this section. Along this section, the aquifer’s resistivity alters from 41.4 to 98.4 Ωm and its thickness varies from 10.7 to 52.9 m. From the above figure, it is understood that the bore well can be recommended at any location from a distance of 1.2 km to 3.8 km from A.

In village Kundada, the soundings used to generate the section DD` are VES-26, 28, 32, and 34. The section follows the E-W direction with a length of 2.04 km (Figure 7). The lithology of the section just below the topsoil is highly weathered khondalite and the next successive layers are weathered and semi-weathered khondalite. The bottom-most layer is hard khondalite. The topography of this section's varies from 526 to 549 meters above mean sea level (amsl). The thickness and resistivity of aquifer is extended from 16.1 to 35.9 m and 30.5 to 195.1 Ωm respectively. The region between the sounding locations VES-26 and VES-34 can be recommended drill a well along this section.

From figure 8, it is clear that the along the section EE`, the inferred lithological formations are top soil followed by highly weathered khondalite and next two successive layers are weathered & semi weathered khondalites. The bottom layer is hard khondalite. The length of the section is 2.3 km that passes in NW-SE direction by joining the sounding points VES-73, 74, 75 and 76 in GM Valasa village. Both the resistivity and thicknesses of the aquifer in this section varies from 86.5 to 238 Ωm and 20.3 to 44.1m. The altitude of the profile alters in between 531 and 559 m. The suggested wells for drilling in this section are VES-74 and VES-76.

The topography of section FF` changes from 448 to 469 meters (Figure 9). The section passes through NW-SE direction with a length of 1400 m. The sounding points conducted in Pujaripakalu village (VES-41, 42, 44, 45, 46 & 48) were joined to generate this profile. The lithological formations weathered and semi weathered khondalites form major aquifer along this section. The aquifer resistivity and thicknesses vary from 153 to 223 Ωm and 9.87 to 41.6 m respectively. The section up to a distance of 1000 m from point F can be recommended for drilling a well.

The soundings carried out in Pujaripakalu village along the section GG` are VES 43, VES 44, VES 47 and VES 49 and it travels in a NE–SW direction. with a length of 901m (Figure 10). The topography of the section changes from 440 m to 489 m. In this section the aquifer resisitivity ranges from16.7 to160 Ωm and the inferred lithological formations such as weathered and semi weathered khondalites form the aquifer of the section. The aquifer thickness differs from 25.9 to 41.6 m. The complete section can be recommended for drilling a well.

This section HH` passes in the direction of N-S with a length of 86 m (Fig. 9). This section was selected in Vetukuru village by joining the soundings VES-86, 94, 95, 97 and 101. The dominant formations of the section are weathered and semi weathered khondalites with an altitude change of 33 meters (Minimum - 483m and maximum - 516 m). Aquifer's resistivity is varying from 43.4 to 223 Ωm. The complete section can be recommended for drilling a well as the minimum aquifer thickness along this profile is 26 m and maximum is 44. 2 m.

Clay and shale, which are extremely impermeable materials with low resistivity values, frequently have high longitudinal conductance values (S), whereas dry sand and gravel, which are permeable materials with high resistivity values, typically have low S values (Adeniji et al. 2014). Low longitudinal conductance (S) values are related to poor and weak APC, whereas high values of S are related to exceptional and good APC. Following the classification (Table 2) of Oladapo et al. (2004), the spatial distribution maps of S for the four villages of Maredumilli mandal have been prepared (Figure 12).

From the resultant values of S and its qualitative spatial distribution maps, it is observed that the aquifers of all the four villages are mostly fallen under moderate protective capacity (Figure 12). The complete area of Devarapalli village is classified under moderate protective capacity except for a small patch between VES-1 and VES-13 (Figure 12a). In Kundada village, the locations VES-20, 28 and 35 are classified as weak, and the VES points VES-21, 24 and 26 are fallen under good protective capacity (Figure 12b). The remaining area of the village is covered by a moderate category of aquifer protective capacity as per longitudinal conductance values.

As per figure 12c, the complete Pujaripakalu village is classified as having moderate aquifer protective capacity except for three locations (VES-42, 45, and 54). Since the longitudinal conductance values obtained from the soundings conducted in Pujarpakalu village are below 0.46 Siements (<0.69). The 3/4th region of Vetukuru village is fallen under moderate aquifer protective capacity (Figure 12d). The central region of the village is characterized by good protective capacity whereas the southernmost region is classified under the weak category.

From the resultant values of total transverse resistance (T), it is observed that at most of the locations the T value is high (> 1000 ohm-m^2). It demonstrates that the entire research region is comprised of hard rock terrain. It means that the lateral movement of infiltrated water dominates the vertical movement. Hence, there is less chance of water storage in these regions and most of the water is getting discharged to the low-lying area.

From the spatial distribution maps of T, it is noticed that higher values (>1770 ohm-m^2) are obtained in Easter regions of Devarapalli village and lower values (<1030 ohm-m^2) are found in Western region (Figure 13a). In Kundada village, the T values are higher than 1600 ohm-m^2 and very high values (> 3750 ohm-m^2) are observed in the Eastern region (Figure 13b). Figure 13c shows that major parts of Pujaripakalu village is covered with higher (>5000 ohm-m^2) values of T. At a few locations (VES-46, 48 and 53) in the central and southernmost regions of the village, the total transverse resistance is less than 2000 ohm-m^2. Whereas, 3/4th region of the Vetukuru village is characterized by higher values (>2000 ohm-m^2) of T (Figure 13d). Only in few patches located in southernmost region of the village, T value is less than 1000 ohm-m^2.

From the results of longitudinal resistivity (ρ_L) and transverse resistivity (ρ_T) it is observed that ρ_L is less than ρ_T at each sounding location. It denotes an inhomogeneous and anisotropic subsurface geology. The spatial distribution maps have been created for the four villages using these two values, which were used to calculate the coefficient of anisotropy (λ). (Figure 14). From the maps of anisotropy and following the report of Singh and Singh (1970), it is found that complete Devarapalli and Vetukuru villages are good zones for groundwater accumulation as λ values obtained in these village is varying in between 1 and 1.5 (Figure 14a and 14b). Whereas in Kundada and Pujaripakalu villages, at a few locations (VES-20, 26, 41 and 52), the λ values is greater than 1.5. Other than these four locations, the remaining parts of the villages are considered as good groundwater accumulation zones (Figure 14c and 14d).

Figure 14. Spatial distribution maps of coefficient of anisotropy for a) Devarapalli b) Kundada c) Pujaripakalu d) Vetukuru villages.

Considering the values of aquifer transmissivity and the classification of (Offodile 1983), the groundwater potential map of four selected villages have been prepared (Figure 15). From figure 15a it is observed that in Devarapalli village, only low and very low categories of groundwater potential locations have been found. Out of 18 locations in the village 13 locations are found as low and 5 remaining 5 locations are found as vary low potential for groundwater. Figure 15b shows that moderate, low and very low categories of groundwater potential in Kundada village. In this village a total of 18 soundings were conducted. Out of which only 3 locations are found moderate potential. The 11 locations are found low and the remaining 4 are very low groundwater potential.

From figure 15c it is clear that only one location is found as moderate potential and 7 locations are low category of groundwater potential. From the total number (15) of soundings conducted in this village 7 locations are found very low groundwater potential. Out of 30 VES locations in Vetukuru village (Figure 15d), only one location is found as moderate and 16 locations are found low category of potential. 12 locations in this village are found very low category and another one location is found as negligible potential for groundwater recharge.

Conclusion

According to the findings, the research region contained three to five lithological layers. The thickness of the topsoil layer and its resistivity values range from 0.75 – 6.48 m and 16-2761 Ωm, the second layer ranges from 1.81- 47.7 m and 16.7-1855 Ωm, the third layer ranges from 4.38 – 88.6 m and 6.56 – 3609 Ωm, and fourth layer ranging from 13.4-33 m and 26.1 - 8500 Ωm finally fifth layer resistivity range is 231- 8265 Ωm. The average depth to the basement is 30.98 m. The research region has been divided into four groundwater potential zones (moderate, low, very low, and negligible) based on the computed transmissivity data. From the results and spatial distribution maps, it is concluded that in the selected four villages, the aquifer thickness is moderate (around 30 m) and its protective capacity is also moderate. The potentiality of groundwater storage is low at the majority of the locations. Electrical resistivity values together with Dar-zarrouk parameters yield useful information in hard rock terrains about the presence of an aquifer. However, it is inadequate to deal with the situation on its own. If other information such as lineaments (From remote sensing) together with hydrologic parameters (aquifer parameters) has revealed detailed information about the exploring groundwater.In hard rock terrains, electrical resistivity values and Dar-zarrouk characteristics provide helpful information concerning the existence of an aquifer. To handle the situation by itself, however, is insufficient. If additional data, such as lineaments (from remote sensing) and hydrologic parameters (aquifer parameters), has provided coprehensive knowledge about the exploration of groundwater.

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Author Statement:

The first author, V. Sulochana Rani, completed this research as part of her Ph.D. The APGWAD (Andhra Pradesh State Groundwater and Water Audit Department) supplied 48 Vertical Electrical Soundings (VES) data for this study, remaining 60 VES data the first author surveyed and processed it under the supervision of the second author, as well as assisting in the text and completion of the paper. The third author was involved in the manuscript draft preparation and finalization.

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Declarations

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Conflicts of interest/Competing interests

The authors declare that they have no conflicts of interest/competing interest.

Availability of data and material:

Not applicable.

Code availability (software application or custom code)

No specific code was developed for this work. The used algorithm was cited in the literature.

Authors' contributions

The first author data analysed and processed it under the supervision of the second author, as well as assisting in the text and completion of the paper.The third author was involved in manuscript draft preparation, and finalization.

Ethics approval

We have followed the ethics and integrity in carrying out this work. We agree to follow the COPE guidelines.

Consent to participate (include appropriate statements)

We agree to participate in the review process and also to follow COPE's rules.

Consent for publication

We declare our consent for publication within the guidelines of COPE

References:

Abudeif, A. M., Abdel Aal, G. Z., Masoud, A. M., & Mohammed, M. A. (2022). Detection of Groundwater Pathways to Monitor Their Level Rise in Osirion at Abydos Archaeological Site for Reducing Deterioration Hazards, Sohag, Egypt Using Electrical Resistivity Tomography Technique. *Applied Sciences*, *12*(20), 10417

Ariyo, S.O. (2007) Hydro-Geophysical Investigations for Groundwater at Atan/Odosenbora Area, Southwestern Nigeria. Ife Journal of Science, 9, 87-92.

Adeniji, A. E., Obiora, D. N., Omonona, O. V., & Ayuba, R. (2013). Geoelectrical evaluation of groundwater potentials of Bwari basement area, Central Nigeria.

Adeniji, A. E., Omonona, O. V., Obiora, D. N., & Chukudebelu, J. U. (2014). Evaluation of soil corrosivity and aquifer protective capacity using geoelectrical investigation in Bwari basement complex area, Abuja. Journal of Earth System Science, 123(3), 491-502.

Aizebeokhai, A. P., Ogungbade, O., & Oyeyemi, K. D. (2018). Geoelectrical resistivity data set for characterising crystalline basement aquifers in Basiri, Ado-Ekiti, southwestern Nigeria. Data in brief, 19, 810-816.

Aluko, K. O., Raji, W. O., & Ayolabi, E. A. (2017). Application of 2-D resistivity survey to groundwater aquifer delineation in a sedimentary terrain: A case study of south-western Nigeria. Water Utility Journal, 17(7), 71-79.

Atwia, M. G., & Masoud, A. A. (2013). Hydrochemical and geoelectrical investigation of the coastal shallow aquifers in El-Omayed area, Egypt. Environmental monitoring and assessment, 185(8), 7065-7080.

Ayuk, M. A., Adelusi, A. O., & Adiat, K. A. N. (2013). Evaluation of groundwater potential and aquifer protective capacity assessment at Tutugbua-Olugboyega area, off Ondo road, Akure Southwestern Nigeria. Int. J. Phys. Sci, 8(1), 37-50.

Butchibabu, B., Jha, P. C., Sandeep, N., & Sivaram, Y. V. (2022). Delineation of Water Seepage Flow Path in the Underground Metro Rail Tunnel Using Cross-Hole GPR Tomography: A Case Study. In Proceedings of Geotechnical Challenges in Mining, Tunneling and Underground Infrastructures (pp. 371-382). Springer, Singapore.

Das, S. (2017). Delineation of groundwater potential zone in hard rock terrain in Gangajalghati block, Bankura district, India using remote sensing and GIS techniques. Modeling Earth Systems and Environment, 3(4), 1589-1599.

Galazoulas, E. C., Mertzanides, Y. C., Petalas, C. P., & Kargiotis, E. K. (2015). Large scale electrical resistivity tomography survey correlated to hydrogeological data for mapping groundwater salinization: a case study from a multilayered coastal aquifer in Rhodope, Northeastern Greece. Environmental processes, 2(1), 19-35.

Greggio, N., Giambastiani, B. M., Balugani, E., Amaini, C., & Antonellini, M. (2018). High-resolution electrical resistivity tomography (ERT) to characterize the spatial extension of freshwater lenses in a salinized coastal aquifer. Water, 10(8), 1067.

Heigold, P. C., Gilkeson, R. H., Cartwright, K., & Reed, P. C. (1979). Aquifer transmissivity from surficial electrical methods. Groundwater, 17(4), 338-345.

Iswahyudi, A., Prabawa, S. E., Warnana, D. D., & Widodo, A. (2021, February). Very low frequency-electromagnetic (vlf-em) for detecting groundwater river patterns in karst area of kaligambir village. In Journal of Physics: Conference Series (Vol. 1825, No. 1, p. 012016). IOP Publishing.

Jha, B. M., & Sinha, S. K. (2009). Towards better management of ground water resources in India. QJ, 24(4), 1-20.

Kumar, D., Rao, V. A., & Sarma, V. S. (2014). Hydrogeological and geophysical study for deeper groundwater resource in quartzitic hard rock ridge region from 2D resistivity data. Journal of Earth System Science, 123(3), 531-543.

Kwami, I. A., Ishaku, J. M., Mukkafa, S., Haruna, A. I., & Ankidawa, B. A. (2019). Delineation of aquifer potential zones using hydraulic parameters in Gombe and environs, North-Eastern, Nigeria. Heliyon, 5(7), e01927.

Nagaiah, E., Sonkamble, S., & Chandra, S. (2022). Electrical geophysical techniques pin-pointing the bedrock fractures for groundwater exploration in granitic hard rocks of Southern India. Journal of Applied Geophysics, 199, 104610.

Obiora, D. N., Ajala, A. E., & Ibuot, J. C. (2015). Evaluation of aquifer protective capacity of overburden unit and soil corrosivity in Makurdi, Benue state, Nigeria, using electrical resistivity method. Journal of Earth System Science, 124(1), 125-135.

Offodile, M. E. (1983). The occurrence and exploitation of groundwater in Nigeria basement complex. J Miner Geol, 20, 131-146.

OLUGBENGA, A. T., & OLADIJI, A. E. (2015). Geo-electrical investigation of aquifer protective capacity in Kubwa basement complex area, Abuja, Nigeria. Journal of Global Ecology and Environment, 3(4), 230-241.

Rao, P. V., Subrahmanyam, M., & Ratnakar, D. (2019). Performance evaluation of different interpretation techniques of vertical electrical sounding data. EDITORIAL OFFICE, 23(1), 55-68.

Sinha, R., Yadav, G. S., Gupta, S., Singh, A., & Lahiri, S. K. (2013). Geo-electric resistivity evidence for subsurface palaeochannel systems adjacent to Harappan sites in northwest India. Quaternary International, 308, 66-75.

Subba Rao N (2012) Indicators for occurrence of groundwater in the rocks of Eastern Ghats. Current Sci, 103: 352–353.

Venkateswara Rao, B., Siva Prasad, Y. Evaluation of aquifer characteristics using well logging tools and pumping tests in a typical khondalitic aquifer in the Northern parts of Eastern Ghats of India. Environ Earth Sci 80, 38 (2021). https://doi.org/10.1007/s12665-020-09286-8

Wahab, S., Saibi, H., & Mizunaga, H. (2021). Groundwater aquifer detection using the electrical resistivity method at Ito Campus, Kyushu University (Fukuoka, Japan). Geoscience Letters, 8(1), 1-8.

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S.NO	VES_CODE	Name of the village	Latitude(Deg)	Longitude(Deg)	layer 1		layer2		layer3		layer4		layer5	H	S	ρl	ρt	λ
					ρ1	h1	ρ2	h2	ρ3	h3	ρ4	h4	ρ5					
1	VES_1	Devarapalli	17.522	81.726	47.8	0.782	17.5	4.36	32.7	20.6	142			25.742	0.895	28.747	30.584	1.031
2	VES_2	Devarapalli	17.519	81.72	75.8	1.96	35.7	11.4	582					13.36	0.345	38.704	41.583	1.037
3	VES_3	Devarapalli	17.525	81.725	113.1	1.137	39.32	3.388	112.4	21.14	326.1			25.665	0.284	90.276	102.784	1.067
4	VES_4	Devarapalli	17.518	81.727	109	1.15	58	10.2	133	19.7	1540			31.05	0.335	92.816	107.473	1.076
5	VES_5	Devarapalli	17.523	81.716	119	3.02	37	16.9	763					19.92	0.482	41.316	49.432	1.094
6	VES_6	Devarapalli	17.524	81.712	134	1.41	27.5	15.3	2545					16.71	0.567	29.477	36.487	1.113
7	VES_7	Devarapalli	17.526	81.728	65.4	0.75	39.9	5.67	82.5	12.7	508			19.12	0.308	62.176	69.196	1.055
8	VES_8	Devarapalli	17.53	81.725	101	2.19	76.9	6.08	131	19.8	317			28.07	0.252	111.437	116.941	1.024
9	VES_9	Devarapalli	17.52	81.723	202	1.23	98.4	16.6	145	14.2	537			32.03	0.273	117.447	123.038	1.024
10	VES_10	Devarapalli	17.521	81.727	144	1.44	42.1	25.8	486					27.24	0.623	43.736	47.487	1.042
11	VES_11	Devarapalli	17.526	81.719	271	1.49	90.5	19	1238					20.49	0.215	95.106	103.626	1.044
12	VES_12	Devarapalli	17.527	81.714	232	1.14	32.2	14.9	409					16.04	0.468	34.299	46.400	1.163
13	VES_13	Devarapalli	17.519	81.727	122	0.75	83.5	4.9	9.36	7.71	76.9	16	1318	29.06	1.093	26.594	61.258	1.518
14	VES_14	Devarapalli	17.525	81.72	247	3.04	52.5	28.6	2452					31.64	0.557	56.797	71.188	1.120
15	VES_15	Devarapalli	17.514	81.729	43.7	0.75	47.6	5.98	65.1	30.6	517			37.33	0.613	60.913	61.867	1.008
16	VES_16	Devarapalli	17.53	81.718	73	2.12	27.9	13.8	1452					15.92	0.524	30.401	33.906	1.056
17	VES_17	Devarapalli	17.519	81.716	49.2	1.9	31.2	6.79	1025					8.69	0.256	33.913	35.136	1.018
18	VES_18	Devarapalli	17.522	81.722	145	2.74	51.2	28.8	829					31.54	0.581	54.249	59.349	1.046
19	VES_19	Kundada	17.569	81.654	131	2.47	313	12.7	41.4	10.7	608			25.87	0.318	81.382	183.288	1.501
20	VES_20	Kundada	18.569	82.654	132	3.47	314	13.7	42.4	11.7	609			28.87	0.346	83.473	182.055	1.477
21	VES_21	Kundada	19.569	83.654	132	4.47	314	14.7	42.4	12.7	609			31.87	0.380	83.823	180.242	1.466
22	VES_22	Kundada	17.555	81.679	231	1.32	353	3.63	98.4	10.9	141	22	3463	38.05	0.284	133.877	152.144	1.066
23	VES_23	Kundada	17.57	81.689	317	1.18	181	8.46	82.1	38.5	1446			48.14	0.519	92.683	105.238	1.066
24	VES_24	Kundada	17.569	81.695	224	0.854	99.2	4.29	45.5	14.6	89	33	231	52.744	0.739	71.399	79.974	1.058
25	VES_25	Kundada	17.57	81.68	448	4.54	70.4	11.7	43.3	31.5	343			47.74	0.904	52.821	88.428	1.294
26	VES_26	Kundada	17.562	81.666	805	4.56	84.9	9.32	30.5	26.6	388			40.48	0.988	40.989	130.271	1.783
27	VES_27	Kundada	17.556	81.672	188	0.75	96.1	13.2	53.2	15.2	460			29.15	0.427	68.257	76.095	1.056
28	VES_28	Kundada	17.563	81.655	141.69	0.75	195.15	20.146	581.14					20.896	0.109	192.543	193.231	1.002
29	VES_29	Kundada	17.566	81.664	111	1.46	59.7	24.4	204					25.86	0.422	61.299	62.596	1.011
30	VES_30	Kundada	17.557	81.692	585	1.81	236	47.7	1442					49.51	0.205	241.262	248.759	1.015
31	VES_31	Kundada	17.563	81.685	267	0.75	174	7.53	59.2	32.2	3131			40.48	0.590	68.610	84.405	1.109
32	VES_32	Kundada	17.563	81.662	80.6	1.83	317	2.33	49.8	16.1	222			20.26	0.353	57.337	83.311	1.205
33	VES_33	Kundada	17.57	81.671	463	1.53	1068	3.41	94.5	52.9	3580			57.84	0.566	102.139	161.641	1.258
34	VES_34	Kundada	17.562	81.674	473	1.02	212	5	93.9	31.2	6260			37.22	0.358	103.964	120.154	1.075
35	VES_35	Kundada	17.557	81.685	726	1.73	261	35.8	1755					37.53	0.140	268.940	282.435	1.025
36	VES_36	Kundada	17.57	81.666	120	1.91	162	7.86	89.5	43.6	387			53.37	0.552	96.757	101.269	1.023
37	VES_37	Munjumamidi	17.54	81.661	107	0.75	21	7.56	36.7	42.8	454			51.11	1.533	33.335	35.409	1.031
38	VES_38	Munjumamidi	17.54	81.664	128	4.5	19.6	12.7	557					17.2	0.683	25.179	47.960	1.380
39	VES_39	Munjumamidi	17.545	81.663	563	1.21	208	5.63	68.6	18.3	895			25.14	0.296	84.938	123.614	1.206
40	VES_40	Munjumamidi	17.542	81.658	150	4.99	21.8	31.2	112					36.19	1.464	24.712	39.477	1.264
41	VES_41	Pujaripakalu	17.613	81.74	73.2	1.8	1198	2.61	47.9	9.87	8500			14.28	0.233	61.334	261.296	2.064
42	VES_42	Pujaripakalu	17.615	81.741	505.2	5.489	1073	9.406	165.7	18.53	8000			33.425	0.131	254.260	476.772	1.369
43	VES_43	Pujaripakalu	17.618	81.736	257	1.44	846	2.45	153	28.9	419			32.79	0.197	166.120	209.347	1.123
44	VES_44	Pujaripakalu	17.619	81.739	208	0.75	340	4.53	160	41.6	759			46.88	0.277	169.285	178.161	1.026
45	VES_45	Pujaripakalu	17.622	81.738	938	0.961	416	4.57	223	35.1	996			40.631	0.169	239.839	261.619	1.044
46	VES_46	Pujaripakalu	17.611	81.742	19.2	1.65	73.2	12.5	374					14.15	0.257	55.122	66.903	1.102
47	VES_47	Pujaripakalu	17.621	81.741	712	0.75	1855	7.43	169	39.8	1544			47.98	0.241	199.450	438.575	1.483
48	VES_48	Pujaripakalu	17.617	81.738	23.3	2.49	76.6	22	130					24.49	0.394	62.146	71.181	1.070
49	VES_49	Pujaripakalu	17.616	81.735	39.6	0.938	16.7	3.13	90	22.8	209			26.868	0.464	57.850	79.701	1.174
50	VES_50	Pujaripakalu	17.612	81.735	527	0.75	1178	11.2	362	88.6	5048			100.55	0.256	393.262	454.123	1.075
51	VES_51	Pujaripakalu	17.612	81.732	368	0.75	238	6.36	80.9	24.5	366			31.61	0.332	95.325	119.321	1.119
52	VES_52	Pujaripakalu	17.613	81.738	1061	1.08	807	19.6	56.7	12.2	1727			32.88	0.240	136.731	536.947	1.982
53	VES_53	Pujaripakalu	17.611	81.73	235	1.14	334	15.1	121	18.6	1267			34.84	0.204	170.969	217.046	1.127
54	VES_54	Pujaripakalu	17.612	81.736	733	1.13	285	2.94	136	11.7	397			15.77	0.098	161.104	206.556	1.132
55	VES_55	Pujaripakalu	17.611	81.734	94.9	1.24	64.6	11.6	828					12.84	0.193	66.655	67.526	1.007
56	VES_56	Sunnampadu	17.509	81.726	26.5	3.66	71.8	23.9	248					27.56	0.471	58.516	65.784	1.060
57	VES_57	Sunnampadu	17.506	81.728	26.8	1.1	39.7	36.7	263					37.8	0.965	39.152	39.325	1.002
58	VES_58	Sunnampadu	17.506	81.727	40.8	1.76	84.8	8.92	26.2	25.2	117			35.88	1.110	32.320	41.485	1.133
59	VES_59	Sunnampadu	17.51	81.729	165	0.989	33	9.6	54.8	24.2	185			34.789	0.739	47.107	51.917	1.050
60	VES_60	Sunnampadu	17.506	81.725	221	0.866	18.6	9.27	52.8	16.1	319			26.236	0.807	32.501	46.268	1.193
61	VES_61	Sunnampadu	17.508	81.725	52.5	3.14	105	4.36	30	11.7	206			19.2	0.491	39.077	50.711	1.139
62	VES_62	Sunnampadu	17.504	81.729	88	1.33	30.2	9.65	14.6	49	95.4			59.98	3.691	16.251	18.737	1.074
63	VES_63	Sunnampadu	17.508	81.728	16	1.08	30.4	5.87	13.8	22.2	474			29.15	1.869	15.594	17.224	1.051
64	VES_64	Addariveedhi	17.605	81.719	662	4.2	95.3	6.09	554					10.29	0.070	146.481	326.606	1.493
65	VES_65	Addariveedhi	17.602	81.708	33.6	3.47	89.4	28.1	3153					31.57	0.418	75.600	83.267	1.049
66	VES_66	Addariveedhi	17.602	81.717	289	1.43	496	4.59	158	15.9	853			21.92	0.115	190.883	237.323	1.115
67	VES_67	Addariveedhi	17.6	81.712	417	1.87	178	9.7	68.1	35.8	472			47.37	0.585	81.019	104.378	1.135
68	VES_68	Mosuru	17.575	81.666	305	0.75	202	33.7	997					34.45	0.169	203.496	204.242	1.002
69	VES_69	Mosuru	17.576	81.67	157	1.1	95.2	12.1	57.1	30.7	670			43.9	0.672	65.351	70.105	1.036
70	VES_70	Mosuru	17.574	81.67	206	1.07	137	5.97	37.4	54.8	1687			61.84	1.514	40.845	49.933	1.106

71	VES_71	Mosuru	17.578	81.663	148	2.08	247	2.78	97.8	24.4	251			29.26	0.275	106.478	115.544	1.042
72	VES_72	Mosuru	17.574	81.661	85.6	6.48	26.7	26.6	206					33.08	1.072	30.859	38.238	1.113
73	VES_73	GM Valasa	17.597	81.645	193	6.32	29.8	22.5	272					28.82	0.788	36.584	65.588	1.339
74	VES_74	GM Valasa	17.586	81.662	236	3.04	90	44.1	1544					47.14	0.503	93.740	99.415	1.030
75	VES_75	GM Valasa	17.594	81.653	60.9	0.833	282	2.27	86.5	20.3	26.1			23.403	0.256	91.272	104.552	1.070
76	VES_76	GM Valasa	17.588	81.658	111	1.21	238	34.7	87.7					35.91	0.157	229.165	233.721	1.010
77	VES_77	Vetukuru	17.625	81.755	88.4	2.23	60.6	7.17	90	33.9	665			43.3	0.520	83.236	85.049	1.011
78	VES_78	Vetukuru	17.64	81.748	107	1.05	46.1	1.86	184	22.6	987			25.51	0.173	147.468	170.776	1.076
79	VES_79	Vetukuru	17.637	81.75	30.5	0.777	48.5	4.97	104	36.8	885			42.547	0.482	88.309	96.175	1.044
80	VES_80	Vetukuru	17.634	81.759	179	0.993	61.8	7.46	109	16.1	384			24.553	0.274	89.621	97.490	1.043
81	VES_81	Vetukuru	17.614	81.749	160	0.825	32	9.71	184					10.535	0.309	34.139	42.024	1.109
82	VES_82	Vetukuru	17.63	81.759	277	1.29	33.3	3.54	141	21.5	301			26.33	0.263	99.945	133.183	1.154
83	VES_83	Vetukuru	17.613	81.752	447	0.929	79.2	3.38	579					4.309	0.045	96.280	158.496	1.283
84	VES_84	Vetukuru	17.621	81.749	961	1.2	489	5.8	161	34.1	635			41.1	0.225	182.739	230.645	1.123
85	VES_85	Vetukuru	17.634	81.748	412	2.07	269	14.4	105	42.2	1145			58.67	0.460	127.416	156.084	1.107
86	VES_86	Vetukuru	17.623	81.752	211	1.06	666	1.81	226	44.2	1889			47.07	0.203	231.511	242.582	1.024
87	VES_87	Vetukuru	17.631	81.745	246	1.07	149	3.6	75.8	34.8	532			39.47	0.488	80.945	87.090	1.037
88	VES_88	Vetukuru	17.635	81.756	389	0.861	154	3.83	92.9	26.6	477			31.291	0.313	99.840	108.526	1.043
89	VES_89	Vetukuru	17.623	81.757	144	3.04	179	18.9	720					21.94	0.127	173.168	174.150	1.003
90	VES_90	Vetukuru	17.618	81.757	339	1.57	146	1.81	849	4.38	59.4	13	8265	21.16	0.248	85.399	250.996	1.714
91	VES_91	Vetukuru	17.624	81.755	224	1.54	135	8.17	69	51.6	3446			61.31	0.815	75.207	81.688	1.042
92	VES_92	Vetukuru	17.615	81.753	157	1.19	88.4	2.84	466					4.03	0.040	101.495	108.657	1.035
93	VES_93	Vetukuru	17.628	81.755	121	0.75	162	8.45	13.3	30.3	954			39.5	2.337	16.905	47.155	1.670
94	VES_94	Vetukuru	17.629	81.751	32.5	1.58	42.1	32.8	379					34.38	0.828	41.536	41.659	1.001
95	VES_95	Vetukuru	17.626	81.751	223	1.2	102	7.31	43.4	29.8	164			38.31	0.764	50.165	60.207	1.096
96	VES_96	Vetukuru	17.617	81.753	201	1.93	60.7	14.9	435					16.83	0.255	65.981	76.789	1.079
97	VES_97	Vetukuru	17.63	81.75	202	3	52.7	35.9	849					38.9	0.696	55.886	64.214	1.072
98	VES_98	Vetukuru	17.637	81.746	232	2.03	77.1	4.74	151	24.4	390			31.17	0.232	134.459	145.037	1.039
99	VES_99	Vetukuru	17.631	81.755	220	2.84	77.6	36.2	452					39.04	0.479	81.434	87.959	1.039
100	VES_100	Vetukuru	17.64	81.742	237	1.91	86.8	11.4	133	21.4	193			34.71	0.300	115.585	123.549	1.034
101	VES_101	Vetukuru	17.631	81.75	234	1.29	146	6.86	76	26	406			34.15	0.395	86.542	96.030	1.053
102	VES_102	Vetukuru	17.634	81.753	446	1.25	325	8.78	80.3	24.1	4081			34.13	0.330	103.442	156.643	1.231
103	VES_103	Vetukuru	17.622	81.756	2761	5.41	1687	31.6	3545					37.01	0.021	1788.708	1843.994	1.015
104	VES_104	Vetukuru	17.62	81.753	1413	3.75	220	6.19	3609					9.94	0.031	322.829	670.075	1.441
105	VES_105	Vetukuru	17.631	81.743	408	0.86	298	7.5	60.8	22.2	540			30.56	0.392	77.878	128.784	1.286
106	VES_106	Vetukuru	17.632	81.74	750	1	366	5.36	257	21.3	1599			27.66	0.099	279.797	295.946	1.028
107	VES_107	Addarivalasa	17.772	81.767	569	1.56	447	15.1	252					16.66	0.037	456.158	458.424	1.002
108	VES_108	Boduluru	17.692	81.704	65	1.57	25.8	4.17	180					5.74	0.186	30.896	36.522	1.087

Table 2.

Longitudinal Conductance (in Siemens)	Protective capacity rating
> 10	Excellent
5 – 10	Very good
0.7– 4.9	Good
0.2 –0.69	Moderate
<0.19	Weak

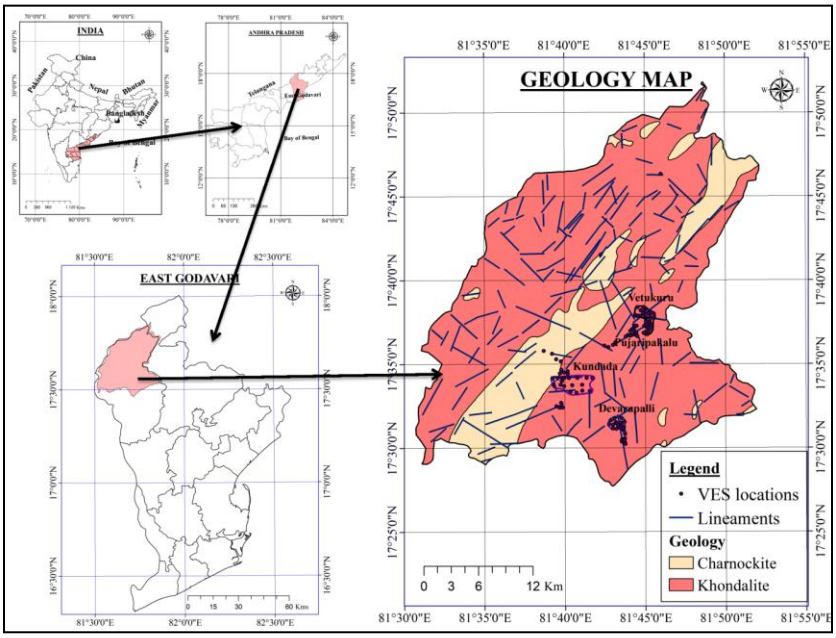
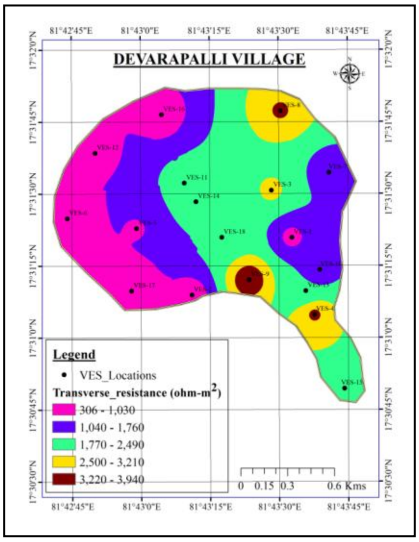


Fig. 1



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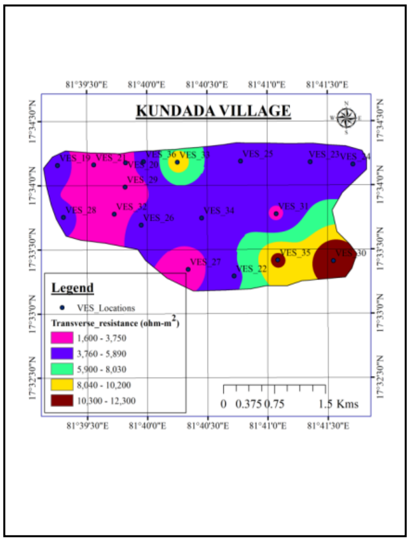

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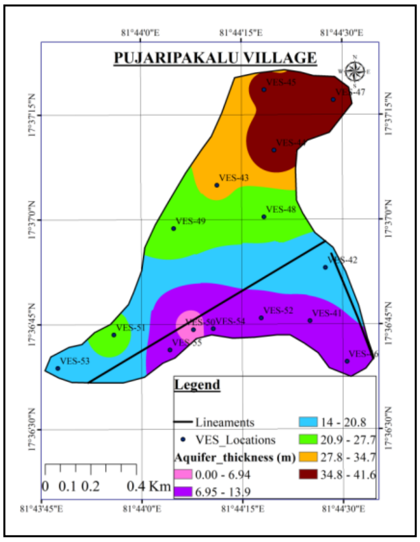

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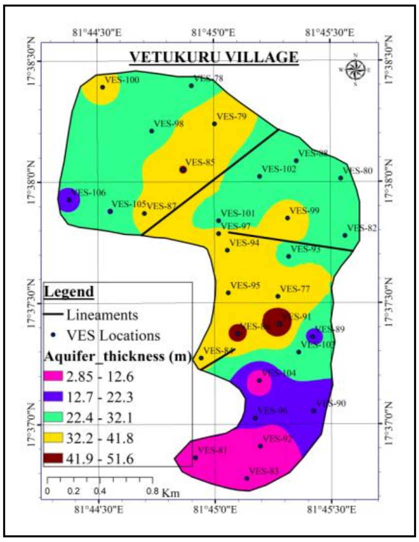

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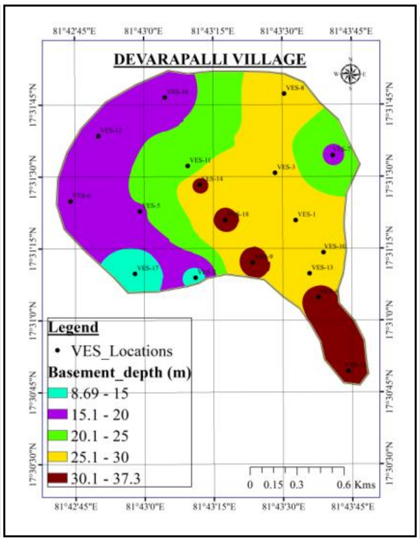

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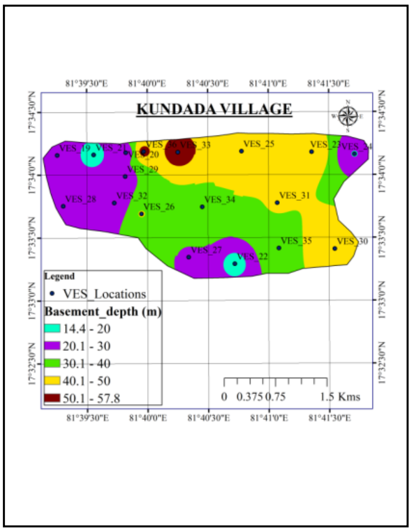

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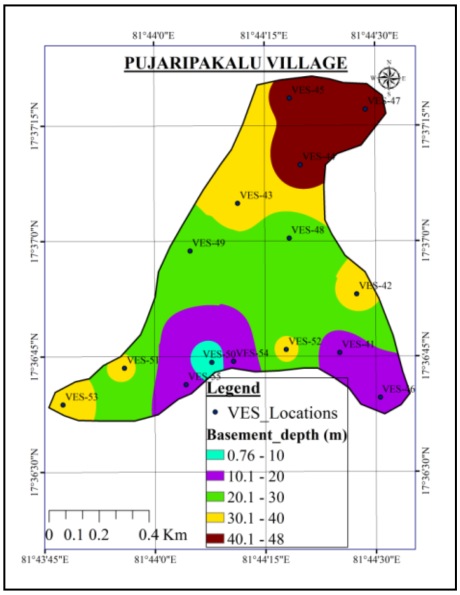

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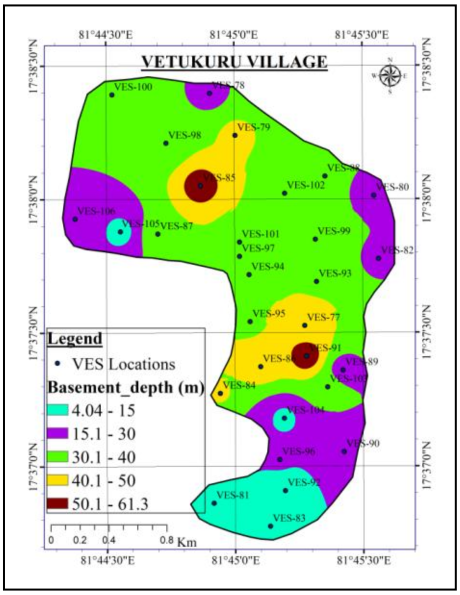

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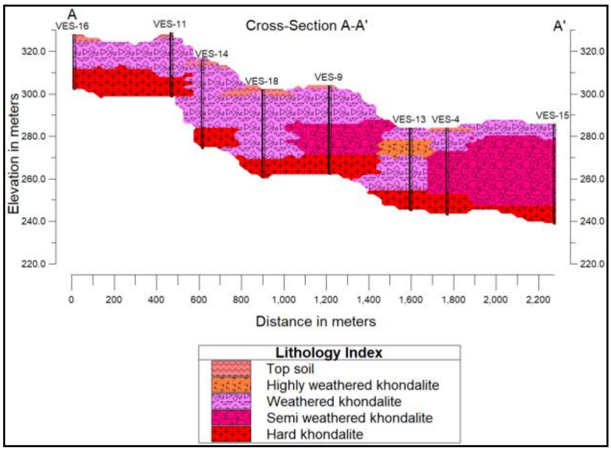

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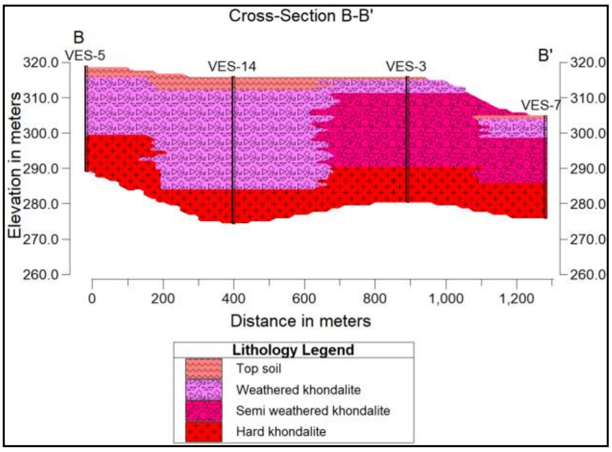
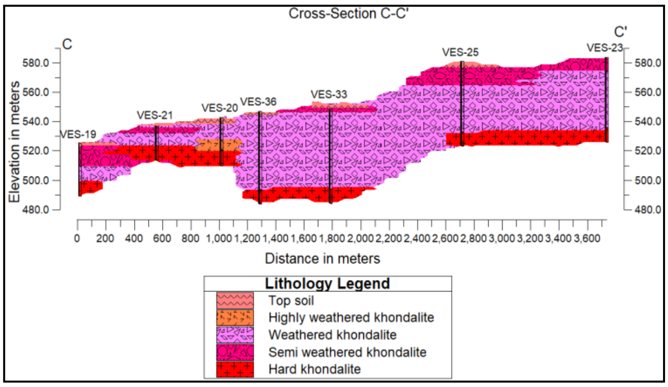


Fig.5



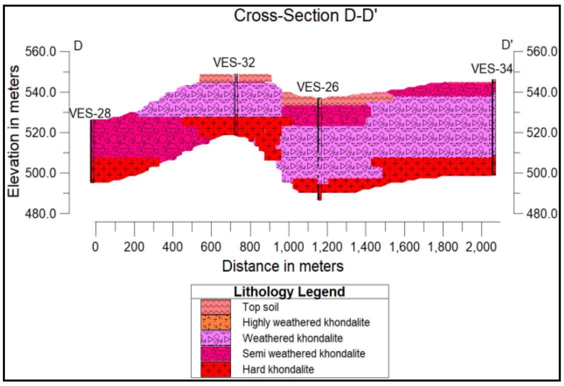
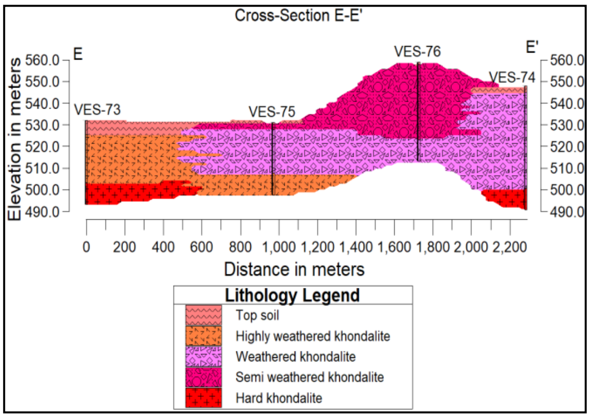


Fig.6

Fig.7



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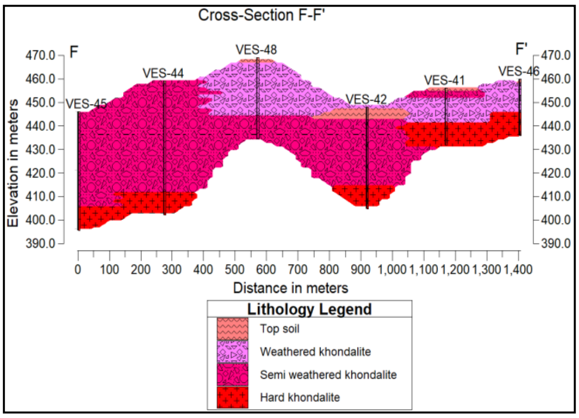


Fig.9

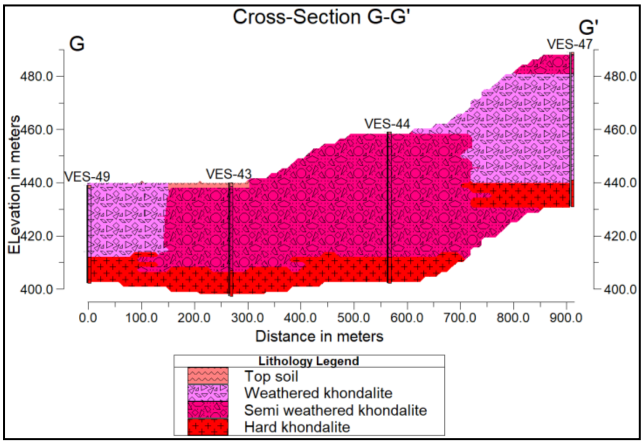


Fig.10

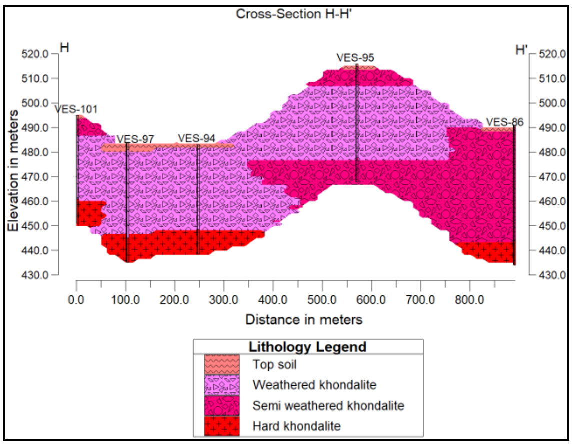


Fig.11

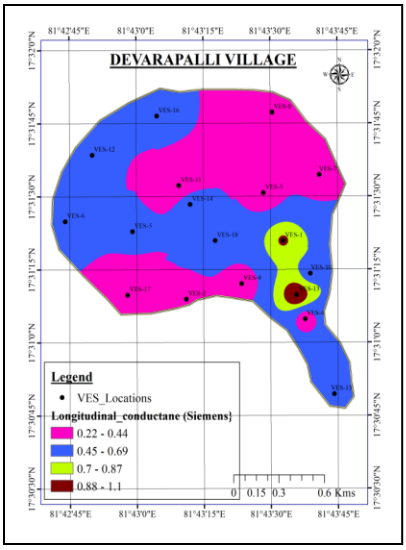
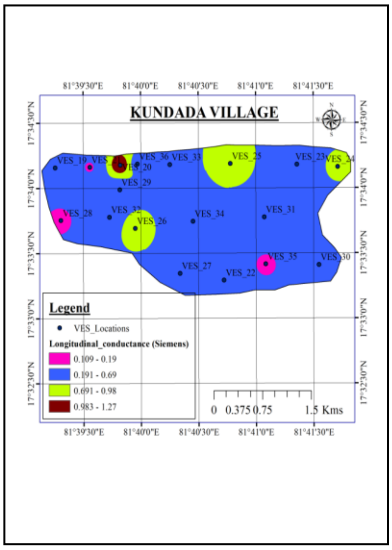


Fig.12(a)



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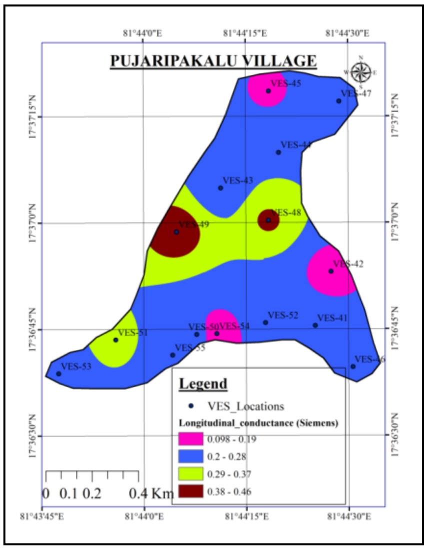
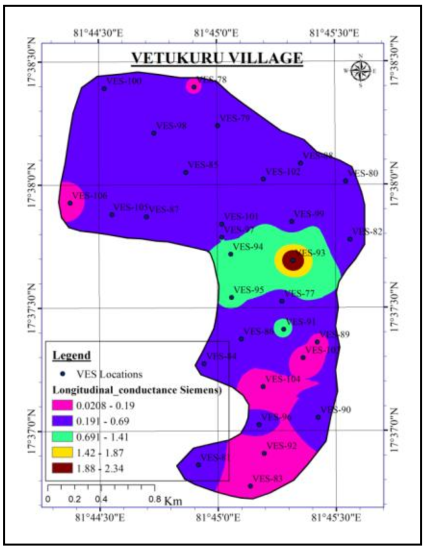


Fig.12(c)



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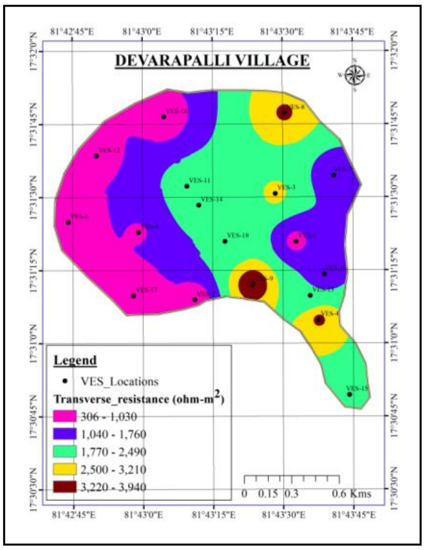
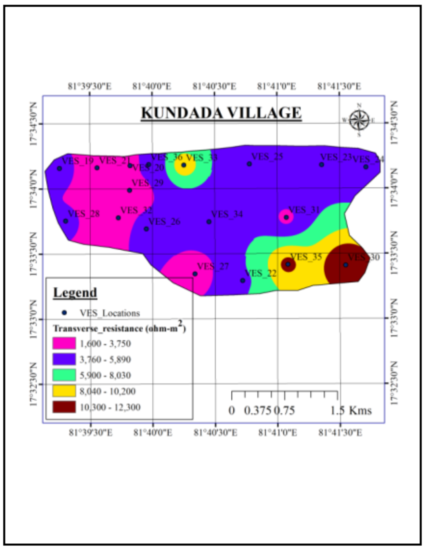


Fig.13(a)



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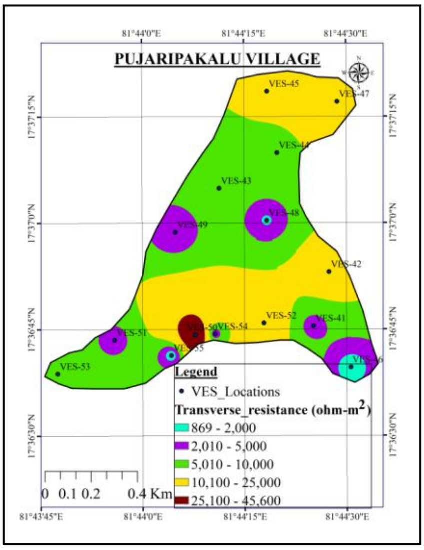

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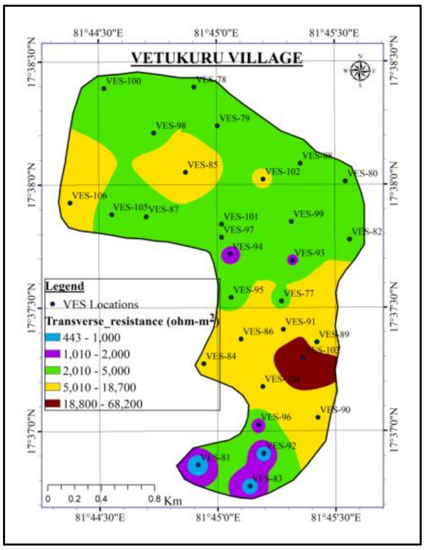

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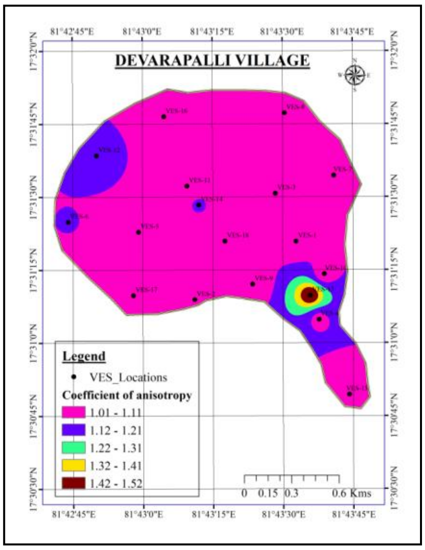

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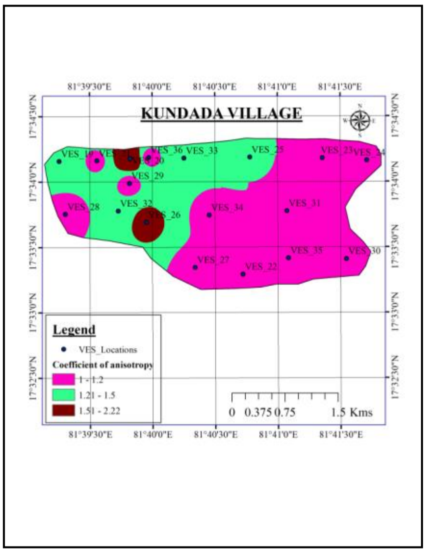

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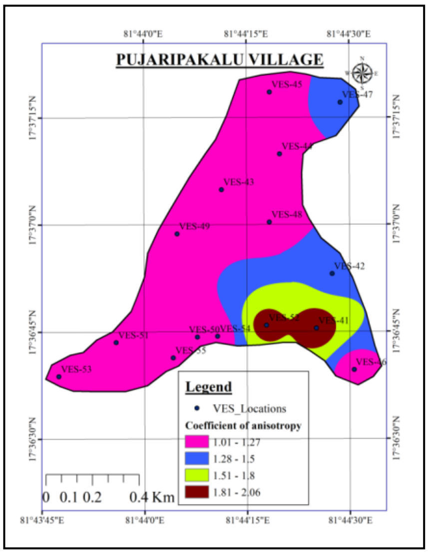

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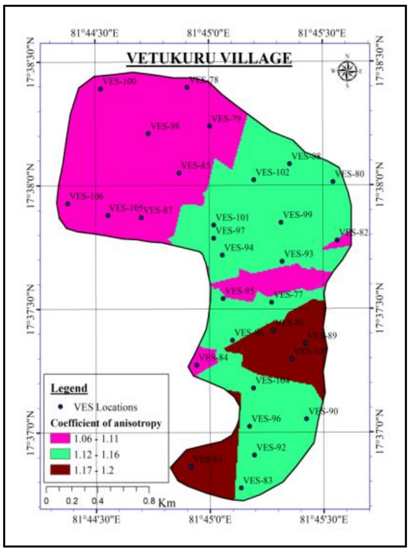

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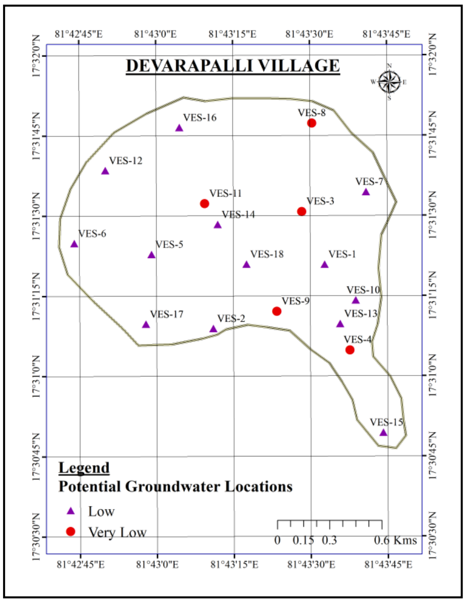

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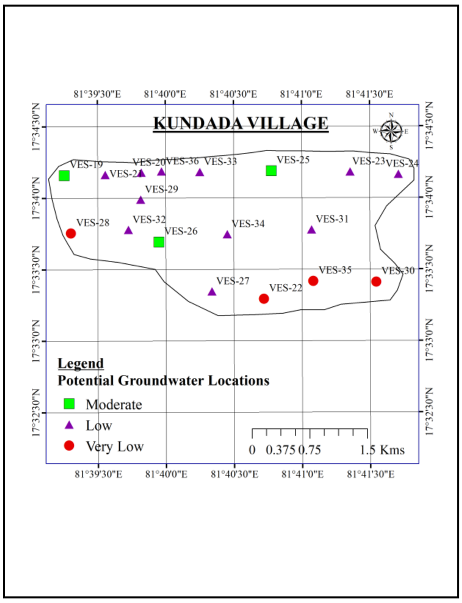

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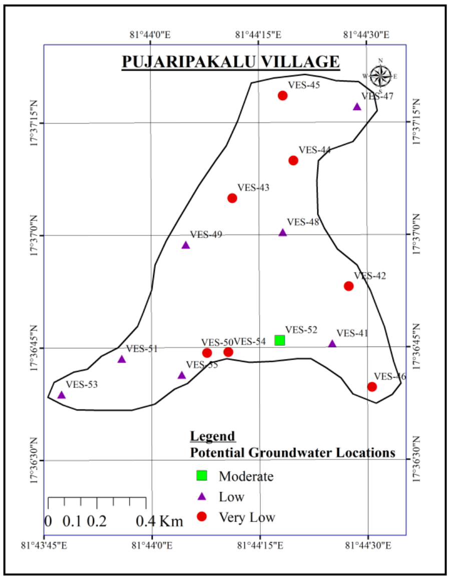

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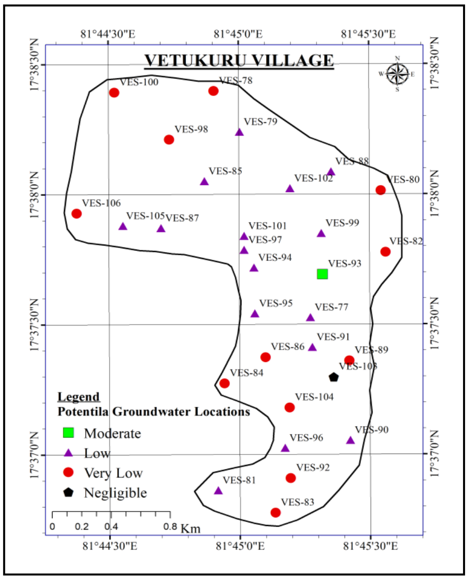

Fig.15(d)