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Determination of aquifer parameters using geoelectrical sounding and pumping test data in Khanewal District, Pakistan

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Abstract: In order to determine the ground water resources and potentials of the Khanewal District of Pakistan, a geophysical method in combination with pumping test data were used. An analytical relationship between the aquifer parameters interpreted from surface geoelectrical method and pumping test was established in order to estimate aquifer parameters from surface measurements where no pumping tests exist. For the said purpose, 48 geoelectric investigations were carried out using Schlumberger vertical electrical sounding (VES). Seven of the soundings were conducted where pumping tests had been carried out at borehole sites. The vertical electrical sounding stations were interpreted, and resistivities and thickness parameters were calculated. The values of transmissivity and hydraulic conductivity were calculated using the Dar Zarrouk parameter. Transmissivity values obtained from pumping test data and the VES method range between 954 – 4263 m^2/day and 200 – 5600 m^2/day respectively. Hydraulic conductivity values determined from pumping test data and geoelectrical technique range between 15.9 – 60.9 m/day and 29.76 - 72.3 m/day respectively. The low values of transmissivity and hydraulic conductivity indicate clay or shale while high values are due to the presence of sand or gravel. A comparison of the transmissivity values obtained from pumping test data and surface geoelectrical method shows a positive correlation (R^2 =0.90). Similarly, the regression between hydraulic conductivity determined from the pumping test data and the geoelectrical method is also positively correlated (R^2 =0.96). The results provide a quick and useful estimation of aquifer properties and potentials.

Keywords: Geophysical methods, Pumping Test, Dar Zarrouk parameters, Transverse unit resistance, Transmissivity, Hydraulic conductivity, Aquifer

1 Introduction

The aquifer parameters like hydraulic conductivity and transmissivity are extremely important for the management and development of groundwater resources [1]. Due to a rapid increase in population and agriculture, the exploitation of groundwater resources is expanding worldwide [2, 3]. The subsurface characteristics like lithology, structure and texture control the occurrence and movement of groundwater [2]. Aquifer parameters including hydraulic conductivity, transmissivity and storativity are commonly applied in groundwater modeling [4–6]. Permeability and formation factor can be estimated using empirical correlation [7–9]. The main target of this hydrogeophysical technique is to determine aquifer hydraulic properties such as transmissivity, hydraulic conductivity and porosity [1, 10]. Hydraulic conductivity can be considered the basic and main aquifer parameter to estimate the characteristics of the aquifer. There can be no physical or potential relationship between the electric resistivity and hydraulic conductivity due to its site restriction [11]. The hydraulic properties of an aquifer are measured by using or applying aquifer-tests such as the slug test, the constant-head test and the pumping test only to obtain discrete information. Regression technique utilizing both the resistivity and pumping test data has been used for the purpose of the present study, in order to determine hydraulic properties of the investigated area.

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The hydraulic analysis of wells to evaluate the groundwater potentials using pumping test data falls in the category of groundwater hydrogeology. Furthermore, the analysis of the hydraulics of wells for the evaluation of groundwater potentials by pumping tests falls in the category of groundwater hydrology. This concept was rapidly developed after the well known law of flow introduced by Henri Darcy. According to this law, the discharge through porous media is proportional to the product of the hydraulic gradient; the cross-sectional area normal to the flow and the coefficient of permeability of the material [12]. The pumping test technique is used to determine the aquifer properties and potentials. However, this technique is very expensive plus labor intensive and requires a considerable amount of equipment. The vertical electrical sounding method is non-invasive, cheap and quantitative evaluation technique to determine the aquifer parameters. Electrical and hydraulic properties should correlate because both properties are related to the pore space structure and heterogeneity [13]. The main aim of this study is to provide a cost effective technique to determine aquifer parameters by integrating the VES data with the pumping test results.

1.1 Background of the study area

Khanewal district lies in the Lower Bari Doab (between the Sutlej and Ravi rivers) of Punjab province in Pakistan with an area of 4,349 square kilometers (latitude 29.85° to 30.43°N and longitude of 71.5° to 72.47°E, Fig. 1). The resistivity points and location of wells in the study area are also given in Fig. 1. There are 48 electrical resistivity soundings (K1 to K48) and 7 tube wells (BR-1 to BR-7) used in the study area.

The district lies in the upper Indus plains, so the present physical features were created by the river action in the area. Soils are mostly alluvial and sand is found at few feet depth within the subsurface almost everywhere in the district. The whole area of the district is an alluvial plain and it slopes gently from northeast to southwest and also from northwest to southeast. The whole area is a recent formation made by the rivers comparatively and irrigation system depends on the network of canals originating from the Chenab and Ravi rivers. The groundwater flow and water table depend on both the river water and canal system [14].

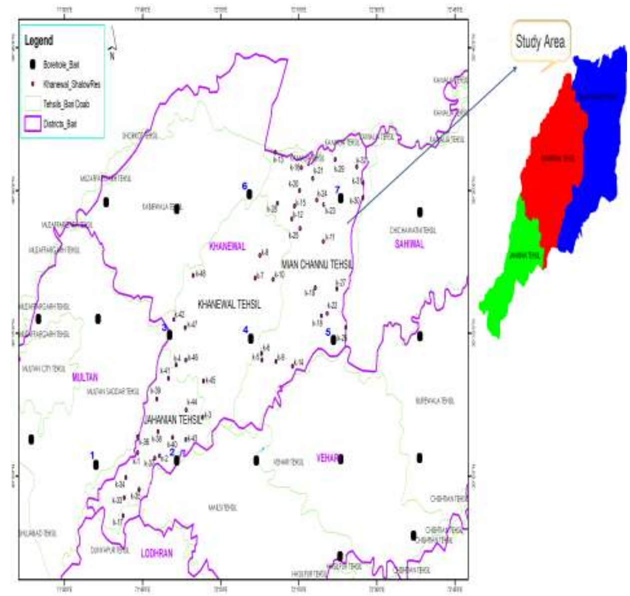

Figure 1: Location map of the study area.

1.2 Hydrogeology

An aquifer is a geological formation which has sufficient water and permeable material to yield a significant amount of water to springs or wells [15]. The alluvium of the Khanewal district overlies semi-consolidated Tertiary rocks or Precambrian age metamorphic igneous rocks [14]. The recent and Pleistocene alluvial complex contains unconsolidated silt, sand with gravel, and minor clay. These sediments have been deposited by the tributaries of the Indus River. The upper portion of the alluvium is an unconfined aquifer with high transmissivity coefficient values [16].

Many test holes have been drilled to 1000 feet depth to estimate the groundwater in the study area. However, bedrock was not encountered in any test hole. This indicates that there is no bedrock in the Khanewal area up to the depth of 1000 feet. The well logs, which were run into the test holes, show the water-bearing characteristics of the alluvial deposits which form the groundwater reservoir. The study of the lithological logs up to depth of 1000 feet gives a clear idea about the texture and structure of the alluvium. The subsurface lithologies of the alluvial complex contain silt, clay, fine sand and gravels. The area contains the alluvial material which forms a part of the extensive heterogeneous and isotropic unconfined aquifer underlying the Indus plains. This unconfined aquifer is believed to be more than 1000 feet thick. Geological evidence also shows that aquifer in the area is unconfined [17]. Most of the alluvial is highly porous and it is capable of storing and transmitting water readily. On the basis of pumping tests, the aquifer characteristics were evaluated. The permeability found in the area is in the range of 0.00033 to 0.01573 ft/sec [14]. There are five potential zones of groundwater in Punjab province of Pakistan defined as High, Medium, Low, Poor and No potential aquifer (N.A) [18]. These five zones are based on the characteristics of the groundwater aquifer. The high zone can yield 100 to 300 m^3/hr or more down to 150 m; it is a fairly thick and extensive aquifer. The medium zone has the capability to yield between 50 to 100 m^3/hr down to 150 m; it is a moderately thick and extensive aquifer. The low zone can yield between 10 to 50 m^3/hr down to 150 m; it is an aquifer of limited thickness and extension. The poor zone which is not considered as potential aquifer can yield less than 10 m^3/hr down to 150 m; it is a poor/patchy, hard rock and discontinuous. Khanewal area lies in the high potential zone (Fig. 2).

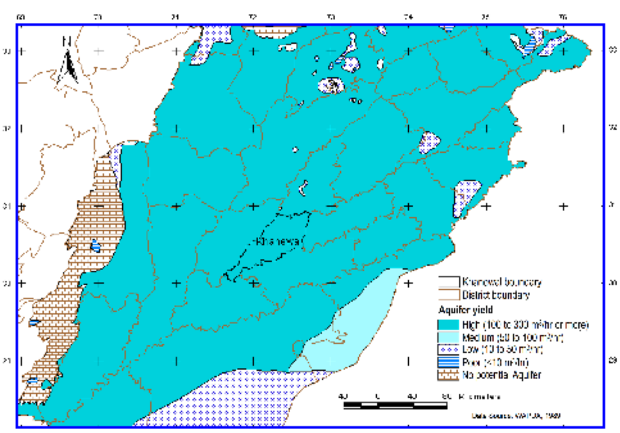

Figure 2: Hydrogeological map of the study area (WAPDA 1989. Hydrogeological map of scale 1:500,000 published by Survey of Pakistan).

Prior to the inception of perennial canal irrigation, the major factor of the ground water recharge in the region was the infiltration of water from the rivers. This was augmented in the upper parts of the Bari Doab by the infiltration of precipitation which exceeds 30 inches per year locally. In contrast, in the lower part of Bari Doab where average precipitation is only about 5 to 12 inches, the infiltration of rain water to the water table was probably negligible. River water was, therefore, the main source of groundwater replenishment in the investigated area. The general direction of groundwater movement in the area was from rivers downstream and towards the central axes of the Bari Doab. The hydraulic gradient was steeper than the topographic slopes in the upper half of the Bari Doab and the water table reached depths of more than 70 feet below the land surface near the center of the Bari Doab. In the lower half of the Bari Doab, the hydraulic gradient was less than the topographic slope and the depth to water diminished downstream until the water table merged with the rivers at the lower end of the Bari Doab.

Prior to the start of regular irrigation, the Punjab groundwater system was in a state of dynamic equilibrium; that is, recharge to the groundwater reservoir balanced discharge and there was no long-term trend of either a rising or declining water table. But the advent of the perennial canal irrigation system disturbed this equilibrium and introduced additional elements to the recharge, which caused the water table to rise. In Bari Doab (Fig. 1), the water table is still rising and has not yet reached the stable position. This rise in the water table, resulting from canal leakage, has caused a reversal in the direction of ground water flow and it is now from the center of the Bari Doab towards the rivers in many parts of the area.

2 Methods

2.1 Analysis of resistivity data

The use of resistivity survey to determine an aquifer's potential has increased due to advancement in numerical modeling solutions [2, 19]. Vertical electrical sounding (VES) is a technique which has been used in various lithological settings successfully [20–22]. The VES method is useful to study groundwater conditions and to evaluate the subsurface layers [23, 24]. Many researchers have evaluated aquifer parameters using the resistivity method [6, 9, 25].

Resistivity field data has been interpreted by using software packages that give the output in the form of the number of subsurface layers, their true resistivity values, thickness and depth from the surface. The interpreted resistivity data was compared with the already existing lithologs and well log data, and subsurface layers have been assigned lithological units in terms of their true resistivity values (Table 1). The dominant lithology encountered in the already drilled holes (vertical geological cross-section) consists of sand having variable grain size. The resistivity value changes with the minor change in sand and clay content (as evident from Table 1). The interpreted lithology based on electrical resistivity data matched with the drilled hole data.

Table 1: Resistivity and lithology calibration.

Formation Resistivity (ohm-m)	Lithology
Below water table and the resistivity less than 30 ohm-m	Silt/clay containing saline water
Below water table and resistivity between 25-35 ohm-m	Mixture of sand and clay/shale containing fresh water
Below water table and resistivity between 30-55 ohm-m	Sand containing fresh water
Below water table and resistivity greater than 55 ohm-m	Mixture of Sand and gravel containing fresh water
Above water table and resistivity greater than 70 ohm-m	Dry strata

2.2 Pumping test

This test was performed to determine the capacity of the well and the hydraulic characteristics of the aquifer. In order to estimate transmissivity and hydraulic conductivity, the tests were carried out in the study area using the single well pumping test approach for seven existing boreholes. Prior to pumping, the static water level was recorded and then after pumping, the drawdown was measured again in the well after the specific time interval. A container of known volume was used to collect the pumped water and subsequently, discharge was calculated with respect to time. Aquifer Test Pro software was used to compute the values of transmissivity and hydraulic conductivity from pump test data for seven wells in the area investigated

2.3 Correction Factor

Archie's law is valid for clay free formations but is not applicable if the formation contains clay thus the apparent formation-factor (F_a) cannot be equivalent to intrinsic formation-factor (F_i). In the present study, clay contents mixed with sand have been encountered at different horizons in the investigated area so; the clay effects are removed before the estimation of aquifer parameters. The relation between F_i and F_a is given by the equation [26]:

$$F_i = F_a[1 + (BQ_v \times R_w)] \tag{1}$$

where BQ_v is associated with the surface conduction (a function of clay particles) and will contain considerable values, if clay material exists in aquifer system; otherwise F_a is equivalent to F_i [26]. Q_v is the stands for cationic exchange-capacity per unit pore-volume for rock (meq/ml) which is the porosity function. B represents the average mobility for the cations close to the surface of the grain (mho-cm^2/meq). The values of Q_v and B can be calculated using the following equations:

$$Log(Q_v) = -3.56 - 2.74 \times \log(\varphi) \tag{2}$$

φ is porosity and

$$B = 3.83 \times [1 - 0.83e^{(-0.5 \times R_w)}] \tag{3}$$

It is clear from equation 3 that B depends on the resistivity of water (R_w).

Although the aquifers are heterogeneous and are not free of clay material, there is a linear relation between formation factor and hydraulic conductivity which can be exploited [1]. In order to find Q_v, porosity values are required. The porosity is can be estimated using a modified equation of Archie [1].

$$\varphi = e^{[(1/m)Ln(a)+(1/m)Ln(1/F_i)]} \tag{4}$$

The value of 'a' is 1 and the value range for 'm' is 1.3 to 2.5. $1/F_i$ is estimated by the plot of $1/F_a$ against R_w. $1/F_i$ is calculated by the straight line intercept and BQ_v/F_i is obtained by the gradient [1, 26]. The plot of $1/F_a$ against R_w is shown in Fig. 3 from which the value of $1/F_i$ is calculated.

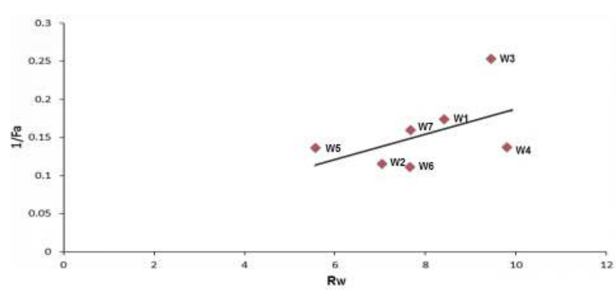

Figure 3: Cross-plot between R_w and $1/F_a$

After calculating $1/F_i$ from the cross plot of $1/F_a$ and R_w, porosity is determined from equation 4. Equations 2 and 3 give the values of B and Q_v. Q_v remains constant but B varies with the resistivity of water R_w. Finally, intrinsic formation-factor F_i is calculated by putting the values of Q_v, R_w and B into equation 1 for all resistivity points and the wells. The calculated F_i values are shown in Table 3.

2.4 Transmissivity

Transmissivity is very useful and important parameter for the estimation of aquifer potential and can be mathemati-

Table 2: Hydraulic conductivity (K) and transmissivity (T) of the selected wells from pumping test.

Well #	K(m/day)	T(m²/day)
1	30.37	2733
2	51.1	2044
3	15.9	954
4	35.8	2506
5	21.5	1505
6	60.9	4263
7	26.3	1841

Table 3: Comparison of pumped and the estimated hydraulic conductivities.

Well#	F_i	K(m/day)	K′(m/day)	%matching
1	2.53	30.37	45	67.5
2	3.33	51.1	55.7	91.7
3	1.84	15.9	29.76	53.4
4	2.33	35.8	30.6	70.3
5	3.69	21.5	72.3	84.2
6	3.62	60.9	63.7	87.6
7	2.46	26.3	40.72	64.6

cally expressed as [12]:

$$T = Kb \tag{5}$$

where K is hydraulic conductivity measured in m/day and b is the thickness of the aquifer measured in meters. The thickness of the aquifer is computed by using a partial curve matching technique and then average thickness of all the layers of each point/probe is estimated. Most of the techniques for the estimation of aquifer hydraulic parameters were introduced for porous media. These parameters are generally calculated using pumping test data. Many attempts have been made to estimate aquifer parameters using VES resistivity data. The estimation of these parameters from a pumping test is time consuming and expensive. The geophysical methods provide an alternative, rapid and cheap technique to calculate the aquifer parameters like transmissivity and hydraulic conductivity. Transverse unit resistance calculated from Dar Zarrouk parameters is proportional to transmissivity [1, 27]. The relationship between transmissivity and transverse unit resistance is given as:

$$T_R = 0.19(T)^{1.28} \tag{6}$$

where T_R is transverse unit resistance measured in ohm-m² and T is transmissivity measured in m²/day. Using this relationship transmissivity is calculated. Data from 48 VES points is used to estimate transmissivity using the above equation. The values of transmissivity estimated by equation 6 are in Fig. 4, which shows the distribution of the transmissivity values with the resistivity points. Minimum and maximum transmissivity values for the study area are 200 m²/day and 5600 m²/day respectively with average value 2420 m²/day. A contour map of transmissivity calculated from geophysical method for all 48 soundings has been drawn in Fig. 5. Green, yellow and the red colors indicate the zones with high transmissivity values where as the zones of low transmissivity values are represented by shades of blue as shown in Fig. 5. Transmissivity has high values in the central part of the area due to the presence of sand or gravel indicating the large amount of ground water in this zone.

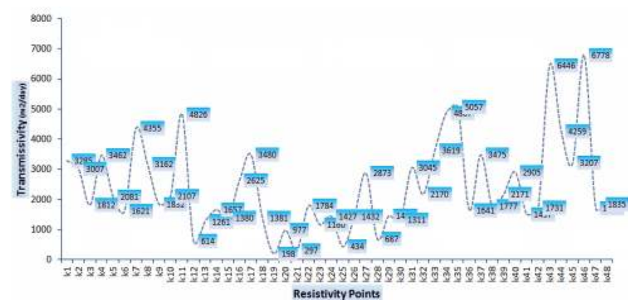

Figure 4: Graph of resistivity points and Transmissivity (m²/day).

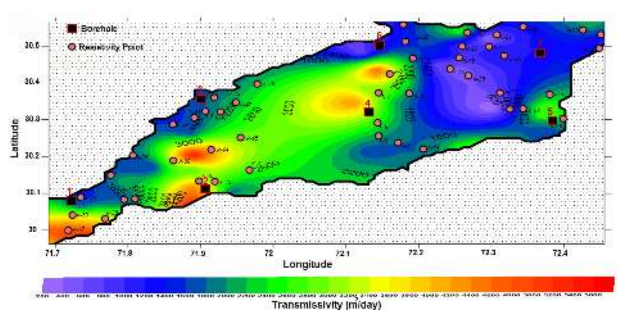

Figure 5: Estimated Transmissivity map for the investigated area.

From the map of transmissivity, it is interpreted that the central portion of the investigated area contains excellent yielding strata which is sand or gravel. Transmissivity values are low in northeast side which suggests that the chance of ground water is low in this part of the study area. The values of transmissivity measured from the pumping test using Aquifer Test Pro software for seven wells are given in Table 2. Fig. 6 shows a graphical plot between measured and modeled transmissivities for seven wells. The value of the correlation coefficient is R^2 =0.9 which shows a strong correlation between measured and modeled transmissivities. It shows that there is a very good match between the measured and modeled transmissivities and the results obtained both from electrical resistivity soundings (ERS) data and the pumping test for transmissivities are congruent.

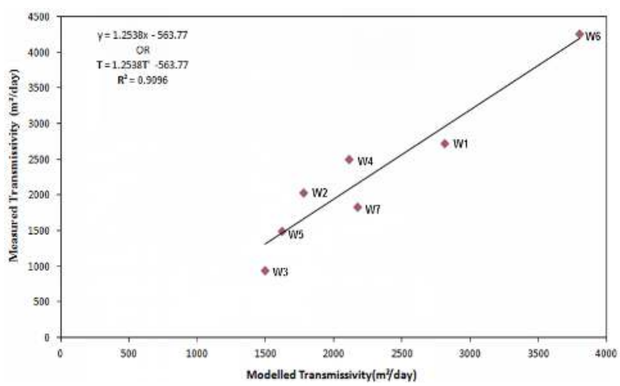

Figure 6: Measured transmissivity versus modelled transmissivity.

2.5 Hydraulic Conductivity

The main aim of hydrogeological investigations is to calculate hydraulic conductivity of the strata. The distribution of hydraulic properties for the porous media is an important step towards understanding and predicting groundwater flow and contamination of an aquifer system [28]. The hydraulic conductivity parameter is generally calculated from the pumping test and the down hole measurements [29]; but these methods are used to calculate the hydraulic properties of large geological media [30]. It is important to predict the hydraulic properties of water bearing strata and the calculation of aquifer properties including hydraulic conductivity is the main objective in water saturated environments [10]. Different approaches have been used to find the association of aquifer hydraulic conductivity with resistivity measurements. Hydraulic conductivity from geophysical methods is determined using the following formula:

$$T = Kb \tag{7}$$

$$K = T/b \tag{8}$$

where T is transmissivity measured in m^2/day, b is the aquifer thickness measured in meters and K is hydraulic conductivity measured in m/day.

Hydraulic conductivity calculated from the equation above 8 using the electrical resistivity sounding data of 48 resistivity probes is contoured as shown in Fig. 8. The hydraulic conductivity values are calculated using Aquifer Test Pro software for the aquifer system by using a pumping test for wells # 1 through 7 and results are given in Table 2.

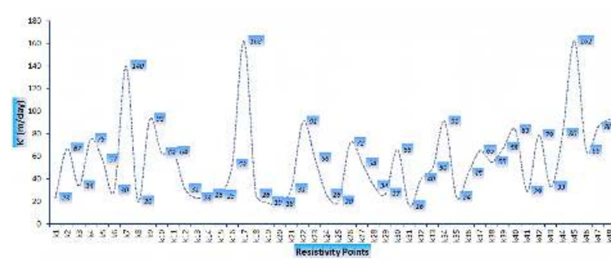

Figure 7: Graph of electrical resistivity points versus hydraulic conductivity in m/day.

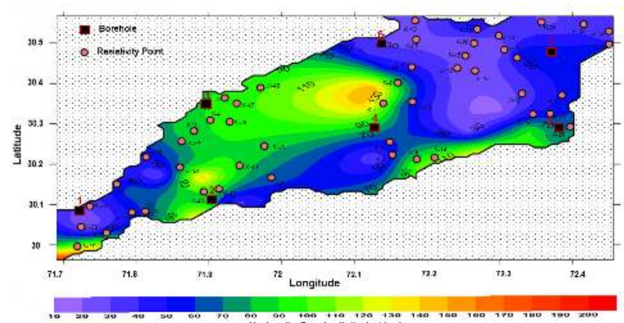

Figure 8: Contour Map for Estimated hydraulic conductivity (K′).

In order to see the relationship between intrinsic formation-factor (F_i) and estimated hydraulic conductivity, an empirical relationship has been established. To see this relationship, a cross-plot between "K"' and "F_i" is represented in Fig. 9. The equation 9 has been obtained by the fitting of polynomial-curve (2nd order) in scattered data-values having square of correlation coefficient "R^2" equivalent to 0.9427. The correlation coefficient is used to study the relationship between 2 variables in linear-regression, its value ranges from 0 to 1. If the value of "R" is closer to unity (1.0) means that both the variables have a strong correlation. One of the variables can be predicted by knowing the value of the other. If its value is 0 that means that there is no correlation between the two variables and there can be no prediction about one of the variables on the basis of the value of the other variable. The equation derived from Fig. 9 is given below:

$$K' = 5.0618F_i^2 - 6.8071F_i + 24.79 \tag{9}$$

(where $K' = y$ and $F_i = x$)

$R^2 = 0.9427$

Equation 9 is applicable for all seven wells of the investigated area.

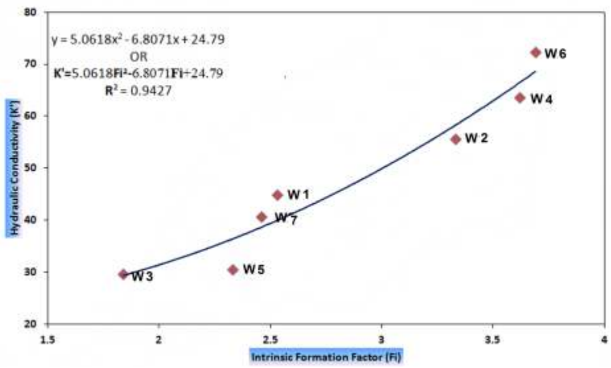

Figure 9: Cross-plot between hydraulic conductivity and intrinsic formation factor.

3 Results and Discussion

The hydraulic conductivity estimated from the electrical resistivity sounding data of 48 resistivity probes is contoured as shown in Fig. 8. The hydraulic conductivity values are calculated from Aquifer Test Pro software for the aquifer system by using a pumping test for well # 1 through well # 7 and the results are given in Table 2. In order to see the relationship between intrinsic formation-factor (F_i) and estimated hydraulic conductivity, an empirical relationship has been established. To see this relationship, a cross-plot between K′ and F_i is represented in Fig. 9. Equation 9 has been obtained by fitting a polynomial-curve (2nd order) of scattered data-values having the square of correlation coefficient R^2 equivalent to 0.9427.

The comparison of estimated hydraulic conductivity (K′) and pumped hydraulic conductivity (K) is given in Table 3. An intrinsic formation-factor with a value less than one suggests fine particles and low hydraulic conductivity whereas a high value suggests coarse-grain particles and high hydraulic conductivity (Table 3). It is evident from Table 3 that three wells (well # 2, well # 5, well # 6) match well with over 80% overlap between pumped hydraulic conductivity values (K) and estimated hydraulic conductivity values (K′). The values between pumped hydraulic conductivity (K) and estimated hydraulic conductivity (K′) overlap more than 60% in well # 1, well # 4 and well # 7, and well # 3 has 53% overlap between these values. Hence, the estimated hydraulic conductivity values are in agreement with the pumped hydraulic conductivity values. A low value for the formation factor indicates particles that have a small diameter and low hydraulic conductivity values, whereas a high formation factor value suggests large diameter particles and high hydraulic conductivity [1].

The values of transmissivity estimated by equation 6 are in Fig. 4 which shows the distribution of the transmissivity values with the resistivity points. Minimum and maximum transmissivity values for the study area are 200 m^2/day and 5600 m^2/day respectively with average value 2420 m^2/day. A contour map of transmissivity calculated from the geophysical method for all 48 soundings has been drawn in Fig. 5. Green, yellow and red colors indicate the zones with high transmissivity values whereas the zones of low transmissivity values are represented by shades of blue (Fig. 5). Transmissivity values are high in the central part of the area due to the presence of sand or gravel indicating a large amount of ground water in this zone. From the map of transmissivity, it is interpreted that the central portion of investigated area contains excellent yielding strata of sand or gravel. Transmissivity values are low in the northeast side which indicates that the chance of ground water is low in this part of the study area.

The values of transmissivity measured from the pumping test using Aquifer Test Pro software for seven wells are given in Table 2. Well 3 had the lowest transmissivity, whereas well 6 had the highest transmissivity (Figure 6). The correlation coefficient (R^2) is 0.9 which indicates a strong correlation between measured and modeled transmissivities. These results show that there is a very good match between measured and modeled transmissivities and the results obtained both from electrical resistivity soundings (ERS) data and the pumping test for transmissivities are in agreement.

The calculated parameters (estimated hydraulic-conductivity, transmissivity, intrinsic formation factor, and aquifer resistivity) of those ERS which are near the wells are given in Table 4. In order to see the distribution pattern of ERS with estimated hydraulic conductivity, a graph has been plotted (Fig. 7) that shows K′ values have not been evenly distributed and there is great variation in the values. This scatter distribution indicates the heterogeneity in the investigated area. In the investigated area, hydraulic conductivity range is 16-162 m/day with average value of 50 m/day. Approximately 16% of the ERS contain hydraulic conductivity values less than 25 m/day which represents subsurface materials consisting of clay or shale. The hydraulic conductivity values greater than 50 m/day were noted in 52% of the ERS and it indicates sand or gravel mixed with clay. Therefore, it is interpreted from the hydraulic conductivity values that sand and gravel, but especially sand, is the dominant lithology in the investigated area. It is clear that there are good zones of hydraulic conductivity with values from 25 m/day to 100 m/day or more (Fig. 8). The hydraulic conductivity of the center portion of investigated area varies between 55 m/day to 100 m/day and seems to be a good aquifer zone. The lithology of this zone is sand and gravel which act as good aquifer. The grey-blue color (northeast side, Fig. 8) shows the zones with low or minimum hydraulic-conductivity values indicating the presence of clay or shale.

Table 4: The interpreted resistivity (R_o), intrinsic formation factor (F_i), estimated hydraulic conductivity and transmissivity

VES POINT	R_o (ohm-m)	F_i	K'(m/day)	T'(m^2/day)
K-34	103	2.53	45	2812.4
K-40	95.6	3.33	55.7	1777.3
K-42	46.1	1.84	29.76	1497.01
K-6	35.2	3.62	63.7	2107.37
K-26	45.8	2.33	30.6	1621.04
K-28	36.1	3.69	72.3	3200
K-23	85.4	2.46	40.72	2170.8

In order to see the correlation, the values of measured and modeled hydraulic conductivity of seven wells has been plotted (Fig. 10). The value of the correlation coefficient is R^2 =0.9 which shows a strong correlation between measured and modeled hydraulic conductivities. Therefore, the hydraulic conductivity values obtained from both the ERS data and the pumping test are in agreement and measured and modeled hydraulic conductivities are well matched.

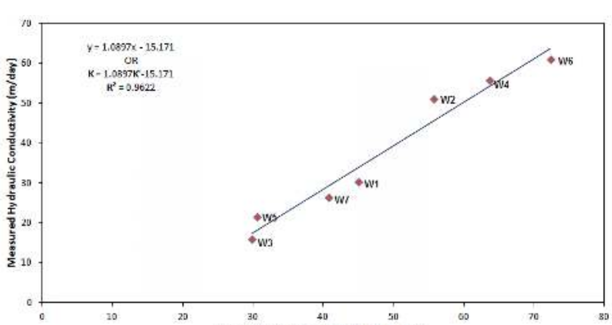

Figure 10: Measured hydraulic conductivity versus modeled hydraulic conductivity

4 Conclusions

This study has shown that the surface geoelectrical or the vertical electrical sounding (VES) method is a useful, cost effective and efficient tool to estimate aquifer hydraulic properties like aquifer transmissivity and hydraulic conductivity. The VES technique has the potential to explain subsurface layers for aquifer characteristics and groundwater exploration. The aquifer parameters of transmissivity and hydraulic conductivity were calculated from the pump test data using Aquifer Test Pro software for seven wells. The aquifer parameters estimated from the geoelectrical method for 48 VES points using Dar Zarrouk parameter (Transverse Unit Resistance) are in agreement with results obtained from pump test. The results of this investigation show that transmissivities computed from pump test data at specific locations range from 954 – 4263 m^2/day and transmissivity values estimated from surface geoelectrical method range from 200 – 5600 m^2/day. Hydraulic conductivity values determined from pumping test data and the geoelectrical technique range between 15.9 – 60.9 m/day and 29.76 – 72.3 m/day respectively. The regression between transmissivity determined from the pump test and that estimated from surface geoelectrical method are well correlated (R^2 = 0.9). Similarly, the regression between hydraulic conductivity obtained from pumping test data and the geoelectrical method is also strongly correlated (R^2 =0.96). The above technique can thus be relied upon to provide rapid complementary data for the evaluation of groundwater potentials in addition to those derived from an aquifer pumping test.

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References

[1] Soupios P.M., Kouli M., Valliantos F., Vafidis A., Stavroulakis G., Estimation of aquifer hydraulic parameters from surficial geophysical methods: a case study of Keritis Basin in Chania (Crete-Greece). *J. Hydrol.*, 2007, 338, 122–131

[2] Dor N., Syafalni S., Abustan I., Rahman M.T.A., Nazri M.A.A., Mostafa R., Mejus L., Verification of surface groundwater connectivity in an irrigation canal using geophysical, water balance and stable isotope approaches. *Water Resour. Manag.*, 2011, 25, 2837–2853

[3] Song X.M., Kong F.Z., Zhan C.S., Assessment of water resources carrying capacity in Tianjin city of China. *Water Resour. Manag.*, 2011, 25, 857–873

[4] Freeze R.A., Cherry J.A., Groundwater. Prentice-Hall, Inc., Englewood Cliffs, 1979

[5] Fitts C.R., Groundwater Science. Elsevier, Netherlands, 2002, 167–175

[6] Singh K.P., Non linear estimation of aquifer parameters from surficial resistivity measurements. *Hydrol. Earth Sys. Sci.*, 2005, 2, 917–938

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

[8] Urish D.W., Electrical resistivity: hydraulic conductivity relationships in glacial out wash aquifers. *Water Resour. Res.*, 1981, 17, 1401–1408

[9] Kumar M.S., Gnanasundar D., Elango L., Geophysical studies to determine hydraulic characteristics of an alluvial aquifer. *J. Environ. Hydrol.*, 2001, 9, 1–8

[10] Lesmes D.P., Friedman S.P., Relationship between the electrical and hydrogeological properties of rocks and soils in hydrogeophysics. Springer, Netherlands, 2005, 87-128

[11] Butler Jr., J., Hydrogeological methods for estimation of spatial variations in hydraulic conductivity. In: *Hydrogeophysics*, Springer, Netherlands, 2005, 23-58

[12] Fetter, C.W., Applied Hydrology. 2^{nd} Edition, Macmillan Publishing Company, London, 1988

[13] Mozac O., Kelly W.E., Landa I., A hydrogeological model for relations between electrical and hydraulic properties of aquifers. *J. Hydrol.*, 1985, 79, 1-19

[14] Water and Power Development Authority (WAPDA), Hydrogeological Data of Lower Bari Doab, 1980

[15] Birpinar, M.E., Aquifer parameter identification and interpretation with different analytical methods. Water SA, 2003, 29, 251–256

[16] Water and Power Development Authority (WAPDA), Hydrogeological Data of Lower Bari Doab, 1978

[17] Bennett G.D., Sheikh I.A., Alr S., Analysis of aquifer tests in the Punjab region of West Pakistan. *United States Geological Survey, Water-Supply Paper* (W1608G), 1967

[18] Water and Power Development Authority (WAPDA), *Annual Reports* 1988-89, *Lahore*, 1989, 21-98

[19] Lashkaripour G.R., Nakhaei M., Geoelectrical investigation for the assessment of groundwater conditions: a case study. *Ann. Geophys.*, 2005, 48, 937–944

[20] Sahu P.C., Sahoo H., Targeting groundwater in tribal dominated bonai area of drought prone Sundargarh District, Orissa, India. A combined geophysical and remote sensing approach. *J Hum Ecol*, 2006, 20,109–115

[21] Dawoud M.A., Raouf A.R.A., Groundwater exploration and assessment in rural communities of Yobe State, Northern Nigeria. *Water Resour. Manag.*, 2009, 23, 581–601

[22] Sikandar P., Bakhsh A., Arshad M., Rana T., The use of vertical electrical sounding resistivity method for the location of low salinity groundwater for irrigation in Chaj and Rachna Doabs. *Environ. Earth Sci.*, 2010, 60, 1113–1129

[23] Lashkaripour G.R., Ghafoori M., Electrical resistivity survey for predicting Samsor aquifer properties, Southeast Iran. *Geophys. Res. Abstract*, 2005, 7, 1–5

[24] Oseji J.O., Asokhia M.B., Okolie E.C., Determination of groundwater potential in obiaruku and environs using surface geoelectric sounding. *Environmentalist*, 2006, 26, 301–308

[25] Bussian A.E., Electrical conductance in porous medium. *Geophys.*, 1983, 48, 1258–1268

[26] Worthington P.F., Reply [to “Comments on ‘Influence of matrix conduction upon hydrogeophysical relationships in arenaceous aquifers’ by P.F. Worthington”]. *Water Resour. Res.*, 1977, 13, 1024-1024

[27] Akaolisa C., Aquifer transmissivity and basement structure determination using resistivity sounding at Jos Plateau state Nigeria. *Environ. Monit. Assess.*, 2006, 114, 27–34

[28] Straface S., Yeh T.C. J., Zhu J., Troisi S., Lee C.H., Sequential aquifer tests at a well field, Montalto Uffugo Scalo, Italy. *Water Resour. Res.*, 2007, 43

[29] Rabaute A., Revil A., Brosse E., In situ mineralogy and permeability logs from downhole measurements: Application to a case study in chlorite-coated sandstones. *J. Geophys. Res.: Solid Earth*, 2003, 108

[30] Butler J.J., Liu W., Pumping tests in nonuniform aquifers: The radially asymmetric case. *Water Resour. Res.*, 1993, 29, 259–269