APPLICATION OF GEOPHYSICAL AND GEOLOGICAL METHODS FOR GROUNDWATER COLLECTION IN AREAS WITH WATER STRESS

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ABSTRACT

The development of sustainable and efficient strategies for identifying and locating groundwater sources is key in rural areas with water scarcity and limited geological information. In the canton of Paján, in the province of Manabí, Ecuador, the climate is variable with a minimum monthly rainfall of up to 2 mm, which indicates low water availability. The primary source of water collection in the sector is groundwater, which is exploited through empirically drilled wells, leading to drilling in areas with low water potential. This scenario highlights the need to apply technical and economic strategies to optimize resources. This study aims to delimit areas with groundwater potential through the integrated application of geophysical methods and geological correlation for the optimization of drilling plans. The methodology consists of three phases: (i) analysis of cartographic, geological, and hydrological information, (ii) geophysical prospecting and interpretation using vertical electrical sounding, electrical resistivity tomography, and transient electromagnetic, and (iii) proposed drilling plan. The results revealed low-permeability materials (clays and silts) in the first 15 m, followed by permeable carbonate sandstone units. The correlation between the geoelectric layers and the lithological arrangement corresponds to a 25 m saturated layer with permeable and transmissive materials, which was validated by drilling an extraction well. The combination of methods allowed for greater spatial coverage, a significant reduction in field time, and optimization of resources, offering an efficient alternative for water projects in semi-arid tropical areas with high geological heterogeneity.

Keywords: aquifers, hydrogeological prospecting, electrical resistivity, drilling, water scarcity, vertical electrical sounding (VES), electrical resistivity tomography (ERT), transient electromagnetic (TEM).

1 INTRODUCTION

The growing demand for water in rural areas, coupled with the impacts of climate change, has intensified the need to identify new sources of sustainable water supply [1]. In many areas, especially semi-arid tropical regions, surface resources are overexploited or polluted, and climate instability reduces water availability [2]. Climate change has accentuated the irregularity of rainfall, causing prolonged dry seasons and extreme phenomena that affect the natural recharge of aquifers [3]. At the same time, population growth and increased agricultural and industrial activities are putting even more pressure on traditional water sources [4].

In addition, the contamination of surface water bodies by agricultural and domestic waste has reduced their viability as a usable source [5], [6]. This situation requires alternative and more technical approaches to ensure access to the resource, prioritizing the exploration and use of groundwater, which accounts for more than 97% of all available freshwater reserves



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worldwide, excluding glaciers and polar ice caps [7]. In this context, the development of groundwater prospecting strategies is presented as a key solution for sustainable supply [8].

Groundwater prospecting is the process of identifying and delimiting areas with potential for extraction. This task was traditionally carried out based on empirical observations, shallow test pits, or random drilling, which often resulted in technical failures or unnecessary costs [9]. These limitations have encouraged the use of more sophisticated methodologies, such as the integration of geological studies and geophysical tools, which are non-destructive and economically efficient and allow for indirect visualization of the subsoil [10]. Geophysical methods, especially vertical electrical sounding (VES), electrical resistivity tomography (ERT), and transient electromagnetic (TEM), have established themselves as practical tools for hydrogeological prospecting [11]. The need for its application arises from the limited availability of lithological data in rural areas and the high heterogeneity of the subsoil [12]. These methods allow the electrical resistivity of the subsoil to be mapped, facilitating the identification of saturated layers and permeable materials that are key to delimiting aquifers and locating boreholes [13]. Its correlation with geological field data, outcrops, well logs, and lithological maps increases the accuracy and reliability of geophysical data interpretation by reducing errors associated with materials with similar resistivities but different aquifer capacities [14]. Various studies have demonstrated the effectiveness of these methods. In India, Pal and Mukherjee [15] combined VES and geological data to locate contaminant-free aquifers. In Canada, Lévesque et al. [16] applied transient electromagnetic (TEM) surveys as a geophysical method to characterize a regional aquifer in the Saint-Narcisse moraine in the Mauricie region of Quebec, Canada. Also, Akip Tan et al. [17] applied ERT to correlate resistivity values with geotechnical results to assess soil capacity in a weathered tropical sedimentary area in Nusajaya, Johor (Malaysia).

The La Cascada sector, in the Paján canton (Manabí, Ecuador), is characterized by a tropical climate with highly seasonal rainfall, reaching monthly minimums of up to 2 mm [18]. Surface water sources are located several kilometres away, as corroborated in the field. Furthermore, according to data from the SIGTIERRAS [19] portal (Sistema Nacional de Información de Tierras Rurales e Infraestructura Tecnológica) regarding water resources in the area, there is no official record of the presence of defined aquifers; however, water wells can be seen approximately 1.5 km away. The current supply depends on empirically drilled wells, many of which have been inefficient. In addition, the area is dominated by loamy and loamy–sandy soil, along with areas of clayey, loamy–silty, and loamy–sandy soil. This diversity in texture influences water retention, drainage, and suitability for agricultural or construction uses [20]. This scenario reveals a significant technical need in groundwater resource management, where technical and economic strategies are required to optimize the identification of areas with aquifer potential [21].

Therefore, this study poses the following research question: To what extent can the integration of geophysical methods and geological data optimize the identification of drilling sites for groundwater extraction in areas with limited hydrogeological information? To answer this question, the following objective is proposed: to delimit areas with groundwater potential through the integrated application of geophysical methods and geological correlation for the optimization of drilling plans.

2 MATERIALS AND METHODS

This research applied geophysical prospecting techniques integrated with geological methods and principles of applied hydrogeology. This combination provided a comprehensive approach to water resources focused on sustainability, which enabled the development of a drilling plan. Fig. 1 shows the process outline, consisting of three phases.

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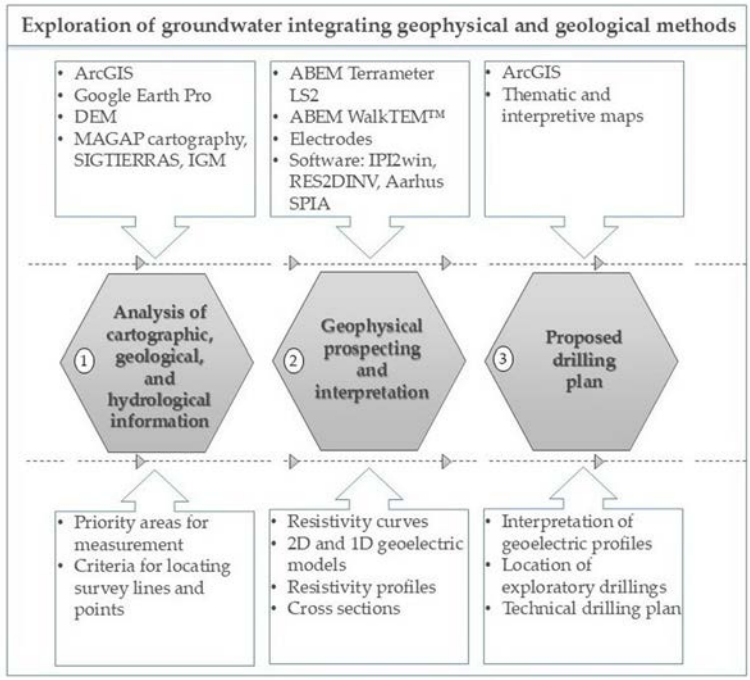


Figure 1: Diagram of methodological organization, structured into three distinct stages.

2.1 Analysis of cartographic, geological, and hydrological information

This initial phase consisted of compiling and reviewing secondary information for the preliminary characterization of the study area. Geological maps, hydrographic maps, precipitation records, and previous studies published by open platforms (e.g., Weather Spark) were used. Surface water sources (estuaries and streams) and existing wells were identified to establish hydrogeological references. Likewise, a preliminary geopedological characterization was carried out considering textures, slopes, and geomorphological units, based on maps from the Ministerio de Agricultura y Ganadería del Ecuador [20] (MAGAP Spanish acronym). Digital elevation models (DEM) and geographic information system tools (ArcMap v10.5 and Google Earth Pro) were used for topographic and geomorphological analysis, allowing for the delineation of micro-basins, drainage networks, slopes, vegetation cover, soil type, and potential recharge areas. In addition, logistical criteria such as accessibility and representativeness of the terrain were considered to define priority areas for geophysical surveying and the location of prospecting points.

2.2 Geophysical prospecting and interpretation

Geophysical measurements were taken using three methods: VES, ERT and TES. For the VES, the Schlumberger configuration with four aligned electrodes was used [22], and the equipment used was the ABEM LS2 Terrameter. The apparent resistivity measurements were processed with the IPI2win software, using curves for layer model adjustment. For ERT, 200 m linear profiles were measured with a system of 42 electrodes (spaced every 5 m)

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connected to the ABEM LS2 equipment via a control cable and a gradient-type array [23], [24]. Processing was performed with RES2DINV software, applying iterative inversion based on the least squares method. Finally, TEM measurements were performed with the ABEM WalkTEM system, using a 40×40 m square transmitter coil connected to an 8-amp current source and a receiver coil placed in the centre of the array [25]. Measurements were taken in the time domain, capturing the electromagnetic response induced in the subsoil. The data were processed using Aarhus SPIA software, generating one-dimensional resistivity models as a function of depth. At each station, coordinates were recorded using GPS, basic field information was collected, and a visual record of surface conditions and the type of cover was made. Based on the local geology and the materials obtained in the samples, the resistivity results were interpreted and compared with the ranges for conglomerates or carbonate sandstones (25–100 Ω·m), medium sand (15.1–25 Ω·m), silty sand (10.1–15 Ω·m), silt (5.1–10 Ω·m), and clay (1–5 Ω·m).

2.3 Proposed drilling plan

Based on geophysical data, areas for drilling were defined considering the presence of permeable materials, thickness, and continuity of the saturated layer. Recommendations were made for each drilling zone regarding depth and preliminary well design. In addition, aspects to be considered during drilling were suggested, such as visual testing of the recovered material every meter to record the type of sediment, texture, colour, and elemental composition to adjust the final well model, allowing for the appropriate selection of accessories.

3 RESULTS

3.1 Analysis of cartographic, geological, and hydrological information

Cartographic, geological, and slope analysis of the La Cascada sector allowed us to delimit the study area on colluvial–alluvial deposits, alluvial deposits, and sedimentary formations (Angostura, Borbón and Onzole). The geopedological units show a predominance of clayey and clay loam–sandy textures, with sporadic occurrences of sandy loam. The relief has slopes between 2% and 25%, with isolated sectors exceeding 40%. The hydrographic network consists of temporary and permanent watercourses that drain to the southwest, and the presence of registered wells indicates the use of groundwater resources in the area. This information formed the basis for the field design of the geophysical survey (Fig. 2).

3.2 Geophysical prospecting and interpretation

Geophysical prospecting in the La Cascada sector yielded a total of seven TEM, seven VES, and seven ERT, strategically distributed over the defined area (Fig. 3). The ERT profiles, with lengths of up to 200 m, show a surface zone characterized by resistivity values associated with clayey (1–5 Ω·m) and silty materials (5.1–10 Ω·m), followed by levels of silty sand (10.1–15 Ω·m) and medium sand (15.1–25 Ω·m), which coincide with field findings and cartographic information. In specific sectors, more resistive units interpreted as carbonate sandstones or conglomerates (25–100 Ω·m) were identified, with lateral continuity in different profiles, which were corroborated by samples taken from outcrops in the field.

The data that reached greater depth and show optimal characteristics for groundwater storage correspond to VES 4, 5, and 6. VES-04 recorded resistivities in the range of 5.1 to

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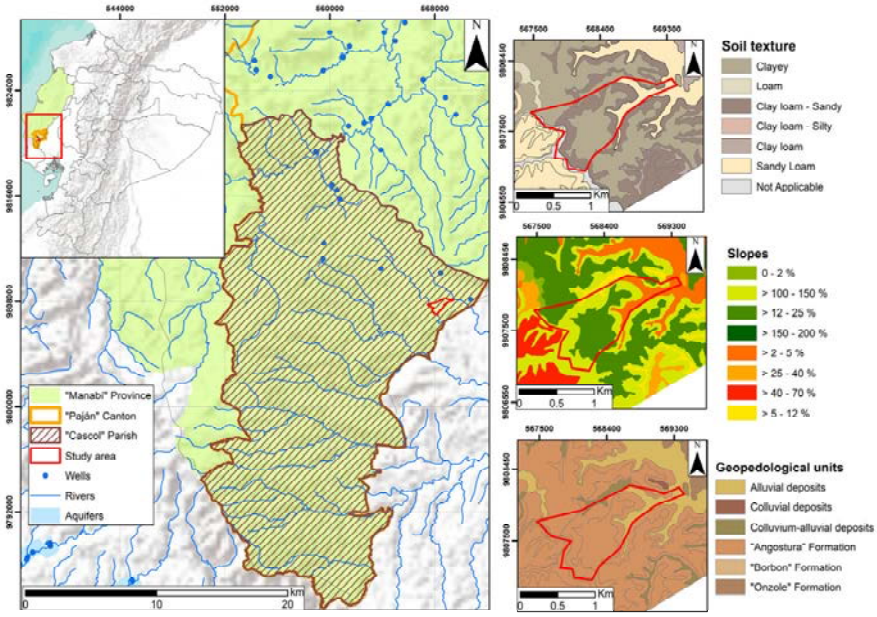


Figure 2: Location of the study area in the La Cascada sector, Paján canton, Manabí province, with the distribution of wells, hydrographic network, geopedological units, slopes, and soil textures.

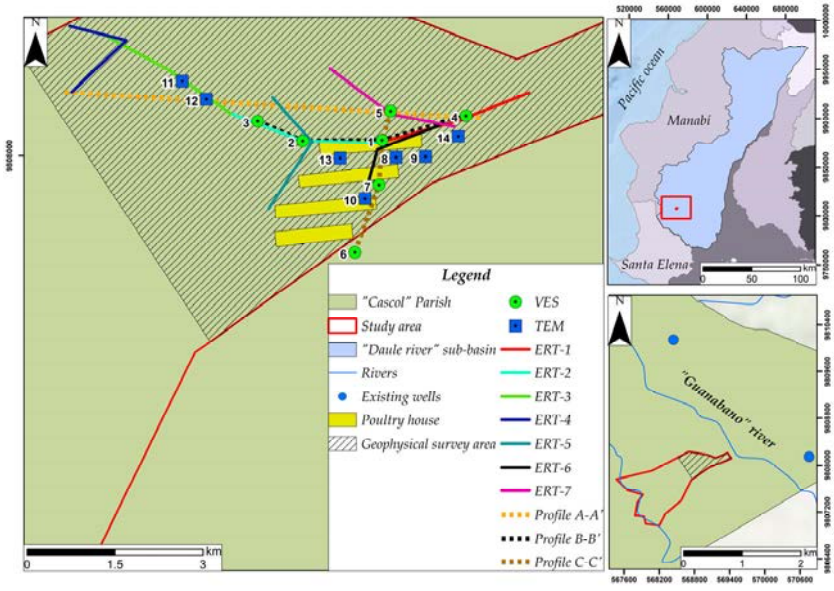


Figure 3: Spatial distribution of geophysical stations in the La Cascada sector. The locations of TEMs, VESs, and ERTs are shown, as well as the layout of profiles A–A′, B–B′, and C–C′.

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100 Ω.m composed of silts, medium sands, and a deep level of carbonate sandstones 49 m thick. VES-05 reached resistivities interpreted at the surface as clays and silts, followed by carbonate sandstones over a layer of medium sands. VES-06 showed a silty surface layer, an intermediate layer of carbonate sandstone, and a final thickness of 48.8 m of the same material at depth. (Fig. 4).

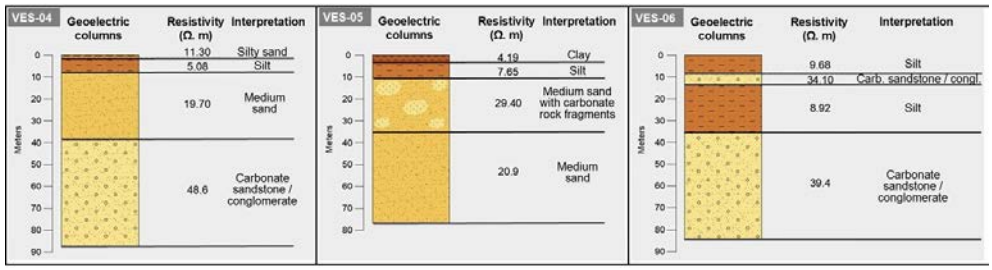


Figure 4: Geoelectric columns obtained at points VES-04, VES-05, and VES-06, showing the lithological distribution and resistivity ranges of each unit.

Profiles A–A′, B–B′ and C–C′ (Fig. 5) show the correlation of the interpreted geoelectric layers considering VES, TEM, and ERT data, which reveal a consistent stratigraphic arrangement in the study area. Profile A–A′ correlates TEM-05, VES-05, and ERT-04 and shows relatively homogeneous lateral continuity. Clays and silts predominate at the surface, while medium sands and carbonate sandstones with greater aquifer potential stand out at depth. Profile B–B′ integrates VES-01, VES-02, VES-03, and VES-04 and shows greater lateral heterogeneity, with variations in thickness, predominantly silts and clays at the surface and, towards the base, medium sands and carbonate sandstones intercalated with less permeable materials. Finally, profile C–C′ shows the correlation between VES-06, VES-07, and VES-01 with more uniform lateral continuity and the notable presence of surface silts and, at depth, carbonate sandstones and conglomerates of significant thickness, favourable for groundwater storage. These characteristics indicate that the three profiles share significant hydrogeological potential, with the central and southern areas being the most favourable for exploratory drilling due to the greater continuity and thickness of the permeable units. TEM surveys confirm the presence of these more permeable levels, recording conductive responses at the top and transitions to higher values at depth. VES complements this information, defining the thicknesses and depths of each layer detected in the profiles. The integration of these results allowed the development of coherent geoelectric models, which represent the lateral arrangement and continuity of the different materials in the subsoil of the studied area.

3.3 Proposed drilling plan

In this phase, an exploratory drilling plan was developed for the study area, where, within the area defined for geophysical studies, three priority zones (1, 2, and 3) were identified for drilling, selected based on the integration of results from geoelectric profiles, lithological units, and hydrogeological characteristics. These zones are strategically located in sectors with permeable layers and good aquifer potential, minimizing interference with existing infrastructure (poultry sheds) and respecting the local hydrographic network. Fig. 6 shows the location of geophysical profiles A–A′, B–B′ and C–C′, as well as the proposed wells and the Guanábano River as the central drainage system the area.

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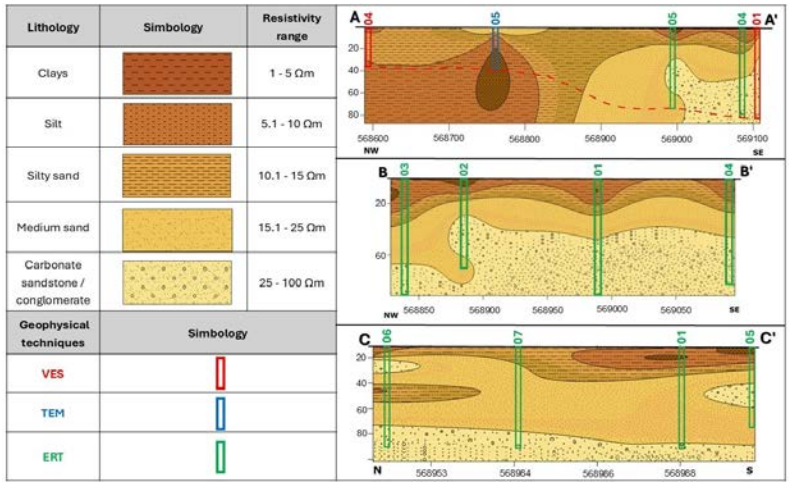


Figure 5: Geoelectric models obtained from the integration of ERT, VES, and TEM methods for profiles A–A′, B–B′ and C–C′, where the lithological symbols classify materials according to their resistivity ranges.

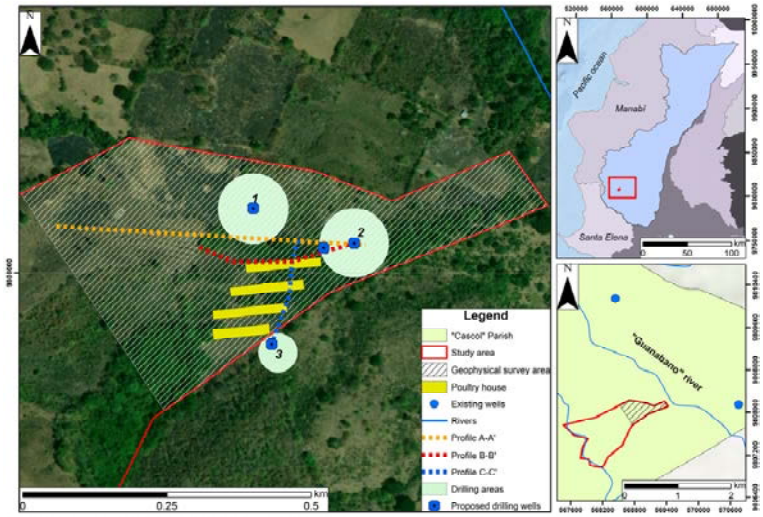


Figure 6: Proposed exploratory drilling plan for the study area. The areas prioritized for drilling (green circles) are shown based on the geophysical interpretation of profiles A–A′, B–B′ and C–C′.

4 DISCUSSION

The hydrogeophysical survey carried out in La Cascada highlights the importance of applying integrated methodologies in semi-arid contexts where surface water availability is limited. In areas with low rainfall, the use of combined techniques allows not only to

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characterize the subsoil but also to guide resource management towards sustainable exploitation, similar to what has been reported in exploration studies in the Bukombe district (Tanzania), where the integration of geophysics, geospatial, and geographic information systems (GIS) significantly reduced uncertainty in the selection of drilling sites [26]. The validation of an approach that integrates geological, geomorphological, and geopedological information with results from electrical methods (VES, ERT, and TEM) made it possible to delimit areas with lateral continuity and favourable aquifer thickness. This coincides with the findings of George et al. [27], who integrated VES, well data, remote sensing (RS), and GIS to identify areas with groundwater potential by obtaining thematic maps of lineament density, lithology, land use, drainage density, and slope as GIS layers.

Compared to studies that apply RS-GIS analysis to generate thematic layers and multi-criteria weighting models, such as in Egypt, where weights derived from AHP were used on morphological and climatic parameters [28], this work offers the advantage of directly measuring subsurface properties. The geoelectric characterization obtained here, with resistivity intervals between 5 and 100 Ω·m, allows impermeable materials (clays and silts) to be differentiated from permeable horizons (sands and carbonate sandstones), providing greater precision in drilling planning. In VES-04, a sequence with silts and silty sands at the surface was recognized, with a thickness of approximately 50 m of carbonate sandstone with a resistivity of approximately 48 Ω·m, indicating good storage capacity. In VES-05, shallow clayey–silty horizons are repeated, deposited on carbonate rock approximately 25 m thick and a medium sand package more than 40 m thick, which gives it high water potential. Finally, VES-06 shows greater heterogeneity, with intercalations of silts and carbonate sandstones, followed by a thickness of around 49 m of permeable material. This heterogeneous behaviour coincides with that described in studies carried out in basaltic environments in Solapur, India, where lateral variability in lithologies directly affects well productivity [29].

The geoelectric profiles A-A′, B-B′, and C-C′ show a consistent pattern of surface horizons with low resistivity silts and clays (<10 Ω·m), followed by more permeable units (medium sands of 15–25 Ω·m and carbonate sandstones >25 Ω·m). This pattern is comparable to the findings of Rey et al. [30] in southeastern Spain, where the aquifer and associated structures were characterized to a depth of approximately 220 m using ERT. In the case of La Cascada, the permeable units reach thicknesses of up to 50 m, confirming significant potential for exploitation. Comparison between profiles reveals that while sections A-A′ and C-C′ show more uniform lateral continuity, profile B-B′ shows greater lithological variability, a feature that makes drilling planning difficult and requires a higher density of boreholes; Similar conditions have been reported in parts of the Tunisian Sahel, where the heterogeneity of the Miocene–Pliocene–Quaternary aquifer directly affects hydraulic parameters and requires greater geological resolution [31].

The identification of carbonate sandstones and medium sands with lateral continuity justifies the design of the drilling plan at La Cascada. Prioritizing these areas reduces the risk of low-production wells, considered a key criterion in hydrogeophysical exploration, as is the case in the arid regions of Madagascar, where geoelectric surveys were integrated with isotopic studies to maximize efficiency in well locations [32]. This type of technical study contributes to water planning in rural areas, where the identification of permeable horizons and optimal drilling depths through the application of geophysical methods provides a basis for the design of community management plans aimed at mitigating water shortages in critical periods [33]. In this context, a comprehensive hydrological assessment with pumping tests and quality analysis would allow for sustainable water exploitation [34]. For example, in the Peshawar basin (Pakistan), the integration of geophysical data and pumping tests made

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it possible to estimate the transmissivity of the aquifer and identify areas of vulnerability associated with high clay content and increases in total dissolved solvents (TDS) levels [35]. Complementarily, various studies show that social participation can enhance technical achievements. For example, Bernedo Del Carpio et al. [36] demonstrated that the establishment of a community monitoring system reduced the overexploitation of aquifers and improved water quality in arid areas, while in Lebanon, a citizen science approach was implemented that involved students, teachers, and community organizations in monitoring groundwater quality, simultaneously strengthening environmental awareness and social ownership of the resource.

Future integration with isotopic tracers and hydrochemical studies would allow for the definition of recharge, residence times, and contamination risks of aquifers, as demonstrated in Madagascar, where this type of analysis complements geophysical prospecting to generate more reliable hydrogeological models [32]. The use of accessible methodologies such as VES, ERT, and TEM, compared to more expensive technologies with greater operational complexities such as high-resolution multispectral sensors and advanced geophysical methods (e.g., ground penetrating radar (GPR) and synthetic aperture radar (InSAR)), is a significant advantage in areas with limited budgets [37], [38]. In this sense, conventional electrical methods, when properly applied, offer equally effective results for guiding drilling.

5 CONCLUSIONS

The findings in the La Cascada sector confirm that the geological correlation of mapping, geopedology, and geophysical prospecting (VES, ERT, TEM) made it possible to delimit areas with greater groundwater potential accurately and constitutes an effective tool for identifying aquifers. The characterization of permeable horizons up to 50 m thick associated with carbonate sandstones and medium sands, through the correlation of geoelectric profiles, enabled the development of an efficient and replicable drilling plan. The results validate that an integrated approach to hydrogeological exploration contributes to the development of technical and sustainable management of groundwater resources, addressing the challenges of climate change and water shortages in vulnerable regions.

This methodological approach constitutes a substantial contribution, as it allowed for the optimization of drilling site selection and reduced uncertainty related to lithological heterogeneity. The correct application of conventional electrical methods can generate results comparable to those obtained with more expensive technologies, ensuring a balance between technical rigor and economic viability. In practical terms, the results represent a reliable input for guiding productive drilling plans and reducing the probability of failed wells, a recurring problem in empirical drilling in rural areas.

This study achieved a robust hydrogeological characterization; however, it recognizes the need to supplement this information with pumping tests, hydrochemical, and isotopic analyses to evaluate transmissivity, effective recharge, and long-term resource quality. Similarly, it is recommended that these results be incorporated into management programs that include maintenance and monitoring of extraction wells, as well as the implementation of Nature-Based Solutions for the sustainable use of resources.

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