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Groundwater investigations in the Hattar industrial estate and its vicinity, Haripur district, Pakistan: An integrated approach

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Abstract

The Hattar industrial estate in the Haripur district, Khyber Pakhtunkhwa (KPK), Pakistan, is investigated for the groundwater potential and aquifer vulnerability using vertical electrical sounding (VES) data, borehole logs, and hydrochemical analysis. A total of eight VES points were acquired in the Haripur region using Schlumberger configuration. The interpreted VES models are further constrained by four borehole logs to delineate comprehensive information of the thin lithological layers, subsurface layers configuration, and spatial extent in the area. A quantitative interpretation based on the VES and the borehole data suggests six main subsurface layers: (i) soil cover, (ii) gravel, (iii) clay, (iv) clay with gravel, (v) silty-clay, and (vi) sand with a boulder in the study area. A fence diagram is also generated to provide a detailed paleo-depositional model of the subsurface layers. The interpreted VES data is utilized to compute aquifer thickness, longitudinal conductance, and transverse resistance within the study area. The lateral extent and protective capacity for the aquifer were inferred from these measurements. The aquifer thickness is relatively low in the central and eastern parts ranging from 10 m to 11 m. The longitudinal conductance map shows values greater than 2 mhos from the central region to northern one. This is indicative of moderate to good protective capacity for the aquifer and is less vulnerable to infiltration of Hattar industrial polluted fluid. However, the values less than 0.19 mhos in the southwest and east are indicative of weak protective capacity with the risk of contamination. The hydrochemical analysis of the surface and subsurface water is carried out at eleven locations to identify the water quality within the study area. The chemical analysis of the water shows the presence of a high concentration of magnesium, bicarbonate, and chlorine away from the World Health Organization (WHO) standard.

Keywords: Apparent resistivity; borehole; groundwater; hydro-chemical analysis; vertical electrical sounding.

1. Introduction

The Indus plain, starting from the Himalayan foothills to the Arabian Sea, supports most of the groundwater resources in Pakistan. The groundwater is mainly stored in alluvial deposits. Several studies have been carried out to evaluate the groundwater quality in Pakistan (Niaz *et al*., 2015). The study area lies in Haripur district, which is located about 80 km northwest of Islamabad (Figure1). After the establishment of the Hattar industrial estate (HIE) in 1970, the population growth in the area demanded an increase in the clean water supply for domestic and industrial use. The area within and in the vicinity of HIE is facing water problems including low quality of surface water resources, continuous shortage of good quality groundwater, and contamination of groundwater from industrial waste from rubber, ghee, cement, ceramic, and leather industries situated in HIE. The geoelectrical methods are widely used to investigate potential groundwater subsurface strata and groundwater contamination (Kelly & Stanislav, 1993; Nazaruddin, 2015; Adesola *et al.,* 2017). The apparent resistivity of soil and subsurface lithologies is measured as a function of depth with the VES method. A reasonable relationship between geological structure and groundwater resources is determined by this method. The hydraulic parameters of aquifers are estimated by the concept of Dar-Zarrouk parameters (Maillet, 1947). The Dar-Zarrouk concept is further applied to estimate the protective capacity of groundwater, transmissivity, and lateral extent of the subsurface lithologies (Ezeh, 2011).

The hydrochemical analysis of surface and groundwater samples was carried out for major ions and trace elements (Freeze and Cherry, 1979; Al-Sulaimi and Al-Ruwaih, 2004). The total hardness of water is also considered in the hydrochemical analysis to check the presence of calcium and magnesium concentrations. This is the first research effort in the Haripur region to delineate subsurface water potential by using geophysical, geological, and hydrochemical methods. The analysis of these data sets enables us (i) to significantly identify the groundwater bearing strata, its lateral and vertical extent, (ii) to identify the protective capacity of the aquifer, and (ii) to delineate the quality of the surface and groundwater. This improved dataset can serve as a benchmark for further geophysical and geological investigations, which in turn will benefit the local community suffering from serious issues related to quality water.

2. The study area

The Haripur district is located about 80 km northwest of Islamabad in the province of Khyber Pakhtunkhwa (Figure 1). The area covers about 1725 km^2 that includes about 460 km^2 of mountains at an altitude of 532 m along Karakoram Highway. The Dor and Haro rivers are the main rivers of the Haripur, which are recharged by the melting snow, rainfall, and groundwater (Figure 1). The stratigraphy of the Haripur region consists of Alluvium, Kuldana Formation, Chorgali Formation, Margalla Hill Limestone, Patala Formation, Lockhart Formation, Hangu Formation, Kawagrah Formation, Lumshival Formation, Data Formation, Abbottabad Formation, and Hazara slates from recent to Pre-Cambrian times (Latif, 1970a). The study area is bounded in the north to the northeast by Nathiagali Hissartang Block, in the west by Attock Cherat ranges, in the east by Margalla hills, and in the west by Gandghar ranges. The exposed rocks in the study area are mainly sedimentary and metamorphic origin (Figure 1).

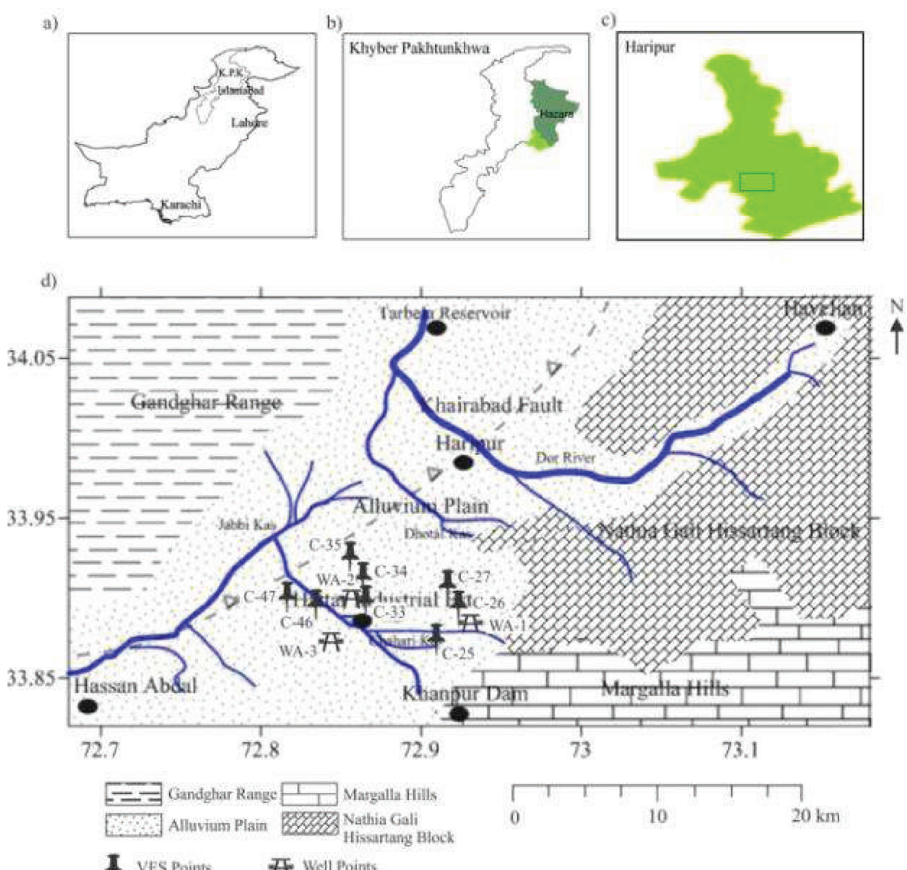

Fig. 1. (a), (b), and (c) Map of Pakistan, Khyber Pakhtunkhwa province, and Haripur region. The study area is highlighted with black rectangle. (d) Geological map of the study area (modified after Umair *et al.,* 2018).

3. Materials and methods

The resistivity techniques, especially the vertical electrical sounding (VES) method, are largely used worldwide for investigating resistive layer properties, groundwater potential, and aquifer studies (Muchingami *et al.,* 2012). The VES survey was carried out by using an ABEM SAS 300c Terrameter with Schlumberger electrode configuration across the Hattar industrial estate and its vicinity (Figures 1 and 2). The system is connected to 4 electrodes, which were laid out in a straight line (Figure 2).

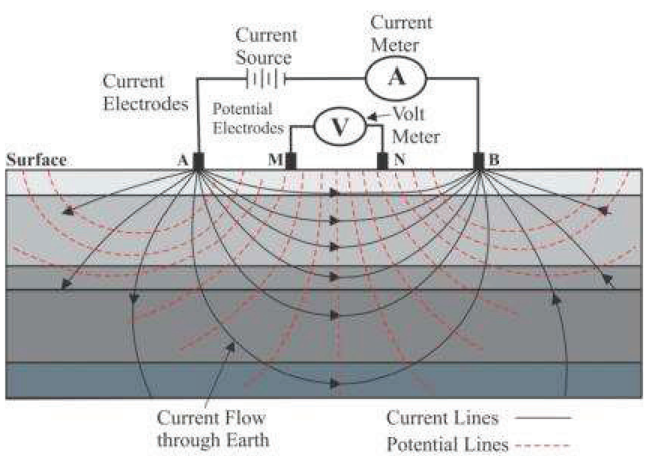

Fig. 2. Schematic illustration of the basic measurements using electrical resistivity method (Modified after J.A. Clark *et al*., 2011). Solid black lines represent current flow through layered subsurface structure. Dashed red line represents contoured electrical potential.

By increasing the spacing between the current electrodes, the depth of current penetration increases, which allows for a deeper depth of investigation. The depth of sounding resulted in the apparent resistivity (ρ_a) measurement as a function of current passed into the ground, voltage drop between electrodes, and current intensity. The relationship between electrical and hydraulic parameters is to calculate the hydraulic parameters such as longitudinal conductance (S) and transverse resistance (T) (Okonkwo & Ezeh, 2012). The hydraulic parameters derived from the apparent resistivity (ρ_a) and thickness are given as:

Longitudinal conductance

$$S = h/\rho_a \quad (1)$$

Transverse resistance

$$T = h.\rho_a \quad (2)$$

where h represents thickness and resistivity of the subsurface layer. The water samples were collected from surface streams and wells. A total of eleven water samples were collected for the hydrochemical analysis. This analysis allowed the correlation between VES data and the water samples. Three samples from each location, about 60 ml each, were collected in plastic high-density polyethylene bottles (HDPE); one of these samples were acidified for trace elements. The collected samples were then analysed by using an atomic absorption spectrometry instrument.

4. Results and discussion

For this paper, we are presenting results from two VES points (Figures 3a and 3b). The results indicate the presence of five to six subsurface layers with different thicknesses and lithologies (Table 1). The lithologies of the subsurface layers are inferred from the resistivity model (Table 1) and constrained by the available borehole data in the study area. The resistivity values range from 10 to 363 Ωm for the gravel layer containing groundwater (Figures 3a, 4b, and 4c). Three aquifer layers are present across the VES points C-25 to C-27 (Figure 4a). For the mapping purpose, we have utilized the thickness of the aquifer, about 60 m deep.

4.1 Geological analysis:

The lithological information obtained from the three boreholes (WA-1, WA-2, and WA-3, Figure 1) is used to constrain the lithological model generated from the resistivity data. Based on the resistivity inferred lithological model and borehole data, three cross-sections (A-A`, B-B`, and C- C`) are prepared (Figures 4a, 4b, and 4c). The cross-section A-A` is generated from the three VES points (C-25, C-26, and C-27) and a single borehole (WA-1, Figure 4a). The cross-section A-A` represents the presence of four lithologies (top soil, gravel, clay with gravel, and clay). The groundwater accumulation is evident in three gravel layers; however, the middle gravel layer, about 35 m deep, is partially capped by clay with gravel layer (Figure 4a). This semi-confined aquifer is about 11 m thick, and its continuation towards west is not evident from the borehole and resistivity data (Figures 3b and 4b). The bottom gravel layer is about 50 m deep, and it is capped by a 5 m thick clay layer. This confined aquifer is about 10 m thick, and it is underlain by impermeable clay layer. The confined aquifer extends towards west, which is evident from the borehole and resistivity data (Figures 3b and 4b).

The cross-section B-B` is generated from the three VES points (C-33, C-34, and C-35) and a single borehole (WA-2, Figure 4b). The cross-section B-B` shows the presence of four lithologies (top soil, silty clay, gravel, and clay). The top layer of gravel is about 25m deep and 5 m thick. The cross-section C-C` is generated from the two VES points (C-46 and C-47) and a single borehole (WA-3, Figure 4c). The cross-section C-C` shows the presence of four lithologies (top soil, silty clay, sand with boulder, and clay and boulder alternating layers). The massive body of sand with boulder is present at two different levels (Figure 4b). The massive body of sand with boulder is present at two different levels (Figure 4c). The top sand with the boulder layer is about 20 m deep and 30 m thick. The bottom sand with the boulder layer is about 60 m deep. The bottom aquifer is confined, and it is correlated with the gravel layer present in cross-sections A-A` and B-B`. It is ensured that the correlated sections are at the same depths (Figures 5a and 5b).

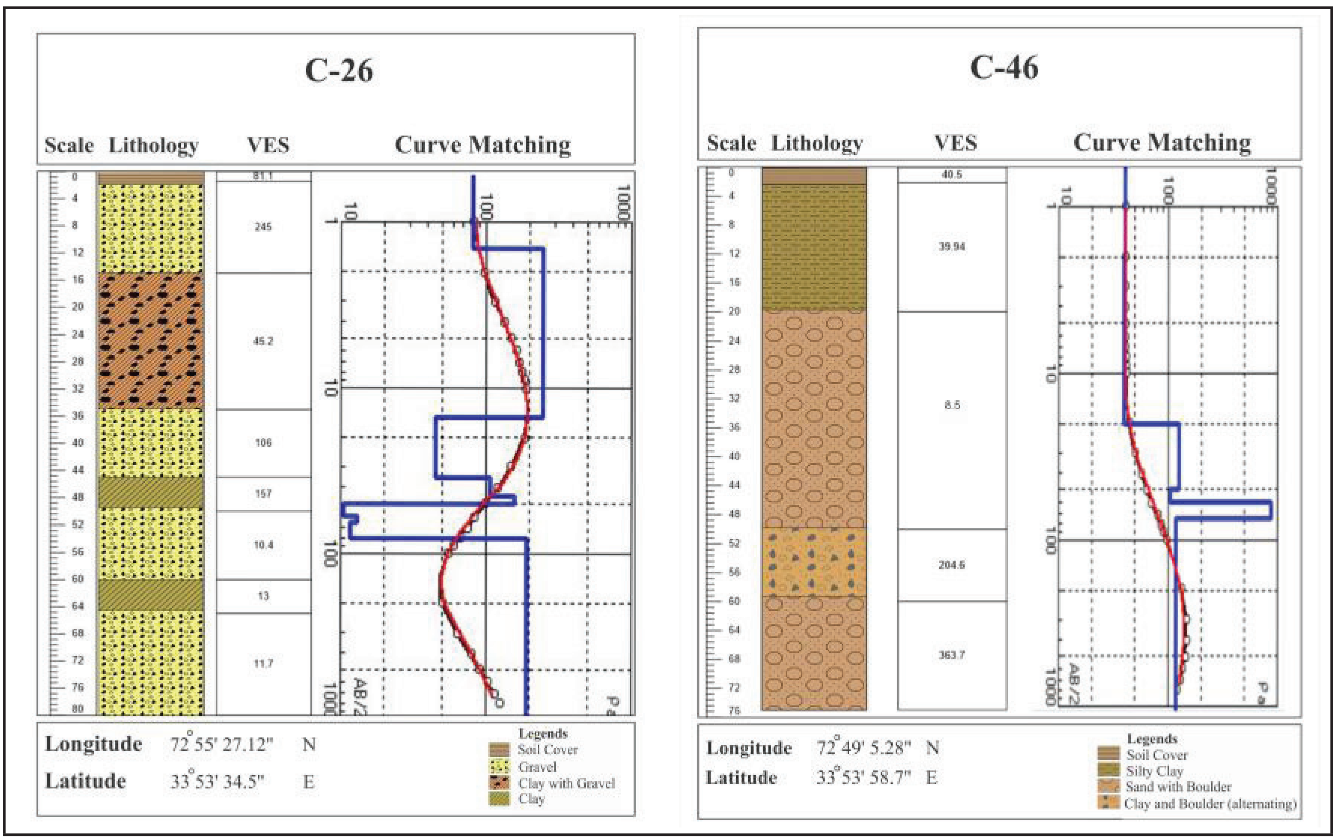

Fig. 3. (a) Vertical electrical sounding (VES) points 26. The resistivity model represents the number of subsurface layers and inferred lithologies with thicknesses. (b) Vertical electrical sounding (VES) point 33. The resistivity model represents the number of subsurface layers and inferred lithologies with thicknesses.

Table 1. Interpreted subsurface geology.

Layer number	Interpreted thickness (m)	Resistivity range (Ωm)	Interpreted lithology
1	2− 3	21− 81	Loose dry soil
2	5− 16	8− 245	Gravel
3	5− 10	11− 157	Clay
4	18− 20	23− 45	Clay with gravel
5	16− 40	16− 52	Silty clay
6	16− 30	126− 876	Sand with boulder
7	10− 12	104− 205	Clay with boulder

4.2 Aquifer thickness:

The interpretation of resistivity and borehole datasets indicates the presence of five to seven subsurface layers. These layers constitute a total thickness of about 90 m in the subsurface (Table 1). The gravel layers are present at three different depths with resistivity values ranging from 10 to 360 Ωm. The groundwater accumulation in the gravel layers is evident at various locations in the region. The bottom gravel layer, present at about 62 m depth, indicates the characteristics of confined aquifer as it is well-capped by impermeable clay layer (Figures 4a, 4b, and 4c). A thickness map of this confined aquifer is generated across the study area (Figure 5). The aquifer thickness map shows a thickness variation from 10 to 17 m. An increase in the aquifer thickness is evident from the east to towards the west (Figure 5).

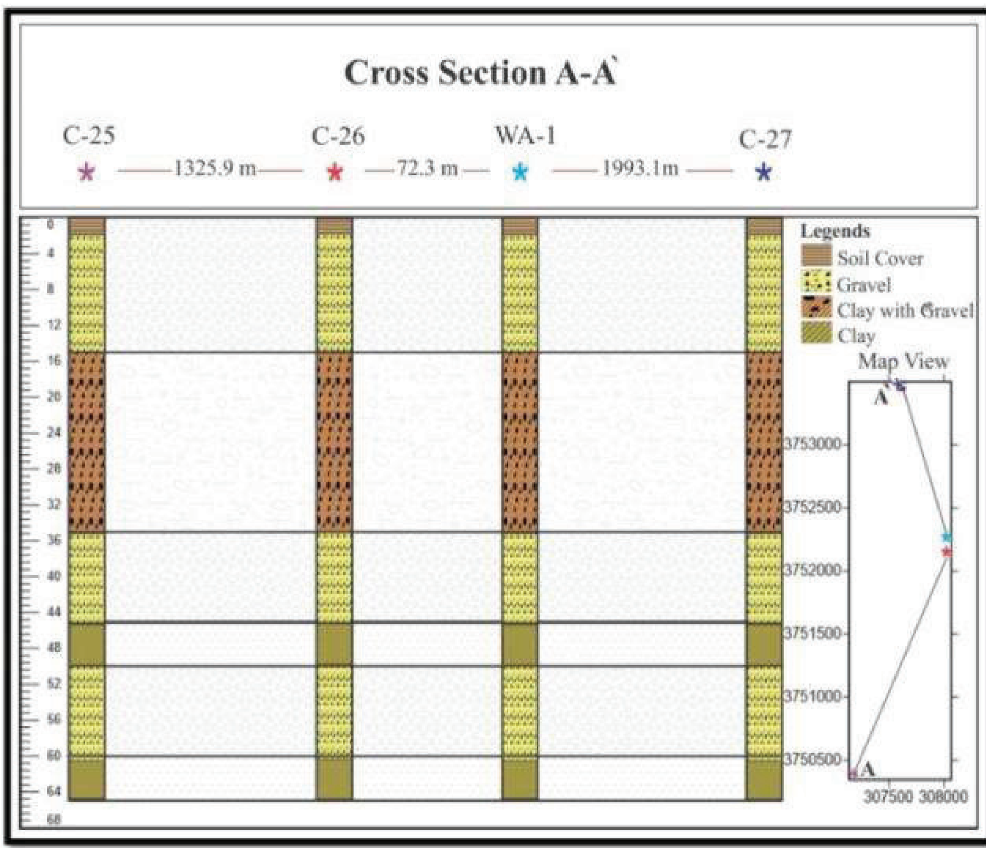

Fig. 4 (a). Cross-section A-A shows correlation between three VES points (C-26, C-27, and C-28) and one borehole (WA-1).

Table 2. Longitudinal conductance and protective capacity rating (modified after Henriet 1976).

Longitudinal conductance (mhos)	Protective capacity rating
0> 10	Excellent
5 – 10	Very good
0.7 – 4.9	Good
0.2 – 0.69	Moderate
0.1 – 0.19	Weak
< 0.1	Poor

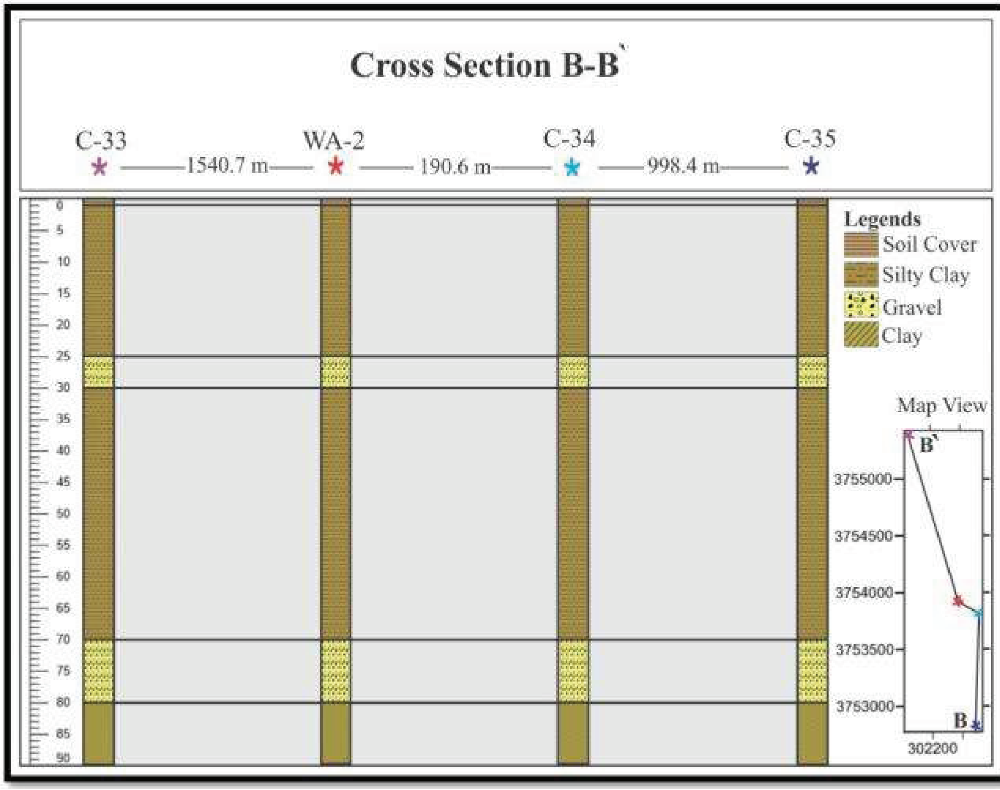

Fig. 4 (b). Cross-section B-B shows correlation between three VES points (C-33, C-34, and C-35) and one borehole (WA-2).

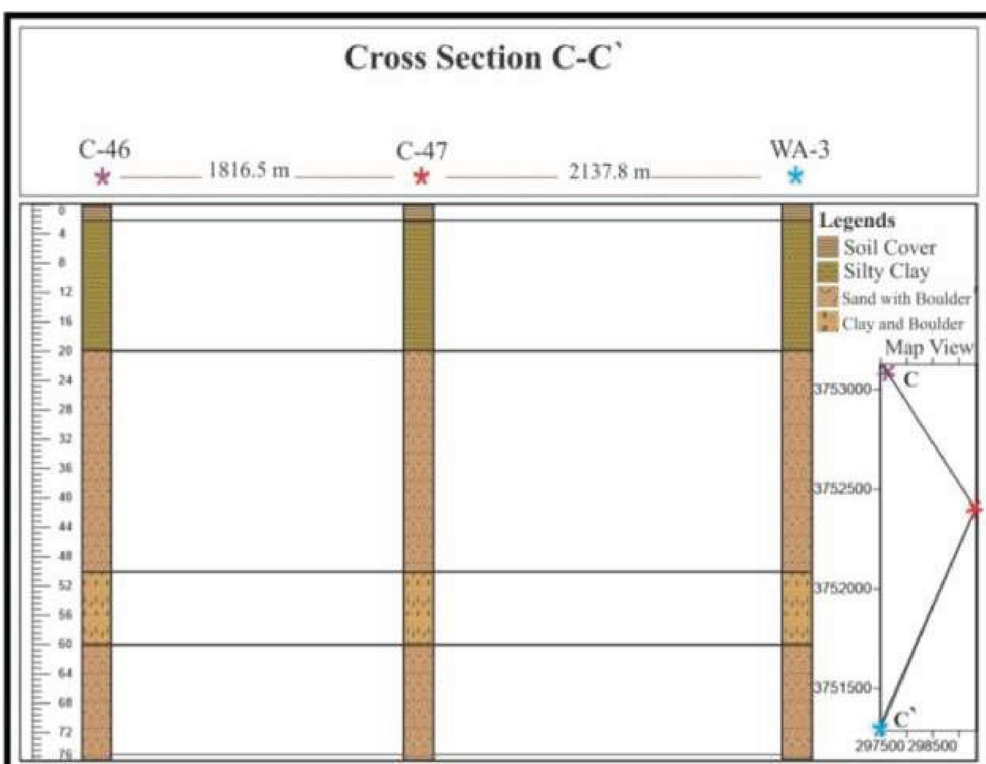

Fig. 4 (c). Cross-section C-C shows correlation between three VES points (C-46 and C-47) and one borehole (WA-3).

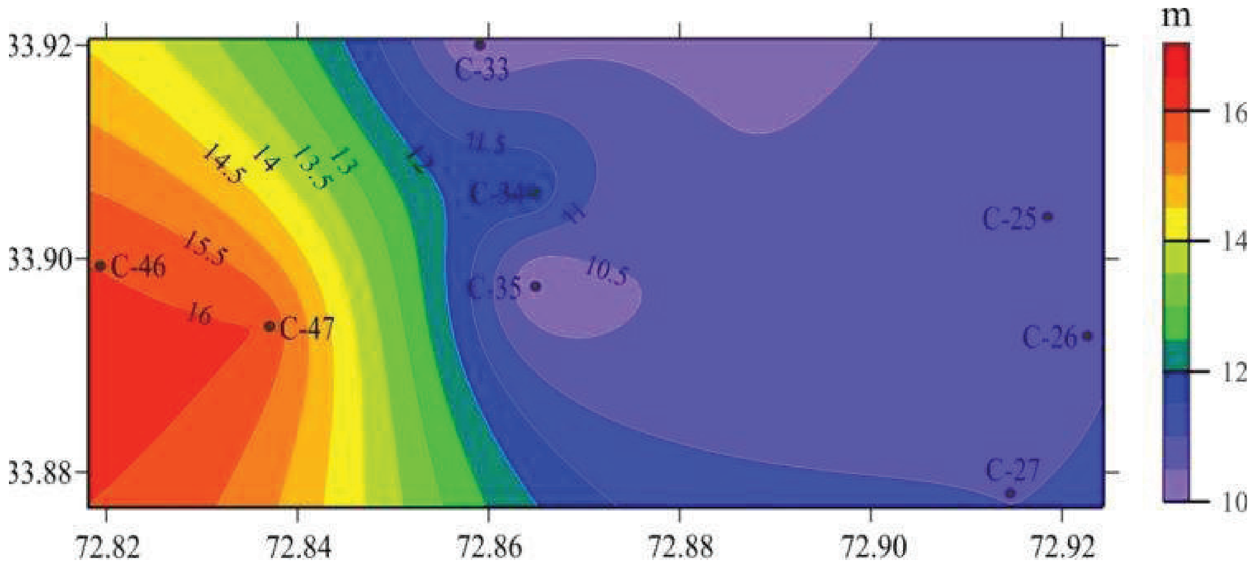

Fig. 5. Aquifer thickness map of the region showing an increase in the thickness in the west and northwest. The black dots represent electrical resistivity sounding locations.

4.3 Hydraulic parameters:

The hydraulic parameters that include longitudinal conductance and transverse resistance are measured to analyse the protective overburden of the aquifer. The subsurface layers such as impermeable clay layers above the aquifer act as an overburden protection. These layers may filter or retard the percolating fluids (Mogaji *et al.,* 2007; Mohammad *et al.,* 2016). The longitudinal conductance map and transverse resistance map (Figures 6a and 6b) are generated for the aquifer at about 60m deep overburden clay layers.

These maps were helpful to determine regions with higher groundwater potential and good protective capacity. Table 2 shows modified longitudinal conductance and protective capacity rating for the study area (Henriet, 1976). The longitudinal conductance map (Figure 6a) generated for the overburden clay layers shows a range of values from 0.045 to 2.41 mhos. It shows an increasing trend from south to north and a decreasing trend from the central region to east and west. The transverse resistance map (Figure 6b) for the overburden clay shows a decreasing trend from the west to east and values ranging from 350 to 2600 ohm.m^2 in the central region to east and west.

The transverse resistance map (Figure 6b) for the overburden clay shows a decreasing trend from the west to east and values ranging from 350 to 2600 ohm.m^2. The highest values of the transverse resistance are concentrated in the west. The central region shows values from 600 to 1100 ohm.m^2. Based on the longitudinal conductance map (Figure 6a), the aquifer can be classified into three zones of protective capacity; 1) north and central regions show good protective capacity with values ranging from 0.7 - 4.9 mhos; 2) the southern region can be rated as a moderate protective capacity zone with values ranging from 0.2 to 0.69 mhos; and 3) the eastern and western regions show values from 0.04 to 0.1 mhos, rated as having a weak to poor protective overburden capacity.

4.4 Hydrochemical analysis:

The water chemistry analyses (Table 3) were carried out to identify and quantify the chemical components of the water samples collected from three streams and eight wells.

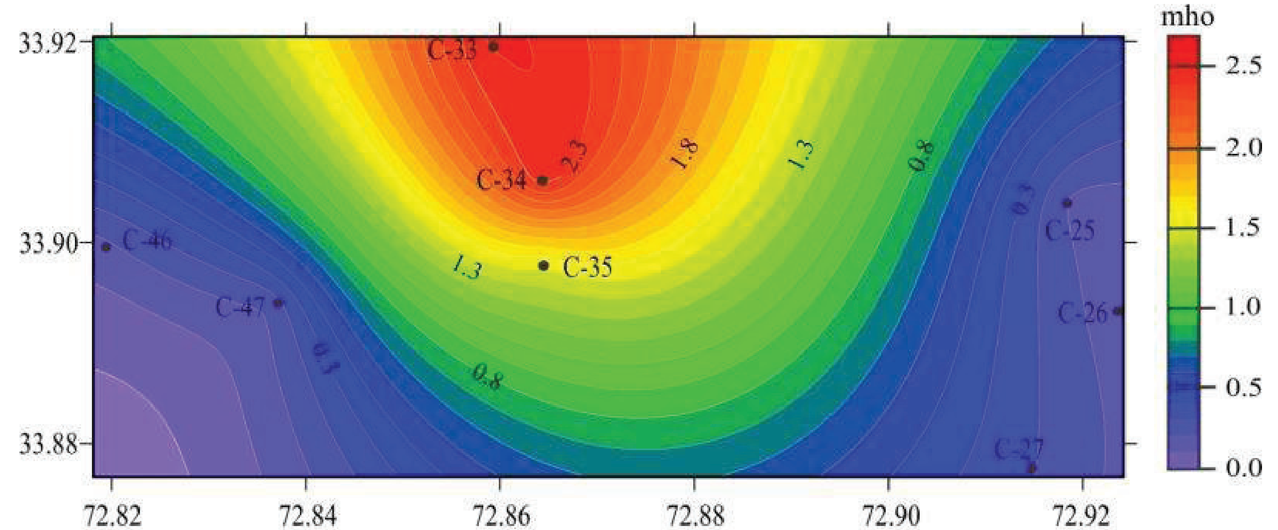

Fig. 6 (a). Longitudinal conductance calculated for the overburden layer in the region. The black dots represent electrical resistivity sounding locations.

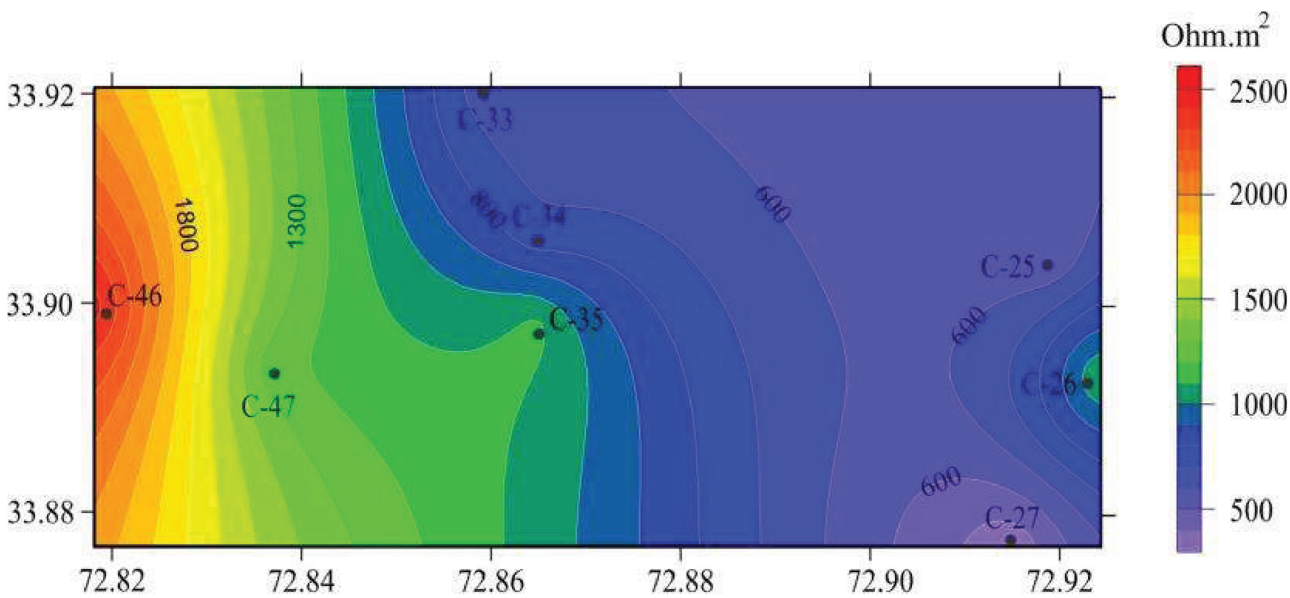

Fig. 6 (b). Transverse resistance calculated for the overburden layer in the region. The black dots represent electrical resistivity sounding locations.

The wells were about 120 feet deep in the study area. The total dissolved solids (TDS) are higher at surface levels (S1, S4, and S3) than the permissible limit (500 mg/L). The total hardness (TH) is also high in all water samples except subsurface sample (SS2). The TH in S1, S2, and S3 is much higher than the permissible limit. The high value of the TH may correspond to high TDS at the surface level. The TH is mainly because of calcium (Ca) and magnesium (Mg), which contribute to carbonate hardness. The concentration of Mg is much higher than the Ca in almost all the water samples. The higher concentrations of Mg in S1, S2, and S3 correspond to high TDS and TH. In non-carbonate hardness, which is due to chlorine (Cl) and sulphate (SO4), chlorine concentration is much higher than the sulphate. Thus, Cl is the major element, which contributes to non-carbonate hardness. The analysis of carbonate and bicarbonate further clarifies that the concentration of carbonate was negligible, and thus, not detected; it provides an understanding that the hardness is due to bicarbonate. The electrical conductivity (EC) measurements show that it is in good agreement with TDS and TH. The water pH in all samples is closer to the neutral (7.0), which is acceptable. The water quality at surface and subsurface is mainly deteriorated by the Mg, bicarbonate, and Cl present in high dissolved concentrations in the study area.

Table 3. Results of hydrochemical analysis of water samples (surface and subsurface) taken from the study area.

Parameter	S1	S2	S3	SS1	SS2	SS3	SS4	SS5	SS6	SS7	SS8	WHO/EU/Canada
EC (µS/cm)	1.15	1.23	1.34	0.69	0.53	0.71	—	—	—	—	—	0.05-0.5
pH	7.15	7.01	7.30	7.48	7.38	7.26	—	—	—	—	—	6.5-8.5
Calcium*	285	231	285	138	113	176	—	—	—	—	—	<200
Chloride*	220	55	260	35	30	50	—	—	—	—	—	<250
TH*	820	800	810	500	430	580	—	—	—	—	—	<500
Calcium C.*	714	557	714	346	283	441	—	—	—	—	—	<500
Magnesium*	645	660	636	415	360	472	—	—	—	—	—	<50
Sulphur Oxide	8	10.3	28	12.8	9.6	10	—	—	—	—	—	<250
Nickel**	—	—	—	—	—	—	11.5	7.9	9.55	10	9.7	<20
Ferric**	—	—	—	—	—	—	3.2			1.59	5.02	<0.2-0.3
TDS**	805	897	930	474	348	460	—	—	—	—	—	<500

WHO, World Health Organization; EU, European Union; S, Surface sample; SS, Subsurface sample (about 120 feet deep); *, (mg/L); ** , (µg/L)

4.5 Correlation between VES and hydrochemical analysis:

The VES dataset provides indirect measurements of the subsurface anomalies (Muchingami *et al.,* 2012). The availability of other datasets such as borehole logs, pumping data, and hydrochemical data can place strong constraints on the results by the VES dataset. In the present study, the VES and borehole datasets are correlated with hydrochemical analysis of the water samples collected from eleven surface and subsurface locations. The higher electrical conductivities are associated with impurities present in the water that would increase conductivity (Niaz *et al*., 2018). The vulnerability mapping (Figures 8a and 8b) indicates clay starved zones towards the eastern, central, and western parts. The starved zones are dominated by coarser lithologies with high permeability, which can transmit the surficial contaminants to shallow subsurface aquifer. The low resistivity values observed in the shallow aquifer (Tables 1 and 2) also suggest the presence of impurities in these layers. The hydrochemical analysis of water samples show higher electrical conductivity, Mg, Cl, and TH for surface and subsurface water samples, which are indicative of low water quality (Table 3).

5. Conclusions

In the study area, the surface and groundwater are contaminated by the wastes excreted from industries. The objective of this study is to evaluate the shallow subsurface water potential and quality using a combination of VES, borehole data, and hydrochemical data. The integrated geological and VES techniques proposed six subsurface lithologies with difference thicknesses and lateral extending. The survey reveals a couple of productive groundwater zones in the study area. However, the aquifer, present at about 60m deep, shows continuous lateral extension and assures adequate drinkable water resource in the study area. The aquifer thickness map shows an increase in thickness from east to west. The hydraulic parameters investigated the groundwater potential and vulnerability of the aquifer. The entire study area can be classified into zones of good to poor protective capacity. The overburden protective capacity of aquifer in the north, central, and southern regions is good to moderate. The eastern, central, and western regions of the study area are highly vulnerable to the infiltration of dumped wastes from the industries. The hydrochemical analysis of the surface and borehole water reveals the presence of contaminants. The high concentrations of magnesium, bicarbonate, and chlorine are the major elements, which cause high dissolved concentration and deteriorate the water quality.

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