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Research Article

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Abstract

The evaluation of groundwater in the Himalayan foothills is challenging due to complicated subsurface conditions and heterogeneous lithology. This study evaluates the aquifer properties in the Tanakpur area of the Champawat district in Uttarakhand state, India, using Dar–Zarrouk parameters. A total of seventeen Vertical Electrical Soundings were conducted using the Schlumberger array with electrode separations ($AB/2$) ranging from 260 to 580 m to identify subsurface resistivity layers. Seven to eight geoelectric layers with resistivity ranging from 42.34 to 187.04 Ω -m were found in the VES data. Boulders, gravels, cobbles, pebbles, weathered/fractures phyllites, granite, quartzite, and sandy clay comprised the fourth to seventh geoelectric layers, which included the main aquifer. The aquifer of overall depth ranged from 29.84 to 142.27 m, and its thickness varied from 13.11 to 118.65 m, Porosity ranged from 42.38% to 57.19%, protective capacities ranged from 0.079 to 1.13 mhos, and transverse resistance ranged from 1336.28 to 15402.0 Ω -m², hydraulic conductivity ranged from 2.94 to 11.74 m/day. Transverse resistivity varied from 15.23 Ω -m to 226.25 Ω -m, longitudinal resistivity from 49.035 Ω -m to 1802.56 Ω -m, and anisotropy values from 0.012 to 0.468. The study demonstrates that the Dar–Zarrouk parameters like aquifer thickness, resistivity, hydraulic conductivity, transmissivity, longitudinal conductance, transverse resistance, and anisotropy coefficient an effective hydrogeophysical approach for evaluating aquifers in structurally complex Himalayan terrains and can facilitate groundwater exploration, well siting, and sustainable groundwater management in the Tanakpur area and comparable foothill environments.

Keywords: Electrical method, Dar-Zarrouk parameters, hydraulic parameters, longitudinal resistivity, transverse resistivity, anisotropy, Champawat district.

1. Introduction

In northern India's Himalayan foothill regions, where surface water availability is highly seasonal and geographically variable, groundwater is an essential freshwater resource. Groundwater systems are under tremendous strain as a result of increased demand brought on by population development, intensified agriculture, and climate variability. To enable sustainable resource management, thorough aquifer characterization is therefore required. However, traditional hydrogeological studies face significant obstacles due to the intricate geological structure of the Himalayan foothills. Tanakpur is situated between the Sharda (Mahakali) river corridor and the Himalayan frontal formations. Siwalik, post-Siwalik successions, and varied weathered/fractured bedrock are covered by fresh sediments like alluvium. Groundwater, which is typically obtained from local aquifers beneath advantageous geohydrological conditions such as river valleys and broken rocks, is crucial for drinking, agriculture, and industry in the study area. (Jodhani et al., 2025; Kuldeep et al., 2024; Selvam et al., 2025; Swain et al., 2022).

Groundwater emergence is also influenced by physiographic variables, such as extensive valleys and gradually sloping slopes (Yuan et al., 2024). Mountains, valleys, and plains make up the variegated landscape study region, with the Siwalik Group of rocks predominating in the south (Yu Hui et al., 2015). Groundwater extraction has significantly increased as a result of human activities including industry and agriculture, raising concerns about its sustainability (Joseph Omeiza Alao et al., 2024). Because alluvial sediments from neighboring mountain ranges, particularly the Doon Gravels along the Sarda River, are present, the study region of aquifer behavior is diversified (Rajiv Sinha et al., 2007; Rameswar Mukherjee and Ram Bilas, 2016). Groundwater emergence is also influenced by physiographic variables, such as extensive valleys and gradually sloping slopes (Yuan et al., 2024). Mountains, valleys, and plains make up the variegated landscape study region, with the Siwalik Group of rocks predominating in the south (Yu Hui et al., 2015). Groundwater extraction has significantly increased as a result of human activities including industry and agriculture, raising concerns about its sustainability (Joseph Omeiza Alao et al., 2024). Because alluvial sediments from neighboring mountain ranges, particularly the Doon Gravels along the Sarda River, are present, the study region of aquifer behavior is diversified (Rajiv Sinha et al., 2007; Rameswar Mukherjee and Ram Bilas, 2016). Reliable aquifer identification is still challenging, nevertheless, because current techniques focus on surface characteristics rather than underlying characteristics (Jasechko S. Seybold et al., 2024; Joseph Omeiza Alao et al., 2025). A thorough grasp of the region's geology, geomorphology, and hydrological aspects is essential for groundwater management.

The Tanakpur area in the Champawat district of Uttarakhand state, India, offers geophysical insights into the aquifer properties. I identify subsurface lithologies, aquifer geometry, depth to water table, hydraulic connectivity, and aquifer protective capacity using surface geophysical surveys (VES) interpreted in conjunction with regional geology, drill logs, and groundwater data. Productive phreatic aquifers are created by the complicated Quaternary alluvium and channel deposits found in the Sharda (Mahakali) River. Heterogeneous Siwalik/post-Siwalik deposits and fragmented bedrock underlie these aquifers. Aquifer transmissivity and protective capacity vary, according to Dar-Zarrouk computed metrics and longitudinal conductance maps. Geophysical techniques enable a more accurate evaluation of the aquifer's depth, thickness, and lateral extension for a better understanding of multi-aquifer systems in the piedmont zone. (Ejepu et al., 2024; Mohammad Israil et al., 2006; Shahzad, 2024). Recent advances in

78 geoelectrical data collection and interpretation techniques have made it possible to directly infer aquifer shape from
79 electrical photos of subsurface structures (Rajkumar Stanly et al., 2021). Thus, by combining data on surface
80 hydrogeological features with subsurface information obtained from geoelectrical research, one can identify
81 subsurface qualities and construct aquifer geometry (Shailesh Bhatnagar et al., 2022). Groundwater potential was
82 assessed using geophysical and hydrogeological methods in dry and semi-arid parts of south India where more than
83 80% of the land is composed of crystalline rocks (Venkateswara Rao and Briz-Kishore 1991, Somvir Singh et al.
84 2016, 2021, 2022). Edet and Okereke (1997, 2002) examined the groundwater potential of Nigeria's Oban massif
85 using a similar methodology. In order to explain the spatial hydrogeology of a soft rock terrain in the Midnapur District
86 of West Bengal, India, Shahid and Nath (1999) used electrical sounds and remote sensing data. The electrodes of
87 Schlumberger arrays offer good horizontal layer resolution, deep sensitivity, and a high signal-to-noise ratio, making
88 them useful for determining subsurface conditions (Stanley, 1990). The expansion aims to identify the underlying
89 geoelectric strata by starting a comprehensive geophysical investigation at Tanakpur in the Champawat district of
90 Uttarakhand state using electrical resistivity measurements. The area will also be separated into zones with high and
91 low groundwater efficiency to enable precise sustainable management. In order to increase the applicability of such
92 successful tactics in next hydrogeological discoveries and groundwater resource management, this study will help
93 develop the groundwater investigation approach. Siwalik formations and Quaternary alluvial deposits in the foothills
94 of the Himalayas control the hydrogeological framework in the area under study. From boulder-conglomerate units to
95 sand, silt, gravel, and clay layers, the region exhibits notable lithological heterogeneity that reflects active tectonics
96 and a variety of sedimentation patterns. Aquifer storage capacity, recharge routes, and groundwater occurrence are all
97 directly impacted by this variability. Despite the region's heavy reliance on groundwater, the underlying aquifer system
98 is still not fully understood. Aquifer geometry characterization, permeable zone detection, and lithological connection
99 have all benefited from recent advancements in hydrogeophysics, particularly electrical resistivity techniques. In
100 order to study aquifer parameters and close present knowledge gaps in groundwater evaluation within the Tanakpur
101 area of Champawat district, Uttarakhand, the current work focuses on integrating geophysical data.

102 Although a number of studies in the Himalayan foothill region have examined groundwater occurrence using
103 electrical resistivity methods, no previous studies have fully characterized the aquifer system of the Tanakpur area in
104 Champawat district using Vertical Electrical Sounding (VES) derived parameters with detailed geophysical layering
105 parameters, structural controls, and local hydrogeological conditions. Prior research in Uttarakhand primarily focused
106 on (i) qualitative delineation of shallow alluvium or (ii) more thorough hydrogeological mapping at the district scale
107 without relating depth-wise lithological variability and resistivity signatures to aquifer properties of the groundwater
108 potential zones. This work is the first to develop a high-resolution aquifer model for the Tanakpur region using a
109 technique of VES inversion and correlation with borehole data and geomorphic settings, providing both vertical and
110 spatial insights into aquifer behavior. Crucially, the study identifies structurally affected groundwater domains,
111 assesses aquifer preventative capacity, and defines groundwater high-yield zones—all of which have not been covered
112 by previous studies. For sustainable groundwater development in this data-poor Himalayan piedmont region, the study
113 offers a novel, site-specific, and practically relevant hydrogeophysical paradigm. In the Tanakpur region, Dar–Zarrouk
114 criteria have not been widely used for systematic aquifer characterisation despite their demonstrated usefulness. By

calculating and evaluating Dar–Zarrouk parameters from VES data to assess aquifer potential and susceptibility, this study closes this gap and advances groundwater management techniques in the foothills of the Himalayas.

2. Study area

The study area of Tanakpur in the Champawat district of Uttarakhand state is shown in Figure 1. It is situated in the southern part of the district between latitudes 28.96567° N to 29.145667° N and longitudes 79.946660° E to 80.20056° E. It is roughly 248.37 km² in size and is a part of the Kumaon Division of Uttarakhand. The climate of the study area is milder and more humid than that of the neighboring areas. Throughout the day, the temperature fluctuates considerably. June and May are the only hot months. The summertime high and low temperatures vary from 36.60°C to 23.4°C and 5.20°C, respectively. The monsoon season, which runs from June to September, brings the most rainfall, and monsoon currents can pass through trenched valleys. The majority of the district is located on the outer Himalayan foothills to the south. According to Dibas Shrestha and Rashila Deshar (2014) and Yuxuan Xiang et al. (2024), rainfall varies significantly with altitude. The Lesser Himalayan Zone's southern region (1000–3000 m above mean sea level) experiences the most rainfall, ranging from 70% to 80%. The wettest months are July and August. After September, rainfall drastically decreases and reaches its lowest point in November. The research region receives 1085.62 mm of rain on average per year (CGWB, 2010).

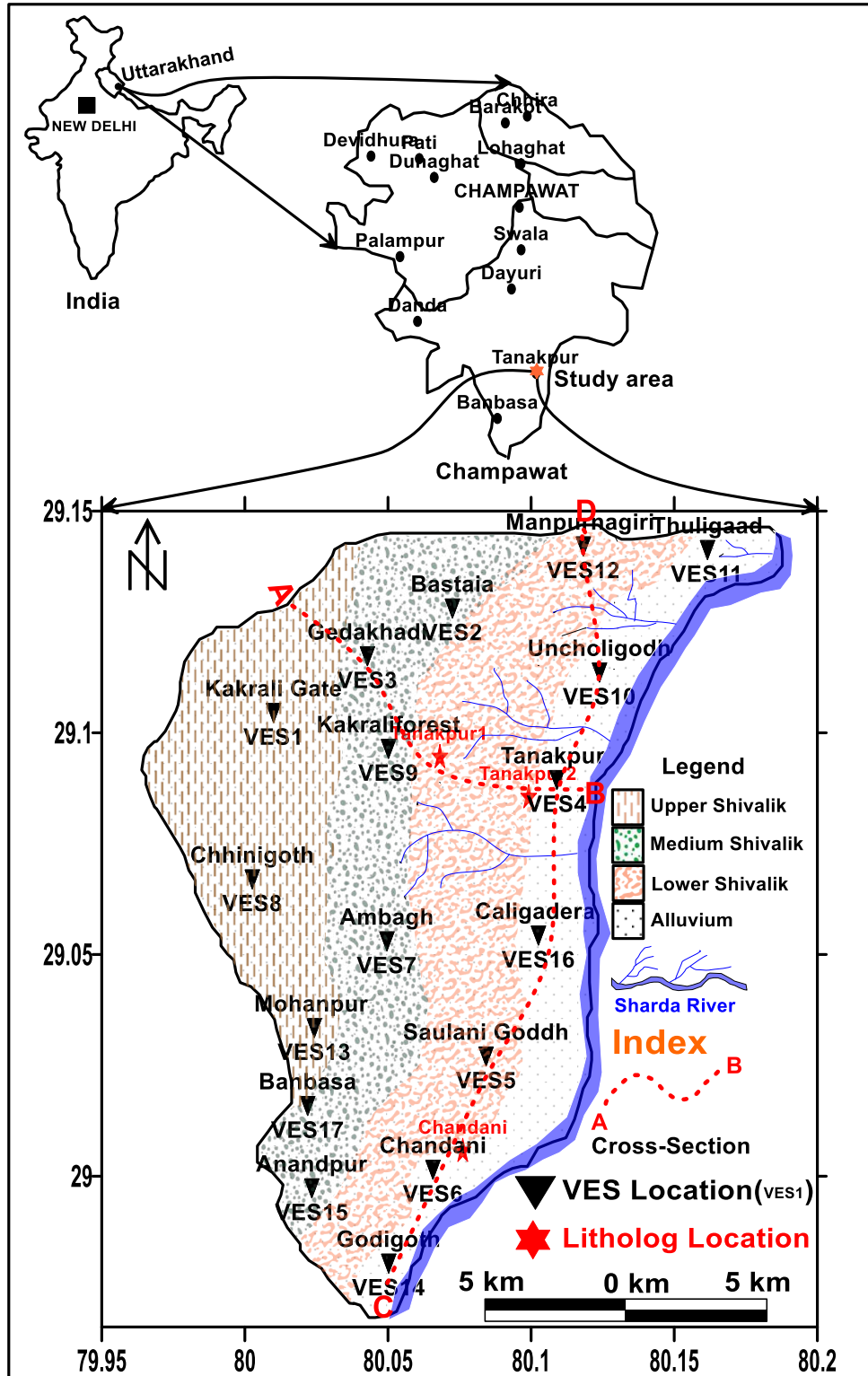


Fig. 1 Location map of the Tanakpur study area

3. Geological and hydrogeological setting of the study area

The geology and rock types of the research area are varied (Figure 1). Because the periodic structural disorders caused by many orogenic cycles make the geological setting extremely complicated, a comprehensive geological and

structural mapping of the area was conducted, according to Valdiya (1980). The Siwalik beds in the Tanakpur region are situated in a row in the northeast and are appropriately exposed at the bank of the Sharda River close to Thuligad, on the Thuligad–Purniyagiri road about 15 km from Tanakpur, and on the Tanakpur–Pithoragarh road and Karaurhi Nala near Bastia, according to Shivendra et. al., (2008). The lower and middle Siwalik deposits fluctuate between sandstone and mudstone strata. Assessment indicates that the alternating mudstone strata and conglomerate with adjacent sandstone lenses distinguish the upper Siwalik sediments. Mahesh Prasad et. al., (2017) An uninterrupted phase of the lower Siwalik sub-group is seen along the Purniyagiri Temple route between Thuligad and Bhairav Mandir (Prasad, 2008). In the bottom part of the segment, bedded floodwater sediments and variegated red, grey, and yellow palaeosols alternate with fine to medium-grained sandstones (Adhikari & Sakai, 2015; Rai & Yoshida, 2021). Compressions and imprints of leaves, fruits, and seeds are among the plant fossils found here (Dines S. Chauhan et al., 2022). The middle of the section is composed of thick, multistory layers of medium-to coarse-grained sandstone and is largely devoid of plant remains. According to Khayingshing Luirei (2022) and Mubashir Mehmood (2023), only carbonized wood and wood fragments can be discovered in sandstones as lenses or in small packages. The Main Boundary Fault (MBF) separates the Ramgarh Group from the wider Siwaliks, which comprise the Bhimtal, Bhamdoli, Maula, and Swala formations, according to CGWB (2009), Singh & Patel (2022), and Valdiya et. al., (1992). In addition to the Champawat granodiorite, the Salla, Gorakhnath, and Gumalikheth formations are part of the Almora Group (Singh et al., 1993, 1995; CGWB, 2009, 2023). The most prevalent rock types include phyllite, metabasitic rocks, garnetiferous biotite mica schist with quartzite interbeds, augen gneiss with paragneisses and a few orthogneissic interbands, black carbonaceous phyllite alternating with black fine-grained, biotite-rich greywacke, garnetiferous mica schist, and micaceous flaggy quartzites (Mahesh Prasad et al., 2017; Rawat et al., 2011; Srivastava Tanya et al., 2024).

The Tanakpur research area is situated in the Bhahbar formation, which is made up of alluvial deposits on sloping plains in the Himalayan foothills, directly south of the Siwalik Mountains. Most of it is composed of unconsolidated sediments, including sand, gravel, boulders, and clays (CGWB, 2009, 2023; Chakrabarti Goswami et al., 2013; Mehta & Adyalkar, 1962). Both confined and unconfined groundwater can be found in these areas. In contrast to high terrain, the aquifer is continuous and evenly distributed. Although this is outside the purview of the study, the Bhabars generally have higher water levels than the Tarai formations south of the district (CGWB, 2016; Mehta & Adyalkar, 1962). As a result, the research region lacks a consistent aquifer system with a broad aerial extent. Groundwater can be found in the hilly region in thrust plains, synclinal folds, tensile joints, strike slip fault/normal fault plains, tensile fractures, and the interface of two distinct rock formations (CGWB, 2013; Choubey, 1971; Valdiya, 1980). Water levels at hand pumps range from 5.48 to 32.28 m bgl prior to the monsoon and from 4.63 to 31.06 m bgl following it. The seasonal variation ranges from 0.85 to 1.22 m. Two wells that were dug for the pre-monsoon and post-monsoon had water levels that range from 7.13 to 11.43 m bgl and 6.83 to 10.96 m bgl, respectively, according to CGWB (2009). Between 0.30 and 0.47 m is the range of seasonal variation. Tanakpur and Chandni have two exploratory wells with drawdowns of 9.68 and 3.94 m, respectively, with discharge rates of 2683 and 3100 lpm. According to CGWB (2008, 2009, 2023), hydraulic conductivity ranges from 32.94 to 171.8 m/day, field permeability

ranges from 119.8 to 175.2 m²/day, and transmissivity ranges from 7484 to 14140 m²/day. Groundwater is produced via tube wells, hand pumps, and dug wells.

4. Material and Methods

4.1. Geophysical data processing and interpretation

An SRMP-ATS resistivity meter made by Hyderabad, Telangana-based IGIS was used to conduct 17 Vertical Electrical Soundings (VES) at different locations around the study region. Figure 1 shows where these VES points are located. Fourteen of the seventeen VES sites had groundwater potential zones. As a result, only these 14 VES locations were used to determine the hydraulic conductivity and transmissivity. The electrical resistivity approach was used for the geophysical investigations. The electrical resistivity method was used in the geophysical investigations. The VES measures the potential difference between two electrode pairs as one applies direct current to the other, according to Ejepu et al. (2024), Gautam Gupta et al. (2010), and Laurent Marescot (2006). The Schlumberger electrode design with a maximum current electrode spacing ($AB/2$) = 470 m was used for the resistivity soundings. Kearey and Brooks (1988), method was used for calculation of apparent resistivity as, $\rho_a = \pi [(L/2)^2 - (b/2)^2] / b \times V/I$ Where, L and b is the current and potential electrode spacing respectively. Using the layered resistivity model ρ_1 , ρ_2 , and ρ_3 and matching observed curves with a set of theoretically computed master curves interpreted using master curves methodologies; the IX1Dv3.1 program performed the VES interpretation (Orellana and Mooney, 1966). The VES pseudo cross section and resistivity cross section maps were produced using IPI2win geoscientific software (Bobachve, 2003).

In such complicated terrain, geophysical methods especially electrical resistivity techniques have proven to be useful instruments for subsurface investigation. Because of its affordability and versatility, vertical electrical sounding (VES) is frequently used to identify aquifer geometry, lithology, and hydrogeological conditions. On the other hand, resistivity data by itself frequently yields qualitative judgments. Dar–Zarrouk (D–Z) characteristics, particularly longitudinal conductance and transverse resistance, are calculated from resistivity and thickness data to quantitatively assess groundwater susceptibility, transmissivity potential, and aquifer protective capacity in order to improve hydrogeological understanding. In a variety of geological settings, Dar–Zarrouk criteria have been effectively used to evaluate natural protection against contamination, identify productive groundwater zones, and assess aquifer characteristics. The use of D–Z characteristics is especially helpful for identifying favorable groundwater-bearing layers and evaluating their spatial variability in Himalayan foothill settings, where aquifers are usually made of unconsolidated sediments such sand, gravel, cobbles, and boulders.

4.2. Analysis of VES data

Geophysical analysis and well lithologs were the two stages of the research approach. Figure 2 displays the data acquisition map and the flow charts for the process. Data from Vertical Electrical Sounding (VES) were examined to identify changes in subsurface resistivity and to deduce the lithological and hydrogeological features of the studied region. The Schlumberger electrode design, which is ideal for examining vertical changes in resistivity and locating groundwater-bearing strata in alluvial and foothill regions, was used to collect the field data. Sounding curves were created by plotting the measured apparent resistivity values versus half current electrode spacing ($AB/2$) on a

logarithmic scale. Initially, resistivity layers and likely subsurface conditions were identified by qualitatively interpreting these curves based on their forms. To determine the actual resistivity and thickness of each subsurface layer, quantitative interpretation was then performed using curve matching and iterative inversion techniques. Using a one-dimensional layered earth model, the interpretation procedure entailed decreasing the discrepancy between calculated and observed apparent resistivity values. Layer resistivity and thickness estimates from the generated geoelectrical models were connected with regional geological data and known lithological information from neighboring boreholes. In general, clay-rich or saturated fine-grained sediments were linked to low resistivity zones, while sandy, gravelly, or compact formations with variable groundwater potential were linked to moderate to high resistivity values. The use of electrical resistivity prospecting for groundwater research has been recorded by a number of writers (Bhattacharya and Patra, 1968; Karanth, 1987; Sharma, 1997; Tellford et al., 1990). The Schlumberger electrode configuration method is widely used, fast, dependable, and yields better results, according to Debabrata Nandi et al. (2015), Duraiswami (2005), Erram et al. (2010), Gupta et al. (2012), Singh and Jamal (2002), and others. The VES technique can be a more useful tool for understanding hydrological problems, as demonstrated by Andradehas (2011). Geophysical studies were employed to manage groundwater supplies and evaluate hydrogeological conditions in the Dehradun district's sub-Himalayan Doon Valley regions (Gautam and Biswas, 2016). For homogeneous and horizontally stratified earth, VES data only show resistivity variation across the strata up to the current study's maximum depth search of about 150 m. A heterogeneous subsurface structure typical of Himalayan foothill habitats was indicated by the interpreted VES results, which showed several geoelectrical layers. Changes in groundwater quality, saturation level, and sediment composition are reflected in variations in resistivity both vertically and laterally. The identification of resistive layers beneath comparatively conductive horizons which are frequently suggestive of confined or semi-confined aquifer conditions was given special emphasis.

Aquifer protective capacity and groundwater potential were assessed using Dar–Zarrouk parameters, such as longitudinal conductance and transverse resistance, which were computed using the derived layer parameters. All things considered, the VES data analysis offered a trustworthy foundation for the research area's subsurface characterization and quantitative evaluation of aquifer characteristics.

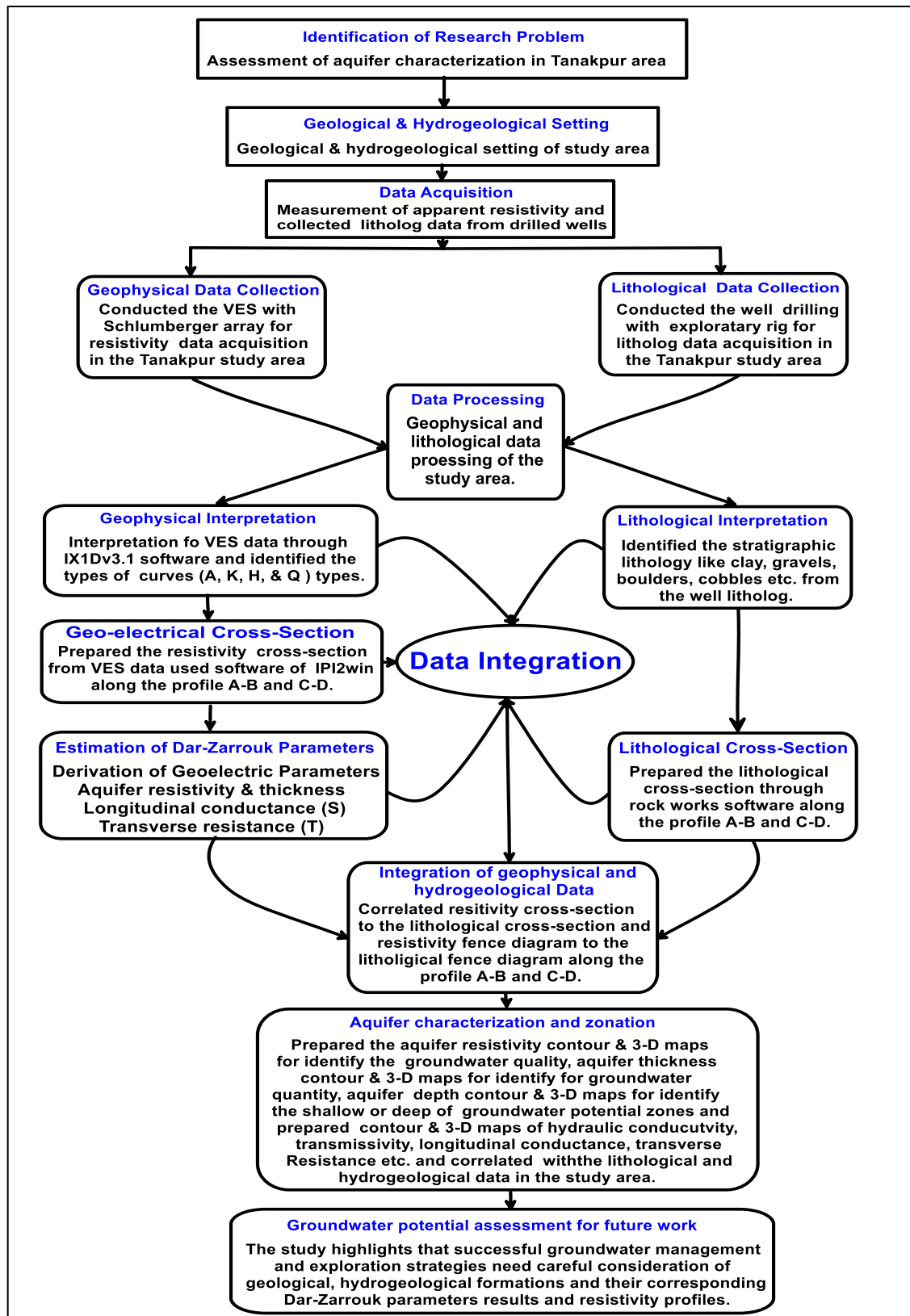


Fig. 2 Methodological flow chart for groundwater potential evaluation in the study area

The total volume of earth included in the measurement grows both horizontally and vertically as the distance between the current electrodes increases (Okwueze et al., 1995; Parasnis, 1997; Reynolds, 2011; Sharma, 1997; Telford et al., 1990). Typically, the distance between the electrodes determines the depth of penetration, and altering this distance reveals details about the ground of stratification (Reynolds, 2011). Using this calibration, a resistivity spectrum for the various lithologic units in the examined region may be identified, as shown in Table 1. The generated 1D resistivity models were calibrated against lithologic units from adjacent well lithologs. Figures 3(a), (b) and (c) illustrate instances of the association between sounding sites VES9, VES4 & VES6 and the WL1, WL2 & WL3 well lithologs, respectively (see Figure 1 for location).

Table 1 Resistivity and Lithounits

Resistivity (Ω-m)	Lithology	Hydrogeological Significance
<10	Clay / silty clay	Poor infiltration
11.0-50	Sand with boulders, cobbles, pebbles and weathered/fractured phyllites/ quartzite/ schist with metabasaltic rocks	Low permeability; possible runoff zone
51-100	Coarse sand with cobbles, pebbles and weathered /fractured phyllites/quartzite with/massive sandstone	Moderately permeable; potential aquifer/ Semi-permeable aquifer
101-200	Coarse sand with gravels, pebbles, cobbles and weathered/fractured phyllites/granite/ quartzite with sand	High yield aquifer zone
201-300	Fractured slates/phyllites/granite/schist with coarse grained and angular boulders with sandy clay	Productive aquifer
301-400	Semi compact weathered/ fractured and jointed phyllites/granite/schist with sandy clay	Low porosity; local fracture flow possible
401-500	Semi fractured phyllites/quartzite /metabasaltic rocks with sand and clay	Potential deeper aquifer/fracture flow
>501	Compact phyllites/granite/chloride schist	Impermeable strata

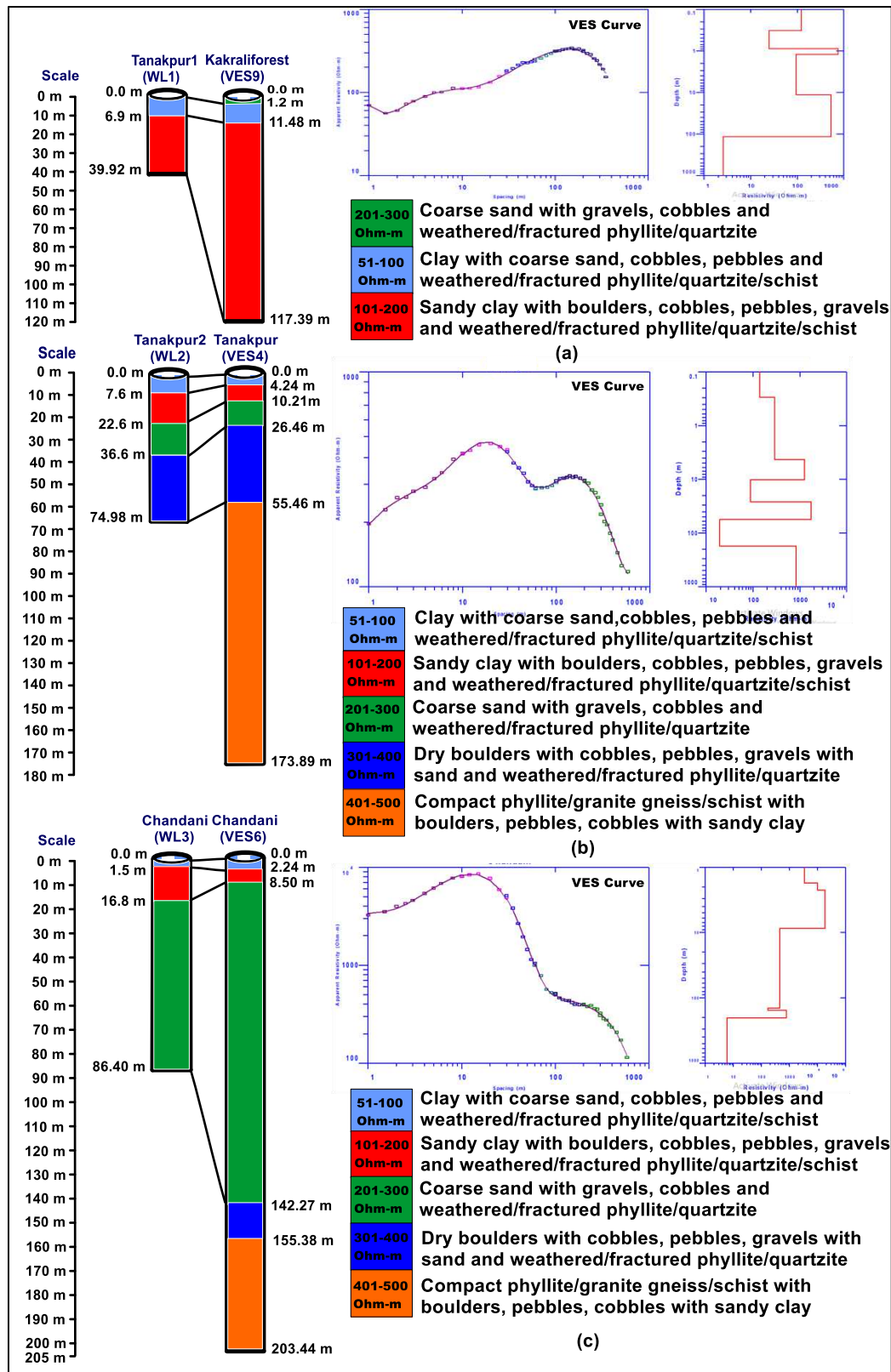


Fig. 3 Examples of correlation between the inverted resistivity models and lithologic data from the nearest wells; (a) VES9 & WL1, (b) VES4 & WL2 and (c) VES6 & WL3 in the study area.

The findings of this study produce a model with six to nine layers across 17 VES study locations. A-B shows a cross-section from northwest to southwest, and C-D shows a cross-section from northwest to southeast. A strong correlation between the two sets of electrical resistivity data and well lithological data was found after comparing the resistivity data from the current results with the lithologic borehole data (Biswas et al., 2017; Reynolds, 2011; Sharma, 1997; Telford et al., 1990). According to Reynolds (2011), Sharma (1997), and Telford et al. (1990), the VES curves were created by plotting the apparent resistivity against electrode spacing. By translating geoelectrical sounding data addicted to layer parameters, Telford et al. (1976) determine the resistivity and thickness of individual layers. A summary of the results for every VES location is shown in Table 2. The interactive inversion program IX1Dv.3 was used to one-dimensionally flip the VES data in order to do quantitative analysis. This study's IX1Dv.3 software lets you pick from a range of comparable solutions and pick the one that best fits the geophysical model with the least amount of error between the inverted and observed data (Osman et al., 2021; Vouillamoz et al., 2012). The profiles A-B (VES3, 9, and VES4) and C-D (VES12, 10, 4, 16, 5, 6 and VES14) are diagonally explained by the one-dimensional inverted resistivity model used to explain VES data, as shown in figure 4(a) & (b). Whereas the circles show observable data, the solid line shows interpreted geophysical VES data. Each layer's resistivity and thickness are shown by the modeled layer parameter. The resistivity curves in the current study are typically K and H-type, and they are regarded as six to nine layers.

268
269

Table 2 Summary of results, resistivity's and their thickness for all VES stations

VES No.	AB/2 (m)	Elevations (masl)	No.s of layers	Resistivity of the layers (Ohm-m)									Thickness of the layers (m)								Rms, error (%)
				ρ_1	ρ_2	ρ_3	ρ_4	ρ_5	ρ_6	ρ_7	ρ_8	ρ_9	h_1	h_2	h_3	h_4	h_5	h_6	h_7	h_8	
VES1	580	288	9	263.52	3616	275.2	51.85	476.69	14.22	64.81	147	234	0.263	0.274	15.66	12.4	15	106.6	17.23	46.93	2.43
VES2	300	421	6	618.45	5404	356.2	90.04	70.62	916.3				0.908	0.621	21.02	68.3	23.5				2.93
VES3	570	276	6	333.96	242.9	106.1	2464.4	731.34	81.74	739.3			2.176	0.317	1.09	5.57	119	42.6			1.9
VES4	580	284	7	139.07	287	1250	88.47	1734.2	105.3	818.1			0.294	3.947	5.98	16.2	28.8	118.7			2.46
VES5	260	247	6	2274.4	483	25453	317.72	234.39	187	311.9			0.622	0.612	2.992	27.9	28.9	27.87			2.88
VES6	580	424	7	3306.1	9893	18233	443.15	166.18	770.6	5.854			1.754	0.486	6.337	134	13.1	48.05			3.9
VES7	500	256	7	322.09	66.35	5395	190.67	101.33	169.6	19.62			0.748	1.871	2.684	19.5	20.9	95.45			3.5
VES8	400	287	6	979.09	223.4	4074	148.47	366.03	6.756				1.153	14.94	1.948	60.1	57.5				2.54
VES9	350	298	6	122.74	24.52	743.8	94.38	532.98	2.533				0.328	0.558	0.336	10.3	106				1.99
VES10	580	264	8	219.5	70.33	134.8	5.91	1544.6	356.8	75.05	3.72		0.568	3.204	12.84	10.9	43.1	42.32	56.05		2.88
VES11	300	301	6	150.55	31.64	60.52	60.46	343.90	6.778				1.942	0.765	40.29	29.9	24.5				2.48
VES12	580	305	6	645.32	2333	309.4	115.48	99.64	40.35				1.404	0.376	9.302	107	74.8				2.88
VES13	400	283	6	295.33	82.91	2540	616.29	184.80	35.23				0.989	0.939	5.642	122	16				2.84
VES14	360	222	6	5709.8	85.96	13077	473.59	1723.1	260.7				2.0	0.121	2.13	62.4	22.6				3.41
VES15	400	222	7	493.1	196.3	2344	132.06	42.34	509	2.366			0.205	2.804	0.738	47.4	31.6	49.08			2.53
VES16	580	247	7	1592.2	38209	1258	2630.4	632.76	80.54	418.1			0.37	2.105	58.85	34.7	26.1	66.98			3.62
VES17	250	246	8	1590.4	5505	2568	1.34	1484.2	162.8	18.77	4.57		0.956	0.219	5.782	0.22	22.7	19.2	35		2.1

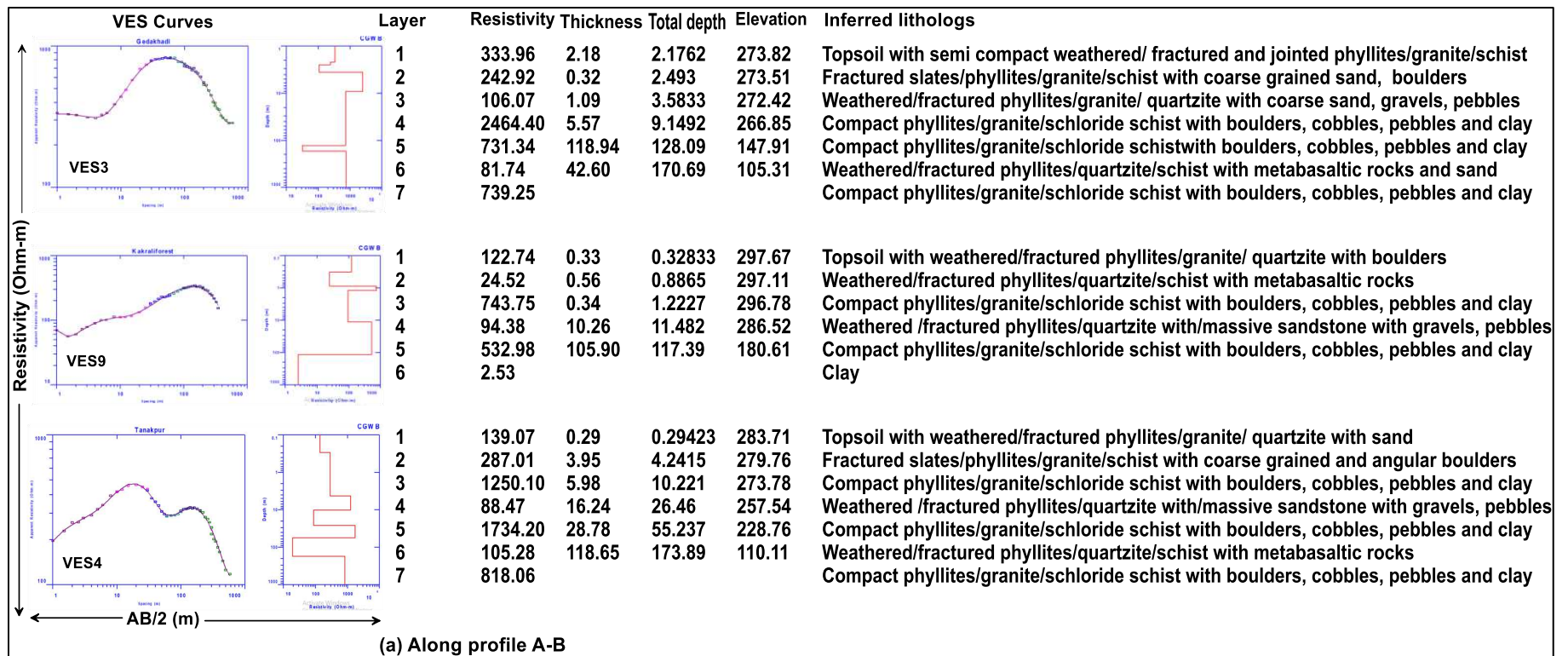


Fig. 4 (a) VES data with interpreted layer model along profile A-B

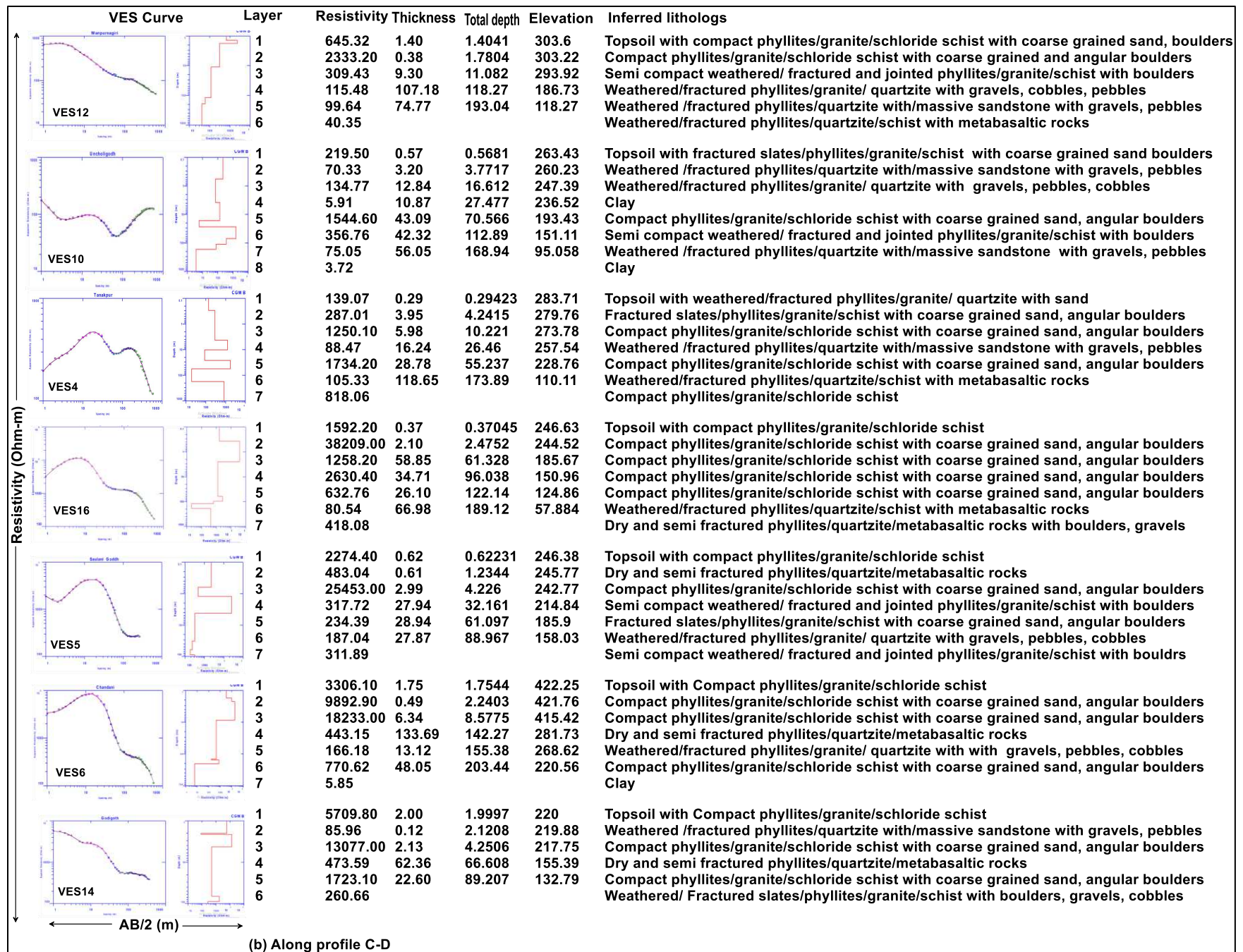


Fig. 4 (b) VES data with interpreted layer model along profile C-D.

The lithological cross-section, pseudo cross-section, and 2D resistivity cross-section that were produced using the chosen Schlumberger configuration of the VES curves and well litholog data to produce an additional precise resistivity image from the subsurface study area are displayed in figures 5 (a) & b) and 6 (c) & d). While the inverted resistivity cross-section shows the vertical distribution of resistivity within a specific volume of the earth, the lithological cross-section shows the lithology of the study area (Griffiths and Barker, 1993; Keller and Frischknecht, 1966; Mukhtar et al., 2000; Singh et al., 2002). Figure 5(a) and (b) show the lithological cross-section created with Rockworks program and the pseudo and resistivity cross-section created with IPI2win software. According to cross section AB along profile A-B (Northwest to Southeast), the research area's Northwest portion comprises compact phyllites/granite/chloride schist with a high resistivity value ($>500 \Omega\text{-m}$) up to 130 m.

A medium resistivity range (201-300 $\Omega\text{-m}$) is revealed with fractured slates, phyllites, granite, and schist with coarse-grained and angular boulders from depths of 10-30m, while a low resistivity zone (21-50 $\Omega\text{-m}$) is seen with weathered/fractured phyllites, quartzite/schist, and metabasaltic rocks from depths of 120m to 200m. The Northwest has a high resistivity zone, the Northeast has a medium resistivity zone, and the medium portion of the study region has a low resistivity range, as demonstrated by VES3, 9, and VES4. The top layer is composed of sand with cobbles, pebbles, and gravels, as the lithological cross section clearly demonstrates. The geological formations of boulders and sand, clay, clay with boulders and gravel, and boulder with sand and gravel made up the majority of the studied area.

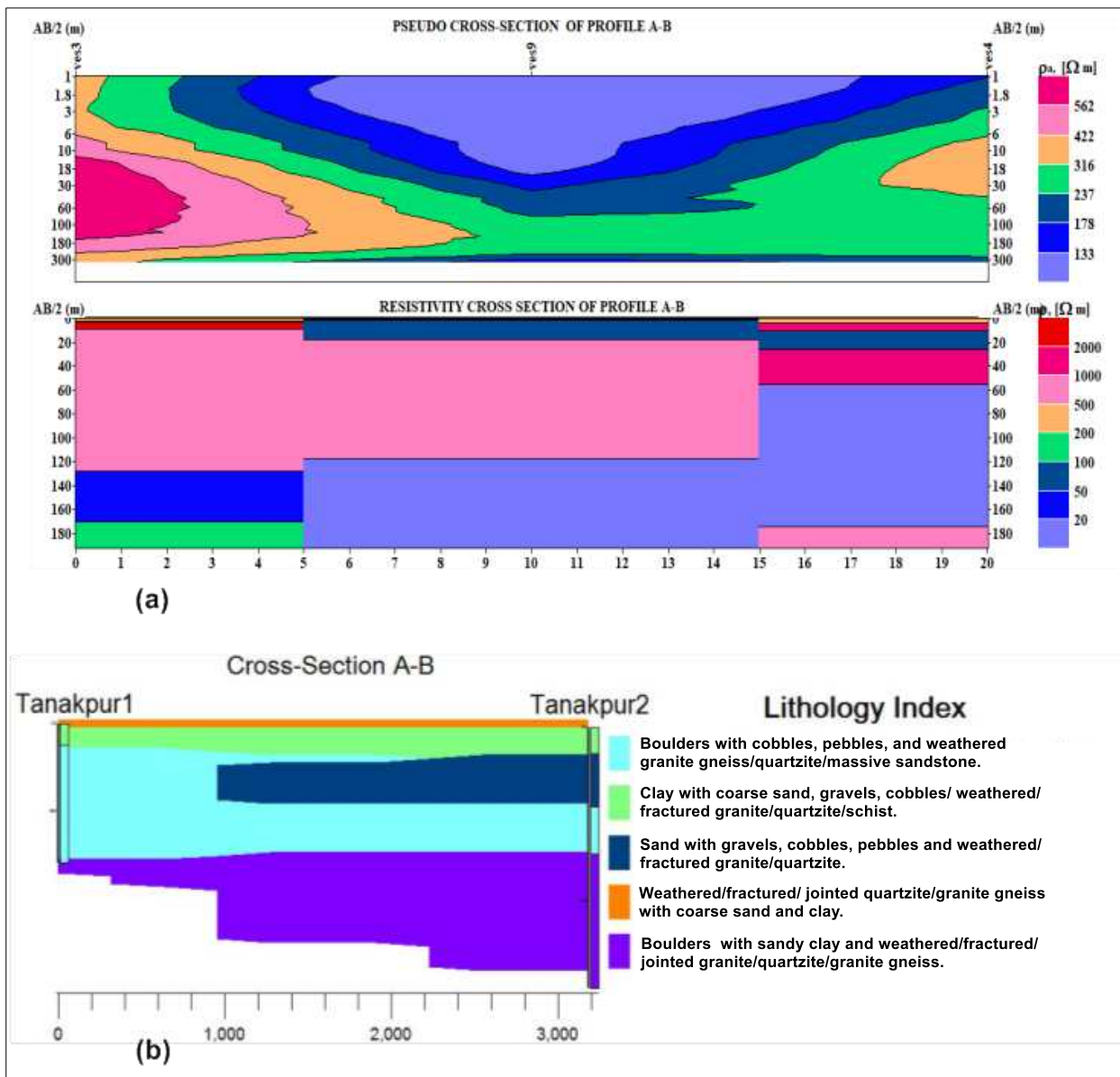


Fig. 5 (a) Pseudo Cross-Section and Resistivity Cross-Section and **(b)** Lithological Cross-Section along the profile A-B.

The pseudo and resistivity cross section of CD along the profile C-D (Northwest to Southeast) is shown in figure 6(c) & (d). The Southeast part of the study area (VES14, 6, 5, & VES16) has a high resistivity value ($>500 \Omega\text{-m}$) up to 180m with compact phyllites/granite/chloride schist, sand and clay. At 110m to 200m, there are low resistivity zones ($11\text{-}100 \Omega\text{-m}$) with the formation of weathered/fractured phyllites/quartzite with massive sandstone at VES4 & VES10, and the depth range of 10-120m shows medium resistivity zones ($101\text{-}300 \Omega\text{-m}$) with geological formation of fractured slates/phyllites/granite/schist with coarse grained and angular boulders at VES4 VES10 & VES12 (towards Northeast part of study area). From the lithological cross section is clear shows that the Southeast part of study area occurred sand with pebbles, cobbles & boulders and middle to Northwest part occurred the geological formation of boulders with sand, clay, boulders with sand & gravels and with boulders & sand.

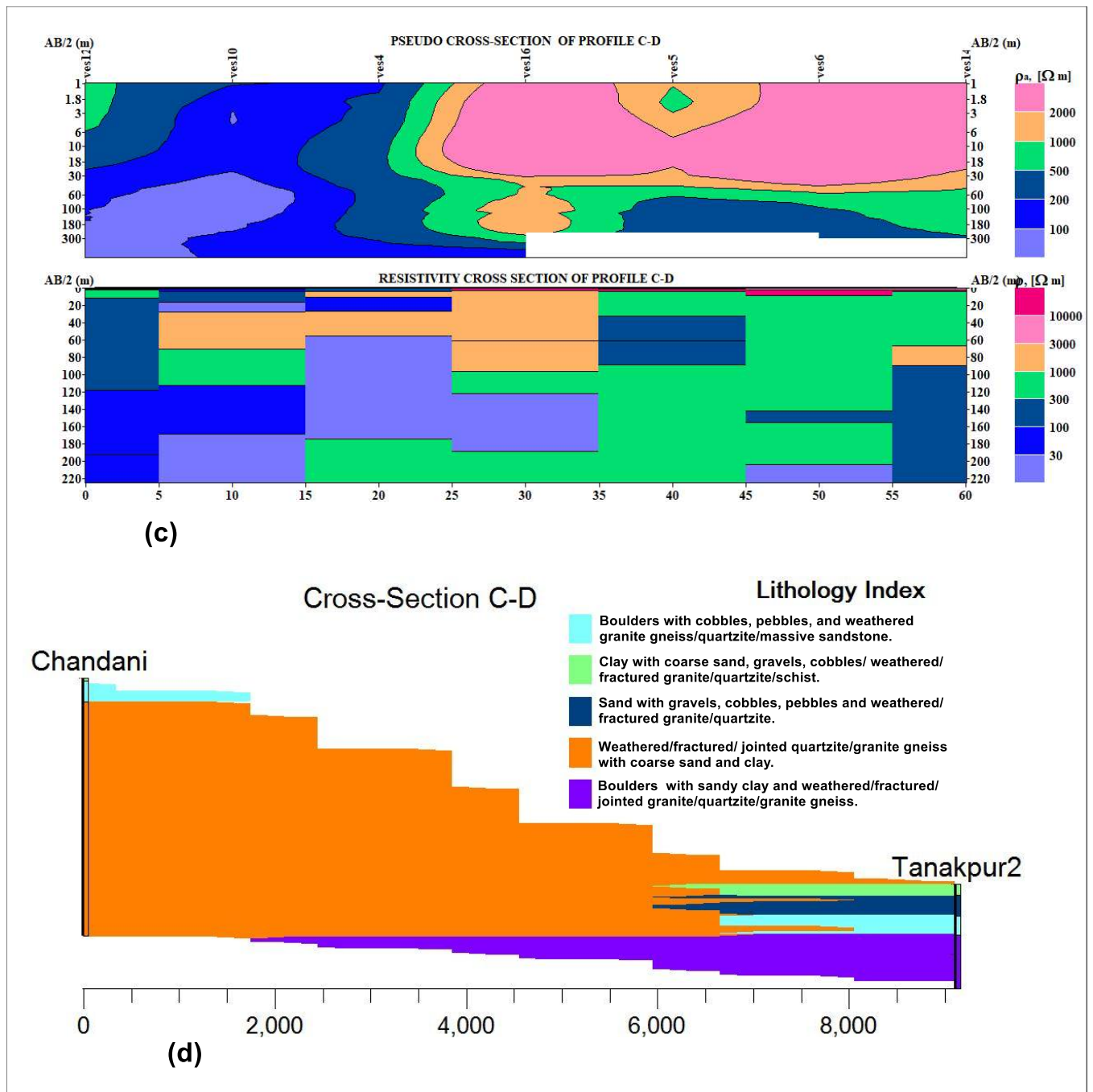


Fig. 6 (c) Pseudo Cross-Section and Resistivity Cross-Section and (d) Lithological Cross-Section along the profile C-D.

4.3. Dar-Zarrouk (D-Z) Parameters

The Dar-Zarrouk parameters, which comprise longitudinal conductance (S_c) and transverse resistance (T_r), were proposed by Maillet in 1947. The parallel conductance to the face is represented by S_c whereas the transverse resistance (T_r) is shown by the resistance normal to the face of a unit cross-section area. The resistivity soundings parameters are required adequate for calculating the distribution of surface potential and electrical resistivity graphs (Henriet, 1976). Subsequent research has emphasized the significance of D-Z parameters in assessing aquifer

hydrological features (Niwas and Singhal, 1981, 1985, Shahid and Nath, 2002, Singh, et. al., 2004, Khalil, 2009, Mondal, et. al., 2013, Mondal, 2021, Kumar et. al., 2024). Present study considers Dar-Zarrouk parameters such as transverse unit resistance (T_r), longitudinal unit conductance (S_c), transverse resistivity (ρ_t), longitudinal resistivity (ρ_l), coefficient of anisotropy (λ), root mean square resistivity (ρ_{rms}), formation factor (F), and porosity (Φ), as defined by authors (Singh and Singh, 1970, Henriet, 1976, Salem, 1999, Ayolabi, et. al., 2010).

A single stratified layer characterized by thickness h and their resistivity ρ of a unit cross-sectional volume, the conductance S_c parallel to the face and resistance T_r perpendicular to the face are given by:

$$S_c = \frac{h}{\rho} \quad (1)$$

$$T_r = \rho h \quad (2)$$

In the case of a prism consisting of n geoelectrical layers, characterized by their thicknesses: $h_1, h_1, \dots, h_n$ and resistivities: $\rho_1, \rho_2, \dots, \rho_n$, respectively, the total conductance of the current flowing parallel to the layers is the sum of conductance from each layer.

$$\text{Longitudinal unit conductance, } (S_c) = \frac{h_1}{\rho_1} + \frac{h_2}{\rho_2} + \frac{h_3}{\rho_3} \dots \dots \dots + \frac{h_n}{\rho_n} = \sum_{i=1}^N \frac{h_i}{\rho_i} \quad (3)$$

Similarly, the total transverse resistance for the current flowing perpendicular to the layers can be expressed as:

$$\text{Transverse unit resistance } (T_r) = \rho_1 h_1 + \rho_2 h_2 + \rho_3 h_3 \dots \dots \dots \rho_n h_n = \sum_{i=1}^N \rho_i h_i \quad (4)$$

The average longitudinal resistivity for the current flowing parallel to the layers is given by:

$$\text{Average longitudinal resistivity } (\rho_l) = \frac{H}{S_c} \quad (5)$$

The average transverse resistivity for the current flowing perpendicular to the layers is:

$$\text{Average transverse resistivity } (\rho_t) = \frac{T_r}{H} \quad (6)$$

where $H = \sum h_i$, and H being the depth to the bottommost geoelectric layer.

The root mean square resistivity, also known as effective resistivity, is calculated as:

$$\text{Root mean square resistivity } (\rho_{rms}) = \sqrt{(\rho_t * \rho_l)} \quad (7)$$

The coefficient of anisotropy is given by:

$$\text{Anisotropy } (\lambda) = \frac{\sqrt{T_r \cdot S_c}}{H} = \sqrt{\frac{\rho_t}{\rho_l}} \quad (8)$$

In these equations, ρ is the layer resistivity in $\Omega\text{-m}$, h is the layer thickness in meters, T_r is the transverse resistance in $\Omega\text{-m}^2$, S_c is the longitudinal conductance in mhos, ρ_l is the longitudinal resistivity, ρ_t is the transverse resistivity, and λ is the anisotropy coefficient.

According to Henriet (1976), the combination of layer resistivity and thickness in D-Z parameters (such as S_c , T_r , and λ etc.) is directly useful in aquifer protection studies and assessing aquifer hydrological qualities. According to Oladapo, et. al., (2004), Ayolabi, (2005), Atakpo and Ayolabi, (2008), and Atakpo, (2013), the protective capacity is proportional to the longitudinal unit conductance. Therefore, the total longitudinal unit conductance (S_c) values were used to measure the overload protection capability (Henriet, 1976, Oladapo, et. al., 2004, Atakpo and Ayolabi, 2008, Atakpo, 2013). The D-Z parameters S_c , T_r , and λ etc. were analyzed to better understand the state of aquifer for groundwater resources in the study area.

4.3.1. Hydraulic Conductivity

Layer resistivity and hydraulic conductance are closely related (Kosinski and Kelly, 1981). As a result, locations in the study region with low resistivity readings, which indicate groundwater pollution, will necessarily have poor hydraulic conductivity. According to Salem (1999), hydraulic conductivity is related to permeability; hence, aquifer portions with high hydraulic conductivity are more permeable to fluid flow, allowing pollutants to move more freely.

In a porous aquifer, the relationship between hydraulic conductivity (K) and layer resistance is expressed by the equation provided by Heigold, et. al., (1979):

$$K = 386.40 \rho_w^{-0.93283} \quad (9)$$

Where, K represents hydraulic conductivity and ρ_w denotes aquifer resistivity. This equation had been employed to estimate hydraulic conductivity in the study area.

4.3.2. Aquifer Transmissivity

Aquifer transmissivity is an essential property for characterizing rocks as water-conducting media. It is defined as the product of hydraulic conductivity and layer thickness. The transmissivity T is calculated using the formula (Todd and Mays, 2004).

$$T = K \times h \quad (10)$$

Where K represents hydraulic conductivity (m/day) and h denotes layer thickness (in meters). This calculation is provides a general perceptive of the water-producing capabilities of the aquifer based on surficial electrical methods.

A geoelectrical layer is characterized by two fundamental parameters like, its resistivity (ρ_i) and its thickness (h_i), where the subscript i indicates the layer of position in the sequence. Additional parameters are derived from these resistivity and thickness values, as outlined by Zohdy, et. al., (1974), and were utilized in this study area.

4.3.3. Porosity and Formation Factor

According to Archie's hypothesis established the formation factor be able to related to the porosity of an aquifer using the following formula.

$$F = a / \Phi^m \quad (11)$$

From this, the porosity can be expressed as

$$\Phi = [a/F]^{1/m} \quad (12)$$

Established a relationship between the formation factor and hydraulic conductivity using the formula (Senthil Kumar et al., 2001) as:

$$F = [K/a]^{1/m} \quad (13)$$

Where, in these equations, F indicates is formation factor, K is hydraulic conductivity (m/day), Φ represents aquifer porosity, $a=0.62$ (the tortuosity factor for unconsolidated sands), and $m=2.15$ (the cementation exponent).

4.3.4. Protective capacity of the aquifer

The longitudinal conductance values were utilized towards assesses the protective capacity of the aquifer (Heigold, P.C., Gilkeson, R.H., Cartwright, K., & Reed, P.C., 1979). The earth medium act the same as natural filter for percolating fluids, and its ability to impede fluid movement is an indicator of its protective capacity (Mogaji, 2017), expressed as:

$$P_c = \sum h_i / \rho_i (\sum S_c \text{ of the overburden layers}) \quad (14)$$

Where P_c represents the protective capacity in mhos, ρ_i is the resistivity of the overburden layer, h_i is the thickness of the overburden layer, and S_c is the longitudinal conductance. The protective capacity of the aquifer be estimated through the geo-electrical parameters from the study area.

4. Results and discussion

4.1. Geophysical and lithological results

4.1.1. Correlation between resistivity and lithology

The fence diagrams were prepared using geoelectrical interpretations of VES data and lithological data to make available a more thorough observation of essential formations (**Figure 7a & b**). The geoelectrical fence diagram represents the subsurface distinction of resistivity inside a convinced degree of subsurface of the earth, where the lithological fence diagram depicts the lithological nature of the study area.

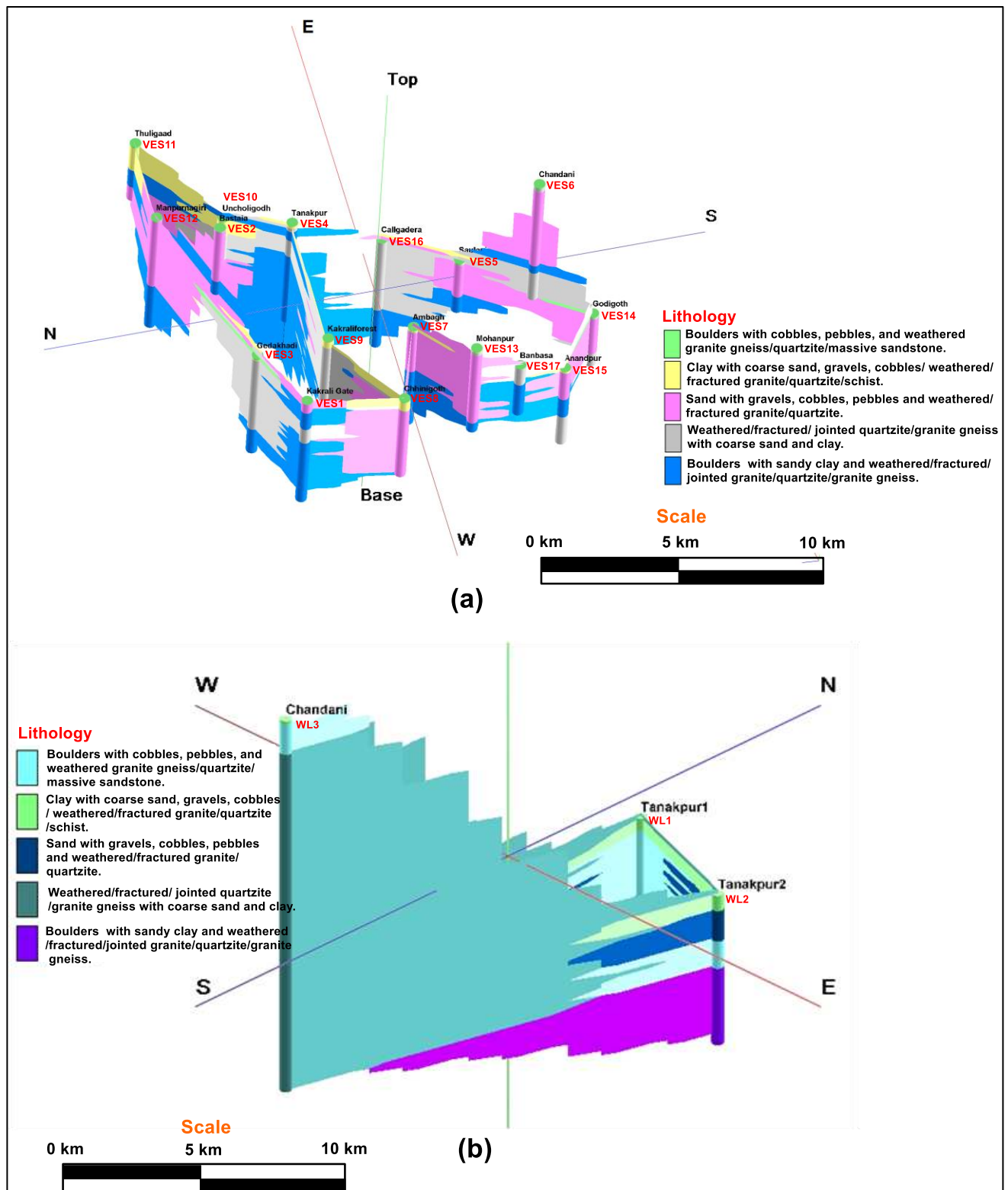


Fig. 7 (a) Resistivity fence diagram (b) Lithological fence diagram of the study area

The prepared fence diagrams with the Rockworks software version 16. With an average of 1923.75 Ω -m and a range of 1.34 Ω -m to 38209 Ω -m, the resistivity values in the analyzed region are highly variable. It was observed that

VES 17 had the lowest resistivity value while VES 16 near Caligedra had the highest. In the Northwest, Southwest, and Northsouth sections of the research area, the semi-compact to compact formations shown in figure 7(a) have resistivity values between 301 and 500 Ω -m. It suggests the persistence of gravels, pebbles, sandy clay, and dry stones all of which are unsuitable for groundwater research. The Northeast and Northwest portions of the research region are made up of shallow groundwater formations with resistivity ranges of 41-200 Ω -m, indicating the presence of granite, quartzite, and water-bearing weathered/fractured phyllites. In the South-West and North-East regions of the research area, deeper groundwater potential formations have been inferred, including schist with metabasaltic rocks, quartzites, and weathered/fractured phyllites. In the region's northeast and northwest, weathered formations with resistivity values between 201 and 400 Ω -m were seen. According to diagram figure 7(b), the lithological fence at Chandani, which is in the northwest section of the research area, plainly shows that there is sand with boulders, cobbles, pebbles, and granite-gneiss on top of the boulders. In the research region, lithological strata of boulders with gravel, pebbles, cobbles, and sandy clay have been found in the south-east sections, while boulders with pebbles, cobbles, and sandy clay, among other materials, predominate in the Northeast parts of the villages of Tankpur 1 and Tanakpur 2.

4.1.2. Aquifer resistivity, aquifer thickness and aquifer depth of the study area

The aquifer resistivity, thickness, and depth derived from lithologic composition, were used to compute longitudinal conductance, hydraulic conductivity, and transmissivity, as summarized in **Table 3**. Using the Surfer software, the interpreted 17 VES of layer parameters were shown as contour maps and 3D map representations. After gridding the spatially distributed data, the krigging method was employed for interpolation since it produced more accurate results than previous interpolation techniques.

The regional variation of an aquifer system with resistivity values is shown in figure 8(a). Total 14 out of the 17 locations have been found to comprise groundwater potential zones, and for easier visualization, the associated resistivity value of the water-bearing zones has been contoured. This aquifer resistivity map of evaluation shows that the average aquifer resistivity value in the studied area is 111.65 Ω -m, with values ranging from 42.37 Ω -m to 187.04 Ω -m. As an aquifer, the weathered/fractured phyllites/quartzite/schist with metabasaltic rocks are found in the resistivity variation range of 10-50 Ω -m at VES15 which make up 7.14% of the groundwater carrying zone in the study area. While the groundwater promising formation at sounding locations VES1, 4, 5, 6, 7, 13 and 17 have 50% groundwater promising formation with weathered/fractured phyllites/granite/quartzite & sand with resistivity range of 100-200 Ω -m, the sounding locations VES3, 3, 10, 11, 12 and VES16 have 42.86% groundwater promising formation with weathered/fractured phyllites/quartzite/massive sandstone with resistivity range of 50-100 Ω -m. Figures 8(a) and 8(b) offer a 3-D picture of the aquifer resistivities of the study area, the related contour maps, and the resistivity contrast caused by difference in geological formations and hydrogeological circumstances. It has been determined that the Southwest Southeast part of the study area has the greatest resistivity peaks. The study area's Southeast and Southwest parts are shown by two separate peaks. In addition, one relatively small peak may be seen in the study area Southwest part. These parts exhibit a strong contrast in resistivity, while the whole study area is nearly uniform and has very little resistivity variation.

The average aquifer thickness in the studied area is 52.12 m, with a range of 13.12 m to 118.65 m. According to figure 8(c), the Northeast and Northwest parts have good groundwater potential zones, and the center parts of the study area are thicker than the South and South and North parts. As a result, the central part of the study area has a higher groundwater potential zone than the other sections. One high peak in the Northeast and one little peak in the Northwest of the study area are depicted in the 3-D perspective presentation of aquifer thickness in figure 8(d). Since a thicker aquifer indicates a larger likelihood of groundwater availability, it may be said that areas with peak have superior groundwater potential. Weathered/fractured phyllites, quartzite/schist, and metabasaltic rocks with resistivity ranging from 10 Ω -m to 50 Ω -m make up the good groundwater promising potential zones creation in the current research, which is located in the midst of the Northeast and Southwest parts of the study area. Based on the interpretation of electrical resistivity, the remaining parts of the study area is classified as a medium to low groundwater potential zone.

462 **Table 3** Summary of D-Z parameters and hydraulic characteristics estimated from the geoelectric parameters of aquifer where found the groundwater potential zones
463 in Tanakpur area of Champawat district, Uttarakhand state, India

Serial No.	Location	VES No.	Aquifer Resistivity (Ohm-m)	Aquifer thickness (m)	Depth of aquifer layer (m)	Hydraulic conductivity (m/day)	Transmissivity (m ² /day)	Longitudinal conductance (mhos)	Transverse Resistance (Ohm-m ²)	Longitudinal Resistivity (H/Sc)	Transverse Resistivity (Tr/H)	Effective Resistivity	Anisotropy	Formation factor (F)	Porosity (Ø)
1	Kakrali Gate	VES1	145.22	106.06	70.657	3.717355	394.2626	0.73034	15402.03	96.74533	217.9831	145.22	1.501054	2.300314	54.34567
2	Bastaia	VES2	70.617	23.537	90.809	7.283147	171.4234	0.333305	1662.112	272.4501	18.30339	70.617	0.259192	3.145145	46.98695
3	Gedakhadi	VES3	81.774	42.597	128.09	6.351733	270.5648	0.520911	3483.327	245.896	27.19437	81.774	0.332555	2.951211	48.39865
4	Tanakpur	VES4	105.328	118.65	55.237	5.015885	595.1347	1.126481	12497.17	49.035	226.2463	105.328	2.148017	2.644265	50.93509
5	Saulani Goddh	VES5	187.04	27.87	61.097	2.935678	81.81735	0.149006	5212.805	410.0317	85.32014	187.04	0.45616	2.061108	57.19323
6	Chandani	VES6	166.18	13.116	142.27	3.278043	42.99481	0.078926	2179.617	1802.564	15.32028	166.18	0.092191	2.169615	55.84456
7	Ambagh	VES7	101.329	95.484	74.846	5.200301	496.5456	0.942317	9675.298	79.42766	129.2694	101.329	1.27574	2.689048	50.53878
8	Chhinigoth	VES8													
9	Kakraliforest	VES9													
10	Unchologodh	VES10	75.051	56.052	112.89	6.880949	385.6909	0.746852	4206.759	151.1544	37.26423	75.051	0.496519	3.063133	47.56794
11	Thuligaad	VES11	60.463	29.886	42.995	8.418023	251.581	0.494286	1806.997	86.9841	42.02808	60.463	0.695104	3.364281	45.53778
12	Manpurnagiri (near by SSB)	VES12	99.642	74.771	118.27	5.282385	394.9692	0.750396	7450.332	157.61	62.99427	99.642	0.632206	2.708707	50.36784
13	Mohanpur	VES13	184.8	16.036	129.59	2.968859	47.60862	0.086775	2963.453	1493.404	22.86791	184.8	0.123744	2.071911	57.05434
14	Godigoth	VES14													
15	Anandpur	VES15	42.337	31.563	51.138	11.73772	370.4777	0.745518	1336.283	68.59391	26.13091	42.337	0.617212	3.926837	42.37786
16	Caligadera	VES16	80.542	66.981	122.14	6.442319	431.513	0.831628	5394.784	146.8685	44.16885	80.542	0.548395	2.970713	48.25061
17	Banbasa	VES17	162.83	27.102	29.84	3.340911	90.54537	0.166444	4413.019	179.28	147.8894	162.83	0.908244	2.188871	55.61553
	Minimum		42.337	13.116	29.84	2.93568	42.9948	0.07893	1336.28	49.035	15.3203	42.337	0.09219	2.06111	42.3779
	Maximum		187.04	118.65	142.27	11.7377	595.135	1.12648	15402	1802.56	226.246	187.04	2.14802	3.92684	57.1932
	Average		111.654	52.1218	87.8478	5.63238	287.509	0.55023	5548.86	374.289	78.7843	111.654	0.72045	2.73251	50.78

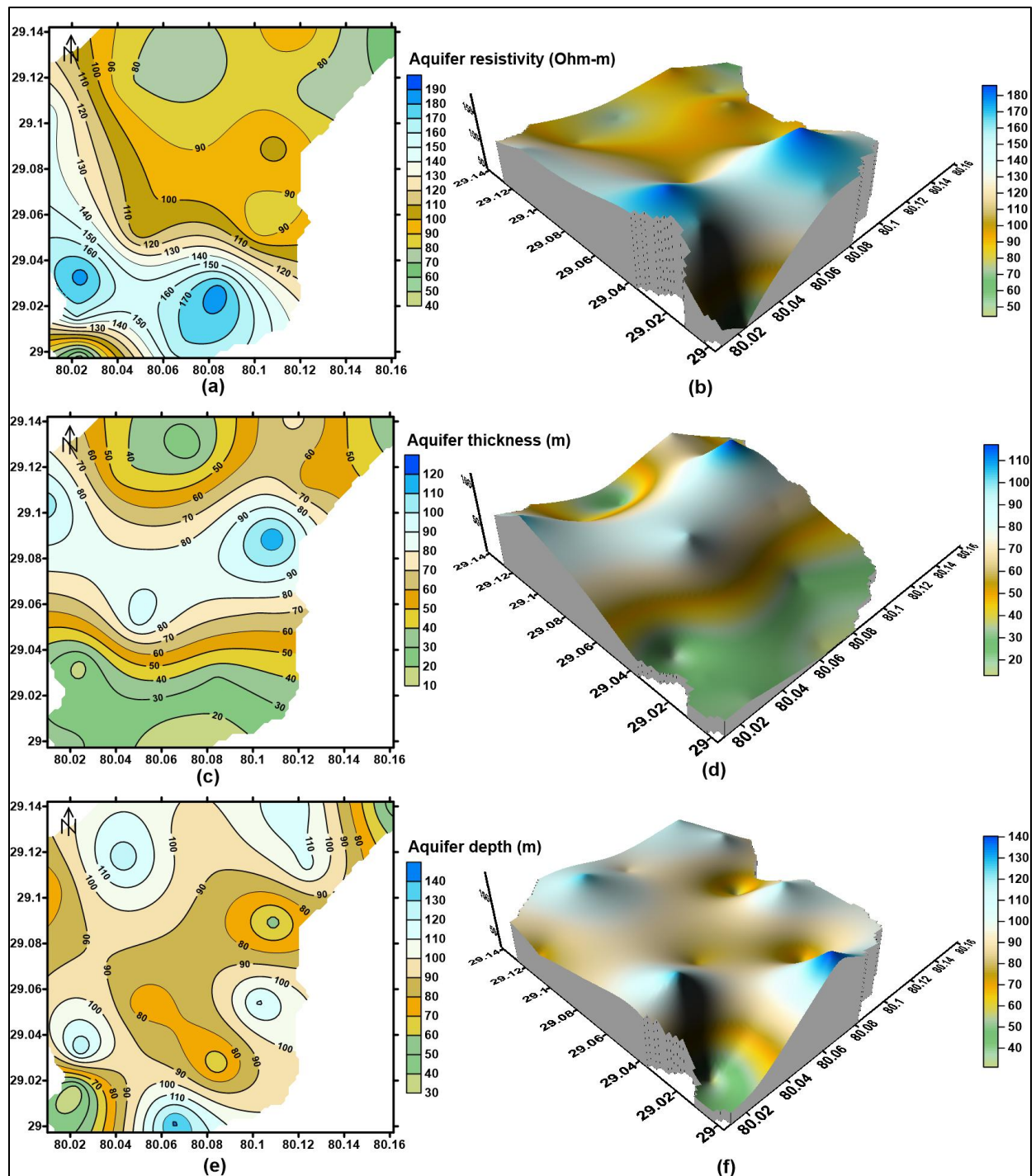


Fig. 8(a) Contour map of aquifer resistivity **(b)** 3-D representation of aquifer resistivity **(c)** Contour map of aquifer thickness **(d)** 3-D representation of aquifer thickness **(e)** Contour map of aquifer depth **(f)** 3-D representation of aquifer depth along with VES positions of the study area.

Contours interval 10 m apart have been used to depict the aquifer's depth (Figure 8e). Within the study area, the aquifer depth varies between 29.84 and 142.27 m, with an average depth of 87.623 m. It has been deduced that the aquifer level is lowest at VES17, close to Banbasa, and highest at VES6, close to Chandani village. The deeper aquifer depths in the Northwest, Northeast, Southwest, Southeast, and South parts of the study area are clearly

depicted. In figure 8(f), the 3-D depiction of the aquifer depth clearly reveals four small peaks in the Southeast and large peaks in the Northwest, Southwest, and South parts. This indicates that the aquifer depth is shallower towards the Northeast and deeper in the center portion. While the remainder of the research region has medium to low/shallow aquifer depths toward the north to Southeast, the Southeast part has the shallowest aquifer depth in the entire area.

4.1.3. Hydraulic conductivity, Transmissivity, Longitudinal conductance, Transverse unit resistances and Anisotropy of the study area

Figure 9(a) illustrates the spatial distribution of hydraulic conductivity across the study area. The hydraulic conductivity values in the study area ranged from 2.93 to 11.73 m/day, with a mean value of 5.63 m/day. The lowest hydraulic conductivity was recorded at VES5 nearby Saulani Goddh village, while the highest was observed at VES15 nearby Anandpur village. Specifically, the hydraulic conductivity ranged from 1 to 5 m/day at VES1, 4, 5, 6, 13 & VES17, the hydraulic conductivity ranged from 5 to 10 m/day at VES2, 3, 7, 10, 11, 12 & VES16 and exceeded 10 m/day at VES15. High hydraulic conductivity was primarily observed in the Southwest & Northeast parts of the study area, while low hydraulic conductivity is noted in the middle Southwest regions. The remaining areas exhibited medium hydraulic conductivity. Hydraulic conductivity is directly proportional to effective permeability, which is a crucial parameter in aquifer studies and in understanding contaminant flow behavior in subsurface environments. Figure 9 (b) revealed two prominent peaks of high hydraulic conductivity in the Northeast, Southwest & East parts and two smaller peaks in the middle-middle Southwest and Northeast. The rest of the study area displayed relatively uniform hydraulic conductivity. High hydraulic conductivity indicated a higher rate of water flow into and through porous storage rocks in aquifers (Kelvin Hefferan and John O'Brien, 2010), suggesting that areas with elevated hydraulic conductivity were more likely to have better aquifer recharge potential.

The transmissivity in the study area ranged from 42.99 to 595.13 m²/day, with an average of 287.57 m²/day in **figure 9 (c)**. The minimum transmissivity was observed at VES6 nearby Chandani village, while the maximum was recorded at VES4 nearby Tanakpur town. Transmissivity exceeded 500 m²/day at VES4, whereas it ranged from 50 to 500 m²/day at VES1, 2, 3, 5, 7, 8, 10, 11, 12, 15, 16 & VES17 and the range from 5.0 to 50 m²/day at VES6 & VES13. This suggested that the increased transmissivity and permeability (hydraulic conductivity) correspond to a higher groundwater flow potential. To classify groundwater potentials in the area, standards for transmissivity as outlined by Krasny (1993) were used, as detailed in **Table 5**. High transmissivity was observed primarily in the Northeast, whereas low transmissivity was observed in Southeast and Southwest Parts, the rest part has the medium transmissivity in the study area (**Figure 9c**). Transmissivity is a crucial parameter for characterizing rocks as water-conductive media (Fatoba et al., 2014).

High groundwater potential zone was noted at VES4, attributed to high hydraulic conductivity, transmissivity, and aquifer thickness, coupled with low aquifer resistivity. This location is considered to have significant regional importance due to their high water-bearing capacity. Moderate groundwater potential zones were observed at VES1, 2, 3, 5, 7, 8, 10, 11, 12, 15, 16 & VES17 where high aquifer resistivity and moderate aquifer thickness, despite some locations having medium transmissivity and hydraulic conductivity. These zones also hold regional significance. Low potential zones or impermeable strata were identified within the study area at VES6 and VES13 locations. One prominent peak in groundwater potential were located in the Northeast and two small peaks

Southeast parts of the study area (**Figure 9d**). Additionally, two smaller peaks were found in the Northwest and Southeast, indicating low or shallow groundwater potential zones.

The longitudinal conductance (S_c) values were utilized to assess the protective capacity of the aquifer using the Equation (14). The evaluation of the aquifer's protective capacity, as described by Oladapo and Akintorinwa (2007), is summarized in **Table 4**. The longitudinal conductance (S_c) ranged from 0.07 to 1.123 with a contour interval of 0.1, as illustrated in **Figure 9(e)**. The Northwest and some parts of Southwest exhibited moderate (S_c) values (approximately 0.20–0.69), surrounding VES locations VES2, 3 & VES11, indicating moderately fresh water zones. Conversely, the Northeast, Middle East & Central parts exhibited higher (S_c) values (0.7–4.9) at VES locations VES1, 4, 7, 10, 12, 15 & VES16, which corresponded to areas with good freshwater quality, VES2 & VES17 indicating the weak water with value 0.1–0.19 in some parts of Southeast & Southwest and VES6, & VES13 indicating the poor water zones with value <0.1 in the some parts of Southeast & Southwest of the study area. The longitudinal conductance (S_c) provided insight into the variation of resistive fresh basement topography, with (S_c) being inversely related to the depth to the basement (Ayolabi et al. 2010). In geoelectric environments with uniform properties, resistivity remained relatively constant, making S_c proportional to the depth to the basement; thus, higher S_c values suggested a deeper basement and vice versa (Murali and Patangay 2006). Clayey overburden, characterized by relatively high longitudinal conductance, offered effective protection to the underlying aquifer. Based on the classifications by Oladapo and Akintorinwa (2007) and Atakpo (2008, 2013), the S_c values categorized the area into zones of poor, weak, moderate, good, very good, and excellent protective capacities. **Figure 9(e)** had demonstrated that approximately 50.0% of the area falls within the 'good' protective capacity zone, while around 21.42% falls within the 'moderate' protective capacity category, 14.29% falls under the weak and 14.29% falls under the poor as detailed in **Table 4**. This indicated that the study area, characterized by moderate to high longitudinal conductance, generally exhibited a good protective capacity for the aquifer. Clayey and silty overburden in this region provided substantial protection to the underlying aquifers. Oteri (1981) noted that a significant increase in S_c could correspond to an increase in clay content and a decrease in aquifer transmissivity. High S_c peaks in the Northeast, middle East & Central parts of the study area suggested good productivity, whereas other regions demonstrated moderate, weak & poor productivity, as shown in **figure 9 (f)**.

The transverse unit resistance (T_r) contour map, with a contour interval of $1000 \Omega \cdot \text{m}^2$, is presented in **figure 9 (g)**. The T_r values ranged from a minimum of $1336.28 \Omega \cdot \text{m}^2$ at VES 15 (nearby Anandpur village) to the maximum of $15402.0 \Omega \cdot \text{m}^2$ at VES1 (nearby Kakraligate village). **Figure 9(g)** had revealed that high T_r values, exceeding the average ($>5548.86 \Omega \cdot \text{m}^2$), were concentrated around VES locations VES1, 4, 7, and VES12, indicating high aquifer transmissivity. Elevated T_r values were particularly prominent in the Northeastern and Northwestern parts of the study area. High peaks in T_r were observed in the northeastern and northwestern regions (**Figure 9 h**). This delineated that areas with high T_r values correspond to high groundwater potential, while areas with medium T_r values indicated medium groundwater potential, and the remainder of the study area, characterized by low T_r values, fallen under the low groundwater potential zone.

Table 4 Rating of protective capacity (Oladapo and Akintorinwa 2007).

Protective capacity (mhos)	Rating	VES sites
----------------------------	--------	-----------

>10.0	Excellence	Nil
5.0-10.0	Very good	Nil
0.70-4.9	Good	VES1, 4, 10, 12, 15 & VES16
0.20-0.69	Moderate	VES2, 3 & VES11
0.10-0.19	Weak	VES2 & VES17
<0.10	Poor	VES6 & VES13

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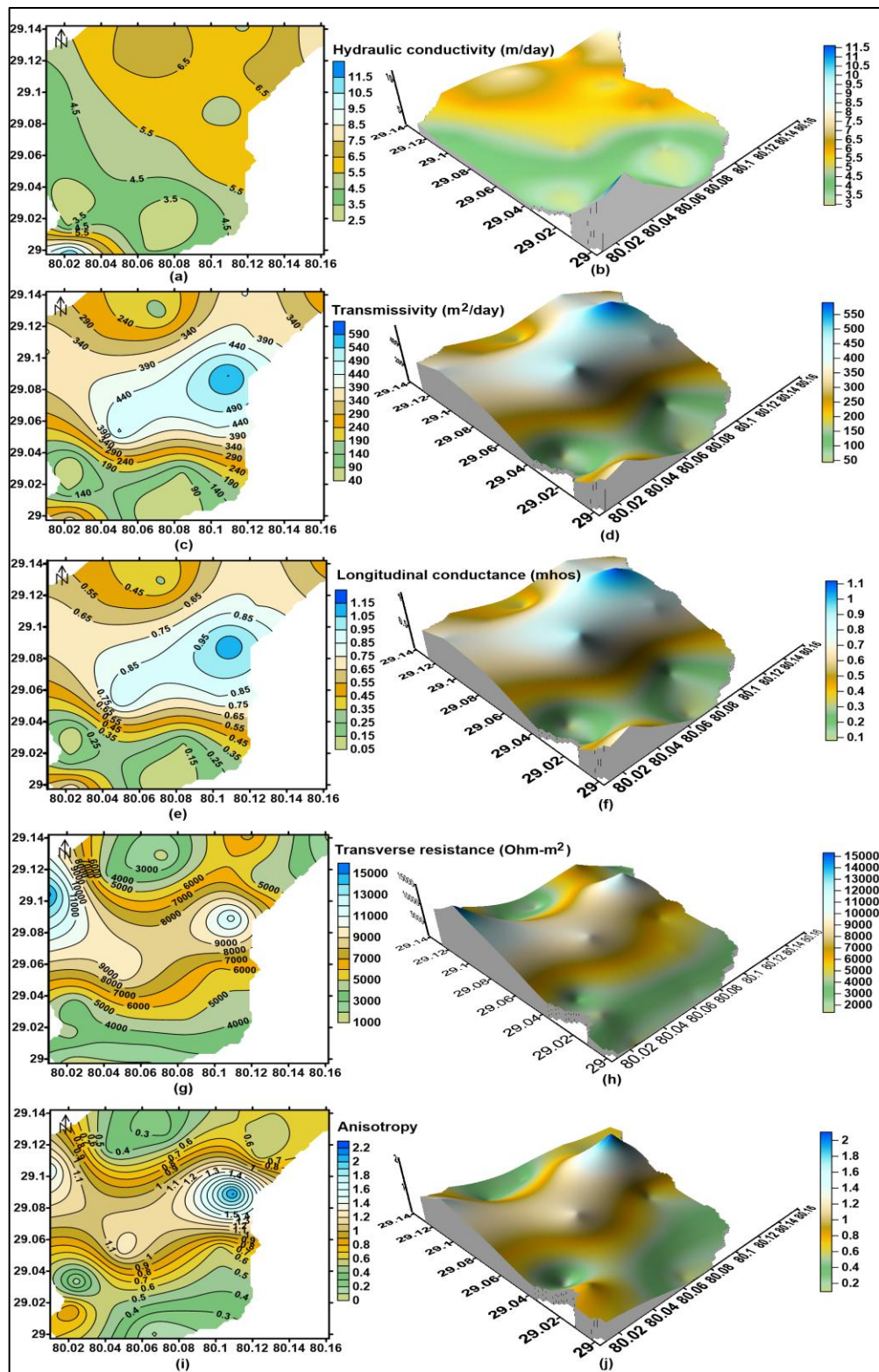


Fig. 9 Map of (a) Hydraulic conductivity contour, (b) 3-D representation of hydraulic conductivity, (c) transmissivity contour, (d) 3-D representation of transmissivity, (e) longitudinal conductance contour, (f) 3-D representation of longitudinal conductance, (g) transverse resistance contour, (h) 3-D representation of transverse resistance and (i) anisotropy contour, and (j) 3-D representation of anisotropy

Aquifer anisotropy, caused by layering, affects the relationship between hydraulic and electrical properties of the aquifer system (Kelly and Reiter, 1984; Batayneh, 2009). The coefficient of anisotropy (λ) reflected differences in conductivity in various directions, with water preferentially flowing along the direction of higher conductivity (Sona Salehian Ghamsari, et. al., 2025). The coefficient of anisotropy provided insights into the aquifer's characteristics in a basement environment (Singh, S., & Mondal, N. C., 2025). In this study, λ -values were typically 1 or greater, with high potential zones in the Northeast and Northwest parts showing isotropic coefficients ranging from 0.09 to 2.14 with an average value of 0.72 (**Figure 9 i**). The rest of the study area, characterized by moderate groundwater potential, had anisotropic coefficient values ranging from 0.09 to 1.0. High and moderate groundwater potential zones were identified in the southwest & southeast parts, respectively (**Figure 9j**). Based on these geophysical investigations, there were some parts of Southeast, Southwest and Northwest identified low, or impermeable groundwater potential zones, suggesting that the area was promising for groundwater exploration.

Table 5. Aquifer classification based on Transmissivity values (Offodile 1992, after Krasny, 1993)

Transmissivity	Classification	Groundwater supply potentials	VES Location number
>500	High potentials	Withdrawal of great regional importance	VES4
50-500	Moderate potential	Withdrawal of lesser regional importance	VES1, 2, 3, 5, 7, 10, 11, 12, 15, 16 & VES17
5.0-50.0	Low potential	Smaller withdrawal for local supply	VES6 & VES13
0.5-5	Very Low potential	Withdrawal for private consumption	Nil
<0.5	Negligible potential	Source for local water are difficult	Nil

4.1.4. Longitudinal resistivity, transverse resistivity and effective resistivity

The contour map of the longitudinal (or horizontal) resistivity component (ρ_l) with a contour interval of 100 Ω -m is presented in **figure 10 (a)**. Resistivity values across the study area ranged from 49.035 to 1802.56 Ω -m, with an average of 374.29 Ω -m. The South and Southwest parts of the study area, including VES locations VES6 & VES13, exhibited resistivities greater than 440 Ω -m. In contrast, VES locations VES2, 3, & VES5 in the Northwest, Southwest & middle parts had resistivities ranging from 240 to 440 Ω -m. Lower resistivities, in the range of <240 Ω -m, were observed at VES locations VES1, 4, 7, 10, 11, 12, 15, 16 & VES17 in the Northwest, Southwest and mostly central parts. **Figure 10 (b)** indicated two prominent peaks in resistivity in the South and Southwest parts, suggesting areas with favorable groundwater potential, while the remainder of the area had shown uniform low resistivity, indicative of lower groundwater potential zones. This pattern suggested that the longitudinal component of resistivity, which measured the current flow along the lithological boundaries, was greater than that perpendicular to the boundary plane (Ayolabi et al., 2010). Kelly (1977) noted that the longitudinal component was influenced predominantly by more conductive layers, such as clay and weathered materials, which could cause a rapid increase in resistivity even with a presence of less resistive layers.

Figure 10 (c) depicts the contour map for transverse resistivity (ρ_t) with a contour interval of 20 Ω -m. The central Northeastern and Northwestern parts of the study area showed broad regions with resistivity values exceeding 140 Ω -m, as seen in VES locations VES1, 4 & VES17, indicating excellent groundwater quality. VES locations VES5, 7 & VES12, located in the central Northwest parts and some parts of Southwest, had resistivities in the range

of 60–140 Ω -m, representing very good groundwater quality. The remaining areas exhibited resistivity values less than 60 Ω -m, which corresponded to good groundwater quality zones. Pockets of low resistivity observed at VES locations VES2, 3, 6, 10, 11, 13, 15, & VES16 might be attributed to contamination, likely from the intermixing of rocks. **Figure 10 (d)** had highlighted two high peaks in the Northeast and Northwest parts, indicating excellent water quality, while the rest of the study area displayed very good to good groundwater quality with minimal contamination fluctuations.

The root means square resistivity (ρ_{rms}), representing the effective resistivity, was calculated using the equation (7) and is summarized in **Table 2**. It ranged from 42.34 Ω -m at VES 5 (SAulani Goddh village) to 187.04 Ω -m at VES15 (Anandpur village), with an average of 111.654 Ω -m. Khalil (2009) observed that variations in longitudinal, transverse, and mean resistivities were influenced by the direction of groundwater flow and lithological variations. These resistivity types differed in layered anisotropic sediments (Mazac et al., 1985; Ayolabi et al., 2010). In this study, the distinct resistivity values reflected the presence of heterogeneous anisotropic lithology in **figure 10 (e)**. High resistivity peaks in the Southeast, Southwest parts indicated greater heterogeneity in hydrogeological formations in **Figure 10(f)**. The remaining study area exhibited less hydrogeological heterogeneity.

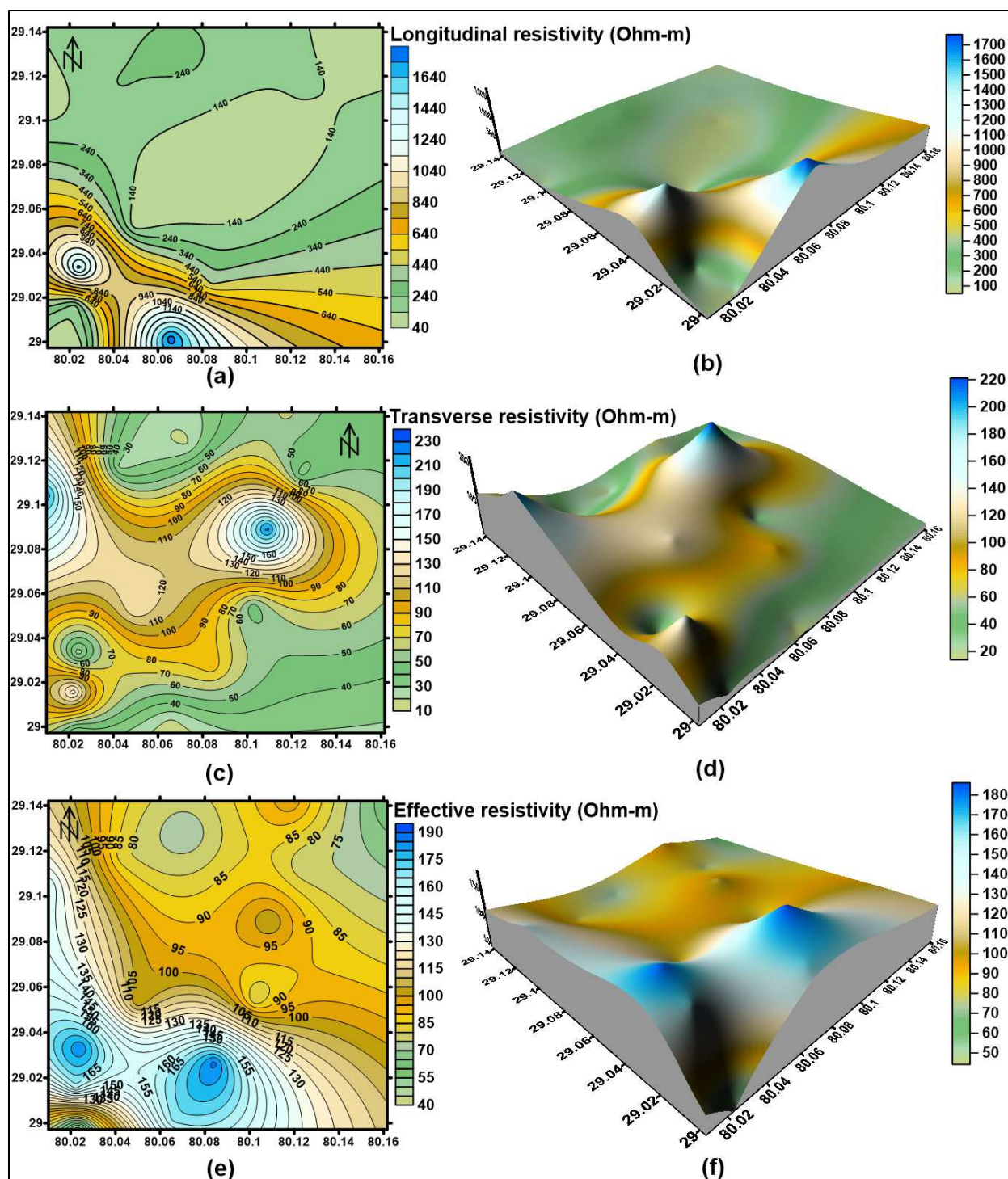
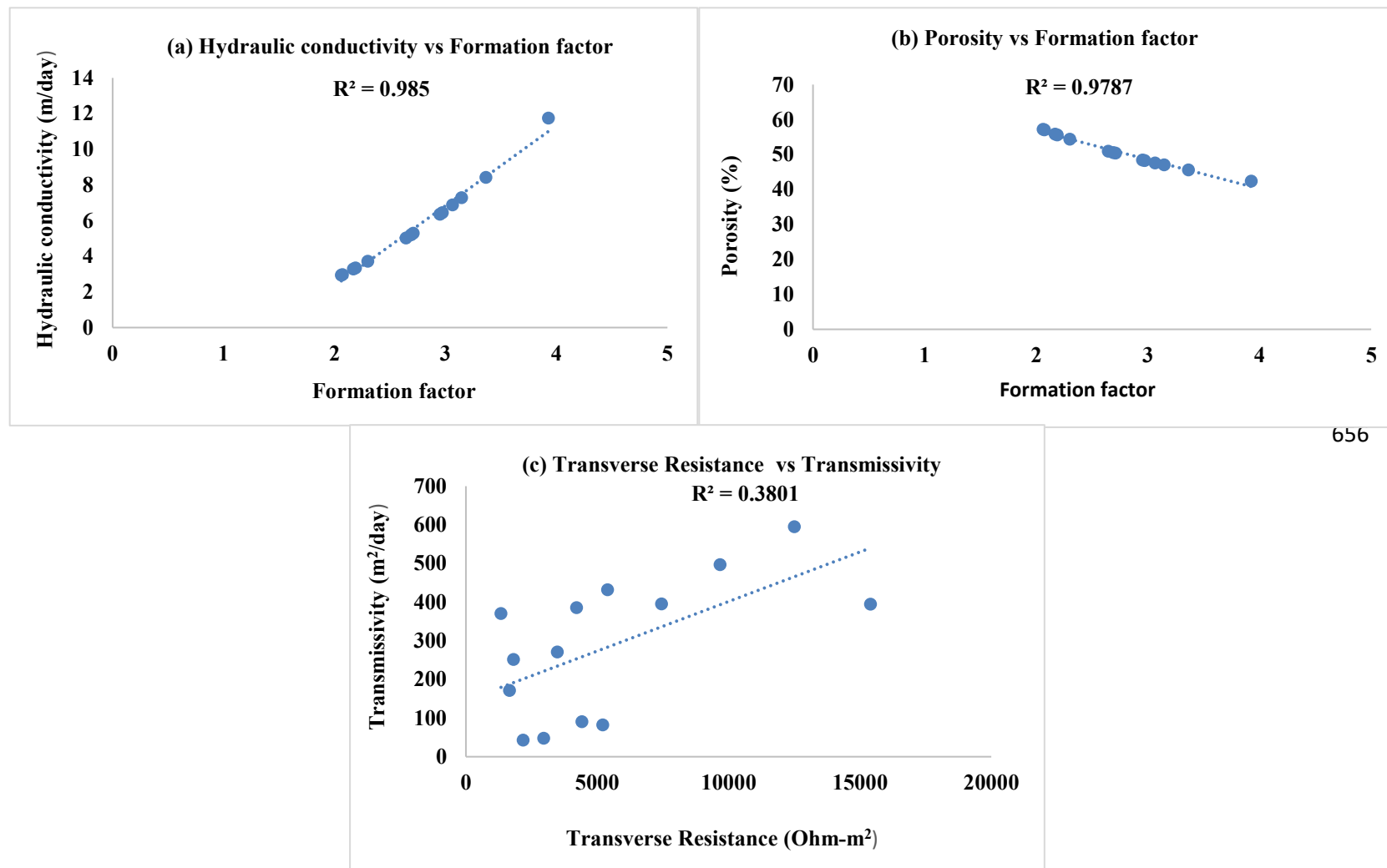


Fig. 10 Map of (a) longitudinal resistivity contour, (b) 3-D representation of longitudinal resistivity, (c) transverse resistivity contour, (d) 3-D representation of transverse resistivity, (e) effective resistivity contour, and (f) 3-D representation of effective resistivity.

5. Hydrogeological inferences and their relationship

In hydrogeological investigations, the relationships among conductivity, formation factor, transverse resistance, transmissivity, porosity, and formation factor can exhibit either linear or non-linear patterns. Non-linearity often arises due to variations in lithological composition and directional heterogeneity. Scatter plots of the data revealed linear relationships between conductivity and formation factor, as well as between porosity and formation factor, as illustrated in figures 11 (a) & 11 (b). For these linear relationships, the regression coefficients (R) were found to be 0.985 and 0.9979, respectively. These high R values indicated a strong linear correlation between the variables. Conversely, the relationship between transverse resistance and transmissivity displayed a non-linear pattern ($R=0.380$), as shown in figure 11 (c). This non-linearity could be attributed to the complex interactions between these parameters, which might be influenced by varying geological conditions and aquifer characteristics. These findings of this study were consistent with those of other researchers who had explored similar relationships among aquifer and geophysical parameters. For instance, Niwas and Singhal (1981, 1985) Chachadi and Gawas (2012) had observed that while some relationships might remain linear and relatively constant across different geological settings, others might be exhibited significant variability due to local geologic and hydrologic conditions. In this study, the linear relationships were predominantly observed in regions with moderate to high aquifer potential. This suggested that understanding these correlations could be provided valuable insights for groundwater management, particularly in areas where aquifer potential was significant. The strong linear relationships observed could be aided in predicting aquifer characteristics and groundwater quality, thereby supporting effective groundwater management strategies. Conversely, the non-linear relationships highlighted the need for more complex modeling approaches to accurately assess and manage groundwater resources in diverse geological settings. By integrating these findings with geophysical and hydrogeological data, it was possible to develop more refined models for predicting aquifer behavior and groundwater quality. This approach will enhance the management of groundwater resources, ensuring sustainable utilization and protection of aquifer systems.



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665 **Fig. 11** Relationship between (a) hydraulic conductivity and formation factor, (b) porosity and formation factor, and (c) transverse resistance and transmissivity in
 666 Tanakpur area of Champawat district, Uttarakhand

667

668 **6. Conclusions and Recommendations**

669 This present study shows that a robust and reliable hydrogeophysical framework for characterizing aquifers in the
670 structurally complex Himalayan foothill terrain of Tanakpur area, in the Champawat district of Uttarakhand state,
671 can be obtained by combining Vertical Electrical Sounding (VES) with Dar-Zarrouk parameter analysis. Significant
672 lithological heterogeneity, including schist, quartzite, phyllite, metabasalt, sandstone, granite, and weathered
673 formations, is present in the studied region. These formations have a significant influence on the occurrence of
674 groundwater and subsurface resistivity patterns.

675 The VES interpretation identified seven to eight different geoelectric strata, indicating differences in
676 lithology and the extent of weathering and fracturing, with resistivity values ranging from 42.34 Ω -m to 187.04 Ω -
677 m. The most promising aquifer horizons were found in the fourth to seventh layers, which are primarily made up of
678 granite, quartzite, pebbles, cobbles, gravels, boulders, worn and fractured phyllites, and sandy clay. There is
679 significant regional variation in groundwater occurrence and storage capability, as evidenced by the range of aquifer
680 depths from 29.84 m to 142.27 m and thicknesses from 13.11 m to 118.65 m.

681 The Dar–Zarrouk parameters that were computed, transverse resistance, hydraulic conductivity,
682 transmissivity, longitudinal conductance, and anisotropy, offered quantitative information about the protective
683 capacity and performance of aquifers. Several sites have moderate to good groundwater potential, according to
684 transverse resistance (1336.28–15402.0 Ω -m²) and hydraulic conductivity values (2.94–11.74 m/day). Favorable
685 groundwater storage conditions are additionally indicated by high porosity values (42.38%–57.19%). Differences in
686 resistivity and anisotropy support the diverse subsurface structure characteristic of foothill regions in the Himalayas.

687 Groundwater extraction prioritizes low to moderate resistivity zones (51–100 Ω -m), which are linked to
688 weathered and fractured strata, because of their improved permeability and storage properties. For long-term
689 sustainability and yield optimization, borewell development should prioritize regions with thicker aquifer parts and
690 higher transverse resistance, especially in the southern Bhabar belt.

691 In areas with moderate slopes and high runoff, artificial recharge structures including check dams,
692 percolation tanks, and recharge pits are advised to improve infiltration and aquifer replenishment and fortify
693 groundwater management. Evaluating seasonal recharge dynamics and long-term aquifer response requires regular
694 resistivity surveys in addition to ongoing groundwater level monitoring. Aquifer performance evaluations and
695 transmissivity estimates should also be improved by combining geophysical interpretations with pumping tests,
696 hydrochemical studies, and thorough structural mapping.

697 Site-specific management techniques are required to prevent over-extraction in foothill zones that are
698 vulnerable and to promote sustainable exploitation in high-potential areas due to the significant geographic
699 heterogeneity in groundwater potential. This methodology of study and conclusions can be applied to other foothill
700 regions of the Himalayas with similar geological complexity. Overall, the study demonstrates that Dar–Zarrouk
701 parameter analysis, when combined with VES, is a reliable and effective method for evaluating aquifers, determining
702 the best location for wells, and developing groundwater resources sustainably in the Tanakpur area in the Champawat
703 district of Uttarakhand state.

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7. Limitations of the Study

In the structurally complex Himalayan foothill terrain of Tanakpur area of Champawat district, Uttarakhand, the integrated VES and Dar–Zarrouk parameter approach has shown itself to be a practical and economical method for preliminary aquifer evaluation. However, it is still primarily a one-dimensional geophysical technique that might not adequately capture the structural discontinuities and lateral heterogeneity typical of such tectonically active regions. Groundwater occurrence and flow are significantly influenced by faults, fractures, shear zones, and abrupt lithological transitions; the assumption of horizontally stratified layers may oversimplify underlying processes.

Therefore, in order to better define fractured zones, subterranean channels, and structural influences on aquifer geometry, future studies should use two-dimensional (2D) and three-dimensional (3D) electrical resistivity tomography (ERT). To validate and improve the indirect estimates obtained from Dar–Zarrouk parameters, extensive aquifer pumping studies are necessary to directly establish hydraulic parameters like transmissivity, storativity, and specific yield. Understanding recharge dynamics, aquifer response to monsoonal variability, and the effects of over-extraction would all benefit from long-term groundwater level monitoring during several seasons. Furthermore, by connecting groundwater flow patterns with lithological controls, weathering processes, and potential contamination pathways, the integration of comprehensive structural mapping with hydrochemical and isotopic data would improve the interpretation. In Himalayan foothill regions, such multidisciplinary integration would help climate-resilient water resource planning, optimal well design, and sustainable groundwater management in addition to increasing the precision and dependability of aquifer characterization.

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Declarations:

Author contribution:

Somvir Singh: Initially processed, analysed, and interpreted the data, Conceptualized, designed. Also, prepared a draft of manuscript.

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Consent to Participate: Not applicable. This study did not involve human participants or animals.

Consent to Publish: Author consent to the publication of this manuscript. This study does not include any human participants or personal data requiring consent for publication.

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