4 Geophysical Characterization of Hard Rock Aquifers

N.S. Krishnamurthy, Subash Chandra and Dewashish Kumar

IFCGR, National Geophysical Research Institute
Hyderabad-500007, India

INTRODUCTION

Geophysics plays a major role for characterizing the hard rocks for groundwater studies. The qualitative and quantitative application has increased since past few years due to rapid development and advancement in microprocessors and associated numerical modelling solutions. Although geophysics has ability to probe deep earth interior (say >1000 m), but its application for groundwater studies is usually restricted to depths less than and around 250 m below the surface. These include mapping the depth and thickness of aquifers, mapping aquitards or confining layers, locating fractures and fault zones and mapping contamination to the groundwater such as that from saltwater intrusion. The theoretical and practical background to geophysics has been extensively reviewed and can be studied in standard texts on the subject, for example Kearey & Brooks (1991); Telford et al. (1976); Parasnis (1979); Dobrin (1976); Grant and West (1965); Reynolds (1997); Miller et al. (1996); Murali et al. (1998); etc.

IMPORTANCE OF FRACTURES IN HARD ROCK AREAS

Fractures often serve as major conduits for movement of water and dissolved chemicals through hard rocks in the underground. The geological structure normally encountered in hard rock areas of places such as in India is granite or granite gneiss overlain by a variable thickness of weathered material. The latter is a regolith produced by the in-situ weathering of the basement rock (Acworth, 1987). The regolith normally grades into solid unfractured basement over several tens of metres, although often the boundary between the two may be fairly sharp. Hydrogeologically the weathered overburden has a high porosity and contains a significant amount of water, but, because of its relatively high clay content, it has a low permeability. The bedrock on the other hand is fresh but frequently fractured, which gives it a high permeability. But as fractures do not constitute a significant volume of the rock, fractured basement has a low porosity. For this reason a good borehole, providing long term high yields, is one which penetrates a large thickness of regolith, which acts as a reservoir, and one which additionally intersects fractures in the underlying bedrock, the fractures providing the rapid transport mechanism from the reservoir and hence the high yield. Boreholes which intersect fractures, but which are not overlain by thick saturated regolith, cannot be expected to provide high yields in the long term. Boreholes which penetrate saturated regolith but which find no fractures in the bedrock are likely to provide sufficient yield for a hand pump only.

HARD ROCK AQUIFER CHARACTERISTICS

The most significant features of the hard rock aquifers are: 1. A topographical basin or a sub-basin generally coincides with ground water basin. Thus, the flow of ground water across a prominent surface water divide is very rarely observed. 2. The aquifer parametres like Storativity (S) and Transmissivity (T) often show erratic variations within small distances. 3. The saturated portion of the mantle of weathered rock or alluvium or laterite, overlying the hard fractured rock, often makes a significant contribution to the yield obtained from a dug-well or bore-well. 4. Only a modest quantity of ground water, in the range of one cu.m. to a hundred cu.m. or so per day, is available at one spot. 5. Draw down in a pumping dug-well or bore-well is often almost equal to the total saturated thickness of the aquifer.

STUDY AREA

The case studies shown in this part are from the geophysical studies carried out in the Maheshwaram watershed having an area of about 60 km^2, situated at about 30 km south of Hyderabad, India. It lies in between geographical coordinates having 17° 06′ 20″ to 17° 11′ 00″ North latitudes and 78° 24′ 30″ to 78° 29′ 00″ East longitudes and forms part of Survey of India toposheet 56K/8. The geology of the Maheshwaram watershed is mainly granites of Archean age intersected by dolerite dykes and quartz veins. They have undergone variable degrees of weathering with depths extending up to even 20 m followed by fracturing at many places. The dyke located in the extreme northern part strikes east-west with about 15 m width. Another dyke exposed about 1 km south of the first one, strikes N60°E-S60°W with a width of about 20 m at places. A quartz vein of about 20 m width with a strike of ENE-WSW is exposed in the drainage divide in the southern boundary of the watershed. Ground water in the area occurs under water table conditions in the weathered granite and in semi-confined conditions in the fractured granites. The depth to water level varies from 11 m to 20 m. The yield of the bore-wells range from 1000 gph to 5000 gph. The high yielding bore-wells are either recharged by the irrigation tanks or tapping the deeper fractures. The yield of the bore-wells in the vicinity of the dolerite dykes is high as they are tapping thick fractured zone. The area comprises thin soil cover of sandy loam and clayey soils and is underlain by granites. These granites are medium to coarse grained and of pink and grey colour.

GEOPHYSICAL METHODS

Several geophysical methods are available for groundwater exploration. Most of the available geophysical methods have been applied here to study the aquifer system of a hard rock granitic terrain. A brief description of the methods is given here.

Electrical Resistivity Technique

Electrical resistivity technique is the most commonly applied method among all the geophysical methods for groundwater exploration, because of the large variation of resistivity for different formations and the changes that occur due to the saturated conditions. Resistivity is defined as the resistance offered by a unit cube of material for the flow of current through its normal surface. If L is the length of the conductor, and A is its cross-sectional area, then the resistance is defined as

$$R = \rho \frac{L}{A}$$

where ρ is constant of proportionality and is called as resistivity. In MKS system the unit of resistivity is ohm-metre (Ωm).

In the case of an inhomogeneous medium, the resistivity measured is called as the apparent resistivity. The apparent resistivity of a geologic formation is equal to the true resistivity of a fictitious homogeneous and isotropic medium. Resistivity of rock formations varies over a wide range, depending on the material, density, porosity, pore size and shape, water content and quality, and temperature. There are no fixed limits for resistivities of various rocks: igneous and metamorphic rocks yield values in the range 10^2 to 10^8 ohm m while sedimentary and unconsolidated rocks, 1 to 10^4 ohm.m.

Generally for measuring the resistivities of the surface formations, four electrodes are required. A current of intensity I is introduced between one pair of electrodes, called as current electrodes, named as A and B and some times as $+I$ 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 as potential electrodes and represented by

M and N. There are different electrode arrangements for measuring the potential difference, which are uniquely used as different purposes in exploration techniques. The most commonly used arrangements are Wenner and Schlumberger configurations.

Wenner Array: Wenner configuration consist a system of earth resistivity measurements with four collinear equally-spaced point electrodes on the ground surface. The two current electrodes A and B and two potential electrodes M and N are placed at surface at equal distance '*a*' as shown here. Current *I* is passed into the ground through A and B and the potential difference is measured through M and N.

```
A        M    O    N        B
↑_______↑____.____↑_______↑
  ← a →← a →← a →
```

The geometrical factor (K) for this array is $2\pi a$ and apparent resistivity is given by

$$\rho_a = 2\pi a\ (\Delta V/I)$$

Schlumberger Array: The Schlumberger array also uses four collinear point electrodes but measure the potential gradient at the mid point. In this array the current electrodes are spaced much farther apart than the potential electrodes, usually five times or more as shown here.

```
A                  M    O    N                  B
↑_________________↑____.____↑_________________↑ where L ≥ 5(l)
                     ← 2(l) →
←- - - - - - - - - - - 2L - - - - - - - - - - - →
```

The geometrical factor for this array is

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

Or $$K = \pi\ (L^2 - l^2)/2l$$

Apparent resistivity $\rho_a = K(\Delta V/I)$, where A and B are the current electrodes, M and N are the potential electrodes, L = half spacing of current electrodes and l = half of spacing of potential electrodes.

Resistivity Profiling

Electrical profiling is used to determine the lateral inhomogeneities up to a particular depth and thereby a particular section of the subsurface is mapped along a profile. This method is highly useful in mineral exploration where the detection of isolated bodies of anomalous resistivity is required and in groundwater exploration to determine the linear features in the subsurface, which control the movement of ground water. In resistivity profiling, the electrode system moves as a whole from one station to other along a line, known as profile or traverse. For a given spacing, the electrode system has its depth of investigation. For higher electrode spacings, the depth of investigation will be more.

When the apparent resistivity observations for all stations on a traverse and for all such traverses spread over the entire area of the survey are made, the resistivity values are plotted at their respective positions over a map. After this, the contours of equal resistivity values for particular electrode spacing are drawn and are called as equi-resistivity or contour maps. Thus the representation is in the form of linear maps for several electrode spacings or contour maps for a particular assumed depth section. The resistivity highs/lows are marked to give an idea about the epicentral location of the target (resistive or conductive zone) and its lateral extent. The resistivity profiles taken across two dykes are shown in Fig. 1. The results show low resistivities at shallow depths and high resistivities at deeper depths over the dyke thus indicating the conductive nature due to weathering/fracturing of the dyke in upper parts and hence suggests that this dyke is not acting as barrier for the ground water to flow at shallow depths, whereas in deeper levels, the dykes may be acting as barriers.

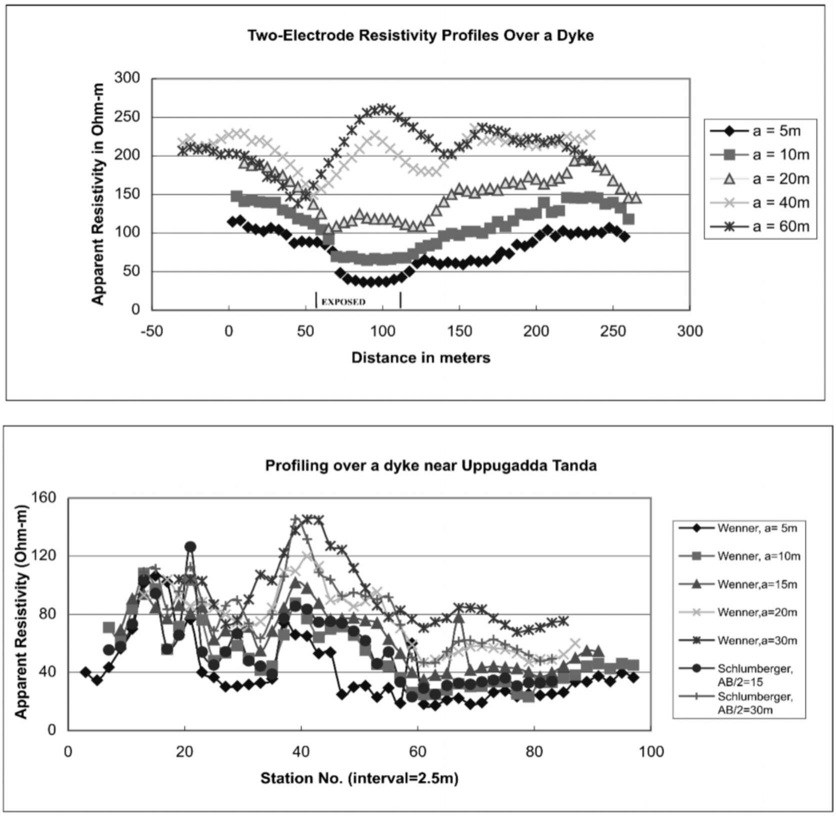


Figure 1. Resistivity profiles in Maheshwaram watershed.

Resistivity Sounding

Vertical Electrical Sounding is applied whenever a depth section is to be determined at a particular place and, in this method, increase in the depth of investigation can be obtained by gradually increasing the distance between the current electrodes such that current penetrates deeper and deeper into the ground. This method gives the information about depth and thickness of various subsurface layers and their resistivities.

The field procedure of a sounding is to use a fixed centre with expanding electrodes. The Wenner and Schlumberger layouts are particularly suited to this technique. But Schlumberger array has some advantages. There are always some naturally developing potentials (self-potential, SP) in the ground, which have to be eliminated and nullified. The potential difference developed, due to the experimentally impressed current, should be taken into consideration. For different spacings, the apparent resistivity of the ground for particular array can be calculated.

Interpretation of Sounding Data

The apparent resistivity is plotted against half current electrode spacing on a double logarithmic paper and the curve so obtained is called sounding curve. To get the layer parametres (resistivity and thickness) of the subsurface, these sounding curves are to be interpreted and there are mainly two types of interpretational techniques: Indirect methods and direct methods.

In the indirect methods, the field curve is compared with a set of theoretical curves, also called as master curves, for different known layered parametres prepared in advance. Several albums of master curves are available which include among others Compagne Generale de Geophysique (1963), Flathe (1963), Orellana and Mooney (1966) and Rijkswaterstaat (1969). These are computed from the expression for surface potential (Stefanesco et al., 1930).

$$V = \frac{\rho_1 L}{2\pi}\left[\frac{1}{r} + 2\int_0^\infty K(\lambda)J_0(\lambda r)\,d\lambda\right]$$

where r = distance of the measuring point from current source, ρ_1 = resistivity of surface layer, $K(\lambda)$ = Stefanesco kernel function determined by thickness and resistivity of surface layer, $J_0(\lambda r)$ = Bessel function of zero order and first kind and λ = Integration variable, a real number with dimensions of inverse length. When a match of the field curve is obtained with the theoretical curve, one can get the layer parametres in terms of resistivity and thickness of the subsurface layers.

In direct methods, one can get the layer parametres from the field curve itself by using the computer code available. Quite often, it is possible that the field curve may not match with the available master curves. In the absence of a proper set of master curves that simulates the geological situation, one has to compute a theoretical sounding curve that best fits the field situation to get the proper layer parametres. In some codes, one requires giving an initial guess model and the curve is interpreted by an iterative process and in another type of direct methods, the field curve is interpreted without the necessity of an initial model.

The method of automatic iterative interpretation given by Zohdy (1974) is based on the similarity in shape existing in many cases between apparent resistivity curves and Dar Zarrouk curves. Zohdy (1989) has developed an algorithm for automatic iterative interpretation of field sounding curve, where no initial guess model of the layered earth are required to be given as initial model. Based on the field curve an initial model is assumed. Then first thickness parametres are changed according to an algorithm till minimum root mean square error is obtained. Later, layer resistivities are changed according to an algorithm till another minimum is obtained in RMS error. Using equivalence principle the layers can be suppressed finally.

When the layer parametres are obtained in terms of resistivities and thicknesses, these can be inferred in terms of lithology of the subsurface by knowing the geology of the area and correlation of resistivities with various formations from a known place.

The resistivity data collected in Maheswaram watershed was interpreted using a computer programme based on the inversion algorithm of Jupp and Vozoff (1975), which uses digital filter theory (Ghosh, 1971a, b). The iterative method successively improves the initial model given, until the error measure is small and the parametres are stable with respect to a reasonable change in the model parametres. Figure 2 is an example of a sounding curve interpreted by the above method.

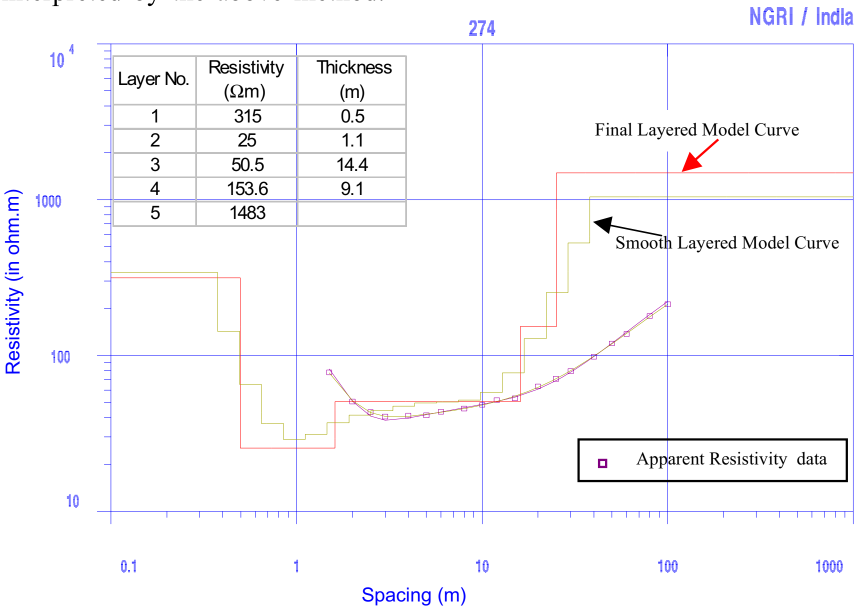


Figure 2. Resistivity sounding interpreted showing the field and computed curves.

It may be necessary to mention that a parameter model derived either by conventional or computer method may not be unique because of an inherent limitation, namely the phenomenon of equivalence resulting in a range of models fitting the same sounding curve. Another limitation is the simplified assumption of horizontal, homogeneous and isotropic model layers, which is never the case in nature. It is, therefore, very essential to gather the hydrogeological knowledge of the area and correlate the sounding data obtained near existing wells with lithology for a reliable interpretation.

Multi Electrode Resistivity 2-Dimensional Imaging (MER2DI)

The improvement of resistivity methods using multielectrode arrays has led to an important development of electrical imaging for subsurface surveys (Griffiths and Turnbull, 1985; Griffiths et al., 1990; Barker, 1992; Griffiths and Barker, 1993). Such surveys are usually carried out using a large number of electrodes, 24 or more, connected to a multi-core cable. A laptop micro-computer together with an electronic switching unit is used to automatically select the relevant four electrodes for each measurement. Apparent resistivity measurements are recorded sequentially sweeping any quadruple (Current and Potential Electrodes) within the multi-electrode array. MER2D data can be interpreted with the help of RES2D inversion software and finally a true

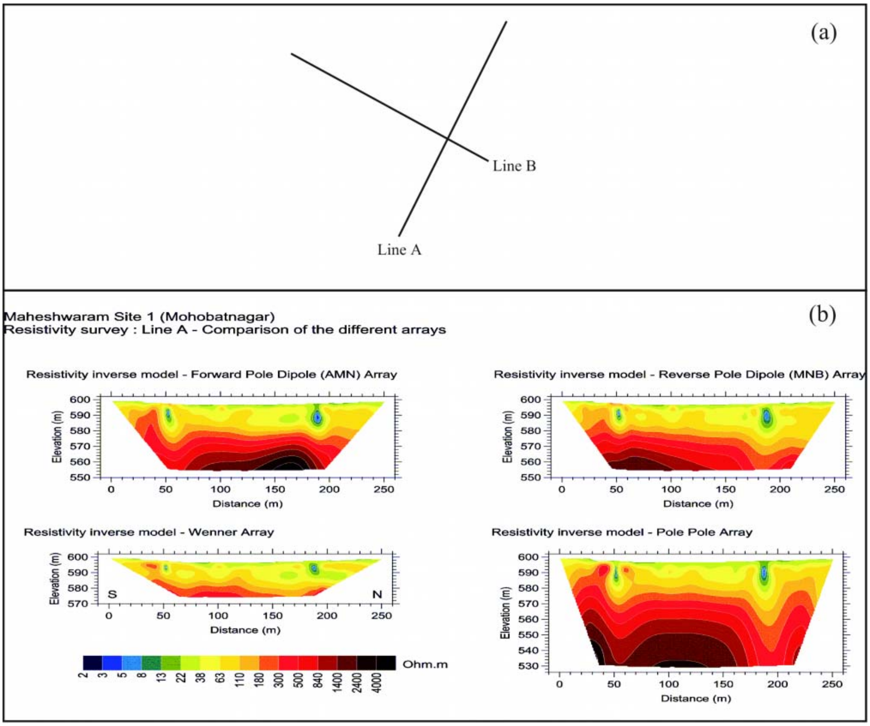


Figure 3. (a) Profile layout and (b) Comparison of different arrays along Line A in Mohabatnagar.

resistivity cross-section can be obtained. As a result, high-definition pseudo-section with dense sampling of apparent resistivity variation at shallow depth (0-100 m) is obtained in a short time. It allows the detailed interpretation of 2D resistivity distribution in the ground (Loke and Barker, 1996).

Figure 3 shows comparison of different configurations along a profile. As seen from the resistivity image, the following are observed.

- The pole-dipole arrays bring rather distorted images at depth. The resistivity of the bedrock is overestimated at the end opposite to the current electrode.
- Only the pole-pole array has sufficient depth of investigation to effectively image the bedrock with resistivity higher than 1500 Ohm.m.
- But with respect to Wenner configuration the image at the surface is much poorer. For instance, the lateral extension at shallow depth of the two conductive anomalies is clearly detected with the Wenner array, but is not seen with the pole-pole array.
- From another point of view, the high depth of investigation of the pole-pole array is counter balanced by a large model uncertainty.

MER2D data interpreted with the help of RES2D inversion software and model uncertainty obtained along two profiles in Mohabatnagar are shown in Fig. 4 and described below. As seen in Fig. 4, there are two clear conductive faults respectively located at distance 55 m and 190 m along line A. The second fault located at 190 m from the profile and at a depth of 20 m seems to be more prominent compared to the first one, located at 55 m. The second one presents a lateral extension at shallow depth. The prominent anomaly also corresponds to large weathered thickness of resistivity 100 Ωm. There is a clear bedrock raise with a resistivity of around 600 Ωm, to the surface at distance 45 m. The second conductive anomaly corresponds to a lineament detected on aerial photography. All the other anomalies observed at depth are not corresponding to geomorphological features. The presence of conductive body at the surface raises the uncertainty of the model at depth. The same anomaly was also prominent in other configurations like Wenner, and pole-pole array and the basement upliftment is more prominent in the pole-pole array with extension of conductive zone about 40 m, which could indicate the fracture in granite.

The bedrock presents a regular deepening from the eastern to the western part along line B (Fig. 4). No faults are detected as interpreted from the inverse model. The result shows low resistivity of 60-100 Ωm, which indicates the weathered fractured granite. At the surface a conductive area is located between distances 160 and 270 m. This conductive area is not corresponding to the black shrinking clayey soils of the paddy fields but to the reddish clayey soils covering the end of a gentle hill slope.

In addition to this, the intrusive lineaments like dykes or quartz veins, which behave resistive to the groundwater flow, can be taken as an indicative tool for exploring the groundwater potential zones. The contact zones of the intrusive material and the host material become weak because of their

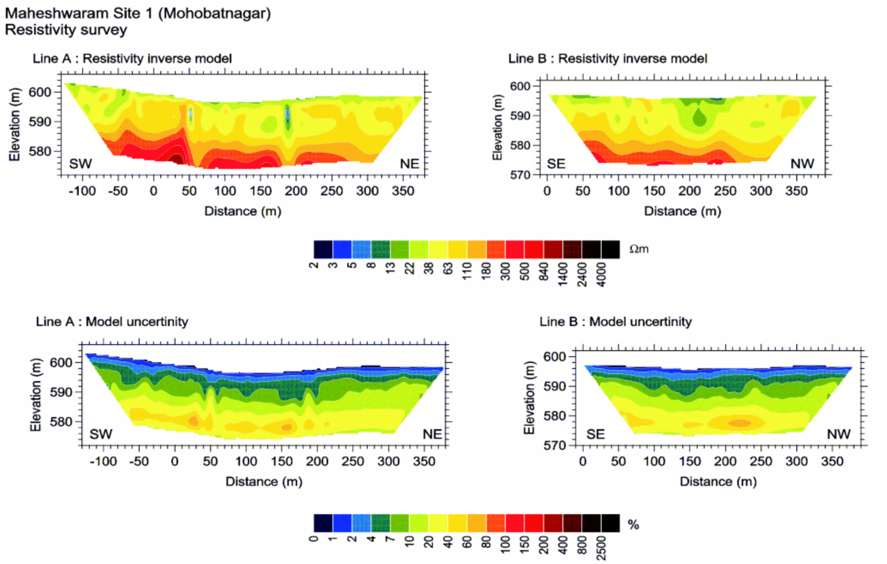


Figure 4. MER2DI Section along Line A and Line B (Mohabatnagar).

formation by cooling and crystallization at different times, development of cracks and fractures at the time of intrusion in the host material, and weathering of the contact zone due to water entrance through the fractures. Even the intrusive bodies may get weathered due to the fracture development and hence become good groundwater potential zones. With this idea Electrical Resistivity Tomography (ERT) was carried out at Kothur quartz vein (~25 m thick) in Maheshwaram watershed. The resistivity image (Fig. 5) has revealed the weathering effect at the contact zone, which was confirmed by the drilling of the bore-well. The top red coloured patch is the impression of high resistive quartz vein; however at coming further deeper it has shown low resistivity, which is nothing but the weathering and fracturing effect. The deepening of the weathering front can be clearly seen (as low resistivity) on either side of the quartz vein.

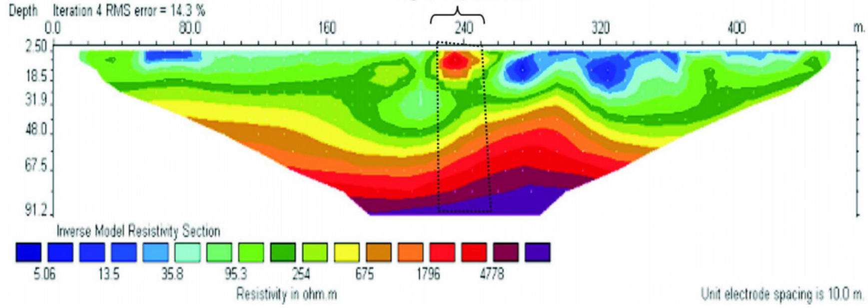


Figure 5. ERT across a quartz vein near Kothur, Maheshwaram watershed.

Magnetic Method

Magnetic methods are based on the observation of anomalies in the magnetic field of the earth that are caused by magnetic susceptibility of different rocks. As dolerite dykes are very common features in hard rock and important for groundwater flow, these methods are very useful to delineate even the buried dykes. Magnetic surveys are classified as grid and profile survey depending upon the density and geometrical distribution of the points of observation. Measurements with a magnetometer are taken 2 to 4 times at a station and their average value is considered to that station. The time of measurement is also noted for every observation since the magnetic field does not remain constant with time and hence necessary correction is applied for each station value by having repeat observations at base station.

Different types of instruments are available for magnetic surveys e.g. Schmidt type or by compensation as in Torsion magnetometer, Induction type of instrument, Fluxgate magnetometer, Proton precession magnetometer, Optical absorption magnetometer or the high sensitivity atomic resonance magnetometer etc. Magnetic systems consist of a permanent magnet, which can be deflected under the influence of geomagnetic field. The value of the magnetic field is determined by the deflection as in Schmidt type or by compensation as in Torsion magnetometer. Induction types of instruments consist essentially of an induction coil operated by a motor in the earth's magnetic field. The electromotive force developed in the coil due to intersection of force of the earth's magnetic field is a measure of the field. Instruments with sensitive fluxgate elements consist of a coil with core made of an alloy whose magnetic permeability strongly depends on the minor changes in the external magnetic field. The change in the electromagnetic parametres of the sensitive element determines the intensity of the earth's magnetic field.

Proton precession magnetometer consists of a container of water with a coil wound around it. When a strong magnetic field is applied in a direction approximately perpendicular to the earth's field, the protons will align parallel to the applied field. At this stage if the field is suddenly cut off, the protons start processing, inducing a small e.m.f. in the coil which is a measure of the earth's field. Optical absorption magnetometer or the high sensitivity atomic resonance magnetometer is the latest type. There are three types namely, the metastable helium, rubidium or cesium magnetometer. All these magnetometres make use of optical pumping technique. They are highly sensitive and also enable the measurement of the vertical gradient of the earth's magnetic field employing two magnetometres kept separated vertically apart from each other. One example of a magnetic profile carried out across a dyke in Maheswaram watershed is shown in Fig. 6.

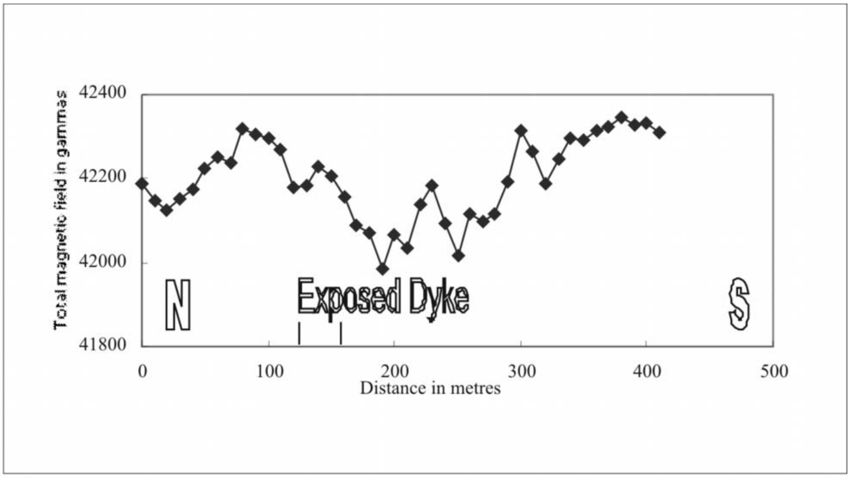


Figure 6. Magnetic traverse across a dyke.

Magnetic Resonance Sounding (MRS)

The initial idea of transforming the well-known proton magnetometer into a tool for water prospecting from the surface is ascribed to R.H. Varian (Varian, 1962). This idea was further developed and put into practice much later by a team of Russian scientists under the guidance of A.G. Semen. The Institute of Chemical Kinetics and Combustion (ICKC) of Russian Academy of Sciences fabricated the first version of the instrument for measurements of magnetic resonance signal from subsurface water ("Hydroscope"). The basic principle of operation of the Magnetic Resonance Sounding or the hitherto called surface Proton Magnetic Resonance (PMR) method for groundwater investigation is similar to that of the proton magnetometer. They both assume records of the magnetic resonance signal from a proton-containing liquid (for example, water or hydrocarbons). However, in the proton magnetometer, a special sample of liquid is placed into the receiving coil and only the signal frequency is a matter of interest. In MRS, a wire loop 100 m in diameter is used as a transmitting/receiving antenna and the water in the subsurface behaves as the sample. Thus, the main advantage of the MRS method, compared with other geophysical methods is that the surface measurement of the PMR signal from water molecules ensures that this method only responds to the subsurface water. Used routinely in Russia and tested in other countries (Shirov et al., 1991; Goldman et al., 1994; Lieblich et al., 1994) the method has demonstrated its potential.

The wire loop/antenna is laid out on the ground, normally in a circle with a diameter between 10 and 200 m, depending on the depth of aquifers; it may also be laid out in a "figure of eight" in order to improve S/N ratio (Trushkin et al., 1994). A pulse of alternating current then energizes the antenna

$$i(t) = I_0 \cos(\omega_0 t),\ 0 < t \leq \tau \qquad (1)$$

where I_0 and τ are respectively the pulse amplitude and duration. The frequency of the current ω_0 is equal to the Larmor frequency of the protons in the geomagnetic field $\omega_0 = \gamma H_0$ with H_0 being the magnitude of the geomagnetic field and γ the gyromagnetic ratio for the protons (physical constant).

The pulse causes precession of the protons around the geomagnetic field, which creates an alternating magnetic field that can be detected using the same antenna after the pulse is terminated ("free induction decay" method). In practice, the PMR response recording is possible after an instrumental delay ("dead time").

Equipment

The parametres of currently available surface PMR equipment, such as Hydroscope (ICKC, Russia) and NUMIS (IRIS Instruments, France), do not permit measurements of the very short signals (less than 30 ms) corresponding to 'bounded' water in the subsurface. Thus, the vertical distribution of the water content deduced from the MRS data corresponds to the location and amount of 'free' water in the aquifers. Free water distribution in the subsurface is a solution of integral equation. Like many other ill-posed problems, the inversion is sensitive to field measurement errors caused by external electromagnetic interference such as electrical discharges in the atmosphere, magnetic storms, and all kinds of electrical currents through the subsurface. Interference may also be due to cultural noise produced by power lines, electrical generators and engines. In addition, the electrical conductivity of the subsurface (the operational frequency is between 1.5 and 2.8 kHz) not only attenuates the signal, but also has an effect on the kernel of the integral equation. Knowledge of this effect is important for the practical application of the method and for the data interpretation. Although further research is required to establish a precise relationship between the decay times of the PMR signal and the hydrogeological parametres of water in a porous medium, the studies show that PMR application allows to assume, with sufficient accuracy, that the decay time for bounded water is less than 20-30 ms and that for free water is between 30 and 1000 ms.

The transmitting antenna usually consists of a 100 m diameter loop laid on the ground, allowing a depth of investigation of the order of 100 m. The Larmor frequency varies between 0.8 and 3.0 kHz depending on the amplitude of the local Earth's magnetic field. The energizing current in the loop will reach intensities of 200-300A during pulses of a few tens of milliseconds. The relaxation field of the protons is measured in the same loop, after the energizing current is turned off. The voltage measured in the loop is of the order of a few tens to a few thousands nanovolts. Stacking is used to enhance the signal. To reduce the noise, 'figure-of-eight' shaped antenna is used which gives a maximum depth of investigation of about 40 m. One example of a sounding in Maheswaram watershed is shown in Fig. 7.

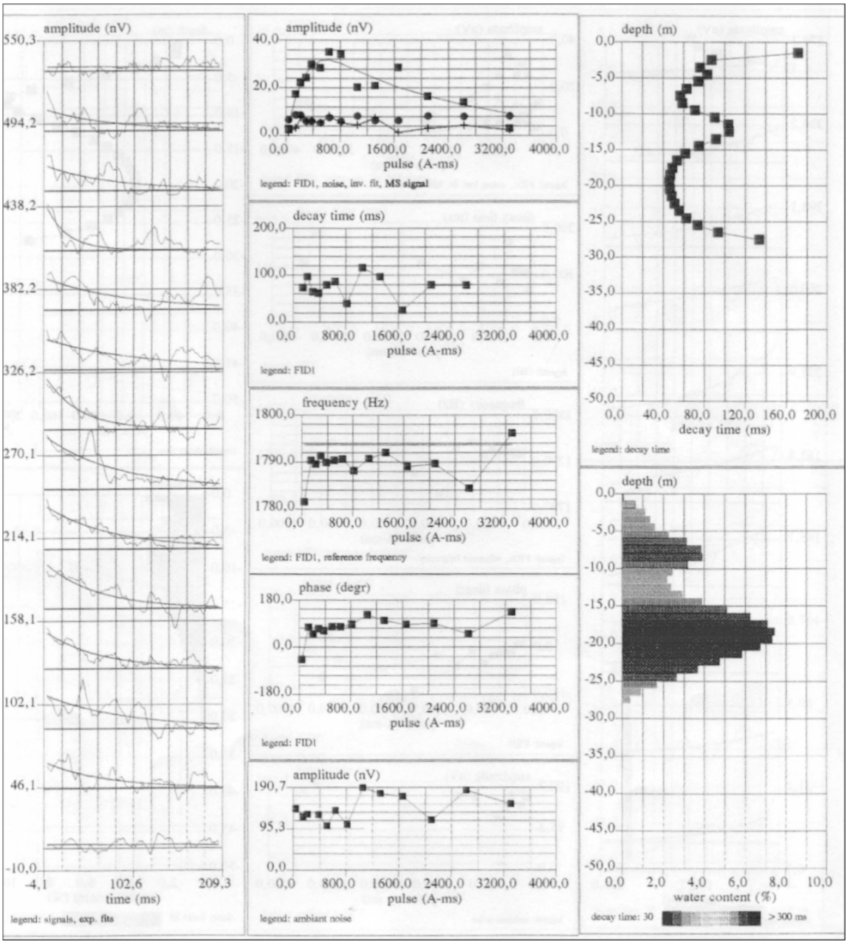
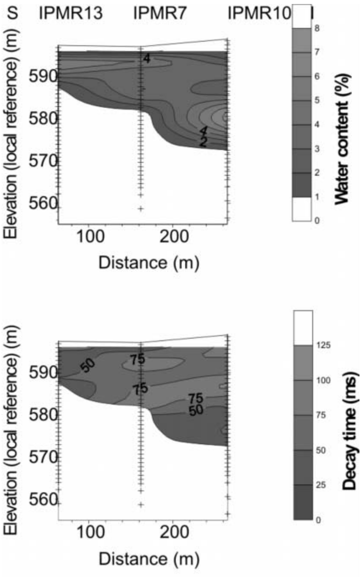


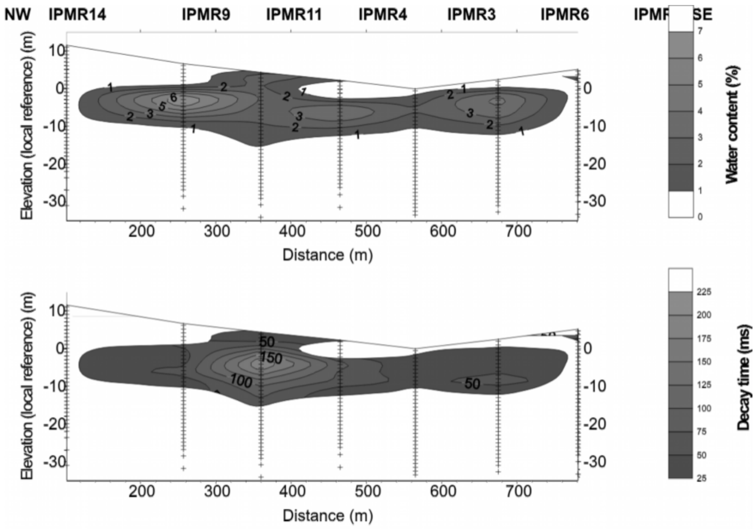
Figure 7. PMR sounding result at IPMR 10.

- To the left, the raw data time series for each value of the pulse parameter (the pulse parameter increases from bottom to top of the page).
- In the centre, measured and reconstructed amplitude, decay time, frequency, and phase of the PMR signals ambient noise versus the pulse parameter.
- To the right, the result of amplitude and decay time data inversion, i.e. water content and decay time distribution versus depth.

The cross section, as shown in Fig. 8a, summarizes the water content and decay time deduced from inversion of the PMR data at Mohabatnagar. The maximum thickness of the water saturated weathered zone was found to be about 25 m on PMR-10. The upper portion of the main part of IPMR13 may be due to alluvial deposits. The underlying probable weathered zone increases from almost non-existent on IPMR 13 to reach the thickness of 20 m for a maximum depth of 30 m on IPMR10 (Fig. 8). This deepening of the weathered zone may be related to the fracture zone in the vicinity of IPMR10. A relatively long signal decay time reveals a small amount of clay in the weathered zone. Higher water content and a longer decay time suggest that more water is stored in this area than in KB Tanda area.



(a)



(b)

Figure 8. 2D sections from PMR soundings.

IPMR13a and IPMR13b measured at the same place but at right angles, show very different water contents and depths, which could be explained by the presence of 2D or 3D structures that are not revealed in the same manner by both soundings. Due to a low signal to noise ratio, it may also be possible that the IPMR13b result are erroneous.

The cross-section presented in Fig. 8b summarizes the water content and decay time deduced from inversion of PMR soundings at KB Tanda. The higher water content and longer decay time suggest that the largest amount of water is stored in the northwestern part of the profile (IPMR9, IPMR11). The maximum thickness of the water-saturated weathered zone was found to be about 15 m. A relatively short decay time and low water content (IPMR3) is most probably caused by a greater amount of clay or silt in the weathered zone. The low water content and almost waterless areas, as observed on IPMR14 and IPMR8 can be attributed to unweathered zones (fresh rocks).

WELL LOGGING

Geophysical well logging provides information on the geologic framework and the groundwater system at disposal sites. Log data can be used to plan the location of pits, trenches and monitoring wells. They can provide specific information on completion problems in monitor or injection wells. Logging provides more continuous data on the vertical and lateral distribution of effluent from waste than can be obtained from samples at a lower cost. Logs can also be used for monitoring changes in water quality. In order to plan a cost effective remediation programme, a thorough understanding of the hydrogeologic system is necessary and much of the needed information can be obtained economically from well logs.

Self-Potential (SP) Logging: The SP log is a measurement of the natural potential differences or self-potentials between an electrode in the borehole and a reference electrode at the surface. The development of SP in bore-wells is contributed mainly due to the differences in salinity and other parametres between the fluid filling the borehole i.e. mud or water and the quality of formation water. The diffusion of ions of different salts from one medium to another and flow potentials generate spontaneous polarization. Normally, clay/shaly rocks produce positive anomalies while porous, permeable layers such as sands, fractured sandstone, and compact sandstone give rise to negative anomalies. The interpretation of SP logs mainly consists of identification of different lithological horizons and marking their boundaries. This is usually done in conjunction with the resistivity logs.

Point Resistance (PR) Logging: One of the simplest and very useful logging methods measuring resistivity variations is called as the point resistance (PR) logging method. In this technique, the resistance between two electrodes (one of them is kept on the surface and the other is moved in the bore-wells) is measured and is invariably used in conjunction with SP logging. Measurement of ground resistance serves more as an indicator of the probable order of resistivity rather than for determining the actual resistivity of formations. The compact zone shows high resistance while the others is indicated by lower values. The PR log has some advantages such as: 1. The anomaly highs or lows are proportional to the resistivity of the formation. 2. Very thin beds with different resistivities can be identified provided the borehole diametres are not very large compared to sonde diameter. 3. The measurement and interpretation of PR logs is simple.

Resistivity Logging: The most commonly used electrode arrangement is normal or potential sonde in which one current electrode and two potential electrodes are located on the sonde. The other current electrode is kept on the surface. The curves obtained by potential or normal resistivity logs are symmetrical in form in which the maximum indicates the layer with the higher resistivity, and the minimum indicates a layer with lower resistivity.

Gamma Ray Log: The gamma ray log is a record of a formation's radioactivity. The radiation emanates from naturally occurring uranium, thorium and potassium. Most rocks are radioactive to some degree. Igneous and metamorphic rocks are more so than sedimentary rocks. However, amongst sedimentary rocks, shales have by far the strongest radiation. It is for this reason that the simple gamma ray log has been called the 'shale log'. A high gamma ray value frequently means shale. Quartzite shows no radioactivity. Sandstones usually show low gamma ray values.

The various well logging techniques used in IFP-19 at Maheswaram watershed are shown in Figs. 9 and 10. The geological sequence encountered while drilling is the top weathered and semi-weathered layer followed by fractured granite underlain by compact granite at a depth of about 36 m. The resistivity sounding result shows a resistivity of 292 Ωm for the semi-weathered zone followed by fracture granite from 16-30 m with a resistivity of 496 Ωm, underlain by bed-rock. Self-Potential, Point Resistance, Temperature log, Short Normal, Long Normal and Gamma logs were done in this well. S.P. and Temperature logs do not indicate any anomalous zone. The SN and LN logs indicate low resistivity around 31 m and the PR log indicates a low resistance around 32 m.The apparent resistivity as observed against weathered zone are 110 Ωm and 600 Ωm by SN and LN respectively whereas against fractured zone are 220 Ωm and 1200 Ωm. The gamma log indicates high activity below 22.5 m onwards, which is in the range of 500 cps compared to that above 22.5 m which is in the range of 300 cps or less. This high activity can be activated to a fractured zone. Combining all these results showed that there is a clear fracture zone around 25 m as shown in Fig. 10. All the electric logs indicate that the bedrock occurs at a depth of 38 m.

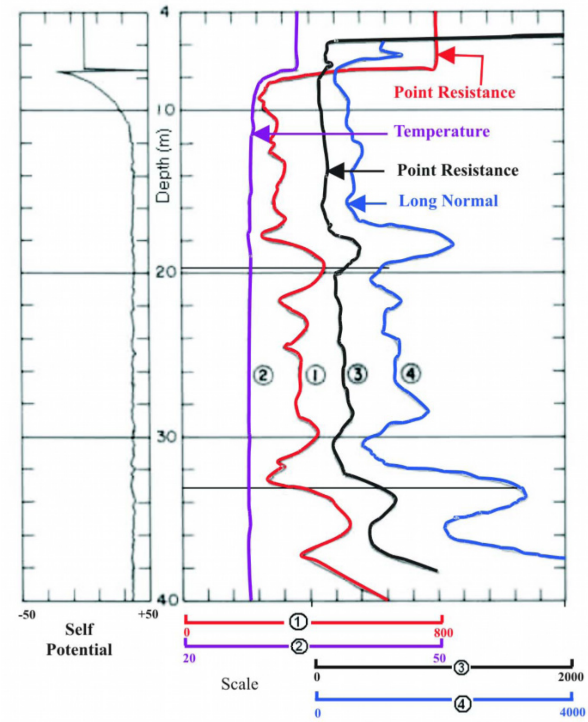


Figure 9. Geophysical Well Logs at IFP-1.

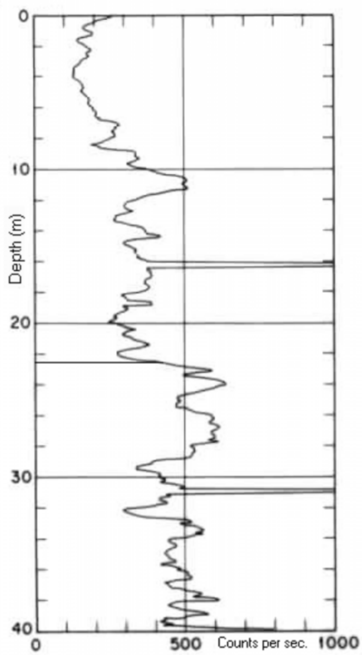


Figure 10. Gamma Log at IFP-1.

SELF POTENTIAL (SP) METHOD

Certain natural or spontaneous potentials occurring in the underground caused by electro-chemical or mechanical activity are called self-potentials. These potentials, when associated with groundwater at geologic contacts, bioelectric activity zones etc., are known as electro-kinetic or streaming potentials. Streaming Potentials generated by subsurface water flow are the source of the great majority of SP anomalies of groundwater interest. In a porous or fractured media, the relative movement between solid matrix and electrolyte (groundwater) causes an electrical potential at the interface, called zeta potential. If the water movement were brought by a hydraulic gradient (ΔP), a difference of electric potential E, called streaming potential, would result between any two points in the direction of motion. The following relation can be observed.

$$E = C \times \Delta P$$

where C, the streaming potential coefficient is dependent on a number of parametres like resistivity, dielectric constant and viscosity of fluid in the rock, the zeta potential, the grain size, the water path and others (Ahmed, 1964; Parkhomenko, 1971; Bogoslovsky and Ogilvy, 1973). The presence of a pressure gradient in the sub-surface, however, is not a sufficient condition to ensure the existence of an electric potential on the surface. As defined by Fitterman (1979), it is necessary to have a pressure gradient parallel to a boundary that separates regions of different streaming potential coefficients. An electric field equivalent to that by a surface distribution of current dipoles along the boundary is developed. The equipment required is extremely simple, consisting merely of a pair of non-polarisable electrodes (to eliminate electrode polarization effect) connected by a wire to a millivoltmeter of high impedance (greater than 108 ohms, so that negligible current will be drawn from the ground during the measurement). The procedure for carrying out the field studies is described by Krishnamurthy et al. (2001).

MISE-À-LA-MASSE METHOD

Schlumberger first attempted the mise-à-la-masse method in 1920. Only very limited case histories are available for this method (Parasnis, 1967, 1979; Ketola, 1972). The idea is to use a subsurface conductive mass (in this case water bearing fracture) as energisation point. The conductor is energized by a point source by lowering one current electrode in borehole below the water table. The other current electrode is kept on the surface at far off place (infinity). Potential on the surface is mapped in a grid pattern by keeping one electrode fixed as the reference electrode on the surface and moving the other potential electrode along the various profiles. The mise-à-la-masse equipotential maps are prepared by normalizing the potential values for 1A current (i.e, units are volts/amp).

Figure 11 shows Mise-à-la-masse and SP equipotential map near borehole no. 265. This bore-well drilled up to 42 m struck water at a depth of 23 m in pink granite and has static water level at 21.18 m. The drill log of existing bore-well indicates minor fractures between 15.84 and 32.90 m and fractured pink granite from 32.90 to 37.50 m. Well developed fractures with high density from 32.90 to 37.50 m substantially increased the yield of the well to 100 lpm. The current electrode in the bore-well was lowered down to depth of 37 m. Mise-à-la-masse map shows a well-developed trend of high equipotential zone in N-S direction along the central profile across the borehole. This indicates the extension of the fractures in N-S direction. SP map also shows similar trend in N-S direction. Two bore-wells (BW-1 and BW-2), one each on southern and northern side of the existing bore-well recommended on the basis of the Mise-à-la-masse measurements intercepted fractures at nearly the same depth as in borehole no. 265. A bore-well (BW-3) recommended on hydrogeological consideration in NW of existing bore-well did not intercept any fracture. This confirms the extension of fracture in N-S direction only.

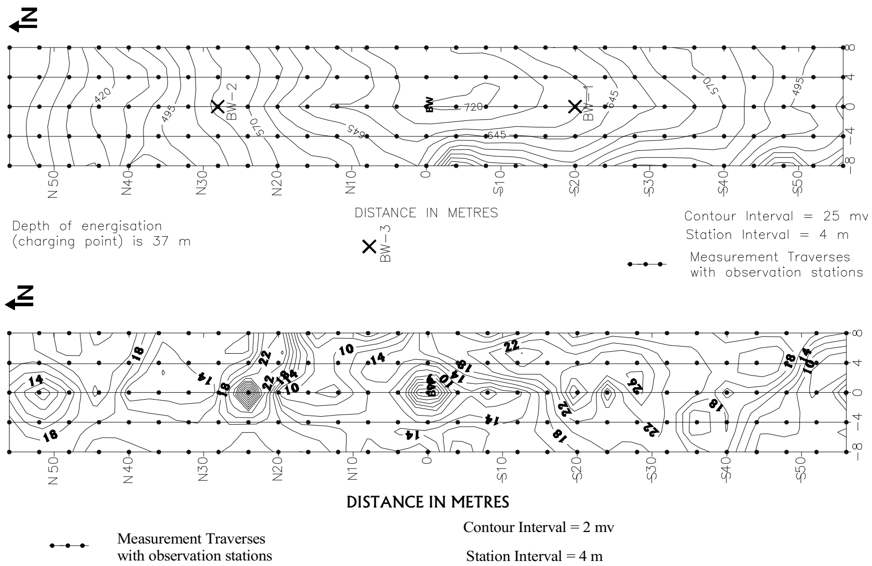


Figure 11. Mise-à-la-masse (above) and SP equipotential map (below) at IFP-11.

CONCLUSION

Many geophysical techniques have been applied to groundwater investigations with some giving more success than others. For resource mapping, it is not the groundwater itself that is the target of the geophysics rather it is the geological situation in which the water exists. Potential field methods, gravity and magnetics, have been used to map regional aquifers and large-scale basin features. Seismic methods have been used to delineate bedrock aquifers and fractured rock systems. Electrical and electromagnetic methods have proved particularly applicable to groundwater studies as many of the geological formation properties that are critical to hydrogeology such as the porosity and permeability of rocks can be correlated with electrical conductivity signatures. Most geophysical techniques have been used for groundwater characterization but once again it is with the electrical and electromagnetic methods that the greatest success has been shown in directly mapping and monitoring contaminated and clean groundwater. The use of geophysics for groundwater studies has been stimulated in part by a desire to reduce the risk of drilling dry holes and also a desire to offset the costs associated with poor groundwater production.

REFERENCES

Acworth, R.I., 1987. The Development of Crystalline Basement Aquifers in a Tropical Environment. *Quarterly Journal of Engineering Geology*, **20:** 265-272.

Ahmed, M.V., 1964. A Laboratory Study of Streaming Potentials: *Geophysical Prospecting*; **12(1):** 49-64.

Barker, R.D., 1992. The Offset System of Resistivity Sounding and its use with a Multicore Cable. *Geophysical Prospecting*, **29:** 128-143.

Bogoslorsky, V.A. and Ogilvy, A.A., 1973. Deformations of Natural Electric Fields Near Drainage Structures: *Geophysical Prospecting*; **21(4):** 716-723.

Compagne Generale De Geophysique, 1963. Mater Curves for Electrical Sounding, 2nd Revised Edition, Eaeg, The Hague, The Netherlands.

Dobrin, M.B. 1976. Introduction to Geophysical Prospecting. New York, Mcgraw-Hill, pp. 630.

Eddy-Dilek, C.A., Hoekstra, P., Harthill, N., Blohm, M., and Phillips, D.R., 1996. Definition of a Critical Confining Zone Using Surface Geophysical Methods. SAGEEP, pp. 387.

Fitterman, D.V., 1979. Calculation of Self-Potential Anomalies Near Vertical Contacts: *Geophysics*; **44(2):** 195-205.

Flathe, H., 1963. Five Layer Master Curves for the Hydrogeological Interpretation of Geoelectrica Resistivity Measurements above a Two Storey Aquifer, *Geophysical Prospecting*, **11:** 471-508.

Ghosh, D.P., 1971a. The Application of Linear Filter Theory to the Direct Interpretation of Geoelectrical Resistivity Sounding Measurements, *Geophysical Prospecting*, **19:** 192-217.

Ghosh, D.P., 1971b. Inverse Filter Coefficients for the Computation of Apparent Resistivity Standard Curves for a Horizontally Stratified Earth, *Geophysical Prospecting*, **19:** 769-775.

Goldman, M., Rabinovich, B., Rabinovich, M., Gilad, D., Gev, I. and Schirov, M., 1994. Application of Integrated Nmr-Tdem Method in Ground Water Exploration in Israel. *Jour. Appl. Geophys*, **31:** 27-52.

Grant, F.S. and West, G.F., 1965. Interpretation Theory in Applied Geophysics. Mcgraw-Hill, New York.

Griffiths, D.H., Turnbull J. and Olayinka, A.I., 1990. Two Dimensional Resistivity Mapping with a Computer Controlled Array. *First Break*, **8:** 121-129.

Griffiths, D.H. and Turnbull, J., 1985. A Multi Electrode Array for Resistivity Surveying. *First Break* **3:** 16-20.

Griffiths, D.H. and Barker, R.D., 1993. Two-Dimensional Resistivity Imaging and Modeling in Areas of Complex Geology. *Journal of Applied Geophysics,* **29:** 211-226.

Jupp, D.L.B. and Vozoff, K., 1975. Stable Iterative Methods for the Inversion of Geophysical Data. *Geophysical Journal of The Royal Astronomical Society*, 957-976.

Kearey & Brookes, 1991. An Introduction to Geophysical Exploration.

Ketola-Matti, 1972. Some Points of View Concerning Mise-À-La-Masse Measurements. *Geoexploration*, **10(1):** 1-21.

Krishnamurthy, N.S., Ananda Rao., V., Negi, B.C., Kumar, D., Jain, S.C., Ahemed, S. and Dhar, R.L., 2001. Electrical Self Potential and Mise-À-La-Masse Investigation in Maheshwaram Watershed, Andhra Pradesh, India. NGRI Technical Report No. NGRI-2001-GW-314.

Lieblich, D.A., Legchenko, A., Haeni, F.P. and Portselan, A., 1994. Surface Nuclear Magnetic Resonance Experiments to Detect Subsurface Water at Haddam Meadows, Connecticut. Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, March 27-31, 1994, Boston, Massachusetts, 2, pp. 717-736.

Loke, M.H. and Barker, R.D., 1996. Rapid Least-Squares Inversion of Apparent Resistivity Pseudosections by a Quasi-Newton Method. *Geophysical Prospectings* **44:** 499-524.

Miller, P.T., Mcgeary, S. and Madsen, J.A., 1996. High-Resolution Seismic Reflection Images of New Jersey Coastal Aquifers. Sageep, pp. 55.

Murali, S., Patangay, N.S., 1998. Principles and Applications of Groundwater Geophysics, AEG, Hyderabad, India.

Orellana, E. and Mooney, H.M., 1966. Master Tables and Curves for Vertical Electrical Sounding over Layered Structures. Interciencia, Madrid, Spain.

Parasnis, D.S., 1979. Principles of Applied Geophysics. Chapman and Hall. pp. 275.

Parasnis, D.S., 1967. Three-Dimensional Electric Mise-À-La-Masse Survey of an Irregular Lead-Zinc-Copper Deposit in Central Sweden. *Geophysical Prospecting*, **15:** pp. 407-437.

Parkhomenko, E.I., 1971. Electrification Phenomena in Rocks. Plenum Press; New York; 285.

Rangarajan, R. and Prasada Rao, N.T.V., 2001. Technical Report No. NGRI-2001-GW-298

Reynolds, 1997. An Introduction to Applied and Environmental Geophysics, 1st Ed. Wiley.

Rijkswaterstaat, The Netherlands, 1969. Standard Graphs for Resistivity Prospecting. European Association of Exploration Geophysicists, The Hague.

Schirov, M., Legchenko, A. and Creer, G., 1991 New Direct Non-Invasive Ground Water Detection Technology for Australia. *Expl. Geophys.*, **22:** 333-338.

Stefanesco, S.S. et al., 1930. Sur La Distribution Electrique Potentielle Author D'une Prise Ae Rerre Ponetuelle Dans Unterrain A Couches Horzontales Homogens Et Isotropes. *Journal Physique Et Radium Sieres*, **7:** 132-141.

Telford, W.M., Geldart, L.P., Sheriff, R.E. and Keys, D.A., 1976. Applied Geophysics. Cambridge University Press.

Trushkin D.V., Shushakov, O.A. and Legchenko, A.V., 1995. Surface NMR applied to an electroconductive medium. *Geophys.Prosp.*, **43:** 623-633.

Varian, R.H., 1962. Ground Liquid Prospecting Method and Apparatus. US Patent 3019383.