# Contribution of Geophysical Methods in Exploration and Assessment of Groundwater in Hard Rock Aquifers

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Abstract

Geophysical studies carried out in granitic hard rock terrain of semi-arid regions in India have resulted in developing various relationships between geophysical properties and hydrogeological parameters. A new approach has been developed to refine and improve the VES (Vertical Electrical Sounding) interpretation with quantitative information from geology using borewells data and geostatistics. This provides a guideline with quantitative information for further improvement of the VES reinterpretation, which helps in sorting the results in various categories of varying reliability. This methodology has important applications in groundwater development and management programs (e.g., implementation of future drilling).

A combined Axial Pole-dipole and Schlumberger (CAPS) configuration method of VES has been introduced to identify the lateral near surface inhomogeneities (NSI), which normally occur in the hard rock and misleads the VES interpretations. Mathematical calculation has yielded the same depth of investigation for axial pole-dipole and Schlumberger configurations for CAPS arrangement that has been confirmed by physical resistivity modeling carried out in a tank filled with water as well as in the field. This approach is comparatively faster and simple to carry out than the other existing methodologies for identification of NSI effects.

Contribution of geophysical methods has been studied for estimating and assessing the various hydrogeological parameters such as natural recharge, hydraulic conductivity and transmissivity in hard rock terrain. Natural groundwater recharge is estimated using the injected tracer technique in the Bairasagara watershed of Kolar district, Karnataka (India) comprising of medium grained granite and granitic gneiss with weathering/fracturing up to 46 m depth. On a macroscopic scale, it is estimated that the weathered granites act as a uniform body having a recharge capacity of about 6 mm to 200 mm per annum for an average value of rainfall of 968 mm. Marked differences of infiltration rates (nil to 130 cm/year) were observed under cultivated and dry areas. Qualitative correlation studies of estimated natural groundwater recharge have been carried out with depth to soil resistivity and depth to basement. Natural recharge has shown its dependency on rainfall, soil characteristics and depth top basement. Empirical relationship has been established between recharge and depth to basement.

A methodology has been developed to estimate the hydraulic parameters of granitic hard rock aquifer from geoelectrical parameters. Positive correlations between hydraulic conductivity (K) and electrical conductivity ($\sigma$), and also between transmissivity (T) and longitudinal conductance (C) have been established. The methodology has been calibrated and validated in granitic hard rock aquifers in India. The good agreement between K and T obtained from the resistivity sounding parameters and those obtained from pumping test analysis proves the potentiality of the methodology. It has been applied to estimate the K and T from the surface electrical resistivity parameters and the results were utilized to prepare the K and T maps of a demonstrative study area (Maheshwaram watershed, southern India).

Lineaments like quartz reef, a common feature in hard-rock context, have been investigated in order to explore the aquifer potential. Synthetic simulation using electrical resistivity tomography (ERT) of quartz reef intrusive body embedded in granite has been carried out for different physical conditions ERT profiles running across and along the quartz reef has been carried out near Hyderabad (southern India). Based on the ERT images, drilling of the bore wells were performed, followed by electrical resistivity logging and yield measurements. Geomorphology, ERT images, lithologs, resistivity logs and yield of the wells are found corroborating with each other. Deepening of the weathering fronts are confirmed along the contacts of the intrusive body and host medium. This has been confirmed from the pumping results, where high yielding (18 m3/h) bore wells were observed at low resistivity zones within the thick quartz reef. The study has revealed that the quartz reefs may provide groundwater high-potential zone.

Keywords: Geophysical methods, groundwater exploration, groundwater assessment, hard rock, VES, ERT

## Introduction

Groundwater is the major source of water supply needed for industrial, agricultural and domestic purposes in many semi-arid regions. In some cases, over-exploitation has resulted in declining groundwater levels and has consequently confined groundwater flow to deeper weathered/fractured zones. Thus the thickness of the vadose zone is increasing continuously. The groundwater is replenished with the surface water coming from the rain or some other sources.

The vadose zone lying just over the aquifer has direct bearing on the moisture flux movement or recharge to the aquifer. Normally it is assumed that the path of infiltration and percolation is vertical in the vadose zone and become horizontal while reaching to the zone of saturation. The vadose zones is consists of various heterogeneities due to presence of lineaments, intrusive, differential weathering and fracturing the rock, changes in mineralogical composition rock, etc. Thus a reliably study of vadose zone will help will help greatly to model the hydrogeological properties of the vadose zone. The reliable understanding of the weathered, fracture and basement mapping will result to better modeling the hydraulic parameters the aquifer. Geophysics can play a major role in characterizing these zones.

The traditional groundwater exploration in India, has been based on a single geophysical technique, where boreholes are sited on anomalies identified by electrical resistivity methods, often with little understanding of the geological structure of the target area. In many areas of complex hydrogeology, these techniques often fail for a variety of reasons, eg. ambiguities in identifying the geophysical anomalies, lack of adequate understanding of the occurrence of groundwater and other factors affecting permeability in these terrains (Chandra et al., 2006).

Vertical electrical sounding (VES) is mostly used for locating suitable site for groundwater exploitation. 1-D resistivity sounding has the greatest limitation that it does not take the lateral changes into account while interpretation. Near surface inhomogeneities (NSI) can lead a severe problem in the interpretation of apparent resistivity. The sheet rocks, dykes, buried boulders, buried channel etc. occurring close to the surface are the main source of NSI effect, which distort the current flow pattern in their surrounding and consequently there is distortion in the resistivity curve. There are several work in order to identify the NSI effects in apparent resistivity curves such as Van Nostrand and Cook, 1960; Rakesh Kumar and Chowdary, 1977; Zohdy et al., 1974; Ballukaraya, et al., 1988; Frohlich, 1968; Ermokhin et al. 1998. The methods of identification of lateral inhomogeneity are either more time consuming as it needs two or more than two number of soundings or not convenient. A combined axial pole-dipole and Schlumberger (CAPS) configuration methods has been initiated, which will help in locating the successful sites for drilling of wells in hard rock areas (Chandra et al., 2004; Chandra, 2006).

In addition to this there is need to manage the groundwater resources reliable in order to stop further over-exploitation. Management of groundwater resources require huge amount of hydrogeological parameters to model the aquifer system. Hydrogeological parameters such as recharge (NR), Hydraulic conductivity (K) and transmissivity (T) are the essential parameters to be estimated reliably for proper management of groundwater resources.

The conventional methods of recharge estimate such as tracer studies, water balance, lysimeter, nuclear technique, etc. (Zimmerman et al., 1967; Munich et al., 1967; Munich, 1968; Sukhija and Rama 1973; Dincer et al., 1974 ; Athavale et al., 1980; Athavale et al., 1992, 1998; Rangarajan et al., 2000) are either costly or time consuming or require analysis of large volume of hydrological data (precipitation, surface runoff, evapotranspiration, change in groundwater storage etc.) accumulated over a considerable time span, which is generally inadequate or lacking or unreliable in many areas (Chand et al., 2004; Chandra, 2006). There have been studies (Chaturvedi 1973; Kumar and

Sathapathi 2002) on recharge estimation from rainfall in alluvium, but lithological control on recharge has been ignored. Lithology will have more dominant role particularly in hard rock terrain, where it is highly variable. Hence there is a need to develop a cost effective and reliable methodology for recharge estimation including the influence of lithological control. Geophysics plays a major role in defining the subsurface lithology and hence it can be utilized to bring the influence of the lithological characteristics while formulating the methodology.

Several researchers worked on various aspects of correlation between hydraulic parameters from geophysical investigation (Jones and Buford, 1951; Pfannkuch, 1969; Kelly, 1977; Sri Niwas, and Singhal 198; Mazac et al., 1985; Huntley, 1986; Mbonu et al., 1991; Frohlich et al., 1996; Singhal et al. 1998; Sri Niwas and Lima, 2003; Singh, 2005, Chandra, 2006; Chandra et al., 2008; etc.). A positive correlation was demonstrated between aquifer resistivity and hydraulic conductivity. Similar correlation was shown between formation factor and the hydraulic conductivity. However, a negative correlation was demonstrated between these properties by Heigold et al., (1979). Hydraulic conductivity (K) was estimated from aquifer resistivity ($\rho$) by using the equation: $K=386.4\ \rho$-0.93283. Mazac and Landa (1979) have also reported similar inverse relationship at the axis of glacial outwash aquifer. However, Kelley and Frohlich (1985) rejected the negative relationship established by Heigold et. al. (1979), with the reason that for correlation, only three data points were used, which are not sufficient to generalize any relationship and shown again a positive correlation between them.

Lineaments are another geological features, which has bearing on the groundwater dynamics. In general, hard rocks are traversed by several geological lineaments, but whether, these lineaments are potential for groundwater occurrence or not need to be studied (Chandra, 2006). Geophysical characterization has been carried out here to understand the groundwater dynamics in granitic hard rock terrain.

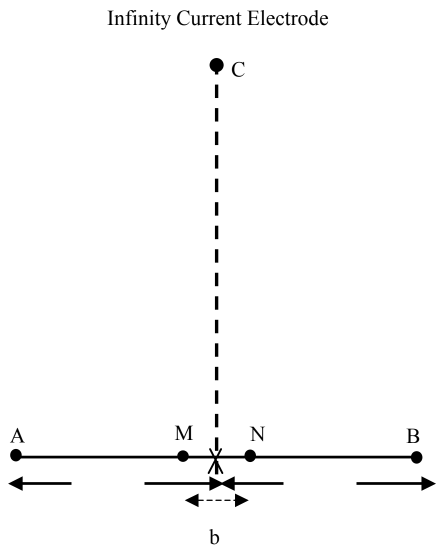
The paper deals with the development of new methodologies in four parts i.e. A, B, C, D and E. These methodologies have been especially for hard rock terrain and have been applied in granitic terrain Dharwar super group of Archean age.

## Developed Methodology And Its Application

The contribution of geophysical methods in estimating various hydrogeological parameters such as electrical resistivity methods in exploring unambiguous hard rock aquifer geometry in laterally inhomogeneous medium, natural recharge, and aquifer parameters estimation worked out here are described systematically under section A, B, C, D and E.

### A. Identification of near surface inhomogeneties in apparent resistivity curve f VES

To identify near surface inhomogeniety effect in apparent resistivity curve of vertical electrical sounding (VES) a Combined Axial Pole-dipole and Schlumberger (CAPS) configuration set up has been established (Fig. 1). The CAPS configuration set up is similar to the Schlumberger array with an additional electrode at infinity. The axial pole-dipole (MNB) array is the mirror image of AMN array. The current flow pattern and equipotent lines will be disturbed over the surface having lateral inhomogeneities. The apparent resistivity ($\rho_a$) can be calculated for Schlumberger and axial pole-dipole configurations as:




$$\rho_a = \pi \frac{(a/2)^2 - (b/2)^2}{b} \frac{\Delta v}{I} \quad (1)$$

$$\rho_a = 2\pi \frac{(a/2)^2 - (b/2)^2}{b} \frac{\Delta v}{I} \quad (2)$$

Fig. 1. CAPS configuration

where, a/2, b/2, I and $\Delta v$ are respectively distance between center of the configuration and outer most active current electrode, half of potential electrode separation, indicate injected current (in mA) into the ground and denotes voltage difference between potential electrodes. Although there are five electrodes in CAPS arrays, but the measurement is done by using only four electrode at a time i.e. two current electrodes and two potential electrodes switching one pair current electrode to other. When additional current electrode C is deactivated the active electrode arrangement (AMNB) is Schlumberger array. When the additional current electrode C becomes active keeping one of the current electrode either A or B inactive, the arrangement is called axial pole dipole (AMN when B deactivated and MNB when A deactivated). The measurements for these three arrays are taken at each a/2 successively. The apparent resistivity values obtained from Schlumberger i.e. AMNB and axial pole-dipoles i.e. AMN & MNB are plotted on log-log sheet and then compared with each other. If all curves are similar, the anomaly refers the effect of subsurface strata. In case these are dissimilar or showing anomaly at different a/2, the curve indicates the effect of NSI.

Geoelectrical soundings have been carried out in the granitic hard rock terrain of Bairasagara watershed district, Karnataka using CAPS configuration at each location to detect the anomaly by comparing the apparent resistivity curves for AMNB, AMN and MNB configurations. All the sounding data have been interpreted by conventional curve matching technique (Koefoed, 1979) and by using "1X1D" software. The typical field examples CAPS configuration is shown in figure 2 a&b. The sites were chosen so that the subsurface should not suffer any lateral NSI. Hence the above exercise confirms that results obtained from axial pole-dipole configuration and Schlumberger over same ground is same. However, in presence of NSI body the Schlumberger and Pole-Dipole curves show a little difference in their nature. In the case of Schlumberger array, the effect of lateral NSI below the entire spread is averaged out, whereas in case of axial pole-dipole array the actual NSI present below the moving current electrode path is reflected very well (Yadav, 1988). Thus the axial pole-dipole curve is more sensitive to the NSI in case the anomalous body present to the side of moving current electrode. This effect can be clearly seen in the figure 2d (CAPS 1), which have been done over granitic terrain traversed by dolerite dykes trending E-W direction.

In sounding no. CAPS 1, a dyke is towards active electrode ‘A‘ (Fig. 2b). The apparent resistivity curves of Schlumberger (i.e. AMNB) and axial pole-dipole (AMN) starts rising from beginning point (i.e. half current electrode separation a/2=1.5 m) up to a/2=4 m and then further these starts lowering (AMN curve up to 12 m and Schlumberger curve up to a/2=8 m) and for further a/2 these values kept on increasing, whereas the apparent resistivity values for axial pole dipole (MNB) is continuously increasing from 51.7 Ωm to 1519.8 Ωm. Thus the resistivity low obtained by axial pole-dipole (AMN) and Schlumberger curves but no deviation in axial pole-dipole (MNB) curve can be attributed due to lateral NSI (i.e. dyke).

In other words, the distortions in the resistivity curve depend upon the position and size of the anomalous body with respect to the moving current electrode. These types of curves mislead in recommendation of a site for drilling. In case, all three curves exhibit low resistivity at same a/2, then anomaly may be attributed to sub-surface strata. If the aquifer resistivity and its thickness are suitable for that particular environment, the location can be recommended for drilling. Thus it can be understood that the combined axial pole-dipole and Schlumberger (CAPS) configurations method will help in locating the successful sites for drilling in hard rock areas. The axial pole-dipole array can be used as substitute for Schlumberger configuration, which yields the same result. The Vertical electrical sounding by axial pole-dipole array has an advantage of carrying out even at places where Schlumberger spread could not be laid due to lack of space on any one side of the sounding point

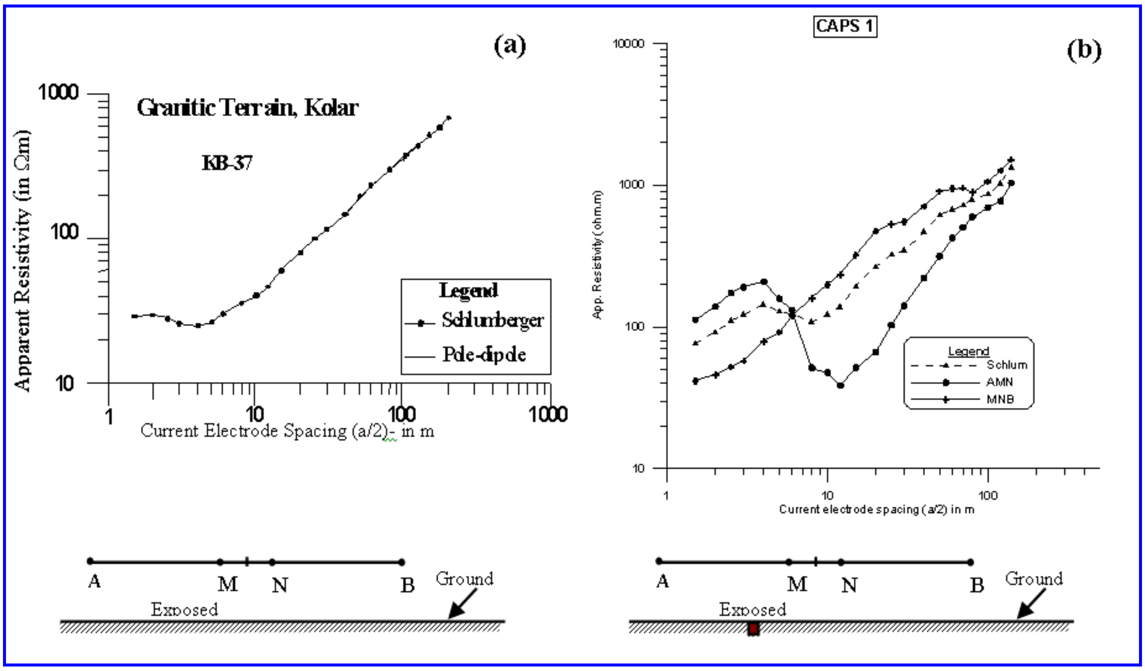



Fig. 2. CAPS resistivity curves for (a) tank water and (b) tank water with vertical wooden sheet , (c) field resistivity curve in granite rock and (d) field resistivity curve

B. Reducing Ambiguity in VES Interpretation: a geostatistical application

In Vertical Electrical Sounding (VES) electrical resistivity method due to large variation in resistivity of the geological formations, as well as inherent nonuniqueness in the resistivity data interpretation techniques, it happens sometimes the obtained results leads to misinterpretation of the layer's parameters. This ambiguous interpretation for VES data thus often makes the results unreliable for taking a crucial decision for any groundwater exploration.

In the present study, a methodology was developed using combined the geostatistical-geophysical approach to reduce such ambiguities to the maximum extent. Using the available lithologs from 39 wells, thicknesses of various layers and bedrock depths were determined. This set of data from the lithologs were analyzed geostatistically and an estimation of these parameters (i.e., weathered, fractured and depth to bedrock) was made at all the 86 VES locations using a final variogram obtained from the variographic analysis. This has provided a range for the estimated values of the above three parameters using the standard deviation of the estimation error. The interpreted parameters from VES were compared with the range thus obtained in above procedure. The interpreted VES results that could not be found within the stipulated range provided by the geostatistical estimation, were categorized separately and a suitable reinterpretation was made for them by fitting realistic parameters obtained from the nearby well data. After a few iterations, a large number of VES results were found falling in the estimated range and thus reduced the ambiguities in the VES results (Fig.3). The study has provided a new and additional method of reducing the ambiguities in VES interpretation as well as providing a quality indicator to each interpretation (Kumar et al., 2007).

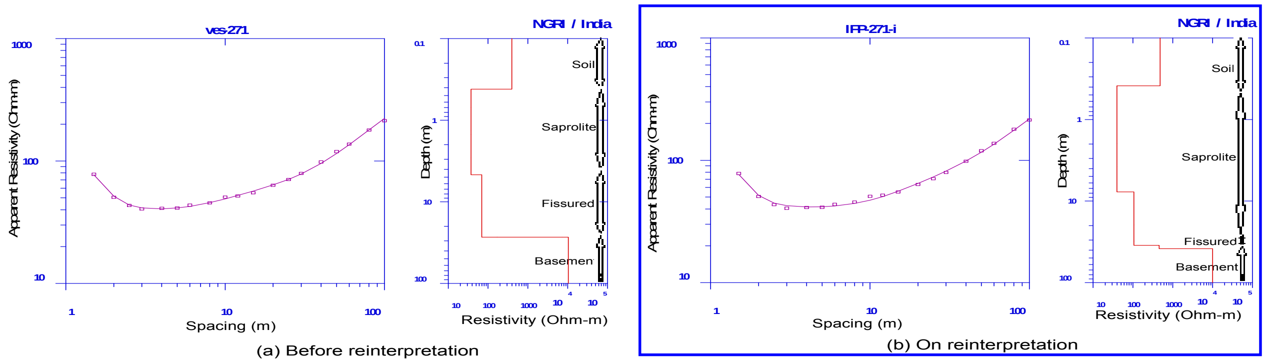



Fig. 3. Resistivity Sounding Curve – VES-271, Observed data, fitted curve and model before reinterpretation (b) Observed data, fitted curve and model after reinterpretation

C. Natural recharge estimation

A relationship has been observed between geoelectrical properties and natural recharge in granitic hard rock terrain.. Earlier empirical relations developed were mostly based on the rainfall, whereas the lithological constraints were not considered. Heterogeneity due to differential, lineaments, sheet rocks etc., is very common and hence it affects recharge processes.

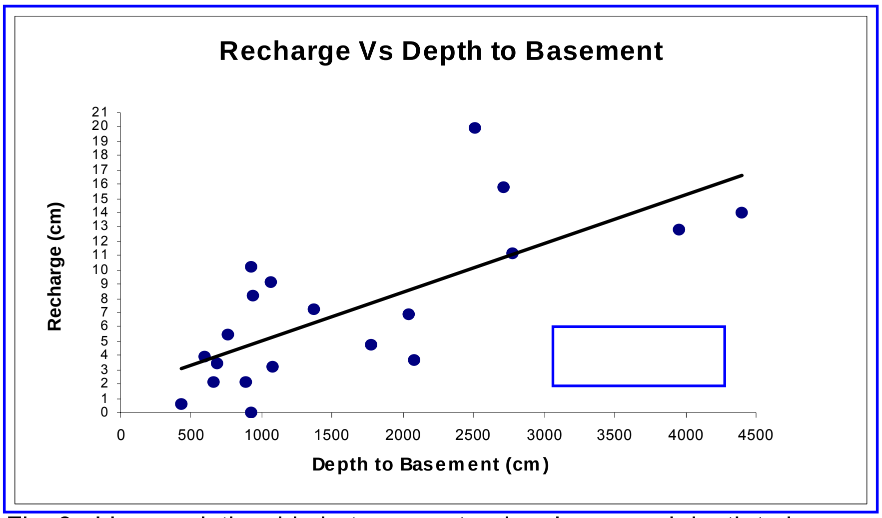



Fig. 3. Linear relationship between natural recharge and depth to basement

Soil texture plays a very important role in infiltration of the surface water (i.e. rain water) to the aquifer, or in other word, recharge is controlled by soil texture up to a great extent. The second factor affecting the recharge is space available bellow the soil zone. The space can be obtained by knowing the depth to basement. These properties can be characterized by the help of geophysics. As depth to basement increases, the thickness of the weathered zone and the soil column above the weathered zone also increases, which can cause more recharge. The opposite is true for the shallow zone. A linear relationship of recharge with depth to basement was found as shown in fig. 3. An attempt has been made to obtain an empirical relation using least square fitting and arrived at the following relation:

$$Re = 0.0034 * D + 1.9 \qquad (3)$$

where D is depth to basement (cm) and Re is recharge (cm). The correlation coefficient is found to be 0.72. This relation is checked for certain values of depth to basement in this watershed and found to be satisfactory.

Thus, basically there are three major parameters affecting the recharge process i.e. soil texture, depth to basement and rainfall. These combined together can decide the natural recharge. Geoelectrical method has been applied on 47 VES results to estimate the NR in the entire Bairasagara watershed. Natural recharge has also been estimated by tritium injection technique at 36 points spread all over the Bairasagara watershed. Recharge map has been prepared based on the recharge values obtained from tritium injection technique. The combined map of natural recharge and basement found very well corroborating with each other. From the correlation coefficient and the recharge map, it is quite clear that the depth to basement plays major role than the soil resistivity in deciding the NR in hard rock region. Although top soil Resistivity in the south-east of the watershed is quite high, but recharge estimated as well as calculated is found low, because of shallow depth to basement. Whereas recharge was found high in the central region of the watershed and is corroborating with the soil resistivity as well as depth to basement.

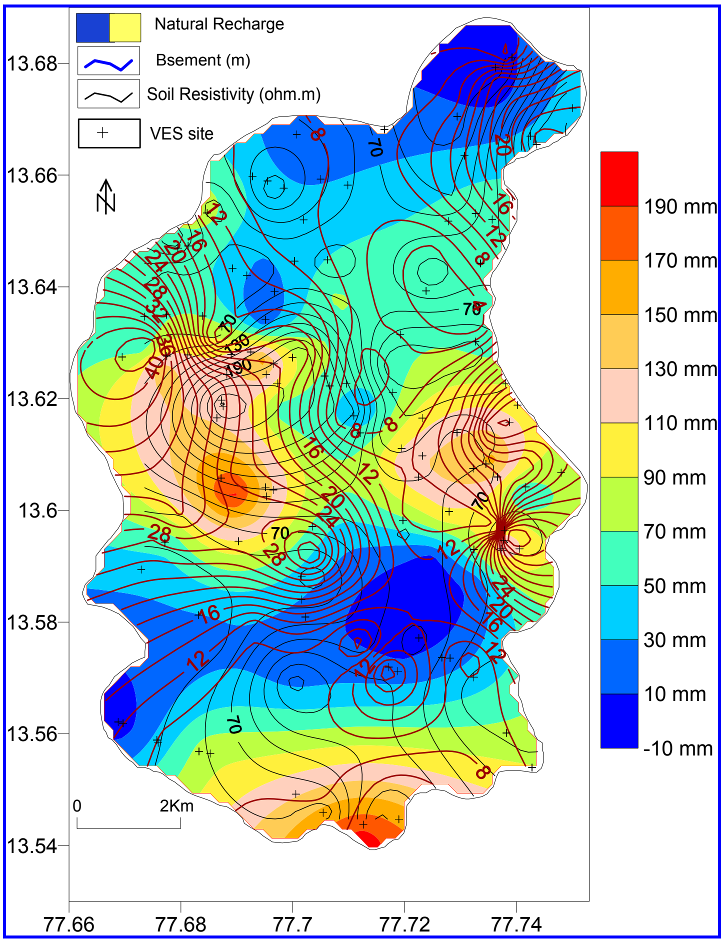


Fig. 4. Combined map of natural recharge, soil resistivity and depth to basement

D. Aquifer Parameter Estimation

There is close analogy between the groundwater flow and electric current flow in the aquifer. Fluid (i.e. subsurface water) and electric currents flow from higher potential to lower potential site and their flow rates depend upon the potential gradient. The flow rate of groundwater depends on the hydraulic conductivity/permeability (K) of the formation, whereas an electric current depends on the electrical conductivity ($\sigma$) of the formation. Since, ions flow through some of the same paths as water, the electrical conductivity and hydraulic conductivity of aquifer are expected to be affected by similar variables. Electronic conduction in the granite is insignificant due to its mineralogical composition and hence water available in the secondary porosity is the main factor controlling the electrolytic conduction. Thus in either the cases, whether Darcy's law of groundwater flow or Ohm's law of current flow, act on a common factor i.e. water. Therefore, groundwater flow and current flow also can be considered inter-related with each other. Since, the rate of water flow and electric currents are inter-related the permeability and electrical conductivity do have inter-relationship. Conceptually electrical resistivity methods deals with the conservation of charge i.e. Ohm's law likewise hydrodynamics deals with the conservation of mass i.e. Darcy's law. A clear analogy in both the mechanism exists.

Based on the analogy between Darcy's law of groundwater flow and ohm's law of current flow, a relationship has been established:

$$K = a\sigma \quad \text{or} \quad K = a\frac{1}{\rho} \qquad (4)$$

The above relation indicates that the permeability (K) is inversely proportional to the aquifer resistivity ($\rho$). The relation looks to be logical because of the fact that low resistive formation is an indication of highly weathered-fractured water saturated material. In such conditions the permeability of the material is expected to be high. This relation may not be true in the clayey formation, which is highly porous but less permeable. Eq. (4) can be transformed by multiplying a factor 't' (i.e. aquifer thickness) on both sides as given below

$$Kt = a\frac{t}{\rho} \quad \text{or} \quad T = aC \qquad (5)$$

where T and C are transmissivity ($m^2$/d) and longitudinal conductance (mho) of the formation.

The above theory has been attempted to examine with the field data collected from granitic hard rock terrain from Hyderabad and its surroundings regions. Normalized longitudinal conductance and transverse resistance have been examined with the subsurface electrical parameters. Normalized aquifer resistivity and hydraulic conductivity of the corresponding location have been correlated (Fig. 5a). The correlation coefficient ($R^2$) obtained between these two parameters is 0.85. Normalized longitudinal conductance and transmissivity have been correlated on the same 11 points at Maheshwaram watershed (Fig. 5b). The correlation coefficient obtained between these two parameters is 0.68.

Thus the correlation studies on the field data have proved the above discussed theory of correlation between hydraulic parameters and geophysical properties in hard rock terrain. Now, the equations (4 & 5) can hereafter be applied for estimation of hydraulic parameters i.e. permeability and transmissivity from geophysical parameter like aquifer resistivity and longitudinal conductance.

The first test was performed on data obtained from granitic hard rock terrain of Maheshwaram watershed in India. The K from the surface resistivity has been calculated using the above relation (eq. 4), where, average value of constant 'A' is taken as 2.176E-03, derived from the known values. The permeability '$K_r$' estimated from the surface resistivity was compared with the permeability '$K_p$' estimated from the pumping tests (Fig. 5c). A good correlation ($R^2$=0.85) was achieved. The transmissivity estimated by the pumping test ($T_p$) and the transmissivity estimated from the longitudinal conductance ($T_r$) (Fig. 5d) have shown excellent correlation ($R^2$ = 0.68).

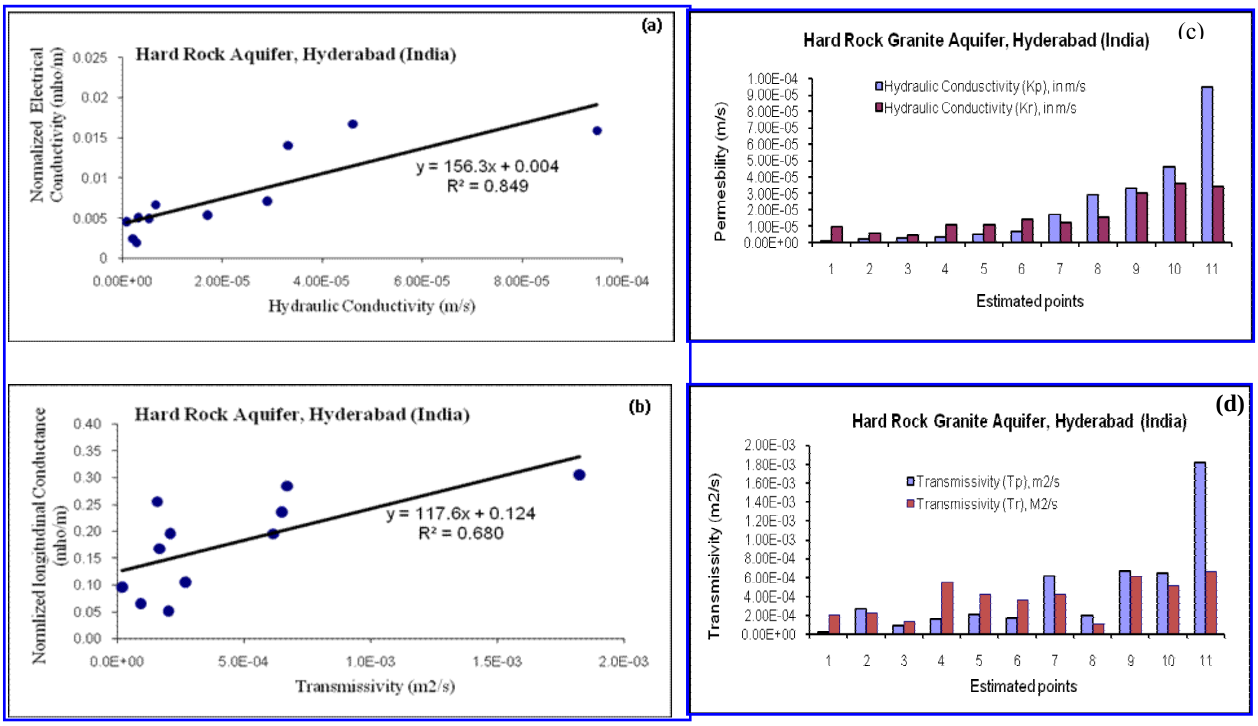



Figure 5. Relationship of (a) normalized aquifer conductivity with permeability, and (b) normalized longitudinal conductance with transmissivity; Comparative plots for (c) hydraulic conductivities ($K_p$ & $K_r$), and (d) transmissivities $T_p$ and $T_r$ at Maheshwram watershed, A.P., India

Hence from the above analysis, it is clear that there is a strong relationship between geoelectrical properties hydraulic parameters of hard rock aquifer. The aquifer resistivity obtained from the surface resistivity methods can be used to estimate the permeability of the aquifer. In hard rocks, this relation holds valid for weathered and weathered-fractured aquifer. With the consequence of the over-exploitation, now fractured aquifer system has also been given importance, but the behaviour of the groundwater dynamics is quite difficult to understand. Therefore, no attempt has been made for fractured aquifer system.

E. Groundwater potentiality of Quartz Reef Lineament

The lineament like quartz reef, a common geological feature occurring as an intrusive body, has been investigated geophysically in order to explore the potential aquifer for sustenance of mankind. Synthetic simulation using electrical resistivity tomography (ERT) of quartz reef intrusive body embedded in granite host rock has been carried out for different physical conditions such as (1) fresh intrusive body with no alteration at contacts, (2) fresh intrusive body with weathered-fissured contacts, and (3) also fissured intrusive body with weathered-fissured contacts. ERT profiles running across and along the quartz reef has been carried out at Kothur village, Hyderabad (India).

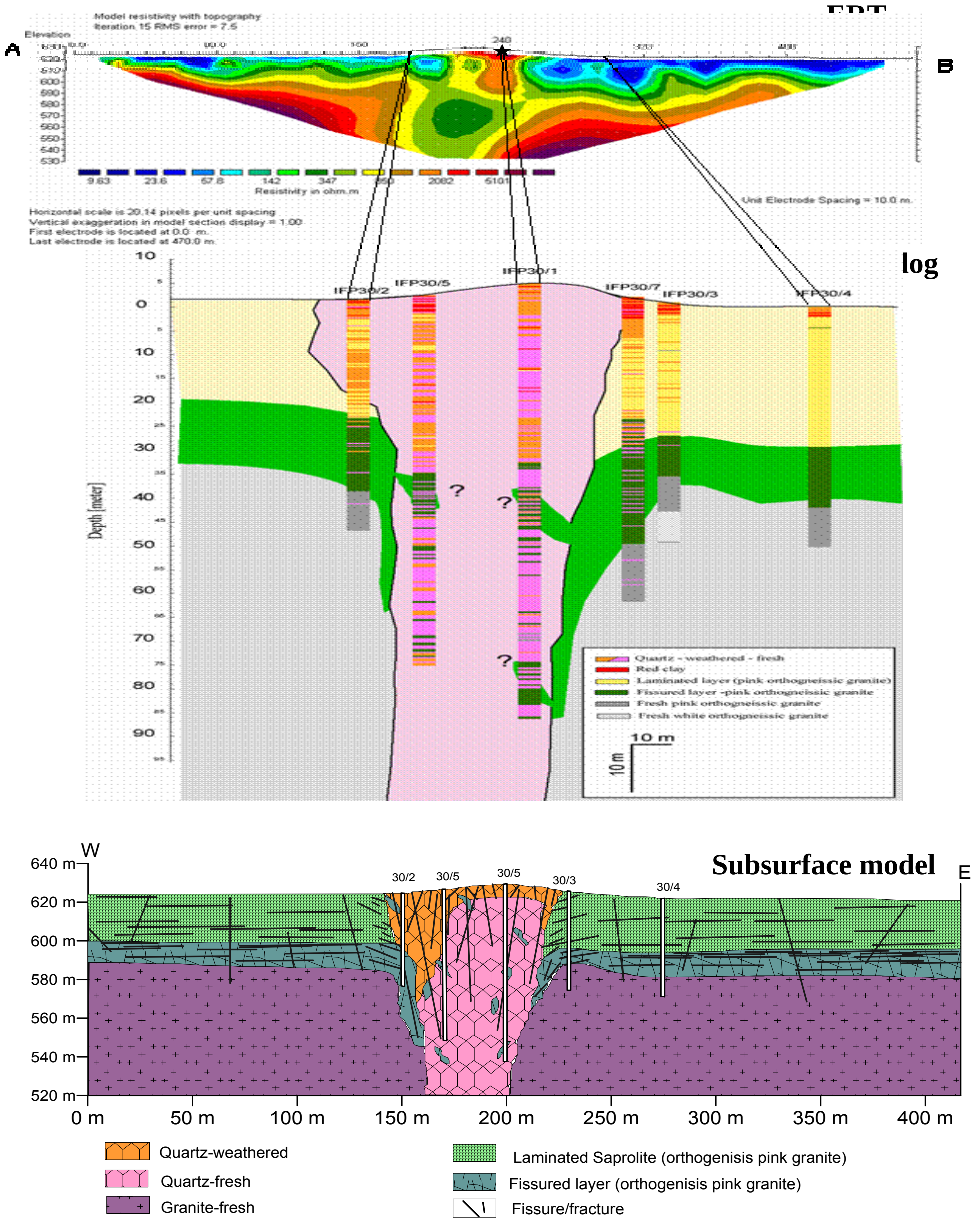



Fig. 6. Field ERT image running across the quartz reef, lithologs and subsurface vertical cross section at Kuthur, Hyderabad

Based on the ERT images a number of bore wells has been drilled followed by yield measurement, litholog collection, and electrical resistivity logging. Geomorphology, ERT images, lithologs, resistivity logs and yield of the wells are found corroborating with each other. Deepening of the weathering fronts are confirmed along the contacts of the intrusive body and host medium, which may qualify for suitable site for groundwater occurrence. This has been confirmed from the drilling results, where high yielding (18 $m^3/h$) bore wells found at low resistivity zones within the thick quartz reef. The study has helped in preparing a map of the structural set up of the quartz reef in granite host medium and finally revealed that the quartz reefs may provide groundwater potential zone.

The field ERT profiles running across the Kothur quartz reef have shown almost the expected response similar to the synthetic model. The perpendicular profiles (i.e. AB, CD and EF) have shown high resistive anomaly at the center, which is nothing but the signature of quartz reef (Fig. 6). The low resistivity within the quartz reef is an indication of weathering and fissuring in it. The resistivity of the weathered and fissured quartz reef ranges from 200 to 400 Ωm. Resistivity of the basement found in the order of $10^3$ Ωm. First six bore wells (i.e. IFP-30/1, 30/2, 30/3, 30/4, 305, and 30/7) were drilled with reference to the AB resistivity profile. Lithologs collected from the drilled wells has well corroborated with the ERT profile AB (Fig. 6). Even the quartz reef has shown weathering and fissuring effects in the rock cutting and can be seen from the lithologs, which satisfy the hypothesis of generation of tensile fracture due to swelling along the contacts. Another 4 bore wells were drilled with reference to the other profiles. Resistivity logging of the borewells has shown deepening of the basement towards the contact. From west IFP-30/2 and 30/5 have shown basement 35 m and 38 m respectively and IFP-30/3 and 30/4 respectively 34 m and 30.5 m deep basement. Though IFP-30/1 falling just at the center of the quartz reef was drilled ~ 90m deep, could not touch the basement that can be seen in the litholog and also was confirmed by resistivity log.

Although, resistivity of quart basement is expected more than 1000 Ωm (i.e. resistivity of granite basement) because of its mineralogy, but hardly around 300 Ωm resistivity was measured even up to the bottom of IFP-30/1 well. Resistivity of 300 Ωm is the indication of weathered-fissured formation. Same result has been reflected in the litholog too. The lowering in the resistivity might be caused due to the well developed crystal of quartz. The joining plane between two crystals may be acting as conduits to facilitate the water percolation even quite deeper compared to the contact zones and hence lowering the electrical resistivity (refer resistivity log of IFP-30/1 in Fig. 6).

The quartz reef also can be inferred as is more susceptible for fracturing than the granite because of its crystallography. Yield of the bore wells were found well corroborating with the above results, however yield was found more towards north as aquifer thickness is comparatively higher as well as resistivity is low that is the indication of high degree of weathering and fissuring.

## Conclusion

The geoelectrical method is an efficient tool for most of groundwater application and new approach is developed to estimate the natural recharge reliably. The near surface inhomogeneity, which distort the current flow patter and hence finally misleads the resistivity interpretation, could be identified by the new approach of CAPS arrangement. The axial pole-dipole array can be used as the substitute of Schlumberger array for groundwater exploration, which yield the same result and can be carried out even at the places where Schlumberger configuration could not be laid due to non-availability of space on any one side of the sounding location. The study suggest site selection for VES is very important and the rock exposure, boulders etc. seen on the surface should be avoided. The NSI, if any, not exposed on the surface, will be detected using CAPS arrays and its effect can be removed while doing interpretation for vertical electrical sounding in hard rock terrain. Even the VES data could be interpreted by applying statistical application to reduce the ambiguity and improve the interpretation.

Natural recharge on a flat ground is controlled by three factors namely soil resistivity ($\rho_s$), depth to basement (d) and rainfall magnitude (p). The soil resistivity ($\rho_s$) is the first and foremost important parameter that plays a major role in defining the recharge. The increase of soil resistivity is indicative of sandy soil, which is permeable enough to encourage greater infiltration rate in order to increase the natural recharge. The second and very important factor affecting the natural recharge is depth to basement (d), which is the indicative of the space availability (i.e. pore space) to accommodate the infiltrated water from the soil zone. In case of shallow basement recharge is found low and high recharge in deeper basement zone. The third and essential parameter is the source of recharge i.e. rainfall (p), which plays a determinant role in calculating the recharge.

A mathematical formulation has been developed between hydraulic conductivity and aquifer resistivity, and between transmissivity and longitudinal conductance. The methodology has been extensively tested with the field data. Based on the developed formula, hydraulic conductivity and transmissivity have been calculated for alluvial as well as granitic terrain and was validated with the corresponding known values. Correlation analysis between hydraulic conductivity Kp and Kr are found greater than 0.85 in granite. Moreover, good correlation (~0.68) is achieved between $T_p$ and $T_r$ with correlation coefficient 0.68 at Maheshwaram watershed

Although, there has been several debate regarding the correlation between hydraulic parameter and geoelectrical properties that whether there is positive correlation or negative correlation, which has been made here very clear that there is a negative correlation between hydraulic conductivity and aquifer resistivity and positive correlation between transmissivity and longitudinal conductance at least in hard rock terrain. However the correlation coefficient does not have any direct bearing on the developed relation. In alluvium, it may not be much useful because of the presence of clay. The value of constant 'A' changes with formation and need to be derived in the field from some known values and hereafter applied to estimate hydraulic properties from surface resistivity using the developed relationship in a close interval of grid, which will be useful for aquifer modeling for flow as well as contaminant migration and also selecting the site for sustainable well.

The surface geophysical method particularly ERT is an efficient tool to characterize the lineament such as quartz reef in granite host medium. A thorough mapping along and across the quartz reef by Electrical resisitivity methods has provided the parameter variation correlating with the weathering processes. The quartz reef traversing the granite rock can be very useful for locating a potential aquifer. The contact zones of quartz reef may provide potential groundwater zone as deepening of the weathering front is found over there. The ground water flow from up stream side to downstream get accumulated in the zone and make favourable location for siting a high yielding well. The drilled well IFP-30/10 has appeared as one of the highest yielding well at Kothur quartz reef site. Thus quartz reef can also be groundwater potential zone provided it is well connected with the contact zone through open fractures. Study also concludes that ERT measurements at the contact running parallel to the reef must be done before the drilling the degree of weathering/fracturing as well as basement depths varies. The deeper basement zone with high degree of weathering/fracturing qualifies potential aquifer. Geological set up of Kothur quartz reef has been prepared.

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## Reference

Athavale, R. N., Rangarajan, R., Murlidharan, D., 1992. Measurement of natural recharge in India. J. of Geol. Soc. India 39, 235-244.

Athavale, R.N., Chand, Ramesh., and Rangarajan, R., 1983. Ground water recharge estimates for two basins in the Deccan trap basalt formation. Hydrological sciences Journal-des-Sciences Hydrologiques, 28, 4, 525-538.

Athavale, R.N., Rangarajan, R., Muralidharan, D., 1998. Influx and efflux of moisture in a desert soil during a one year period. Water Resour. Res. 34(11), 2871-2877.

Athavale, R.N., Murti, C.S., and Chand,R.,1980. Estimation of recharge to the phreatic aquifers of the Lower Maner basin, India, by using the tritium injection method. Journal of Hydrology, 45,185-202.

Ballukaraya, P.N., Sharma, K. K., Reddi B. Rukmangada and Jagatheesan, M. S., 1988. Identification of lateral inhomogeneities from VES curves, J. of Assoc. Expl. Geophysics, V. 10, No. 4, p. 171 - 183.

Chand R., Chandra, S., Rao V. A. & Jain S. C., (2004); Estimation of Natural Recharge and its Dependency on Sub-surface Geoelectric Parameters, *J. Hydrol* v. 299: 67–83

Chandra, S., 2006. Contribution of Geophysical properties in estimating the Hydrogeological parameters of an aquifer, Ph.D. thesis (unpublished) from Banaras Hindu University.

Chandra, S., Ahmed, S., Ram A., and Dewandel B., 2008. Estimation of Hard Rock Aquifers Hydraulic Conductivity from Geoelectrical Measurements: A theoretical development with field application, *J. Hydrol*" 35, pp. 218-227

Chandra, S., Ananda Rao V, and Singh, V. S., (2004): A Combined approach of Schlumberger and axial Pole-dipole Configurations for Groundwater Exploration in Hard Rock Areas. *Cur Sci India* vol. 86 no. 10, pp 1437 to 1443.

Chaturvedi, R. S., 1973. A Note on the Investigation of Ground Water Resources in Western Districts of Uttar Pradesh", Annual Report, U.P. Irrigation Research Institute, pp. 86-122.

Dincer, T., Al-Murgin, A. and Zimmerman, U., 1974. Study of infiltration and recharge through the sand dunes in arid zones with special to the stable isotopes and thermonuclear tritium. J. Hydrology. 23(1/2): 79-109.

Ermokhin, K.M., Tsokas, G.N., Tsourlos, P. and Glasunov, V.V., 1998. Calculation of the azimuthal inhomogeneity ratio response of 3-D structures using an analytical forward modelling scheme, Journal Of The Balkan Geophysical Society, Vol. 1, No. 4, p. 53-59,

Frohlich, R. K., 1968. The influence of lateral inhomogeneities on the dipole methods, Geophysical prospecting, p, 314 - 325.

Frohlich, R.K., Fisher, J.J. and Summerly, E., 1996. Electrical hydraulic conductivity correlation in fractured crystalline bedrock: Central Landfil, Rhode Island, USA. J. Appl. Geophys., v. 35, pp. 249-259.

Heigold, P.C., Gilkeson, R.H., Cartwright, K., Reed, P.C., 1979. Aquifer transmissivity from the surfacial electrical methods. Ground Water, v.17(4), pp.338-345.

Huntley, D., 1986. Relations between permeability and electrical resistivity in granular aquifers. Ground water, v.24, pp.466-474.

Jones, P.H. and Buford, T.B., 1951. Electrical logging applied to groundwater exploration. Geophysics, v.16, pp.115-139.

Kelly W.E, and Frohlich, R.K., 1985. Relation between aquifer electrical and hydraulic properties. Groundwater, v.23 (2), pp. 182-189.

Kelly, W.E, 1977. Geoelectrical sounding for estimating hydraulic conductivity. Groundwater, v.15, pp.420-425.

Kumar C.P. and Seethapathi P.V. 2002. Assessment of natural groundwater recharge in Upper Ganga Canal Command Area. J. of Appl. Hydrol. V. 15(4), 13-20.

Mazac, O., Kelly, W.E. and Landa, I., 1985. A hydro-geophysical model for relations between electrical and hydraulic properties of aquifer. J. Hydrol., v.79, pp.1-19.

Mbonu, P.D.C., Ebeniro, J.O., Ofoegbu, C.O. and Ekine, A.S., 1991. Geoelectric sounding for the determination of aquifer characteristics in parts of the Unuahia area of Nigeria. Geophysics, v.56, pp.284-291.

Munich, K.O., 1968. Moisture movement measurement by Isotope tagging. In: Guide book on nuclear techniques in Hydrology, IAEA, pp. 112-117

Munnich, K.O., Roether, W. and Thilo, L., 1967. Dating of groundwater with tritium and C-14. In: Isotope Hydrology, IAEA, Vienna, pp. 305-320.

Pfannkuch, H.O., 1969. On the correlation of electrical conductivity properties of porous systems with viscous flow transport coefficients. Proceeding IAHR 1st Int. Symp. Fundamental of transport phenomena in porous media, Haifa. pp. 42-54.

Rakesh Kumar and Chowdary M.V.R., 1977. Effect of vertical contact on Wenner resistivity soundings, Geophysical prospecting, vol. 25, p. 471 - 480

Rangarajan, R., and Athavale, R.N., 2000. Annual replenishable groundwater potential of India-an estimate based on injection tritium studies. J. of Hydrol. 234, pp. 38-53

Singh, K.P., 2005. Nonlinear estimation of aquifer parameters from surfacial resistivity measurements. Hydrol. Earth Sys. Sci. Discuss., v.2, pp.917-938.

Singhal, D.C., Sri Niwas, Shakeel, M. and Adam B.M, 1998. Estimation of hydraulic characteristics of alluvial aquifer from electrical resistivity data. Jour. Geol. Soc. India, v. 51, pp.461-470.

Sri Niwas, and Singhal, D.C., 1981. Estimation of aquifer transmissivity from Dar Zarrouk parameters in porous media. J. Hydrol., 50, 393-399.

Sukhija, B.S. Rama, 1973. Evaluation of groundwater recharge in semi-arid region of India using environmental tritium. In Proceedings of Indian Acad. of Sci., vol. 77, sec. A, no. 6, pp. 279-292.

Van Nostrand, R.E., and Cook, K.L., 1960. Interpretation of resistivity data, USGS professional paper 499, Washington,.

Yadav, G. S., Pole-Dipole Resistivity Sounding technique for Shallow investigations in hard rock areas: PAGEOPH, 1988, Vol. 127, p. 63-71

Yadav, G.S. and Abolfazli, H., 1998. Geoelectrical soundings and their relationship to hydraulic parameters in semi-arid regions of Jalore, Northwestern India. Jour. Appl.. Geophys., 39, 35-51.

Yadav, G.S., 1995. Relating Hydraulic and geoelectric parameters of the Jayant Aquifer, India. J. Hydrol., 167, 23-28.

Zimmerman, U., Ehhalt, D.. and Munich, K.O., 1967. Soil water movement and evapotrainsipiration, changes of isotopic components of soil water. Isotopes in Hydrology, IAEA, Veenna, pp. 567-585.

Zohdy, A.A.R., Eaton, G.P., and Mabey, D. R., 1974. Application of surface geophysics to groundwater investigations USGS, Washington.