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Contribution of geoelectric parameters to investigate the hydraulic characteristics of an aquifer in hard rock terrain

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Resumen: *CONTRIBUCIÓN DE PARÁMETROS GEOELÉCTRICOS PARA INVESTIGAR LAS CARACTERÍSTICAS HIDRÁULICAS DE UN ACUÍFERO EN TERRENO DE ROCA DURA.* El trabajo relaciona las mediciones de resistividad eléctrica con la transmisividad en los acuíferos alojados en rocas graníticas de una cuenca del estado de Andhra Pradesh, India. Se interpretaron las curvas de sondeo eléctrico y se correlacionaron las propiedades eléctricas de la zona saturada con las conductividades y transmisividades hidrológicas obtenidas en testeos tipo slug. Trabajos anteriores apoyan la relación directa entre los parámetros geoeléctricos e hidráulicos en el medio poroso, de manera contraria a lo observado en esta oportunidad, donde existe una relación inversa en el terreno de roca dura (principalmente terreno granítico). Alternativamente, también se analizaron los tipos de medios porosos con diferentes combinaciones de resistividades dentro de una misma capa del acuífero. Todos ellos muestran una relación directa entre la resistencia transversal revisada y la transmisividad, apoyando así los hallazgos que en áreas de roca dura, especialmente en terrenos graníticos, no existe una relación directa entre transmisividad y resistividad transversal. El estudio concluye que establecer una relación global entre dos parámetros no es significativo y tiende a generar errores. La relación empírica entre ellos podría definirse apropiadamente sobre una base zonal, dado que en los acuíferos de roca dura se reconoce un marco hidrogeológico más heterogéneo.

Abstract: An attempt has been conducted to relate the electrical resistivity measurements with the transmissivity in the granitic aquifers of a watershed in the hard rock terrain of Andhra Pradesh state, India. Electrical sounding curves were interpreted and the electrical properties of the saturated zone were correlated with hydraulic conductivities and transmissivites obtained from slug tests. Earlier works support the direct relationship between the geoelectric and hydraulic parameters in the porous medium. Contrary to this, an inverse relationship is observed in the hard rock terrain (mainly granitic). Alternatively, the constitution of equivalent porous media with different combination of resistivities within the same thickness of the aquifer layer were also analyzed. All of them show a direct relationship between revised transverse resistance and transmissivity to some extent, thereby supporting the findings that in hard rock areas especially in granitic terrain, this direct relationship between transmissivity and transverse resistance do not exist. Establishing a global relationship between two parameters is not meaningful and has large errors, however, the empirical relationship between them could be very well established on a zonal basis. It is justifiable as hard rock aquifers are well known compartmented and hydrogeology is more heterogeneous.

Palabras clave: Parámetros de Dar-Zarrouk, transmisividad, conductancia, ERT.

Key words: Dar-Zarrouk parameters, transmissivity, conductance, ERT.

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Introduction

The electrical resistivity sounding method is used for groundwater exploration. Several attempts have been made in the past to correlate transmissivity (T) and transverse resistance (R) when resistivity values are available at all points at known transmissivity. By knowing the resistivity and thickness of the aquifer, its transverse unit resistance (R) and longitudinal unit conductance (C) can be calculated easily. Maillet (1947) was the first to give the concept of these parameters and named them Dar-Zarrouk parameter and Dar-Zarrouk function. Already in the past some empirical and semi-empirical relationships exists between various aquifer parameters and the parameter obtained by resistivity measurements (e.g. Croft, 1971; Henriet, 1976; Kelly, 1977).

Ungemach *et al.* (1969) correlated transverse resistances in the Rhine aquifer with transmissivites determined from pumping tests. Zohdy (1965) calculated the transverse unit resistance and the longitudinal unit conductance of a prism by cutting it into n homogeneous and isotropic layers of varying resistivity and thickness. Croft (1971) has established an empirical relation between the formation factor, computed from electrical log measurements and the hydraulic conductivity from a particular porosity. Barker and Worthington (1973) have described a few interrelationships between aquifer parameters like bulk density, porosity, permeability, formation resistivity factor, compressional wave velocity, etc. Kelly (1977) established an empirical relation between aquifer electrical resistivity and aquifer hydraulic conductivity and a semi-empirical relation between the aquifer formation factor and hydraulic conductivity. Kosinski and Kelly (1981) calculated the longitudinal resistivity and the apparent formation factor of individual aquifer layers and then calculated the normalized transverse resistance in order to establish a regression model between transmissivity and transverse resistance of the aquifer. Again Kelly and Reiter (1984) have introduced the anisotropy effect while relating the hydraulic conductivity to the longitudinal resistivity. Mazac *et al.* (1985) described a general hydro geophysical model considering all the possibilities of relating the hydraulic and electrical properties of the aquifer to each other. Sri Niwas and Singhal (1981 and 1985) studied few regression models with transmissivity and compared the different results. Ahmed *et al.* (1988) used the resistivity and specific capacity data along with transmissivity values to estimate the data even at unmeasured location with the method of geostatistical estimation. Yadav (1995) correlated the normalised aquifer resistivity with hydraulic conductivity and normalised transverse resistance with aquifer transmissivity. The hydraulic conductivity is found closely related with normalised resistivity and the transmissivity with normalised transverse resistance. Frohlich *et al.* (1996) showed the relation between average hydraulic conductivity and resistivity in fractured crystalline bedrock.

Singhal *et al.* (1998) concluded that in an alluvial area where darcy flow is deemed to be valid, hydraulic conductivity and transmissivity of aquifers can be estimated with reasonable accuracy at aquifer level by using relations between hydraulic properties and resistivity parameters. Purvance and Andriecevic (2000) claimed to have developed few relationships for calculating hydraulic conductivity field spectrum at a high resolution over an area composed of quaternary alluvium. A procedure has been described for converting apparent resistivity measurements of an aquifer into hydraulic conductivities based on the site-specific correlation between log electrical and hydraulic conductivities.

Lima *et al.* (2001) simulated the electrical current density distribution in porous aquifer using the potential field equation of Sato (2000). Kumar *et al.* (2001) have estimated the aquifer parameters of an alluvial aquifer with a reasonable accuracy using the relations between hydraulic properties and electrical resistivity parameters. This study implied that geoelectrical techniques offer an alternate approach for estimating the hydraulic characteristics of alluvial aquifers.

Niwas (2003) impounded that in macroscopic scale i.e. at the dimension corresponding to the depth of investigation of a surface electrical sounding the relationship between hydraulic conductivity and electrical resistivity can be strongly controlled by the nature of the aquifer substratum. When this substratum is highly resistive both the current and the hydraulic flows are dominantly horizontal in a typical unit column of the aquifer and the relationship between hydraulic conductivity and electrical resistivity is inverse. On the other hand when the substratum is very conductive, the hydraulic flow is still horizontal but the current flow is a characteristic unit column is now dominantly vertical. For this conduction hydraulic conductivity and electrical resistivity shows a direct relationship.

Niwas and Lima (2003) assumed a multi-layer aquifer model in which aquifer system overlays an impervious substratum such that the hydraulic flow in it is dominantly horizontal. Electrically the substratum may be either more conductive or more resistive than the aquifer material. In each case, the current flow within the aquifer is greatly influenced by the electrical nature of its substratum.

The works cited above pertains mostly to the porous medium. In the present study, an analytical relationship between transmissivity and transverse resistance in compact hard rocks has been attempted. These formulae have been tested using the data from the study area.

Geological framework of the study area

The study area pertains to the Maheshwaram watershed (Figure 1), situated in Ranga Reddy district, Telangana State, India. It lies between geographical coordinates of longitude 78° 24’30”E – 78°29’00” E and latitude 17°06’20” N – 17°11’00” N, forms a part of survey of India toposheet 56 K/8 with an areal extent of about 64 km^2 and is at about 30 km south of Hyderabad.

The area in general is undulating and majority of it has a slope percentage of about 2%. Maheshwaram watershed is a closed basin. There are no major streams in the area. The area is drained by network of 1st and 2nd order streams, which ultimately form small ephemeral streams draining into the mankal cheruvu. The mankal cheruvu in the north forms the northern boundary. The excess water from the tank is left over as spill over water that flows further towards northeast. The valley portion on the eastern part of KB Tanda perhaps must have been occupied by the presence of a buried valley as revealed through the presence of transported materials comprising sand and clay. Though the presence of lineaments has caused for high permeability aquifers, the upland areas are relatively of low permeability.

The weathered zone has completely become dry. The existing wells tap the fractured bedrock and are in semi-confined situation. In general the water striking level is around 25-30 m bgl, whereas the water levels are at depths ranging from 8 to 12 mts. The yield of wells also varies from negligible to about 5000 gallons per hour (gph). The southern part of the basin, which forms the boundary for the watershed and assumed to be the recharge area, may not form the perfect boundary.

In the granites groundwater mostly occurs under semi-confined conditions in the fractured zone. Groundwater is tapped mostly through bore-wells. The columns of weathered and fractured granites as observed in litho-logs vary very much in size that would result in variable aquifer thickness and disposition from place to place. Thickness of highly weathered zone in the area varies from 5 m to 15 m and is underlain by semi-weathered and fractured granite (Subrahmanyam *et al.* 2000).

The water-striking surface is always found to be at deeper depth than the static water level indicating that the aquifers are in semi-confi-

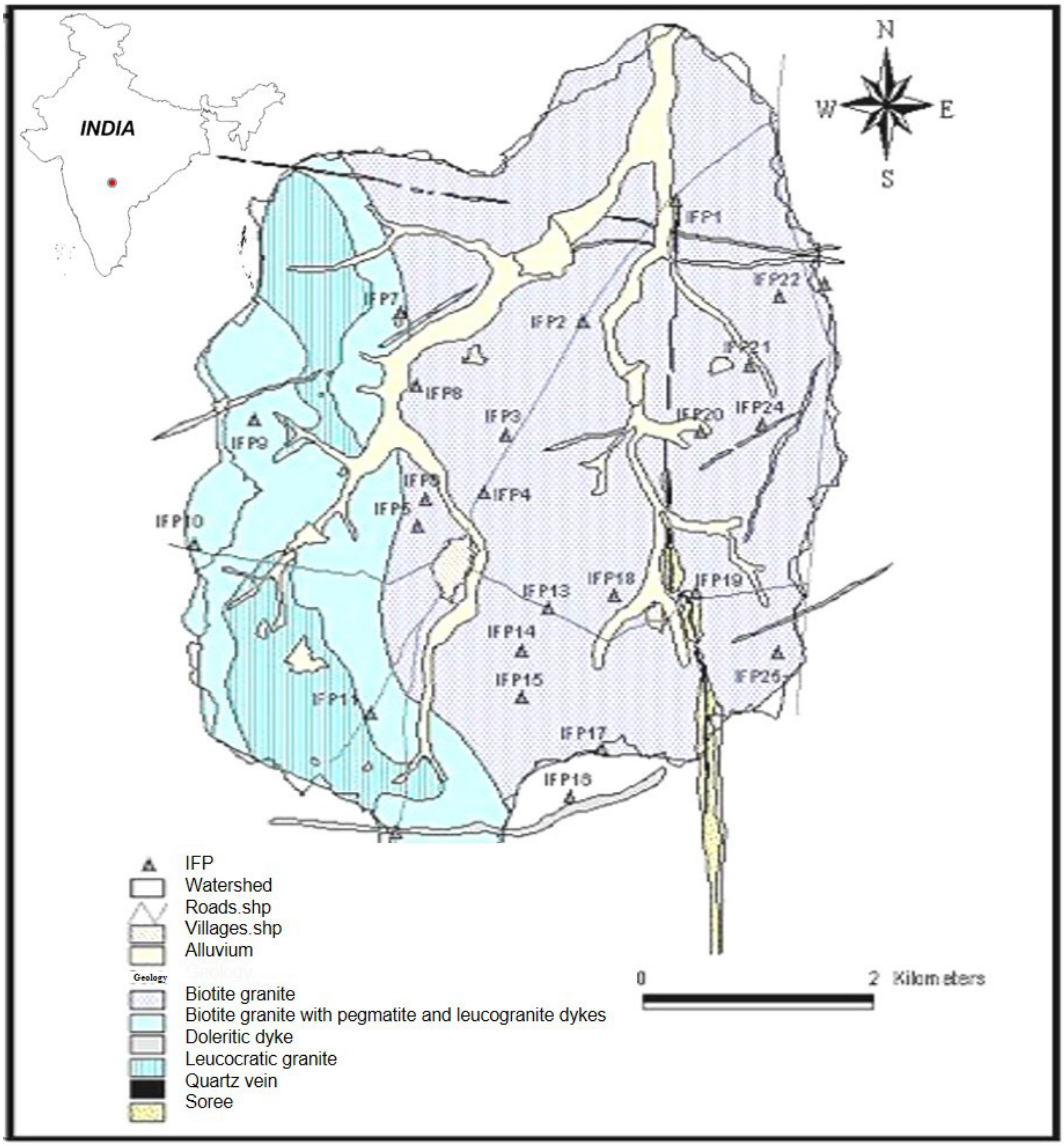

Figure 1. Location map for Maheshwaram watershed showing the VES data points and geology of the area. / **Figura 1.** *Mapa de ubicación de la cuenca hidrográfica de Maheshwaram que muestra los puntos de datos VES y la geología del área.*

ned condition. In the granite the static water levels do not reflect the upper surface of the saturated zone. The water striking surfaces in dug wells seem to be shallower than the bore wells. But the static water levels in shallow dug wells and deep- bore wells are more or less at the same level. Thus it is to be noted that there exists continuity between these two aquifer systems. The water levels in dug wells and bore wells represent piezometric surface only and do not show water-table surface.

Data acquisition

More than 80 Vertical Electrical Sounding (VES) were carried out in the study area (Krishnamurthy *et al.*, 2000), Dutta *et al.*, 2006 interpreted using a computer program based on the inversion algorithm of Jupp and Vozoff (1975), which uses digital filter theory of Ghosh (1971a, 1971b). A total number of 14 IFP bore wells were monitored for the study.

Fracture zones were identified in the

study area by the combined analyses of the sub surface well logging and resistivity sounding (Krishnamurthy *et al.*, 2003) as shown in figura 2. The details of the correlation of lithologs, well logging results and geo-electrical sections at one such site are shown in figura 2.

The values of resistivity lie in the range of 22.5 to 557 ohm mts. Corresponding values of transverse resistance (product of resistivity and aquifer thickness from VES data) were calculated. It is the only parameter which can be identified uniquely from the interpretation of VES data of a confined aquifer. The hydraulic conductivity values were obtained from the slug tests of the IFP bore wells where previously VES was performed (Krishnamurthy *et al.*, 2001). The slug test data of hydraulic conductivity and thickness of the aquifer zone was taken for the corresponding wells (14 in number) whose VES data were considered for calculating transverse resistance. Knowing the thickness of the aquifer zone the relative transmissivites (product of hydraulic conductivity and aquifer thickness) were calculated. The transmissivity ranges between 1.18 m^2/day to 13.59 m^2/day and the hydraulic conductivity values are between 0.059 m/day to 6.78 m/day.

Electrical Resistivity Imaging

Since the resistivity imaging is an improved technique (Arora and Ahmed, 2010; 2011) over the conventional resistivity sounding and attempt has been made to obtain the transverse resistance from the imaging. The resistivity imaging was carried out at the borewell IFP-24. Two survey profiles were laid passing through the borewell, one in north-south direction and the other one in east west direction. The resistivity values were extracted at

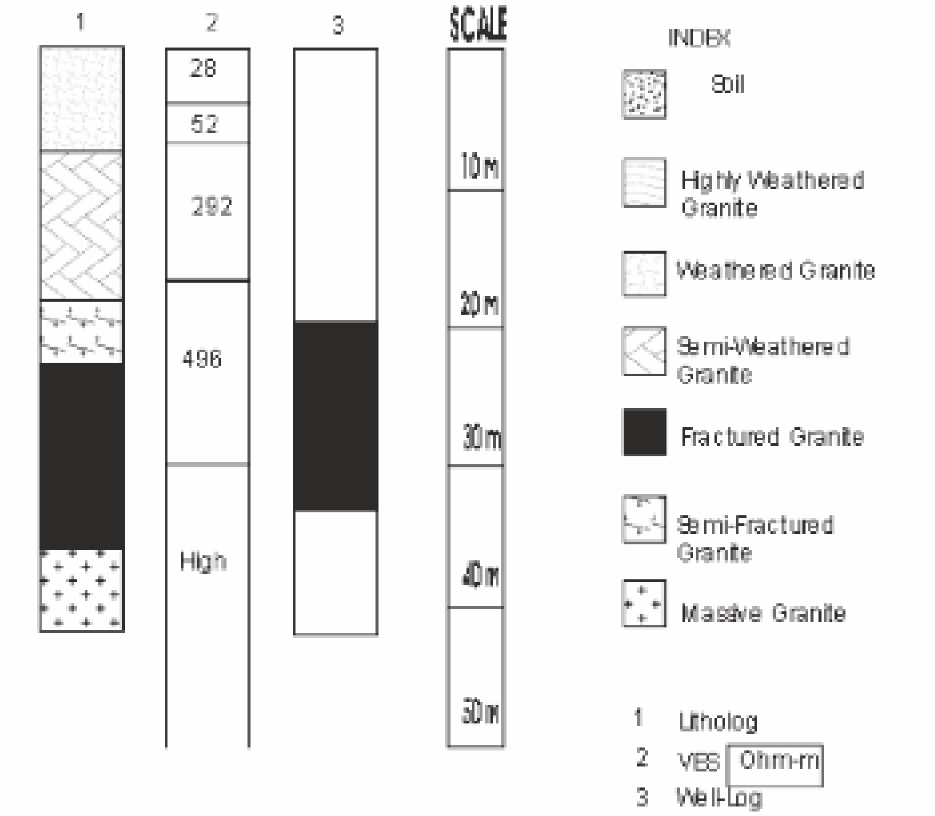

Figure 2. Showing VES results as true resistivities of layers. / **Figura 2.** *Mostrando resultados de VES como resistividades reales de capas.*

several points on the profile for various depths at each point. These values of resistivity were normalized by the average resistivity of water of the area divided by the resistivity of water in borewell IFP-24. The thickness of the aquifer at IFP-24 has been taken from the litholog of the well.

Material and Methods

According to the fundamental Darcy's law, the fluid discharge Q can be given as:

$Q=KIA$ …(1)

And the differential for of Ohm's law gives:

$J=\sigma E$ …..(2)

Where K is the hydraulic conductivity, I is the hydraulic gradient; A is the area of cross-section perpendicular to the direction of flow; J is the current density; E is the electric field and σ is the electrical conductivity $\equiv 1/\varrho$, ϱ being the resistivity.

Taking into account a prism of aquifer material having unit cross-sectional area and thickness h, the two fundamental laws can be combined. Therefore

$T= K\sigma R$ ……(3)

and

$T= K/\sigma . C$ ...…. (4)

Where T is the transmissivity which is obtained by multiplying the aquifer thickness with the hydraulic conductivity of the aquifer; and R is the transverse resistance of the aquifer, and is obtained by multiplying the aquifer thickness and resistivity (h, ϱ), where C is the longitudinal conductance of the aquifer, and can be calculated by multiplying the aquifer thickness and its conductivity (h, σ). Equation 3 and 4 give the analytical relationship between transmissivity and the so-called Dar-Zarrouk parameters.

Construction of Equivalent porous medium

The actual relationship between transmissivity (T) and transverse resistance (R) plotted (Figure 3) from the results of VES interpretation related to the study area shows no correlation. However, the previous works (Worthington, 1975; Henreit, 1976; Kelly, 1977 and 1985, Sri Niwas and Singhal, 1981 and 1985) correlates the T and R of the aquifer zone with linear relations. An inverse relationship between the electrical resistivity and hydraulic conductivity has been reported for a glacial outwash aquifer in central Illinois (Heigold *et al.*, 1979). However, these authors found the inverse relationship utilizing the data of only three test sites presenting broadly the same hydraulic conductivity and without an adequate knowledge of the pore water resistivity. Even Schimschal (1998) reported an inverse relationship between the two parameters but in this case for a consolidated formation near New Mexico consist of bedded dolomite and limestone with interbedded shale siltstone and sandstone. All the empirical relationships mentioned above have been established either by means of laboratory measurements on rock samples or by direct measurements of the porous field datasets. But in the present study based on the real field data of the hard rock terrain, T and R show neither a direct nor an inverse correlation (Figure 3).

There could be possible answer to such a query that all the cited examples relating geoelectrical parameters with the hydraulic parameter were confined to porous medium and the present study pertains to the hard rock terrain. The basis of correlations between the aquifer parameters depends on the material level relationship between grain size, density and porosity. Since transverse resistance is the property depending on the resistivity and thickness of the aquifer zone identified from the VES interpretation it does not match accordingly with the intrinsic properties of the matter. In order to solve the hydrogeological problem it is necessary to understand the variation of different parameters like transmissivity, hydraulic conductivity, porosity, storage capacity, permeability, degree of saturation and the nature of pore electrolytes, which govern the resistivity of rocks.

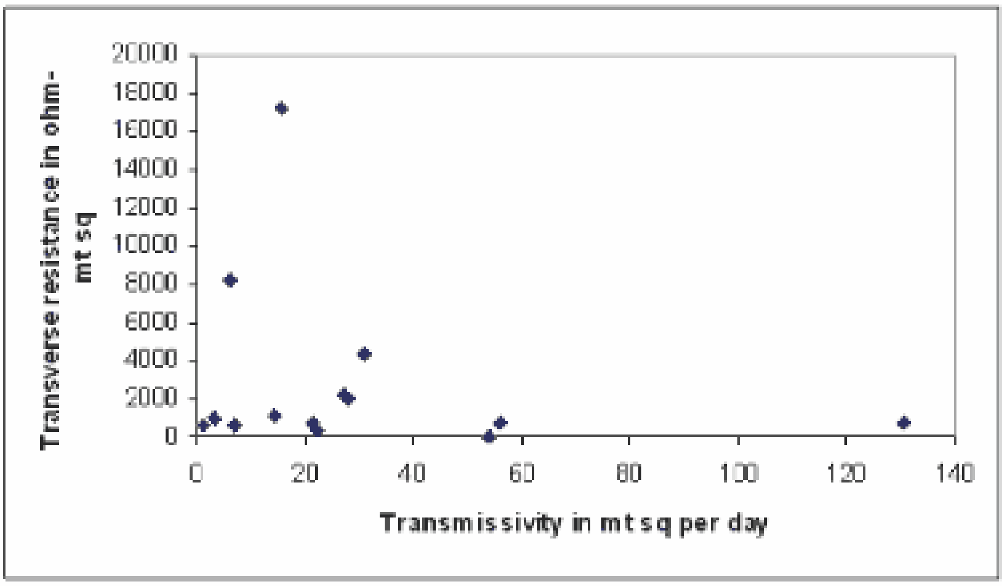

Figure 3. Showing the relation between Transmissivity and Transverse Resistance (Actual Values). / **Figura 3.** *Mostrando la relación entre la transmisividad y la resistencia transversal (valores reales).*

Results and Discussion

To understand the system it was thought to construct an equivalent medium constituting the porous media within the same aquifer thickness. A layered structure of porous media was framed with three types of aquifer material consisting of gravel or loose sand, clay and sandstone. These materials have different porosity in different layers. A number of models were studied with the material in different proportion, assuming the same thickness for each layer. Two of them are being discussed here in detail.

Case 1

The first model was assumed with the thickness of clayey layer to be the 35% of the total aquifer thickness, sandstone covers 20% of the total thickness and gravel almost lies in the rest 45%. The porosity values of different material lie within a range of 8% to 50 %. As clay varies from 20% to 45%; sandstone between 8 % to 25 % and gravel lies between 35 % to 50 %. The percentage of clay present in granular aquifers is the most contributing factor towards the transmissivity value. Because of the variation in the clay content in fresh water aquifers, the total resistivity of the aquifer also varies. From the porosity values the formation factor is calculated using the humble's formula for soft formation (equation below)

$$\boxed{F = 0.62/\Phi^{2.15}}$$

The values of resistivity of pore water (ϱw) were obtained from the electrical conductivity (EC) logging available for the referred IFP wells. The EC log shows the value of EC that lies in the range of 489.86 micro Siemens per cm to 1830 micro Siemens per cm. The values of ϱ_w ranged from 5.46 to 20.4 ohm m. If ϱ_t is the resistivity of water-saturated rock then using the formation factor and the resistivity of pore water, ϱ_t can be calculated using the formula developed by Archie (1942) given as

$$\boxed{F = \rho_t / \rho_w}$$

Depending on the porosity variations, the resistivity of the water-saturated rock varies from a minimum of 22.04 to a maximum of 1677 ohm m. Wells of low resistivity corresponds to that of high porosity. Corresponding values of transverse resistance were calculated by multiplying the resistivity and thickness for the particular combination of clay, gravel and sandstone. Then the average transverse resistance was calculated and adopted for further investigations. This value of R was corrected and modified using the pore water resistivity and the average of water resistivity. Thus the value of transverse resistance, which is being used here, is the "normalized transverse resistance".

It is quite clear from the figure 4, that by considering the aquifer as a porous medium gives a better correlation between the transverse resistance and the transmissivity.

Case 2

One of the factors controlling the transmissivity or K values of the granular aquifers is the percentage of clay present in them. Higher the clay content lower would be the value of transmissivity and in some of the wells the quality of water is good and its EC value is less than 1000 micro Seimens per cm. Since the variation in bulk resistivity varies largely due to the clay content. Still some of the data points vary from the linear relationship due to the effect of the weathered material being transported to the site. The fracture density of the aquifer zone provides more liberty in making the medium porous. Thereby the porosity of the clay content is increased from 20% to 60%; sandstone from 8% to 30% and gravel content lies with the porosity value of 35% to 60%. Similar calculations were made to calculate the normalized transverse resistance and were plotted against the transmissivity (Figure 5).

VES technique is considered to be an outdated technology in hard rocks, but the resistivity imaging is a new tool. Barker *et al.,* 2003, 2010, 2011 has shown the use of the electrical resistivity imaging for the borehole siting in the hardrock regions of India. From the resistivity imaging profile, corresponding transverse resistance are calculated from the value of the thickness of the aquifer and the resistivity. These values are plotted against their respective points along the profile line. As evident from the plot in figure 6, it is quite clear that there are variations in the values of transverse resistance. Both the plots of the transverse resistance show opposite trend. The profile along west-east direction shows a decreasing trend towards east and that along north-south shows an increasing trend from north to south.

They concluded that the resulting images from the electrical imaging can be used

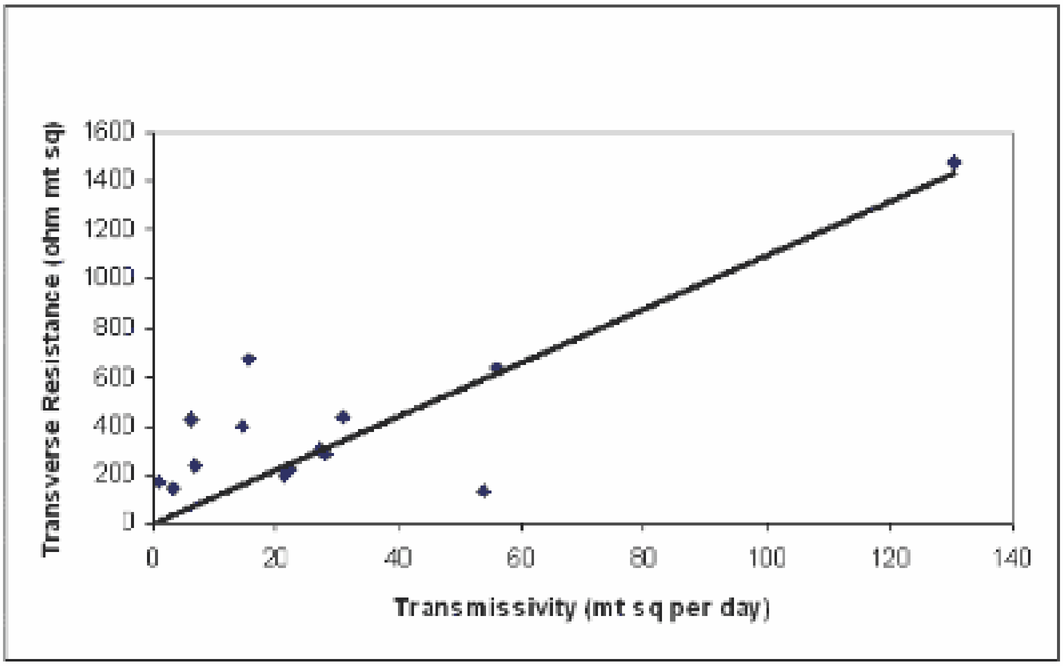

Figure 4. Transverse Resistance against Transmissivity (case 1). / **Figura 4.** *Resistencia transversal a la transmisividad (caso 1).*

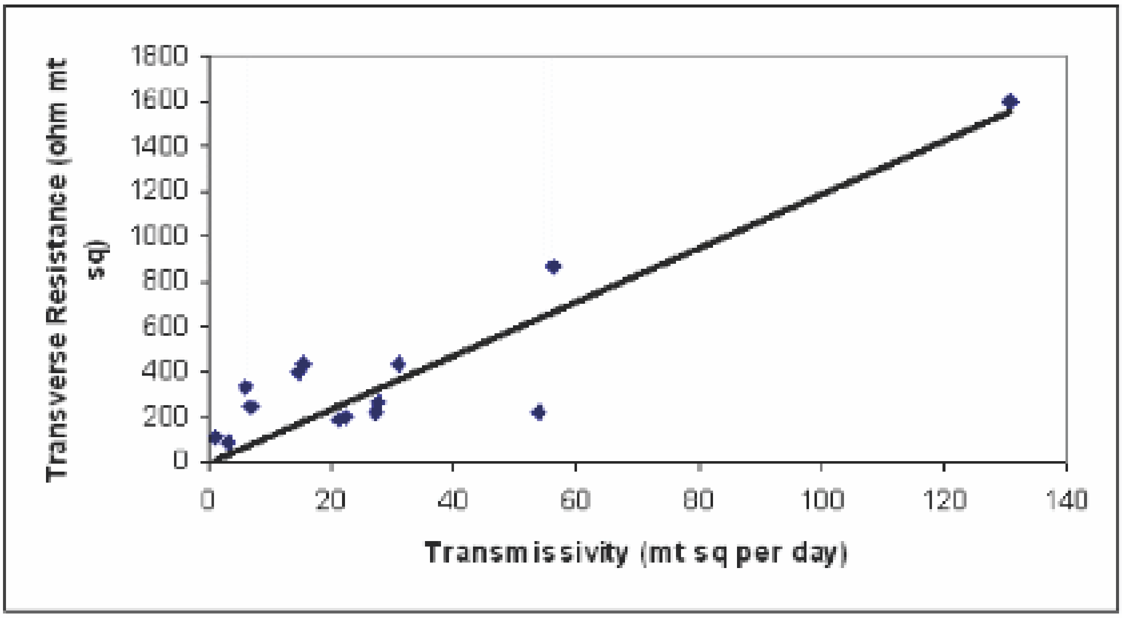

Figure 5. Transverse Resistance against Transmissivity (case 2). / **Figura 5.** *Resistencia transversal a la transmisividad (caso 2).*

to plan the borehole investigations more cost effectively. As evident from the plots of the transverse resistance acquired from the resistivity values of the different profiles it is clear that the transverse resistance show much fluctuations within a small area of 400mts, whereas transmissivity may not show so much variations. Hence, it is not feasible to establish a relationship between the transverse resistance and the transmissivity values in hard rock areas.

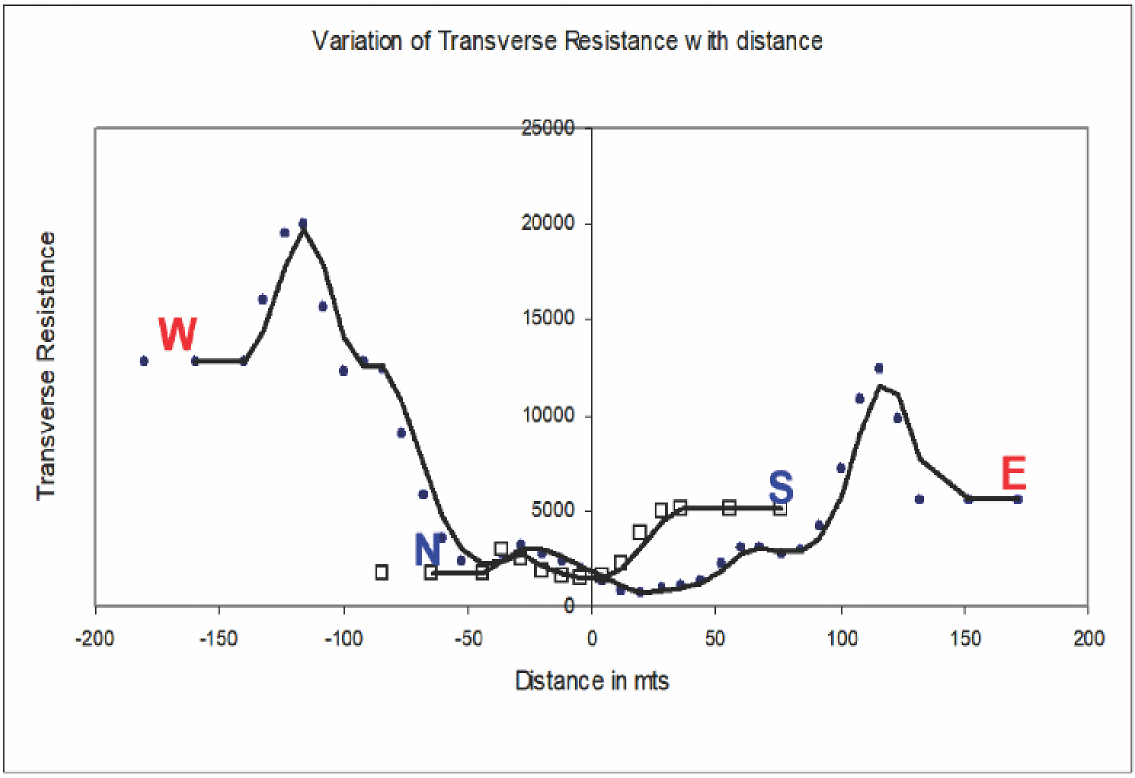

Figure 6. Showing the variation of transverse resistance with the distance along the IFP 24. / **Figura 6.** *Mostrando la variación de la resistencia transversal con la distancia a lo largo del IFP 24.*

Conclusions

Correlating electrical properties with that of the hydraulic properties in an aquifer has been quite common in stimulating hydraulic properties where electrical measurements are available, through regression. Although regression coefficient has been limited to the specific area studied but with a thorough analysis in this study it is found that all the successful studies belong to the aquifer in porous medium. Contrary to this, an inverse relationship or no relationship is being observed in the hard rock terrain (mainly granitic terrain). Alternatively cases constituting porous material in different combination, within the same thickness of the aquifer layer were also analyzed.

The worked out equivalent porous medium although arbitrary but could provide meaningful relationship. Thus following points are concluded:

1. The relationships between electrical and hydraulic parameters are restrictive in hard rock aquifers and if at all, may be very site specific.
2. If a hard rock aquifer shows less variation, at least zonal relationship could be established.
3. Electrical resistivity imaging, an updated tool for the resistivity interpretation as compared to vertical electrical sounding, can help in understanding the heterogeneity within short intervals.

This study is confined to fractured media only, as due to over exploitation, the flow in the aquifer remained only in fractured medium underlying the weathered portion. Perhaps a relationship similar to porous medium may exist in the weathered zone.

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References

Arora, T. and Ahmed, S. 2010. Electrical Structure of an Unsaturated Zone - A Case Study related to hard rock aquifer. *Current Science*, 99(2): 216-220.

Arora, T. and Ahmed, S. 2011 Characterization of Recharge through complex vadose zone of a granitic aquifer by time-lapse electrical resistivity tomography. *Journal of Applied Geophysics*, 73: 35-44.

Ahmed, S., Marsily, G. and Talbot, A. 1988. Combined use of hydraulic and electrical properties of an aquifer in a geostatistical estimation of transmissivity, *Groundwater,* 26 (1):78-86.

Archie, G.E. 1942. The electrical resistivity log as an aid in determining some reservoir characteristics. *Amer. Inst. Min. Met. Eng., Tech.* Pub. 1422 ,

Barker, R.D. and Worthington, P.F. 1973. Some hydrogeophysical properties of the Bunter Sandstone of northwest England. *Geoexploration,* 11: 151

Barker, R.D. Rao, T.V. and Thangarajan, M. 2003. Application of Electrical imaging for borehole siting in hard rock regions of India. *Journal of Geological Society of India,* 61:147–158

Croft, M.G. 1971. A method of calculating permeability from electric logs. In: Geological Survey Research. *U.S. Geol. Surv., Prof. Pap.,* 750-B: 265–269.

Dutta, S., Krishnamurthy, N.S., Arora, T., Rao, V.A. and Ahmed S. 2006. Localization of water bearing fractured zones in a hard rock area using integrated geophysical techniques in Andhra Pradesh, India. Hydrogeology Journal, 14(5): 760-766

Frohlich, R.K., Fisher, J.J, and Summerly, E. 1996. Electric–hydraulic conductivity correlation in fractured crystalline bedrock: Central Landfill, Rhode Island, USA. *J. Appl. Geophys.*, 35: 249–259.

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.

Heigold, P.C., Gilkeson, R.H., Cartwright, K. and Reed, P.C. 1979. Aquifer transmissivity from surficial electrical methods. *Ground Water,* 17, 4: 338–345.

Henriet, J.P. 1976. Direct application of Dar–Zarrouk parameters in ground water surveys. *Geophys. Prospect,* 24:344–353.

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.

Kelly, W.E. and Reiter, P.F. 1984. Influence of anisotropy on relations between electrical and hydraulic properties of aquifers. *Journal of Hydrology,* 74:311–321.

Kelly, W.E. 1977. Electrical resistivity for estimating permeability. *J. Geotech. Eng. Div.,* 103:1165–1168.

Kelly, W.E. 1977. Geoelectric sounding for estimating hydraulic conductivity. Ground Water, 15,6:420–425.

Kosinski, W.K., Kelly, W.E. 1981. Geoelectric soundings for predicting aquifer properties. *Ground Water,* 19,2:163–171.

Krishnamurthy, N.S., Dewashish Kumar, V., Ananda, R., Jain, S.C. and Ahmed, S. 2003. Comparison of surface and sub-surface geophysical investigations in delineating fracture zones. *Current Science,* 84(10):1242-1246.

Krishnamurthy, N.S., Kumar D., Negi B.C., Jain S.C., Dhar R.L. and Ahmed, S. 2000. Electrical resistivity investigations in Maheshwaram Watershed, Andhra Pradesh, India, Technical Report No. NGRI-2000-GW-287.

Krishnamurthy, N.S., Syama Prasad, B., Md. Zaman, G., Anjaneyulu, G.R. and Jain, S.C., 2001. Well Logging for Identifying Fracture Zones in Boreholes in Maheshwaram Watershed, A.P., India, Technical Report No. NGRI-2001-GW-322.

Kumar, M.S., Gnanasundar, D. and Elango, L. 2001. Geophysical studies to determine hydraulic characteristics of an alluvial aquifer. *Journal of Environmental Hydrology,* 9: 15.

Lima, O.A.L., Sato, H.K. and Sri N. 2001. Mathematical modeling and simulation of electrical current density distribution in aquifer settings. *Proceedings of the International Congress of Brazilian Geophysical Society, Salvador, Brazil.*

Maillet, R. 1947. The fundamental equation of electrical prospecting. *Geophysics*, 12:529-556.

Mazac, O., Kelly, W.E. and Landa, 1985. A hydro geophysical model for relations between electrical and hydraulic properties of quiver. *Journal of Hydrology,* 79:1-19.

Niwas, S. and Singhal, D.C. 1985. Aquifer transmissivity of porous media from resistivity data. *Journal of Hydrology,* 82:143–15.

Niwas, S. and Singhal, D.C. 1981. Estimation of aquifer transmissivity from Dar–Zarrouk parameters in porous media. *Journal of Hydrology,* 5:393–399.

Purvance, D.T. and Andricevic, R. 2000. On the electric-hydraulic conductivity correlation in aquifers. *Water Resources Research,* 36(10): 2905-2913.

Sato, H.K. 2000. Potential fields from a dc current source arbitrarily located in a non uniform layered medium. *Geophysics*, 65:1726-1732.

Schimschal, U. 1998. The relationship of geophysical measurements to hydraulic conductivity at the Brantley Dam Site, New Mexico. *Geoexploration,* 19:115–126.

Singhal, D.C., Sri, N., Shakeel, M. and Adam, E.M. 1998. Estimation of Alluvial aquifers from electrical resistivity data. *Journal of the Geological Society of India,* 51:461-470..

Sri N. and Lima, O.A.L. 2003. Aquifer Parameter estimation from surface resistivity data. *Groundwater,* 41(1):94-99.

Subrahmanyam, K., Ahmed, S. and Dhar R.L. 2000. Geological and Hydrogeological Investigations in the Maheshwaram Watershed, R.R. Dist., Andhra Pradesh, India, Technical Report No. NGRI-2000-GW-292.

Ungemach, P., Moslaghimi, F. and Duprat A. 1969. Essais de determination du coefficient demmagasinement en nappe libre application a la nappe alluvial du Rhin. *Bull. Int. Assoc. of Scientific Hydrol.* XIV, 3:169–190.

Yadav, G.S. 1995. Relating hydraulic and geoelectric parameters of the Jayant aquifer, India. *Journal of Hydrology,* 167:23–38.

Zohdy, A.A.R. 1965. Geoelectrical and seismic refraction investigations near San Jose, California. *Ground Water,* 3:41-48.

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