

Integrated Geophysical and Geochemical studies Coupled with Statistical Analysis for Groundwater Potential Assessment of Sahaspur Block in the Himalayan foothills

Somvir Singh

somvir81-cgwb@gov.in

Central Ground Water Board

Surendra Kaur Rawal

Shri Guru Ram Rai University

Preeti Tiwary

Shri Guru Ram Rai University

Research Article

Keywords: Vertical Electrical Sounding (VES), water quality, hydrogeochemistry, multivariate statistical, groundwater potential, Sahaspur block

Posted Date: September 15th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10945706/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Integrated Geophysical and Geochemical studies Coupled with Statistical Analysis for Groundwater Potential Assessment of Sahaspur Block in the Himalayan foothills, Uttarakhand, India

^{*1}Somvir Singh, ²Surendra Kaur Rawal, ³Preeti Tiwary

¹Somvir Singh, Email: somvir81-cgwb@gov.in, Orcid Id: 0000-0001-9169-7744

Central Ground Water Board, Uttaranchal Region, Dehradun-248001, Uttarakhand, India,

²Surendra Kaur Rawal, Email: surendrakaurawal@sgrru.ac.in, Orcid Id: 0000-0001-8708-8444.

³Preeti Tiwary, Email: priti07tewary@gmail.com, Orcid Id: 0009-0000-4451-2962.

^{2,3}Shri Guru Ram Rai University, Pathribagh, Dehradun-248001, Uttarakhand, India.

^{*1}Corresponding author Email Id: somvir81-cgwb@gov.in

Abstract

Groundwater is a vital resource for household, commercial, and agricultural uses in the Himalayan foothills. This study uses geophysical, geochemical, and statistical techniques to assess the groundwater potential and quality in the Sahaspur Block, Dehradun District, Uttarakhand, India. The Schlumberger array was used to perform 58 Vertical Electrical Sounding (VES) measurements in order to detect aquifer zones and define subsurface lithology. The analyzed resistivity data showed multilayered subsurface formations made up of saturated aquifers, worn strata, and topsoil, suggesting generally good groundwater potential throughout the study area. Thirteen groundwater samples were taken from wells at varying depths in order to assess the quality of the groundwater. These samples were examined for major physicochemical parameters, such as pH, electrical conductivity, total dissolved solids, and main ions. According to the analytical findings, every measured parameter is within the acceptable ranges suggested for irrigation and drinking. The relationships between hydrochemical variables and geoelectrical parameters were examined using statistical analyses. Aquifer resistivity and groundwater EC were shown to be significantly inversely correlated, supporting the interpretations of resistivity and proving the value of combining hydrochemical and geophysical data. The combined findings show a substantial correlation between groundwater quality conditions and subsurface resistivity features, making it possible to reliably identify freshwater-bearing aquifers and zones with increased groundwater potential. In the Sahaspur Block and other comparable hydrogeological settings, the integrated method enhances the characterization of hydrogeological conditions and offers a strong foundation for groundwater resource assessment, quality evaluation, and sustainable groundwater management.

Keywords: Vertical Electrical Sounding (VES), water quality, hydrogeochemistry, multivariate statistical, groundwater potential, Sahaspur block.

1. Introduction

One of the most significant renewable natural resources, groundwater is essential to sustaining household, agricultural, and industrial operations across the globe (Carrard et al., 2019; Alao et al., 2024; Monika et al., 2024). Groundwater demand has significantly increased due to rapid urbanization, agricultural expansion, and population growth, underscoring the necessity of accurate groundwater availability and quality assessment for sustainable water-resource management (Kar et al., 2022; Ahmed et al., 2020; Rusli et al., 2024; Fuqaha, 2025). Therefore, integrated scientific methods that can characterize groundwater quality and aquifer geometry are necessary for effective groundwater exploration (Llamas, 2024; Patil and Saraf, 2025; Masood et al., 2022). Groundwater investigations have made extensive use of a variety of approaches, such as hydrogeological, hydrogeochemical, remote sensing, and geophysical techniques (Kumar et al., 2020; Paul et al., 2020; Singh et al., 2021; Gupta et al., 2021; Kumar et al., 2021; Singh et al., 2022; Kumar et al., 2023; Alao et al., 2025). According to Javed et al. (2024) and Alao et al. (2025), electrical resistivity techniques are acknowledged as economical and effective instruments for defining subsurface lithology and locating groundwater-bearing formations. To ascertain aquifer depth, thickness, and lateral continuity in various geological settings, Vertical Electrical Sounding (VES) has been widely employed (Zohdy et al., 1974; Stampolidis et al., 2005; Soupios et al., 2007; Kalisperi et al., 2009; Sharma and Biswas, 2013; Egai et al., 2024; Menegbo et al., 2024). The VES technique's simplicity, non-invasiveness, and capacity to yield useful information on subsurface hydrogeological conditions are major factors in its success (Lashkaripour, 2003; Sahu and Sahoo, 2006; Raju et al., 2023; Som Nath et al., 2024).

Lithology, porosity, saturation, and groundwater salinity have a significant impact on the electrical resistivity of subsurface materials (Palacky, 1987; Oliveira et al., 2023; Li et al., 2024). As a result, indirect information on groundwater quality can be obtained by geoelectrical approaches. However, similar resistivity values may correspond to different lithological conditions, making it difficult to distinguish lithological variations from water-quality effects using resistivity data alone (Choudhury and Saha, 2004; Hibbs, 2024; Ali et al., 2025). This restriction can be addressed by combining hydrochemical and geophysical data to increase the accuracy of groundwater quality evaluation and aquifer characterisation (Adewoyin et al., 2021; Oyeyemi et al., 2022; Hibbs, 2024). According to recent research, correlations between groundwater electrical conductivity (EC) and aquifer resistivity offer important information on groundwater quality and aquifer conditions (Wiederhold et al., 2021; Javed et al., 2024; Alao et al., 2025). Situated in the piedmont zone of the Doon Valley, the Sahaspur Block of Dehradun District, Uttarakhand, features complicated hydrogeological conditions. Doon Gravels, which are mostly composed of boulders, pebbles, gravel, sand, and clay from the Siwalik and Lesser Himalaya formations, underlie the region (Singh et al., 2001; Patel and Kumar, 2003; CGWB, 2023). Concerns about the sustainability and quality of groundwater in the area have been raised by growing groundwater extraction brought on by urbanization, agricultural intensification, and population growth (CGWB, 2020; CGWB, 2023; Moniruzzaman et al., 2024). There are still few comprehensive integrated studies that connect aquifer geometry and groundwater quality, despite the local residents' reliance on groundwater supplies.

Thus, the current study uses an integrated geophysical, geochemical, and statistical technique to assess groundwater potential and quality in the Sahaspur Block. In order to identify groundwater-bearing zones and designate

underlying lithological formations, 58 Vertical Electrical Sounding (VES) measurements were performed. Additionally, groundwater samples were examined to evaluate physicochemical parameters. Additionally, statistical correlations between groundwater electrical conductivity and aquifer resistivity were investigated to enhance comprehension of groundwater conditions and validate geoelectrical interpretations. The findings of this study give the piedmont region of Uttarakhand a solid foundation for groundwater resource assessment, aquifer characterisation, and sustainable groundwater management.

2. Study area

The Sahaspur Block is situated between Latitudes 30°25'N to 30°55'N and Longitudes 77°80'E to 78°08'E in the eastern portion of Dehradun District, Uttarakhand, India (Figure 1). Situated between the Siwalik Hills and the Lesser Himalaya, the study area is a portion of the Doon Valley. Its varied hydrogeological conditions affect the occurrence and movement of groundwater. The area has a subtropical, comparatively humid environment with year-round moderate temperatures. The lowest winter temperature can fall to 5.2°C, while the highest summer temperature is approximately 36.6°C (CGWB, 2013). The southwest monsoon season, which runs from July to September, brings the highest precipitation, with an average annual rainfall of about 1800 mm. Groundwater replenishment is mostly provided by this rainfall. The Doon Gravel Formation, which is composed of boulders, pebbles, gravel, sand, silt, and clay from the Siwalik and Lesser Himalayan regions, dominates the study area's geology. The multilayered aquifer systems formed by these unconsolidated alluvial deposits have different groundwater potential and thicknesses. The region is part of the Song River's catchment, which makes a substantial contribution to subsurface water movement and groundwater recharge. A thorough evaluation of the groundwater resources in the area is becoming more and more necessary as a result of increased urbanization, agricultural practices, and groundwater extraction. The Sahaspur Block is a crucial region for integrated geophysical and geochemical studies targeted at sustainable groundwater management due to its advantageous hydrogeological environment and reliance on groundwater.

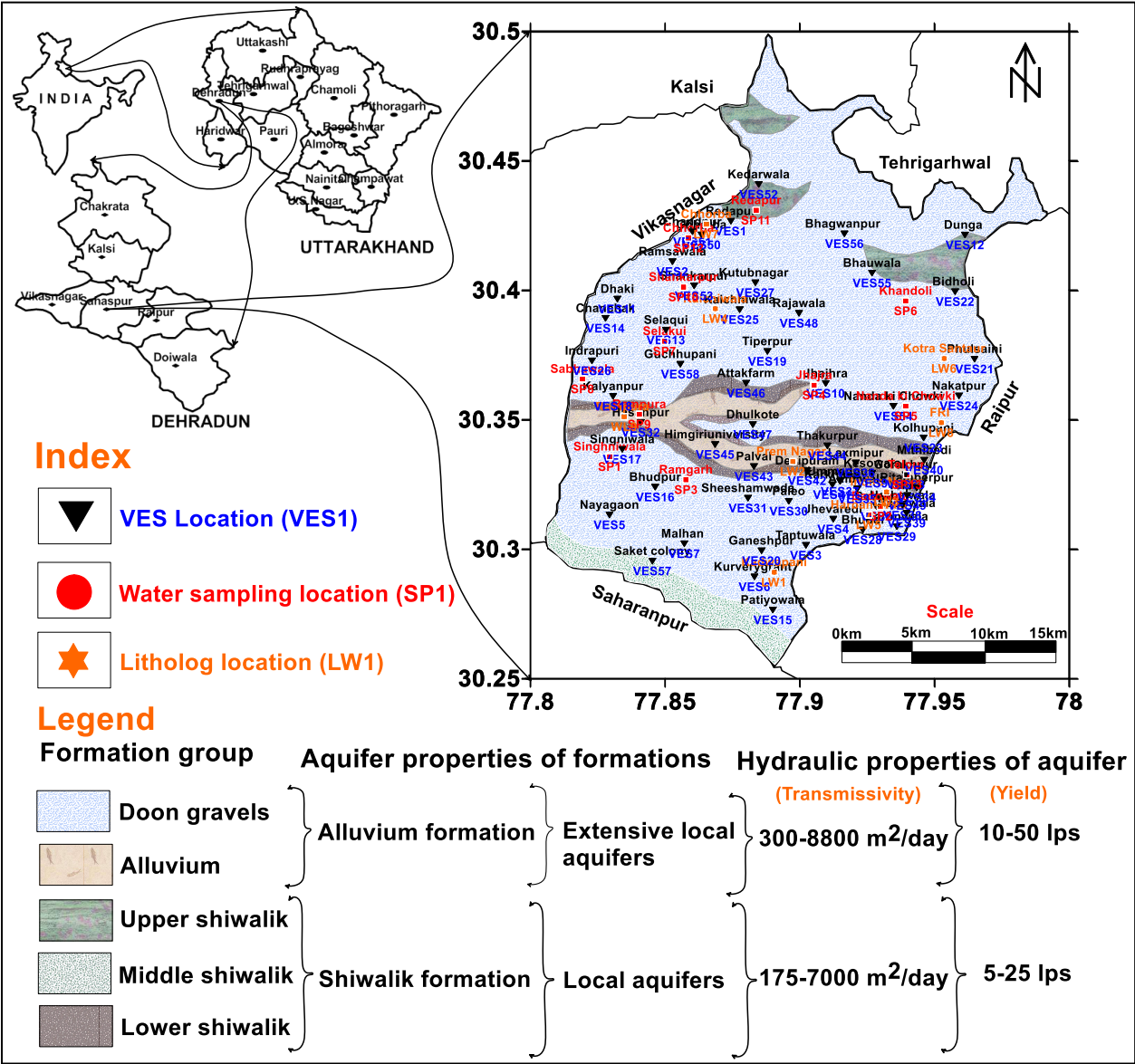


Fig.1 Location and lithological map of Sahaspur block, Dehradun district.

3. Geology and hydrogeology

The Doon Valley, an intermontane basin confined to the north by the Lesser Himalaya and to the south by the Siwalik Hills, is home to the Sahaspur Block. The area has a complicated geological structure with rock formations that date from the Archean to the Quaternary (Thakur, 1981; CGWB, 2013). Numerous scholars (Meijerink, 1974; Valdiya, 1980; Philip, 1995; Bartariya, 1995, 1996; Sati and Rautela, 1998; Chandel and Singh, 2000; Singh et al., 2001; Patel and Kumar, 2003; Singh et al., 2004; Thakur and Pandey, 2004; Thakur et al., 2007; Singh and Mondal, 2025) have conducted extensive research on the geology of the Doon Valley. The Doon Gravels, a Quaternary alluvial deposit made up of boulders, pebbles, gravel, sand, silt, and clay from the erosion of the Siwalik and Lesser Himalayan formations, cover the majority of the study area. Lithological heterogeneity, geomorphology, and structural features play a major role in determining the hydrogeological conditions of the region. The Jaunsar Group's quartzite, schist,

shale, slate, phyllite, sandstone, limestone, and dolomite are the main hard-rock formations. In these cemented formations, secondary porosity created by fissures, joints, fractures, and weathered zones is primarily responsible for groundwater occurrence (Bagchi et al., 2020; CGWB, 2023). As a result, both unconfined and confined groundwater are typically found in isolated and discontinuous aquifer systems (CGWB, 2013; Fetter, 2018).

The Doon Valley's unconsolidated alluvial deposits make up the region's most productive aquifer systems. Due to the high porosity and permeability of these deposits, substantial groundwater storage and transport are made possible. Deposited along river terraces, alluvial fans, and piedmont zones, fluvial and colluvial sediments create ideal groundwater-bearing horizons and are crucial recharge zones (Das and Gupta, 2021; CGWB, 2013). Through subterranean flow and infiltration, the Song River and its tributaries also aid in aquifer recharging. The study area's groundwater availability varies significantly because of variations in terrain, lithology, and recharge conditions. According to Bartariya (1995), Collins and Walling (2007), and CGWB (2013), springs and seepages are the main groundwater discharge features in hilly and structurally controlled terrains. There are about 70 gravity springs in the area, and their discharge rates range from less than 1 L/s to roughly 113 L/s (CGWB, 2011). The Upper Siwalik Formation's boulder-conglomerate units are extremely porous and permeable, yet in some places, the steep terrain limits groundwater retention by encouraging fast runoff (CGWB, 2013; Fetter, 2018). Detailed subsurface characterisation is required due to the aquifer system's heterogeneity and the growing abstraction of groundwater for agricultural and domestic uses. Therefore, defining aquifer geometry, measuring groundwater potential, and determining groundwater quality in the Sahaspur Block require an integrated geophysical, geochemical, and statistical methodology.

4. Methodology

4.1. Geophysical techniques

Due to their efficiency in defining subsurface lithology, aquifer geometry, and groundwater-bearing formations, electrical resistivity methods have been used extensively for groundwater exploration (Bhattacharya and Patra, 1968; Karanth, 1987; Telford et al., 1990; Sharma, 1997; Biswas and Sharma, 2013; Gautam and Biswas, 2016; Singh et al., 2021; Singh et al., 2025). Vertical Electrical Sounding (VES) is one of the resistivity techniques that works best for assessing aquifer characteristics and examining layered subsurface conditions (Sharma, 1997; Andrade, 2011; Vasudev et al., 2021). The Schlumberger electrode arrangement was used in the current investigation to measure 58 VES over the Sahaspur Block. This array was chosen for hydrogeological research due to its great depth of investigation, good vertical resolution, ease of operation, and appropriateness (Duraishwami, 2005; Nandi et al., 2015; Abdulameer et al., 2021; Cahyadi and Widodo, 2025). The survey was conducted by measuring the potential difference between two potential electrodes (M and N) after electrical current was injected into the ground through two current electrodes (A and B) (Telford et al., 1990; Sharma, 1997; Andrade, 2011).

The center point of the electrode array was maintained constant while progressively increasing the current electrode spacing ($AB/2$) from 1 m to 575 m, allowing the investigation of subsurface layers up to an approximate depth of 150 m. The apparent resistivity (ρ_a) was calculated using the Schlumberger array equation:

$$\rho_a = \pi \frac{(L/2)^2 - (b/2)^2}{b} \times \frac{V}{I} \quad (1)$$

Where L and b represent the current and potential electrode spacing, respectively.

To determine layer resistivities and thicknesses, the collected field data was processed and analyzed. Subsurface lithological units, groundwater-bearing horizons, and groundwater potential in the research area were all determined using the interpreted resistivity models. Differentiating between the weathered and saturated zones that make up the main aquifers in the Doon Gravel Formation was given special consideration.

4.2. Hydrogeochemical Investigation

The quality of the groundwater was evaluated and the geophysical interpretations were confirmed through hydrogeochemical analysis (Appelo and Postma, 2005). In September 2019, a total of thirteen groundwater samples were taken from springs, drilled wells, and hand pumps located throughout the study region (Figure 1). The principal hydrogeological units found in the geophysical study were represented by the sampling sites chosen. Water samples were taken using pre-cleaned containers in accordance with routine sampling procedures, and the methods suggested by APHA (2020) were followed for analysis. Electrical conductivity (EC) and pH were measured in the field using calibrated digital meters as soon as samples were collected (U.S. Geological Survey, 2021).

The empirical relationship (McNeil and Cox, 2000; Bairwa et al., 2024) was used to estimate total dissolved solids (TDS) from EC:

$$\text{TDS (mg/L)} = k \times \text{EC (}\mu\text{S/cm)} \quad (2)$$

where the constant k (sometimes called conversion factor) depends on water chemistry often in the range ~ 0.5 to ~ 0.9 for natural waters.

Major cations and anions were analyzed using standard laboratory methods. Calcium (Ca^{2+}), magnesium (Mg^{2+}), and bicarbonate (HCO_3^-) concentrations were determined by titrimetric techniques (Janardhana Raju et al., 2011; Khan et al., 2023), while sodium (Na^+) and potassium (K^+) were measured using flame photometry (Subramani et al., 2005; Khare and Kushwaha, 2025). Total hardness (TH) was calculated using the following relationship (Todd, 1980; El Alaouy et al., 2022):

$$\text{Total Hardness (TH)} = 2.5 \times [\text{Ca}^{2+}] + 4.1 \times [\text{Mg}^{2+}] \text{ (as mg/L CaCO}_3\text{)} \quad (3)$$

where the concentration of ions is in milligrams per liter.

4.3. Integrated Geophysical–Geochemical Analysis

The geophysical and hydrogeochemical data were combined using statistical correlation analysis to enhance aquifer characterisation. Groundwater electrical conductivity readings from adjacent sampling sites were compared with aquifer resistivity values obtained from the VES interpretations. Groundwater quality was assessed, interpreted resistivity models were validated, and freshwater-bearing aquifers were distinguished from zones with comparatively higher mineralization using the link between resistivity and EC. Compared to each strategy used separately, this integrated approach produced a more accurate evaluation of groundwater potential and quality.

5. Results and Discussion

5.1. Geophysical data

5.1.1. Interpretation of Geoelectrical Data

The Schlumberger electrode design with a maximum current electrode spacing ($AB/2$) of 575 m was used for 58 Vertical Electrical Sounding (VES) measurements. The model parameters were optimized through iterative inversion until the root mean square (RMS) error was typically less than 5%, indicating good agreement between observed and calculated apparent resistivity values (Javed, U., et. al., 2024; Kamaraj and Karuppannan, 2024; Syaputri, T. D., et. al., 2024, Beabu G. Menegbo., et. al., 2024; Ibuot et al., 2025; Somvir Singh and Mondal, N.C., 2025; Olisah Nzemeka C., et. al., 2025). The one-dimensional inversion software IX1D v3.1 was used to interpret the field data. A diverse multilayered subsurface system made up of topsoil, clay, sandy clay, gravels, pebbles, cobbles, boulders, and saturated alluvial deposits is revealed by the interpreted resistivity models. The subsurface succession is depicted by four to nine geoelectrical layers with primarily K-, H-, HKH-, and KHKH-type curves based on the inversion data (Figure 2). Significant lateral and vertical differences in groundwater occurrence and lithology throughout the research area are reflected in these curve types. Table 1 summarizes the generalized resistivity ranges together with the appropriate lithological inferences and a summary of all the VES data interpretation conducted at Sahaspur block in the Dehradun district is presented in Table 2. While saturated gravel, sand, pebble, and cobble formations are typically associated with intermediate resistivity levels (10–100 Ω -m), very low resistivity values (<10 Ω -m) are linked to clay-rich horizons. Compact boulder formations, dry gravels, and unsaturated coarse sediments are represented by higher resistivity values (>200 Ω -m).

Table 1 Resistivity and Lithounits.

Serial No.	Resistivity (Ω -m)	Inferred Lithounits
1	0-10	Clay
2	10-50	Cobbles, pebbles, gravel, sand, and clay
3	50-100	Gravels and sand with a thin clay layer
4	100-200	Cobbles, pebbles, and sandy clay
5	200-300	Sandy clay with cobbles, pebbles, and gravels
6	300-400	Boulders, pebbles, and sandy clay
7	>500	Dry boulder formation with clay

The topmost layer is mostly composed of weathered boulders, sandy clay, and topsoil with thicknesses ranging from 0.1 to 2.8 m and resistivity values between around 200 and 2000 Ω -m. The Doon Gravel Formation's varied depositional history is reflected in the alternate sequences of clay, gravel, cobbles, pebbles, and boulders found beneath this layer. These layers exhibit significant geographical heterogeneity as a result of differences in moisture content, compaction, and grain size distribution. The fifth through ninth geoelectrical layers were found to contain the most important groundwater-bearing formations. Resistivity values in these layers range from 12.7 to 262.6 Ω -m, with an average aquifer resistivity of roughly 79.7 Ω -m. Saturated cobbles, pebbles, gravels, coarse sand, and sandy clay

deposits make up these lithological units. Aquifer thicknesses range from 11.0 to 79.6 meters, with an average of about 33.2 m. The piedmont deposits contain moderately deep to deep groundwater systems, as shown by the depths of the primary aquifer horizons, which range from 18.2 to 178.8 m.

Significant lateral differences in underlying materials are visible throughout the Sahaspur Block in the inferred lithological columns obtained from VES inversion (Figure 3a). Highly resistant boulder and cobble formations predominate in the northern and northeastern regions, while saturated gravelly and sandy deposits are linked to comparatively lower resistivity zones in the centre and southern regions. The Doon Valley's depositional environment, where sediments carried from the Siwalik and Lesser Himalaya ranges have created intricate piedmont and alluvial fan sequences, is compatible with these differences. Aquifer continuity and subsurface variability are comprehensively visualized in the three-dimensional lithological model (Figure 3b). Multiple aquifer strata interbedded with clay and sandy-clay layers are seen in the model. The observed heterogeneity in groundwater occurrence across the research area can be explained by such multilayered aquifer systems, which are typical of piedmont environments. The 3D model also shows that laterally extensive gravel-sand-pebble units with moderate resistivity values are primarily linked to productive aquifers. These formations are significant groundwater reservoirs due to their advantageous porosity and permeability properties. On the other hand, clay-rich layers restrict groundwater circulation locally and serve as aquitards.

The Sahaspur Block appears to have generally favourable groundwater potential based on the integrated interpretation of resistivity and lithological data. Several VES locations include thick, saturated gravelly deposits that show good transmissivity and a high capacity for storing groundwater. The most suitable groundwater zones are those with notable aquifer thicknesses and moderate resistivity values (about 20–150 Ω -m). The Doon Gravel Formation's significant groundwater-storage capacity is shown in the presence of deep, laterally continuous aquifers. Groundwater replenishment is mostly dependent on permeable alluvial deposits, infiltration from the Song River system, and recharge from monsoonal rainfall. These results support the ongoing development of groundwater resources in the area as long as extraction is sustainable and are in line with the hydrogeological framework published by CGWB (2013, 2023). The geoelectrical findings provide a solid foundation for the hydrogeochemical validation and integrated groundwater quality evaluation that follow. The determined aquifer zones serve as the foundation for establishing a relationship between aquifer resistivity and groundwater electrical conductivity as well as assessing the groundwater's suitability for residential, irrigation, and drinking uses.

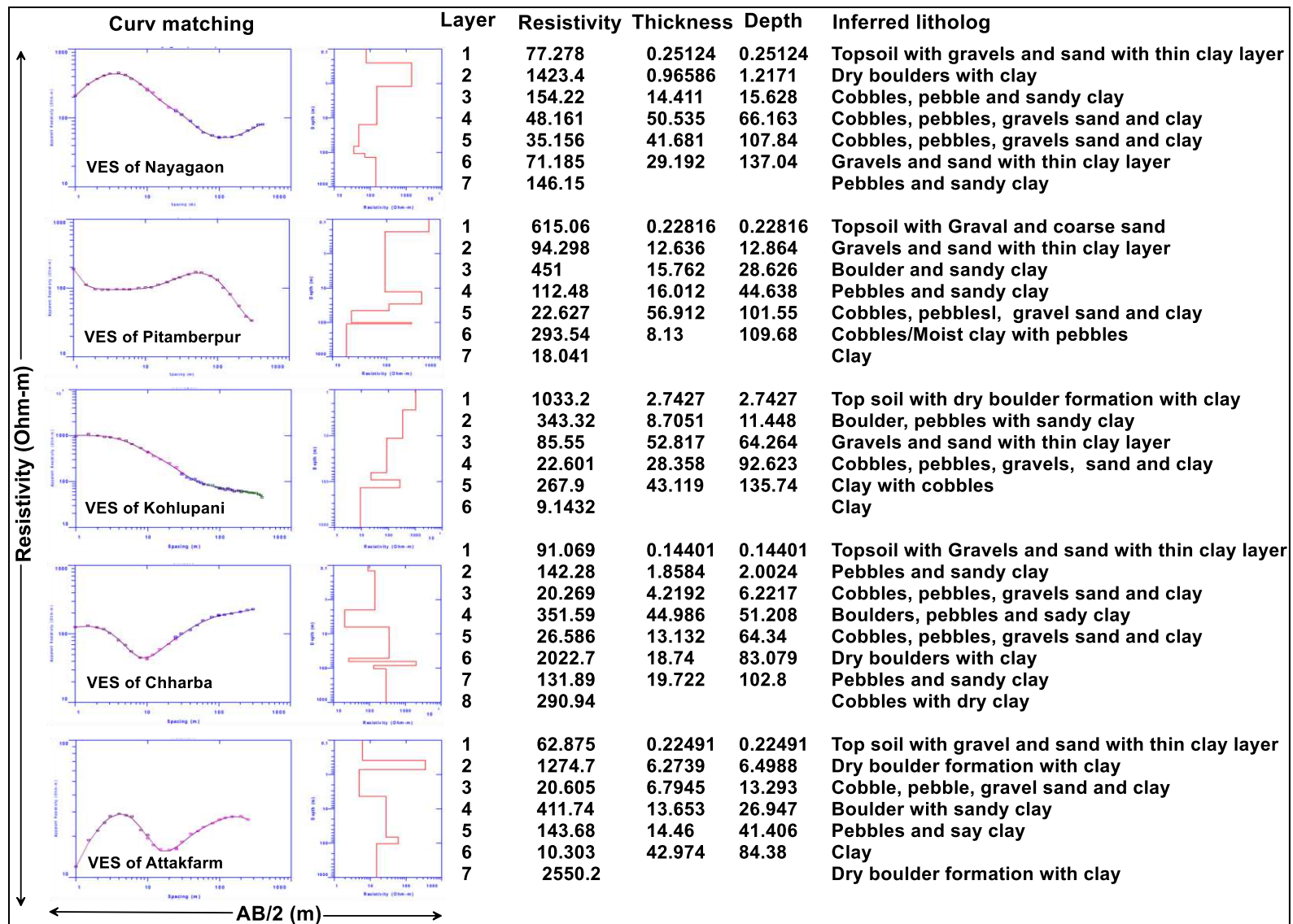


Fig. 2 Some VES data correlated with the interpreted layer model

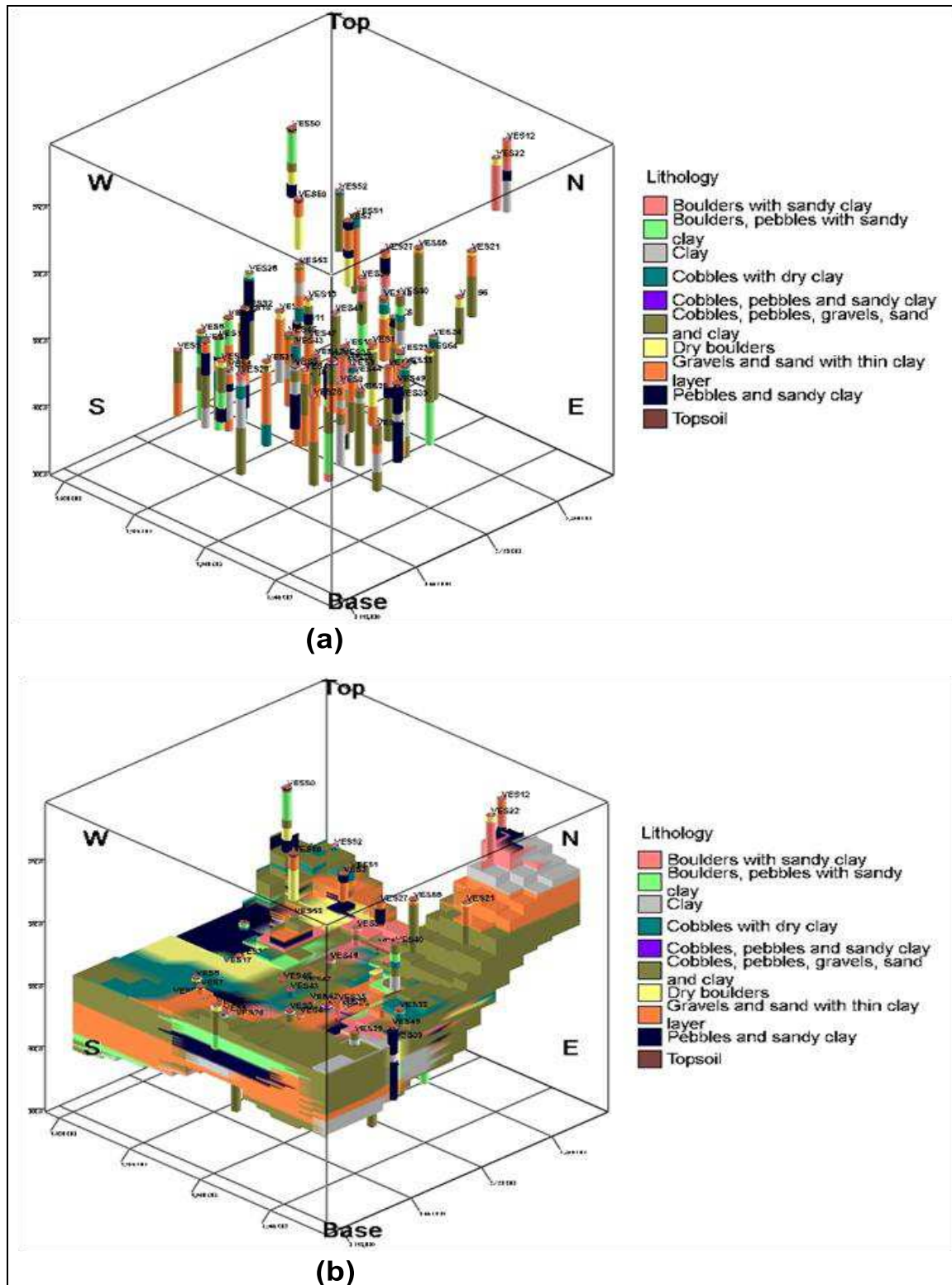
Table 2 Summary of interpreted resistivity data

VES No.	Resistivity of the layers in (Ω -m)									Thickness of the layers (m)								Aquifer Resistivity (Ω -m)	Aquifer thickness (m)	Total Depth (m)	AB/2 (m)	Error (%)	Types of curves
	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	962	66.17	109	29.3	641.6	31.46	408.6	132.8		0.679	0.32	12.55	11.46	20.36	35.3	23.2		31.46	35.32	45.36	300	3.15	HKHK
VES2	283	36.57	255	66.7	102.1	2070	25.45			1.147	0.38	11.21	29.9	12.02	42.7			102.07	12.02	42.65	300	2.43	HKHK
VES3	188	17.38	40	7.66	234	112.4	2.283			1.54	3.7	16.81	18.89	26.1	25.9			112.42	25.90	92.93	300	2.78	KHKH
VES4	114	1051	71	38.1	79.84	24.92				0.33	1.49	16.41	46.89	47.31				58.95	47.10	18.24	300	2.47	KHKH
VES5	486	1293	217	360	27.21	372.2	39.32			1.273	3.9	27.05	19.88	35.37	43.7			27.21	35.37	52.11	400	3.17	KHKHA
VES6	88.7	8.828	244	7.89	646.3	124.8	9.264	64.2	24.3	1.539	0.46	1.48	4.403	14.13	11	41.8	13	64.20	13.43	74.84	400	2.15	KHKHK
VES7	1164	17684	55.9	232	47.92	28.03	10.84	3050		1.987	1.38	12.96	33.32	21.13	28	30.25		37.97	24.56	49.65	400	4.65	HKHKH
VES8	257	1165	75	13.4	91.07	168.3	6.541	894.8		0.493	0.95	20.91	12.43	9.13	15.7	62.11		168.30	15.71	43.92	400	3.3	KHKH
VES9	4.2	212.9	10.6	81.2	16.77	25.69	1.488			0.832	6.45	11.59	32.72	30.82	13.1			21.23	21.95	51.60	300	3.42	KHKH
VES10	281	96.65	1341	21.4	14481	50.87	550.5			0.957	5.49	4.698	52.06	29.93	28.3			50.87	28.26	93.13	400	4.07	HKHA
VES11	485	149.1	68.3	478	28.83	485	516.4	3.508		0.28	7.7	5.128	6.76	13.47	20.3	24.04					300	2.80	HKHK
VES12	79.7	365.2	90.6	493	133.5	10.13	2099			0.106	3.51	26.44	13.88	15.42	47.1						350	4.49	KHKH
VES13	322	918.7	29.3	132	31.15	113.7	14.7	61.98		0.991	8.42	11.93	16.24	32.23	37.8	21.87		72.43	35.02	37.59	400	2.9	KHKH
VES14	2501	138	1102	99.2	8.64	137.4				0.163	0.21	0.475	9.479	60.21	35.8			137.42			300	3.65	KHKH
VES15	474	1985	45.1	18.5	308.9	112.1	4.147			0.374	7.82	19.83	18.02	23.81	20.2			112.05	20.23	69.86	300	3.94	KHKH
VES16	200	598.9	376	149	55.33	298.4	20.57	329	116	1.198	5.47	20.01	6.128	16.05	28.2	45.16	15	20.57	45.16	77.08	400	3.00	KHKH
VES17	473	10149	320	50.4	316.8	19.9	445.4	240.4		2.209	1.52	36.08	29.94	44.29	44	11.13		19.90	43.95	114.04	475	40.04	HKHK
VES18	2280	528.8	955	92	243.5	10.13	210.3	3577		1.26	0.56	13.14	53.05	37.57	34.5	20		210.29	20.00	140.11	470	3.81	KHKH
VES19	224	38.91	243	19.9	213.6	23.37	99.24	28.61	360	0.661	0.42	0.604	1.603	2.894	7.88	59.56	80	28.61	79.61	73.61	470	2.99	KHKH
VES20	119	455.3	10.8	218	10.13	196.3	9.272			0.856	8.39	7.731	19.01	43.87	69.9			196.34	69.91	79.86	470	3.2	KHKH

VES21	182	594	1028	97.8	58.76	185.2	49.84			1.101	0.12	3.553	31.74	25.62	35.4			58.76	25.62	36.52	390	2.26	КНKH
VES22	216	1517	418	546	98.22					0.718	8.95	34.59	33.84					98.22		78.10	300	2.91	КНKH
VES23	1033	343.3	85.6	22.6	267.9	9.143				2.743	8.71	52.82	28.36	43.12				145.25	35.74	64.26	390	3.6	КНKHА
VES24	381	1427	277	38.6	153.7	54.23				0.215	0.82	15	37.98	38.9				153.71	38.90	54.02	375	2.5	КНKH
VES25	823	2436	481	34.5	437.6	22.54	398.6	11.79		0.647	1.1	8.182	8.559	15.02	34.3	50.07		22.54	34.27	33.50	375	3.48	КНKHК
VES26	209	350.6	220	115	16.27	132.9				0.57	5.54	4.352	60.04	52.23				16.27	52.23	70.50	375	2.07	КНKH
VES27	293	39.8	670	110	567	10.81	154	4775		0.822	0.23	8.266	23.58	18.93	32.7	22.32		154.02	22.32	84.49	375	1.68	HKHKH
VES28	225	88.31	77.5	28.5	8441					0.821	14.8	50.86	65.6					28.51	65.60	66.50	350	2.31	HKHA
VES29	131	25.62	192	7.35	40.99	50.8				0.49	5.15	3.848	8.102	93.57				50.80		111.1 6	300	1.52	HKHA
VES30	167	1471	155	63.7	92.74	77.38	59.78			0.101	2.76	11.42	22.72	28.56	36.8			77.38	36.81	65.56	400	3.56	КНKH
VES31	528	900	203	1875	66.98	556.7	262.6	2.367		0.742	4.15	2.506	6.489	38.66	41.1	31.6		262.63	31.60	93.63	400	2.67	КНKH
VES32	255	1358	202	117	68.22	146.5	77.42			1.007	1.3	26	46.11	39.1	35			146.50	35.00	113.5 1	400	3.11	КНKH
VES33	244	174.4	13.3	287	180.2	13.55	43.4	9039		0.853	3.43	1.534	11.49	50.63	37.5	31.74		43.40	31.74	105.4 8	400	1.59	HKHA
VES34	615	94.3	451	112	22.63	293.5	18.04			0.228	12.6	15.76	16.01	56.91	8.13			18.04		109.6 8	300	2.22	HKHA
VES35	276	4444	629	325	20.5	450.7	228.4	3.978		0.387	0.43	6.839	40.41	26.23	40.9	20.43		228.37	20.43	115.1 4	400	4.9	КНKH
VES36	380	2162 2	7.55	670	521	275.5	76.64			1.02	0.99	2.86	17.28	21.38	22.1			76.64		65.65	300	2.7	КНKH
VES37	77.2	220	1464	136	380.2	32.83	311.2	435.6	37.4	0.104	2.83	0.893	43.64	11.53	39.6	61.66	11	37.36		170.7 8	400	3.20	КНKH
VES38	268	166.1	21.8	35.3	69.43	18.53	27.4	135.1		0.536	3.53	12.82	7.268	13.03	28.7	27.74		135.08		93.63	300	2.79	КНKH
VES39	6.91	236.2	9.19	5240	787.7	336.5	86.28	15.66		0.645	1.47	3.216	19.07	17.55	22.1	25.02		15.66		89.07	300	2.67	КНKH
VES40	3.16	37.12	364	232	42.48	7.303	1.493			0.155	14.2	12.57	10.28	13.47	22.1			42.48	13.47	37.22	300	2.3	КНKH
VES41	11.9	1643	171	23.6	82.67	16.89				0.688	2.34	3.079	28.59	42.33				16.89		77.02	300	4.1	КНKH
VES42	130	32.32	416	26	150.9	64.22	12.69			0.962	0.41	1.37	3.326	35.65	32.8			12.69		74.52	300	2.85	HKHK
VES43	9.22	246.7	31	22.4	112.1	20.26	5.809	894		0.714	23.8	0.12	4.77	7.808	13.4	47.96		20.26	13.43	37.23	250	4.95	КНKH

VES44	1048	826.2	11.1	452	24.62	90.71				0.428	8.78	0.701	5.833	21.23	31.1			90.71	31.07	36.97	250	4.55	HKHK
VES45	114	278.4	193	66.3	3.516	68.68	2.275			0.141	1.18	6.446	35.77	21.76	41.4			68.68	41.40	65.31	300	3.77	HKHK
VES46	6.11	346.8	4.94	27.9	60.68	15.07				0.387	0.34	3.6	62.64	36.63				15.07		103.59	250	2.28	KHKH
VES47	45.3	78.52	61.3	200	45.45					0.4	2.71	44.15	51.55					45.45		98.81	300	1.36	KHKH
VES48	251	38.93	165	3.59	204.7	25305	13.17	2892		1.036	2.36	3.649	1.407	14.73	7.37	62.7		13.17	62.70	30.55	300	3.07	HKHA
VES49	377	846.5	127	5.74	131	108.3	35.63			2.679	0.8	41.47	11.61	31.72	29.6			108.32	29.63	88.27	400	2.85	KHKH
VES50	91.1	142.3	20.3	352	26.59	2023	131.9	290.9		0.144	1.86	4.219	44.99	13.13	18.7	19.72		131.89	19.72	83.08	300	2.76	KHKHA
VES51	46	5783	289	58.8	164.1	38.51				0.162	0.27	16.45	76.74	21.89				38.51		115.51	300	2.49	KHKH
VES52	79.3	3131	244	29.9	191.7	10.13				0.182	0.31	5.242	65.32	18.81				191.71	18.81	89.86	300	3.11	KHKH
VES53	113	307.8	171	58	17.1	99.03	232.1	14.33		0.133	1.73	4.756	18.76	19.04	18.9	20.57		14.33		83.86	250	3.38	KHKH
VES54	411	75.38	570	23.2	276.9	32.5	371.6	19.12		0.916	0.12	5.077	5.366	19.59	45.2	63.47		19.12		139.75	400	1.99	HKHKHK
VES55	316	37.56	681	69.1	190	33.55	2186			0.61	1.98	1.492	4.169	83.37	24.4			33.55	24.42	91.62	400	3.2	HKHK
VES56	2063	21078	713	175	91.09					0.445	2.31	11.51	54.5					91.09		68.77	200	2.85	KHKH
VES57	855	128.2	97.8	80.5	69.83	28637				1.439	45.6	29.23	9.746	11				69.83	11.00	86.01	250	2.4	HKHA
VES58	293	55.57	1728	4170	6056	91212				4.212	21	12.93	9.902	25.71							200	4.11	KHKHA

1
2



3

4 **Fig.3 (a)** Lithology map based on VES data of the study **(b)** 3-D Resistivity lithological model.

5.1.2. Correlation between VES and Borehole data

The resistivity fence diagram was created using VES data to provide a more accurate resistivity picture of the area's subsoil (Figure 4a). Moreover, a lithological fence diagram was prepared from the borehole data (Figure 4b). The inverted resistivity fence diagram depicts the vertical resistivity distribution inside a certain earth volume. (Keller and Frischknecht, 1966; Mukhtar et al., 2000; Griffiths and Barker, 1993; Singh et al., 2002, Kamaraj, P., & Karuppanan, S., 2024), Moreover, the lithological fence diagram shows the actual lithology of the study area. The resistivity range in the study area is from 1.48 Ω -m to 91121 Ω -m with an average value of 1179.85 Ω -m and the minimum resistivity value at VES9 near Keshowala village and maximum resistivity value at VES58 near Guchhupani. Figure 4(a) shows that the north-west part of the study area (VES58) has high resistivity values (200–500 Ω -m) with dry boulders, pebbles, and sandy clay and gravels and has a more compact geological formation. This type of geological formation of the study area is not a suitable groundwater-promising zone. The north-east part of the study area shows the formation of boulders, pebbles, cobbles, gravel, and sandy clay with a medium to high resistivity range (100–400 Ω -m). This type of geological formation has good groundwater-promising zones. In the south-west and south-east parts of the study area, the geological formation of coarse sand with gravels, pebbles, cobbles, boulders, and clay with resistivity ranges from 50–200 Ω -m. This formation is more favorable for groundwater zones than other geological formations in the study area. From Figure 4(b), the lithological fence diagram clearly shows that the north-west part of the study area occurred gravels with boulders, cobbles, pebbles, and clay, whereas the north-east part shows the geological formation of boulders with pebbles, cobbles, and clay. The south-west part occurs bajri with boulders, cobbles, gravels, pebbles, and coarse sand, and the SE part of the study area occurs boulders with bajri, gravels, pebbles, cobbles, and sandy clay.

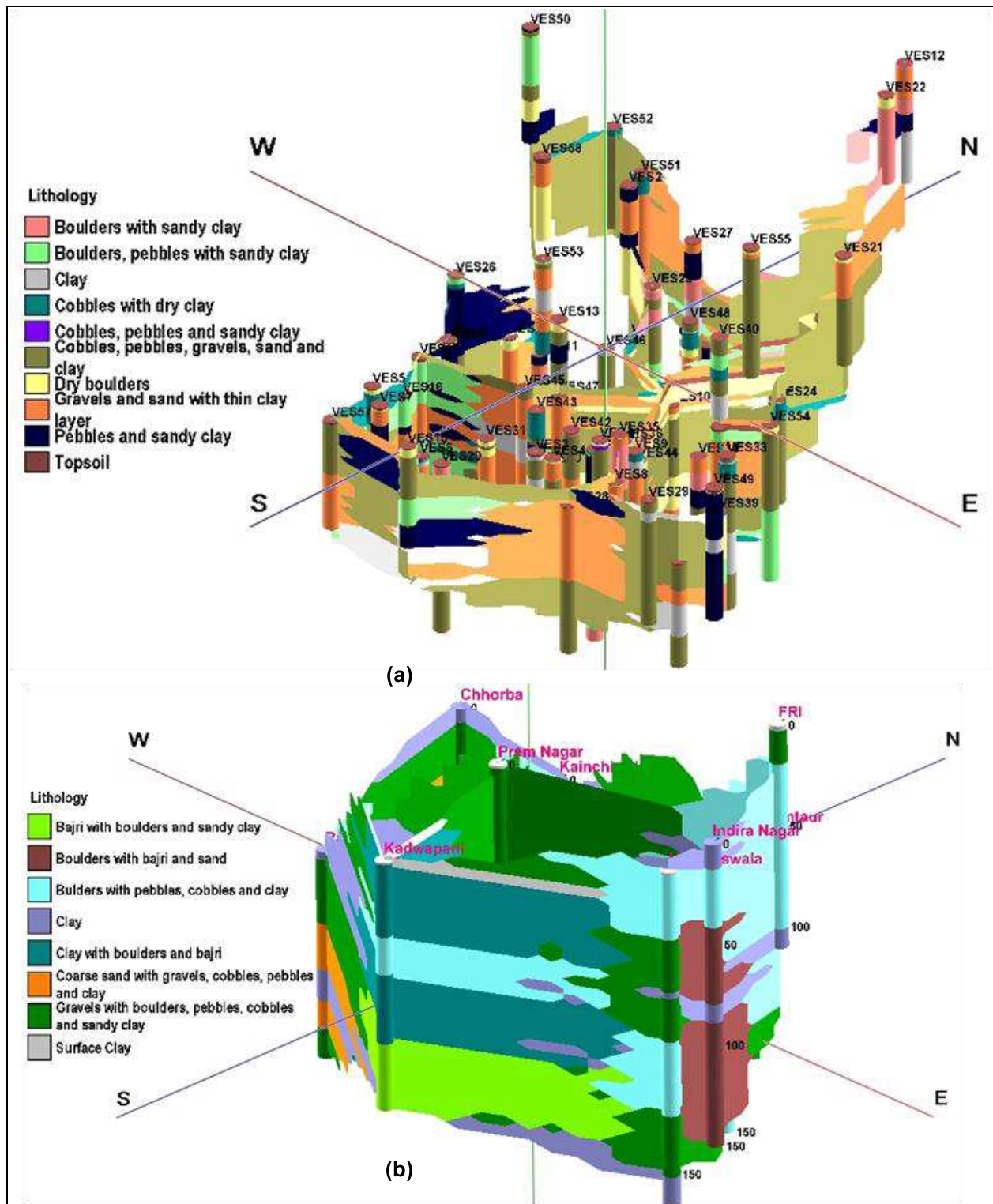


Fig. 4(a) Fence diagram based on VES data and **(b)** Lithological fence diagram of the study area.

5.1.3. Aquifer resistivity, thickness and total depth of the study area

Interpreting the results of these 58 VES surveys, the resistivity subsurface of different layers was inferred. These layers were shown as contours and 3-D representations. Because the VES sites were scattered geographically and arbitrarily over the study area, multiple gridding methods were explored, and the cross-validation methodology was used to obtain reliable findings and a near estimate of input data with output contours and 3-D views. The kriging method was superior to all other gridding approaches for this data (Kebede, H., et. al., 2024, Nugraha, G. U., et. al., 2025). The aquifer resistivity and their water-bearing characteristics, a special variation of the contour map on groundwater lithological formation, have been prepared and shown in figure 5 (a). The comparative analysis has been made using the VES data of 55 locations out of 58 VES locations where the groundwater promising potential zone is in the study area. An examination of this aquifer resistivity map reveals that aquifer resistivity Varies from 12.69 to 262.63 Ω -m, with an average aquifer resistivity value of 79.65 Ω -m in the study area. The resistivity ranges from 10 to 50 Ω -m of groundwater promising formation comprising cobbles, pebbles, gravels, sand, and clay have been seen at VES1, 5, 7, 9, 16, 17, 19, 25, 26, 28, 33, 34, 37, 39...43, 46–48, 51, 53, 54, and VES55, respectively. In these sounding locations, 43.10% of groundwater occurred in the study area. The sounding locations VES4, 6, 10, 13, 21, 28...30, 36, 44, 45, 56 and VES57 have a 22.41% groundwater-promising formation with gravels and sand with a thin clay layer where the resistivity ranges from 50–100 Ω -m. The sounding locations VES2, 3, 8, 14, 15, 20, 23, 24, 27, 32, 38, 49, 50 and VES52 have a 24.13% Groundwater promising formation with cobbles, pebbles, and sandy clay with a resistivity range from 100 to 200 Ω -m. Finally, locations VES18, 31 and VES35 have 5.17% Groundwater promising formation comprising of dry clay with cobbles with resistivity range from 200 to 300 Ω -m.

The variation in resistivity is mostly attributed to variations in geological formations and hydrogeological conditions (George, N. J., 2025, Mohammed, M. A. A., et. al., 2024). The corresponding contour map and a 3-D view of the aquifer resistivities and thickness from the ground surface of the study area are shown in figure 5 (b) & 5 (d). There is one peak resistivity value in the northwest part, two high in the southeast, and two small peak resistivity values in the northwest part of the study area. These can be shown in 3-D views (Figure 5 b), which are also clearly identified in the contour map of the study area. These observations clearly show in figures 5 (a) and 5(b) that the rest area has a few more variations in the resistivity values. The resistivity of the groundwater aquifer system is not constant, and it is changing due to its hydrogeological formation and conditions. The soil type observed in the work was predominantly loam with varied percentages of sand.

The thickness in the study area varies from 11.0 m to 79.6 m, with an average value of 33.2 m. The minimum thickness is at VES57, which is near Saket colony, and the maximum thickness is at VES19, which is near Tiperpur. The aquifer thickness (h) line varies from 10-20m at locations VES2, 6, 8, 18, 40, 43, 50, 52 & VES57, which are in the North-East & South-East parts of the study area. The map shows that the aquifer thickness > 50m is located at VES 19, 20, 26, 28 & VES48, which lies in the North-East of the study area. The aquifer thickness ranging from 20-30 m is found at ten locations at VES 3, 7, 9, 10, 15, 21, 27, 35, 49 and VES55, while VES locations of VES1, 5, 13, 23, 25, 30, 31, 32, 33 and VES44 have aquifer thickness from 30-40m. Similarly, aquifers at VES locations VES4, 16, 17, 24 and VES44 have thicknesses between 40-50m. So, a higher thickness gradient is interpreted in the south-east to north-west direction compared to other parts of the study area (Fig. 5c).

In the 3-D view of aquifer thickness (Figure 5 d), it can be seen that there is one high peak in the middle part, two peaks in the southeast part, and two small peaks in the northwest part of the study area. It clearly shows that the higher the thickness of the aquifer, the greater the groundwater potential zone. In the present study, the good groundwater promising potential zones formation comprising cobbles, pebbles, gravels, sand, and clay with resistivity range of 10 Ω -m to 50 Ω -m in the middle part, south-east and some part of the north-west of the study area. The rest of the study area is a medium to low groundwater potential zone based on electrical resistivity interpretation.

The depth of the aquifer of the study area has been prepared with a contour interval of 10 meters (Figure 5e). In the study area, the aquifer depth ranges from 18.3 m to 170.8 m with an average depth of 78.2 m, which are the minimum depth at VES4 near the village of Jhevareddi and the maximum at VES37 near the village of Ummedpur. It is demarcated that the deeper aquifer depth is in the study area's East, West, and South-East parts. Figure 5(f) shows a 3-D representation of aquifer depth, which shows three high peaks in the East, West, and South-East parts. There are four small peaks in the South-East, Middle, and North-West parts, which is the deeper aquifer depth. The shallow aquifer depth towards North-East to South-West and North-West to South-West part. The southeast part is the shallowest in the study area, and the rest is medium aquifer depth to low/shallow aquifer depth towards the north and southwest.

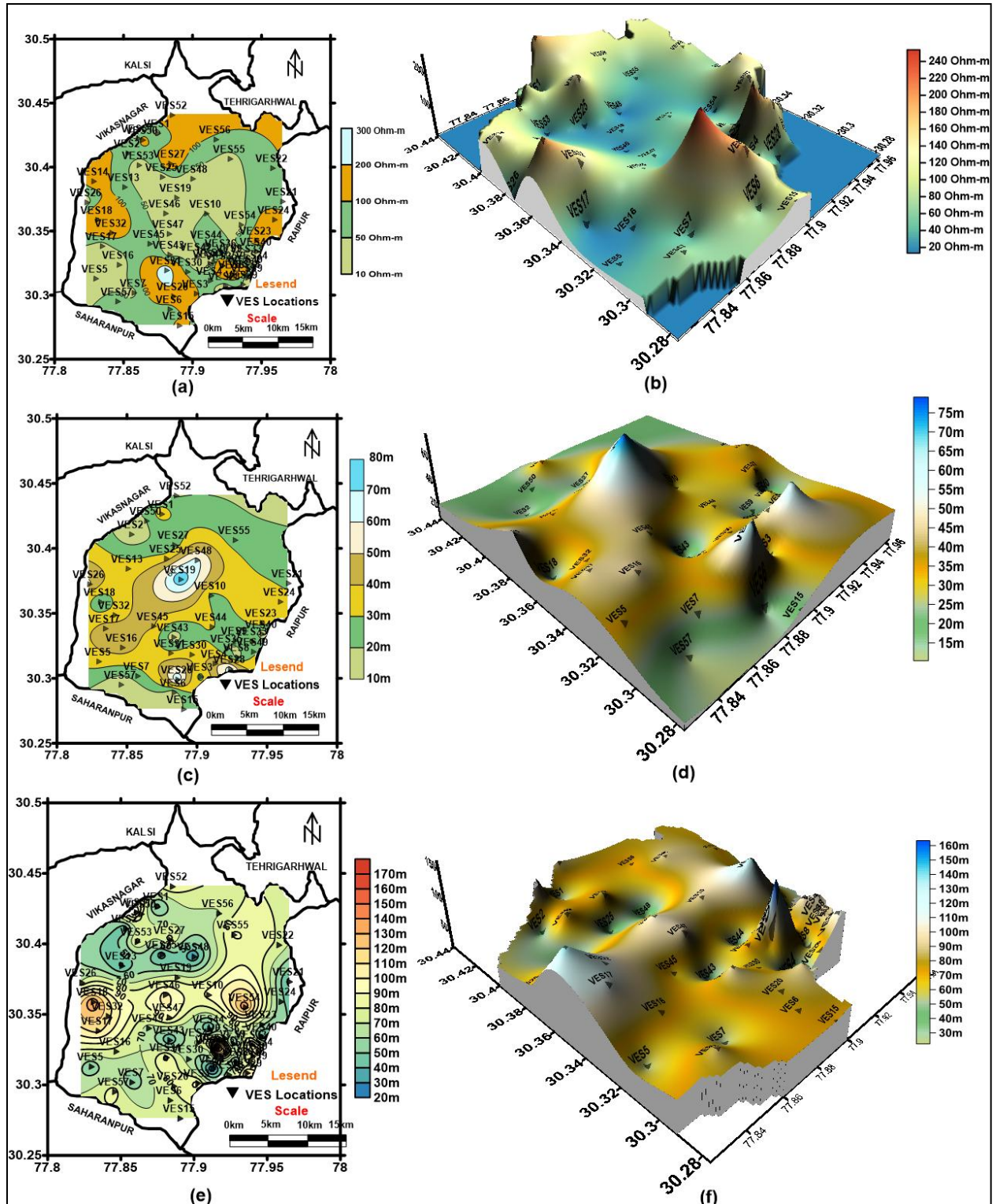


Fig. 5 (a) Contour map of aquifer resistivity (b) A 3-D representation of Aquifer Resistivity (c) Contour map of aquifer thickness (d) A 3-D representation of aquifer thickness (e) Contour map of aquifer depth and (f) A 3-D representation of aquifer depth along with VES positions in the study area.

5. 2. Hydrogeochemical data

5.2.1. Analysis of Geochemical data

The analyzed values of Cl^- , Na^+ , Ca^{2+} , Mg^{2+} , SO_4^{2-} , NO_3^- , TDS, EC, and SiO_2 other parameters are compared with WHO standards (Janardhana Raju et al., 2011). The pH of the groundwater in the study area ranges from 6.90 to 7.98, with an average value of 7.41. TDS of the water samples was found to be 41 to 422, with an average value of 232. The EC ranges from 65 to 659, with an average of 420. Table 3 summarizes the hydrochemical parameters for the investigated groundwater samples ($N = 13$) from the study area. Comparison of hydrochemical data with drinking water standards (WHO, 2020) showed that about 7.72% ($N = 1$), 23.38% ($N = 3$) and 15.38% ($N = 2$) of the samples exceeded the guideline values for Calcium (Ca^{2+} , 75 mg/l), Magnesium (Mg^{2+} , 30 mg/l) and Total Hardness (CaCO_3 , 300 mg/l), respectively. This showed an important water quality decline in the study area. The ranges of Ca^{2+} , Mg^{2+} , and TH ions are 2 to 86 mg/l (mean, 31.0 mg/l), 1 to 49 mg/l (mean, 17 mg/l), and 22 to 311 mg/l (mean, 143 mg/l), respectively. Such solute concentration ranges showed that a number of complicated hydrochemical processes produced the chemical composition of groundwater. The high Ca^{2+} concentrations is observed at observation wells at SP3 (= 86 mg/l) nearby Ramgarh, Mg^{2+} concentrations at SP1 (=37 mg/l) nearby Singhniwala, SP2 (=49 mg/l) nearby Badowala & SP13 (=35 mg/l) nearby Telpur and TH concentrations at SP2 (=311 mg/l) nearby Badowala & SP3 (=310 mg/l) nearby Ramgarh. This also echoes significant groundwater degradation due to the intermixing of rock materials. The physical and chemical characteristics of groundwater analysis findings and the drinking water quality were compared to the standard guideline levels recommended by the WHO (2020) for consumption and community health standards.

Table 3 Physico-chemical parameters of the study area

Sample No.	Location	pH	EC	TDS	Na^+	K^+	Ca^{2+}	Mg^{2+}	TH	HCO_3^-	Cl^-	SO_4^{2-}	F^-	NO_3^-	SiO_2
SP1	Singhniwala	7.91	588	376.32	9	1.4	48	37	273	256	14	47	0.01	20	9.7
SP2	Badowala	7.56	658	421.12	8	1.0	43	49	311	244	21	78	0.08	22	7.7
SP3	Ramgarh	7.81	659	421.76	9	1.2	86	23	310	238	21	86	0.12	18	10.5
SP4	Jhajra	7.98	325	208	9	1.2	43	9	143	146	21	6	0.08	7	9.3
SP5	Nanda ki Chowki	7.26	315	201.6	26	6.0	10	17	94	143	21	8	0.01	3	5.4
SP6	Khandoli	7.52	65	41.6	5	0.1	2	4	22	31	4	3	0.09	0.01	13.0
SP7	Selakui	7.2	188	120.32	12	1.0	20	4	66	57	14	18	0.01	11	12.2
SP8	Sabhawala	7.12	360	230.4	16	10.1	24	17	133	122	21	23	0.09	34	7.9
SP9	Rampura	7.43	190	121.6	10	1.0	19	6	73	73	7	22	0.01	2	10.1
SP10	Shankarpur	6.91	143	91.52	10	0.8	10	6	50	63	7	9	0.07	2	12.4
SP11	Redapur	7.06	107	68.48	11	0.7	10	1	29	44	7	3	0.08	5	17.3
SP12	Chhorba	7.23	106	67.84	11	0.7	10	1	28	46	7	5	0.01	1	8.1
SP13	Telpura	7.29	589	376.96	9	1.0	52	35	275	231	14	68	0.01	18	7.7

Table 4 shows the most required and maximum tolerable limits of various parameters. The groundwater classification based on total hardness (TH) shows that most groundwater samples fall in the soft water category, and the remaining samples fall in the moderately hard to very hard water category. The hardness of the analyzed samples ranges from 22 to 311 mg/l with an average value of 143 mg/l, and the hardness values are given in Table 5. Six samples were found to be soft, and three water samples were moderately hard within the allowable hardness limit. 15.38% of water samples under the hard water category and 15.38% of the samples exceed the maximum permissible limit of 300 mg/l, which indicates that the groundwater from the study area is unsuitable for drinking. The presence of calcium and magnesium in abundance may contribute to groundwater hardness. Water hardness can hinder soap lather development and raise the boiling point of water, although it has no known long-term harmful effects on human health.

Table 4 Summary statistics of the analytical data indicated by WHO (2020) and BIS (2020).

S. No.	Parameters	Minimum	Maximum	Mean	SD	Permissible Limits mg/l (BIS 20202) and (WHO 2020) (mg/l)	Numbers of samples exceeding allowable limits	Percentage of samples exceeding allowable limits
1	pH	6.91	7.98	7.44	0.76	6.5-8.5	Nil	Nil
2	EC	65	659	362	420.02	750	Nil	Nil
3	TDS	41.6	421.76	231.68	268.81	500	Nil	Nil
4	Na ⁺	5	26	15.495	14.84	200	Nil	Nil
5	K ⁺	0.1	10.1	5.095	7.06	25	Nil	Nil
6	Ca ²⁺	2	86	43.8	59.11	75	1	7.72
7	Mg ²⁺	1	49	24.96	33.94	30	3	23.07
8	TH	22	311	166.25	204.71	300	2	15.38
9	HCO ₃ ⁻	31	256	143.04	159.16	600	Nil	Nil
10	Cl ⁻	4	21	12.40	12.53	250	Nil	Nil
11	SO ₄ ²⁻	3	86	44.5	58.69	200	Nil	Nil
12	F ⁻	0.01	0.12	0.065	0.08	1.5	Nil	Nil
13	NO ₃ ⁻	0.01	34.46	17.23	24.36	45	Nil	Nil
14	SiO ₂	5.4	17.3	11.37	8.44	120	NIL	Nil

pH:-log₁₀H⁺ at 25°C; EC in μS/cm, All Ions inmg/l; samples were collected on September 2019; SD standard deviation; TH total hardness as CaCO₃.

Long-term intake of very hard water, on the other hand, may increase the frequency of health issues and induce encrustation in water supply distribution systems (Agrawal and Jagetia, 1997).

Table 5 Groundwater classification based on Total Hardness.

Total Hardness (mg/l)	Types of water	Sample numbers	Number of samples	Percent of samples
<75	Soft	SP6, 7, 9, 10, 11 and SP12	6	46.15
75-150	Moderately Hard	SP4, 5, and SP8	3	23.08
150-300	Hard	SP1 and SP13	2	15.38
>300	Very hard	SP2 and SP3	2	15.38
Total			13	100

From figures 6 (a), (b), and (c), a comparative representation of EC, TDS, and TH clearly shows the fluctuation in the study area. The EC, TDS, and hardness of the water gradually increased from the North part to the South part with a gentle sloping, and the maximum was found at SP3, which is near Badowala village, and the minimum was found at SP6, which is near Khandoli village. In the present study, 46.15% of water samples is soft type of SP6, 7, 9, 10, 11, and SP-12, about 23.08% of water samples is moderately hard of SP4, 5, SP8, around 15.38% of water samples is hard type water of SP1 & SP13, and 15.38% of water samples of SP2 & SP3 is very hard type water and beyond the permissible drinking limit in the study area. The classification of water samples based on electrical conductivity (EC) is given in Table 6. In the study area, 53.85% of water samples are in good water, and 46.15% are in excellent water.

Table 6 Drinking water quality classification based on Electrical Conductivity (EC).

EC ($\mu\text{S/cm}$)	Types of water	Sample numbers	Number of samples	Percent of samples
<250	Excellent	SP-3, 7, 9, 10, 11, 12	6	46.15
250-750	Good	SP1–5, 8, 13	7	53.85
750-2250	Fair	Nil	Nil	Nil
>2250	Poor	Nil	Nil	Nil
Total			36	100

5. 2. 2. Characterization of the hydro-geochemical facies

The chemical analysis of groundwater samples is shown on a Piper trilinear diagram, allowing for easy classification and comparison of different kinds of water (Piper, 1944). The principal anions and cations concentrations are represented in two trilinear diagrams and a diamond-shaped field of a Piper diagram. Water is classified chemically into two types: Mg-type, Ca-type, Na+K-type, and no dominant type water in cation facies, and SO_4^{2-} -type, HCO_3^- -type, Cl-type, and no dominant type water in anion facies (Figure 6d) (Table 7). The observations infer that no dominant type facies dominate in the study area, and the percentage of samples categorized under the Mg-type, Ca-type, and no dominant type water in cation facies, and SO_4^{2-} -type, HCO_3^- -type, and no dominant type water in anion facies is 23.08%, 23.08%, 53.85%, 92.31%, and 7.72% respectively. The Cationic (TDS versus $\text{Na}^+ / \text{Na}^+ + \text{Ca}^{2+}$) and anionic (TDS versus $\text{Cl}^- / \text{Cl}^- + \text{HCO}_3^-$) plot in Gibbs's (1970) diagram shows that the bulk of the water samples is in the rock dominance zone. (Figure 6e).

Table 7 Characterization of hydrochemical facies in groundwater.

Water type	Sample numbers	Numbers of samples	Percentage of samples
------------	----------------	--------------------	-----------------------

(i) Cation Facies			
a) Mg type	SP1, 2 and SP3	3	23.08
b) Ca type	SP3, 4 and SP7	3	23.08
c) Na+K type	Nil	Nil	Nil
d) No dominant type	SP8, 9, 10, 11, 12 and SP13	7	53.85
(ii) Anion Facies			
a) SO_4^{2-} type	Nil	Nil	Nil
b) HCO_3^- type	SP1–6, 8–13	12	92.31
c) Cl^- type	Nil	Nil	Nil
d) No dominant type	SP7	1	7.72

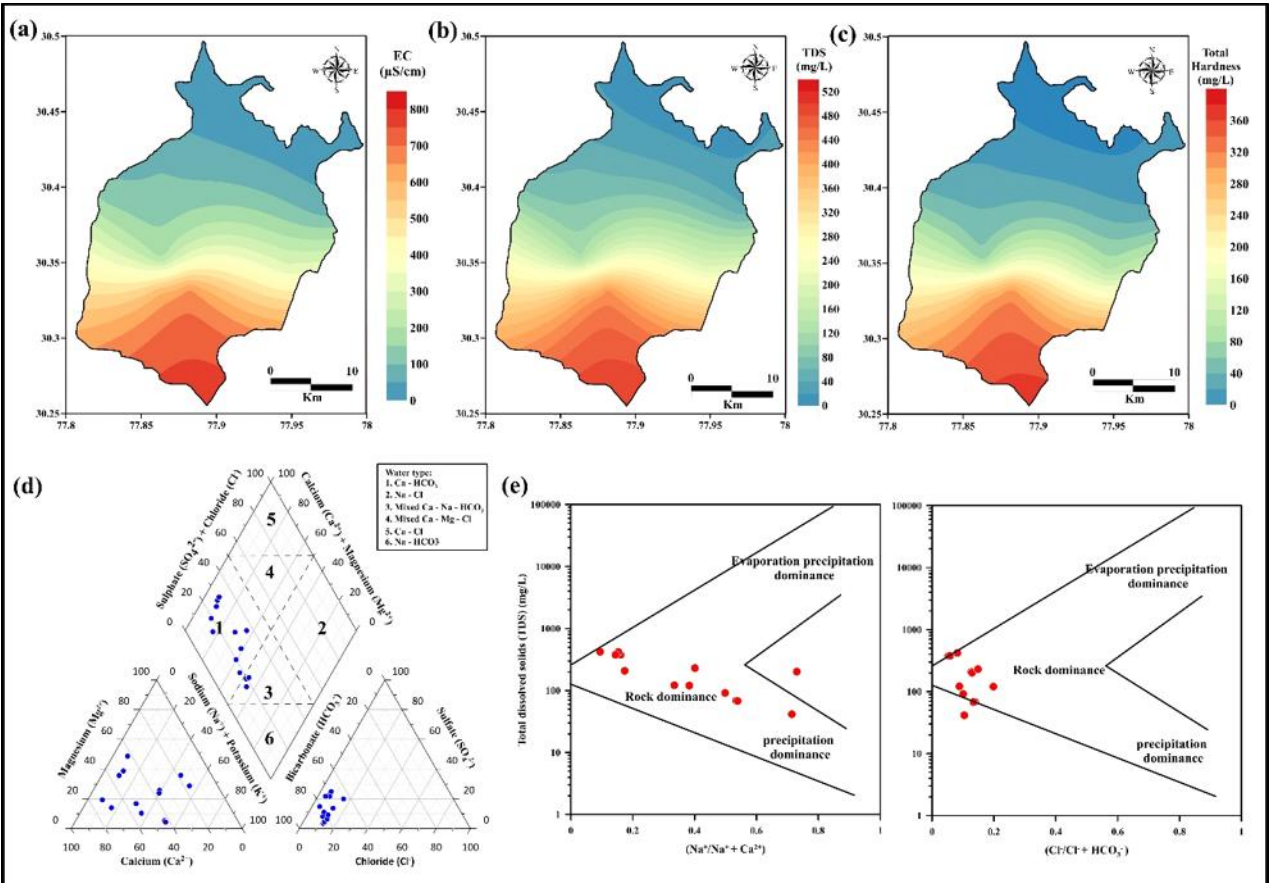


Fig. 6 (a-c) Spatial map of EC, TDS, and TH; (d) Piper Tri-linear Diagram representing the chemical analysis of samples; and (e) Gibb's plot.

5. 3. Hydrogeochemical Characteristics and Statistical Relationships

According to the physicochemical characteristics of the groundwater samples, the Sahaspur Block of Dehradun district groundwater is typically fresh and fit for household, drinking, and irrigation uses. The groundwater conditions are neutral to slightly alkaline, with pH values ranging from 6.91 to 7.98. TDS ranges from 41.6 to 421.8 mg/L, indicating mild to moderate mineralization, whereas electrical conductivity (EC) ranges from 65 to 659 $\mu\text{S}/\text{cm}$. Ramgarh (659

$\mu\text{S/cm}$), Badowala (658 $\mu\text{S/cm}$), Telpura (589 $\mu\text{S/cm}$), and Singhniwala (588 $\mu\text{S/cm}$) had the highest EC values, whereas Khandoli (65 $\mu\text{S/cm}$), Chhorba (106 $\mu\text{S/cm}$), and Redapur (107 $\mu\text{S/cm}$) had the lowest values. Groundwater is primarily fresh and has experienced little geochemical evolution, as indicated by the comparatively low EC and TDS values. Groundwater conductivity is predominantly controlled by dissolved ionic components, as demonstrated by the nearly perfect positive relationship between EC and TDS ($R = 1.00$) found in statistical analysis. EC and bicarbonate ($R=0.985$) and EC and total hardness ($R=0.992$) all showed strong positive associations. These correlations show that interactions with alluvial sediments and the dissolution of carbonate-bearing minerals are the primary factors controlling groundwater mineralization. The correlation matrix indicates the following relationships in Table 8.

Table 8 correlation matrix relationship

Parameters	Correlation Coefficient (R)
EC – TDS	1.000
EC – Total Hardness	0.992
EC – HCO_3^-	0.985
Total Hardness – HCO_3^-	0.976

The significant correlation between EC, hardness, and bicarbonate indicates that water-rock interaction processes in the Doon Valley's gravel, sand, pebble, and cobble aquifers play a major role in controlling groundwater chemistry. The predominance of bicarbonate ions and the modest quantities of calcium and magnesium show the impact of silicate weathering and carbonate dissolution.

The PCA information is utilized to identify correlations, trends, and waters with risky chemical composition for further statistical modeling (Xu et al., 2019, Naskar, S., et al., 2025, Somvir Singh et. al., 2025). The three factors contribute 73.9% of the total variance of all parameters evaluated in factor analysis. Moreover, it is mainly attributed to higher loading of EC, TDS, Na^+ , K^+ , Mg^{2+} , Ca^{2+} , Cl^- , and SO_4^{2-} (Figure 7a), and are major contributors to the groundwater chemistry. The biplot of PC-1 and PC-2 in figure 7(b) shows the relationship between factor scores for the water sample locations and factor loading for the physicochemical parameters. PC-1 and PC-2 have positive

loadings of all physicochemical parameters except for the negative loading of TH, Mg^{2+} , SO_4^{2-} , Ca^{2+} , and pH in PC-2.

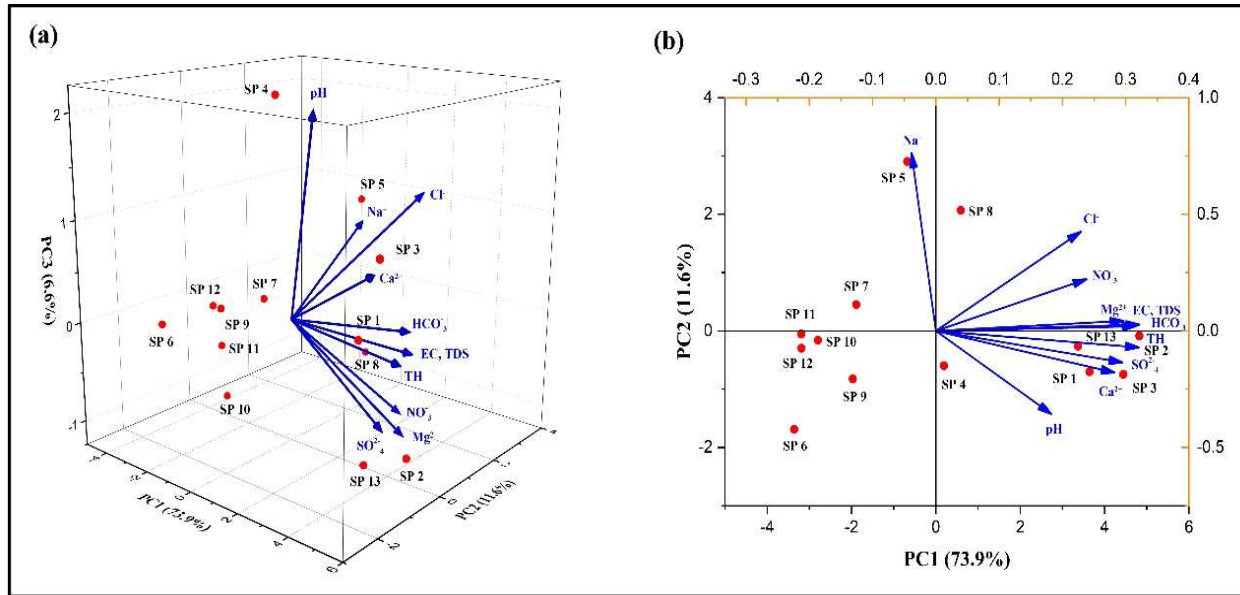


Fig. 7(a) 3D Rotation plot of R-mode factor analysis showing ion association, **(b)** Biplot of principal component explaining the relationship of physicochemical parameters and sample locations.

The hydrochemical findings corroborate the geophysical interpretation that the aquifer system is mostly composed of permeable sandy and gravelly strata that hold fresh groundwater. While comparatively greater EC values are linked to prolonged groundwater residence durations and increased mineral dissolution, areas with lower EC and TDS values are probably associated with more permeable recharge zones. The groundwater-bearing formations found in the VES survey are therefore confirmed by the combined geophysical and hydrochemical investigation to be productive freshwater aquifers fit for household, agricultural, and drinking purposes.

5. 4. Geophysical–Geochemical Statistical Integration

Aquifer resistivity derived from VES interpretation was statistically combined with hydrochemical data, such as electrical conductivity (EC) and total dissolved solids (TDS), to examine the predictive potential of geophysical parameters for groundwater quality assessment. The association between groundwater quality indicators and aquifer resistivity was measured using regression analysis, Pearson correlation, and Spearman rank correlation.

(a) Correlation Analysis

The Pearson correlation coefficient between aquifer resistivity (ρ_a) and groundwater EC was found to be:

$$R_{Pearson}(\rho_a, EC) = -0.081 \quad (4)$$

Similarly, the Spearman rank correlation coefficient was:

$$R_{Spearman}(\rho_a, EC) = -0.137 \quad (5)$$

Aquifer resistivity and groundwater EC have a weakly inverse connection, according to both coefficients. The low correlation indicates that bulk aquifer resistivity is significantly impacted by lithological changes, porosity, saturation conditions, and clay content in addition to groundwater chemistry, even though groundwater conductivity normally rises with increasing ionic concentration.

(b) Power-Law Regression Model

A non-linear regression model was developed between groundwater EC and aquifer resistivity using the commonly adopted power-law relationship:

$$EC = 590\rho_a^{-0.22} \quad (6)$$

where: EC = Electrical conductivity ($\mu\text{S}/\text{cm}$) and ρ_a = Aquifer resistivity ($\Omega\text{-m}$)

The coefficient of determination obtained from the model was:

$$R^2 = 0.08$$

Aquifer resistivity accounts for just around 8% of the variability in EC, according to the low R^2 value. This shows that resistivity measurements alone cannot be used to accurately estimate groundwater quality in the Sahaspur Block, Dhradun district, Uttarakhand.

5. 5. Hydrogeophysical Relationship Between Aquifer Resistivity and Groundwater Quality

The quality of groundwater aquifers in the study area was investigated using a hydrochemical and geophysical approach. Attempts were made to gather as much data as possible to develop a more efficient formula (Abdelfattah, M., et. al., 2023, Hibbs, B. J., 2024). Aquifer resistivity values (ρ_a) obtained from VES interpretation were compared with groundwater quality parameters acquired from 13 water samples collected near selected VES locations in order to assess the relationship between aquifer electrical characteristics and groundwater quality (Table 9). Total dissolved solids (TDS), groundwater resistivity (ρ_w), and electrical conductivity (EC) were among the metrics examined. Aquifer resistivities ranged from 14.33 to 168.30 $\Omega\text{-m}$, and groundwater EC values ranged from 65 to 659 $\mu\text{S}/\text{cm}$. The corresponding values of groundwater resistivity were between 15.17 to 153.85 $\Omega\text{-m}$. According to Vouillamoz et al., 2007, Lubang, J., Liu, H., & Chen, R., 2023, Kouadio K. J. O., et. al., 2024, the groundwater resistivity (ρ_w) was calculated from measured EC values using the inverse relationship:

$$\rho_w = \frac{10000}{EC} \quad (7)$$

where ρ_w is groundwater resistivity ($\Omega\text{-m}$) and EC is electrical conductivity ($\mu\text{S}/\text{cm}$). From figure 8a, the relationship between groundwater resistivity and aquifer resistivity was examined through linear regression analysis, equation is:

$$\rho_w = 0.1622\rho_a + 41.673 \quad (8)$$

The regression produced a coefficient of determination of $R^2 = 0.041$, meaning that aquifer resistivity accounts for just 4.1% of the variation in groundwater resistivity. This incredibly poor link implies that groundwater conductivity is not the only factor directly controlling aquifer resistivity. Instead, the aquifer system's saturation conditions, porosity, clay content, grain-size distribution, and lithological heterogeneity all have a significant impact on the bulk resistivity reaction. A second regression analysis was conducted between groundwater electrical conductivity and aquifer resistivity to establish a direct hydrogeophysical relationship (Figure 8 b):

$$EC = -0.3464\rho_a + 351.64 \quad (9)$$

The negative slope shows the anticipated inverse relationship between resistivity and electrical conductivity, with lower resistivity values often found in groundwater with larger dissolved ionic concentrations. The statistical association was still poor, though, which is indicative of significant data scatter and the limited ability of aquifer resistivity to predict groundwater salinity. To further assess the geophysical–geochemical relationship, TDS values were correlated with the inverse of aquifer resistivity (Figure 8 c). The resulting regression equation was:

$$TDS = 179.68 + 1020.33 \left(\frac{1}{\rho_a} \right) \quad (10)$$

with $R^2 = 0.03$ as the coefficient of determination. Aquifer resistivity can only account for 3% of the variance in TDS, according to the extremely low R^2 value, indicating a negligible link between the two variables. This finding implies that the observed resistivity changes are not primarily caused by groundwater mineralization. The Doon Gravel Formation's heterogeneous composition of alternating layers of boulders, cobbles, pebbles, gravels, sand, and clay is responsible for the poor correlations seen in all regression models. The impacts of groundwater chemistry are frequently obscured by such lithological heterogeneity, which has a substantial impact on bulk formation resistivity. As a result, formations with identical resistivities may contain groundwater with diverse chemical compositions, whereas aquifers with equal groundwater quality may show differing resistivity values.

Overall, the hydrogeophysical analysis shows that while VES-derived resistivity data is very useful for characterizing and delineating aquifers, groundwater quality indicators like EC and TDS in the study area cannot be accurately predicted by aquifer resistivity alone. Therefore, an integrated strategy that combines hydrochemical analysis and geophysical investigations should serve as the foundation for groundwater quality assessment. The combined interpretation demonstrates the significance of integrating geophysical and geochemical datasets for sustainable groundwater resource assessment and management and confirms that fresh groundwater primarily occurs within multilayered gravelly aquifers in the Sahaspur Block, Dehradun district, Uttarakhand.

Table 9 Summary of Correlation between EC, TDS and geoelectrical resistivity.

Sl. No.	VES No./SP No.	Aquifer resistivity (ρ_a in $\Omega\text{-m}$) from VES	EC ($\mu\text{S/cm}$) from Water sample	TDS (mg/L)	Groundwater Resistivity (ρ_w in $\Omega\text{-m}$) =1/EC	$\frac{1}{\rho_a}$ ($\Omega^{-1}\text{-m}^{-1}$)
1	VES1/SP11	31.456	107	68.48	93.46	0.03179
2	VES2/SP12	102.07	106	67.84	94.34	0.009797
3	VES8/SP2	168.3	658	421.12	15.2	0.005942
4	VES10/SP4	50.87	325	208	30.77	0.019658
5	VES13/SP7	72.427	188	120.32	53.19	0.013807
6	VES16/SP3	20.569	659	421.76	15.17	0.048617
7	VES17/SP1	19.895	588	376.32	17.01	0.050264
8	VES22/SP6	98.22	65	41.6	153.85	0.010181
9	VES26/SP8	16.266	360	230.4	27.78	0.061478
10	VES32/SP9	146.5	190	121.6	52.63	0.006826
11	VES33/SP13	43.398	589	376.96	16.98	0.023043
12	VES53/SP10	14.334	143	91.52	69.93	0.069764
13	VES54/SP5	19.123	315	201.6	31.75	0.052293

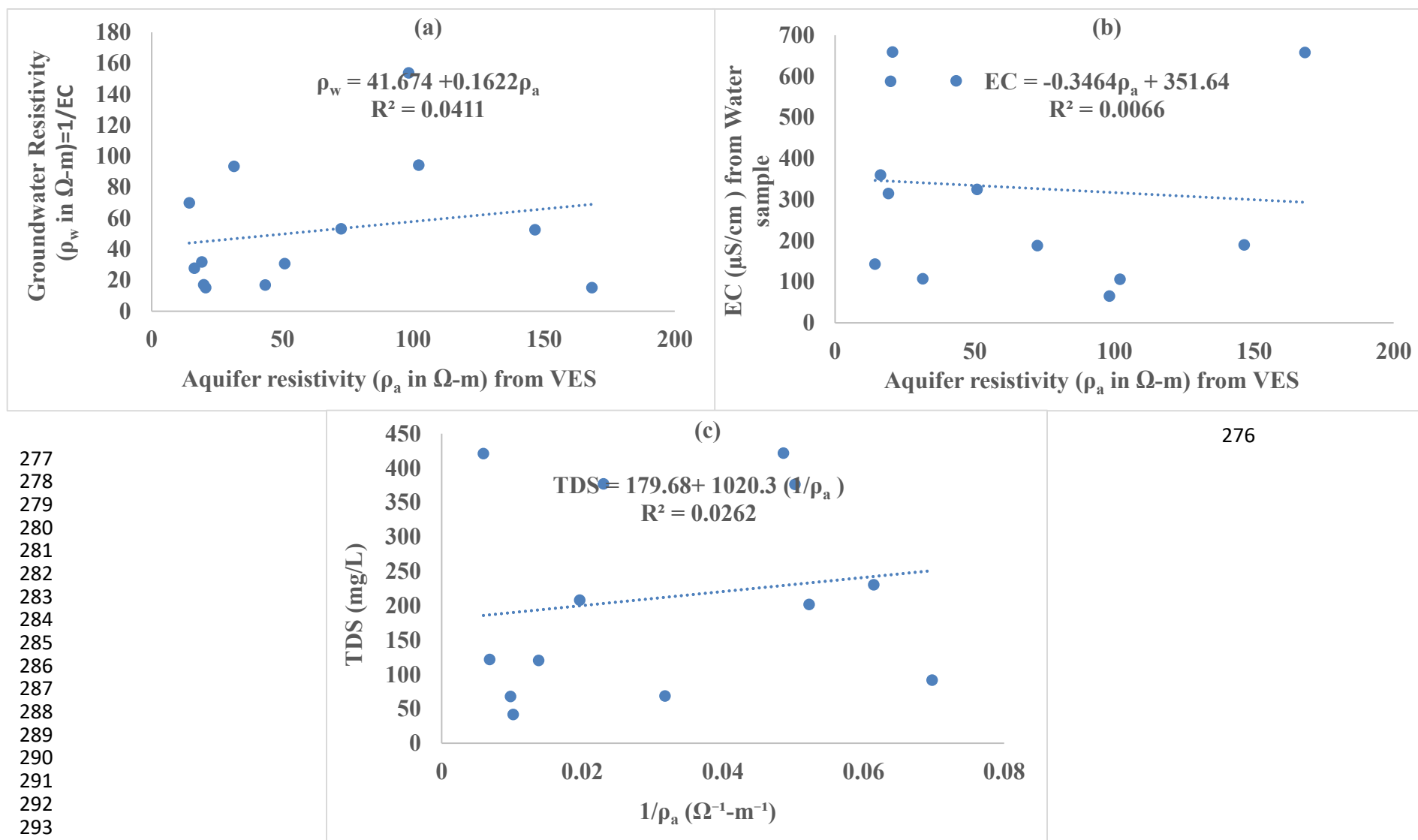


Fig. 8 (a) Correlation between aquifers resistivity (VES) and groundwater resistivity, **(b)** Correlation between aquifers' resistivity (VES) and electrical conductivity (EC), and **(c)** Correlation between TDS and $\frac{1}{\rho_a}$.

6. Conclusions

The Sahaspur Block, Dehradun District, Uttarakhand, India's groundwater potential and quality were assessed using a combination of geophysical, geochemical, and statistical methods. To describe the aquifer system and determine groundwater suitability, 58 Vertical Electrical Sounding (VES) measurements and 13 groundwater samples were examined. A heterogeneous multilayered subsurface made of clay, sandy clay, gravel, pebbles, cobbles, and boulders was revealed by the geoelectrical interpretation. With an average resistivity of 79.7 Ω -m and aquifer resistivity values ranging from 12.7 to 262.6 Ω -m, the main groundwater-bearing formations were found in gravelly and sandy layers. Groundwater-bearing zones were found at depths between 18.2 and 178.8 m, indicating moderate to high groundwater potential across the majority of the research area. Aquifer thickness ranged from 11.0 to 79.6 m (average 33.2 m).

According to hydrogeochemical study, groundwater is often fresh and appropriate for household, drinking, and irrigation uses. The measured pH, EC, and TDS ranged from 6.91 to 7.98, 65 to 659 μ S/cm, and 41.6 to 421.8 mg/L, respectively. All key physicochemical parameters were found to be within the acceptable limits of drinking water regulations. Aquifer resistivity and groundwater EC showed a weak inverse connection (Pearson $R = -0.081$; Spearman $R = -0.137$) according to the statistical integration of geophysical and geochemical information. The low coefficient of determination ($R^2 = 0.08$) obtained from the power-law regression model, $EC = 590\rho_a^{-0.22}$, indicates that aquifer resistivity has limited predictive capacity for groundwater quality assessment in the research area. The TDS–resistivity model also showed a weak correlation ($R^2 = 0.03$). These findings imply that groundwater mineralization alone is not the primary factor influencing bulk aquifer resistivity, but rather the lithological heterogeneity of the Doon Gravel Formation.

Groundwater occurrence and quality are better understood when VES-derived aquifer characteristics are combined with hydrochemical measurements than when either method is used separately. The results show that the Sahaspur block aquifer system is primarily made up of freshwater-bearing gravelly deposits with acceptable water quality and positive groundwater potential. The study offers a scientific foundation for sustainable groundwater development and management in the Himalayan piedmont region and emphasizes the significance of integrated hydrogeophysical investigations for groundwater resource evaluation.

Principle contribution of this study is to assess the hydrogeological importance of aquifer resistivity in a complicated alluvial setting by integrating geophysical, geochemical, and statistical analysis. The findings demonstrate that although VES is a useful tool for identifying groundwater-bearing formations, substantial lithological restrictions prevent aquifer resistivity from being a reliable indicator of groundwater quality. In heterogeneous piedmont aquifer systems, our discovery highlights the need to integrate geophysical and hydrochemical datasets for precise aquifer characterisation and groundwater-resource evaluation.

7. Limitations of the Study

The Sahaspur Block's groundwater potential and quality were revealed by the integrated geophysical, geochemical, and statistical technique; however, a number of restrictions should be noted. First, the multilayered alluvial aquifer system's complex lateral heterogeneities may not have been properly captured by the geophysical study's one-dimensional (1D) VES interpretation. Second, the robustness of the geophysical–geochemical correlations may be

limited because there were only 13 groundwater samples available for hydrochemical and statistical analyses. Third, the weak correlation between groundwater quality parameters and aquifer resistivity indicates that bulk resistivity is more influenced by lithological variability than by groundwater mineralization, which lowers the predictive power of resistivity-based water-quality assessment. Additionally, because groundwater samples were gathered during a single sampling campaign, seasonal variations in groundwater chemistry and water-table fluctuations were not assessed. In order to enhance aquifer characterization and groundwater-quality prediction in the diverse piedmont aquifer systems of the Himalayan foothill region, future research should integrate high-resolution 2D/3D geophysical imaging, larger hydrochemical datasets, seasonal monitoring, and sophisticated statistical or machine-learning techniques.

Acknowledgments

The authors would like to thank the Chairman of the Central Groundwater Board (CGWB) and Regional Director of CGWB, UR, Dehradun, for providing us with the required facilities, encouragement, and support. We want to express our noble gratitude to all those who have supported the data collection, data processing, and laboratory analysis process in this research work.

Authors contribution:

Somvir Singh: Initially processed, analysed, and interpreted the data. Also, prepared a draft of manuscript.
Surendra Kaur Rawal: Conceptualized, designed, and revised critically and significantly improved the article.
Preeti Tiwary: Edited and significantly modified the language of article.

Declaration:

Data availability statement: All the data used during the study appears in the manuscript.
Ethical Responsibilities of Authors: “All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors”.
Consent to participate: The paper is submitted with the consent of all the listed authors.
Competing interests: The authors declare no competing interests.
Funding Statement: The author declares that no funding was provided for this work

References

- Abdelfattah M, Abu-Bakr HAA, Mewafy FM, Hassan TM, Geriesh MH, Saber M, & Gaber A (2023) Hydrogeophysical and hydrochemical assessment of the northeastern coastal aquifer of Egypt for desalination suitability. *Water*, 15(3), 423. <https://doi.org/10.3390/w15030423>.
- Abdulameer A, Thabit JM, Al-Menshed FH, & Merkel B (2021) Evaluating Three Conventional Electrode Arrays in 2D Electrical Resistivity Imaging Surveys for Studying the Sedimentary Layers and the Hydrogeological Situation in Southern Iraq. *Journal of Hydrogeology and Hydrological Engineering*, 10(2).
- Adewoyin OO, Awoyemi MO, Oladunjoye M.A, & Oyeyemi KD (2021) Hydrogeophysical assessment of aquifer quality using combined VES and water-quality parameters. *Groundwater for Sustainable Development*, 13, 100551, <https://doi.org/10.1016/j.gsd.2021.100551>.
- Afolabi O, Adewumi JR, & Oladunjoye MA (2023) Application of electrical resistivity methods for groundwater exploration in basement terrains of Nigeria. *Groundwater for Sustainable Development*, 22, 101005.
- Agrawal V, Jagetia M (1997) Hydrogeochemical assessment of groundwater quality in Udaipur city, Rajasthan, India. In: Proceedings of national conference on dimension of environmental stress in India. Department of Geology, M S University, Baroda, India, pp 152–154

- Ahmed T, Zounemat-Kermani M, & Scholz M (2020) Climate change, water quality and water-related challenges: a review with focus on Pakistan. *International Journal of Environmental Research and Public Health*, 17(22), 8518.
- Alao JO, & Abubakar F (2025) Groundwater exploration, management strategies and sustainability: Geophysical approaches. *Geosystems and Geoenvironment*, 4(3), Article 100395. <https://doi.org/10.1016/j.gegeo.2025.100395>.
- Alao JO, Bello AY, Lawal HA, & Abdullahi D (2024) Assessment of groundwater challenge and the sustainable management strategies. *Results in Earth Sciences*, 2, Article 100049. <https://doi.org/10.1016/j.rines.2024.100049>.
- Ali N, Chappuies J, Sloan G, Rouland G, Rai A, & Dong Y (2025) A global perspective on electrical resistivity tomography, electromagnetic and ground penetration radar methods for estimating groundwater recharge zones. *Frontiers in Water*, 7, 1636613. <https://doi.org/10.3389/frwa.2025.1636613>.
- Andrade R (2011) Intervention of electrical resistance tomography in resolving hydrological problems of a semi arid granite terrain as Southern India, *Jour. Geol. Soc. India*, (78), 337-344.
- Appelo CAJ, & Postma D (2005) *Geochemistry, Groundwater and Pollution (2nd ed.)*. CRC Press.
- Bagchi D, Khanna A, & Bussa R (2020) Mapping and Management of Hard Rock Aquifer System in Uttarkashi District; Uttarakhand; India. *Journal of Hydrogeology & Hydrologic Engineering*, 9(3). [https://doi.org/10.37532/jhhe.2020.9\(3\).201](https://doi.org/10.37532/jhhe.2020.9(3).201).
- Bairwa AK, Gupta AK, Mishra V, & Gupta K (2024) Physico-chemical and correlation study of ground drinking water of Tonk district of Rajasthan (India). *Discover Water*, 4, Article 23. <https://doi.org/10.1007/s43832-024-00077>.
- Beabu G Menegbo, Onengiyeofori Anthony Davies, & Opiriyabo Ibim Horsfall (2024) “Assessment of Aquifer Resistivity, Depth, and Thickness using Vertical Electrical Sounding (VES) in Parts of Bori Metropolis for Groundwater Exploration.” *World Journal of Advanced Research and Reviews*, 24(2), 275–285.
- Bhartariya SK (1995) Hydrogeology and Water Resources of Intermontane Doon Valley. *Himalayan Geology Vol.6* (2). PP.17-28.
- Bhattacharya PK, & Patra HP (1968) *Direct Current Geoelectric Sounding: Principles and Interpretation*. New York: Elsevier Publishing Company.
- Cahyadi R, & Widodo W (2025) Studi komparatif triangular dan quadrilateral mesh pada inversi geolistrik 2D Wenner-Schlumberger untuk zona high resistivity di Terowongan 11 Padalarang. *Jurnal Fisika Unand*, 14(6), 546–553.
- Carrard N, Foster T, & Willetts J (2019) Groundwater as a source of drinking water in southeast Asia and the Pacific: A multi-country review of current reliance and resource concerns. *Water*, 11(8), 1605.
- Central Ground Water Board (CGWB) (2013) *District Groundwater Brochure: Dehradun District, Uttarakhand*.
- Central Ground Water Board (CGWB) (2020) *Ground Water Year Book 2019–2020: Uttarakhand State*. Ministry of Jal Shakti, Government of India.
- Central Ground Water Board (CGWB) (2022) *District Groundwater Brochure: Dehradun District, Uttarakhand*.
- Central Ground Water Board (CGWB) (2023) *District Groundwater Brochure: Dehradun District, Uttarakhand*.
- Central Ground Water Board (CGWB) (2011) Groundwater exploration in Uttarakhand, pp 112.
- Chandel RS, Singh IB (2000) Morphostratigraphy and fan morphology of Doon Valley. *J Indian Soc Rem Sens* 28:265–274.
- Choudhury K, Saha DK (2004) Integrated geophysical and chemical study of saline water intrusion. *Ground Water* 42:671–677.
- Das P, & Gupta S (2021) Hydrogeological evaluation of alluvial fan aquifers in the Indo-Gangetic plains, India.” *Hydrogeology Journal*, 29, 1183–1197. <https://doi.org/10.1007/s10040-021-02389-0>.
- Debabrata Nandi, Ipsita Mohanta, and Sandeep Ranjan Mishra (2015) Delineation of Groundwater Prospective Zones by Schlumberger electrode array in Bangripasi block of Odisha, *International Research Jour. of Earth Sciences* 3(4) 5-11.
- Duraiswami RA (2005) Dykes as potential groundwater reservoir in semi-arid areas of Sakri Taluka, Dhule District, Maharashtra, *Gond. Geol. Magz*, 21(1), 1-9.
- Edet AE, Okereke CS (2002) Delineation of shallow groundwater aquifers in the coastal plain sands of Calabar area (Southern Nigeria) using surface resistivity and hydrogeological data. *Journal of African Earth Sciences*, , 35, Number 3, 433-443(11).
- Egai AO, Paaru M, & Victor-Gow A (2024) Aquifer delineation using Vertical Electrical Sounding (VES) and correlation of borehole logs in Opolo-Epie, Yenagoa Bayelsa State, Nigeria. *Global Journal of Earth and Environmental Science*, 9(2), 69–81. <https://doi.org/10.31248/GJEES2024.153>.

- El-Alaouy N, Sebbar B, Bouras EH, Moumni A, Laftouhi NE, & Lahrouni A (2022) Seasonal Variation of Drinking Water Quality and Human Health Risk Assessment: A Case Study in Rural Village of the Eastern Cape, South Africa. *Water*, 14(13), 2013. <https://doi.org/10.3390/w14132013>,
- Erram VC, Gupta G, Pawar JB, Gupta Suyashkumar, and Pawar NJ (2010) Potential groundwater zones in parts of Dhule District, Maharashtra a joint interpretation based on Resistivity and Magnetic data, *J. Ind. Geol. Cong.*, 2(1) 3745.
- Fetter CW (2018) *Applied Hydrogeology* (4th ed.). Waveland Press.
- Fuqaha S (2025) Global Trends and Research Frontiers of Water Harvesting and Groundwater Recharge: A Comprehensive Bibliometric Review. *Opportunities and Challenges in Sustainability*, 4(2), 110–134. <https://doi.org/10.56578/ocs040204>.
- Gaikwad S, Pawar NJ, Bedse P, Jadhav S, & Patil K (2022) Delineation of groundwater potential zones using vertical electrical sounding (VES) in a complex bedrock geological setting of the West Coast of India. *Modeling Earth Systems and Environment*, 8, 2233–2247, <https://doi.org/10.1007/s40808-021-01223-3>.
- Gautam Gupta, Vinit C. Erram, Saumen Maiti, Nandkishor R. Kachate and Sanjay N Patil (2010) Geoelectrical studies for delineating Seawater intrusion in parts of konkan coast, *International Journal of Environment and Earth Sciences* 1(1) 62-79.
- George NJ, Ekanem KR, Ekanem AM, Udosen NI, & Thomas JE (2025) *Georesistivity assessment of lithological and hydrodynamic factors in groundwater sanitation of Akwa Ibom river channel aquifer system*. *Geosystems and Geoenvironment*, 4(3), Article 100411. <https://doi.org/10.1016/j.geogeo.2025.100411>.
- Gibbs RJ (1970) Mechanisms controlling world water chemistry. *Science*, 170(3962), 1088-1090.
- Gourshetty D, & Abdul Hakkim VM (2025) Geophysical Characterization of Aquifers Using Vertical Electrical Sounding in Perumatty Panchayat, Palakkad, India. *Journal of Geography, Environment and Earth Science International*, 29(5), 28–38. <https://doi.org/10.9734/jgeesi/2025/v29i5892>.
- Gupta DS, Biswas A, Ghosh P, Rawat U, & Tripathi S (2021) Delineation of groundwater potential zones, groundwater estimation and recharge potentials from Mahoba district of Uttar Pradesh, India. *International Journal of Environmental Science and Technology*, 1-24.
- Gupta G, Erram VC, and Gupta Suyashkumar (2012) Temporal geoelectric behavior of dyke aquifers in northern Deccan Volcanic Province, India, *Jour. Earth Syst. Sci.*, (121) 723– 732.
- Hibbs BJ (2024) Hydrogeological, Hydrochemical, and Geophysical Analysis of a Brine-Contaminated Aquifer Addressing Non-Unique Interpretations of Vertical Electrical Sounding Curves. *Water*, 16(24), 3557. <https://doi.org/10.3390/w16243557>.
- Ibuot JC, Obiora DN, Obiora D, Nnaemeka Igwe EA, & Ugwu NM (2025) Evaluation of groundwater vulnerability using index-based model approach within parts of Nsukka Sedimentary Basin, Nigeria. *Solid Earth Sciences*, 10(2), 100232. <https://doi.org/10.1016/j.sesci.2025.100232>.
- Janardhana Raju N, Shukla UK, Ram P (2011) Hydrogeochemistry for the assessment of groundwater quality in Varanasi: a fasturbanizing center in Uttar Pradesh, India. *Environ Monit Assess* 173:279–300.
- Javed U, Kumar P, Hussain S, Nawaz T, Fahad S, Ashraf S, & Ali K (2024) Geospatial analysis of soil resistivity and hydro-parameters for groundwater assessment. *Discover Geoscience*, 2, Article 3. <https://doi.org/10.1007/s44288-024-00004-6>.
- Kalisperi D, Soupios P, Kouli M, Barsukov P, Kershaw S, Collins P, Vallianatos F (2009) Coastal aquifer assessment using geophysical methods (TEM, VES), case study: Northern Crete, Greece, 3rd IASME/WSEAS international conference on geology and seismology (GES '09) Cambridge, UK, 24–26 February 2009
- Kamaraj P, & Karuppannan S (2024) *Dataset of geophysical electrical resistivity and subsurface profiling for natural resources exploration in a hard rock terrain of Tamil Nadu, India*. *Data in Brief*, 54, 110311. <https://doi.org/10.1016/j.dib.2024.110311>.
- Kar A, Dastidar DG, Adhikari, SK, Sinha A K, Talukdar T, Chowdhury AN & Bhattacharya A (2022) Augmentation of arsenic free drinking water supply in West Bengal through innovative groundwater exploration technique: A case study. In *Innovative Exploration Methods for Minerals, Oil, Gas, and Groundwater for Sustainable Development* (pp. 241-248). Elsevier.
- Karanth KR (1987) Ground Water Assessment, Development and Management, *Tata Mc Graw Hills Publications Company Limited, New Delhi*, (27) 449-460.
- Kearey P, and Brooks M (1988) An introduction to geophysical exploration, *ELBS Blackwell Scientific Publication, Oxford*, (3) 296
- Kebede H, Demissie, Z, Tadesse H, & Eshetu A (2024) *Spatial interpolation techniques comparison and evaluation: The case of ground-based gravity and elevation datasets of the central Main Ethiopian rift*. *Heliyon*, 10(12), e32806. <https://doi.org/10.1016/j.heliyon.2024.e32806>.

- Khan J, Gupta G, Singh NK, Bhawe VN, Bhardwaj V, Upreti P, Singh R, & Sinha AK (2023) Geophysical and geostatistical assessment of groundwater and soil quality using GIS, VES, and PCA techniques in the Jaipur region of Western India. *Environmental Science and Pollution Research*, 30(31), 77713–77728. DOI: 10.1007/s11356-023-28004-y.
- Khare R, & Kushwaha SS (2025) *Qualitative Assessment of Water Using Flame Photometer and GIS Techniques*. International Journal of Environmental Sciences, 11(4). <https://doi.org/10.64252/d9qbpd39>.
- Kouadio KJO, Mangoua OMJ, Koffi B, Soro DD, Dibi B, & Kouassi KL (2024) Identification of hydrogeological and geoelectrical parameters influencing the productivity of boreholes in the commune of Daloa (Central-Western Côte d'Ivoire). *Heliyon*, 10(8), e29468. <https://doi.org/10.1016/j.heliyon.2024.e29468>.
- Kumar D, Rao VA, & Sarma VS (2014) Hydrogeological and geophysical study for deeper groundwater resource in quartzitic hard rock ridge region from 2D resistivity data. *Journal of Earth System Science*, 123, 531–543.
- Kumar P, Biswas A, & Banerjee S (2023) Spatio-temporal variability of seawater mixing in the coastal aquifers based on hydrogeochemical fingerprinting and statistical modeling. *Journal of Environmental Management*, 346, 118937.
- Kumar P, Tiwari P, Singh A, Biswas A, & Acharya T (2021) Electrical Resistivity and Induced Polarization signatures to delineate the near-surface aquifers contaminated with seawater invasion in Digha, West-Bengal, India. *Catena*, 207, 105596.
- Kumar P, Tiwari P, Biswas A, & Acharya T (2020) Geophysical and hydrogeological investigation for the saline water invasion in the coastal aquifers of West Bengal, India: a critical insight in the coastal saline clay–sand sediment system. *Environmental Monitoring*
- Lashkaripour GR (2003) An investigation of groundwater condition by geoelectrical resistivity method: a case study in Korin aquifer, southeast Iran. *J Spat Hydrol* 3:1–5
- Lashkaripour GR, Ghafoori M, Dehghani A (2005) Electrical resistivity survey for predicting Samsor aquifer properties, Southeast Iran. *Geophysical Research Abstracts*, European Geosciences Union 7:1–5
- Li Zixin; Li Donghui, Lei Wenjie Li Zhe (2024) Experimental Study on the Relationship Among Complex Resistivity, Water Saturation, and Salinity in the Jiaozuo Anthracite Reservoir. *ACS Omega*, 9(29), 31754–31764. <https://doi.org/10.1021/acsomega.4c02850>.
- Llomas MR (2024) Groundwater Management: Sustainability, Environment and Hydrogeoethics. *Discover Applied Sciences*, 6, 219.
- Loke MH (2016) *Tutorial: 2-D and 3-D Electrical Imaging Surveys*. Geotomo Software, Penang, Malaysia.
- Lubang J, Liu H, & Chen R (2023) Combined Application of Hydrogeological and Geoelectrical Study in Groundwater Exploration in Karst-Granite Areas, Jiangxi Province. *Water*, 15(5), 865. <https://doi.org/10.3390/w15050865>.
- Masood A, Tariq MAUR, Hashmi MZUR, Waseem M, Sarwar MK, Ali W, Farooq R, Almazroui M, & Ng A WM (2022) An Overview of Groundwater Monitoring through Point-to Satellite-Based Techniques. *Water*, 14(4), 565. <https://doi.org/10.3390/w14040565>.
- McNeil VH, Cox ME (2000) Relationship between conductivity and analysed composition in a large set of natural surface water samples, Queensland, Australia. *Environ Geol* 29(1325):1333.
- Meijerink AMJ (1974) Photographical Reconnaissance Surveys, Special Publication ITC Enschede, P.371.
- Menegbo BG, Davies O A, & Horsfall OI (2024) Assessment of Aquifer Resistivity, Depth, and Thickness using Vertical Electrical Sounding (VES) in Parts of Bori Metropolis for Groundwater Exploration. *World Journal of Advanced Research and Reviews*, 24(02), 275–285. <https://doi.org/10.30574/wjarr.2024.24.2.3293>.
- Mogaji KA, Olatunji SO, & Abiodun OI (2021) Integrated geophysical and GIS-based assessment of groundwater potential. *Environmental Earth Sciences*, 80, 1–14.
- Mohammed MAA, Szabó NP, Alao JO, & Szűcs P (2024) *Geophysical characterization of groundwater aquifers in the Western Debrecen area, Hungary: insights from gravity, magnetotelluric, and electrical resistivity tomography*. Sustainable Water Resources Management, 10, Article 67. DOI: 10.1007/s40899-024-01062-x.
- Mondal NC, Singh VS (2007) Integrated approach to delineate the contaminated groundwater in the tannery belt: a case study from Groundwater Group, National Geophysical Research Institute Hyderabad, India
- Monika D, Dimple Kumar S, & Giri A (2024) Watering Sundarban's fields: a systematic review of groundwater and surface water suitability for irrigation. *Applied Water Science*, 14, Article 66. <https://doi.org/10.1007/s13201-024-02122-5>.
- Moniruzzaman M, Sarker SC, & Islam ARMT (2024) A critical review on groundwater level depletion monitoring based on GIS and data-driven models: Global perspectives and future challenges. *HydroResearch*, 7, 285–300. <https://doi.org/10.1016/j.hydres.2024.05.001>.

- Naskar S, Mandal D, & Biswas B (2025) *Hydro-chemical assessment of groundwater quality using pollution index, quality indexes, fuzzy-GIS, graphical and multivariate techniques from a mining region of Eastern India*. Discover Water, 5, Article 48.
- Nugraha GU, Bakti H, Lubis RF, Mulyono A, Ulfa Y, & Sudrajat Y (2025) *Data driven resistivity zonation integrating inversion, Kriging and clustering for subsurface characterization in groundwater exploration*. Discover Water, 5, Article 62.
- Olisah Nzemeka C, Obichukwu Obiajulu O, & Chukwuarum Okechukwu D (2025) *Georesistivity, Aquifer Hydraulic Characteristics and Groundwater Potential Zones Using Vertical Electrical Sounding and Dar-Zarrouk Parameters at Umunze, Anambra State*. International Journal of Research and Innovation in Applied Science (IJRIAS), 10(6), 1561–1574. <https://doi.org/10.51584/IJRIAS.2025.100600117>.
- Oliveira MC, Lima RM, & Santos RL (2023) *Hydrogeophysical Characterization of Groundwater Using Resistivity Methods*. Hydrogeology Journal, 31, 1017–1035. <https://doi.org/10.1007/s10040-023-02610-5>.
- Orellana E, and Mooney HM (1966) Master tables and curves of vertical electrical sounding over layered structures. *Interciencia Madrid Spain* 150-166.
- Oseji JO, Asokhia MB, Okolie EC (2006) Determination of groundwater potential in Obiaruku and environs using surface geoelectric sounding. Environmentalist 26:301–308
- Oyeyemi KD, Adedoyin OO, Arogundade AB, & Olatinsu OB. (2022) Integrated geoelectrical and hydrochemical investigation for groundwater quality and aquifer characterization. *Environmental Earth Sciences*, 81, 307. <https://doi.org/10.1007/s12665-022-10358-8>.
- Palacky GJ (1987) Clay mapping using electromagnetic methods. First Break 5:295–306
- Patel RC, & Kumar Y (2003) Geomorphological study of Quaternary tectonics of the Doon Valley, Garhwal Himalaya, Uttarakhand, India. *Journal of Nepal Geological Society*, 28, 121–132.
- Patil VB, & Saraf VR (2025) Review of Groundwater Mapping and Water Quality Assessment Using GIS and Water Quality Index (WQI). International Journal of Intelligent Systems and Applications in Engineering.
- Paul RS, Rawat U, Sen Gupta D, Biswas A, Tripathi S, & Ghosh P (2020) Assessment of groundwater potential zones using multi-criteria evaluation technique of Paisuni River Basin from the combined state of Uttar Pradesh and Madhya Pradesh, India. *Environmental Earth Sciences*, 79, 1-24.
- Philip G (1995) Active tectonics of the Doon Valley. *Himal Geol* 6:55–62.
- Philip G (1996) Landsat thematic mapper data analysis for quaternary tectonics in parts of the Doon valley, NW Himalaya, India. *Int J Remote Sens*, 17(1):143–153.
- Piper AM (1944) A graphic procedure in the geochemical interpretation of water-analyses. *Eos, Trans. America. Geophys. Uni*, 25(6), 914-928.
- Raju BA, Rao PV, & Subrahmanyam M (2023) Estimating aquifer transmissivity using Dar-Zarrouk parameters to delineate groundwater potential zones in Alluri Seetharama Raju District, Andhra Pradesh, India. *Journal of Groundwater Science and Engineering*, 11(2), 116–132. <https://doi.org/10.26599/JGSE.2023.9280011>.
- Reynolds JM (1997) *An Introduction to Applied and Environmental Geophysics*. Wiley. Gives a clear explanation of field resistivity operation, electrode spacing, and measurement procedures used in VES.
- Rusli SR, Bense VF, Mustafa SMT, & Weerts AH (2024) The impact of future changes in climate variables and groundwater abstraction on basin-scale groundwater availability. *Hydrology and Earth System Sciences*, 28, 5107–5131.
- Rusli SR, Bense VF, Mustafa SMT, & Weerts AH (2024) The impact of future changes in climate variables and groundwater abstraction on basin-scale groundwater availability. *Hydrology and Earth System Sciences*, 28, 5107–5131. <https://doi.org/10.5194/hess-28-5107-2024>.
- Sahu PC, Sahoo H (2006) Targeting groundwater in tribal dominated Bonai area of drought-prone Sundargarh District, Orissa, India. A combined geophysical and remote sensing approach. *J Hum Ecol* 20:109–115
- Sarker MMR, Van Camp M, Hermans T, Hossain D, Islam M, Uddin MZ, Ahmed N, Bhuiyan MAQ, & Karim MM (2021) Geophysical delineation of freshwater–saline water interfaces in coastal area of Southwest Bangladesh *Water*, 13(18), 2527. <https://doi.org/10.3390/w13182527>.
- Sati D, Rautela P (1998) Neotectonic deformation in the Himalayan foreland fold-and-thrust belt exposed between the rivers Ganga and Yamuna. *Himal Geol*. 19:21–27.
- Sawyer CN, McCarty PL, Parkin GF (2003) *Chemistry for environmental and engineering Science*, 5th edn. McGraw Hill Inc., New York, pp 587–590
- Scanlon BR, Fakhreddine S, Rateb A, de Graaf I, Famiglietti J, Gleeson T, Grafton RQ, Jobbagy, E, Kebede S, Kolusu SR, Konikow LF, Long D, Mekonnen MM, Schmied HM, Mukherjee, A., MacDonald, A., Reedy, R. C., Shamsudduha, M., Simmons, C. T., Sun, A, Taylor RG, Villholth KG, Vörösmarty CJ, & Zheng C (2023)

- Global water resources and the role of groundwater in a resilient water future. *Nature Reviews Earth & Environment*, 4(2), 87–101. <https://doi.org/10.1038/s43017-022-00378-6>.
- Shankar KR (1994) Affordable water supply and sanitation. In: Groundwater exploration 20th WEDC Conference Colombo, Sri Lanka, 1994, pp 225–228.
- Sharma Prem V (1997) Environmental and Engineering Geophysics, *Environmental and Engineering Geophysics*, 1(1)
- Sharma SP, & Biswas A (2013) A practical solution in delineating thin conducting structures and suppression problem in direct current resistivity sounding. *Journal of earth system science*, 122, 1065–1080.
- Sharma ML, & Naik PK (2011) Integrated geophysical and hydrogeological approach for aquifer characterization in alluvial terrains.” *Journal of Applied Geophysics*, 75, 199–209. <https://doi.org/10.1016/j.jappgeo.2011.08.004>.
- Sharma PV (1997) Environmental and Engineering Geophysics. *Cambridge University Press*.
- Sharma S, & Choudhury P (2017) “Hydrogeological investigations in piedmont zones using VES and GIS: A case study.” *Environmental Earth Sciences*, 76, 511.
- Sikandar P, Bakhsh A, Rana T (2008) Geoelectrical resistivity method for assessing fresh groundwater layer at farmer’s fields. Paper submitted to the J Environ Geol
- Singh AK, Parkash B, Mohindra R, Thomas JV, & Singhvi AK (2001) Quaternary alluvial-fan sedimentation in the Dehradun Valley piggyback basin, NW Himalaya: tectonic and palaeoclimatic implications. *Basin Research*, 13(4), 449–471. <https://doi.org/10.1046/j.0950-091X.2001.00160.x>.
- Singh AK, Prakash B, Manchanda ML (2004) Tectonic geomorphology of the Dehradun Valley using digital terrain models and optically stimulated luminescence dating. *HimalGeol* 25(1):59–78.
- Singh AK, Prakash B, Mohindra R, Thomas JV, Singhvi AK (2001) Quaternary alluvial fan sedimentation in the Dehradun Valley piggyback basin, NW Himalaya: tectonic and palaeoclimatic implications. *Basin Res* 13:449–471
- Singh R, & Singh AK (2021) Groundwater quality degradation due to unplanned extraction and rapid urbanization in northern India.” *Environmental Monitoring and Assessment*, 193, 1–18.
- Singh RP, and Jamal A (2002) Dykes as groundwater loci in parts of Nashik District, Maharashtra, *J. Geol. Soc. India*, 59(2), 143–146.
- Singh Somvir, Gautam PK, Sarkar T, & Taloor AK (2022) Characterization of the groundwater quality in Udhm Singh Nagar of Kumaun Himalaya, Uttarakhand. *Environmental Earth Sciences*, 81(19), 468.
- Singh Somvir, Gautam PK, Kumar P, Biswas A, & Sarkar T (2021) *Delineating the characteristics of saline water intrusion in the coastal aquifers of Tamil Nadu, India by analysing the Dar-Zarrouk parameters*. Contributions to Geophysics and Geodesy, 51(2), 141–163. <https://doi.org/10.31577/congeo.2021.51.2.3>.
- Singh Somvir, & Mondal NC (2025) Aquifer hydraulic characteristics using Dar-Zarrouk parameters: A case study of Lohaghat block, Champawat district, Uttarakhand, India, *Discover Applied Sciences*, 7, 1293.
- Som Nath, Jayant Nath Tripathi, Upadhyay VK, & Harsh Kumar Verma (2024) Ground Water Potential Zone Estimation Using Vertical Electrical Sounding (VES) in Some Parts of Bundelkhand Region of Jhansi District of Uttar Pradesh, India *American Journal of Water Resources*, 12(3), 77–85.
- Somvir Singh, Farooq Ahmad Dar, Imran Khan (2025) Evaluating the groundwater suitability for drinking and irrigation purposes in Bhojpur district of Bihar, India, *Journal of Environmental Quality Management*, 18 September 2025, <https://doi.org/10.1002/tqem.70183>.
- Soupios P, Kouli M, Vallianatos F, Vafidis A, Stavroulakis G (2007) Estimation of aquifer parameters from surficial geophysical methods. A case study of Keritis Basin in Crete. *J Hydrol* 338:122–131.
- Stampolidis A, Tsourlos P, Soupios P, Mimides TH, Tsokas G, Vargemezis G, Vafidis A (2005) Integrated geophysical investigation around the brackish spring of Rina, Kalimnos Isl., SW Greece. *J Balk Geophys Soc* 8(3):63–73.
- Subramani T, Elango L, Damodarasamy R (2005) Groundwater quality and its suitability for drinking and agricultural use in Chithar River Basin, Tamil Nadu, India. *Environ Geol* 47:1099–1110.
- Syaputri TD, Suhendra S, Halauddin H, Lidiawati L, & Nurhidayah R (2024) Groundwater Study Using Vertical Electrical Sounding (VES) Data Based on Resistivity and Porosity of Rocks in Kampung Melayu, Bengkulu City.” *Jurnal Ilmiah Sains*, 24(1), 38–47.
- Telford WM, LP Geldart, and Sheriff RE (1990) Applied Geophysics, *Cambridge university press, New York*, 522577.
- Thakur PK, & Thomas T (2020) Aquifer characterization and groundwater potential assessment in Himalayan foothills using geophysical and GIS techniques.” *Environmental Earth Sciences*, 79, 1–18.

658 Thakur VC (1981) An overview of thrusts and nappes of Western Himalaya. In: Price NJ McClay KP (eds) Thrust
659 and Nappe Tectonics, Geol. Soc. Lond. (Spec. Publ.), pp 287–392.

660 Thakur VC, Pandey AK (2004) Late quaternary tectonics evolution of Dun in fault bend/propagated fold system,
661 Garhwal subHimalaya. *Curr Sci.* 87(11):1567–1576

662 Thakur VC, Pandey AK, Suresh N (2007) Late Quaternary-Holocene evolution of Dun structure and the Himalayan
663 frontal fault zone of the Garhwal Sub-Himalaya, NW India. *J Asian Earth Sci* 29(2–3):305–319.

664 Todd DK (1980) Groundwater hydrology. Wiley, New York.

665 Geological Survey US (2021) *Chapter A6.4. Measurement of pH*. In National Field Manual for the Collection of
666 Water-Quality Data. Techniques and Methods 9-A6.4. DOI:10.3133/tm9A6.4.

667 Valdiya, KS (1980) Geology of Kumaun Lesser Himalaya (p.291). Dehradun WIHG

668 Vasudev V, Sitharam TG, & Anbazhagan P (2021) Application of VES for groundwater potential assessment in hard-
669 rock terrain. *Environmental Earth Sciences*, 80, 123.

670 Venkateswara Rao B, Briz- Kishore BH (1991) A methodology for locating of potential aquifers in a typical semi-
671 arid region in India using resistivity and hydrogeological parameters. *Geoexploration*, 27, 55-64.

672 Wiederhold H, Kallesøe AJ, Kirsch R, Mecking R, Pechnig R, & Skowronek F (2021) Geophysical methods help to
673 assess potential groundwater extraction sites. *Grundwasser*, 26(4), 367-378.

674 Zohdy A, Eaton GP, Mabey DR (1974) Application of surface geophysics to ground-water investigations: techniques
675 of waterresources investigations of the United States Geological Survey, chap D1, book 2, 116 p.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [Table1.docx](#)
- [Table1.docx](#)
- [Table1.docx](#)
- [Table1.docx](#)
- [Table9.docx](#)
- [Table9.docx](#)
- [Table9.docx](#)
- [Table9.docx](#)
- [Table3.docx](#)
- [Table3.docx](#)
- [Table3.docx](#)
- [Table3.docx](#)
- [Table7.docx](#)
- [Table7.docx](#)
- [Table7.docx](#)
- [Table7.docx](#)
- [Table8.docx](#)
- [Table8.docx](#)
- [Table8.docx](#)
- [Table8.docx](#)
- [Table6.docx](#)
- [Table6.docx](#)
- [Table6.docx](#)
- [Table6.docx](#)
- [Table5.docx](#)
- [Table5.docx](#)
- [Table5.docx](#)
- [Table5.docx](#)
- [Table4.docx](#)
- [Table4.docx](#)
- [Table4.docx](#)

- [Table4.docx](#)
- [Table2.docx](#)
- [Table2.docx](#)
- [Table2.docx](#)
- [Table2.docx](#)