

Subsurface Structure Analysis Using the Geoelectric Resistivity Method for Groundwater Potential Identification

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Abstract

This article analyzes the use of the geoelectric resistivity method for interpreting subsurface structures and identifying groundwater potential. Groundwater exploration requires information on lithology, layer thickness, depth, lateral continuity, weathering, fracturing, and the distribution of water-bearing formations. A literature-based analytical approach was applied to synthesize 20 scholarly publications covering direct-current resistivity, Vertical Electrical Sounding (VES), Electrical Resistivity Tomography (ERT), and integrated hydrogeophysical applications. The synthesis shows that resistivity is controlled by lithology, porosity, pore-water salinity, saturation, clay content, and structural conditions, so resistivity anomalies should be interpreted together with geological and hydrogeological information rather than by a single numerical threshold. VES is particularly useful for resolving vertical changes in layered subsurface conditions, whereas ERT provides stronger visualization of lateral and vertical heterogeneity, including weathered zones, fractures, clay barriers, and possible aquifer bodies. Published case studies demonstrate that geoelectrical surveys can delineate aquifer depth, thickness, continuity, and structural controls and can support borehole siting when interpreted and validated with borehole, geological, or hydrochemical information. The article proposes a practical interpretation workflow consisting of survey design, apparent-resistivity acquisition, quality control, inversion, geoelectrical-layer interpretation, hydrogeological correlation, groundwater-potential classification, and field validation. The findings emphasize that the geoelectric method is a non-invasive and cost-effective reconnaissance tool, but groundwater potential should be confirmed through direct hydrogeological investigation.

Keywords

Geoelectric resistivity; Electrical Resistivity Tomography; Vertical Electrical Sounding; subsurface structure; groundwater potential; aquifer characterization.



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INTRODUCTION

Groundwater is a strategic component of water security because it can provide relatively stable supplies where surface-water availability is seasonal or spatially uneven. However, the resource is hidden below the ground surface, and the location, thickness, continuity, and hydraulic behavior of an aquifer cannot be determined reliably from surface observations alone. Geophysical methods therefore provide an important reconnaissance stage before drilling because they can characterize subsurface physical contrasts without extensive excavation. Electrical resistivity is especially useful because the measured response is influenced by lithology, pore-water content, fluid conductivity, and textural conditions (Binley & Kemna, 2005; Samouëlian et al., 2005).

The physical basis of the method is the contrast in the ability of subsurface materials to conduct an applied electrical current. In saturated granular formations, pore water commonly provides an important conduction pathway, while clay-rich materials may also produce low resistivity because of surface conduction and high water retention. Archie (1942) established an important relationship between formation resistivity, pore-fluid resistivity, and formation properties, although its assumptions are most appropriate for relatively clean granular formations. Consequently, resistivity should be treated as a proxy for subsurface conditions rather than as a direct measurement of groundwater volume or hydraulic conductivity.

Geoelectrical surveys are commonly implemented as Vertical Electrical Sounding (VES) and Electrical Resistivity Tomography (ERT). VES emphasizes the variation of apparent resistivity with electrode spacing and is therefore effective for estimating the depth and thickness of approximately layered formations. ERT, in contrast, acquires many measurements along a profile and inverts them into a two-dimensional or three-dimensional resistivity model, making it more suitable for heterogeneous settings with lateral changes, faults, fractures, weathering fronts, and irregular aquifer geometry (Dahlin & Zhou, 2004; Loke et al., 2013). Earlier methodological work also shows that electrical imaging is useful across groundwater, environmental, and engineering applications, but interpretation is sensitive to array geometry, resolution, and subsurface complexity (Griffiths & Barker, 1993).

Groundwater exploration studies illustrate the practical value of the method. VES surveys have been used to distinguish topsoil, clayey layers, weathered zones, fractured basement, and fresh basement and to identify horizons with stronger

groundwater potential (Coker, 2012). In Indonesia, VES in Manggar, Balikpapan identified several aquifer horizons and used formation-factor analysis to strengthen the interpretation of water-bearing sand (Sastrawan et al., 2020). A more recent East Java study combined VES and Advanced Data Modeling Techniques and reported aquiferous layers at approximately 90–120 m depth, demonstrating the continuing relevance of resistivity-based exploration in Indonesian hydrogeological settings (Wahyuni et al., 2024).

Despite its usefulness, resistivity interpretation is non-unique. Similar resistivity values may arise from different combinations of lithology, porosity, saturation, temperature, and water salinity. Low-resistivity material, for example, can represent clay or saline groundwater rather than a productive freshwater aquifer. Van Dam (1976) therefore emphasized that resistivity methods have important hydrogeological limitations and cannot independently provide parameters such as recharge, groundwater flow, or transmissivity. Contemporary studies similarly show the value of integrating ERT with borehole logs, sediment characterization, hydrochemistry, or other geophysical information (Uhlemann et al., 2017; Mishra et al., 2023).

Based on this context, the objective of this article is to synthesize how geoelectric resistivity data can be used to analyze subsurface structure and identify groundwater-potential zones. The specific objectives are to explain the physical interpretation of resistivity, compare VES and ERT for subsurface characterization, formulate an evidence-based interpretation workflow, and identify the principal uncertainties that should be considered before groundwater development.

METHODS

This study used a literature-based analytical design. Twenty scholarly publications were selected to represent the development of resistivity-based groundwater exploration from the foundational relationship between electrical properties and formation characteristics to recent applications of VES, ERT, and integrated hydrogeophysical interpretation. The literature includes methodological papers, review-oriented contributions, and case studies from Indonesia, Africa, Asia, and other hydrogeological settings. The selection emphasized studies that directly addressed subsurface structure, aquifer characterization, groundwater potential, resistivity interpretation, or methodological limitations.

The literature was analyzed in four stages. First, the physical controls on electrical resistivity were identified, including lithology, porosity, saturation, pore-water conductivity, clay content, and structural discontinuities. Second, the acquisition and

interpretation logic of VES and ERT was compared. Third, reported field cases were examined to identify recurring relationships between resistivity patterns and aquifer-bearing formations. Fourth, the evidence was synthesized into an interpretation workflow that distinguishes geophysical observation from hydrogeological inference.

For VES, the apparent resistivity response is interpreted as a function of electrode spacing and fitted to a layered-earth model. For ERT, a sequence of current injections and potential measurements is inverted to estimate a spatial distribution of subsurface resistivity. Array choice affects depth of investigation, lateral sensitivity, and model resolution; therefore, survey geometry should be selected according to the expected target depth and geological structure (Dahlin & Zhou, 2004; Loke et al., 2013). Quality control should include electrode contact checks, removal or review of anomalous measurements, assessment of inversion misfit, and geological plausibility checks.

The final interpretation in this article follows a correlation principle: a groundwater-potential zone is not defined by resistivity alone. Instead, resistivity anomalies are evaluated together with layer geometry, continuity, expected lithology, structural position, topographic setting, existing wells, and—where available—borehole and water-quality information. This approach is consistent with studies showing that resistivity can be highly informative for aquifer delineation but becomes substantially stronger when constrained by independent geological or hydrogeological observations (Muchingami et al., 2012; Mainoo et al., 2019).

FINDINGS AND DISCUSSION

1. Electrical resistivity as a proxy for subsurface structure

Electrical resistivity provides a spatially variable physical property that can be translated into geological and hydrogeological hypotheses. In a simple conceptual model, dry or compact competent materials tend to be more resistive than water-saturated and clay-rich materials, but the relationship is not universal. Water salinity can reduce resistivity substantially, while coarse, clean, and well-drained sediments can remain relatively resistive even when saturated. The resistivity response therefore reflects the combined effect of the solid matrix and pore fluid (Archie, 1942; Binley & Kemna, 2005).

An important implication is that the same numerical resistivity interval can have different meanings in different geological environments. For example, Mainoo et al. (2019) reported promising water-bearing zones in a Ghanaian sedimentary terrain

within a broad range of approximately 10–300 Ωm , whereas Sastrawan et al. (2020) associated potential aquifer sand in Manggar with values of about 221–281 Ωm . These examples should not be converted into a universal groundwater threshold. They demonstrate instead that local calibration against lithology and water chemistry is essential.

ERT adds a spatial dimension to this interpretation. Changes in resistivity that persist laterally may indicate facies changes or stratigraphic boundaries, whereas localized anomalies may indicate fractures, weathering pockets, channels, or discontinuities. In complex geology, 2D imaging can therefore provide information that a set of independent 1D soundings may not resolve adequately (Griffiths & Barker, 1993; Muchingami et al., 2012).

2. Subsurface layering and aquifer identification

A productive aquifer generally requires both water availability and a material or structure capable of transmitting and storing water. In unconsolidated settings, permeable sand and gravel may form the main aquifer, while clay can act as an aquitard. In hard-rock settings, groundwater may be concentrated in weathered and fractured zones rather than in intact bedrock. Consequently, interpretation should focus on the geometry and continuity of candidate water-bearing units rather than simply selecting the lowest or highest resistivity value.

Case studies support this structural interpretation. Coker (2012) used VES to identify topsoil, clayey sand, sandy clay, shale/clay basement, and fresh basement, and interpreted weathered and fractured horizons as productive zones. In the Bulawayo aquifer, Muchingami et al. (2012) demonstrated the advantage of resistivity imaging for assessing fractured unconfined aquifers and noted the limitations of purely 1D models for complex lateral structures. In Cambodia, Uhlemann et al. (2017) showed that ERT could map variable clay-layer thickness and discontinuities that influenced surface-water–groundwater interaction and aquifer vulnerability.

Examples from Egypt further demonstrate the structural value of VES. Mohamaden et al. (2017) identified a sandstone unit as the principal shallow aquifer in the northeast Qattara Depression and used resistivity and GIS to delineate probable structures. In El-Themed, Mohamaden et al. (2016) interpreted six geoelectrical units and used the resulting sections to investigate deep groundwater and subsurface structure. These cases indicate that the most useful interpretation is often the combination of layer resistivity, thickness, depth, and spatial continuity.

3. VES and ERT: complementary rather than competing approaches

VES is efficient when the primary question concerns the vertical sequence of approximately horizontal layers. By progressively increasing current-electrode spacing, the method samples greater effective depths and can estimate the resistivity and thickness of successive layers. This makes VES attractive for reconnaissance, especially where a limited number of soundings can be positioned using existing geological information. The East Java study by Wahyuni et al. (2024) demonstrates how VES can be integrated with additional modeling to improve aquifer interpretation.

ERT is preferable when lateral heterogeneity is expected. A profile can reveal inclined boundaries, channels, weathered zones, fractures, fault-related discontinuities, and changes in aquifer thickness that may be obscured by a 1D assumption. Dahlin and Zhou (2004) demonstrated that electrode arrays have different resolution and sensitivity characteristics, while Loke et al. (2013) documented the development of direct-current geoelectrical imaging and its expanding application to complex subsurface environments. Thus, survey design should follow the geological question rather than a fixed preference for one array.

The complementary use of VES and ERT can be especially valuable. VES can provide deeper vertical control at selected points, while ERT can map lateral continuity between points. A combined approach can also be strengthened by borehole lithology and hydrochemical measurements. Recent work on alluvial recharge settings, for example, combined ERT, sediment characterization, and time-lapse monitoring to identify permeable zones and evaluate changes in saturation following rainfall infiltration (Mishra et al., 2023).

Table 1. Indicative interpretation framework for groundwater-oriented resistivity surveys

Observed condition	Possible geological meaning	Groundwater implication	Interpretation caution
Low resistivity anomaly	Clay-rich layer, saline/brackish water, highly saturated fine sediment	May represent aquitard or water-bearing zone depending on lithology and water quality	Do not equate low resistivity automatically with freshwater aquifer

Moderate resistivity layer	Saturated sand/gravel, weathered rock, fractured zone in suitable geology	Potential water-bearing unit	Requires lithological and structural correlation
High resistivity layer	Dry coarse sediment, compact/fresh bedrock, resistive volcanic or crystalline rock	May represent aquifer boundary or low-permeability competent rock	High resistivity is not evidence of groundwater by itself
Laterally continuous contrast	Stratigraphic boundary, facies change, or regional contact	Can indicate aquifer extent or confining boundary	Check whether contrast is geological or caused by electrode/contact effects
Localized low/high anomaly	Fracture, channel, weathering pocket, cavity, or contamination	May indicate preferential flow or localized groundwater accumulation	Requires 2D/3D context and independent validation

4. Evidence from groundwater case studies

The reviewed case studies show that the method can provide operationally useful information at different scales. In Nigeria, Eugene-Okorie et al. (2020) used twenty VES locations to assess groundwater potential and aquifer vulnerability, demonstrating the value of a dense sounding network for spatial interpretation. Raji and Abdulkadir (2020) similarly used 110 Schlumberger soundings to investigate groundwater storage potential in bedrock aquifers, illustrating how extensive VES coverage can support regional hydrogeological mapping.

In Indonesia, the Manggar study identified four aquifers at depths of approximately 48–53 m and linked the interpretation to sand layers and formation-factor calculations (Sastrawan et al., 2020). In East Java, Wahyuni et al. (2024) reported aquiferous layers at 90–120 m with estimated production rates of 2–6 L/s when VES was integrated with ADMT. These studies show that the practical output of geoelectrical exploration can extend from qualitative layer identification to the

selection of candidate drilling targets, although the final well yield still depends on hydraulic properties and well construction.

ERT-based investigations provide additional evidence for structural interpretation. Mainoo et al. (2019) found strong correspondence between ERT results and drilling logs and reported improved borehole success when drilling was guided by ERT in the studied Ghanaian terrain. Sauret et al. (2015) found ERT useful for characterizing superficial aquifer heterogeneity when combined with geological, hydrogeological, and HVSR information. These findings support an integrated approach in which resistivity is used to reduce uncertainty about where to investigate, while direct observations are used to confirm the hydrogeological model.

5. From resistivity sections to groundwater-potential zones

A defensible groundwater-potential interpretation can be organized into seven steps. First, define the hydrogeological target, including expected depth, geological environment, and likely aquifer type. Second, select electrode configuration and profile orientation to maximize sensitivity to the expected structure. Third, acquire and quality-control apparent-resistivity data. Fourth, invert the data using an appropriate model and evaluate inversion misfit. Fifth, identify geoelectrical units and their boundaries. Sixth, correlate candidate units with lithology, structural setting, existing wells, and water-quality information. Seventh, rank candidate sites for verification drilling or complementary investigation.

The sixth step is critical because geophysical inversion is inherently non-unique. Two different subsurface models can sometimes reproduce similar surface measurements. The risk is especially important where clay and saline water generate overlapping low-resistivity signatures. Van Dam (1976) emphasized that resistivity cannot independently determine several hydrogeological parameters, and modern hydrogeophysics likewise treats resistivity as one component of a broader conceptual model (Binley & Kemna, 2005). Therefore, groundwater potential should be expressed as a level of evidence rather than as certainty.

Time-lapse ERT can extend this workflow from static mapping to dynamic monitoring. Coscia et al. (2012) showed that time-lapse ERT can track changes associated with groundwater dynamics, while Müller et al. (2010) demonstrated its value for imaging tracer movement and heterogeneity in a shallow aquifer. These applications indicate that changes in resistivity through time can provide additional evidence about infiltration, transport, and groundwater movement, provided that temperature, salinity, saturation, and other confounding factors are considered.

6. Methodological limitations and validation requirements

The first limitation is equivalence: different combinations of layer thickness and resistivity may produce similar apparent-resistivity responses. The second is environmental sensitivity: electrode contact, cultural electrical noise, topography, temperature, and pore-water chemistry can influence the measurements. The third is interpretive ambiguity: clay, saline water, and some highly saturated fine sediments can all appear electrically conductive. The fourth is scale dependence: a survey may resolve a structure at one spatial scale while missing smaller features that control local well productivity.

Validation should therefore be proportional to the importance of the groundwater decision. At minimum, candidate anomalies should be checked against regional geology and existing wells. Where drilling is planned, lithological logs and groundwater-level observations provide direct constraints. Hydrochemical measurements are also valuable because water quality can distinguish freshwater from saline or contaminated conductive zones. The integrated use of geophysics, geology, and hydrochemistry is consistent with recent groundwater-management literature emphasizing that geophysical methods are strongest when embedded in a broader hydrogeological framework (Nguyen et al., 2022; Mishra et al., 2023).

Overall, the evidence indicates that geoelectric resistivity is most appropriately used as a decision-support tool for groundwater exploration. Its major contribution is the ability to reduce uncertainty about subsurface geometry before expensive drilling. It should not, however, be presented as a direct measurement of groundwater quantity. Hydraulic testing, well performance, recharge assessment, and water-quality analysis remain necessary for final resource evaluation.

CONCLUSION

The geoelectric resistivity method provides a practical, non-invasive means of analyzing subsurface structure and identifying candidate groundwater-potential zones. The reviewed literature demonstrates that resistivity contrasts can help delineate lithological layers, aquifer thickness, weathered and fractured zones, confining units, and structural discontinuities. VES is particularly useful for estimating the vertical sequence of layered formations, while ERT offers stronger visualization of lateral and vertical heterogeneity. The two approaches can therefore be used complementarily according to the geological objective.

Groundwater-potential identification should be based on integrated interpretation rather than a universal resistivity threshold. Lithology, pore-water salinity,

saturation, clay content, structural position, layer continuity, and depth all influence the observed response. The most defensible workflow combines survey design, quality-controlled acquisition, inversion, geoelectrical interpretation, geological and hydrogeological correlation, and direct validation through boreholes, water levels, and water-quality measurements. The principal value of geoelectrical surveying is consequently its ability to focus subsequent investigation and reduce drilling uncertainty while recognizing the inherent non-uniqueness of geophysical interpretation.

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