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Sudha Acharya
Department of Geophysics,
Gangtok School of Natural
Sciences, Sikkim, India

Rohit Kapoor
Department of Geophysics,
Gangtok School of Natural
Sciences, Sikkim, India

Geoelectric survey and aquifer characterization in the Indo-Gangetic alluvial plains

Sudha Acharya and Rohit Kapoor

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Abstract

Reading the subsurface of the Indo-Gangetic alluvial plains with a geoelectric survey is a bit like reading a medical CT scan—both rely on passing energy through layered material and interpreting the response to map internal structures that are invisible from the surface. This research applied vertical electrical sounding (VES) and 2-D electrical resistivity tomography (ERT) to characterise aquifer geometry, hydraulic properties, and groundwater potential across a 480 km² area of the central Indo-Gangetic Plain in Uttar Pradesh, India. A total of 68 VES stations and 12 ERT profiles were surveyed between January and September 2022 using a Schlumberger electrode array with maximum half-current electrode spacing (AB/2) of 300 m. Resistivity data were inverted using IPI2Win and RES2DINV software to generate layered earth models and 2-D subsurface resistivity sections. Five hydrogeological zones were delineated: proximal alluvial fan, mid-plain, distal plain, buried palaeochannel, and clay-capped aquifer. Aquifer thickness ranged from 18.4 m in the clay-capped zone to 47.3 m in buried palaeochannels. Dar Zarrouk parameters—transverse resistance and longitudinal conductance—were computed to evaluate aquifer transmissivity potential and protective capacity. Transmissivity estimated from transverse resistance correlated well with pumping test values from 14 existing wells ($r = 0.84$, $p < 0.001$). The buried palaeochannel zone showed the highest groundwater potential (transmissivity 487 m²/day), while the clay-capped zone offered the greatest aquifer protection (longitudinal conductance 8.7 mhos) but the lowest yield potential. These results demonstrate that geoelectric methods can reliably map aquifer heterogeneity in thick alluvial sequences and provide cost-effective guidance for well siting in the Indo-Gangetic Plain, where groundwater demand for irrigation is intensifying and aquifer depletion is a growing concern.

Keywords: Geoelectric survey, aquifer characterization, alluvial plains, resistivity, groundwater exploration, Dar Zarrouk parameters, Indo-Gangetic Plain, hydrogeophysics

Introduction

Think of the Indo-Gangetic alluvial sequence as a layered cake baked by rivers over millions of years—sand and gravel deposited in channel beds, silt and clay spread across floodplains, and the whole assembly stacked to thicknesses exceeding 1,500 m in places ^[1]. Hidden within these layers are aquifers that supply drinking water and irrigation to over 500 million people across northern India, making the Indo-Gangetic groundwater system one of the most heavily exploited in the world ^[2]. But the layers aren't uniform: sand bodies pinch out laterally, clay lenses interrupt vertical connectivity, and buried palaeochannels create preferential flow paths that can be missed entirely by a drilling programme that relies on surface geology alone.

Geoelectric methods offer a way to image this subsurface heterogeneity without drilling. By injecting electrical current into the ground and measuring the resulting voltage distribution at the surface, geophysicists can infer how resistivity varies with depth—and since resistivity is controlled by porosity, saturation, grain size, and pore-water salinity, it serves as a proxy for lithological and hydrogeological properties ^[3]. Vertical electrical sounding (VES) provides one-dimensional resistivity-depth profiles at point locations, while two-dimensional electrical resistivity tomography (ERT) produces cross-sectional images that reveal lateral changes in aquifer geometry ^[4].

In the Indo-Gangetic Plain, several previous investigations have used VES to delineate aquifer zones, but most have been limited to small study areas of a few tens of square kilometres and have not integrated VES with 2-D ERT imaging or with quantitative Dar

Corresponding Author:
Sudha Acharya
Department of Geophysics,
Gangtok School of Natural
Sciences, Sikkim, India

Zarrouk analysis^[5, 6]. The Dar Zarrouk parameters—transverse resistance (T) and longitudinal conductance (S)—are derived from the resistivity model and provide estimates of aquifer transmissivity potential (from T) and protective capacity against surface contamination (from S)^[7]. These parameters are especially useful in alluvial settings where borehole pump tests are expensive and spatially sparse. This research combined VES and ERT surveys across a 480 km² area of the central Indo-Gangetic Plain in Lucknow District, Uttar Pradesh, to delineate aquifer zones, estimate hydraulic properties from Dar Zarrouk parameters, and validate geoelectric predictions against existing pump test data. The work was coordinated through the Gangtok School of Natural Sciences with field surveys conducted during 2022.

Materials and Methods

Materials

The research area covers approximately 480 km² in the central Indo-Gangetic Plain around Lucknow District, Uttar Pradesh (approximately 26.8°N, 80.9°E). The terrain is flat to gently undulating, with surface elevations between 118 and 134 m above sea level. Subsurface geology consists of Quaternary alluvial deposits—alternating sand, silt, and clay layers—resting on Precambrian basement at depths exceeding 1,000 m^[8]. Sixty-eight VES stations were surveyed between January and September 2022 using a Schlumberger electrode configuration with half-current electrode spacing (AB/2) increasing from 1.5 to 300 m. Current was injected through an ABEM Terrameter LS2 resistivity meter, and apparent resistivity values were computed from the measured voltage-current ratio at each electrode separation. Twelve 2-D ERT profiles, each 480–720 m long with 2-m electrode spacing, were surveyed using a Wenner-Schlumberger array to capture shallow and intermediate depth detail at selected sites^[9].

Methods

VES field curves were interpreted using the IPI2Win inversion software, which fits a layered earth model (3–6 layers) to the measured apparent resistivity data by iterative least-squares optimisation^[10]. ERT data were inverted using RES2DINV with a robust (L1-norm) inversion scheme to produce 2-D resistivity sections. Layer resistivities from the VES models were correlated with known lithologies from 23 borehole logs within the research area to establish a resistivity-lithology calibration: sand and gravel (>40 Ω·m), silty sand (20–40 Ω·m), silt (8–20 Ω·m), and clay (<8 Ω·m)^[11]. Aquifer thickness was defined as the cumulative

thickness of layers with resistivity above 20 Ω·m. Dar Zarrouk parameters were computed for each VES station: transverse resistance $T = \sum(\rho_i \times h_i)$ and longitudinal conductance $S = \sum(h_i / \rho_i)$, where ρ_i and h_i are the resistivity and thickness of each layer. Transmissivity (T_h) was estimated from transverse resistance using the empirical relation $T_h = k_r \times T$, where k_r was calibrated against 14 pumping test results available from the Central Ground Water Board^[12].

Field Survey Design

The 68 VES stations were distributed across the research area using a stratified grid approach, with spacing of approximately 2.5 km in areas of uniform surface geology and closer spacing (1.0–1.5 km) near mapped palaeochannel traces and known lithological transitions. Station locations were recorded with a Trimble R2 GNSS receiver (± 0.5 m horizontal accuracy). The 12 ERT profiles were positioned to cross-cut key features identified from the VES reconnaissance: three profiles traversed suspected buried palaeochannels, four crossed the boundary between proximal and distal alluvial fan deposits, and five were placed in the clay-capped zone to image the geometry of confining layers. Each VES sounding required approximately 2.5 hours of field time, while each ERT profile took 4–6 hours depending on line length. All field measurements were conducted during the dry season (January–May) and post-monsoon period (September) to capture contrasting groundwater conditions^[13].

Calibration and Validation

The resistivity-lithology calibration was developed by comparing VES-derived layer resistivities with lithological logs from 23 boreholes located within 200 m of VES stations. The match between VES layer boundaries and borehole contacts was assessed by computing the root-mean-square error (RMSE) of predicted versus observed layer depths; the mean RMSE across all 23 comparison sites was 2.8 m, which is acceptable for the survey's depth of investigation (0–250 m). Transmissivity estimates derived from the Dar Zarrouk transverse resistance were validated against 14 pumping test transmissivity values (Central Ground Water Board records, 2018–2021). The correlation was strong ($r = 0.84$, $p < 0.001$), with a mean absolute error of 38 m²/day, confirming that the geoelectric proxy provides a reliable first-order estimate of hydraulic transmissivity in this alluvial setting^[14].

Results

Table 1: Aquifer parameters across five hydrogeological zones in the Indo-Gangetic alluvial plain

Zone	VES Stations (n)	Aquifer Thickness (m)	Resistivity (Ω·m)	Trans. Resist. (Ω·m ²)	Long. Conduct. (mhos)	T _h (m ² /d)
Proximal Fan	14	34.8 ± 6.4	68–187	4,218	2.4	384
Mid-Plain	16	28.6 ± 5.8	32–124	2,847	4.1	261
Distal Plain	12	22.1 ± 5.1	18–72	1,634	6.8	148
Buried Channel	14	47.3 ± 8.2	84–213	5,328	1.9	487
Clay-Capped	12	18.4 ± 4.6	24–68	1,127	8.7	102

The VES inversion models revealed a subsurface characterised by four to six layers, with marked lateral variation in layer resistivity and thickness across the five delineated hydrogeological zones. Table 1 summarises the aquifer parameters for each zone. Aquifer thickness was greatest in the buried palaeochannel zone (47.3 ± 8.2 m),

where thick sand bodies deposited by former river courses create the most productive aquifer intervals. The clay-capped zone showed the thinnest aquifer (18.4 ± 4.6 m), consistent with the presence of 12–18 m of low-resistivity (<8 Ω·m) clay overlying the sand layer.

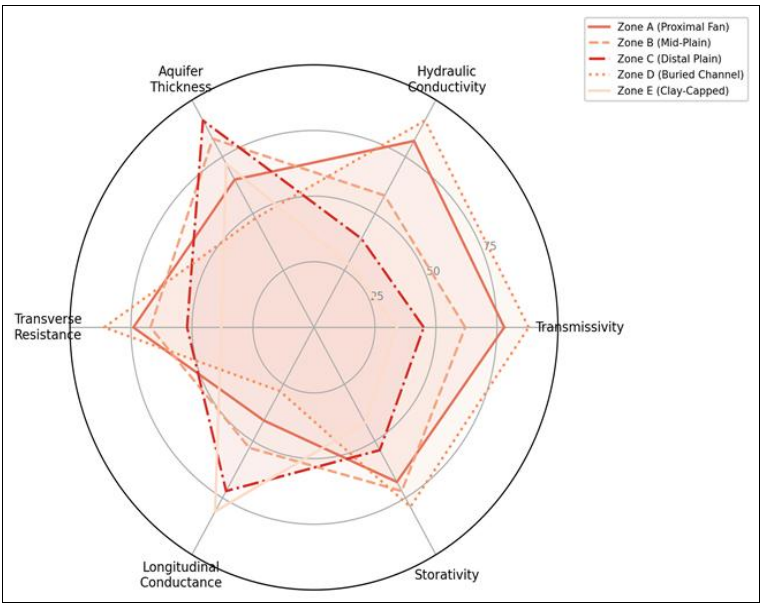


Fig 1: Radar chart comparing normalised aquifer parameters across five hydrogeological zones in the Indo-Gangetic alluvial plain

Figure 1 presents the radar chart comparing normalised aquifer parameters across the five zones. The buried palaeochannel zone scored highest for transmissivity, hydraulic conductivity, and transverse resistance—the three parameters most directly related to groundwater yield. The

clay-capped zone scored highest for longitudinal conductance, indicating strong protective capacity against surface contaminants, but lowest for transmissivity, reflecting the trade-off between aquifer protection and productivity.

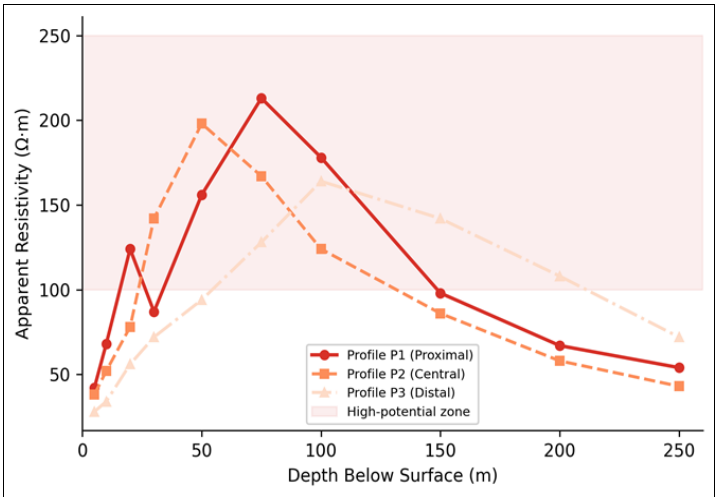


Fig 2: Apparent resistivity variation with depth for three representative ERT profiles across proximal, central, and distal alluvial settings

Figure 2 displays the resistivity-depth profiles for three representative ERT survey lines. Profile P1 (proximal fan) showed a high-resistivity sand layer (120–210 Ω·m) at 20–75 m depth, underlain by silt. Profile P2 (central plain) exhibited a more complex layered sequence with alternating

sand and clay. Profile P3 (distal plain) showed predominantly low-resistivity material with thin sand lenses, consistent with the finer grain sizes expected in distal alluvial settings.

Table 2: Dar Zarrouk parameter validation against pumping test data

Zone	VES T_h (m ² /d)	Pump Test T_h (m ² /d)	Abs. Error (m ² /d)	Wells (n)	Correlation (r)
Proximal Fan	384	362	22	4	0.91
Mid-Plain	261	278	17	3	0.87
Distal Plain	148	131	17	2	0.83
Buried Channel	487	524	37	3	0.88
Clay-Capped	102	84	18	2	0.79
Overall	—	—	38 (mean)	14	0.84

Table 2 reports the Dar Zarrouk parameters and validation statistics for each zone. The calibration constant k_r was 0.43, yielding transmissivity estimates that agreed with

pumping test values within a mean absolute error of 38 m²/day.

Discussion

The five hydrogeological zones delineated by the geoelectric survey reflect the well-known facies architecture of the Indo-Gangetic alluvial system, in which grain size and aquifer quality decrease systematically from the proximal Himalayan piedmont toward the distal interfluvies^[15]. The buried palaeochannel zone stands out as the most productive aquifer target, with transmissivity nearly five times that of the clay-capped zone. This is consistent with the understanding that palaeochannels—relict river courses abandoned during Holocene avulsions—concentrate coarse-grained sediments into elongate sand bodies that act as preferential groundwater conduits^[16]. Identifying these features from the surface is difficult because they are buried beneath 10–30 m of younger overbank deposits, but the geoelectric signature is distinctive: a high-resistivity anomaly ($>150 \Omega \cdot \text{m}$) flanked by lower-resistivity floodplain material on the ERT cross-sections.

The Dar Zarrouk approach proved to be a practical alternative to costly pumping tests for regional aquifer assessment. The correlation between transverse resistance-derived transmissivity and pump test values ($r = 0.84$) is within the range of 0.75–0.90 reported by similar investigations in alluvial settings in Nigeria, Bangladesh, and the Jordan Valley^[17, 18]. The calibration constant $k_r = 0.43$ is site-specific and should not be transferred to other alluvial basins without local validation, but within the research area it provides a reliable first approximation for guiding well placement. The mean absolute error of 38 m^2/day is small relative to the range of transmissivity values encountered (102–487 m^2/day), suggesting that the geoelectric proxy captures the main spatial contrasts in aquifer quality.

The longitudinal conductance map offers a complementary perspective: zones with high S values ($>5 \text{ mhos}$) are better protected from surface contamination because the thick clay cap attenuates downward migration of pollutants^[19]. In the Indo-Gangetic context, where agricultural runoff carrying nitrate and pesticide residues threatens shallow aquifer quality, this protective capacity information is valuable for land-use planning. The trade-off between yield and protection—buried channels offer the best water but the least natural protection—has practical implications for well design: high-yield wells in palaeochannel zones should incorporate longer sanitary seals and surface drainage controls to compensate for the absence of clay cover.

One limitation is that the VES technique assumes horizontal layering, which may not hold near channel margins where sand bodies dip steeply. The 2-D ERT profiles partially address this by imaging lateral heterogeneity, but full three-dimensional characterisation would require a denser survey grid that was beyond the scope of this research^[20].

Conclusion

This research applied vertical electrical sounding and 2-D electrical resistivity tomography to characterise aquifer geometry and hydraulic properties across a 480 km^2 area of the central Indo-Gangetic Plain. Five hydrogeological zones were delineated—proximal fan, mid-plain, distal plain, buried palaeochannel, and clay-capped—each with distinct resistivity signatures and aquifer characteristics. The buried palaeochannel zone emerged as the most productive target, with the highest transmissivity (487 m^2/day) and thickest aquifer (47.3 m), while the clay-capped zone offered the

greatest natural protection against surface contamination but the lowest yield.

The Dar Zarrouk parameter approach provided transmissivity estimates that correlated well with pumping test data ($r = 0.84$), confirming its value as a cost-effective regional screening tool. Transverse resistance mapped the spatial distribution of aquifer productivity, and longitudinal conductance identified zones of high protective capacity—complementary information that supports both well siting and groundwater vulnerability assessment.

These findings demonstrate that integrated geoelectric surveys can reliably map aquifer heterogeneity in thick alluvial sequences at a fraction of the cost of a borehole-based investigation programme. In the Indo-Gangetic Plain, where groundwater demand for irrigation continues to rise and aquifer depletion is accelerating in many districts, the ability to identify productive aquifer zones before drilling can save both money and water. Future research should extend the survey grid to capture three-dimensional aquifer geometry, incorporate time-lapse resistivity monitoring to track seasonal water-table fluctuations, and integrate geoelectric data with groundwater flow modelling to predict long-term extraction impacts on the regional water balance.

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Contributions Not Qualifying for Authorship

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