

# The use of vertical electrical sounding resistivity method for the location of low salinity groundwater for irrigation in Chaj and Rachna Doabs

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**Abstract** A geoelectrical resistivity survey using vertical electrical sounding (VES) was conducted at Chaj Doab (land between rivers Jhelum and Chenab, Pakistan) and Rachna Doab (land between rivers Chenab and Ravi, Pakistan), with the objective of investigating groundwater conditions. A total of 90 sites were selected with 43 sites in Chaj and 47 sites in Rachna Doabs. The resistivity meter (ABEM Terrameter SAS 4000, Sweden) was used to collect the VES data by employing a Schlumberger electrode configuration, with half current electrode spacings (AB/2) ranging from 2 to 180 m and the potential electrode (MN) from 1 to 40 m. The field data were interpreted using the Interpex IXID computer software and the resistivity versus depth models for each location was estimated. The outputs of subsurface layers with resistivities and thickness presented in contour maps and 3-D views by using SURFER software were created. A total of 102 groundwater samples from nearby hydrowells at different depths were collected to develop a correlation between the aquifer resistivity of VES and the electrical conductivity (EC) of

the groundwater and to confirm the resulted geophysical resistivity models. From the correlation developed, it was observed that the groundwater salinity in the aquifer may be considered low and so safe for irrigation if resistivity  $>45 \Omega \text{ m}$ , and marginally fit for irrigation having resistivity between 25 and  $45 \Omega \text{ m}$ . The study area has resistivities from 3.9 to  $2,222 \Omega \text{ m}$  at the top of the unsaturated layer, between 1.21 and  $171 \Omega \text{ m}$ , in the shallow aquifers, and  $0.14\text{--}152 \Omega \text{ m}$  in the deep aquifers of the study area. The results indicate that the quality of groundwater is better near the rivers and in the shallow layers compared to the deep layers.

**Keywords** Resistivity survey · Irrigation · Groundwater · Salinity · Bore hole

## Introduction

Groundwater exploration is of increased importance not only in Pakistan but worldwide due to the ever increasing demand for irrigation water. Pakistan has an arid to semi-arid climate and is largely dependent on irrigation through a well established irrigation network which is mainly confined to the Indus basin. During the last decade, the cropped area increased by 1.3% annually, whereas the population increased by 3.1% annually. This gap between supply and demand of agricultural products is expected to widen in the coming decades (Malik 1990). Currently, irrigation water supplies are about 30% lower than required for the present cropping intensity (Badrudin 1983; World Bank 2005). Poor agricultural productivity is often explained by poor irrigation system performance in Pakistan and Canal water supplies are highly inadequate, variable and unreliable (Bhutta and Vander Velde 1992;

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Kuper and Kijne 1992). Moreover, environmental problems such as waterlogging, salinity and sodicity are encountered in large tracts of the irrigated area (World Bank 2005). This situation has led farmers to exploit groundwater resources to increase their water supplies, to overcome the canal water scarcity and to get more control over irrigation water supplies.

According to the data published by the Ministry of Food, Agriculture and Livestock, Government of Pakistan, Islamabad, the total number of private tubewells in the country has been estimated to be about 957,916 including 824,879 in the Punjab (MINFAL 2007). These records obtained from the related agencies, demonstrate the challenges and problems currently faced by the irrigation sector in Pakistan. A significant percentage of the irrigated area in the country is either totally dependent on groundwater or is irrigated in combination with surface water supplies. In a number of canal command areas where surface water supplies are inadequate, irrigation with groundwater of marginal quality is resulting in the depletion of groundwater resources and causing secondary salinization (Sarwar and Eggers 2006).

Groundwater has many advantages compared to surface water, since it demands little or no treatment and it is available when surface supplies are not. However, groundwater quality is generally not good (Ahmed and Chaudhry 1987; Wannakomol 2005) and high salinity in groundwater is common, becoming worse with depth (Gupta et al. 1994). Some deep wells penetrate down to the groundwater having more dissolved salts and so the wells become useless. Deep wells are expensive and unprofitable if drilling is done without knowing the groundwater quality (salinity, possible contamination by natural or manmade activities, etc.).

The quality of groundwater in Chaj and Rachna Doabs varies both in depth and latitude, ranging from fresh to extremely saline. A huge number of hydrowells that were installed and continue to be installed by farmers without any prior investigation are abstracting brackish/saline water, which in turn affects soil health and badly affects crop yield. A systematic and scientific approach to the problem is therefore essential in order to overcome these problems. In such circumstances mapping of fresh groundwater in the subsurface aquifer system is vital for better management of groundwater resources for its future development and to improve the productivity of the agricultural activities in the area.

Geophysical methods have been successfully used in groundwater exploration, since they are usually noninvasive and relatively cheap (Stampolidis et al. 2005; Kalisperi et al. 2009). The resistivity methods and especially the VES method have been used successfully for investigating groundwater quality in different lithological settings

because the instrumentation is simple, field logistics are easy and the analysis of data is straight forward compared to other methods (Zohdy et al. 1974; Stampolidis et al. 2005; Soupios et al. 2007; Kalisperi et al. 2009). The VES survey technique has been used effectively for the study of groundwater conditions and to assess the subsurface geo-electrical layers (Shankar 1994; Lashkaripour et al. 2005; Oseji et al. 2006). This survey technique can also be employed to establish the thickness and depth of water bearing formation (Lashkaripour 2003; Sahu and Sahoo 2006).

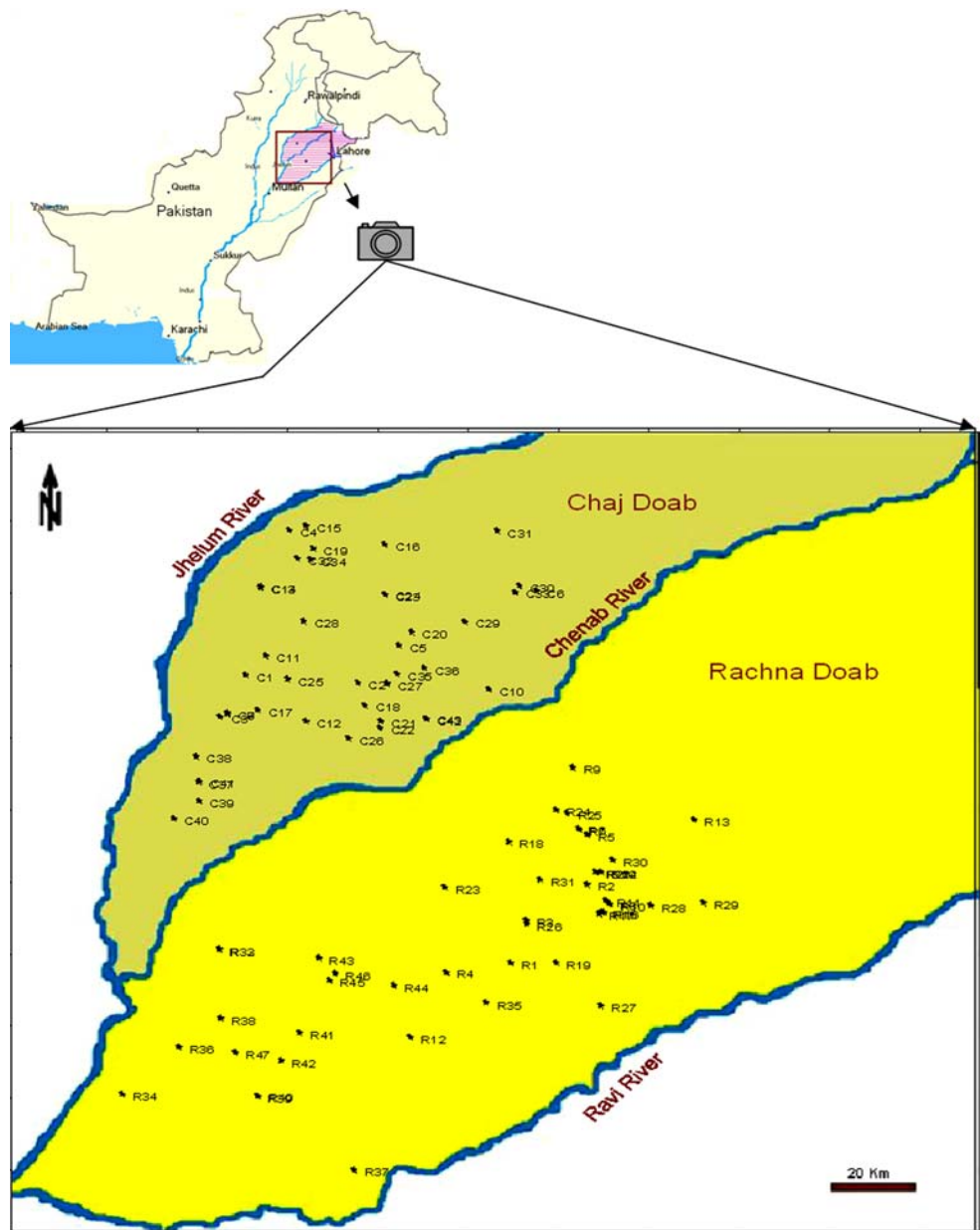
The resistivity of a geological structure can vary significantly, depending on the porosity, water content and the concentration of salts in groundwater. This enables both a quantification of the water content and an estimation of the groundwater quality (i.e., salt content). However, the resistivity for different materials, is not unique. Resistivity of water may vary from 0.2 to over 100  $\Omega$  m depending on its ionic concentration and the amount of dissolved solids (Palacky 1987). Resistivity of natural water and sediments without clay vary from 1 to 120  $\Omega$  m (Zohdy and Martin 1993). Because of these confusing effects, the lithology and groundwater quality effects cannot be differentiated by the geoelectric resistivity survey alone (Choudhury and Saha 2004). For an effective use of VES survey, correlation with the chemistry of groundwater obtained by sample data is required. As such, Chaj and Rachna Doabs were selected for this study because correlations between subsurface conductivity distribution (based on soil and groundwater samples) and VES survey interpreted data had already been established in a previous study (Sikandar et al. 2008).

The main purpose of this research was to provide useful information to the farmers of Rachna and Chaj Doabs to distinguish fresh groundwater aquifers from the high salinity groundwater to instal their tubewells for pumping out fresh groundwater. The methodology was tested by water samples from existing bores near the VES survey sites to evaluate its accuracy and usefulness and to get the knowledge for future VES surveys.

## Study area

This research study was conducted on farms located in Chaj Doab (land between rivers Jhelum and Chenab) and Rachna Doab (land between rivers Chenab and Ravi), Punjab, Pakistan (Fig. 1). Ninety sites were selected in these two Doabs (Chaj and Rachna) with 43 sites in Chaj Doab and 47 in Rachna Doab to conduct the VES survey and collect data on resistivities of the subsurface lithological layers. These sites were selected in collaboration with the Department of Agricultural Engineering, Field Wing,

**Fig. 1** Map showing the selected sites of the study area



Government of Punjab, according to the willingness of the farmers and their bookings for VES surveys at their fields. The sites selected in Chaj Doab were C1, C2, C3,....., C43 and in Rachna Doab were R1, R2, R3,....., R47 as shown in Fig. 1.

**Chaj Doab**

The region of Chaj Doab, lies between longitudes 72°20'E and 73°30'E and latitude 31°60' to 32°60'. The area is bounded by the Chenab and Jhelum rivers. It also covers a vast canal network of distributaries and minors. The mean annual rainfall is 426 mm (I and P 2005). The mean annual temperature is 24°C with the mean annual maximum of

31°C and mean annual minimum of 18°C. The Monsoon rainfalls are also dominant and contribute major part towards annual precipitation. The Chaj irrigation system mainly consists of Lower Jhelum Canal (LJC) and Upper Jhelum Canal (UJC) in the south-west and north-east (Ashraf and Ahmad 2008).

**Rachna Doab**

The Rachna Doab, as a whole, is an inter-fluvial area between the Ravi and Chenab Rivers. It lies between longitudes 71°48'E and 75°20'E and latitude 30–32°51'. Rachna Doab covers a gross area of about 2.97 million hectares. The area of Rachna Doab falls in the rice–wheat

and wheat–sugarcane agro-ecologic zones of the Punjab province. The average annual precipitation estimates to 400 mm (I and P 2005). It covers a vast canal network upto distributaries and minors. The Rachna irrigation system consists of Lower Chenab Canal (LCC), Upper Chenab Canal (UCC), Bomban–Wala–Ravi–Badian–Depalpur (BRBD) Canal, Marala–Ravi (MR) Link and Trimu–Sidhnai (TS) Link.

#### Geology and hydrogeology

The topography of the Chaj and Rachna Doab is mostly flat and the general slope is towards south-west. Medium to moderately coarse soil texture dominates the Doab. The canal system in the area of Chaj Doab is mainly fed by water supplies of the Jhelum River and in Rachna by Chenab River. The major portion of river flows is contributed by monsoon rainfalls and a minor by snow and glaciers melt water flowing down from high mountains of Himalayas in the north. The sediments carried by these river waters form the vast alluvial basin of the aquifer that composed of geomaterials originating from the erosional processes of the Himalayan Mountains. The irrigation supplies in Chaj and Rachna Doabs are mainly fulfilled through conjunctive use of surface and groundwater resources. Groundwater is mainly utilized to supplement canal water supplies where these are not adequate especially during summer season when river discharges are at their lowest level. In the last drought of 1999–2002, groundwater abstractions increased due to a rapid increase in number of private tubewells for irrigation. Pumping of groundwater from these wells is causing a gradual decline in water table. In low relief area of the central Doabs of Chaj and Rachna, seepage from the conveyance system and excessive irrigation in the fields often causes problem of waterlogging and salinity in the Indus basin which threatens the livelihood of farmers (Bhutta and Wolters 1996).

In general, like other aquifers in the Punjab, the aquifers of Rachna and Chaj are unconfined. However, at sites with significant clay horizons, particularly if these are near the surface, confined conditions may be encountered. The uppermost 183 m of the alluvium consists predominantly of fine to medium sand and silt. Alluvium was encountered in test holes drilled to a maximum depth of about 457 m (1,500 ft), hence no information is available concerning the total thickness of alluvium and the depth to basement complex in the Chaj and Rachna Doab area (Kidwai 1962; WASID 1964). The amount of total dissolved solids in the groundwater varies considerably and salinity is probably the major problem associated with the groundwater in most of the regions of Chaj and Rachna Doabs (Gupta et al. 1994; Ahmed and Chaudhry 1987; Bakhsh and Awan 2002).

#### Geophysical methods and investigation techniques

Electrical resistivity survey involving Vertical Electrical Soundings (VES) was carried out by applying current to the ground through two current electrodes (A and B) and then measuring the resultant potential difference ( $\Delta V$ ) between two potential electrodes (M and N). The center point of the electrode array remains fixed but the spacings of the electrodes is increased and information from deeper sections of the subsurface can be retrieved. Depth of current penetration is proportional to the spacing between the electrodes in homogeneous ground, and varying the electrode separation provides information about the stratification of the ground (Koefoed 1979). Different types of electrode configurations are being used, depending on the type of investigation, field conditions and the sensitivity of the resistivity meter. Though both Wenner and Schlumberger electrode configuration methods are popularly employed, the Schlumberger electrode configuration method is more suited to the study area, ensuring better results. The method has practical, operational, and has interpretational advantages over the Wenner method of electrode arrangement (Zohdy et al. 1974; Bhimasankaram and Gaur 1977; Ward 1990). The other reason to select this configuration was that it is also being used by the Agricultural Engineering Department to conduct surveys at the farmer's field.

Vertical electrical resistivity soundings (VES) survey, using the Schlumberger electrode configuration with current electrode separation ( $AB/2$ ), starting from 2 m to a maximum length of 180 m, were carried out in the study area. The separation ( $AB/2$ ) of the current electrodes was 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. Similar spacings of 10, 25, 50 and 100 indicate the step at which increase in the spacing of potential electrode was made and the two readings were obtained for the same  $AB/2$  but different  $MN/2$  spacings. The Schlumberger data are mostly taken in overlapping segments because at each step of  $AB$  spacing, the signals of the resistivity meter become weaker. Therefore,  $MN$  spacing was enlarged and two values for the same  $AB/2$  were measured, one for the short and one for the long  $MN$  spacing. The potential electrode separations ( $MN/2$ ) were installed and enlarged at 0.5, 2, 5, 10, and 20 m. The increase of the potential electrode separation  $MN$  allowed that readings from the same current electrode spread  $AB$  with the previous and expanded  $MN$  were taken.

A total of 90 VES were carried out in the study area. Forty-three sites were surveyed in Chaj Doab and 47 in Rachna Doab. The instrument, used to measure apparent resistivity measurements in the research area, was DC Terrameter SAS 4000 (ABEM, Sweden) without booster.

The instrument is owned by the Department of Agricultural Engineering, Field Wing, Govt. of Punjab (Pakistan). The field investigations were conducted at the farmer's field in collaboration with this Department.

The interpretation of the VES data was conducted using the 1-D inversion technique software (IX1D, Interpex, USA). This software produces the resistivity model, fitting the acquired field data with the least root mean square (RMS) error between the synthetic data generated from the model and the actual data themselves. The method of iteration was performed until the fitting errors between field data and synthetic model curve became least and constant. The positions and surface elevations of VES sites were also recorded during survey with a GPS receiver to make contours and 3-D maps of the study area. A computer software SURFER, Version 8.1, was used to prepare iso-resistivity contour and 3-D maps of the study area.

A summary of all the VES data interpretation conducted at Chaj and Rachna Doabs with their corresponding RMS errors are presented in Tables 1 and 2. The RMS error of all the VES survey data ranged between 0.7 and 7.5%, which is acceptable. Interpretation of VES data suggests that there is a topmost thin layer of thickness ranging from 0.265 to 29.11 m at sites C29 and C20 in Chaj Doab and 0.335 to 10.32 m at sites R15 and R23 in Rachna Doab. This topmost layer was mostly loam with varying quantities of sand silt and clay across the whole study area of Rachna and Chaj Doabs. The layered earth model from VES interpretation also shows further thin layers below the topmost layers at many sites of Chaj and Rachna, which are actually the parts of top layer but due to varying moisture contents and sand ratio, the model split them. The top layer is unsaturated and underlying this top layer is the aquifer which is unconfined with varying thickness over the entire research area. In most of the sites of Chaj and in some sites of Rachna, semi-confined aquifers exist, which is separated by a thin layer of stiff clay from the unconfined aquifer at the top (Sikandar et al. 2008).

The resistivity varies greatly for different geological materials (Singh 2005). Most rocks and minerals are insulators in their dry state. However, in nature, they usually contain some water with varying quantity of dissolved salts within their pores and cracks (primary and secondary porosity, respectively). The degree of interconnected and water-filled pores together with the concentration of dissolved salts are major factors affecting the resistivity. The resistivity of fresh groundwater varies usually from 7 to 100  $\Omega$  m, depending on the degree of dissolved solids and seawater or highly saline water has resistivities down to 0.2  $\Omega$  m (Palacky 1987), which makes resistivity method the ideal technique to distinguish the interface between saline and fresh water. But on the other hand, the resistivity of different earth materials is not exclusive, e.g., clay

overlaps with both freshwater and brackish water. Vouillamoz et al. (2007) argue that in an environment where aquifers are not free of low resistive clayey material, a rough estimation for the electrical conductivity EC of groundwater can still be made using a linear relationship between the resistivity of groundwater from samples and the resistivity of the aquifer from VES interpreted data. Therefore, chemical analysis of the groundwater samples were carried out to confirm the calculated EC values from VES data.

For reasons of analytical convenience, a practical index of salinity is electrical conductivity, expressed in units of dS/m (deci Siemens per meter). Classification of fresh to saline groundwater suitable for irrigation purpose can be made if a correlation between electrical conductivity and aquifer resistivity is built for that area. The criteria for fit, marginally fit and unfit groundwater based on electrical conductivity was already developed by WAPDA 1978. Where the electrical conductivity of groundwater less than 1.5 dS/m it is safe for irrigation purpose, between 1.5 and 2.3 dS/m is marginally fit and EC more than 2.3 dS/m is unsafe to use for irrigation purposes.

## Results and discussion

### Correlation between EC of groundwater samples and geoelectrical resistivity

A combination of hydrochemical and geophysical technique was used to study the salinity of groundwater aquifers in the study area. Efforts were made to collect as much data as possible to derive at a more efficient formula. For this purpose, the groundwater samples from all the nearest already installed hand pumps and tubewells close to every VES site, where possible, were taken for analysis. The total depth of these hand pumps and tubewells as well as their strainer and blind pipe lengths were also recorded to get the exact correlation between the groundwater quality and the geoelectrical VES result of that layer. A total of 102 data were collected from different sites of Chaj and Rachna Doabs and chemical analyses were conducted to determine their major ion, total dissolved solids and electrical conductivity to get the correlation.

The geophysical and hydrochemical data were proved as follows. The electrical conductivity measurements of groundwater converted into water resistivity ( $\rho_w = 1/EC$ ), where  $\rho_w$  is the resistivity of the groundwater samples. Finally, in order to obtain a relationship between the groundwater quality and earth resistivity, the values of groundwater resistivities were plotted as a function of aquifer resistivity ( $\rho_e$ ). The  $\rho_e$  values of those interpreted subsurface layers were used from which groundwater

**Table 1** Summary of VES interpretations with positions in Chaj Doab

Names of VES	Longitude (M)	Latitude (M)	No of layers	Resistivity of the layers ( $\Omega$ m) $\rho_i$						Thickness of layer (m) $T_i$						RMS error
				$p_1$	$p_2$	$p_3$	$p_4$	$p_5$	$p_6$	$T_1$	$T_2$	$T_3$	$T_4$	$T_5$	$T_6$	
C1	251161.6	3536580.6	4	179	877	44	16.1	–	–	–	1.88	2.94	31.4	–	–	3.1
C2	276071.7	3534466.3	4	19	2,222	32.61	1.33	–	–	–	0.877	0.263	21.15	–	–	7.5
C3	245509.9	3524932.5	3	5.55	18.61	23.32	–	–	–	–	2.2	37.29	–	–	–	3.8
C4	260808.22	3576556.0	3	15.2	1,977	4.08	–	–	–	–	2.05	1.39	–	–	–	4.7
C5	285074.4	3544751.7	5	40	25	15	0.5	30	–	–	2	8	20	3	–	5.7
C6	315603.2	3559753.7	3	14.26	55.62	1.78	–	–	–	–	2.74	45.4	–	–	–	5.1
C7	247178.4	3525879.2	5	3.9	8.5	11.6	53	8.7	–	–	1.3	3.1	33.4	60.3	–	0.7
C8	247178.9	3525997.8	4	6.7	611	12.5	37	–	–	–	2.5	0.85	7	–	–	1.2
C9	247048.84	3525808.6	3	7.03	16.8	13	65	–	–	–	2.4	31	7.5	–	–	2.2
C10	304990.1	3532686.0	4	8.89	27	4.68	245	–	–	–	3.37	43.24	27.52	–	–	4.6
C11	255589.6	3541944.3	5	9.43	1,436	18	25	384	–	–	0.8	0.5	7.2	118	–	1.7
C12	264579.3	3523677.9	5	48	24	17	12	14	–	–	5.5	10	15	22	–	1.9
C13	254402.2	3560688.0	4	13.86	2,040	8.61	36.01	–	–	–	1.25	1.45	10.5	–	–	4.3
C14	254568.2	3560904.4	3	74.4	1,131	40.5	–	–	–	–	1.32	4.16	–	–	–	5.3
C15	264530.9	3577801.6	3	8.46	52.6	2.5	–	–	–	–	3.36	12.52	–	–	–	6.4
C16	281919.5	3572693.9	3	50	30	10	–	–	–	–	3	27	–	–	–	4.4
C17	253873.8	3526758.7	4	30	50	32	20	–	–	–	3	3	9	–	–	7.1
C18	277593.3	3528192.0	4	13.26	74.51	388.8	1.21	–	–	–	1.91	1.12	5.1	–	–	3.4
C19	266084.4	3571513.7	4	37	36	27	17	–	–	–	5	14	12	–	–	3.9
C20	287933.9	3548306.5	3	17	91.74	0.05	–	–	–	–	29.11	16.27	–	–	–	4.6
C21	281128.94	3523741.5	4	101	2,015	27.9	4.33	–	–	–	0.618	2.32	37.83	–	–	3.3
C22	280902.7	3521828.7	5	7.7	1641	20.1	0.9	196	–	–	0.5	0.63	4.77	23.9	–	3.2
C23	282050.3	3558771.5	4	14	10.07	28.32	4.33	–	–	–	0.8	20.01	32.19	–	–	4.1
C24	282060	3558798.8	4	63.73	30.73	63.29	16.96	–	–	–	1.61	4.77	20.35	–	–	2.8
C25	260451.6	3535403.0	4	26.03	5.86	1.53	21.18	–	–	–	7.26	30.97	25.82	–	–	4.2
C26	273933.85	3519001.8	3	218.7	705.1	29.85	–	–	–	–	4.17	4.39	–	–	–	3.2
C27	282555.4	3534200.0	3	24.5	55.75	1.28	–	–	–	–	2.51	14.29	–	–	–	3.7
C28	263992.2	3551338.0	4	65.86	341.5	27.13	2.48	–	–	–	1.42	2.02	32.66	–	–	2.5
C29	299692.8	3551225.3	5	4.67	17.1	5.57	34.43	0.418	–	–	0.265	9.82	29.13	31.92	–	2.6
C30	311800.1	3561131.5	4	61.61	23.61	45.67	1.17	–	–	–	0.528	3.79	65.25	–	–	3.0
C31	306924.5	3576412.0	4	31	21	20	12	–	–	–	2	25	25	–	–	3.8
C32	262684.4	3568745.3	4	10	20	30	11	–	–	–	2	20	10	–	–	5.6
C33	310846.5	3559392.1	3	15	60	13	–	–	–	–	2	48	–	–	–	6.2
C34	265546.3	3568401.5	5	26.58	4,077	28.09	122	2.71	–	–	0.737	1	0.9	22.4	–	1.1
C35	284743.56	3536821.8	6	4.79	7	577	3.78	4.68	1.56	–	0.46	0.26	0.2	3.68	34.11	3.2
C36	290708.6	3538512.5	4	17.12	32.18	2.53	0.382	–	–	–	1.74	6.77	108	–	–	0.8
C37	240696.9	3506863.8	4	237.5	2.82	376	21	–	–	–	0.513	1.31	1.42	–	–	2.7
C38	240194.6	3513926.4	5	51	67	1298	34	39	–	–	0.993	2.28	1.6	3.44	–	4.4
C39	240855.23	3501587.0	4	11.5	1,091	14.39	12.44	–	–	–	2.35	0.826	64.8	–	–	2.9
C40	235251.1	3496723.7	4	29.22	21.34	370.2	29.21	–	–	–	2.89	1.84	2.37	–	–	3.7
C41	240986.7	3507091.4	4	53	560	41.63	2.47	–	–	–	2.02	2.25	34.51	–	–	1.7
C42	291243.3	3524370.1	4	63.3	460	8.07	36.6	–	–	–	1.78	4.83	11.12	–	–	1.6
C43	291233.9	3524516.1	4	28	3,456	9.94	1.06	–	–	–	2.34	0.524	99.52	–	–	3.5

$\rho_i$  Resistivity of the  $i$ th subsurface geoelectric layer,  $T_i$  thickness of the  $i$ th subsurface geoelectric layer

**Table 2** Summary of VES interpretations with positions in Rachna Doab

VES names	Longitude (M)	Latitude (M)	No of layers	Resistivity of the layers ( $\Omega\text{m}$ ) $\rho_i$						Thickness of layer (m) $T_i$					RMS error
				$p_1$	$p_2$	$p_3$	$p_4$	$p_5$	$p_6$	$T_1$	$T_2$	$T_3$	$T_4$	$T_5$	
R1	309909.9	3456656.6	5	11.4	2.18	18.6	2.55	552	1.34	2.35	22.1	44.5	4.7		
R2	326809.2	3478425.6	4	19.03	28.77	45.42	7.88		3.45	0.828	21.94		5.7		
R3	313341.7	3468420.0	3	14.44	237	8.04			1.6	5			5.1		
R4	295637.6	3454035.5	4	44.3	504	18	2		2.76	1.9	41.7		0.7		
R5	326875.3	3492235.2	4	53.57	115.4	89.27	7.4		1.3	6.86	45.7		1.2		
R6	324894.2	3493972.0	3	152	130	6.01			2.23	16.24			2.2		
R7	325031.8	3493802.6	3	43	101	8.65			1.41	14			4.6		
R8	331596.5	3473080.8	4	3.36	10	26.5	40		3.4	9.4	100		1.7		
R9	323666.1	3510855.6	3	112	1700	29.7			1.57	18.63			1.5		
R10	331920.1	3473001.0	3	9.3	208	17			0.45	15.53			4.0		
R11	331012.2	3474009.8	3	21.8	1700	6			0.72	12.5			5.1		
R12	287647.1	3436092.2	4	20.7	23.32	1.7	152		3.76	2.89	95.5		6.4		
R13	350547.8	3496291.1	5	6.46	18.41	1830	14.31	29	0.5	0.3	0.2	40.7	4.4		
R14	329952.4	3481927.1	4	16.8	66.6	15.3	8.1		0.65	5	152		2.1		
R15	330056	3470651.6	4	2222	65	16.8	4.2		0.335	16.6	53.2		3.4		
R16	330514.9	3470667.3	4	23.4	40	11.36	12.91		0.21	20	43		3.9		
R17	329451.5	3470282.7	4	586	65	17	4.3		0.4	16.6	52.4		4.6		
R18	309455.8	3490287.4	3	10	101	11.4			1.43	9.6			3.3		
R19	319973.5	3456724.0	4	57	19	32	24		0.825	2	17.6		3.2		
R20	328724.1	3481964.7	5	5.14	5.74	908	8.7	13	0.232	0.405	1.12	4.2	4.1		
R21	328688.5	3481917.9	3	20	111	13.66			1.52	8.15			2.8		
R22	329952	3481941.5	5	58	5	42.5	14.5	4.32	0.633	1.3	3.7	119	4.2		
R23	295263.3	3477700.5	4	20.3	33	8	26		10.32	9.5	22.2		3.2		
R24	319955.1	3499144.5	4	7.2	37	18.4	30		4.42	6.25	45.5		3.7		
R25	322379.7	3498133.8	3	5.2	13	9			1.94	35.6			2.5		
R26	313403.5	3467475.9	4	6.43	13	5	10		2.52	10.43	32		2.6		
R27	329880.7	3444769.9	4	14	27	16.4	23.5		1	3	20.5		3.0		
R28	340933.3	3472571.8	4	340	10	51	8.09		0.47	0.25	52.6		3.8		
R29	352624.7	3473356.7	4	12	289	0.3	39		1.4	3.54	1.74		5.6		
R30	332496.5	3485251.0	5	14	2103	182	5.25	22	1.7	0.3	3	8	6.2		
R31	316406.7	3479697.4	4	51.6	5413	171	3.11		1.93	2.04	28		1.1		
R32	245402.8	3460521.8	3	33.3	424	18			3.94	14			3.2		
R33	245305.7	3460423.1	3	11	1575	28			1.3	4.62			1.8		
R34	223853.4	3420120.8	4	584	3	937	13.6		0.405	1.36	2.18		2.7		
R35	304461	3445619.3	3	35	67	3			4.5	23.5			4.4		
R36	236423.6	3433201.5	4	10	30	24	5		1.88	6.4	31.5		2.9		
R37	275183.6	3399154.5	3	12	143	21			2.8	16.1			3.7		
R38	245653.9	3441254.7	3	13	86	7.7			3.5	22.5			3.7		
R39	253698	3419686.4	3	37	48.3	6.2			2.02	14			6.6		
R40	253882.4	3419738.8	3	27	123	4.02			1.6	13.01			5.5		
R41	263137.3	3437209.5	4	5.35	345	65	0.4		0.714	1.4	53.3		3.8		
R42	259019.7	3429477.8	5	166	0.175	186	5	0.14	0.5	0.04	2.3	39	5.6		
R43	267396.3	3458009.0	4	31	1098	6.12	31		2.81	3.78	14		6.2		
R44	284011.1	3450396.1	3	6.76	113	7			2.78	7.25			1.1		
R45	269743.2	3451794.5	3	36	3320	1.5			2.03	1.31			3.2		
R46	270959.7	3453722.1	4	4.5	45	19.5	5		0.4	7.12	93		4.8		
R47	248853	3431771.6	4	53.4	8	201	11		3.2	2.14	7.5		2.5		

$\rho_i$  Resistivity of the  $i$ th subsurface geoelectric layer,  $T_i$  thickness of the  $i$ th subsurface geoelectric layer

samples were taken from specific depths. The best fitted line between earth resistivity and groundwater resistivity (Fig. 2) indicates the following relationship:

$$\rho_w = 0.12 \times \rho_e + 2.12 \quad (1)$$

where,  $\rho_w$  is the groundwater resistivity in  $\Omega$  m and  $\rho_e$  is the earth resistivity in  $\Omega$  m. Similar type of linear relationship was also derived by Mondal and Singh 2007.

This empirical relationship between earth resistivity and groundwater resistivity reveals that the earth resistivity is strongly affected by the groundwater salinity, and provides a reaffirmation of the basis for applying resistivity methods to study the groundwater contamination. Figure 2 shows the best fit which is obtained with coefficient of determination,  $R^2 = 0.90$  for groundwater from different sites at different depths of the study area.

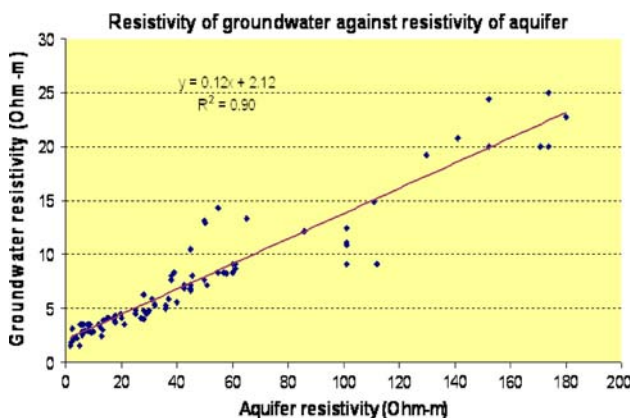
Finally in order to obtain a direct relationship between groundwater salinity and corresponding interpreted aquifer layer resistivity, the groundwater quality in electrical conductivity (dS/m) from the water samples analysis were also plotted as a function of interpreted layer resistivity ( $\Omega$  m) from VES data. The fitted line between subsurface layer resistivity and groundwater EC (Fig. 3) indicates the following empirical relationship:

$$EC_w = -1.035 \ln(\rho_e) + 5.43 \quad (2)$$

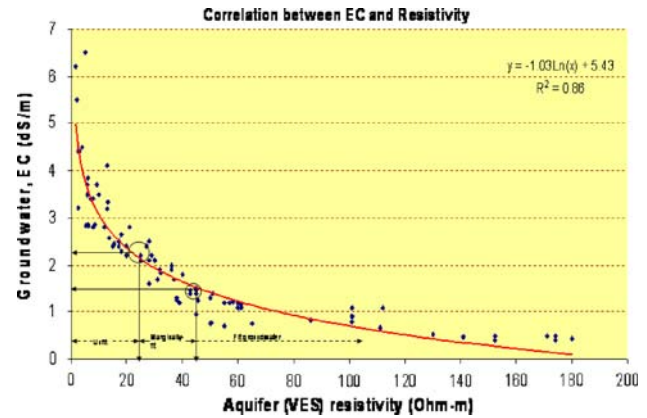
where  $EC_w$  is the electrical conductivity of groundwater in dS/m and  $\rho_e$  is the resistivity of the earth from VES data in  $\Omega$  m.

From Figs. 2 and 3, it is clear that up to the value of 60  $\Omega$  m of aquifer resistivity, the fit is very good and after this value the data looks scattered may be due to fewer points. Even then the coefficient of determination  $R^2 = 0.86$ , which is acceptable.

The hydrochemical data (primary data) obtained from this study, together with hydrochemical and lithological data (secondary data) from the previous study in the same



**Fig. 2** Correlation between aquifers resistivity (VES) and groundwater resistivity



**Fig. 3** Correlation between aquifers resistivity (VES) and groundwater salinity (EC)

research area (Sikandar et al. 2008), were used in the interpretation of the overall data.

Therefore, by using the classification of groundwater salinity developed by WAPDA, and from the correlation developed between EC and aquifer resistivity (Eq. 2), the boundary between fresh and brackish groundwater zone is developed. Resistivity values for the groundwater layer higher than 45  $\Omega$  m (resistivity at EC 1.5 from Fig. 3) is interpreted as fresh water zone while values lower than 45  $\Omega$  m represents brackish water zone. Based on these criteria, 3-D maps delineating fresh and brackish groundwater zones were established.

### Geoelectrical model

Different subsurface layers were obtained after interpreting the results of these 90 VES surveys. These layers were presented in forms of contours and 3-D representations by using the SURFER software. Since the VES positions were spatially and randomly distributed over the study area, different gridding methods were tried and the cross validation technique in the SURFER software was applied to get accurate results and close approximation of input data with output contours and 3-D views. Out of all other gridding methods, Kriging was found better for this type of data.

### Top layer resistivity

Interpretation of VES data with computer software IX1D Interpex suggests that there is a topmost thin layer of thickness ranging from 0.265 to 29.11 m at sites C29 and C20 in Chaj Doab and 0.335 to 10.32 m at sites R15 and R23 in Rachna Doab.

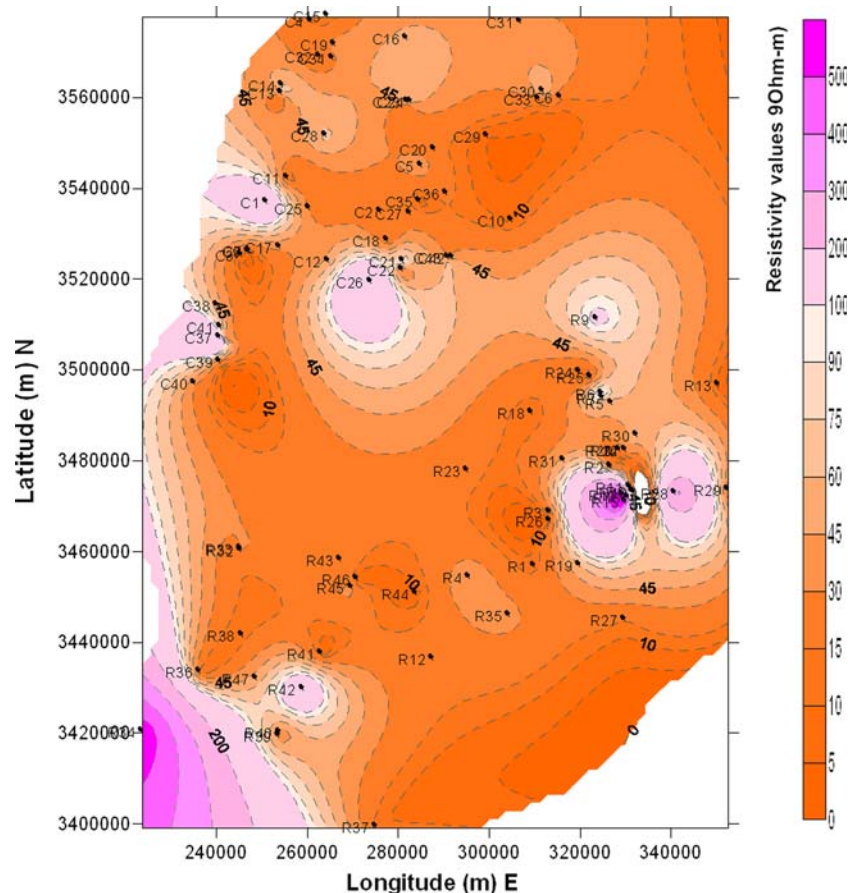
The resistivity values range in between 3.9 and 219  $\Omega$  m at sites C7 and C29, respectively, in Chaj Doab. Similarly in Rachna Doab the resistivity values were



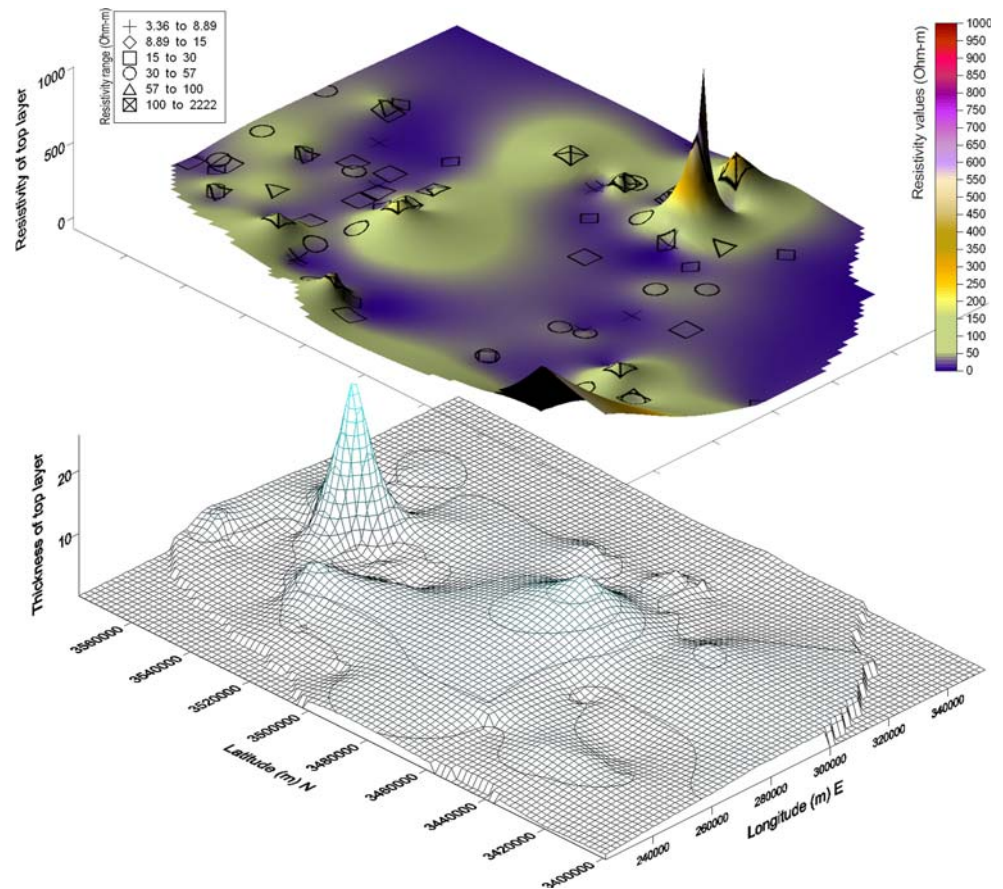
found with maximum of 2,222  $\Omega$  m at R15 and 4.5  $\Omega$  m at R46 sites. The variation in resistivity is mostly attributed to variation in moisture content and changes in soil textural conditions. The corresponding contour maps and a 3-D view of the resistivities of the top layer of Chaj and Rachna Doabs is shown in Figs. 4 and 5, respectively. A 3-D view of the resistivities of the top layer along with its thickness from the ground surface is also shown in a combined map of the study area of Chaj and Rachna Doab in Fig. 5. There are two peak resistivity values of top layers at the north-east part and two small peak resistivity values at the north-west part and one at the boundary of Chaj and Rachna Doab near the center of the study area. One more peak at the south-west corner of the study area is also present. These can be clearly seen in 3-D views (Fig. 5), which are also clearly identified in the contour map of the study area (Fig. 4). The three small peaks which are at the north-west side and one near the center of the study are in the Chaj Doab, which are more clear in the separate 3-D map of Chaj Doab (Fig. 6). The peaks, which are in the north-east side and one at the south-west corner of the study area, lie in Rachna Doab. These are clearly identified in separate 3-D views

(Figs. 6, 7) of Chaj and Rachna Doabs. Rest of the area has not so much variation in resistivity. The thin top layer resistivities would not remain constant and continuously changing every day because of varying moisture contents due to irrigation, precipitation, evaporation, sunshine, etc. but thick-layer resistivities may change seasonally. Similarly, the depth of this top layer changes with the presence of moisture. The type of soil in the whole study was mostly found as loam with varying percent of sand ratios. The resistivity value of the top layer increases due to the increasing sand ratio with low moisture content and vice versa. The thickness of this topmost subsurface layer also varied site to site. The maximum thickness was found at site C29 which is also clear in Fig. 5. The thickness of this top layer was 29.11 m which is in Chaj Doab and can be more clearly seen in Fig. 6. The rest of the areas have not much more variations. From Fig. 7, the thickness of the top subsurface layer in Rachna Doab as can be seen has considerable variations. There are lot of peaks and lows in the area of Rachna Doab. However, the topmost peak having a thickness of 10.32 at site R23 can be seen in Fig. 7. These figures from 4 to 7 give a good picture of the resistivity values of top layer in the study area.

**Fig. 4** Contour map of top layer resistivity along with VES positions in the study area



**Fig. 5** A 3-D representation of the top layer resistivity and its thickness



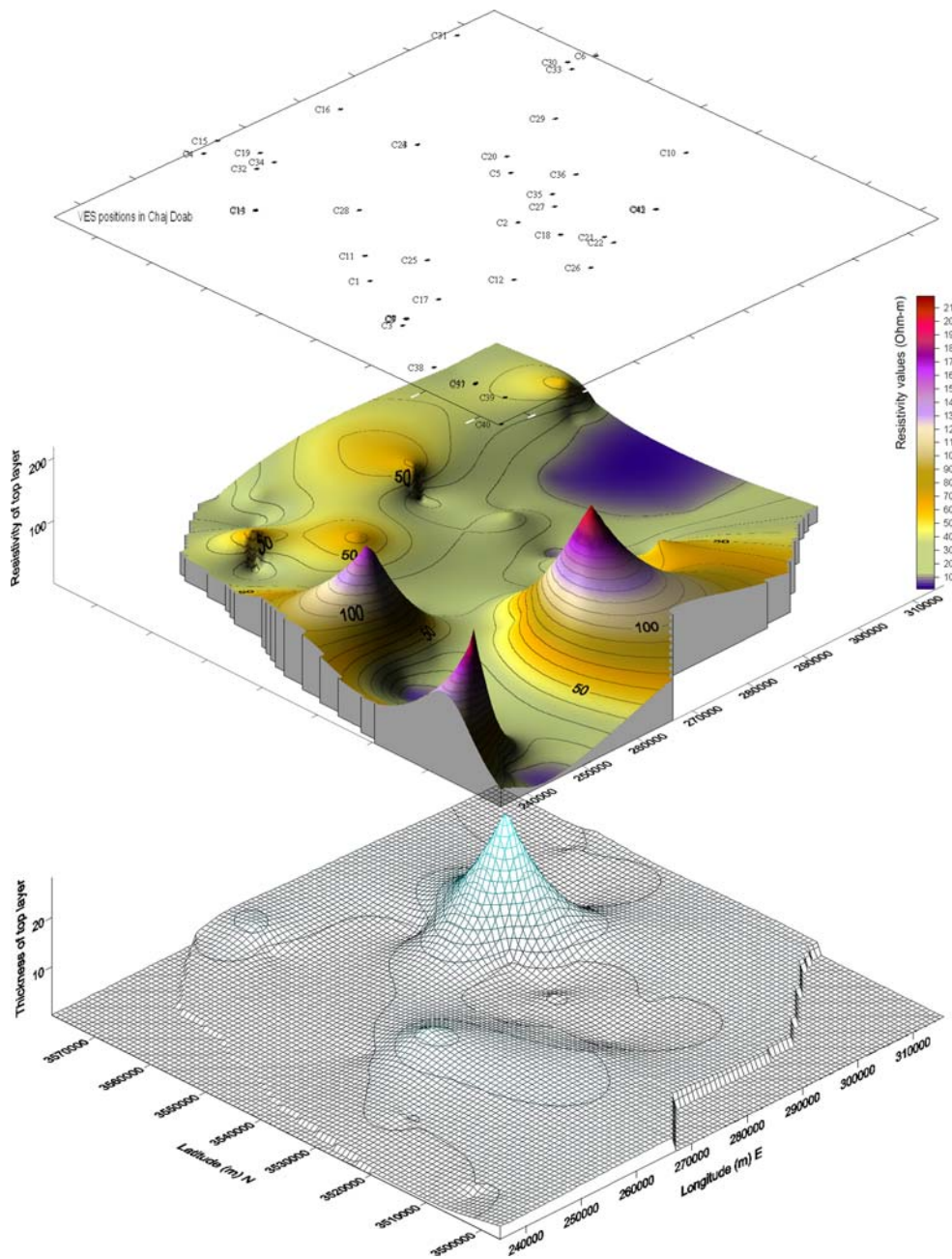
### Shallow aquifer resistivity

The resistivity values of the shallow groundwater layer aquifer ranged from 1.21 to 122  $\Omega$  m at sites C18 and C34 in Chaj Doab, whereas, it ranges from 1.5 to 171  $\Omega$  m at sites R45 and R31 in Rachna Doab, respectively. The corresponding contour map and 3-D representation of the resistivity of the shallow aquifer is given in Figs. 8 and 9. The highest resistivity value is 171  $\Omega$  m, can be seen in the Fig. 8, at longitude 316406.7 and latitude 3479697.4. The other peak value 122  $\Omega$  m in Chaj Doab at longitude 265546.3 and latitude 3568401.5 is also clear in the Figs. 8 and 9. The elevated and low lying areas are in almost perfect conformity with the resistivity contour maps and 3-D representation.

Similarly, the thickness of this shallow groundwater layer ranges from 7 to 118 m at sites C8 and C11 in Chaj Doab, whereas, it ranges from minimum to 14 m at both of the sites R7 and R39 and goes upto 100 m at R8 of Rachna Doab. These high and low thickness values of shallow aquifer layer are presented in Fig. 9. In most of the cases in the study area it is observed that the larger thickness of the subsurface aquifer is a representation of both shallow and deep groundwater layers. Because if the saturated layer starts from water table depth and goes upto deeper depth

without any water quality and soil formation change, then the interpretation of resistivity model gives us one resistivity value of one layer with undefined depth. The possible reason is that the thickness of layer exceeds the limit of VES penetrated depth.

Correlation of the resistivity and the groundwater EC (Fig. 3) indicated that the groundwater aquifer having resistivity more than 45  $\Omega$  m is considered to be safe for irrigation purpose. Similarly from Fig. 3, we can also get the marginal resistivity of groundwater from the marginally fit groundwater EC between 1.5 and 2.3 dS/m. Therefore, the resistivity of groundwater layer between 25 and 45  $\Omega$  m can be considered as the aquifer having marginally fit groundwater. From the contour map of shallow aquifer in the study area (Fig. 8), it can easily be distinguished between fresh, brackish and saline groundwater. The contours having blue color are the representation of the area having fresh groundwater in the shallow aquifer. The contours having yellow color represents the marginally fit groundwater for irrigation and the rest of the colors from light red to dark red represents the aquifer having groundwater unfit for irrigation. The dark red colors are highly saline zones in the study area. The 3-D representation of the safe groundwater of the research area is also presented in Fig. 10. In Fig. 10, the flat surface having dark

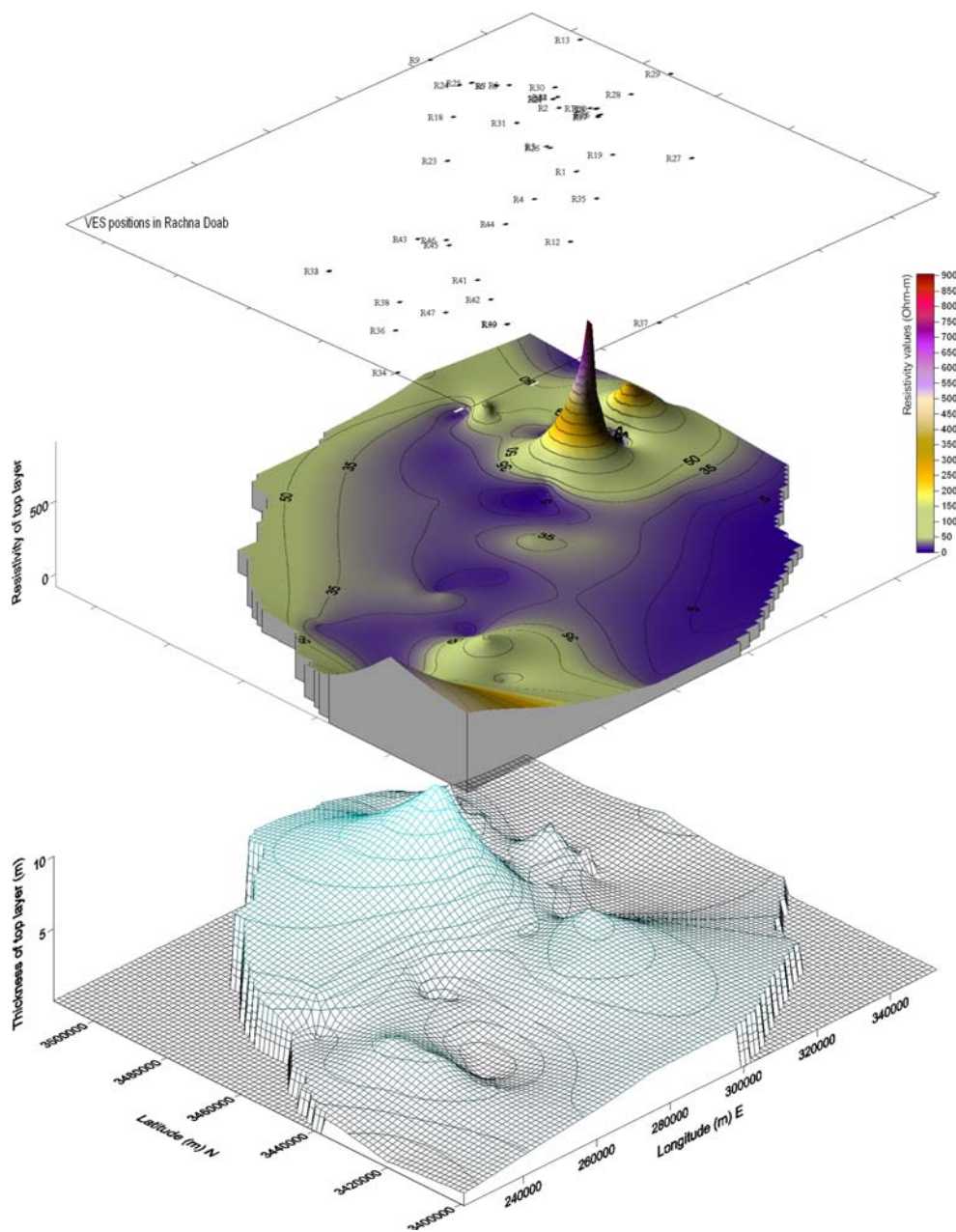


**Fig. 6** A 3-D representation of the top layer resistivity, its thickness and VES positions in Chaj Doab

brown color is the dividing line between fresh and saline groundwater having resistivity equal to  $45 \Omega \text{ m}$ . Above this surface, the zones having blue color have fresh groundwater in the shallow aquifer layers which is safe to use for irrigation purposes.

Below this layer, groundwater is marginally fit to unfit. Similarly, the 3-D representation of the boundary between saline and brackish groundwater quality is also shown in the Fig. 11. In Fig. 11, the flat surface of brown color is the boundary, which cuts the quality of groundwater in shallow aquifer at  $25 \Omega \text{ m}$ . Above this surface, the quality of

groundwater is marginally fit to fresh (fit) and below this surface the quality is saline to highly saline and should not be used for irrigation purposes. It is also clear from the Figs. 10 and 11 that a very small area of the Chaj and Rachna Doabs have fresh groundwater in the shallow aquifer. These fresh groundwater zones mostly lie near the rivers, and the rest of the area has no fresh shallow groundwater. If we move this criteria of groundwater quality little bit downward from fresh to marginally fresh, then the area above this limit has increased, especially near the rivers of Ravi and Jhelum. But most of the area under



**Fig. 7** A 3-D representation of the top layer resistivity, its thickness and VES positions in Rachna Doab

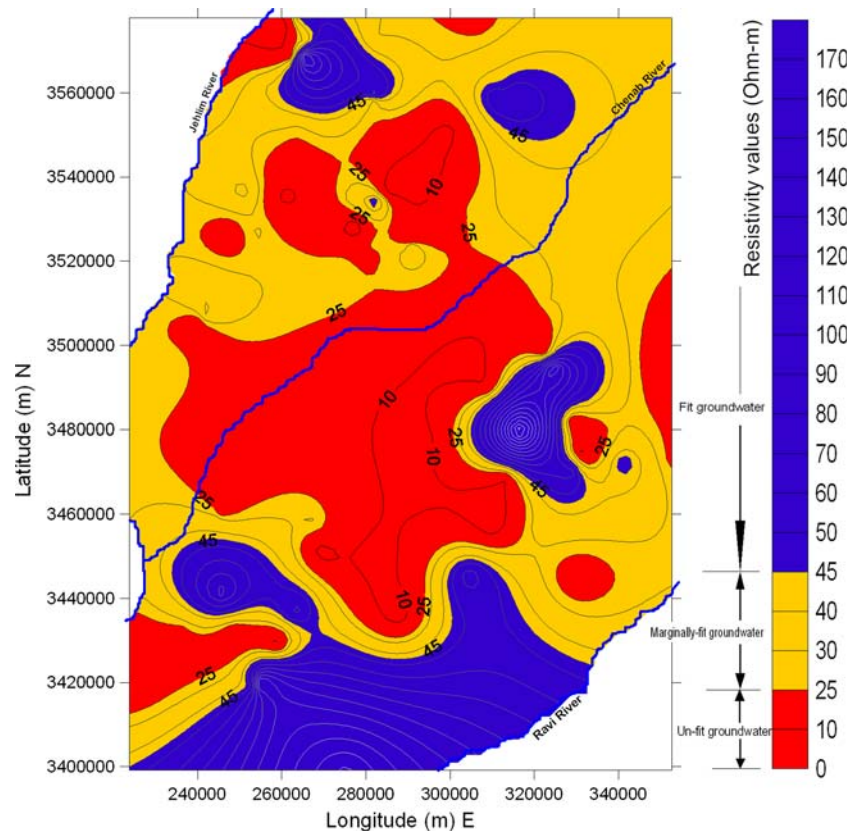
study still has saline groundwater and about half of the research area of Chaj and Rachna Doab has shallow (upper layer of groundwater) groundwater quality marginally fit to fit for irrigation and the about half of the rest has low quality groundwater, which is saline and unsafe for irrigation.

#### Deep aquifer resistivity

Similarly, the contour map of the resistivity of groundwater layer lying below this shallow layer of groundwater is also presented in Fig. 12. The resistivity values of the deep

groundwater layer range from 0.9 to 91.74  $\Omega$  m at sites C22 and C20 in Chaj Doab, whereas, it ranges from 0.14 to 152  $\Omega$  m at sites R42 and R12 in Rachna Doab, respectively. These two peak resistivities values, one in Chaj Doab, having resistivity value of 91.74  $\Omega$  m at longitude 28734 and latitude 3548306.5, while the other 152  $\Omega$  m in Rachna Doab at longitude 287647.1 and latitude 3436092.2 can be clearly seen in the contour map (Fig. 12) with blue color. The thickness of this deep aquifer in the study area of Chaj and Rachna Doabs could not be fixed due to the fact that the VES surveys were done with a maximum current electrode AB/2 upto 180 m. The maximum depth

**Fig. 8** Contour map of the shallow aquifer resistivity in the study area



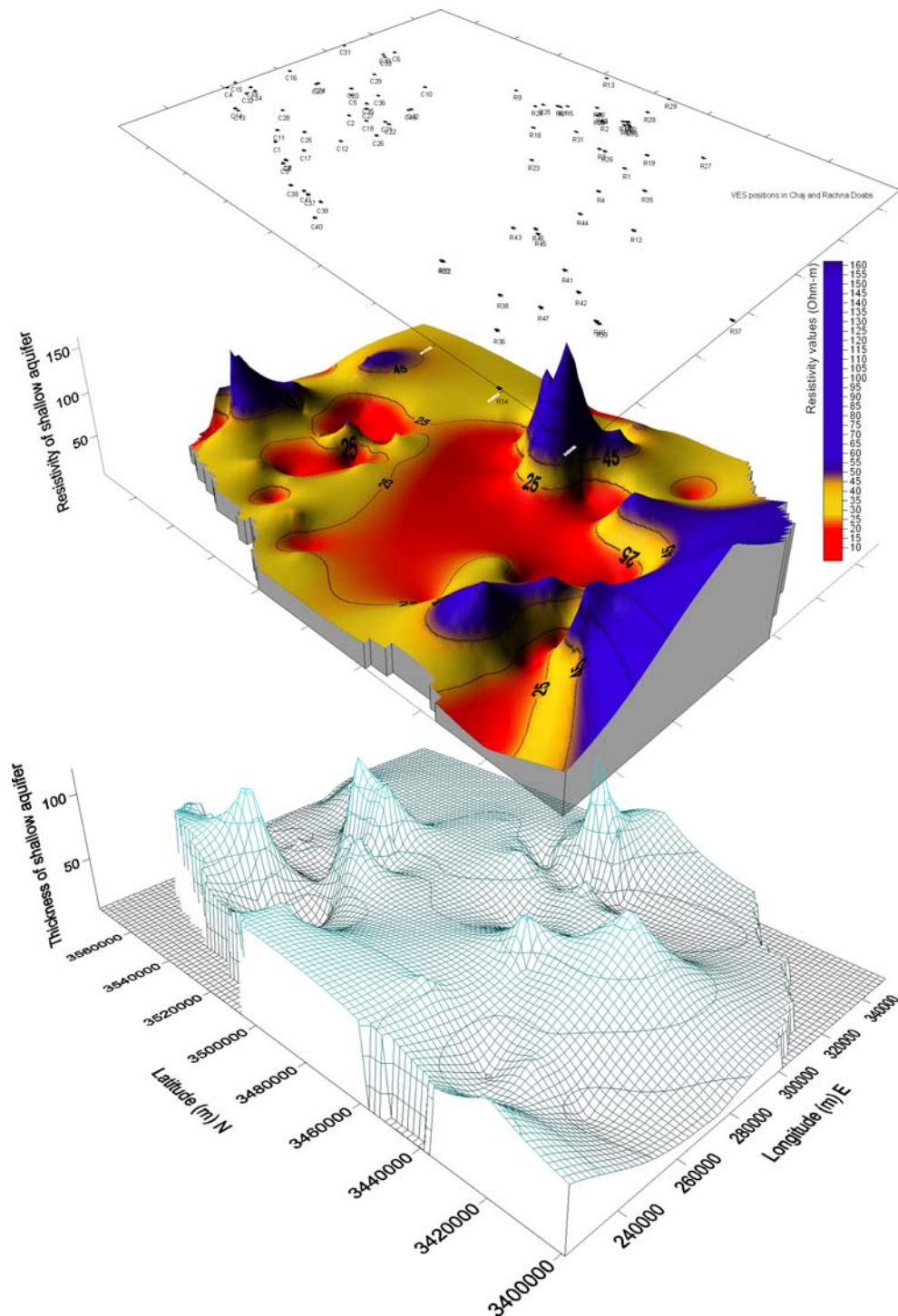
of effective current penetration depth at a maximum of 180 m AB/2 might remain less than the thickness of deep aquifer. It is a common rule of thumb to say that the depth of investigation is of the order of 0.1–0.3 times the current AB length. Therefore, 360 m AB line leads to a depth 36–108 m, depending on the type of layering. Even then the knowledge of groundwater qualities in the deep aquifer at these depths gives a very good picture if it be compared with shallow aquifer groundwater.

From Fig. 12, the study area can easily be separated into the fresh, marginal and saline groundwater in the deep aquifer. The contours having dark blue color are the representation of the area having fresh groundwater in the deep aquifer. The contours having yellow color represents the marginally fit groundwater for irrigation and the rest of the contours having dark red color represent the aquifer having groundwater unfit for irrigation. These dark red color zones are highly saline zones in the study area. The safe groundwater having resistivity more than 45 Ω m in the deep layers of research area is presented in blue color. Similarly, the boundary between yellow and red color was fixed at 25 Ω m of aquifer resistivity. Therefore, yellow color zones represents marginally fit groundwater and red color zones are the representation of saline groundwater.

In the deep low lying groundwater layer, the conductive material in the groundwater, associated with the presence

of more salts is extended towards all directions, occupying now a greater part of the investigated area. From Fig. 12, it is clear that large part of the study area of Chaj and Rachna Doabs have groundwater quality in the deep aquifers below safe limits. There are only two very small areas which have fresh groundwater in deep: one on the north side in Chaj Doab and other in east-west corner (in Rachna Doab) of the research area. If again we move the limit of deep groundwater from fresh to marginally fit, then the area increased little bit especially in the north-west corner and the other on the eastern side of research area as shown in the Fig. 12. The rest of the area was largely comprised of saline groundwater in the deep aquifer. From Fig. 12, it is also clear that the groundwater is somewhat better near the rivers than in the center of Doabs.

The sites C4, C11, C13, C14, C18, C26, C36, 37, C38 and C40 have the same resistivity values of shallow and lower groundwater layers. Therefore, same quality of the groundwater starts from groundwater level and extends upto deep without any quality change (Figs. 8, 12). The sites C7, C9, C20, and C30 are different from other sites of Chaj Doab, because the resistivity of lower layer of groundwater is higher than the shallow layer of groundwater. This higher resistivity of the groundwater layer lying below the low resistivity groundwater layer of these sites can also be observed in the Figs. 8 and 12. Therefore, at

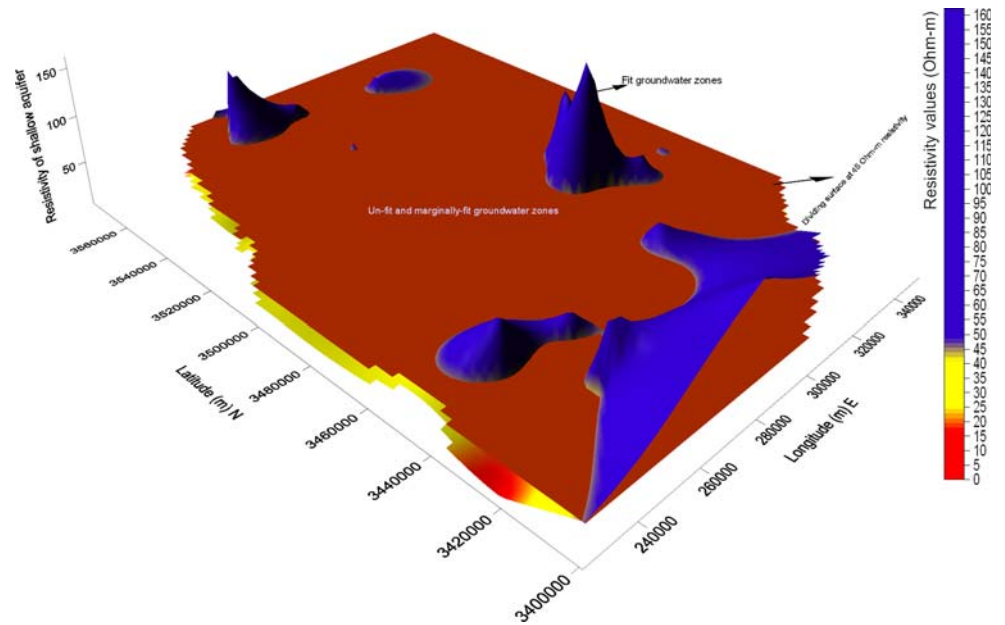


**Fig. 9** 3-D representation of the shallow aquifer resistivity, its thickness and VES positions in the study area

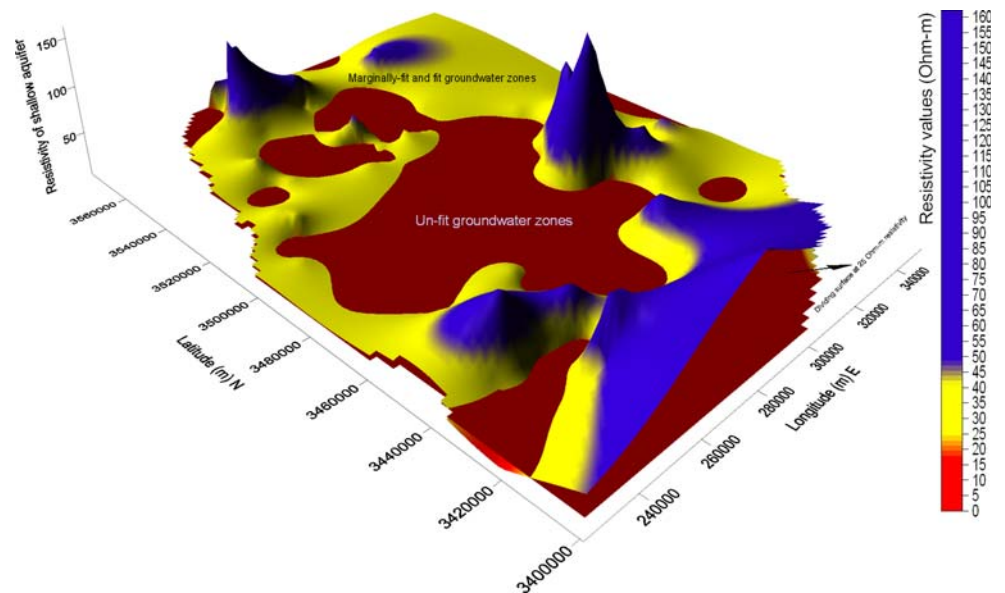
these sites which are different from the rest of the study area have good quality of groundwater layer lying below the brackish groundwater layer. In spite of having higher resistivity values at the sites R13, R23, R24 and R27, the groundwater quality in the lower layer is still not of good quality because these sites have resistivity value still lower

than  $45 \Omega \text{ m}$ . The sites R1 and R12 have very high resistivity values of 142 and  $152 \Omega \text{ m}$  at the lower layer of groundwater and fit for irrigation. This is also clear in the Fig. 12 that south-west corner side of the study area have blue color. This was also clear from the VES data that Tehsil Toba Tek Singh which lies in the south-east part of

**Fig. 10** Dividing surface between fresh and brackish groundwater of shallow aquifer



**Fig. 11** Dividing surface between marginal fit and saline groundwater of shallow aquifer



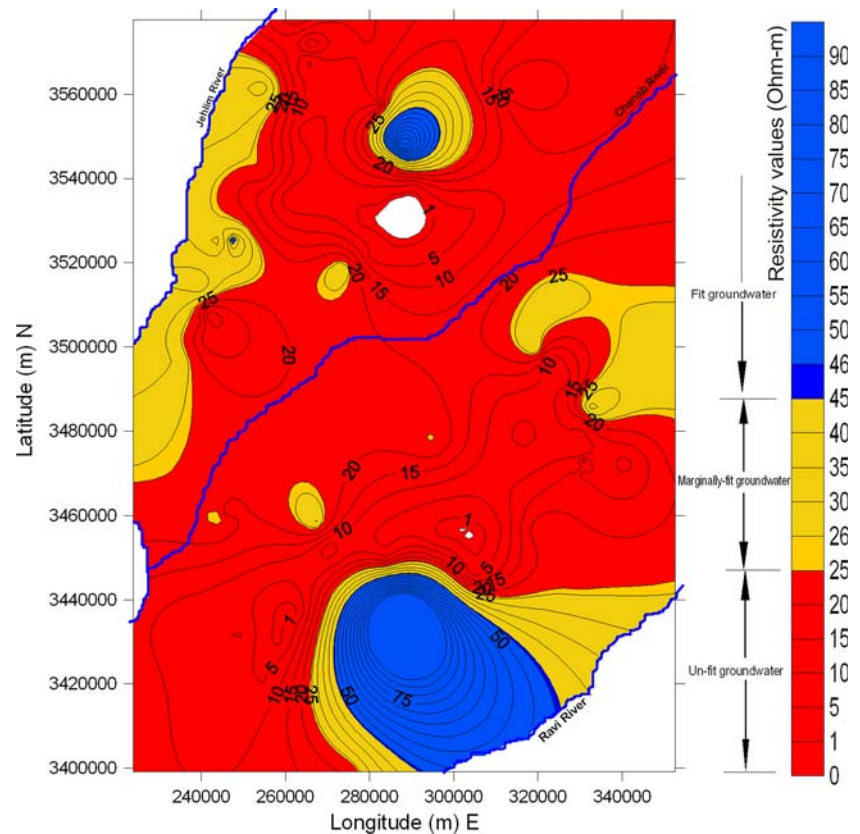
the study area have comparatively good quality groundwater in shallow and deep aquifers for irrigation.

**Conclusions**

VES survey can be used successfully to identify subsurface aquifer layers and to characterize the salinity of groundwater. Below the top unsaturated surface layer mainly two layers of different groundwater quality were identified in the study area of Chaj and Rachna Doabs. Based on the interpretation of geoelectrical VES survey conducted at both of the Doabs (Rachna and Chaj), the following conclusions are drawn:

- The top layer resistivity ranged between 3.9 Ω m at C7 and 2,222 Ω m at R15, with varying thickness ranging from 0.335 to 29.11 m at sites C29 and C20, depending upon the moisture conditions.
- The subsurface geoelectrical layers also showed different resistivity values at all the selected sites due to different types of soil formation but mainly due to the salinity of groundwater in study area. In the saturated layers, resistivity ranged between 1.21 and 171 Ω m at sites C18 and R31 in the shallow aquifers, where as it ranged from 0.14 to 152 Ω m at the sites R42 and R12 of the deep aquifers in the study area.
- An empirical relationship was developed between the interpreted layer resistivity and the EC of water with  $R^2$

**Fig. 12** Contour map of the deep aquifer resistivity in the study area



of 0.85, which can be helpful for further VES survey studies at other sites in Rachna and Chaj Doabs. This empirical relationship may also be used to estimate local EC values from iso-resistivity maps.

- The empirical relationship between EC of groundwater and the layer resistivity showed that greater than  $45 \Omega \text{ m}$  of aquifer resistivity, the water can be safely used for irrigation purposes.
- The groundwater quality in the shallow layers was found to be better than in the deep groundwater layer at most of the sites of Chaj and Rachna Doabs except some sites. Moreover, the quality of groundwater is better near the rivers and deteriorates as we move towards the center of each Doab.

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