

Integrated Geophysical and Hydrochemical Approach for Locating Fresh Water Locations in a Coastal Terrain

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Abstract An integrated geophysical investigation viz., Vertical Electrical Sounding (VES), Electrical Resistivity Tomography (ERT) and Ground Penetrating Radar (GPR) were carried out in a coastal terrain at Vizag Steel Plant (VSP), Visakhapatnam, Andhra Pradesh., India for locating fresh water locations. The entire area was underlain by recent alluvial of varying thickness consists of sand, clay and silt with basement as Kondalite rock formation consisting of saline water in some parts of the area. Locating favorable groundwater locations in such a terrain is a difficult task. The area consists of saturated clay, saturated silt and saline water has the same resistivity signature and misleads resistivity data interpretation for identifying and recommending the suitable groundwater locations in a coastal terrain. To overcome these uncertainties, a second geophysical approach or combinations of geophysical methods become necessary to resolve these resistivity ranges in a more reliable and better fruitful interpretation of sub-surface layers. In order to pin-point the groundwater locations at VSP; VES, ERT and GPR investigations were carried out. Interpreted results of VES, ERT pseudo-section and GPR images (radargram) were correlated with each other to ascertain confidently the geophysical signature of the sub-surface. Combination of geophysical methods gives better resolution or interpretation of sub-surface information before made any recommendations for drilling of borewell. Based on integrated geophysical investigation few borewell sites were recommended and drilled. The observed drilled lithologs was well correlated with the VES, ERT and GPR data. Besides, this hydrochemical analysis of water samples was carried out from the existing borewells and dugwells. Total Dissolved Solids (TDS) and chloride concentration were ranges from 189 to 3398 mg/l and 5 to 1610 mg/l. The eastern and north-eastern part of the area has elevated concentration of TDS and chloride indicating intrusion of saline water. TDS concentration of drilled borewell was found to range from 400 to 500 mg/l. The observed yield of drilled borewells ranges from 104 to 3623 gal/hr.

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1 Introduction

Groundwater exploration is becoming more and more important now-a-days to meet the increasing demand of water supply for industrial and agriculture sector, especially in areas where inadequate surface water supply is not available. The surface geophysical investigations, namely Vertical Electrical Sounding (VES) (Stampolidis et al. 2005; Kumar et al. 2007; Yadav and Singh 2007; Dhakate et al. 2008, 2012), Electrical Resistivity Tomography (ERT) (Olorunniwo and Olorunfemi 1987; Olayinka and Mbachii 1992; Emenike 2001; Ariyo and Banjo 2008; Gabr 2011) and Ground Penetrating Radar (GPR) (Beres and Haeni 1991; Benson 1995; Garsmueck 1996; Grandjean and Gourry 1996; Awni et al. 2001; Benedetto 2010; Dhakate et al. 2014) are the most widely used geophysical techniques for the hydrology, engineering, archaeological and groundwater exploration.

The regional geophysical resolution of the subsurface layers in terms of their resistivities reflects their water-bearing potential, which can be fairly well understood by the VES and ERT investigations. In the hard rock terrains, like granites and basalts, the aquifers are mostly weathered, semi-weathered, jointed and fractured zones (Yadav and Singh 2007; Hodlur and Dhakate 2010). Whereas, compact hard sandstones, shales and limestones host the aquifers in bedding plain gaps as well as in cavities (Cumbie and McKay 1999). The resolution of this is mainly the identification of water bearing zones, is quite satisfactory for the shallow depth aquifers. The thick semi-weathered zones, followed by hard rocks associated with closely spaced joints, show convincing geophysical anomalies of low resistivity, which are potential aquifers in hard rock terrain (Hodlur and Dhakate 2010). Moreover, the sub-surface lithological units viz., semi-weathered zones and sediments show variations in their resistivities in space due to differential grain size, compaction and variation in mineralogical aggregations.

In coastal terrain, the resistivity of saturated clay, silt and saline water have the same resistivity signature. They have very small resistivity contrast and become difficult to distinguish and resolve them fairly. To overcome these uncertainties in VES investigation, other geophysical method or combination of geophysical methods become necessary for better understanding the resistivity signature as well as reliable information of the sub-surface.

Advantage of ERT is not only mapping the sub-surface information of the area, in terms of geo-electrical layers but also generation of reliable data information of large dimension vertically and laterally. ERT provides a true resistivity pseudo-depth section of the sub-surface and it also resolves the principle of suppression to a greater extent through its data acquisition and interpretation technique (Hodlur and Dhakate 2010). ERT is not only useful in groundwater studies, but also has wide range of applications in environmental, mining, water pollution, engineering and archeological studies (Bernstone and Dahlin 1997; Vickery and Hobbs 1998; Fels 1999; Atekwana et al. 2000; Lago et al. 2009; Tamma Rao et al. 2014).

Applications of GPR are abundant, which including mineral exploration, groundwater exploration, geotechnical exploration, archaeological investigations, rock mechanics and mine development requirements. Some specific applications are mapping of bedrock depth, changes in rock type, fractures in bedrock, change in soil strata, water table in coarse-grained soils, mining activities, geomorphology changes and geotectonic (Cook 1973, 1975; Davis and Annan 1989; Beres and Haeni 1991; Singh and Chauhan 2002; Singh 2003; Patidar et al. 2007; Soni et al.

2007; Dhakate et al. 2014). The GPR offers a high resolution sounding capability with detection of features ranging from a few tens of millimeters to several meters of thickness. The GPR has been demonstrated to sound to depths of 50 m in low conductivity ($<1 \mu\text{S/m}$) materials such as sand, gravel, rock and fresh water. The range decreases to a few meters in highly conductive materials such as clays, silts, soils with saline water and contaminated pore water.

In order to locate the favorable fresh groundwater locations at Vizag Steel Plant (VSP), Visakhapatnam, India. Combination of geophysical investigations like VES, ERT and GPR was carried out for ascertaining and identifying locations for groundwater exploration. VSP was one of the core steel producing plant operating under Rashtriya Ispat Nigam Limited (RINL) and main producers of Wire Rods, Rounds, Reinforcement Bars, Angles, Channels, Beams, Blooms and Billets. Recently, the VSP has set up the expansion of its plant to increase its production from 3.6 MT to 6.3 MT per year. For this purpose more amount of water is required.

2 Study Area

The study area is about 30 km away from Visakhapatnam city. The area falls in Survey of India Toposheet No. 65 O/2 and O/3 with longitude $83^{\circ} 5'$ to $83^{\circ} 15'$ East and latitude $17^{\circ} 35'$ to $17^{\circ} 40'$ North. The total area of VSP was 11,000 acres and township area occupies 12,000 acres. Presently, VSP is getting the water supply from Kanithi Balancing Reservoir (KBR). There are four borewells in the steel plant area and about 50 borewells in the Township area of which about 30 borewell are giving poor yield and they go dry in the summer seasons. The key map of the study area along with VES, ERT and GPR investigation locations is shown in Fig. 1.

3 Geology of Area

Geology of Visakhapatnam and its surroundings was mapped by King (1986); Mahadevan and Sathapathi (1949). Harbour area is in Marine tidal flat and a part is crossing the fluvial plain of Mehadrigedda. Prithi Raju and Vaidyanadhan (1978) reported 18 m thickness of marine clay followed by weathered rock towards the south. Natarajan et al. (1979) reported 10-17 m of loamy sandy clay or fine clay near Balacheruvu and 40-80 m thickness of marine clay north of Tummedalametta. Major geological formations covering Visakhapatnam District shows the predominant Khondalite group rock and it consists of quartz, feldspar, garnet, sillimanite, graphite, schist, gneiss (Khondalite), quartzite and calc-gneiss/calc-granulite, which represent the metamorphosed equivalents of the original argillaceous, arenaceous and calcareous sediment respectively. Quartz-feldspathic gneiss with or without garnet, biotite, sillimanite, commonly referred to as leptynite/leptite, forms a distinct litho-unit of this group. Migmatization of Khondalite, Charnokite and pyroxene granulite gave rise to a variety of rock types. The migmatites, predominantly occurring along the foot hills and coastal plains are associated with intrusive granitic rocks. Laterites occur as their capping on hill tops and high grounds. Along foot hills, lateritic gravel occurs. At places, it is cemented to form colluvial laterites. However, the extent of laterites is rather limited and does not form potential aquifers. Surficial deposits include colluvium, alluvium, red sediments and coastal sediments. Colluvium is debris material along the foot hills essentially derived from Khondalite hill ranges by fluvial action. It is composed of sand, silt, clay and gravel in varying proportions. The thickness of colluvium varies widely depending on bedrock configuration.

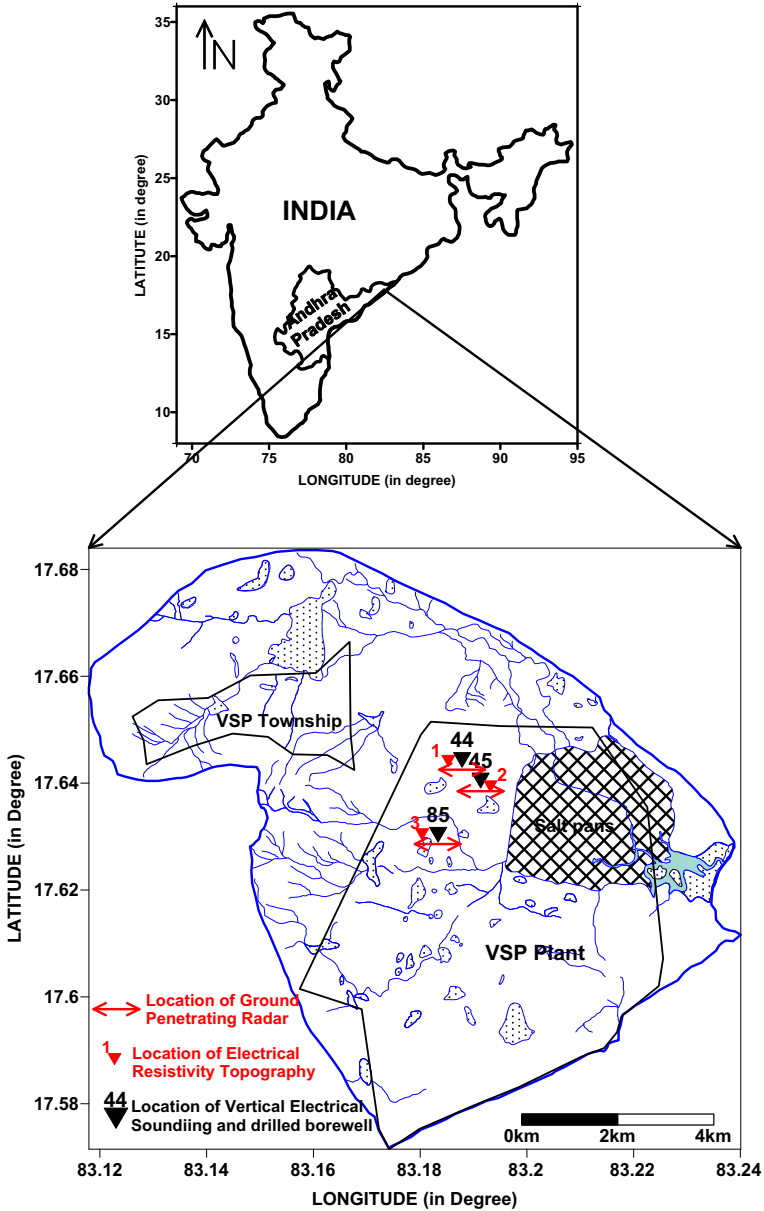


Fig. 1 Key map showing Visakhapatnam Steel Plant premises and township area with VES, ERT and GPR investigation locations

Alluvium is confined to major stream course of Boremmagedda. The alluvium extends as a narrow strip along the stream course and thickness is <5 m. Quaternary sediments are of both fluvial and marine regimes. The fluvial sediments are restricted to river courses, in the form of flood plains mostly comprising brown silty clay. Channel bars and active channels contain brown silts and coarse sand. The marine sediments of active beach and tidal flat are seen in the

narrow coastal plain. The steel plant was actually built on a mud flat area. Alluvial plains are flat and gently sloping zone formed by deposition of fluvial sediments. It is composed of unconsolidated sediments of gravel, sand, silt and clay in varying proportions with variable depths. Occurrence of thick weathered zone has been found beneath the sediments. The nature of alluvial plain varies from near flat to rolling plain. Mudflats is a low lying tidal flat generally barren and is composed of unconsolidated sediment comprising fine silt, clay and mud in varying proportions mixed with shells and kankar and it is saline in nature. The geological map of Visakhapatnam is shown in Fig. 2.

4 Hydrogeology

The groundwater occurs in all the formations in the area. However, the nature and occurrence depend on various factors like rainfall, topography, landform, geology and structure. With regard to groundwater, the geological formations of the area are classified into two types, such as hard crystalline rocks and unconsolidated sediments. Crystalline rocks are Khondalites, Charnokites, feldspathic gneisses and granites are grouped into hard rocks, while the unconsolidated formations include red sediments, colluvium, alluvium and coastal sands. The area is characterized by red loamy soil in the northern part and red sandy soils in the southern part. Coastal alluvial and sandy soils are seen in the coastal plain. A patch of lateritic soil occurs in the northeastern part. The tidal flats (mud flat) are unconsolidated to semi consolidated sand, silt and clay material.

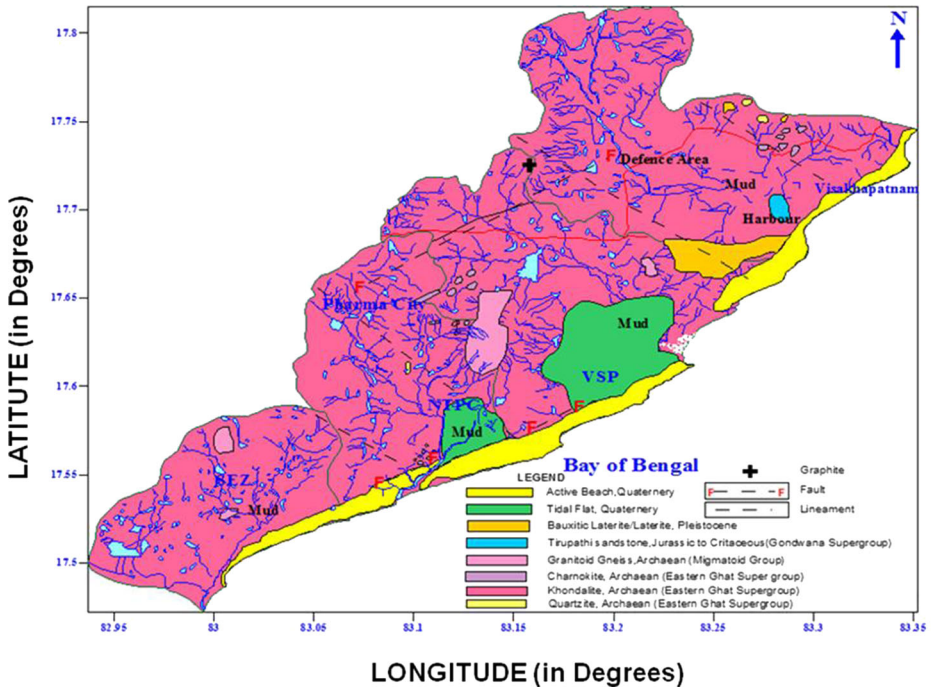


Fig. 2 Geological map of the Visakhapatnam District

4.1 Groundwater in Khondalitic Rocks

The hard crystalline rocks in Khondalites lack primary porosity. The occurrence and movement of groundwater is usually limited to the secondary porosity developed through weathering and fracturing. As a result, the groundwater prospects are limited, and depend on the degree and depth of fracturing and weathering. The thickness of weathering varies from place to place depending on local topography, lithology and structure. Similarly, intensity of fracturing also varies widely. These aquifers are anisotropic and non-homogeneous, as such hydrogeological conditions vary widely with in short distances. Groundwater occurs at water table conditions under weathered residuum and semi-confined to confined conditions in deeper fractured zones. The thickness of weathering varies from 5-45 m. The weathered zone in Khondalites is generally more porous due to high quartz content. The feldspathic gneiss gives rise to clayey weathered zone, while Charnokites by virtue of their texture are massive in nature and are more resistant to weathering. The intensity of fracturing has been found to be more in Khondalites compared to leptynites and Charnokites. Dugwells and borewells are in use for groundwater pumping indicating poor storage nature of the formation. The depths of the wells were varying from 4-16 m, while the general depths are being 8-12 m. The depths of borewells are varying from 15-60 m.

The main landforms are structural ridges or hogbacks with intermittent softer migmatitic rocks forming low plains referred to as pediplain-pediment complex. In pediment-pediplain Charnokite-Khondalitic terrain groundwater occurrence is restricted to 60 m depth. The permeability varies from 0.5-20 m/day and specific yield 0.005-0.25 and yield prospect 15 m³/hr. Most of the study area is under less than 10 % slope area between 0-50 m elevations. The aquifers have secondary intergranular porosity and aquifers are mostly discontinuous in nature. The northern and northwestern part has high elevations with lateritic capping which form plateaus. The coastal plain is made of beach ridges, tidal flats and lagoons. Occurrence of groundwater is confined to shallow depths in flood plains. Quality of groundwater suffers in the coastal plains but potable water is tapped from shallow depths in the beach ridges.

5 Methodological Approach

5.1 Vertical Electrical Soundings (VES)

The geophysical exploration mainly comprises measurements and interpretation of signals from natural or induced physical phenomena generated as a result of spatial changes in one or more physical properties of sub-surface formation. These signals measured repetitively at several points in space and time. They are appropriately interpreted, considering the available geological information, in terms of sub-surface structures/features may themselves have good groundwater potential or indicative of good aquifers. Electrical Resistivity Method is the most widely applied method for groundwater exploration. This is because of its efficacy to detect the water bearing layers, besides being simple and inexpensive to carry out the field investigations (Zodhy 1965). In general, for measuring resistivities of subsurface formations, four electrodes are required. Current of electrical intensity (I) is introduced between one pair of electrodes, called current electrodes, identified as A & B and sometimes +I and -I denoting source and sink respectively. The potential difference produced as a result of current flow is measured with the help of another pair of electrodes, called potential electrodes or probes and represented as M & N.

5.1.1 Schlumberger Array

This array uses four collinear point electrodes, but measures the potential gradient at the mid-point by keeping the measuring electrodes close to each other. Four electrodes are placed along a straight line symmetrically over center point 'O'. Current (I) is sent through the outer current electrodes A & B and the potential is measured across inner potential electrodes M & N. The separation between the potential electrodes is kept small with compared to the current electrodes separation ($MN < 1/5 AB$). The configuration or geometric factor for the Schlumberger array is given by

$$G = \frac{(AB/2)^2 - (MN/2)^2}{(MN/2)} \frac{\pi}{2}$$

where 'AB' is distance between current electrodes, 'MN' is the distance between potential electrodes, and the apparent resistivity is obtained with the formula

$$\rho_a = G(\Delta V/I)$$

where ($\Delta V/I$) is potential difference between potential electrodes to that of current flowing.

Depending upon the electrode separation, apparent resistivity value increases or decreases. Hence, shape of the curve changes and it is helpful for qualitative interpretation of sub-surface layer resistivity distribution. A curve is drawn by plotting the observed apparent resistivity values against the current electrode separation on a log-log graph sheet, and interpreted by matching the field curve with master curves of two, three and four layer cases for various ratios of absolute resistivity (Orellana and Mooney 1966). The manual interpretation was further subjected to inversion iteration through software by using a RESIST program (Jupp and Vozoff 1975).

5.2 Electrical Resistivity Tomography (ERT)

ERT in broad sense is a combination of both electrical sounding and profiling, designed to overcome several constraints raised from independent methods of electrical methods (Keller and Frischknecht 1966; Griffiths and Turnbull 1985; Dahlin 1996). The basic concept of ERT was first described by Lytle and Dines for generation of new data inversion methods of tomography. Development of both the theory and practice of ERT was confined mostly to the late 1980s and 1990s (William et al. 2004). Advantage of resistivity imaging is not only mapping the sub-surface information of the area in terms of geo-electrical layers but also generation of reliable data information of large dimension vertically and laterally. ERT provides a true resistivity pseudo-depth section of the subsurface and also resolves the principle of suppression to a greater extent through its data acquisition and interpretation technique. The ERT data were process using RES2DINV Software (Loke and Barker 1996; Loke 2002). Here in this article the resistivity tomography survey results discussed was acquired by using a multi-electrode resistivity imaging system, Syscal Pro. SWITCH 48, France made.

5.3 Ground Penetrating Radar (GPR)

GPR method utilizes the transmission and reflection of high frequency (25 MHz to 1.5 GHz) electromagnetic (EM) waves within the earth. The reflected energy is recorded by the receiver

antenna. The propagation of EM wave in the sub-surface is governed by properties of the medium, namely dielectric permittivity, electrical conductivity and magnetic permeability. GPR tool has the advantage of providing high-resolution images at a scale varying from few millimeters to few meters (Annan and Cosway 1994; Knight 2001). The GPR data acquired using Terra SIRch System-3000 single channel GPR meter (Geophysical Survey System Inc.), USA made, and processed by RADAN 6.0v software. The basic processing operations applied were stacking and zero correction. Stacking has been applied to prune the data size and zero correction is applied to correct for the first arrival. The positions of reflections corresponding to the change in the dielectric constant and electrical conductivity are deciphered from the radargrams. The advanced features in RADAN 6.0v like local peaks, filters, deconvolution, velocity analysis and migration interpretation techniques are applied to extract the configuration of sub-surface horizons. The local peak module is applied on the data to pick the maximum peaks corresponding to significant reflections. Besides, this Hilbert transform is applied on the data to map and understand how the injected energy/radar pulse is captured by the media and how it is filtered through the media. The magnitude part of the Hilbert transform indicates the pattern of absorbance of the incident energy of the GPR whereas the phase component indicates how the incident energy is filtered in the subsurface. The success of Hilbert transform in identifying the edges of electrical conductivity contrast in the sub-surface. In the present exercise, the Hilbert transform is implemented on GPR data to identify the zones of conductivity contrast. These zones of conductivity contrast correspond to water bearing formations or other features of geological interest in terms of groundwater exploration.

5.4 Groundwater Quality

In order to assess the groundwater quality at VSP and township, 38 groundwater samples from existing borewell/dugwell were collected with in-situ measurements of pH and Total Dissolved Solids (TDS). The samples were analyzed for major ions to understand the groundwater quality. TDS value of these samples ranges from 189 to 3398 mg/l, the samples show high TDS value along the eastern and northern part of the area. In more than 50 % of samples, the TDS value was higher than the permissible limit of drinking water standards (WHO 1993) which shows its non-suitability for drinking and has saline in nature. Similarly, the Chloride values range from 5 to 1610 mg/l, the samples show high Chloride concentration along the eastern and northern part of the area, which is well correlated with the variation of TDS values. This shows that the water quality along the eastern and northern part of the area, have saline in nature and so it is not suitable for drinking purpose. The spatial distribution of TDS and Chloride concentration is shown in Fig. 3a and b.

6 Results and Discussions

In order to assess the groundwater conditions at VSP and township, 94 VES using Schlumberger configuration with 100–200 m half-current electrode separations were carried out. VES data are initially interpreted using the curve matching technique (Orellana and Mooney 1966) and then by inversion iteration method (Jupp and Vozoff 1975) to arrive at absolute resistivities values of sub-surface layers. After analyzing the resistivity data

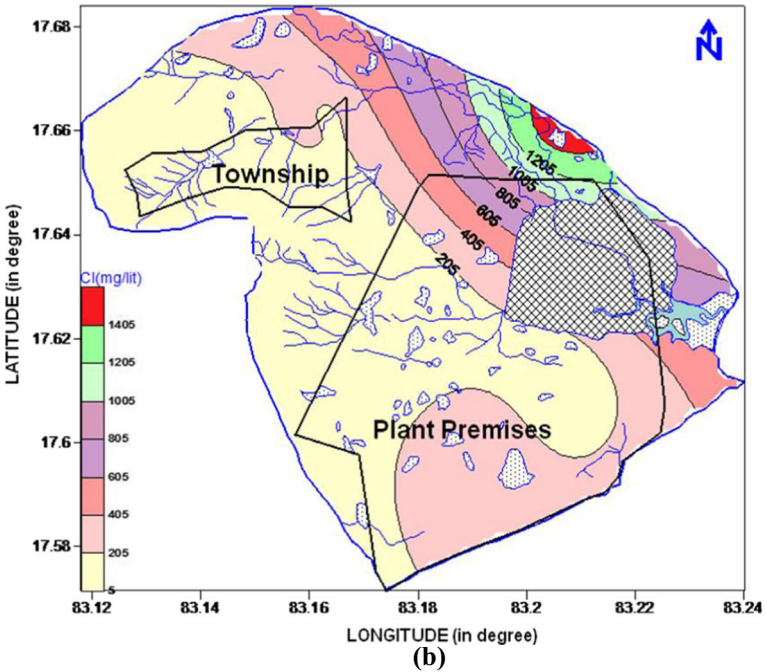
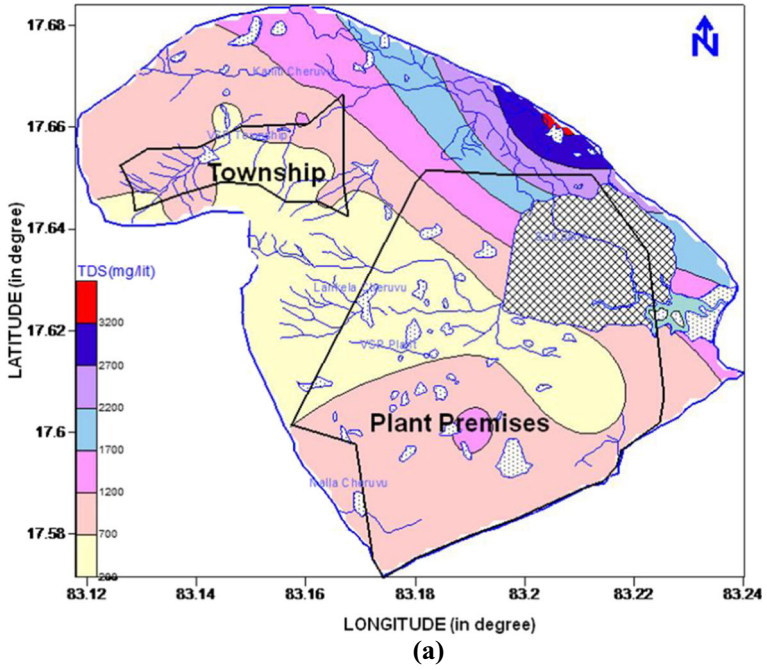


Fig. 3 (a, b) Spatial variation of TDS and Chloride concentration (mg/l) in the VSP area

interpretation, it is found that the resistivity of the weathered zone ranges from 20 to 80 Ω -m. Similarly, at few selected places ERT using Wenner-Schlumberger configuration with 5 m inter-electrode spacing using 48 electrodes and GPR investigations were carried out. The combine approach of geophysical investigation and integration of data is more useful to arrive at better and reliable resolution of sub-surface layers for recommendation of borewells for exploration of groundwater resources at VSP. Based on interpretation of VES, ERT and GPR three sites were initially recommended for drilling of borewells. The locations of recommended VES, ERT and GPR were shown in Fig. 1. The interpreted results of these recommended VES was given in Table 1.

First borewell was recommend and drilled in the FMD area up to a depth of 100 m at VES No. 44, whose resistivities are 44, 18, 46 and 569 Ω -m with thicknesses 1, 12 and 17 m respectively. The resistivity of 18 and 46 Ω -m belongs to highly weathered and saturated weathered formation followed by a high resistivity zone beneath. The interpreted VES curve is shown in Fig. 4a. ERT which is carried out nearby this location correlates with the VES interpreted data. From ERT pseudo-section it is observed that a resistivity range of 7 to 14 Ω -m is occurred around a depth of 13 m and a resistivity range of 26–48 Ω -m is occurred around a depth of 30 m, which is very well correlates with the VES interpreted results. ERT pseudo section is shown in Fig. 5a. A GPR profile of 20 m length is also carried out at VES location using 40 MHz antenna in time mode (continuous mode) using setup with dielectric constant: 8; range: 800 nS; samples per scan: 512; resolution: 16 bits; number of gain points: 5; vertical high pass filter: 10 MHz; vertical low pass filter: 80 MHz; scans per second: 32 and transmit rate: 12 KHz. Radargram is also very well correlates with VES and ERT data obtained at this location. Radargram shows highly weathered formation up to a depth of 13 m, followed by saturated weathered formation up to a depth of 33 m. A more reflections signals were observed up to a depth of 13 m indicated a highly weathered formation, followed by moderate reflection from 13 m to 33 m indicative of weathered formation (Fig. 6a). Continuous discharge measurements were recorded after the drilling of borewell and found that the borewell yield about 104.7 gal/h of water (Table 2). Comparison of observed drilled litholog with interpreted VES results is shown in Fig. 7a.

The second borewell was also recommended and drilled in the FMD area at VES No. 45, whose resistivities are 33, 17, 36 and 333 Ω -m with thicknesses 1.6, 4.8 and 46 m respectively. The resistivity of 17 and 36 Ω -m representing highly weathered and weathered formations followed by high resistivity. The interpreted VES curve is shown in Fig. 4b. ERT carried out at this location also correlates with VES data. ERT pseudo-section represented a resistivity range of 4–14 Ω -m up to 10 m depth indicating of highly weathered formation, followed by resistivity range of 26–48 Ω -m up to a depth of 30 m representing weathered formation, after 30 m a resistivity range of 80–162 Ω -m with a thickness of 6-7 m observed which is not

Table 1 Interpreted layer parameters of Vertical Electrical Soundings recommended for drilling of boreholes at VSP, Visakhapatnam

| VES No. | Location | ρ_1 | h_1 | ρ_2 | h_2 | ρ_3 | h_3 | ρ_4 | Total Depth (m) |
|---------|------------------|----------|-------|----------|-------|----------|-------|----------|-----------------|
| 44 | FMD area | 44 | 1 | 18 | 12 | 46 | 17 | 569 | 30 |
| 45 | FMD area | 33 | 1.6 | 17 | 4.8 | 36 | 46 | 333 | 52.4 |
| 85 | Pump House No. 3 | 44 | 0.5 | 5.4 | 40 | 16 | | | 40.5 |

' ρ ' is resistivity in Ohm-m and 'h' is thickness in meters

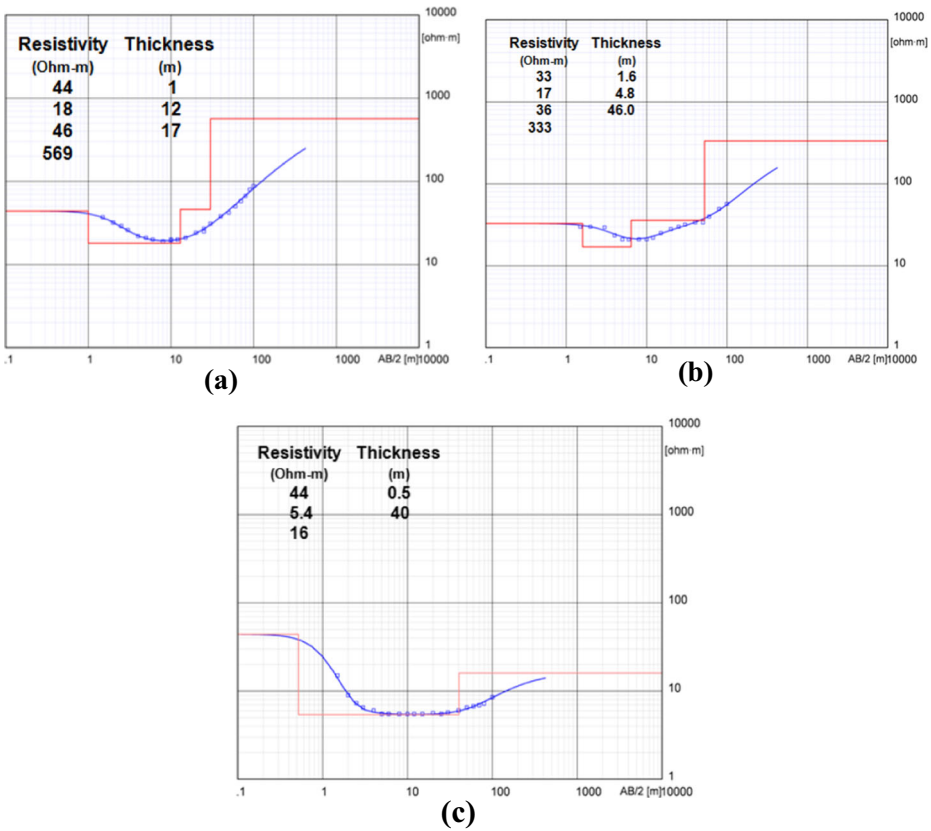


Fig. 4 (a, b, and c) Interpreted Vertical Electrical Sounding curves carried out FMD area and Pump House No.3 (Borewell Nos. 1, 2 & 3) at VSP

encountered in VES interpretation representing a fracture zone followed by high resistivity zone. ERT pseudo-section is shown in Fig. 5b. Similarly, a GPR profile is carried out in time mode keeping the dielectric constant 8. Radargram is also correlated well with the data obtained by VES and ERT. Radargram shows highly weathered formation up to a depth of 20 m, as more reflected signals were observed at this depth, followed by weathered/fractured formation up to a depth of 38 m due to moderate reflected signals (Fig. 6b). Continuous discharge measurement of this borewell were recorded and found that the borewell yield is very high i.e., 3623 gal/h water (Table 2). The comparison of observed drilled litholog with interpreted VES result is shown in Fig. 7b.

The third borewell was recommended and drilled at Pump House No. 3 at VES No. 85, whose resistivities are 44, 5.4 and 16Ω-m with thicknesses 0.5 and 40 m respectively. The resistivity of 5.4Ω-m represents a clayey/saline water formation followed by highly weathered formation. The interpreted VES curve is shown in Fig. 4c. ERT carried out at this location represents a resistivity range of 5–8Ω-m up to a depth of 25 m indicating a clay/saline nature of the sub-surface, another zone of resistivity 14–24Ω-m occurred at a depth from 25–40 m indicating highly weathered formation, followed by a resistivity 40–120Ω-m represents weathered formation beyond 40 m depth. A good correlation was observed between VES

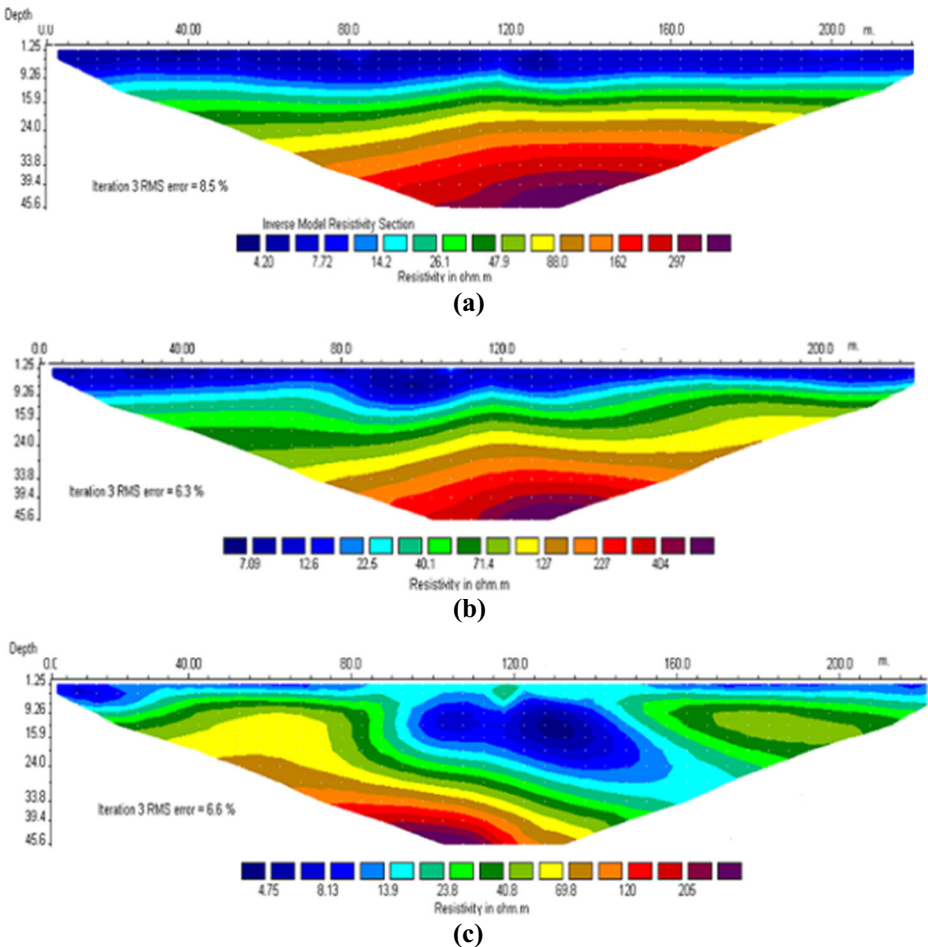
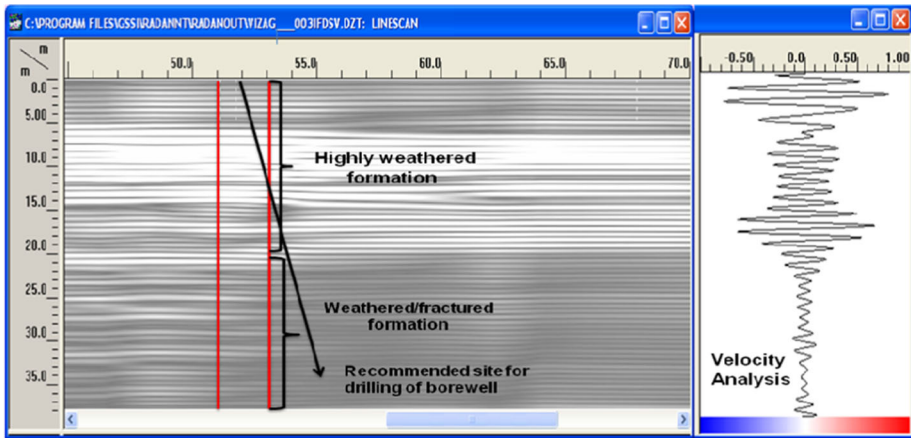


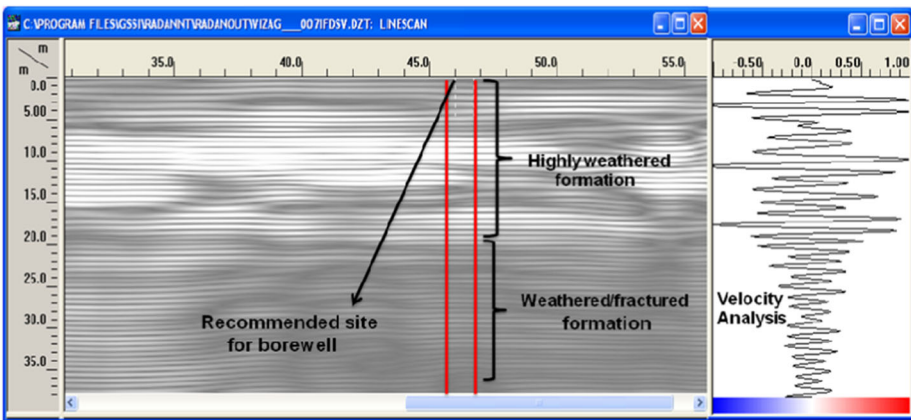
Fig. 5 (a, b, and c) Electrical Resistivity Tomography pseudo section carried out near FMD and Pump House No. 3 at VSP

and ERT at this location. ERT pseudo-section is shown in Fig. 5c. Similarly, a GPR profile of 20 m length is carried out at this location using 40 MHz antenna in time mode (continuous mode) using setup with dielectric constant: 8, range: 800 nS, samples per scan: 512, resolution: 16 bits number of gain points: 5 vertical high pass filter: 10 MHz, vertical low pass filter: 80 MHz scans per second: 32 and transmit rate: 12 KHz. Radargram is also correlated with VES and ERT data obtained at this location. Radargram shows highly saturated formation up to a depth of 30 m followed by weathered formation up to a depth of 42 m. Good reflected signals were observed up to a depth of 30 m due highly saturated clay, followed by moderate reflected signals from 30–42 m indicative of weathered formation (Fig. 6c). A continuous discharge measurement recorded for this borewell was found to be 1916 gal/h (Table 2). The comparison of observed drilled litholog with interpreted VES results is shown in Fig. 7c.

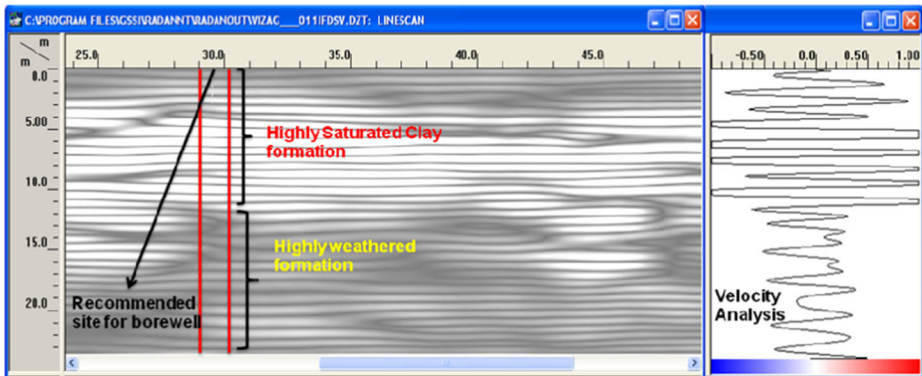
The uncertainly observed in VES interpretation about resistivity $5.4\Omega\text{-m}$ with thickness 40 m about the nature of the formation whether clay/saline is somewhat resolved by ERT pseudo-section. ERT pseudo-section represents a resistivity range $5\text{--}8\Omega\text{-m}$ up to a depth of



(a)



(b)



(c)

Fig. 6 (a, b, and c) Radargram image after application of Filters, Deconvolution, Velocity analysis and Migration interpretation techniques carried out at FMD area and Pump House No. 3 at VSP a) Radargram at Borewell No. 1, b) Radargram at Borewell No.2, c) Radargram at Borewell No. 3

Table 2 Discharge measurement of drilled boreholes at VSP, Visakhapatnam

| Well No.1, FMD area | | | Well No.2, FMD area | | | Well No.3, Pump House No. 3 | | |
|-----------------------------|-------------------------------------|------------|---------------------|-------------------------------------|------------|-----------------------------|-------------------------------------|-------------------------------------|
| Time (IST) | Time (sec) taken to fill 200 litres | Time (IST) | Time (IST) | Time (sec) taken to fill 200 litres | Time (IST) | Time (IST) | Time (sec) taken to fill 200 litres | Time (sec) taken to fill 200 litres |
| 5:03 pm | 199 | 10:25 am | 10:25 am | 52.5 | 12:00 pm | 12:00 pm | 93 | |
| 5:18 pm | 191 | 10:35 am | 10:35 am | 52.5 | 12:15 pm | 12:15 pm | 103 | |
| 5:37 pm | 150 | 10:50 am | 10:50 am | 52.5 | 12:35 pm | 12:35 pm | 94 | |
| 5:43 pm | 172 | 11:05 am | 11:05 am | 52.5 | 12:50 pm | 12:50 pm | 101 | |
| 5:59 pm | 180 | 11:20 am | 11:20 am | 51 | 1:00 pm | 1:00 pm | 99 | |
| 6:15 pm | 189 | 11:35 am | 11:35 am | 51 | 2:00 pm | 2:00 pm | 106 | |
| 6:25 pm | 189 | 12:35 pm | 12:35 pm | 52 | 3:00 pm | 3:00 pm | 99 | |
| 6:35 pm | 183 | 12:50 pm | 12:50 pm | 53 | 4:00 pm | 4:00 pm | 100 | |
| | | 1:20 pm | 1:20 pm | 53 | 5:00 pm | 5:00 pm | 99 | |
| | | 2:00 pm | 2:00 pm | 53 | 6:00 pm | 6:00 pm | 99 | |
| | | 3:00 pm | 3:00 pm | 53 | 7:00 pm | 7:00 pm | 99 | |
| | | 4:00 pm | 4:00 pm | 54 | 8:00 pm | 8:00 pm | 99 | |
| Average Time (sec) | 181.62 | | | 52.5 | | | 99.25 | |
| Discharge rate (gallons/hr) | 396.36 ltr/hr OR 104.7 gal/hr | | | 13714.28 ltr/hr OR 3623 gal/hr | | | 7254 ltr/hr OR 1916 gal/hr | |
| TDS concentration (mg/l) | 500 mg/l | | | 500 mg/l | | | 450 mg/l | |

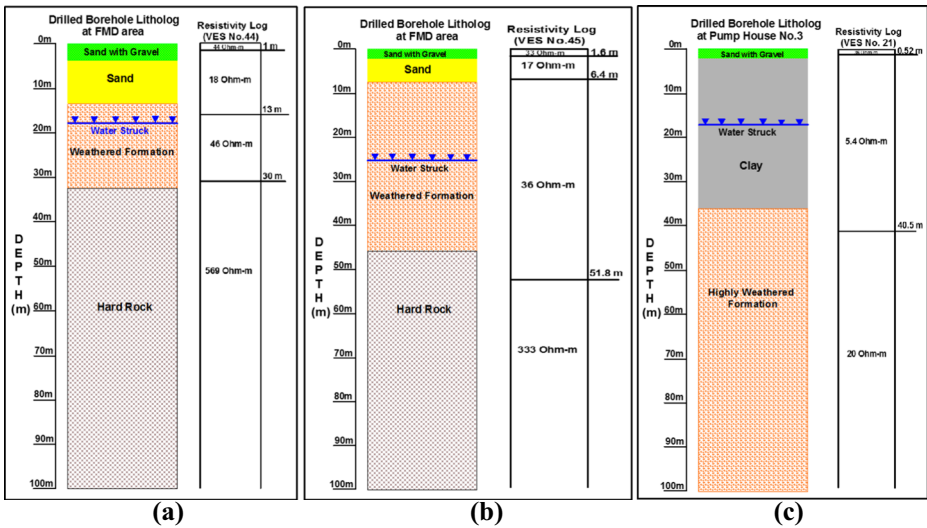


Fig. 7 (a, b, and c) Comparison of drilled borewell litholog and Vertical Electrical Sounding carried out at (a&b) FMD area (Borewell No. 1 & Borewell No. 2) (c) Pump House No. 3 (Borewell No. 3) at VSP

25 m followed by a resistivity zone of 14–24Ω-m up to depth of 40 m which is certainly not a clay/saline nature. Moreover, in radargram a highly reflected portion is seen up to a depth of 30 m, this indicates a highly saturated sub-surface formation, followed by a moderate reflection up to the depth of radargram. In a presence of dry clay the GPR signals get attenuated and getting deeper signals from the sub-surface will be difficult. Due to saturation condition of the clay, we got better reflected signals for understanding the sub-surface conditions. The constrained in VES interpretation of resistivity 5.4Ω-m with thickness 40 m about the clay/saline nature of sub-surface is got resolved by applying combination of geophysical methods for groundwater exploration.

First and second borewell drilled at FMD area, VSP, Visakhapatnam (Fig. 1) lies in the TDS concentration zone of 700–1700 mg/l and chloride concentration zone of 200–600 mg/l (Fig. 3a and b). These drilled borewell lies in the zone of having salinity nature of groundwater. According to (WHO 1993) the maximum permissible limit for TDS and chloride concentration for drinking purpose is 1000 mg/l and 250 mg/l. Accordingly these drilled borewell give rise to high TDS concentration. The measured TDS concentration in these borewell was 500 mg/l, which is quite good for drinking and domestic purpose. Similarly, the concentration of TDS and Chloride zone at third drilled borewell near Pump House No. 3 was around 200–700 mg/l and >200 mg/l within the permissible limit of drinking purpose.

7 Conclusions

Vertical Electrical Soundings, Electrical Resistivity Tomography and Ground Penetrating Radar investigations were carried out in a coastal terrain for locating fresh water pockets. The combined geophysical data interpretation is advantageous over the application of a single method data interpretation for pin-pointing fresh groundwater resources in a saline affected area. Interpreted Vertical Electrical Soundings data was correlated with Electrical Resistivity

Tomography and Ground Penetrating Radar found to be good and confidence level was increase in many folds before giving any recommendation for drilling of borewells in saline affected areas. From the interpreted resistivity data, the range of 20–80 Ω -m were found to be a good zone for groundwater exploration in this area. The recommended drilled borewells found to be yield in the range of 104–3623 gal/h fresh water to meet the demand of Vizag Steel Plant. The measured TDS concentration of these borewell is around 500 mg/l indicating the fresh groundwater. The observed drilling lithologs were well correlates with VES data, ERT pseudo-section and GPR images (Radargram). Based on integrated study few more points were recommended for drilling of borewell.

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