Available Online at http://www.journalajst.com

ISSN: 0976-3376

ASIAN JOURNAL OF
SCIENCE AND TECHNOLOGY

Asian Journal of Science and Technology
Vol. 6, Issue 01, pp. 915-923, January, 2015

RESEARCH ARTICLE

USE OF VERTICAL ELECTRICAL SOUNDING (VES) TECHNIQUES TO EXPLORE THE GROUNDWATER POTENTIAL

[1]*Hafiz Umar Farid and [2]Allah Bakhsh

[1]Department of Agricultural Engineering, Bahauddin Zakariya University, Multan, 60800 Pakistan
[2]Department of Irrigation and Drainage, University of Agriculture, Faisalabad, 38040 Pakistan

ARTICLE INFO

Article History:
Received 10th October, 2014
Received in revised form
10th November, 2014
Accepted 08th December, 2014
Published online 30th January, 2015

Key words:

Resistivity survey,
Groundwater quality,
Pumping test,
Aquifer parameters.

ABSTRACT

VES survey can be used to determine aquifer parameters and fresh groundwater formation below ground surface for pumping to minimize secondary salinization problems. Two VES surveys (VES 1and VES 2) were conducted at farmer's field, in District Toba Tek Singh, Punjab, Pakistan. Resistivity meter Tarrameter (SAS 4000, Sweden) was used to collect resistivity data. Drilling operation was performed at VES site. 100 soil and water samples were collected to analyze groundwater quality and prepare well log profile. Well log profile was compared with VES interpretation of subsurface lithology. Based on the VES surveys results, well parameters were designed and installed at study area. Pumping test was performed to verify VES survey results. 1X1D (Interpex, USA) computer model was used to analyze resistivity data. Model output showed 4-layers model (KQ type) at VES 1 position and 3-layers model (K type) at VES 2 position, which matched well with well log of borehole data. The results indicated that fresh groundwater was available from 8 to 15 m depth below ground surface having resistivity values of more than 41 Ω-m. Marginal quality groundwater with resistivity values of 41 to 21 Ω-m was found from 15 to 20 m depth. The groundwater quality deteriorated further downwards. Values of k ranged from 92 to 96 m day^{-1} and of T from 1163 to 1256 m^2 day^{-1} computed from VES data were in close agreement with those determined from pumping test data showing potential of VES technique to assess groundwater quality configuration, aquifer parameters and finally to design well parameters.

INTRODUCTION

Groundwater is contributing significantly in the development of agricultural economy of Pakistan. As the canal water supplies are decreasing, the pressure on groundwater resources is increasing. Thus, groundwater usage has become increasingly important for irrigated agriculture in Pakistan because tube wells are providing a reliable source of water to the farmers particularly in case of canal water scarcity as well as during drought conditions. Total water availability in Pakistan during 2010-11 was of 168 billion cubic meter (BCM) out of which 59 BCM was available from tube wells and this contribution of groundwater have been increasing over the years (ASP, 2011). According to PES, (2012) the number of tube wells in the country has increased to 1 million, which shows contribution of groundwater to meet the crop water requirements due to increasing shortage of canal water supplies. Over 80 percent of groundwater pumpage takes using small tube well of capacity less than 1 cusec. Also, there is no regulatory body to monitor installation of the tube wells or register their growth, which has resulted in sever problems of falling water table along with secondary salinization (Qureshi *et al*., 2003; Qureshi *et al*., 2010). The major reason for these repercussions of groundwater usage is management of the groundwater resources, which could not keep balance between recharge and discharge quantum (Bakhsh and Kanwar, 2008). Pumping more than the replenishment has resulted in deterioration of groundwater quality as well as lowering of groundwater levels. The lessons regarding management of groundwater resources, however, could not be implemented in Pakistan, which needs immediate attention for mitigation of groundwater issues. The difficult part of groundwater management in Pakistan is mushroom growth of small-scale tube wells. A major barrier that prevents transition from groundwater development to management mode is the lack of information of groundwater quality and quantity. Therefore, knowledge of the aquifer characteristics and groundwater quality is important in determining potential of the aquifer and its response to water extraction. The methods commonly used for determining the aquifer characteristics are borehole and pumping test methods, which are laborious and time consuming. Now the resistivity survey has shown potential to determine the aquifer characteristics (Lashkaripour *et al*.,

---

***Corresponding author: Hafiz Umar Farid**
Department of Agricultural Engineering, Bahauddin Zakariya University, Multan, 60800 Pakistan

2005). Therefore, resistivity survey was used in this study to estimate the aquifer parameters and to install the appropriate well screen for efficient use of groundwater. The vertical electrical sounding (VES) survey has been used extensively for location of the aquifer and determining their hydraulic parameters because the instrument is simple and analysis of the data is easy and less tedious than other methods (Lashkaripour *et al.*, 2005; Batayaneh, 2007; Sikandar *et al.*, 2009). Various investigators have established relationships between aquifer parameters derived from VES data and pumping test technique (Khan *et al.*, 2008; Mbonu *et al.*, 1991; Yadav *et al.*, 1993). Kelly, (1977) developed a relationship between aquifer hydraulic conductivity and aquifer resistivity. Similarly, Niwas and Singhal, (1985) developed an analytical relationship between aquifer transmissivity and transverse unit resistance. The above referred studies show use of VES survey for assessing aquifer potential and hydrogeological parameters. Few studies, however, have verified the VES outcome with the actual aquifer parameters determined from the borehole or pumping test data. Therefore, this study was designed to verify the VES survey outcome and asses the aquifer potential for sustainable exploitation of groundwater with the following specific objectives:

- Investigate the relationship between aquifer characteristics and vertical electrical sounding (VES) data and to design irrigation well.
- Verify the aquifer parameters determined from VES technique with those from borehole and pumping test data.

MATERIAL AND METHODS

Study area

The study was conducted at Chak No. 405/JB Tehsil and District Toba Tek Singh, Punjab, Pakistan with latitude, 30^0 96′67″ N and longitude, 72^0 48′33″ E. The area is located in Rachna Doab, land between river Ravi and river Chenab. The area is at the tail on Jhang branch canal of Lower Chenab canal originating from river Chenab at Khanki headworks (Figure 1). Canal water supplies are meager in the area and irrigation requirements are met using canal and groundwater supplies. Groundwater is mostly of poor quality except the top fresh groundwater layer, which needs to be identified using VES survey and skimmed carefully to avoid secondary salinization problems.

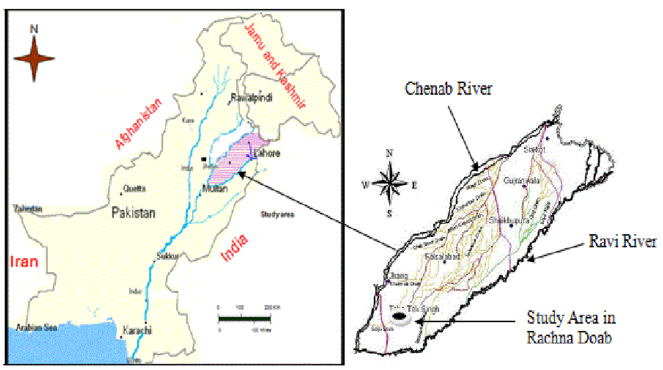


Fig. 1. Study area in Rachna Doab (land between river Ravi and Chenab)

VES Survey

Tow resistivity surveys were conducted at the site. These surveys were performed to get information regarding potential of groundwater resources in the area, thickness of fresh groundwater layers and soil layering below the ground surface. Resistivity, the inverse of electrical conductivity, is the resistance of the geologic medium offered to current flow when a potential difference is applied, R=V/I in which R is resistance in ohms (Ω), V is voltage in Volt, I is current in Ampere. For resistivity surveys, a direct current was applied through ground surface between two metal electrodes A and B (Figure 2). The voltage loss that occurs as the current moves through the ground was measured at the potential electrodes M and N placed in between the current electrodes. Resistivity values were measured using electrical sounding for vertical exploration. In this procedure, a series of stations were established and careful depth soundings were taken. Resistivity survey was conducted at the site using resistivity meter (Terrameter ABEM SAS 4000, Sweden) in collaboration with the Agricultural Engineering Department, Field Wing, Government of Punjab, as survey meter is owned by this Department. The survey cost was at the rate of Pak Rs. 3,150/- per survey. The Schlumberger electrode configuration with current electrode spacing (AB/2) of 2, 4, 6, 8, 10, $10^¥$, 15, 20, 25, $25^¥$, 30, 35, 40, 45, 50, $50^¥$, 60, 70, 80, 90, 100, $100^¥$, 120, 140, 160 and 180 m was followed.

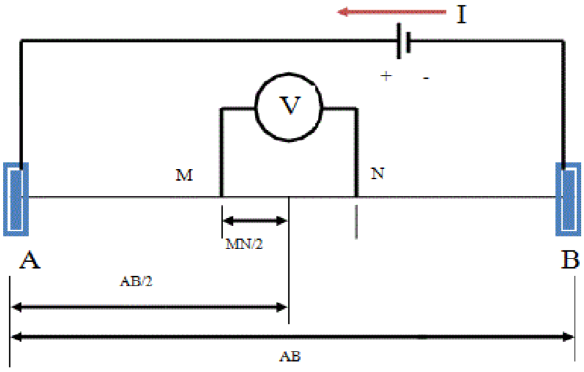


Fig. 2. Layout of Schlumberger array

Similarly the potential electrode separation (MN/2) was kept at 0.5, and was extended to 2, 5, 10 and 20 m in relation to above mentioned AB/2 spacing (Farid, 2009). The ratio between voltage and current was calculated automatically and was displayed in digital form in kilo-Ω, ohms (Ω), and milli-Ω. The overall range thus extended from 0.05 milli-Ω to 1999 kilo-Ω. By using resistance of the earth, which was measured in the fields with the help of resistivity meter, the apparent resistivity for Schlumberger electrode configuration was calculated using the following relationship (Raghunath, 2007):

$^¥$ spacing (AB/2) at which MN/2 spacing was extended

$$\rho = K_c \text{ x resistance} \tag{1}$$

Where

ρ =Apparent resistivity (Ω-m)
K_c =Geometric constant

$$K_c = \frac{\pi\, (AB/2)^2 - (MN/2)^2}{MN} \qquad (2)$$

AB = Spacing between current electrodes (m)
MN = Spacing between potential electrodes (m)

The analyses of the VES survey data were made using the computer software IXID (Interpex, USA). The success of any geoelectrical resistivity survey depends on the subsurface truthing, where VES survey is performed. After collecting the VES resistivity survey data, drilling operation of the production well (PW) was performed up to 36 m depth. Three observation wells (OW) in the west and three in the south-east directions were drilled up to 15, 23 and 29 m depth to monitor and record water table data. The bottom 3 m length of all observation well was screened to allow water movements into the observation well. Soil samples were collected starting from ground surface to the drilling depth with an interval of 1.5 to 3 m and also depending on variability of the subsurface strata. Groundwater samples were collected during drilling operation, starting from water table to depth of the observation well with an interval of 1.5 m. These about 100 soil and groundwater samples were analyzed in laboratory, to carry out the soil textural and water quality analysis. These data were used to prepare well log for the observation well to compare with the vertical profile of the VES interpreted results in terms of subsurface lithological layers and the corresponding resistivity values and groundwater quality status.

Subsurface layer models

The subsurface layering was derived as computer model output based on the distinct resistivity values of the upper layer (ρ_1), second layer (ρ_2), third layer (ρ_3) and so on. These layer types can be defined in terms of the number of geoelectrical layers and their corresponding resistivity relationship (Batayneh, 2007). Orellana and Mooney (1966) presented four types of interpreted curves based on three layered earth configuration. Accordingly, the three layered subsurface profile were classified into H, K, A, and Q type curves, based on their shapes (Oseji *et al.*, 2005). The detail of these curves and their corresponding resistivities data is described below:

H-type	$\rho_1 > \rho_2 < \rho_3$
K-type	$\rho_1 < \rho_2 > \rho_3$
A-type	$\rho_1 < \rho_2 < \rho_3$
Q-type	$\rho_1 > \rho_2 > \rho_3$

Similarly in this way we can extend these types for four layers KQ-type ($\rho_1 < \rho_2 > \rho_3 > \rho_4$. On basis of the above motioned criteria, the apparent resistivity field curves of the study area were classified.

Aquifer characteristics and VES data

Vouillamoz *et al.* (2007) reported that in aquifers having low resistive clayey layers, electrical conductivity (EC) of groundwater can be investigated using a linear relationship between resistivity values of the aquifer and resistivity data of groundwater from VES interpreted data. Therefore, according to eq. 3, resistivity of the saturated sand (ρ_{ws}) is directly proportional to resistivity of the water (ρ_w=1/EC) filling the pores (Archie, 1942; Yadav, (1995).

$$F = \rho_{ws}/\rho_w \qquad (3)$$

Where F is known as the formation factor, which is constant for pure sand. Thus layer-wise knowing resistivity values of the groundwater and resistivity of the aquifer, F was calculated. The formation factor (F), computed from resistivity survey data was used to determine the layer-wise hydraulic conductivity (k) values using relationship (k = 21.18 F – 4.48) given by Yadav, (1995). The product of thickness of different subsurface geoelectric layer and their respective electrical conductivity is known as the longitudinal conductance of that layer, which is defined for a specific layer as (Yadav, 1995):

$$LC_i = \sigma_i \times H_i \qquad (4)$$

Where LC_i is the longitudinal conductance of ith layer, σ_i is electrical conductivity (σ=1/ρ) of that layer from VES data and H_i is thickness of ith subsurface layer. Whereas product of subsurface geoelectric layer and its respective resistivity is known as transverse resistance of that layer. Transverse resistance (TR_i) is also known as the Dar-Zarrouk variable (Maillet, 1947), which can be calculated for a specific layer as below:

$$TR_i = \rho_i \times H_i \qquad (5)$$

Where TR_i is the transverse resistance of ith layer, ρ_i is resistivity of that layer from VES data and H_i is thickness of ith subsurface layer. Various researchers have reported significant correlation between LC_i and TR_i (Niwas and Singhal, 1981; Saleem, 1999) with good results in homogenous geological conditions, where aquifer resistivity is not sensitive to variations in groundwater electrical conductivity. The following relationship is an analytical relationship between aquifer transverse resistance (TR_i) or longitudinal conductance (LC_i) and transmissivity (T_i) determined by Niwas and Singhal (1981) as given below:

$$T_i = k_i \text{ x } TR_i \text{ x } \sigma_i = k_i \text{ x } LC_i \text{ x } \rho_i \qquad (6)$$

Where

k = Hydraulic conductivity of the aquifer (m day^{-1})
σ = Electrical conductivity (S m^{-1})
ρ = Resistivity of the subsurface layer (Ω -m)
i= number of layers 1, 2, 3,…………

The aquifer hydraulic conductivity (k) and transmissivity (T) values were estimated as the weighted average taking into account the corresponding thickness of the layers.

Irrigation Well Design and Evaluation

Required well discharge was selected following the cropping pattern of the study area. The rate of pumping depends on the area under different crops, crop water requirement, rotation period and operating duration of pump. It was computed by the following relationship as described by Michael, (1986);

$$Q=27.78\ Ay/RT \qquad (7)$$

A= Area to be irrigated (ha)
y= Depth of irrigation (cm)
R= Rotation period (days)
T= duration of pumping (hours/day)

The depth of the well was determined based on VES survey results and the well log profile of the site. Well casing was decided on the basis of the required discharge capacity of the well from the data recommended by Rahman, 1983.The optimum length of the well screen was determined using the relationship described by (Raghunath, 2007)

Screen length =3/4*aquifer thickness (8)

Mechanical analysis of the soil samples were carried out. A typical grain size distribution curve was prepared to determine uniformity coefficient ($Cu = d_{60}/d_{10}$) and slot size (Figure 3). Because, the gravel packing was provided to avoid the segregation of the fine particles near the strainer openings when the uniformity coefficient Cu is less than 3 (Raghunath, 2007). The selection of the screen material was made on the basis of groundwater quality, strength, availability in the market and corrosion resistance of the material. The entrance velocity was calculated by dividing the expected yield of the well by the total opening area in the length of the screen which is 15 to 20%. Because the entrance velocities near the well should not exceed 3 to 6 cm/sec to prevent the incrustation, corrosion and to minimize the friction losses (Raghunath, 2007). The relationship was used as:

$$Ve = Q/A \quad (9)$$

Ve = entrance velocity (cm/sec)
Q = expected discharge (cm^3/min)
A = opening area of the screen (20% of screen length) (cm^2)

Then well assembly was lowered into the drilled hole according to the designed parameters.

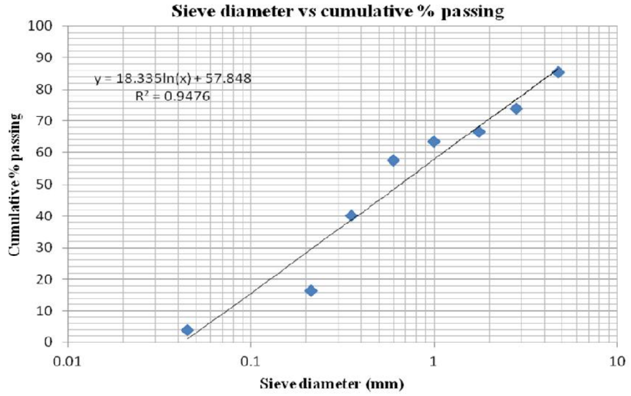


Fig. 3. Mechanical analysis data curve for well design parameters

Pumping test

The pumping test was performed to verify the aquifer parameters estimated from the VES data. The test continued till drawdown in the observation wells reached steady state condition. This situation arrived after 12 hours of continuous pumping. Drawdown data were recorded at each observation well using water level indicator during pumping test. Drawdown data were plotted against time on the log-log scale to determine the aquifer type whether confined or unconfined. On basis of the inferences drawn from analysis of the time-drawdown data of pumping, the aquifer was identified having characteristics of the confined aquifer. Similarly from well log data of the aquifer and plot of the time versus drawdown data showed behavior of the confined aquifer. A graphical procedure, developed by Theis (1935) and Lohman (1972), for determining hydraulic parameters of the confined aquifer such as transmissivity and hydraulic conductivity was used. Data curve of drawdown (s) vs r^2/t was superimposed on the type curve W(u) vs u, where r is distance of OW from PW and t is the time since pumping. A match point was arbitrarily selected, and values of s, r^2/t; u and W(u) were determined for all dataset (graphs not shown here). Transmissivity (T) and hydraulic conductivity (k) of the aquifer were calculated.

RESULTS AND DISCUSSION

Apparent resistivity data from the field survey showed an increasing trend along with increase in electrode spacing at both the survey sites of VES 1 and VES 2 (Figures 4, 5). The apparent resistivity values started from 27 Ω-m at current electrode spacing of 2 m and increased to 60 Ω-m at spacing of 17 m. This showed peak of resistivity value, which decreased to 1.5 Ω-m when spacing was extended to 180 m. Similar trend was observed at the second site of VES 2 with slight difference in the peak value of the apparent resistivity as 40 Ω-m at spacing of 10 m. Higher values of apparent resistivity indicate improvement in groundwater quality for saturated strata and variations in the lithological layers in the unsaturated media as to be discussed in the subsequent sections. The apparent resistivity data were used as input to the model and output was a subsurface four layered model for VES 1 data and three layered model for VES 2 data (Figures 4 & 5). Less number of layers at VES 2 was due to shorter current electrode spacing of 100 m compared with 180 m at VES 1. The apparent resistivity curves at position VES 1 (Figure 4) indicated four geoelectrical layers and these were classified as KQ type. This curve type indicated four layers with their layer resistivity relationship as $\rho_1 < \rho_2 > \rho_3 > \rho_4$. The second apparent resistivity curve at the position VES 2 (Figure 5) was classified as K type curve because the layer resistivity relationship was as $\rho_1 < \rho_2 > \rho_3$. The watertable depth, 8 m from the ground surface, was predicted accurately from interpretation of the smooth model. Maximum apparent resistivity values in the smooth model showed start of the saturated geological formation affected by groundwater quality. The depths of the maximum apparent resistivity data at both the sites, however, were similar showing same water table depths as determined from the borehole data (Figure 4 and 5).

The results of VES 1, VES 2 surveys and soil samples collected from the drilled borehole were compared (Figure 4 and 5). The average resistivities of the four subsurface layers model for VES 1 position were: 22.9, 95.9, 6.4, and 2.3 Ω -m for depths of 1.7, 1.7 to 15.4, 15.4 to 42.3 m and beyond 42.3 m, respectively. Similarly the average resistivities for three layers for VES 2 position for depths from ground surface to 1.2, 1.2 to 14.3 and below 14.3 m were: 24.5, 55.6, and 6.25 Ω -m, respectively. The resistivity values of the 2nd layer (1.7 to 15 m) showed that good quality groundwater was available in this layer at a depth of 8 m below the ground surface due to its high resistivity data in the smooth model (Figures 4 and 5). Similarly, resistivities of the 3rd layer (15 to 42 m depth) also compared well with the borehole data, which indicated coarse sand with alternate layer of clay containing poor quality groundwater up to depth of 42 m. The fourth layer (>42 m depth) contained very poor quality groundwater in fine sand due to resistivity values lower than 22 Ω-m. The decreasing trend in resistivity values showed deteriorating ground water quality downwards. Bernard (2003) has reported similar criteria for interpreting VES data into subsurface layering. The EC and SAR values increased with increase in the depth below ground surface. These results compare well with the resistivity values obtained from the smooth model in Figure 4 for VES 1 position.

Table 1. Aquifer resistivity and groundwater quality data

Sr. No.	Depth (m) of Groundwater Samples	Aquifer resistivity (Ohm-m) (Smooth model Fig. 4)	Ground water EC ($dS\ m^{-1}$)	Ground water SAR
1	8	82	1.01	7
2	11	45	1.20	8
3	14	40	1.40	9
4	17	20	2.01	12
5	18	18	2.50	13
6	19	17	3.20	15
7	23	13	4.50	18
8	26	10	5.20	20
9	29	7	5.50	22

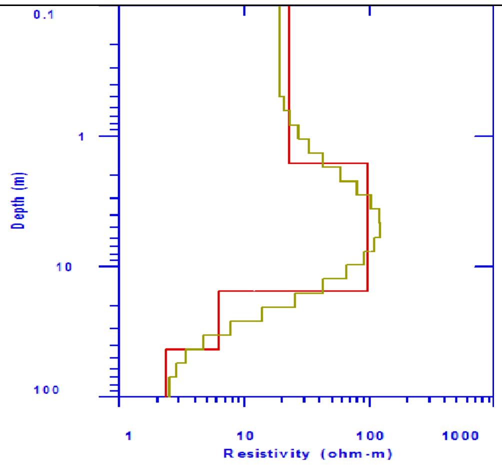
	Layers	Depth (m)	Resistivity (Ω-m)	Interpretation	VES Model
(VES 1)	1	0-1.61	22.9	Sand and clay with contain with moisture content	
	2	1.61-15.37	95.9	Layer of course sand mixed with clay contain good quality ground water	
	3	15.37-42.35	6.4	Alternate layers of clay and sand containing poor quality ground water	
	4	42.90-100	2.3	Very fine sand with alternate layers of clay containing very poor/ brackish groundwater	

Fig. 4. Computer software 1X1D output at VES 1

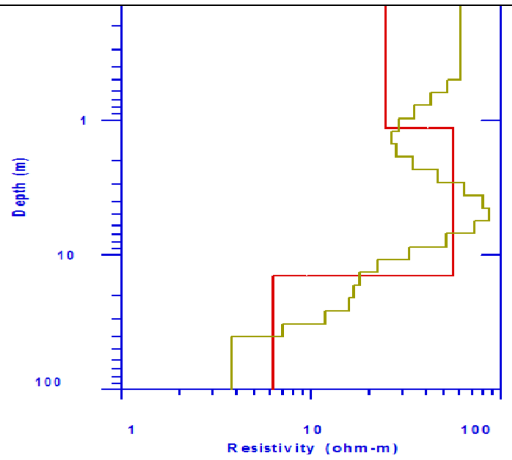
Site (VES)	Layers	Depth (m)	Resistivity (Ω-m)	Interpretation	VES Model
(VES 2)	1	0-1.14	24.5	Loam with contain with conserved moisture content	
	2	1.14-14.24	55.6	Layer of course sand mixed with clay contain good quality ground water	
	3	14.37-100	6.25	Alternate layers of clay and sand containing poor quality ground water	

Fig. 5. Computer software 1X1D output at VES 2

These resistivity values shows decreasing trend as moving downwards below ground surface, however, EC and SAR values increased downwards showing deteriorating groundwater quality Table-1. At 15.6 m depth from ground surface, EC, SAR and resistivity values were within permissible limits, which indicated that good quality groundwater was available up to depth of 15 m from watertable. Beyond this depth, groundwater quality deteriorated as moving down with lower resistivity values of 6.4 Ω-m (Table 1; Figure 4 and 5) (Farid, 2009).

Well Design Parameters and Evaluation

The required discharge was calculated using the eq. 7 which was found to be 1.50 m^3/min (0.89 cfs). Screen length was determined by means of eq.8, which was of 12 m for the aquifer thickness of 29 m. The slot size of the screen was determined at d_{60} of the aquifer material 50 x 3.5 mm. Hence, screen diameter of (8") 200 mm with opening area of 20% was selected as recommendation by Rahman, 1983. The entrance velocity was of 2.98 cm/sec for required well yield of

Table 2. Summary of well design parameters at study area

Well Design Parameters	Specification
Required Discharge (m^3/min)	1.50
Actual discharge (m^3/min)	1.52
Depth (m)	36
Casing Pipe length (m)	29
Casing Pipe Diameter (cm)	30
Screen Length (m)	12
Screen Diameter (mm)	20
Slot Opening (mm)	2
Screen Open Area (%)	20
Gravel Pack	Naturally Gravel Pack
Method of Drilling	Cable Tool Method

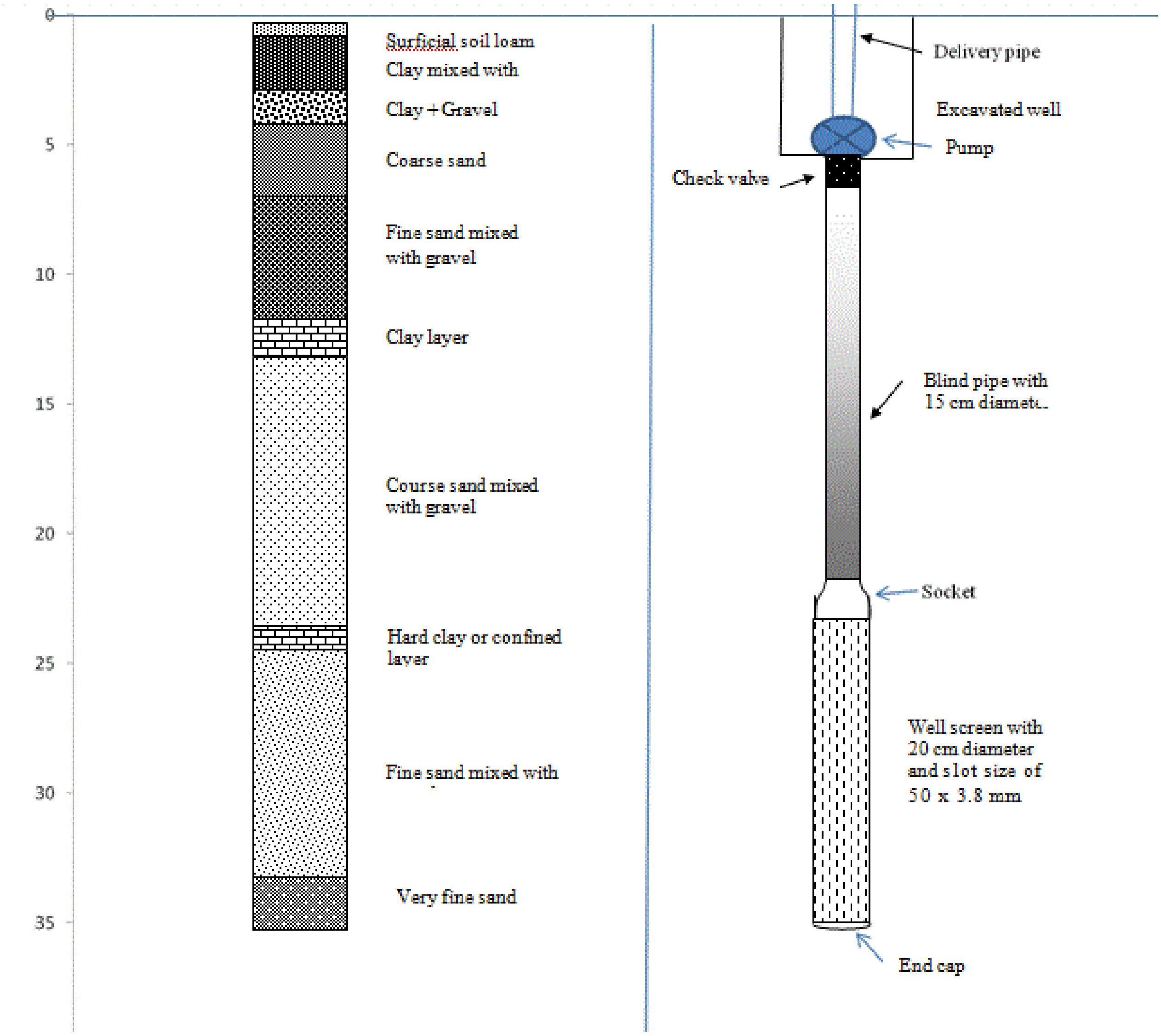


Fig. 6. Relationship between subsurface lithology and tubewell assembly

1.50 m^3/min and 20% screen opening area, which is under permissible limit (Raghunath, 2007). Using the typical grain size distribution curve from Figure 6, the following values were obtained as $d_{10} = 0.08$ mm, $d_{60} = 1.5$ mm and Uniformity Coefficient (Cu) = $d_{60} / d_{10} = 1.5/0.08 = 18.75$. The uniformity coefficient is greater than 3 (Cu > 3) hence, it was decided that the aquifer is naturally packed and there is no need to specify gravel pack (Driscol, 1986). After determining the well design parameters, well assembly was lowered into the drilling hole. A filter of diameter 20 cm (8 inch) was lowered up to 12 m (39 ft) depth (3 pipe lengths, each length of 4 m (13 ft)). Above the filter, 5 pipe lengths of 20 m (65 ft) of blind pipe of diameter 15 cm (6 inch) were connected to the filter (Table 2). The estimated entrance velocity is about 2.98 cm/sec for required well yield of 1.50 m^3/min and 20% opening area of the screen. The calculated entrance velocity is less than recommended entrance velocity of 3 cm/sec by Raghunath, (2007) which is under permissible limit. The measured well yield was of 1.52 m3/min (0.89 ft^3/sec) which was very close to the required well yield of 1.50 m3/min. The groundwater quality was also determined, which was of 4 dS/m. The clay layer was found at depth 24 m below the ground surface shown in Figure 6. Below this layer the groundwater is saline. The same well will be used to recharge the groundwater using Aquifer Storage and Recovery (ASR) technology. The ASR technology is better suited for the saline aquifer (Goyal *et al.*, 2008). Therefore, the strainer was lowered below the clay layer (Figure 6).

Aquifer parameters

The greater value of the formation factor shows presence of more resistive particles in the soil having bigger diameter, which are most likely sand and gravel particles. The minimum value of the formation factor was 1.27, (Table 3) indicating presence of finer particles composition and low hydraulic conductivity values (Soupios *et al*, 2007), whereas maximum value of the formation factor was of 9.68, showing presence particles composition of bigger diameter and higher hydraulic conductivity of the aquifer. The hydraulic conductivity values determined from formation factor ‘F’ were averaged as 96 m day^{-1} for VES 1 and 92 m day^{-1} for VES 2, which were in close

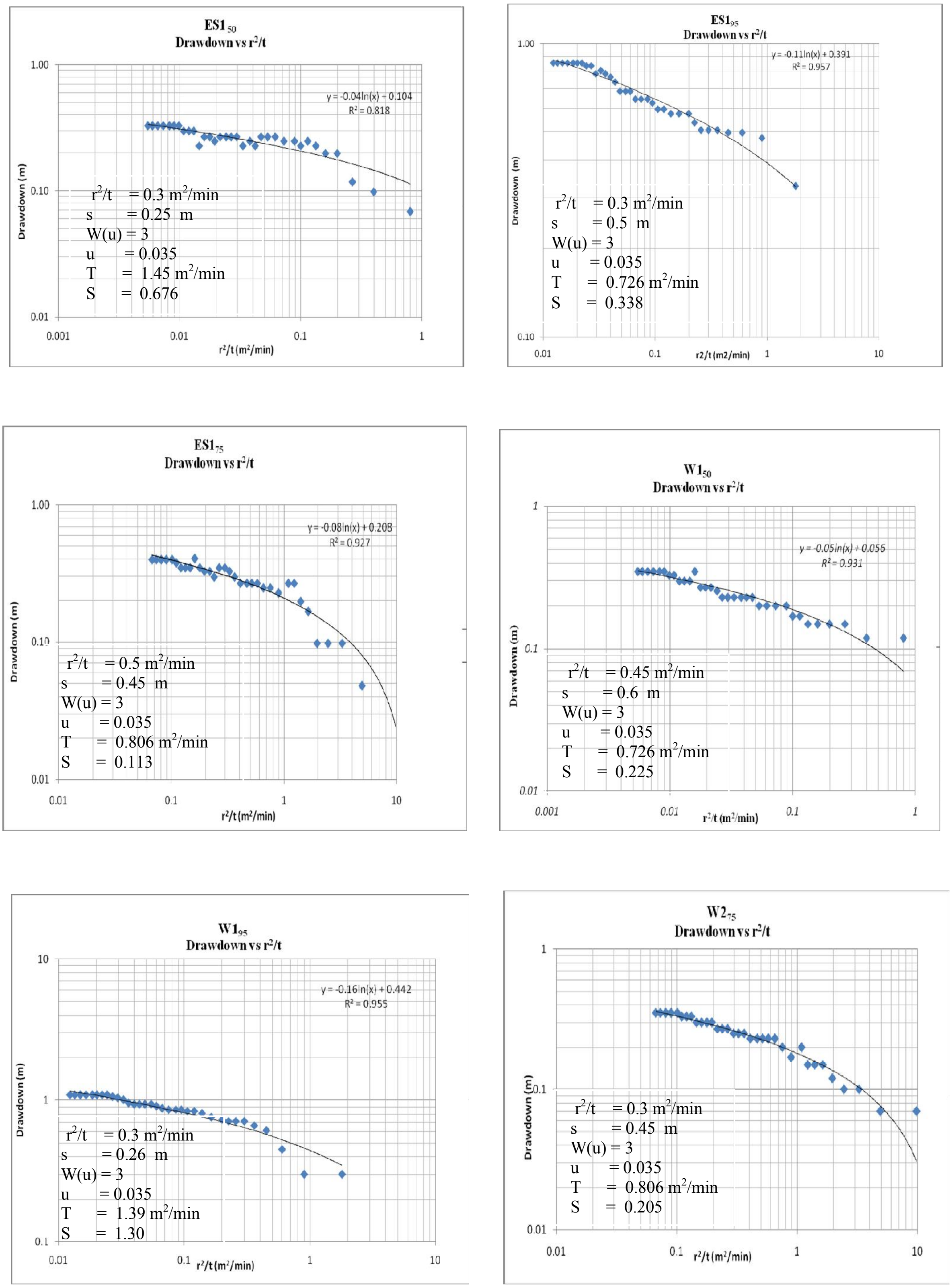


Fig. 7. Logarithmic plot between r^2/t vs s for observation wells

Table 3. Formation factor

VES Site	Depths (m)	VES Resistivity (Ω-m)	Remarks	Groundwater Resistivity (Ω-m)	Formation Factor F
VES 1	1.61	22.9	Unsaturated		
	13.75	95.9	Saturated	9.59	10
	27.61	6.4	Saturated	1.92	3.33
		2.3	Saturated	1.81	1.27
VES 2	1.14	24.5	Unsaturated		
	13.10	55.6	Saturated	9.80	5.61
		6.25	Saturated	1.81	3.45

Table 4. Longitudinal conductance and transverse resistance

VES Sites	Depths (m)	VES Resistivity (Ω-m)	Remarks	Transverse resistance (Ω-m^2)	Longitudinal Conductance (Siemens)
VES 1	1.61	22.9	Unsaturated	36.86	0.07
	13.75	95.9	Saturated	1318.62	0.14
	27.61	6.4	Saturated	176.70	0.431
		2.3	Saturated	undefined	undefined
VES 2	1.14	24.5	Unsaturated	27.93	0.04
	13.10	55.6	Saturated	728.36	0.23
		6.25	Saturated	undefined	undefined

agreement with the range of 39.6 to 118 m day^{-1} determined by WAPDA (WASID, 1964) for Rechna Doab. Similarly the average transmissivity was found to be 1256 m^2 day^{-1} for VES 1 and 1163 m^2 day^{-1} for VES 2 position. The average values of hydraulic conductivity and transmissivity, determined from pumping test data were 96 m day^{-1} and 1156 m^2 day^{-1}, respectively, closer to the above referred values (Figure 7). The higher values of transverse resistance are associated with higher resistivity values and higher thickness of the aquifer layering showing good quality groundwater (Table 4). The higher values of longitudinal conductance are associated with the low resistivity values indicating poor quality groundwater.

Conclusions

Based on VES survey, borehole well log and pumping test data, and computer model output, the following conclusions were derived:

- The use of geoelectrical soundings survey proved to be a useful technique for characterizing the groundwater conditions of the study area. The output of computer software, 1X1D, showed four layers model and presence of alluvial aquifer that mainly consisted of sand and clay. The second subsurface layer extended from 1.7 to 15 m depth below ground surface having resistivity value of 95 Ω-m indicating the saturated strata had good quality groundwater. Beyond 15 m depth, the resistivity value started decreasing showing groundwater quality deteriorating downwards.
- The average transmissivity values computed using longitudinal conductance and transverse resistance were 1256 m^2 day^{-1} for VES 1 and 1163 m^2/day for VES 2, which were in close agreement with the average value of 1160 m^2/day determined from the pumping test data showing potential of the VES technique for estimating aquifer characteristics. The average hydraulic conductivity of 94 m day^{-1} determined from VES data was also very close to that of 96 m day^{-1} estimated from pumping test data.
- A well was designed and installed at study area upto depth of 36 m below the ground surface with screen length of 21 m, opening area of 20% and screen diameter 20 cm, which was efficient design for the required discharge 1.50 m^3/min.

These results indicate that VES survey technique has the potential to characterize the groundwater quality configuration, estimate transmissivity and hydraulic conductivity parameters.

Acknowledgements

The authors wish to express their sincere thanks to the Endowment Fund Secretariat, University of Agriculture, Faisalabad, for providing financial assistance, Ch. Saeed, farmer at T.T. Singh for his cooperation and assistance, Agriculture Department, Agricultural Engineering Field Wing, Government of Punjab, for facilitating resistivity survey using resistivity meter. Appreciations are also extended to the overseas collaborating scientist, Prof. Dr. R.S. Kanwar for his valuable suggestions and guidance throughout execution of this project.

REFERENCES

Archie, G.E., 1942. The electrical resistivity log as an aid in determining some reservoir characteristics. Trans. Am. Inst. Min. Metal. & Petr. Eng., 146, 54-62.

ASP. 2011. Agricultural Statistics of Pakistan. Govt. of Pakistan, Statistics Division, Pakistan Bureau of Statistics, pp 139.

Bakhsh, A. and Kanwar, R.S. 2008. Soil and landscape attributes interpret subsurface drainage clusters. Aus. J. Soil Res., 46, 735-744.

Batayneh, A. 2007. Mapping subsurface formations on the eastern red sea coast in Jordan using geoelectrical techniques: Geological and hydrogeological implications. Earth Sci. Res. J., 11, 97-107.

Bernard, J. 2003. Short note on the principles of geophysical methods for groundwater investigation. www. Terraplus.com.

Driscoll, 1986. Text book on groundwater and wells.

Farid, H.U. 2009. Determining aquifer characteristics using resistivity survey and pumping test techniques. A M.Sc. Dissertation submitted to Department of Irrigation and Drainage, University of Agriculture Faisalabad.

Goyal, V., Jhorar, B.S., Malik, R.S. and Streck, T. 2008. Performance evaluation of aquifer storage and recovery wells for conjunctive water management as influenced by buffer storage volume and storage time. Current science, 94(4): 465-472.

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

Khan, S., Shahbaz, M., Hanjra, M.A. and Schaeffer, J. 2008. Estimating potential costs and gains from an aquifer storage and recovery. Agri. Water Manag. 95, 477-488.

Lashkaripour, G.R., Ghafoori, M. and Dehghani, A. 2005. Electrical resistivity survey for predicting Samsor aquifer properties, southeast Iran. Geophysical Research Abstracts, 7: 01999, 2005. European Geosciences Union 2005.

Lohman, S.W. 1972. Groundwater hydraulics. U.S. Geol. Survey Paper 708, 70pp.

Maillet, R. 1947. The fundamental equations of electrical prospecting. Geophysics, 12, 529-556.

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

Michael, A.M. 1986. Irrigation Theory and Practices. Vani Educational Books, a division of Vikas Publishing, New Delhi, India.

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

Niwas, S. and Singhal, D.C., 1985. Aquifer transmissivity of porous media from resistivity data. J. Hydrol., 82, 143-153.

Orellana, E. and Mooney, H., 1966. Master tables and curves for vertical electrical sounding over layered structures. Interciencia, Modrid. Geophysical Prospecting 4, 249-279.

Oseji, OJ., Atakpo, E.A. and Okalie, E.C. 2005. Geoelectric investigation of the aquifer characteristics and groundwater potential Kwale, Delta state, Nigeria, J. Appl. Sci. Environ. Mgt. 9, 157-160.

PES. 2012. Pakistan Economic Survey. Govt. of Pakistan, Finance Division, Economic Advisor's Wing, Islamabad.

Qureshi, AS., Shah, T. and Akhtar, A. 2003. The groundwater economy of Pakistan, Working paper 64, Pakistan Country Series No. 19, International Water Management Institute.

Qureshi, A.S., Gill, M. A. and Sarwar, A. (2010) Sustainable Groundwater Management in Pakistan: Challenges and Opportunities. Irrig. and Drain. 59: 107–116.

Raghunath, H.M. 2007. Groundwater. Third edition. New Age International Publishers, New Delhi, India.

Rahman, A.C. 1983. Manual for water well design and testing, Irrigation Drainage and Flood Control Research Council (IDFCRC), Islamabad, Pakistan.

Saleem, H.S. 1999. Determination of fluid transmissivity and electric transverse resistance for shallow aquifers and deep reservoirs from surface and well-log electric measurements. *Hydrology and Earth System Sciences*, 3, 421-427.

Sikandar, P., Bakhsh, A., Arshad, M. and Rana, T. 2009. The Use of Vertical Electrical sounding Resistivity Method for the Location of Low Salinity Groundwater for Irrigation in *Chaj* and *Rachna Doab*s. Environ Earth Sci. 60:1113-1129.

Soupios, P.M. Kouli, M.. Valliantos, A.V. and Stavroulakis, G. 2007. Estimation of aquifer hydraulic parameters from surficial geophysical methods: A case study of Keritis Basin in Chania (Crete-Greece). J. Hydrol., 338: 122-13.

Theis, C.V. 1935. The relation between the lowering of the piezometers surface and the rate and duration of discharge of a well using groundwater storage. Trans. *Am. Geoph. Un*. 16:519-524.

Vouillamoz, J.M., Baltassat, J.M., Girard, J.F., Plata, J. and Legchenko, A. 2007. Hydrogeological experience in the use of MRS. Boletin Geologicoy Minero, 118: 531-550.

WAPDA. 1977. Report on soil salinity survey and research division. Vol.1, Water and Power Development Authority (WAPDA)-Lahore. (Supplement to Revised Action Program for Irrigated Agriculture, Annexes for water quality.

WASID. 1964. Analysis of aquifer tests in the Punjab Region of West Pakistan, Water and Soils Investigation Division, Water and Power Development Authority, Lahore.

Yadav, G.S., Kumar, R., Singh, P.N. and Singh, S.C. 1993. Geoelectrical soundings for aquifer characterization around Jayant colony-Singrauli, Sidhi District, M.P.J. Assoc. Expl. Geophys., XIV: 123-131.

Yadav, G.S. 1995. Relating hydraulic and geoelectric parameters of the Jayant aquifer, India. *J. Hydrol.* 167, 23-38.

****