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Establishing hydrogeophysical relationship between geoelectric and hydraulic parameters for a basaltic aquifer, Ahmednagar district, Maharashtra, India

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ABSTRACT
Quantitative assessment of the spatial distribution of intensity of groundwater pollution caused by untreated industrial effluents requires development of numerical transport models which in turn needs information on the spatial distribution of hydraulic characteristics of the subsurface. The most effective way to evaluate such aquifer characteristics is by performing the pump-out tests. However, sparse location of boreholes posed problems in modeling the subsurface pollution at Mula sugar factory area, Ahmednagar district, Maharashtra, India. A well established site specific relationship between geoelectric and hydrogeological parameters of the aquifer was adopted as an alternative approach to assess the hydraulic characteristics of the subsurface layers.

The geoelectrical parameters were determined from the Vertical Electrical Soundings (VES) data carried out at pump-out test wells. The values of hydraulic conductivity (K) and transmissivity (T) computed from the pump-out tests were correlated with the normalized aquifer resistivity (ρ′) and normalized transverse resistance (Z′) respectively which suggested a linear relationship.

This study has established a valuable site specific relationship between hydraulic and electrical parameters in a basaltic aquifer of Mula sugar factory area. The calibrated relationship could contribute to assess the spatial distribution of hydraulic conductivity value as an input to construct a pragmatic numerical model. Hence, the use of geoelectrical soundings provides a cost effective alternative technique for calculating the hydraulic parameters and characterizing the aquifer system of the virgin areas.

INTRODUCTION

Many sugar industries emerged in the rural areas of Maharastra, India during the past few decades, boosting its economy, initiating various economic activities by setting up dairies, distilleries, paper mills and poultries in their respective regions. However, it has been found that enormous quantity of untreated effluent emerging from the sugar factories is deteriorating the quality of groundwater (Pondhe, 1992). Very few studies were carried out regarding the intensity and areal extent of the groundwater pollution resulting from the discharge of effluents from sugar mills and Mula sugar factory is one among them where mapping of migration of pollutants was not attempted quantitatively so far. Rural population in this area mainly depends on groundwater. Prior to the commissioning of sugar factory, the groundwater from this area was uncontaminated and potable. Residents of this area, however, have realized the change in the quality of water and the soil after the factory became operational (Pondhe, 1992). Thus, a need was felt to assess the intensity of the distribution of the pollution in the area under study by constructing a numerical model which requires the spatial hydraulic characteristics of the subsurface. Further, Krishnaiah (2011) demonstrated that the assessment of the hydraulic conductivity of the aquifer is an important parameter for the numerical flow model leading to the development of pollutant transport model.

Acquaintance of spatial distribution of aquifer characteristics such as hydraulic conductivity and transmissivity would improve the understanding of hydrodynamics of pollution spreading in the porous media and its response to the fluid extraction. Among the most effective ways to evaluate such aquifer characteristics are the pump-out tests performed in certain boreholes where hydrogeological information is sought. However, sparse location of boreholes poses problems in hydrogeological modeling. Further, techniques such as drilling, logging and pump-out tests on a large scale are expensive and time consuming. In such circumstances, surface geoelectric methods offer an alternative approach to determine the distribution of aquifer characteristics at an appropriate scale that is required for model studies economically in terms of areal coverage.

As the same physical principles and lithological attributes govern the electric conduction and fluid flow in the ground, the hydraulic and electrical conductivities are interrelated (Soupios et al. 2007). In most rocks, the resistivity of the medium is controlled by pore water resistivity as well as the resistivity of the rock matrix. The relationship between geo-electric and hydro-geological parameters of aquifer has been studied by various researchers. Archie (1942) established a relationship between formation factor and permeability, and formation factor and Resistivity. Ungemach et al (1969) correlated transmissivities with transverse unit resistance. Duprat et al (1970); Croft (1971); Worthington (1976); Kelly (1977); Heigold et al (1979); Koinski and Kelly (1981); Urish (1981); Frolich and Kelly (1985) and Mbonu et al (1991) worked out several relationships between geoelectric and hydro-geological parameters.

Sri Niwas and Singhal (1985) reported case histories of alluvial aquifers establishing the applicability of the relations in various geological conditions in Northern India. Singhal et al. (1998) examined the applicability of geophysical techniques for evaluating aquifer properties like transmissivity and hydraulic conductivity of alluvial anisotropic aquifers at Saharanpur area, Uttar Pradesh, India. They concluded that in an alluvial area where Darcy flow is deemed to be valid, hydraulic conductivity and transmissivity of aquifers could be estimated with reasonable accuracy at aquifer level by using relations between hydraulic properties and resistivity parameters.

Recently, Batayneh (2009) obtained a significant correlation between the transmissivity and modified transverse resistance as well as linking the hydraulic conductivity and formation factor for two hydraulic units, in Central Jordan. Asam Farid et al (2012) showed a good match connecting pumped hydraulic conductivity and estimated hydraulic conductivity by conducting VES to delineate the aquifer system at the Western part of the Maira area, Khyber Pakhtun Khwa, Pakistan. Okiongbo and Odubo (2012) in their study used the approach of correlation between hydraulic and electrical properties to estimate aquifer transmissivity in numerous locations providing effective and inexpensive characterization of the study area aquifer system in parts of Bayelsa State, South Nigeria.

This paper presents the relationship between hydraulic and geoelectrical parameters of aquifers to develop a hydrogeophysical representation to construct a pragmatic numerical transport model for a basaltic aquifer of Mula sugar factory area of Ahmednagar district, Maharashtra.

LOCATION, GEOLOGY AND HYDROGEOLOGY

The Mula sugar factory is located at Sonai village in Newasa tahsil of the Ahmednagar district, Maharashtra, India. It covers an area of 15.12 km^2 and is included in toposheet number 47 I/15 of the Survey of India and lies between $19^0 22'$ to $19^0 24'$ North latitude and $74^0 49'$ to $74^0 51'$East longitude (Fig. 1). The climate of the study area is generally dry; the maximum temperature during summer is as high as 41^0 C whereas the minimum temperature is as low as 10^0 C during winter. The area gets rainfall mainly from the Southwest monsoon with an annual average of 600 mm (Pondhe, 1992). One third of Sonai area is under single crop cultivation i.e., sugarcane. Shani Shingnapur is the important place in this area.

Groundwater flow in this area occurs depending on water table conditions in the weathered basaltic aquifers prevailing at depths ranging from 1.0 m to 4.5 m below ground level. The massive basalts have porosity of 0.03 where as zeolitic basalts have 0.15 and fractured/weathered rocks have secondary porosity of about 0.24. Occurrence and movement of groundwater in the basalts is primarily controlled by the degree of jointing, presence of vesicles, fractures and contacts between lava flows and flow units (Pawar and Shaikh, 1995). Groundwater from this aquifer is extracted mostly from large diameter wells that vary in size (4.5 m to 7.5 m) and depths ranging from 14 m to 20 m.

Data Acquisition and Interpretation

An integrated approach of hydrogeological, geoelectrical and laboratory measurements of resistivity of groundwater samples has been used to study the relationship between the geoelectric and hydraulic parameters in the weathered basaltic aquifer. In view of this, nine VES were conducted using Schlumberger array, four short duration pump-out tests were performed and groundwater samples were collected from nine wells where the VES were carried out to find out the groundwater resistivity. The locations of these soundings were selected in the close vicinity of the dug wells (Fig 1).

Pump-out tests

In order to evaluate aquifer hydraulic parameters (hydraulic conductivity and transmissivity), a total of four numbers of short duration pump-out tests ranging from 3 to 4 hours were performed on the dug wells at the locations shown in the Fig 1. Time drawdown/recovery were recorded in the pumping well itself while carrying out pump-out tests (Singh and Thangarajan, 1998a, b). Analysis of pump-out test data was carried by using Papadopulos and Cooper (1967) method. A typical pump-out test curve is presented in the Fig 2. The estimated transmissivities and discharges are tabulated in the Table 1. The transmissivity of the basaltic aquifer of this area varies between 43.7 and 61.2 m^2/day and hydraulic conductivity differs from 5 to 6 m/day whereas the discharge ranges from 104.5 to 126 m^3/day.

Basalts usually have medium to lower permeability values depending the presence of primary and secondary porosity (Sharad et al. 2007). According to them, transmissivity of these aquifers is generally in the range of 25 to 100 m^2/day and the hydraulic conductivity varies from 0.05 to 15 m/day and further, the pumping tests in basalts of the Ahmednagar district of Maharashtra have given transmissivisity values ranging from 15 to 150 m^2/day. Comparatively the lower values of transmissivity (43.7 - 61.2 m^2/day) and hydraulic conductivity (5 - 6 m/day) obtained from the pumping tests of this area shows

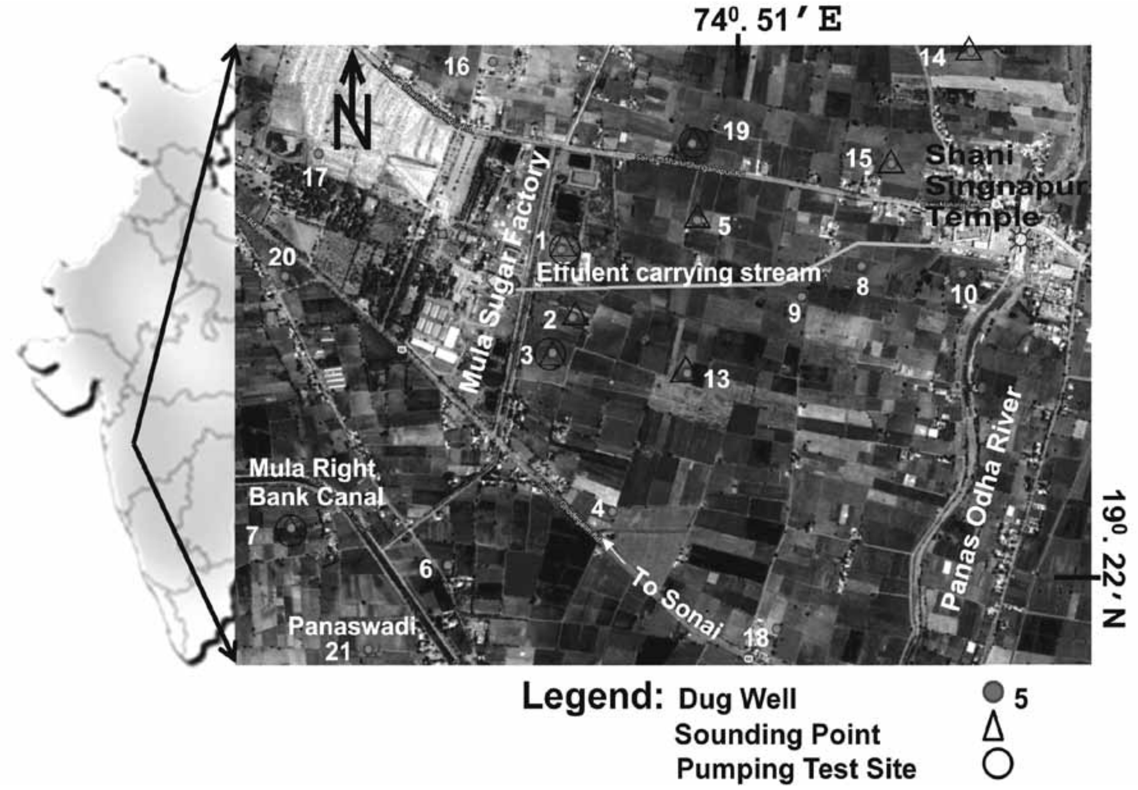

Figure 1. Location map showing Mula sugar factory area, sounding points and pump-out test sites.

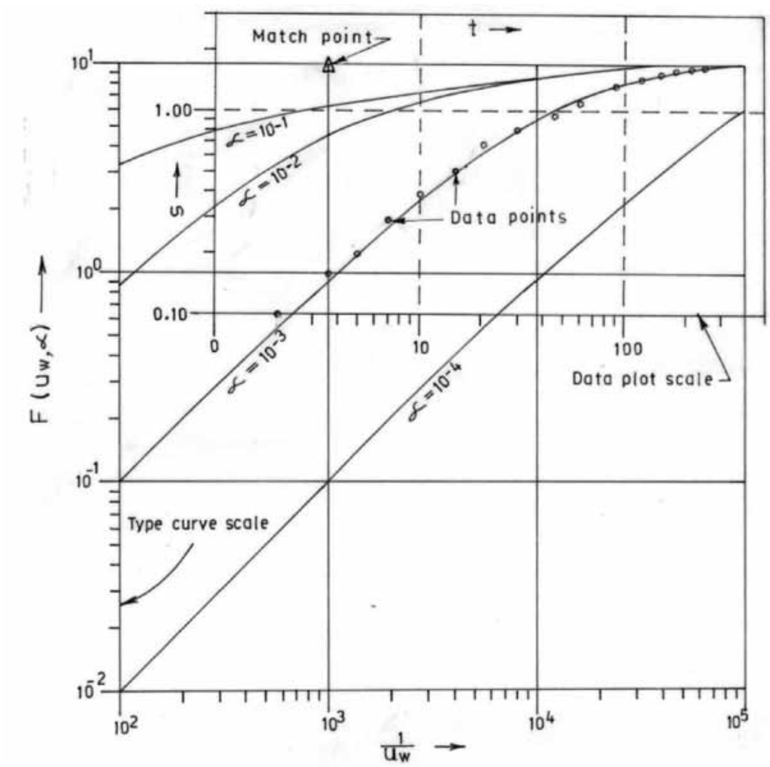

Figure 2. Analysis of pump-out test curve by matching of time-drawdown data of large diameter well (W1) with Papadopulos-Cooper type curve.

Table 1. Results of pump-out tests

Well No.	AMSL (m)		Diameter (m)	Transmissivity m^2/day	Aquifer Thickness (VES) (m)	Discharge m^3/day
	GL	Depth (m)				
W1	515.8	495.8	7.5	61.20	10.2	126.0
W3	516.0	498.0	6.0	43.68	8.4	104.5
W7	516.7	497.7	6.5	49.00	9.8	108.0
W19	515.5	597.5	7.0	51.04	8.8	110.0

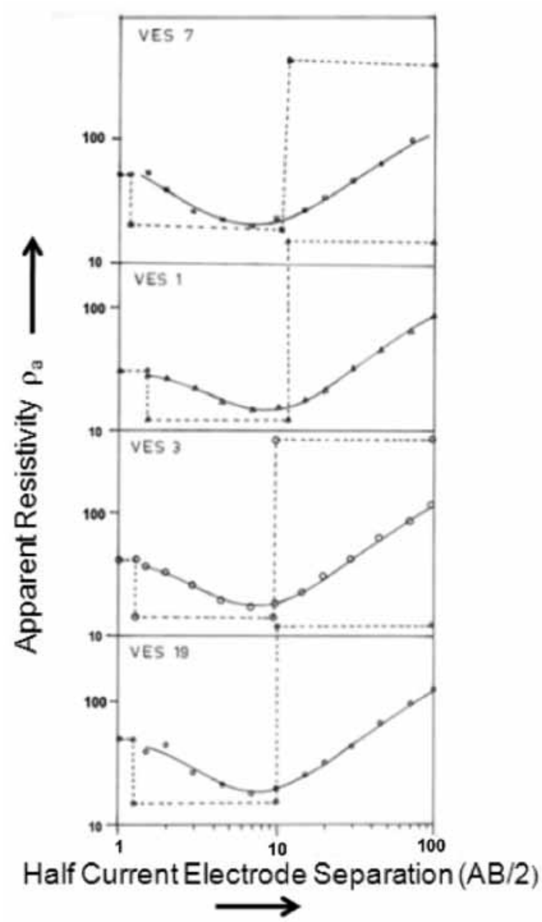

Figure 3. Typical sounding curves where the pump-out tests were carried out

that groundwater in this area is mostly controlled by the less degree of weathering and fracturing.

Electrical resistivity soundings

Surface resistivity methods have been used in groundwater research for many years. Resistivities measured on the earth are attributed to important subsurface geologic formations, porosity, and degree of saturation. In the present study, nine VES were conducted using Schlumberger array to find out geoelectric parameters covering area severely affected by the discharge from the sugar factory. Some typical sounding curves where the pump-out tests were carried out are shown in the Fig 3.

A preliminary interpretation of the sounding curves using partial curve matching (Orellana and Mooney, 1966) provided the initial estimates of the resistivities and thickness (layer parameters) of the various geoelectric layers. These initial estimates were then used to fine tune the model using a 1-D inversion technique (RESIX-IP™, 1993). Inversion analyses of the sounding curves were carried out with an average fitting error of about 5% to 10%. To overcome the ambiguity of quantitative interpretation of geoelectrical sounding curves due to

Table 2. Geo-electrical parameters obtained by VES

Location	VES No.	AMSL (m) (Above Mean Sea Level)			Resistivity-Ω-m			Depth (AMSL)/Thickness - m		
		GL	Well Depth	GWL	ρ_1	ρ_2	ρ_3	D1/h_1	h_2	D2/H(=h1+h2)
W1	1	515.8	495.8	513.8	30.2	12.0	350.0	514.3/1.5	10.2	504.0/11.7
W2	2	514.8	498.8	513.4	35.0	15.0	365.0	513.4/1.4	9.0	504.4/10.4
W3	3	516.0	498.0	514.5	40.8	14.0	400.0	514.7/1.3	8.4	506.3/9.7
W5	5	514.7	495.7	512.9	41.2	9.0	415.0	513.55/1.15	9.3	504.25/10.45
W7	7	516.7	497.7	515.5	95.0	19.8	600.0	516.0/0.7	9.8	506.9/10.5
W13	13	515.6	498.6	514.4	55.0	20.0	480.0	514.8/0.8	10.1	505.5/10.9
W14	14	515.8	495.8	513.7	40.0	14.5	800.0	514.0/1.8	10.8	505.0/12.6
W15	15	515.5	500.5	514.0	32.0	9.5	560.0	514.41.1	9.8	505.7/10.9
W19	19	515.5	497.5	513.0	45.3	15.0	450.0	514.31.2	8.8	506.7/10.0

Table 3. Observed geo-electric and aquifer parameters

Well No.	Aquifer		TDS (kg/m^3)	Water Resi. ρ_w	Norm. Resi ρ'	Norm. Trans Resis Z'	K	T
	Resis. (Ω-m)	Thick. h (m)						
1	12.0	10.2	0.57	11.22	15.5	158.1	6.0	61.2
3	14.0	8.4	0.48	13.33	15.2	127.8	5.2	43.7
7	19.8	9.8	0.33	19.3	14.9	146.0	5.0	49.0
19	15.0	8.8	0.45	14.22	15.3	134.5	5.8	51.0
average ρ_w = 14.5 Ω-m								

equivalence problem (Koinski and Kelly, 1981), data from well inventory observations were used to minimize the choice of equivalent models, by fixing thicknesses and depths to certain levels and allowing the adjustment of resistivity. Table 2 presents the results of interpretation of the VES stations. The depths obtained from the interpretation of VES data are reduced to above mean sea values (AMSL) and presented in the Table 2 along with the groundwater levels.

The inventory of dug wells and the results of VES conducted in this area indicate two distinct lithological layers that overlie the impermeable bedrock. The topmost unit with a thickness varying between 0.7 to 1.8 m is a soil cover represented by a resistivity range of 30 Ω-m to 95 Ω-m. Weathered and fractured basalts with thickness changing from 8.4 to 10.8 m and resistivity from 9.0 Ω-m to 20.0 Ω-m forms the second unit. From the observations of the VES results, it can be seen that the aquifer under study has more or less uniform thickness. From the inventory of wells and results of VES, it was also observed that there is no evidence of existence of any preferential flow paths or impermeable structures which play an important role in the spread of pollution in the aquifer.

Collection of water samples

In order to find out normalized aquifer resistivity (ρ'), water samples were collected from the wells where the resistivity soundings were conducted. Resistivity, which is the inverse of conductivity of the water sample, was computed in the laboratory according to the standards mentioned in APHA (1989) using conductivity meter. Normalized aquifer resistivity was worked out using the formula $\rho'=(\rho/\rho_w)\rho_{\overline{w}}$ and tabulated in Table 3, where ρ_w is the groundwater resistivity and $\rho_{\overline{w}}$ is the average groundwater resistivity.

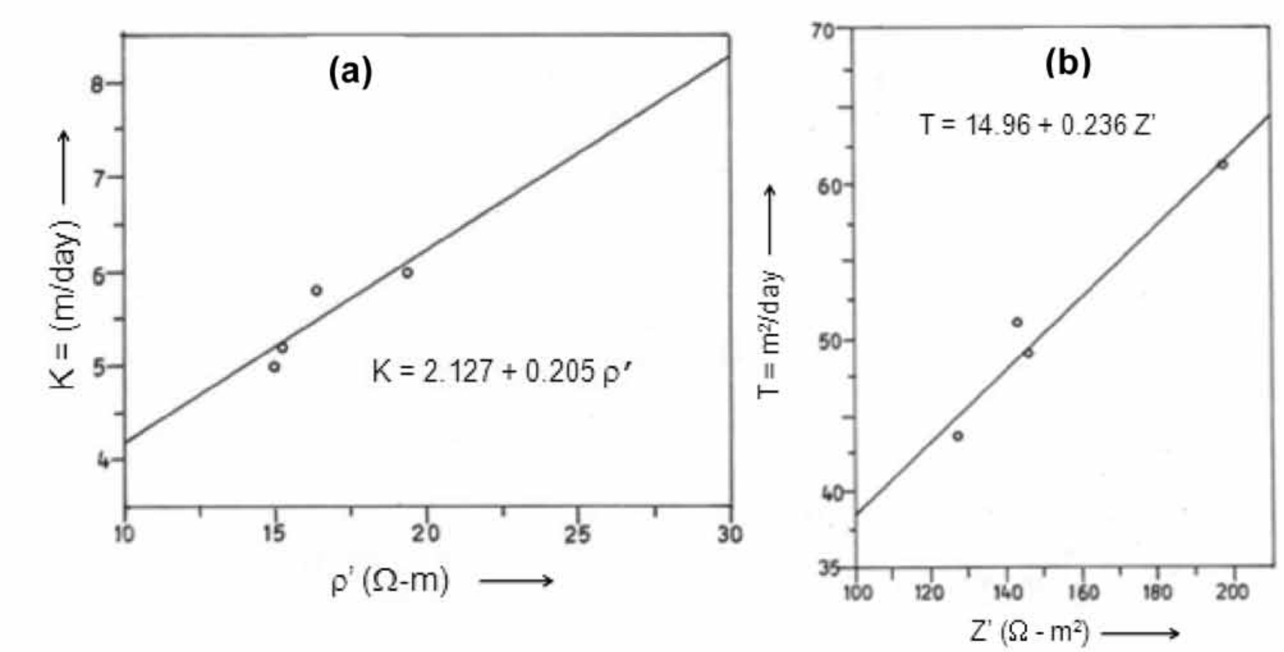

Figure 4. Correlation curves of: (a) K Vs ρ′ and (b) T Vs Z′

Table 4. Computed aquifer parameters from the regression lines

Well No.	Aquifer		TDS Kg/ m^3	Water Resi. ρ_w	Norm. Resis ρ'	Norm. Trans. Resis. Z'	K^*	T^{**}
	Resi. ρ	Thick. h						
2	15.0	9.0	0.53	12.1	18.0	162.0	5.8	53.2
5	9.0	9.3	0.86	7.4	17.6	163.9	5.7	53.4
13	20.0	10.1	0.38	16.8	17.3	174.7	5.6	56.0
14	14.5	10.8	0.51	12.5	16.8	181.4	5.6	57.8
15	9.5	9.8	0.78	8.2	16.8	164.6	5.6	57.8
$K^* = 2.127 + 0.205'$ and $T^{**} = 14.96 + 0.236 Z'$								

Correlation study: Hydraulic versus Geoelectric parameters

As discussed in the introduction, in the present study, the values of hydraulic conductivity and transmissivity computed from the pump-out tests on four dug wells have been used to correlate with the normalized aquifer resistivity (ρ') and normalized transverse resistance (Z') respectively. For this purpose, the following formulae were used (Yadav et al. 1993):

1. Transverse resistance, Z is defined by the equation $Z = \rho h$ where ρ is aquifer resistivity and 'h' is thickness,
2. Transmissivity, T is defined by $T = Kh$ where K is hydraulic conductivity and 'h' is thickness, as Normalized aquifer resistivity (ρ') is the apparent formation factor (ρ/ρ_w) multiplied by an average resistivity value ($\rho_{\overline{w}}$) as $\rho'=(\rho/\rho_w)\rho_{\overline{w}}$
3. Normalized transverse resistance $Z' = \rho' h$

The hydraulic conductivity (K) was correlated with normalized aquifer resistivity (ρ') and transmissivity (T) with normalized transverse resistance (Z') of the water bearing formation from the data presented in the Table 3, and shown in the Fig 4. It shows a scatter plot of K verses ρ' and T verses Z'. From the scatter plot following relationships were obtained:

$$K = 2.127 + 0.205\ \rho'$$
$$T = 14.96 + 0.236\ Z'$$

Fig 4 shows good correlation between hydraulic and geo-electric parameters suggesting linear relationships.

The regression lines were then used for estimating the transmissivity (T = Kh) and hydraulic conductivity (K) by using the results of electrical soundings in the area under study at other VES points.

The hydraulic conductivity values obtained from the above regression lines for other VES points are shown in the Table 4 where pump-out tests could not be performed. From the results obtained from this study it can be observed that there is no large variation in the transmissivity values in the area under study. Lower values of transmissivity and hydraulic conductivity of this area shows that groundwater in this area is mostly controlled by the less degree of weathering and fracturing. These estimates were utilized as input values in the calibration process of groundwater flow model which was further applied in the construction of transport model (Krishnaiah, 2003).

Findings from the study

From the detailed study of the well inventory, geo-electrical surveys and pump-out tests the following observations were inferred.

- Movement of the groundwater in this area is mainly controlled by the degree of weathering in basalts and by zones having secondary porosity.
- Based on the inventory of dug wells and the results of VES conducted in this area it can be concluded that there is not much lithological variation in the area.
- The combined study of the inventory of dug wells and the results of VES conducted in the study area indicate two distinct lithological layers overlie the impermeable bedrock. The topmost unit is a soil cover while the second unit is weathered and fractured basalt which forms the aquifer with its thickness ranging from 8.4 to 10.8 m indicating it to be more or less uniform.
- The pump-out tests conducted on 4 dug wells and the subsequent correlation of these results with that of VES have shown that the values of hydraulic conductivity in this area range from 5 to 6 m/day. Comparatively the lower hydraulic conductivity of this area obtained from the pumping tests can be attributed to lesser degree of weathering and fracturing. These values are important in development of numerical pollutant transport model.

CONCLUSIONS

The above study has established a viable relationship between hydraulic conductivity and electrical parameters in a basaltic aquifer of Mula sugar factory area where borehole information is very sparse. This calibrated relationship was helpful for estimating the spatial distribution of hydraulic conductivity value as an input in the construction of pragmatic numerical model that can improve the understanding of hydrodynamics of pollution spreading in the porous media of the area under study. Hence, the use of geoelectrical soundings provides an inexpensive alternative technique for calculating the hydraulic parameters and characterizing the aquifer system of the area.

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