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Intervention of Electrical Resistance Tomography (ERT) in Resolving Hydrological Problems of a Semi Arid Granite Terrain of Southern India

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Abstract: Electrical Resistivity Tomography (ERT) has been used in association with several geohydrological, geotechnical and geophysical methods in resolving several site specific problems in hydrological science. Advancement in the field of computers and automation in the field of electronics has jointly resulted in the development of this geophysical innovation which has wide application in groundwater, environmental and engineering problems including monitoring of vadose zone water movement, steam injection etc. In this paper application of ERT in association with geohydrological and other exploration methods in resolving groundwater sustainability problem of a micro-watershed area in semi arid granite terrain is presented as three independent cases. In a hard rock terrain the probability of complexities in understanding the sub-surface lithology and its corresponding hydrological parameters are more. Hence appropriate resistivity survey configuration and suitable inversion of acquired data in congregation with other geo-scientific investigations were carried out to understand the site specific problem. The study demonstrated as 3 independent cases shows the usefulness of the ERT method in hydrological investigations, which is economic, efficient and less time consuming in comparison to the other exploration methods.

Keywords: Electrical resistivity, Hydrology, Granite, Semi-arid zone.

INTRODUCTION

Geophysical investigation act as a primary tool in almost all hydrological studies in visualizing and conceptualizing the subsurface complexities through transient or permanent response of measurable physical parameters integrated with the site geological inference. In groundwater studies, several geophysical methods have been deployed since late 1915, of which the electrical method has shown a wider approach and better applicability in groundwater science. Electrical method is used to determine the subsurface resistivity distribution by making suitable measurements on the surface. The ground resistivity is related to various geological parameters such as the mineral content, intergranular compaction, porosity, degree of water saturation in the rocks etc (Marescot, Laurent, 1995). In resistivity investigation the most important and complex criteria is the selection of site. Although in practice a site is selected on the basis of hydrogeological information gathered over the area and supported by remote sensing data if available, but in all probabilities the best location may be always away from the point selected. Basically there are two types of procedures involved in resistivity survey, of which resistivity profiling is adopted to understand qualitatively the nature of sub-surface, were as resistivity sounding quantifies the resistivity variation with depth and thickness (Gangadhar Rao, 1999).

In this paper, the results pertaining to 2D resistivity imaging (E.R.T) investigations in association with geo-hydrological and other geophysical exploration methods have been attempted in resolving different site specific problems pertaining to groundwater sustainability in a semi-arid hard rock terrain of southern granulite province of Indian sub-continent. Correlation of 2D resistivity tomography results with other methods has emphasized its utility in resolving several hydrological fallacies within a geological setup.

RESISTIVITY MEASUREMENTS

Basic Concept and Principle

Electrical resistivity (also known as *specific electrical resistance*) is a measure of how strongly a material opposes

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the flow of electric current. Resistivity measurements are normally carried out by injecting current through two current electrodes (C1 and C2), and measuring the resulting voltage difference through potential electrodes (P1 and P2). The calculated field resistivity value is not the true resistivity of the subsurface, but an "*apparent*" value, which is the resistivity of a heterogeneous medium, which gives variable resistance value for different electrode position and spacing. In order to determine the true subsurface resistivity, the measured field apparent resistivity has to be subjected for inversion using computer program. Resistivity surveys are broadly of two types namely (1) Vertical Electrical Sounding (VES), also known as electrical drilling, or expanding probe. It gives the resistivity behavior of horizontal or near horizontal interfaces occurring at varying depths; and (2) Constant Separation Traversing (CST), also known as electrical profiling or scanning. It gives the lateral variation in electrical conductivity within the subsurface (Andrade, Rolland, 2009).

Geological Inference of Electrical Resistivity

In order to transform the true resistivity achieved after subjecting the acquired apparent resistivity data to suitable inversion into a meaningful geological picture of the site requires knowledge of typical resistivity values for different types of subsurface materials and the geology of the area surveyed. The resistivity range for different rock types, soil and other chemicals have been tested and tabulated, which is used as catalog in interpretation as shown in Table 1. (Palacky, 1987). In the classification table, igneous and metamorphic rocks do represent higher resistivity values. The resistivity of these rocks is greatly dependent on the degree of fracturing (secondary porosity/openings), and the percentage of fluid saturation. Comparatively other materials do show resistivity on the lower side but however there always exist an overlap in the resistivity values of the different classes of rocks and soil due to several factors like porosity, intergranular compaction, mineral content, concentration of dissolved salts etc. Resistivity values have a much larger range compared to other physical parameters mapped by other geophysical methods. In comparison, density values used by gravity surveys usually change by less than a factor of 2, and seismic velocities usually do not change by more than a factor of 10. This makes the resistivity and other electrical or electromagnetic based methods very versatile geophysical techniques.

Table 1. Resistivity range of different rock types, soil and chemicals

Material	Resistivity (Ohm–m)	Conductivity (Siemen/m)
Igneous and Metamorphic Rocks		
Granites	$5 \times 10^{2} - 10^{3}$	$10^{-6} - 2 \times 10^{-4}$
Basalt	$10^{3} - 10^{6}$	$10^{-6} - 10^{-3}$
Slate	$6 \times 10^{2} - 4 \times 10^{7}$	$2.5 \times 10^{-8} - 1.7 \times 10^{-3}$
Marble	$10^{2} - 2.5 \times 10^{8}$	$4 \times 10^{-9} - 10^{-2}$
Quartzite	$10^{2} - 2 \times 10^{8}$	$5 \times 10^{-9} - 10^{-2}$
Sedimentary Rocks		
Sandstone	$8 - 4 \times 10^{3}$	$2.5 \times 10^{-4} - 0.125$
Shale	$20 - 2 \times 10^{3}$	$5 \times 10^{-4} - 0.05$
Limestone	$50 - 4 \times 10^{2}$	$2.5 \times 10^{-3} - 0.02$
Soils and Waters		
Clay	1 –100	0.01 – 1
Alluvium	10 – 800	1.25 x 10 – 0.1
Groundwater(Fresh)	10 – 100	0.01 – 0.1
Salt Water	0.2	5
Chemicals		
Iron	9.074×10^{-8}	1.102×10^{7}
0.01M Potassium Chloride	0.708	1.413
0.01M Sodium Chloride	0.843	1.185
0.01M acetic acid	6.13	0.163
Xylene	6.998×10^{16}	1.429×10^{-17}

ERT (Electrical Resistivity Tomography)

The basic concept of ERT was first described by Lytle and Dines as a marriage of traditional electrical probing (introduced by the Schlumberger brothers) and the new data inversion methods of tomography. Development of both the theory and practice of ERT was confined mostly to the late 1980s and the 1990s (William Daily et al. 2004). 2D resistivity imaging (ERT) in broad sense is a combination of both electrical profiling and sounding, designed to overcome several constraints raised from independent methods (Dahlin, 1996; Keller and Frischknecht, 1966; Griffiths and Turnbull, 1985). 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. 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 technique. Here in this paper the resistivity tomographic survey results discussed are based using a multi-electrode resistivity imaging system, Terrameter SAS 1000 of ABEM make.

Field Measurements and Survey Design

The resistivity of the ground is measured by transmitting a controlled current (I) between two electrode pushed into the ground while measuring the potential (U) between two other electrodes. In homogeneous ground the resistivity measured is true resistivity, but in practice it is the combination of all the contributing strata and hence is regarded as apparent resistivity. 2-D electrical imaging / tomography surveys are usually carried out using a large number of electrodes, 41 or more, connected to a multi-core cable. The data coverage of the subsurface depends upon the number of electrode, the measurement array type used etc. Field measurement is carried out after setting up the necessary parameters using a laptop or any microcomputer together with an electronic switching unit; later by stacking of data at each electrode position arithmetically using mean, median or standard deviation method is stored under the given file in '*.S4K' format. The sequence of measurements taken, type of array used and other survey parameters is downloaded and converted into appropriate protocol type format using SAS 1000/4000 utility software.

In practice, there are different arrays that are commonly used for 2-D imaging surveys under different prototypes as (a) *Wenner,* (b) *dipole-dipole* (c) *Wenner-Schlumberger* (d) *pole-pole* etc. The characteristics of an array that should be considered for resolving a definite problem depends upon (i) the sensitivity of the array to vertical and horizontal changes in the subsurface resistivity, (ii) the depth of investigation, (iii) the horizontal data coverage and (iv) the signal strength. To interpret the data from a 2-D resistivity imaging survey, a 2-D model for the subsurface is usually generated using RES-2D-INV program. And finally the best-suited true resistivity model for the measured field resistivity is calculated and represented as inverse model resistivity.

FIELD INVESTIGATION

The application of 2D resistivity tomography in association with other geophysical exploration techniques and hydrological investigation has shown a better prospect in understanding the geo-hydrological condition in a semi-arid granite terrain. Under the project of sustainable groundwater development for rural water supply in a fluoride endemic semi-arid region of southern India, a watershed area of ~2 sq km was selected for a pilot scale study. A new concept of in-situ dilution of groundwater fluoride was adopted using appropriate artificial recharge and water harvesting strategies. Subsurface lithology and structural distribution are one of the preliminary requisites in assessment of recharge, site selection for engineering structures etc., which was achieved in the study area by geophysical mapping mainly through resistivity imaging survey (ERT).

Certain site specific problems within the study area were encountered, which were attempted and understood using ERT in close association with different surface geophysical techniques and hydrological test results. In a semi-arid granite terrain, the aquifer in general is in the weathered granite followed by semi-weathered to fractured granite sitting over the compact basement. Geological cross section of the study area with respect to elevation reduced to the mean sea level (m.s.l) was prepared based on conventional resistivity sounding and bore well lithologs. Analysis of periodic groundwater quality and water level behavior with monsoon demanded suitable water harvesting and artificial recharge structures at appropriate sites.

Further, investigation in depth with close grid for better resolution of shallow horizon was attempted in integration. 2D Resistivity imaging with close electrode spacing and suitable configuration was used to map the subsurface and also to concur the findings from previous investigations at the same sites which are illustrated as independent cases in the following.

RESULTS AND DISCUSSION

Case 1: Mapping Buried Dyke Across Fault Occupied Stream

Satellite imagery analysis followed by ground check showed the presence of a dolerite dyke across the stream course (2nd to 3rd order stream) trending east-west in the study area. Hence the weathered and fractured granite which forms the aquifer, mapped through bore well litholog and VES (vertical electrical sounding) along the stream course had been bifurcated. During the summer (pre-monsoon) months when the water level fluctuates down to a depth below 2 to 2.5 m from the surface, the aquifer acts as two independent system. Whereas during monsoon season due to rise in regional water table up to the ground surface, the entire aquifer stretch gets interconnected, indicating a hydraulic passage through weathered dyke up to 2 m depth.

In order to confirm the fault occupied by stream and a dyke cutting across, different geophysical investigation techniques were deployed in integration to one another over the small area, at the suspected juncture (dyke cutting stream course). Resistivity profiling survey using DC resistivity meter (Terra Science; Model TSRM-4/4117) was carried out with wenner configuration for three different electrode spread (a = 5 and 10 m) and station interval of 2 m was carried out perpendicular to the suspected dyke alignment. A resistivity high of considerable width of 20-25 m is predominantly seen in both the profile signatures. Similarly VLF (very low frequency) survey was carried out along the same profile line with inter station interval of 2mts. The VLF instrument used was (Scientrex Make) which measures the ellipticity of the magnetic field and also its tilt. Being a profiling tool it is assumed that VLF responds most prominently to the presence of vertical, conductive and shallow bodies (Murali Sabnavis and Patangay, 1998). Generally, the location of the top of the body on a VLF profile may be obtained from a cross over of ellipticity and tilt percentage, signifying a change in the secondary field direction, which is visually seen in the field profile.

The interpreted results of both wenner resistivity profiling and VLF have shown the presence of shallow, almost vertical contact between two contrasting formations with distinct resistivity range in the form of a profile. It is generally suspected that natural radon gas emanation is high in granite terrains, and which might be more in the vicinity of a fault, fissures or cracks. In order to concretize the findings of geophysical survey, radon measurements were carried out within the suspected zone, and is shown as alpha (“) counts represented in bar chart within the dotted circle in the resistivity profile of Fig.1.

In order to visualize the dyke segment cutting across a fault occupied by a stream, along the profile direction in two dimension, exhibiting true resistivity distribution with depth, 2D resistivity imaging survey was carried out with ‘a=1mt’ station interval and configuration of wenner32SX (wenner á) for a profile length of 80 m covering the anomalous part indicated in the previous geophysical surveys. Data acquired was subjected to inversion using RES2DINV software in which robust inversion was applied as the data set showed sharp contrast in resistivity (150 ohm-m / 1200 ohm-m) with respect to a plane, depicting the fault associated with dyke segment.

Hence all the findings of the previous geophysical and hydrogeological investigations are visually seen in two dimensions in the form of true resistivity pseudo-section and also the weathered dyke upto a depth of 2-2.5 m, acting as a hydraulic passage in the monsoon period is identified. In this case study the results of 2D resistivity tomography clearly depict its advantage over other geophysical techniques, in terms of data reliability and resolution.

Case 2: Mapping of Shallow Subsurface Lithology through Imaging

Based on hydrological investigations like stream discharge measurements, quality assessment, water level behavior with rainfall etc and geomorphological study analysis, several suitable sites along the stream course were recommended for construction of artificial recharge structures like check dams, percolation tanks etc. The thickness of the weathered and fractured granite under the recommended sites were studied and analyzed from the geological cross section prepared, based on geophysical investigation and bore well litholog. Unlike appropriate space in the sub-surface beneath any artificial recharge structure other hydrological parameters like infiltration rate, soil permeability, soil type etc., are equally important to be quantified, to access the suitability of the site.

One such hydrological test was performed to quantify the infiltration rate at more than one site within a proposed percolation tank bed area during the pre-monsoon period. Double ring infiltrometer were used for this test, for a short duration (150-180 min). Soil core samples were collected for variable depths (50 cm, 1 m and 1.5 m) at every 5 cm interval, in order to measure the grain size analysis and categorize the soil type with depth. Infiltration test results showed intermittent stabilization (*Step like behavior*) of infiltration rate, which was different from the conventional smooth exponentially decaying curve. Such anomalous behavior in infiltration rate might be attributed to the subsurface lithological variations in the shallow depth (50 cm to 2m/2.5 m).

2D Electrical Resistivity Tomography with (‘a’=1.0 m) inter-electrode spacing was carried out at two sites within the tank bed area encompassing all the infiltration sites as shown in Fig.2. The depth of investigation from the resistivity pseudo-section with a=1 m spacing is ~6 m from the surface, which was further reduced to a shallower depth of ~2 m using an option of ‘*splice large data set*’ in RES2DINV software, hence resolving the shallow information in detail. Several layers with varying resistivity contrast were visualized in the spliced resistivity pseudo-section. The results from of the grain size analysis for the soil core samples collected were used in interpreting the resistivity images, based on which lithological section were prepared as shown in Fig.2. During the construction period of percolation tank, excavation along the proposed tank axis upto a depth of 2m was used for visual cross check of the lithological section, and was found to be in concurrence with the 2D resistivity image results and grain size analysis of soil core samples.

The efficacy of 2D ERT application in this case study is seen and analyzed in mapping the shallow subsurface geology with appreciable resolution in determining certain hydraulic properties like permeability, porosity etc., and its significance in determining the infiltration rate.

Case 3: Mapping Basement to Aid Engineering Construction

Following hydrological investigation like water level monitoring, rainfall analysis, water quality analysis, and also impact of recharge structures over water level, it was deciphered that over a period of 5 years, the artificial recharge strategy had worked effectively in bringing down

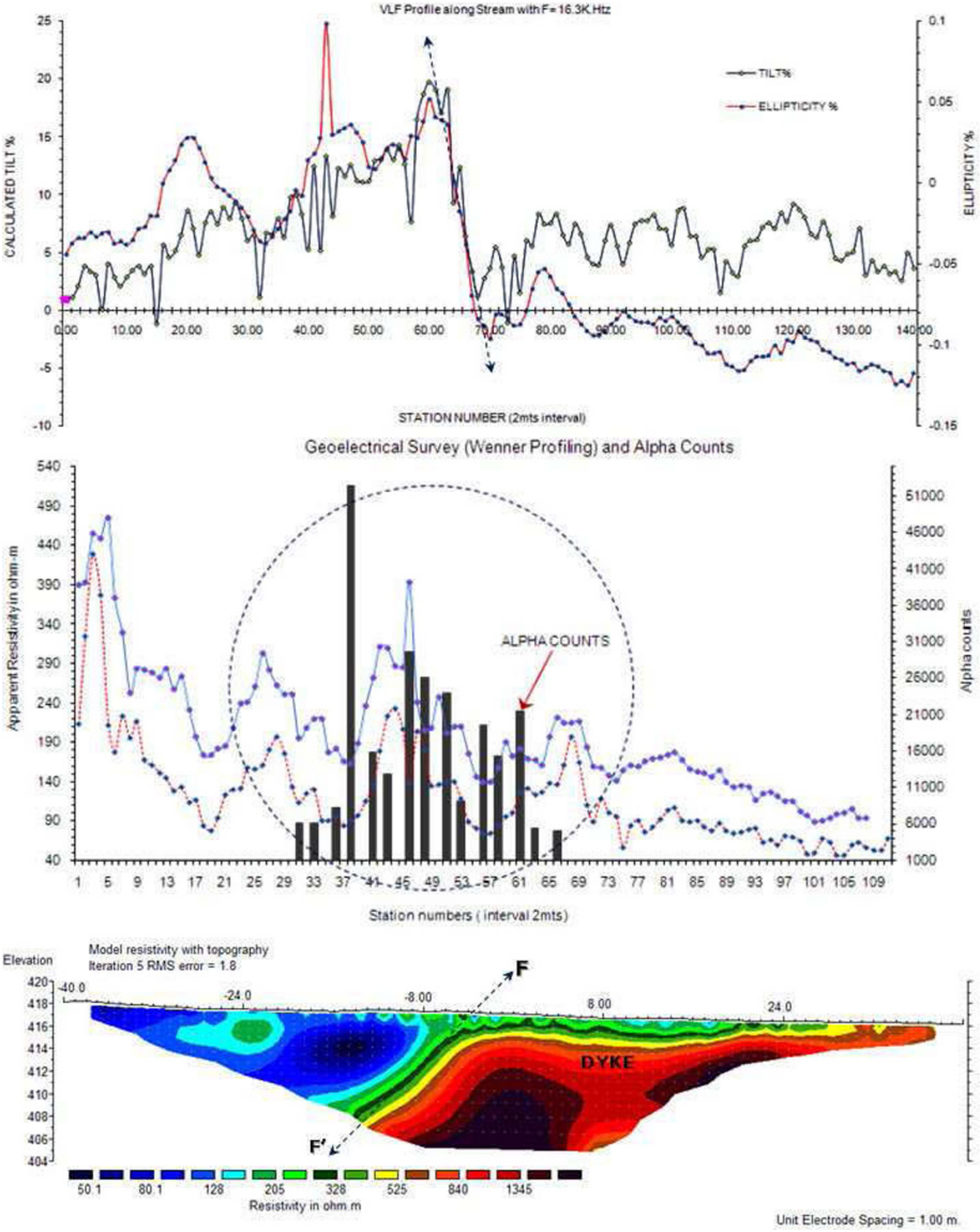
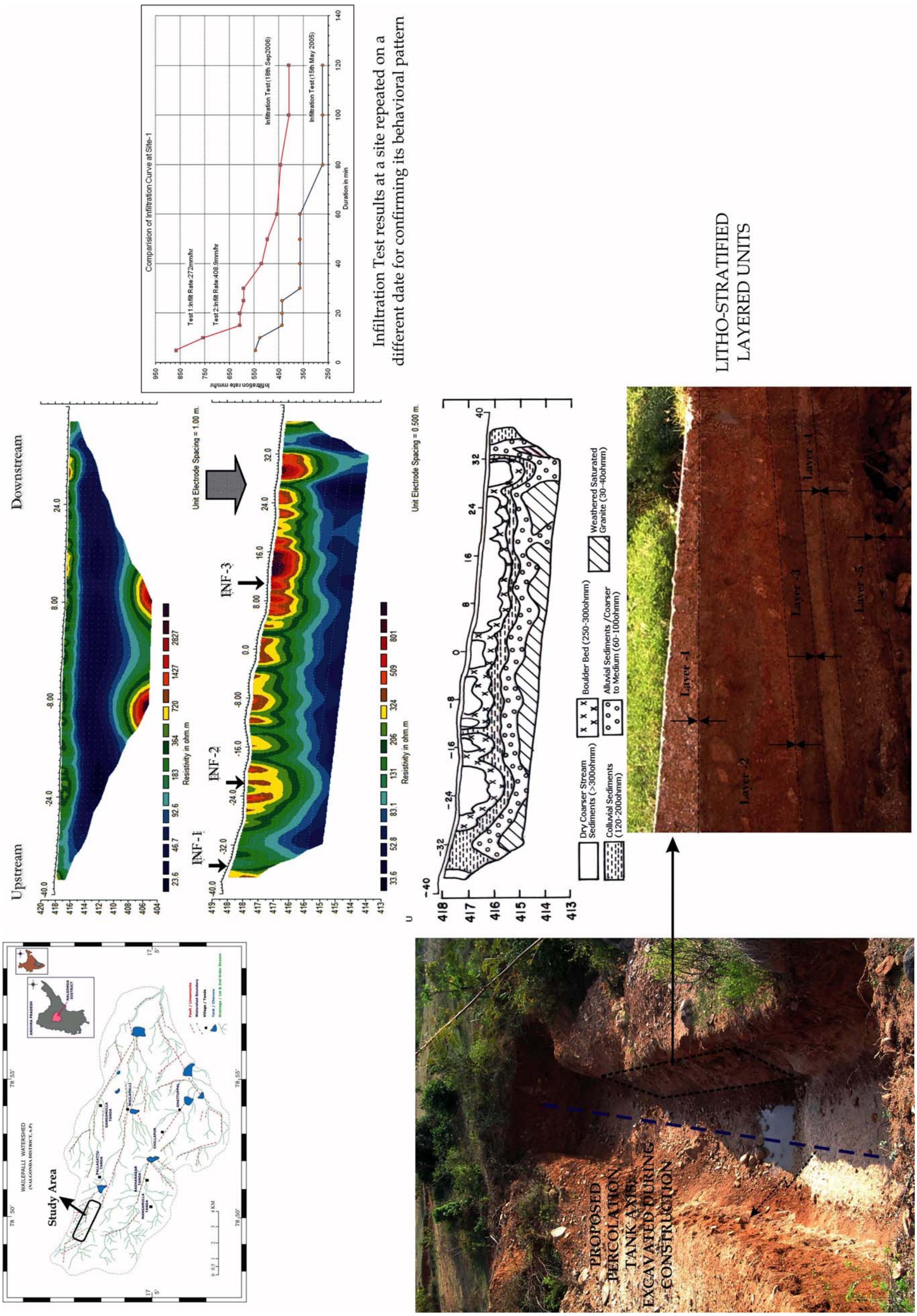


Fig.1

the pre-existing high fluoride (F^-) in groundwater from 3 mg/l to 1.3 mg/l. This fluoride less water was tapped in the downstream of the study area through a large dimension dug well (Diameter: 8 m and Depth: 15 m) coined as resource well for village water supply. Groundwater flow velocity analysis, using tracer studies had shown that under the natural hydraulic gradient, there was always a possibility for this portable water to migrate away from the study area, creating a loss to the efforts made in reducing the fluoride concentration.

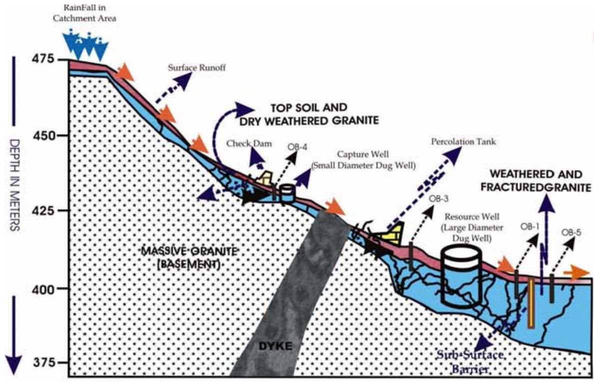
In order to check or retard the outflow of this portable (F^- less water) water away from the resource well, a site was selected at a distance 136 m downstream for the construction of a sub-surface barrier. 2D Resistivity imaging



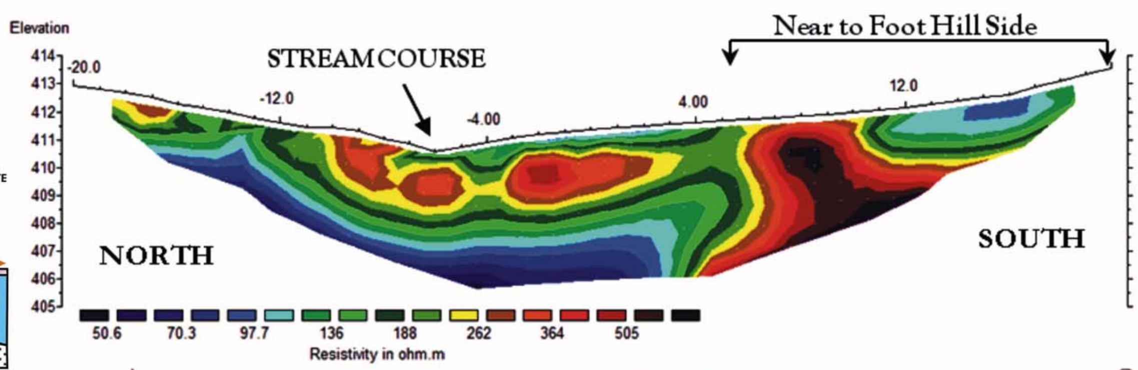
Infiltration Test results at a site repeated on a different date for confirming its behavioral pattern

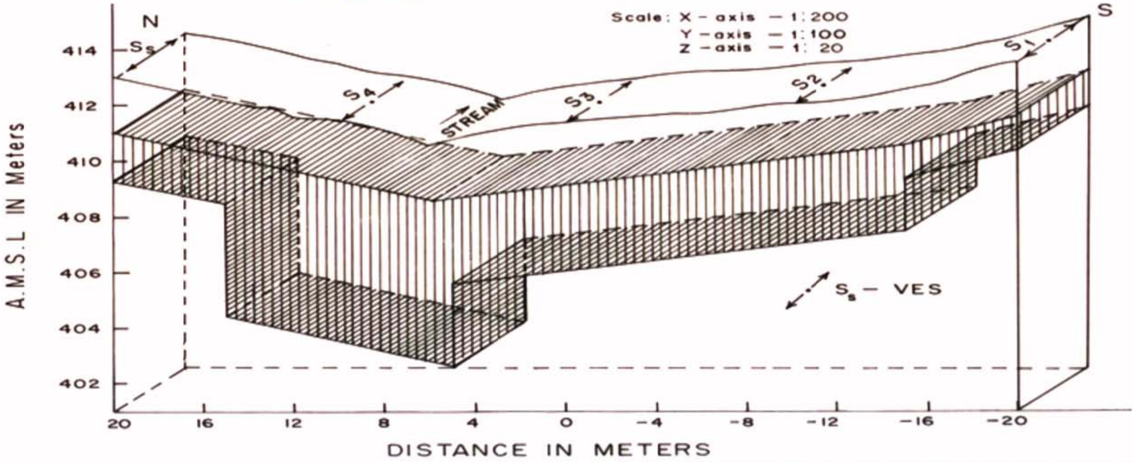
LITHO-STRATIFIED LAYERED UNITS

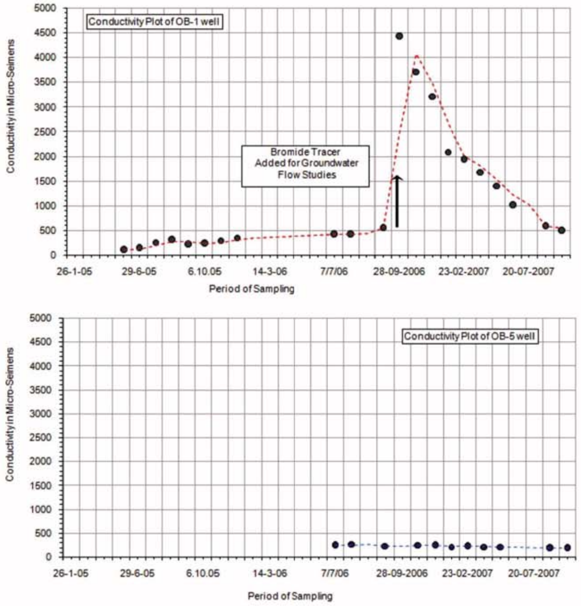
Fig.2



Geological cross section of the study area prepared based on geophysical and geological investigation







Addition of Bromide Tracer in the Upstream Well of Subsurface barrier after construction and periodic monitoring of wells in the upstream and downstream

Snap-shot showing Sub-surface barrier constructed below the surface

Fig.3

along the proposed barrier axis was conducted measurements at every electrode position using cadastral survey for a profile length of 40 m. The analysis of the resistivity pseudo-section with field remarks showed stream bed portion in the north with lower resistivity and the southern hill side with higher order of resistivity.

The engineering design planned for the barrier was facilitated in terms of its depth from the surface. Depending upon the subsurface true resistivity distribution with depth at every electrode position is plotted and analyzed independently. Based on this analysis, optimal depths of excavation on the northern and southern sides were recommended. From the resistivity pseudo-section shown in Figure.3, it is seen that the basement is shallow on the southern flank of the profile, having a considerable width of 4-5mts. On the northern side of the profile from the center, the stream course is marked with lower resistivity, indicating weathered granite with considerable moisture.

Based on the analysis of 2D ERT image the wall depth along the profile was recommended with uniform thickness and variable depth depending on the basement depth. On the basis of ERT image recommended design, the sub-surface barrier was constructed at the proposed site. In order to check the efficiency of the barrier, tracer study was initiated using Potassium bromide (KBr salt) tracer. A known concentration of KBr salt (tracer) was added into the groundwater through an observation bore well in the upstream of the barrier and the conductivity change in water before and after addition of salt was monitored periodically. An observation bore well on the downstream of the barrier was also monitored for the same time period as shown in Fig.3. There was no change in conductivity in the downstream observation well due to addition of bromide in the upstream well after the barrier construction, which implied that the groundwater outflow from the site area has been restricted/retarded by the barrier. Hence the design of the sub-surface barrier recommended based on 2D imaging results, proved to be effective.

CONCLUSION

From the above discussed case studies, pertaining to independent hydrological problems, it has been shown that geophysics plays a major role in understanding the subsurface. With scientific advancements in instrumentation, the data acquisition has improved in depth and accuracy. 2D resistivity tomography technique is an example for the same in hydrological studies for its precision and reliability in integration with other survey methods. Processing and plotting the results in a pseudo-section using RES2DINV has shown a reduction in lateral inhomogenity effect as experienced in conventional resistivity survey. Corroboration of 2D resistivity results with other supplementary geophysical techniques and lithological studies can be a versatile tool in solving several complex hydrological problems.

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