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Original Research

Site-Specific Aquifer Characterization and Identification of Potential Groundwater Areas in Pakistan

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Abstract

Detailed knowledge about site-specific aquifer characteristics, subsurface lithology, and groundwater potential can help to determine the depth and location of fresh groundwater quality. The present research study was carried out by conducting 80 vertical electrical sounding surveys (VESs) in Rahim Yar Khan District (RYK), Punjab, Pakistan to distinguish the fresh groundwater aquifer from saline groundwater and to evaluate the aquifer protective capacity (APC) of overburden. 1XID software (Interpex, USA) was used to accomplish the interpretation of VES data. The VES interpreted data was used to prepare spatial distribution maps of aquifer apparent resistivity (AR), layer thickness, longitudinal conductance (LC), and transverse resistance (TR) for the second, third, and fourth subsurface layers using ArcGIS 10.1. The results showed that the greater part of the study area (65%) had four subsurface geo-electric layers. The spatial distribution maps for AR showed that the fresh groundwater quality was present on the northwestern and northeastern sides of the study area for all the layers. The results also indicated that the APC of overburden increased with the increase of depth from the ground surface. Layer 4 with thickness of 57.09 m showed good APC in the northern and central parts with LC values of >0.7 mhos. Similarly, the higher values of TR showed higher yield potential in the north-eastern part as compared to the southern part. Overall analysis indicated that the spatial distribution maps of AR, layer thickness, LC, and TR should be helpful for future groundwater development in terms of quality and quantity.

Keywords: VES, apparent resistivity, APC, groundwater potential zones, groundwater development

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Introduction

The agricultural sector is considered one of the most important components of Pakistan's economy. Its current contribution to gross domestic product (GDP) is about 20.9% [1]. Moreover, the agriculture sector creates prolific employment opportunities for 45% of the country's labor force and also provides direct or indirect livelihood to 67% of the rural population. It has been reported that the present population of Pakistan is more than 180 million, which is projected to rise to 246 million by 2025 [2-3]. At the same time, the need to meet the growing demands of food for the increasing population will require and increase in crop production, whereas crop production mainly depends upon availability of irrigation water. However, Pakistan has the world's largest gravity flow canal irrigation system carrying 82 MAF canal water, but due to poor management its efficiency is very low (in the range of about 40%) [4-5]. So water availability is becoming the most important factor for sustaining the agricultural sector in Pakistan.

Currently, irrigation water supplies are about 30% lower than those required for the present cropping intensity [3, 6], and canal water supplies are highly inadequate, variable, and unreliable. On the other hand, most of the area in the Indus River Basin of Pakistan receives average annual rainfall of <250 mm (showing the arid nature of the region), which is not sufficient to grow a single crop [7-8]. This situation has led farmers to exploit groundwater resources to increase their surface water supplies, to overcome canal water scarcity, and to get more control over irrigation water supplies. On average, every fourth farming family has its own tube wells, and a large proportion of non-owners purchase groundwater through local fragmented groundwater markets [9-10]. It has been reported that more than 50% of Pakistan's irrigated lands are now served by groundwater wells [11].

More irrigated area by the groundwater means more exploitation of groundwater. As a result, groundwater is gradually turning saline along with increasing water table depth. This increase in depth has increased the pumping cost of groundwater [12]. Similarly, irrigation with brackish groundwater may cause an excessive accumulation of salts in the soil profile. Latif and Ahmed [13] reported that more than 60% of groundwater pumped by farmers for irrigation purposes has brackish groundwater quality. One of the major reasons for pumping brackish/saline water is the installation of tube wells by a large number of farmers without any prior investigation about groundwater quality and quantity [14-16]. Moreover, rapid urbanization and industrialization have increased solid waste and wastewater generation. So, disposal of solid waste, sewage, urban runoff, agricultural chemicals, and polluted surface water are the major contributors to deteriorate the quality of groundwater resources. Of course landfill sites generally seem adequate for the urban areas to handle garbage issues, but groundwater is a major threat from these sites due to unplanned activities. So, it is suspected that leachate goes down through the soil and is mixed with groundwater because there is no proper mechanism to collect leachate and protect the aquifer. The need, therefore, arises to evaluate the aquifer protective capacity (APC, which is defined as the capacity of the aquifer material to underline and filter percolating surface polluted water into the aquifer) of the overburden material in the area in order to establish the level of safety of the hydrogeologic system [17-19].

Therefore, a systematic and scientific approach to the problem is essential in order to overcome these problems. In such circumstances, the geophysical methods have been successfully used in groundwater studies since they are usually noninvasive and relatively cheap [20-21]. Geophysical methods, especially vertical electrical soundings (VES), have been used successfully for investigating groundwater quality and APC in different lithological settings [19-23]. The VES survey technique also has been used effectively for the study of groundwater conditions and to asses the APC of subsurface geoelctrical layers [24-25]. This VES survey data can be employed to develop spatial distribution maps of groundwater quality, layer thickness, APC, and water-bearing formation potential [26-27]. Such maps can provide information to farmers about the subsurface layering and groundwater quality for installation of tube wells at suitable depths below the ground surface. These can also be used for better management of groundwater resources for its future development and to improve the productivity of agricultural activities in the area.

Keeping this in view, the present research study was carried out to provide useful information to the farmers of Rahim Yar Khan (RYK) in Southern Punjab, Pakistan, to distinguish the fresh groundwater aquifer from saline groundwater. Additionally, the APC of overburden was determined and mapped using VES data in geographic information system (GIS).

Materials and Methods

Location of Study Area

The experimental study was conducted in Rahim Yar Khan (RYK) District in Pakistan's southern Punjab Province (Fig. 1). The district is located between latitude 27.66° to 29.27° and longitude 69.05° to 71.02°. It has three main physical regions: 1) the riverside area (on the southern side of the Indus River), 2) the canal irrigated area in the southern part of the district, and 3) the desert area in the southeastern part. Cotton, sugarcane, and wheat are the major crops. The climate of the district is hot and dry in summer and cold and dry in winter. The average annual rainfall is about 165 mm [28].

Data Collection and Interpretation

A total of 80 VESs were conducted within the study area in collaboration with the Agricultural Engineering Workshops (Field Wing) District RYK Punjab, Pakistan because the instrument is owned by this department.

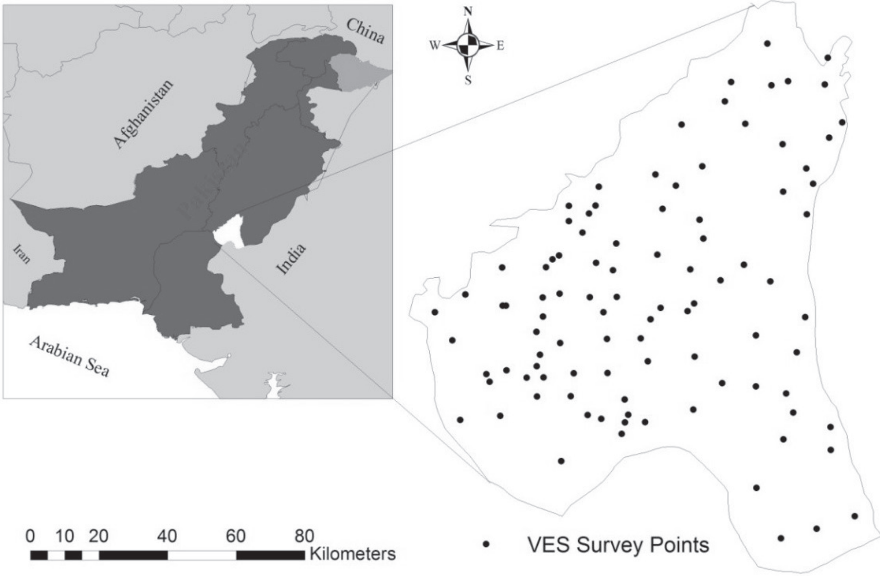


Fig. 1. Study area in RYK District of Punjab Province, Pakistan.

A resistivity meter (ABEM SAS 4000 Tetrameter) was used to determine the apparent resistivity (AR) data with Schlumberger electrode configuration having maximum current electrode separation (AB/2) of 180 m. A series of measurements for earth resistivity were made by increasing the electrode spacing in each successive step around a fixed point for all the VES surveys (almost 25 values were obtained for each of 80 VESs). Measured earth resistivity (*R*) was multiplied with respective geometric constant (K) to determine the AR as obtained by many other researchers [14-16, 29-30]. The mean, maximum, and minimum AR values calculated from field VES data of 80 locations are given in Table 1. The mean AR values were obtained in the range of 0.97-113.04 Ohm-m. The maximum AR value of 2067.84 Ohm-m was determined at VES-66 position having latitude of 28.21º and longitude of 70.20º. Similarly, the minimum value of -1889.43 Ohm-m was obtained at the VES-12 position.

1-D inversion computer software (1XID, Interpex, USA) was used to interpret VES data. The software has the ability to generalize the resistivity data in the form of a subsurface layer model by fitting the observed field data with least root mean squire error (RMSE) between the measured and predicted resistivity data. The software dialog box has dynamic columns and rows to make the data entry more convenient. Similarly, toll bar buttons are provided for the most used menu commands, including new sounding, open and import data, save, display selection, zoom status, un-zoom, edit data, forward, equivalence and inverse calculations, and determination of layered and smooth models. The methods of iteration in the software were performed until the fitting error between the measured and the predicted field data became minimum and constant [14, 18]. Two boreholes were drilled to a depth of 80 m below the ground surface to verify the VES results [15]. About 35 soil and water samples were collected at a 3-5 m interval from each drilled borehole. Soil textural analysis and water chemical analysis were carried out in the Soil and Water Testing Laboratory, Punjab Agriculture Department, RYK. The borehole data were used to prepare the two well-logs that further validated the interpreted VES results. From the interpretation of VES data, the Dar Zarrouk Parameters (the combination thickness and resistivity into a single variable) were computed to evaluate the aquifer properties and protection capacity of groundwater resources [31-32]. The Dar Zarrouk Parrameters consist of longitudinal conductance (LC) and transverse resistance (TR). For a homogeneous, isotropic, and horizontal layer, LC (mho) is expressed as $LC_i = h_i/AR_i$ and TR is expressed as $TR_i = AR(h_i)$, where h_i is the thickness in meters of the ith layer, and AR_i the apparent resistivity in Ohm-meters of the ith layer. Similarly, the LC has been used to evaluate the APC of the aquifer overburden [18]. The total dissolved solids (TDS) were also determined from water chemical analysis, and the relationship between TDS and AR was developed to examine groundwater quality.

Preparation of Spatial Distribution Maps

Spatial distribution maps for aquifer AR, layer thickness, LC, and TR were prepared for the second, third, and fourth layers using ArcGIS 10.1. The spatial distribution maps for the first layer were not prepared because the first layer almost contained the unsaturated strata. The VES locations were obtained using a GPS receiver. The ordinary kriging from the ArcGIS spatial analyst tool was used to obtain the spatial distribution of aquifer parameters such as aquifer AR, layer thickness, LC, and TR over the study area. Kriging is most suitable interpolation technique and has many advantages over the others as reported in literature. Such an approach has been recommended and used by many other researchers [33-36]. Kumar and Remadevi [37] compared the

Table 1. Mean, maximum, and minimum apparent resistivity (AR) values obtained using an ABEM SAS 4000 Tetrameter resistivity meter.

VES number	E	N	Apparent resistivity (Ohm-m)			VES number	E	N	Apparent resistivity (Ohm-m)		
			Mean	Max	Min				Mean	Max	Min
1	70.29	28.39	9.18	56.85	-3.59	41	70.37	28.15	4.44	19.23	0.65
2	70.22	28.44	9.43	23.86	0.01	42	70.43	28.33	7.44	26.02	1.25
3	70.42	28.32	113.04	213.11	51.85	43	70.02	28.09	30.68	47.77	11.81
4	70.42	28.32	1.51	6.59	0.00	44	70.30	28.44	36.83	83.23	9.80
5	70.81	29.21	66.75	545.24	0.00	45	70.43	28.42	2.19	44.26	-41.19
6	70.34	28.51	46.12	80.94	0.00	46	70.94	28.12	61.82	72.06	49.18
7	70.36	28.34	40.17	62.78	17.37	47	70.99	28.84	58.55	86.58	22.08
8	70.43	28.35	22.90	119.91	5.58	48	70.29	28.42	19.07	26.86	12.27
9	70.43	28.35	12.88	31.38	1.15	49	70.81	29.09	41.16	65.02	47.95
10	70.43	28.35	21.36	62.89	3.02	50	70.01	28.41	27.98	48.50	11.90
11	70.43	28.35	85.14	635.97	7.25	51	70.32	28.40	1.51	2.61	0.27
12	70.51	28.63	95.41	1,297.06	-1,889.43	52	70.32	28.40	26.55	42.34	10.14
13	70.51	28.63	5.15	47.63	-0.77	53	70.16	28.25	3.72	23.60	1.25
14	70.51	28.63	85.14	635.97	7.25	54	70.27	28.37	13.42	118.31	-5.77
15	70.35	28.29	20.97	44.73	0.82	55	70.27	28.37	10.56	25.28	5.88
16	70.35	28.29	6.08	95.57	0.83	56	70.94	28.12	39.65	51.84	19.23
17	70.81	27.76	15.41	20.74	11.28	57	70.08	28.92	23.46	39.67	12.12
18	70.58	28.44	2.26	10.13	-2.51	58	70.81	27.79	5.28	9.59	4.44
19	70.67	28.47	28.91	115.70	1.08	59	70.06	27.89	5.93	8.02	4.22
20	70.85	29.00	39.48	61.02	19.63	60	70.32	28.40	30.18	34.92	20.86
21	70.27	28.22	12.55	162.17	0.00	61	70.34	28.51	9.31	21.01	0.68
22	70.63	28.48	7.92	15.75	2.62	62	70.27	28.42	6.71	11.84	2.60
23	70.63	28.48	9.42	41.50	1.83	63	70.66	28.65	27.40	81.97	6.49
24	70.25	28.20	6.34	53.31	-13.97	64	70.10	27.86	35.04	52.22	12.90
25	70.25	28.20	16.31	31.53	3.41	65	70.15	27.86	90.90	190.38	65.55
26	70.67	28.47	8.93	22.91	1.43	66	70.20	28.21	54.07	2,067.84	-188.40
27	70.67	28.47	4.58	22.91	0.68	67	70.81	29.21	51.85	173.34	0.00
28	70.67	28.47	11.06	22.91	2.74	68	70.20	28.21	63.47	1,666.68	-20.30
29	70.67	28.47	25.43	56.63	7.30	69	70.20	28.21	28.20	111.91	-31.23
30	70.02	28.12	16.25	35.99	1.30	70	70.51	28.81	52.85	144.88	28.00
31	70.02	28.12	8.23	16.16	0.69	71	71.01	27.70	5.18	21.01	0.68
32	70.98	28.98	17.60	57.15	2.52	72	71.03	28.88	9.31	11.84	2.60
33	70.98	28.08	7.79	16.81	0.76	73	71.06	27.84	6.71	9.49	3.45
34	70.99	29.05	1.18	2.03	0.01	74	71.11	27.81	7.40	9.22	2.32
35	70.13	28.36	40.47	56.18	15.29	75	69.75	28.44	15.04	19.23	0.67
36	70.08	28.34	42.55	103.09	14.35	76	69.80	28.16	20.90	27.61	1.74
37	70.08	28.34	38.98	66.19	18.25	77	69.86	28.32	17.07	32.91	0.88
38	70.14	28.14	4.19	27.45	-3.11	78	69.90	28.44	21.85	26.81	1.74
39	70.02	28.12	14.49	54.25	-4.23	79	69.96	28.23	23.47	32.13	3.32
40	70.02	28.09	0.97	2.11	0.67	80	69.97	28.21	18.20	36.60	1.73

Inverse Squire Distance (ISD) and kriging interpolation techniques for the spatial analysis of groundwater levels and reported that the ISD method resulted in higher error as compared to the kriging method. In the present study, the best fit model was selected based on the model fitness to the data using ordinary kriging. The kriged data were grouped using different classification techniques.

The AR kriged data were classified into four groups based on the AR standards for good, marginal, and saline groundwater. It has been reported that AR values >42 Ohm-m are considered good-quality groundwater for irrigation, AR values in the range 21-41Ohm-m are marginally suitable, and AR values <21 Ohm-m are not suitable for irrigation. AR values of >150 Ohm-m contain sand and gravel with very good quality groundwater [14, 16, 25, 38]. The kriged data for layer thickness were classified into four groups using the manual classification technique. The kriged data for LC were classified into five groups based on the LC standards for poor, weak, moderate, good, and very good protective capacity of the aquifer material as reported by Ojo et al. [19] and Oladapo et al. [39]. Similarly, the kriged data for TR were classified into four groups based on the aquifer potential to water resources and groundwater quality [25].

Results and Discussion

Table 2 showed the interpreted 1XID (Interpex, USA) model's geo-electrical parameters such as AR, average layer thickness, average depth from the ground surface, average LC, and average TR for the study area. The 28 VES locations had five and 52 VES locations and four subsurface geo-electric layers indicating that the greater part of the area (65 %) had four subsurface geo-electric layers. Average thicknesses of 6.58, 16.68, 41.13, and 57.09 m were recorded for Layer 1, Layer 2, Layer 3, and Layer 4, respectively. We observed that layer thickness increased from Layer 1 to Layer 4, indicating the greater homogeneity of aquifer material as it moved downward. Similarly, average LC and TR increased from Layer 1 to Layer 4. It was also observed that Layer 4 had greater APC against polluting the aquifer because it has greater average LC as compared to the other three layers [19, 39]. The increasing trend for TR values were also observed from Layer 1 to Layer 4, indicating the potential of the aquifer for groundwater quality and quantity with increasing depth from the ground surface.

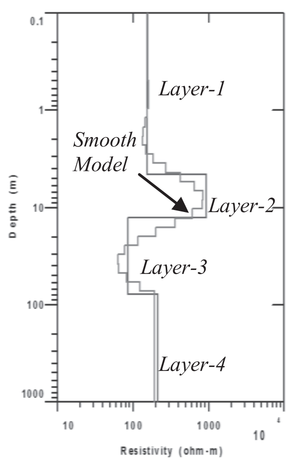
Verification of VES model (1XID, Interpex USA)

Table 3 shows a comparison of the VES model (1XID, Interpex USA) with the borehole data at position VES-1. Layer 1 contained the moist sand and clay that may be a result of the application of irrigation water. The average AR of 936 Ohm-m interpreted for Layer 2 indicated the course sand and gravel with saturated strata of good quality groundwater. Layer 3 was comprised of course sand with alternate layers of clay containing good quality groundwater. Layer 4 exhibited resistivity of 212 Ohm-m and also contained the good quality groundwater (Fig. 2).

Table 2. Summary of interpreted 1XID (Interpex, USA) model geo-electrical parameters.

Layer number	Apparent resistivity (AR) (Ohm-m)	VES number	Average layer thickness (m)	Average depth from ground surface (m)	Average LC (mhos)	Average TR Ohm-m^2
Layer1	<21	22	7.23	7.23	1.16	62.41
	22-42	13	7.38	7.38	0.38	146.54
	43-150	28	6.61	6.60	0.12	448.79
	>150	17	5.12	5.11	0.02	2020.65
Layer2	<21	22	13.36	20.59	1.84	104.59
	21-42	12	30.08	37.46	1.79	516.41
	43-150	27	14.70	21.3	0.31	963.85
	>150	19	8.58	13.69	0.03	3056.47
Layer3	<21	50	42.45	63.04	4.96	446.82
	22-42	9	53.78	91.24	1.68	1791.44
	43-150	13	52.65	73.95	1.08	2947.10
	>150	8	15.62	29.31	0.06	4667.34
Layer4	<21	21	62.63	125.67	13.03	395.18
	22-42	8	48.54	139.78	4.12	579.16
	43-150	14	65.48	139.43	1.28	3893.43
	>150	9	51.69	81.00	0.18	18451.76

Table 3. Comparison of VES model (1XID, Interpex USA) and lithology at RYK-1.

	Layers	Layer thickness (m)	AR (Ohm-m)	Lithological data	VES model (1XID Output)
(VES-1)	1	0-4.8	155	Sand and clay containing moisture content due to application of irrigation water	
	2	4.9-14	936	Subsurface soil containing course sand and gravel also containing good quality groundwater	
	3	15-79	85	Course sand with alternate layers of clay containing good quality ground water	
	4	>80	212	Course sand mixed with gravel also containing good quality ground water	

Analysis of the water sample collected from the borehole also showed water electrical conductivity (EC_w)<1.5 dS/m from 7 to 80 m below the ground surface. According to the criteria developed by WAPDA [40], groundwater of EC_w< 1.5 dS/m is considered fit for irrigation.

VES survey data of the VES-50 position were also compared with the borehole lithology, which showed that Layer 1 from 1-11 m depth had interpreted AR value of 23 Ohm-m showing the hard clay and surficial soil (Table 4). Layer 2 contained poor quality groundwater as it had AR value of 3 Ohm-m from 12 to 29 m depth from the ground surface. We observed very fine sand with alternate layers of clay; it also contained salted water of EC_w> 3 dS/m from 12-29 m depth. In Layer 3, deeper than 30 m, the aquifer material of coarse sand mixed with gravel with AR value of > 42 Ohm-m showed the presence of good quality groundwater. The overall comparison of VES survey data

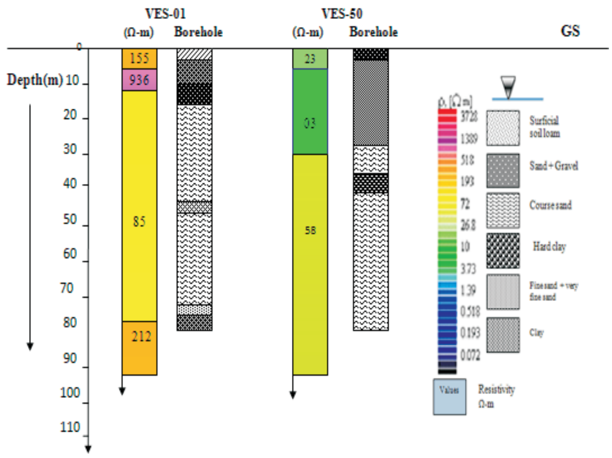
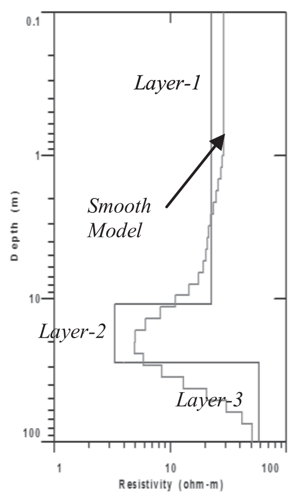


Fig 2. Verification of VES output with the borehole data.

Table 4. Comparison of VES model (1XID, Interpex USA) and lithology at RYK-50.

	Layers	Layer thickness (m)	Resistivity (Ohm-m)	Lithological data	VES model (1XID Out Put)
(VES-50)	1	1-11	23	Surficial soil (hard clay) containing moisture content	
	2	12-29	3	Very fine sand with alternate layers of clay containing saline groundwater may be due to leaching of salts from the surface	
	3	>30	58	Layer of course sand mixed with gravels contain good quality groundwater	

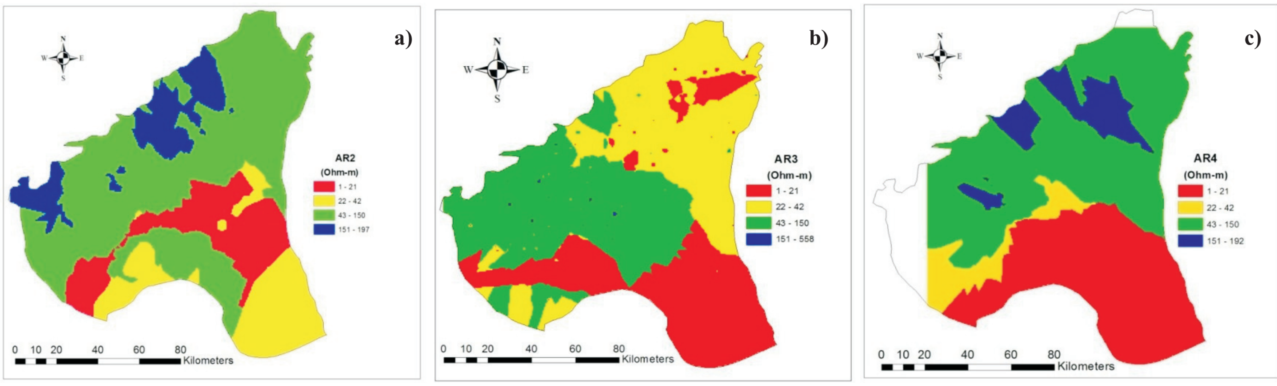


Fig. 3. Apparent Resistivity (AR) of aquifer for subsurface layers for: a) Layer 2, b) Layer 3, c) Layer 4.

interpreted using 1XID (interpex USA) at both sites (VES-1 and VES-50) showed close agreement with borehole data, also indicating the effective use of VES survey for groundwater studies (Fig. 2).

Spatial Distribution Maps of Groundwater Quality

Fig. 3 showed the spatial distribution maps of groundwater quality based on the integration of AR data for subsurface geo-electric layer (Layer 2 to Layer 4).The fresh water in Layer 2 was found in the northwest and northeast parts of the study area as it had AR values of 43-197 Ohm-m. The marginal quality groundwater predominated in the southeast as well as part in the southern part in the westerly direction with AR values of 22-42 Ohm-m. The brackish quality groundwater with AR value <21 Ohm-m was predicted in the central part and running west to southeast of the study area (Fig. 3a). The fresh groundwater quality in Layer 3 was present in the northwest part and marginal quality groundwater was found in the northeast side. The brackish quality groundwater was observed in southeasterly direction (Fig. 3b). Similarly, in Layer 4, fresh groundwater quality was observed in the northeast and northwest parts of the study area. The brackish groundwater quality was found from a south to southeasterly direction (Fig. 3c). The white color in Figure 3c (Layer 4) in the west side and some

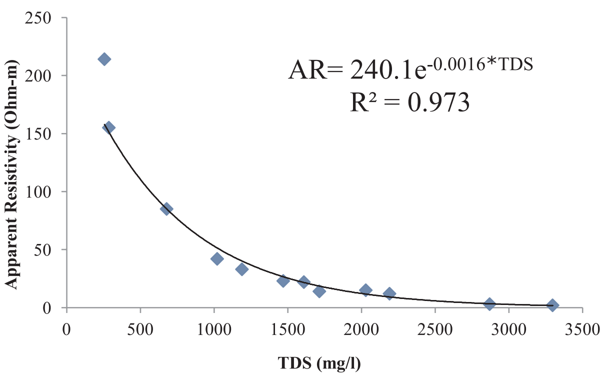


Fig. 4. Relationship between the AR and TDS.

portion in the north side showed that Layer 4 was not present there. The results indicated that the greater area of fresh groundwater quality was present in the northwest and northeast side for all the Layers (Figs 3a-c), which may be due to a recharge from the Indus River. It has been reported that the quality of groundwater is better near the river side and the recharge effect was more dominant in the shallow layer [14]. The results also showed that fresh groundwater quality could be pumped from Layer 2 or Layer 4 in the northeast side of the study area instead of Layer 3. The relationship between the total dissolved salts (TDS) and AR showed that the AR value of >48 Ohm-m (TDS value <1,000 mg/l) is fit for irrigation purposes, AR value between 23-48 Ohm-m is marginally fit for irrigation, and <23 Ohm-m is considered brackish groundwater quality (Fig. 4). The criteria developed for groundwater quality based on the TDS relationship with AR was in close agreement as criteria developed based on the relationship between EC and AR in Rachna and Chaj Doabs [15].

Spatial Distribution Maps of Layer Thickness

Fig. 5 showed the layer thickness maps of the geo-electric layers (Layers 2, 3, and 4). The thicknesses were observed in the range of 1-22 m for Layer 2, 1-60 m for Layer 3, and 1-73 m for Layer 4. The increase in layer thickness from Layer 2 to Layer 4 indicated the homogeneity of aquifer material as well as showing the aquifer potential to store water with the increase in depth from the ground surface. Similarly, Daniel et al. [41] reported that the area of thick overburden was expected to yield groundwater in economically useable quantity. The spatial distribution map of layer thickness for Layer 2 showed that maximum thickness of 16-22 m was found in the eastern part of the study area as well as some part was detected in the western part (Fig. 5a). The spatial distribution map of layer thickness for Layer 3 showed a trend similar to that of Layer 2 (Figs 5a and 5b). The maximum layer thickness for Layer 4 was examined in the northwest and northeast side and minimum layer thickness was observed in the southeastern part (Fig. 5c).

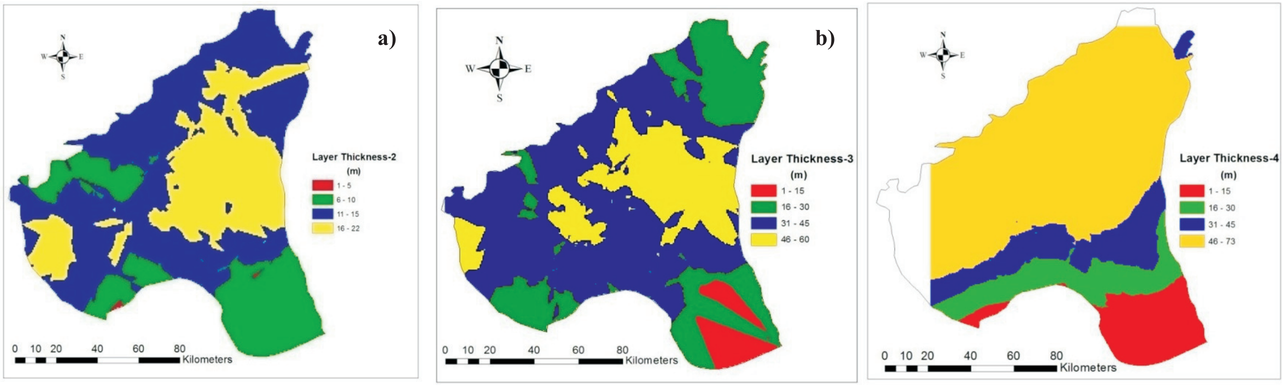


Fig. 5. Map of subsurface layers thickness for: a) Layer 2 , b) Layer 3, c) Layer 4.

The results also indicated that layer thickness was higher in the northern part along the Indus River side for all the Layers (Layers 2-4). The higher layer thickness along the riverside may be due to the formation of an aquifer by alluvial deposits brought by the river from the mountains. The higher thickness in that part showed the potential of aquifer formation to store surplus water. It has been reported that the Indus basin aquifer is formed by alluvial sediments and it behaves as homogenous and highly transmissive on a large scale [42-43].

Aquifer Protective Capacity

The second-order geo-electric parameter, LC, was used to evaluate the aquifer protective capacity (APC) of the geo-electric subsurface layer for the study area (Fig. 6). The spatial distribution map for Layer 2 has an average thickness of 16.68 m, showing that LC values were lower in the northern side and LC values were higher in the central part and again decreased in the southeastern part of the study area. The lower LC values of 0-0.69 mhos in the northern side and southeastern part indicated poor to moderate APC, and the higher LC values of >0.69 mhos showed good APC (Fig. 6a). The poor APC in that part may be due to alluvial deposits brought by the river because that part was present along the Indus. It has been reported that pervious material such as sand and gravel have low LC values resulting from their higher resistivity values as a result of having low APC [19]. The spatial distribution map for Layer 3 with layer thickness of 41.13 m showed that the maximum areas in the northern and central parts have good APC because it has LC values >0.69 mhos [18], while some part in the southeastern side has lower to moderate APC with LC values of 0-0.69 mhos (Fig. 6b). Similarly, the spatial distribution map for Layer 4 with layer thickness of 57.09 m showed that maximum area in the northern and central parts has good APC as well as some part in the western side having excellent APC with LC values of > 10 mhos. Some part in the southeastern side has moderate APC with LC values of 0.2-0.69 mhos (Fig. 6c). The results also indicated that the area of good APC increased with the increase of depth from the ground surface. Similarly, Rahman [44] reported that the APC increased with an increase in water depth because the deeper the water table, the lower the chance of pollutants interacting with the water. It has also been reported that the industrial and domestic effluents discharged into the open drains and fresh water bodies lead to pollution of groundwater into the shallow aquifer [44-45].

Groundwater Potential Zones

Spatial distribution maps of TR showed the potential of the aquifer for groundwater quality and quantity in the

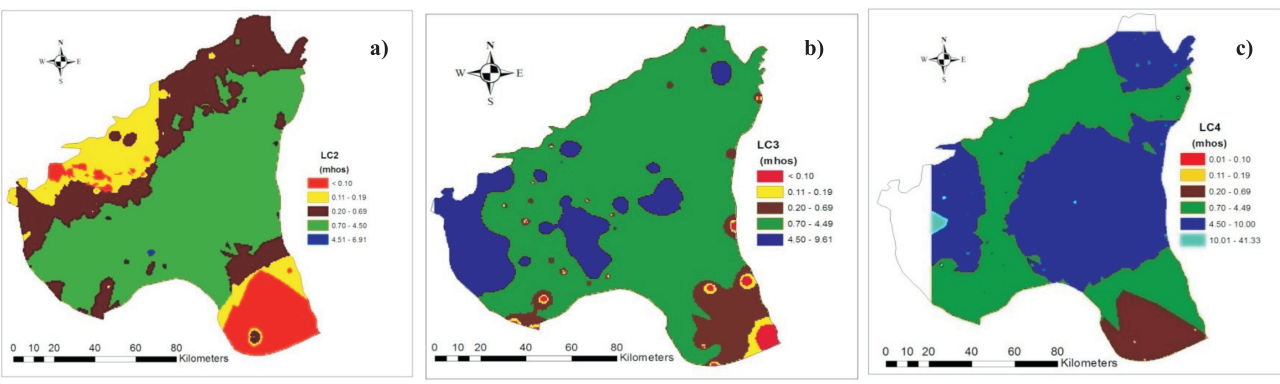


Fig. 6. Longitudinal conductance (LC) map of aquifer for subsurface layers for: a) Layer 2 , b) Layer 3, c) Layer 4.

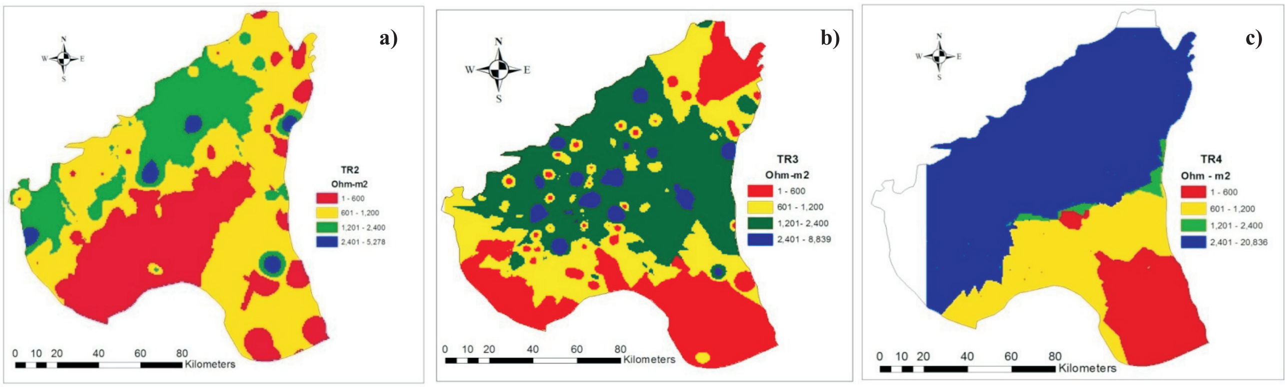


Fig. 7. Transverse resistance (TR) map of aquifer for subsurface layers for:: a) Layer 2 , b) Layer 3, c) Layer 4.

whole study area (Fig. 7). Lashkaripour et al. [25] reported that higher TR (AR multiplied by layer thickness) values constituted higher yield potential and lower TR values constituted lower yield potential. The TR maps for Layer 2 with a layer thickness of 16.68 m showed that the northeastern and northwestern parts of the study area constituted the higher yield potential; on the other hand, the extreme center of the southwestern part of the study area constituted lower yield potential (Fig. 7a). The TR map for Layer 3 with a thickness of 41.13 m showed that the area of higher yield potential was running from the northwestern to the central southeastern part of the study area, whereas the lower yield potential area was present at the northeastern corner, the southeast, and some part at the corner of the southwest study area (Fig. 7b). Figure 7c clearly showed that TR values were higher in the northeast and northwestern parts and lower TR values were found in the extreme southeastern part of the study area for Layer 3, which has average thickness of 57.13 m. It was also observed that TR values increased from the northern to southern sides, also showing the increased yield potential from north to south (Fig. 7c). Overall analysis indicated that higher yield potential was observed in the northeastern part along the Indus side as compared to the southern part. The higher yield potential in that part may be due to the recharge of the groundwater from the river. These results also indicated that the best part for future groundwater development was present in the northeastern and northwestern parts of the aquifer because in this part the best quality and quantity of groundwater was found with respect to higher layer thickness and higher AR.

Conclusions

We drew the following conclusions based on the interpretation of VES data and spatial distribution maps of aquifer parameters:

- The results revealed that VES and spatial distribution maps are effective tools to provide information about the site-specific aquifer characteristics, subsurface lithology, and groundwater potential for exploitation of groundwater in better quality and quantity.
- The average layer thicknesses of 6.58, 16.68, 41.13, and 57.09 m were recorded for Layers 1-4, respectively. Layer thickness increased from Layer 1 to Layer 4, indicating greater homogeneity of aquifer material as it moved downward.
- The higher average layer thickness for Layer 4 (57.09 m) also indicated that the area of thick subsurface formation was expected to have higher groundwater potential aquifer as it has higher TR values.
- The results also indicated that greater fresh-quality groundwater with AR values >42 Ohm-m were present in Layers 2 and 4 in the northwest and northeast sides of the study area, which could instead be pumped from Layer 3.
- The area of good APC increased with the increase of depth from the ground surface, indicating that the aquifers at shallow depth are susceptible to pollution through infiltration of leachate from decomposed refuse dumps that goes down through the soil and mixes with groundwater.
- We observed that the TR values increased from the northern to southern sides, also showing the increase in yield potential from north to south. Overall analysis indicated that the best part for future groundwater development was in the northeastern and northwestern parts of the aquifer (preferably from Layer 4) because in this part the best quality and quantity of groundwater was found with respect to higher layer thickness, good APC, and higher AR.

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