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Using Electrical Methods for Groundwater Reservoirs Exploration in Cristalline Area of Man (West Côte d'Ivoire)

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Abstract

In West Africa, drinking water supply relies on the hard-rock aquifers. In Ivory Coast, the population growth along with the climate changes make drinking water resources highly vulnerable. Hard-rock aquifers, which occur within the weathered and fractured zones, are important groundwater resources in tropical region. These aquifers complexity, the lack of exhaustive studies lead to bad boreholes points siting. Geophysical investigations are used to obtain information about the crystalline basement rocks, which relates to the occurrence of groundwater. In Tonkpi region (western Côte d'Ivoire) is located such aquifer, poorly known, both in its reservoir's geometry and in the hydrogeological potential of the reserves it contains. This work deals with combining resistivity profiling, vertical electrical sounding with surface 2D geoelectrical resistivity mapping to characterize the ground and aquifers in a crystalline basement complex area of the Tonkpi region. Results allow to precise the local thicknesses of the 3 main units of our study area down to 50 m, being from top to down, saprolite, fissured-rock zone and rock substratum. The study shows that Schlumberger and Wenner alpha arrays for vertical electrical soundings integrated with the resistivity profiling imaging is efficient and enhances the aquifer characterization in basement complex terrain.

Keywords

Hard-Rock Aquifers, Electrical Methods, Groundwater Exploration, Côte d'Ivoire

1. Introduction

Hard rocks are plutonic and metamorphic rocks, from which we exclude marbles, as they can be karstified, and obviously limestones and non-metamorphosed volcanic rocks [1]. The geological formations of western Côte d'Ivoire are essentially made up of metamorphic rocks. These formations may contain aquifers which are generally located at a depth of less than 150 meters below ground surface. Hard rock aquifers very often have horizontal and vertical heterogeneity resulting from spatial variation in the lithology, geometry and hydraulic properties of their various composite parts [2]. In the Man region, boreholes equipped with hand-pumps and shallow wells are being drilled to exploit these hard rock aquifers. This mainly meets the needs of local populations for the water supply and small-scale irrigation. Unfortunately, water problems persist in this part of Côte d'Ivoire, as many of the boreholes that have been drilled have insufficient discharge or have fallen considerably. The study of Aoulou *et al.* (2021) [3] shows a significant heterogeneity of instantaneous discharge in this region. It varies between 0 and 60 m^3/h and the median and standard deviation are 2.7 m^3/h and 8.5 m^3/h, respectively. The discharge rate class [0, 5 m^3/h] is most represented (69.6%). Within this class, the discharge classes between 0.5 and 2 m^3/h are the most represented [3]. As a result of population growth and uncertainty about the intra-seasonal sustainability of surface water, new drinking water supply projects in rural areas are looking for minimum discharges of 5 m^3/h [4]. Unfortunately, the occurrence to have a minimum discharge of 5 m^3/h is about 30% in this region [3]. However, it should be noted that groundwater and aquifers in this region have already been studied using different approaches: remote sensing and geographic information system [5]-[8], statistical and geostatistical [3] [9]-[11], hydrogeological modeling [12]. Overall, it emerges from these works the need to continue investigations to improve the characterization of these aquifers, particularly their geometries and structures. Geophysics can greatly contribute to this better understanding of aquifers. Indeed, geophysical methods are essential for reducing uncertainties related to borehole placement and improving the understanding of the hydrogeology of hard rocks at different scales [13]-[16]. Geophysical methods have the particularity of being non-destructive and investigating large areas by giving much more information [17]. The main objective of this study is to determine the geophysical parameters as a guide in the establishment of high yield of boreholes in the basement zone. Specifically, this involves implementing electrical profiling to detect conductive anomalies; establish the resistivity map of the sites studied to identify conductive axes and potential zones; and to determine the lithological structuring in place by means of vertical electrical soundings and electrical resistivity tomography.

2. Study Area

The study area in Man (Tonkpi region, **Figure 1**) is located between latitudes 6.57˚ and 8.15˚ North and longitudes −7.07˚ and −8.43˚ West. It is bordered to the West by Guinea and Liberia. It covers an area of 12,284 km^2 and constitutes the extension of the Fouta Djalon mountains chain, most of which is in Guinea. The relief of the Tonkpi region which is of mountainous type, is the most rugged area of Côte d'Ivoire. The climate is of tropical type, with an annual average temperature of 25˚C and rainfall of 1632 mm. The hydrographic network is fed by the Sassandra, Cavally and Bafing rivers, and their tributaries. From the geological point of view, the Tonkpi region is located in the Liberian domain of the Man Ridge. This ridge continues westward through Archean formations of Liberia and Sierra Leone. It is bounded in its eastern part by the Sassandra fault, the boundary between the Liberian and Eburnean domains. This region can be divided into two vast sets separated by the Man-Danané fault, oriented N 70˚ [18] [19]. There is a very old zone of crystalline and crystallophyllian basement, with among others charnockites, norites, orthogneiss, sillimanites paragneiss, quartzites, enderbites rocks. The relief of the Tonkpi region which is of mountainous type, is the most rugged area of Côte d'Ivoire.

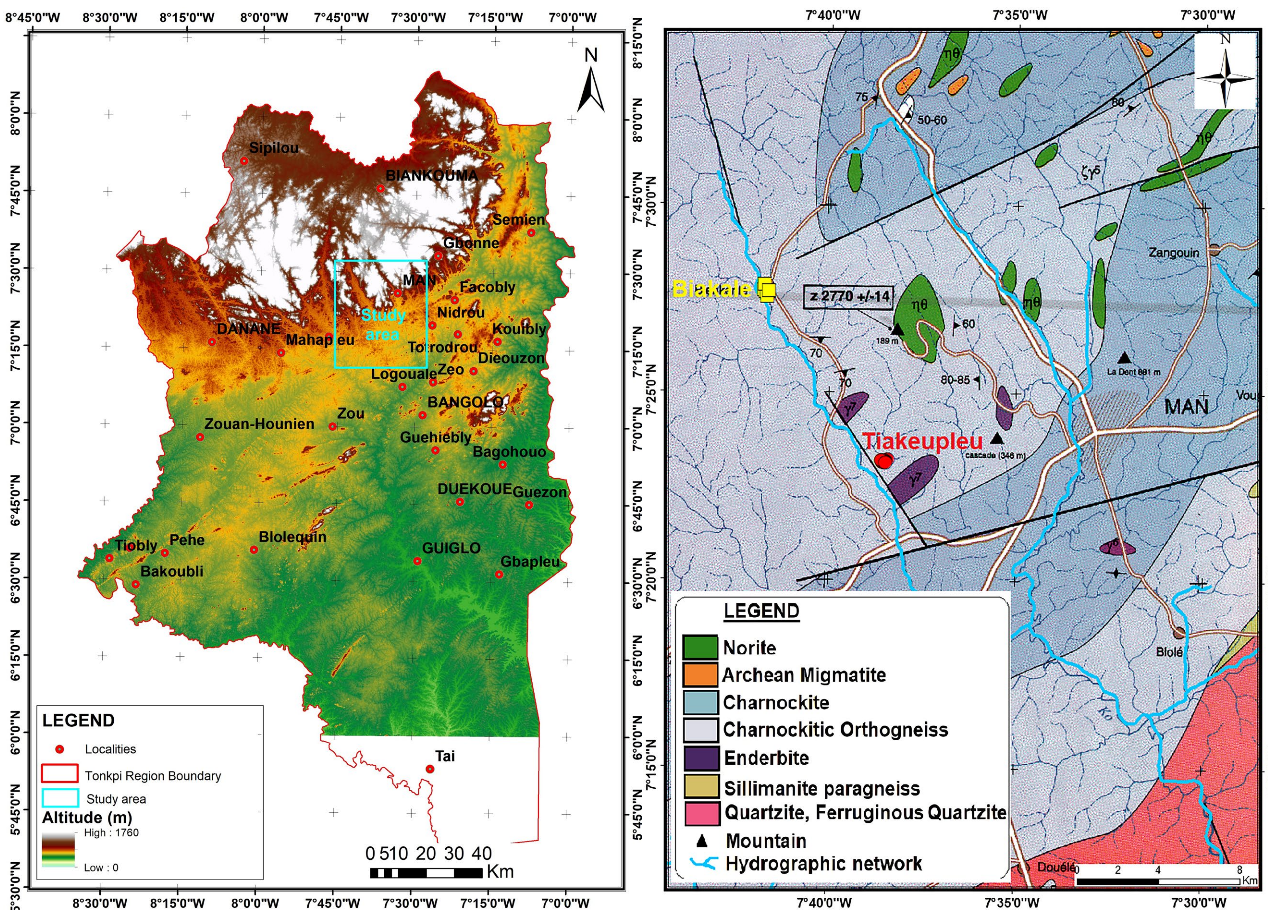


Figure 1. Map of the Tonkpi region/Geology of the study area.

3. Material and Methods

3.1. Geophysical Field Survey Equipment

Several materials are used to carry out this study. For electrical profiling and vertical electrical soundings, the equipment used consists of the following: A resistivity meter was used to perform various resistivity measurements (1D profiling, VES, and 2D ERT). It was associated with two multinode boxes (16 electrodes each) for intelligent electrode recognition and a multiplexer. A Garmin GPS was used to locate points and record the geographical coordinates of the field measurement stations.

In the context of geophysical studies, a sequence of operations is to be carried out for effective prospecting and ground characterization. These activities are schematized in a diagram in Figure 2.

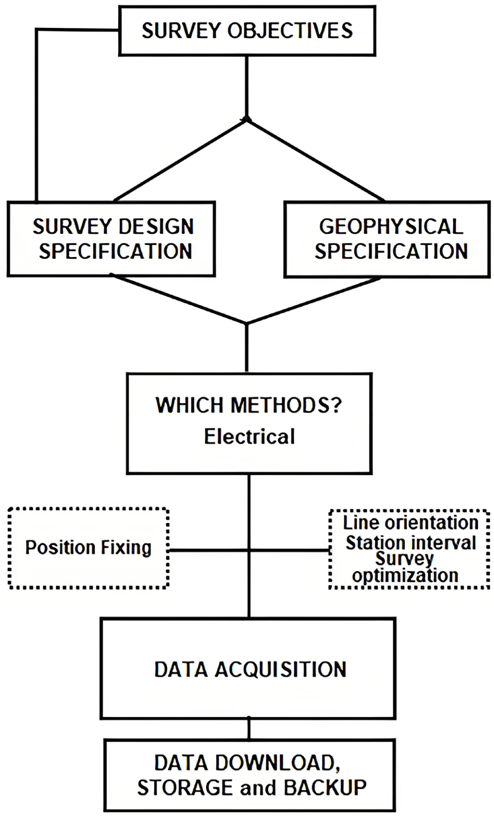


Figure 2. Schematic flow diagram to illustrate the decision-making leading to the selection of geophysical and utility software [20].

3.2. Processing Equipment

The data processing equipment used consists essentially of computer tools and software such as Electre II for generating the measurement sequence; Prosys II for transferring the data from the resistivity meter to the computer, their analysis and the pseudo-section display; WinSEV 6 for processing VES data and their interpretation; and BERT for ERT data inversion [21].

3.3. Implementation Method and Procedures

3.3.1. Data Measurements

Electrical methods are applied to map the resistivity structure of the underground.

Rock resistivity is of special interest for hydrogeological purposes: it allows, e.g., to discriminate between fresh water and salt water, between soft-rock sandy aquifers and clayey material, between hard-rock porous/fractured aquifers and low-permeable clay stones and marlstones, and between water-bearing fractured rock and its solid host rock. The ground resistivity is measured by injected currents and the resulting potential differences at the surface. The pairs of electrodes are required: electrodes A and B are used for current injections, while electrodes M and N are for potential difference measurements (**Figure 3**). For an inhomogeneous ground (with real geological conditions) and arbitrary electrode arrangement, the apparent resistivity as the relevant petrophysical parameter can be calculated from the current I and the potential difference U by:

$$\rho_a = K\frac{U}{I} \tag{1}$$

where ρ_a is the apparent resistivity (unit: Ω·m), U is the potential (unit: volts), I is the current injected (unit: amperes). K is called geometric factor (unit: meter) and can be calculated from the electrode spacing by:

$$K = \frac{1}{2\pi}\left[\left(\frac{1}{AM}-\frac{1}{BM}\right)-\left(\frac{1}{AN}-\frac{1}{BN}\right)\right] \tag{2}$$

This dataset is computer-processed to obtain the underground resistivity distribution, which needs to be interpreted in terms of geological structures.

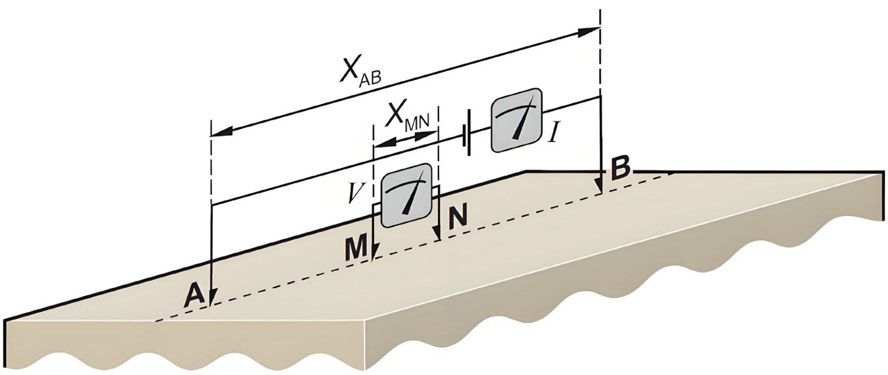


Figure 3. Electrode arrays for Schlumberger configuration.

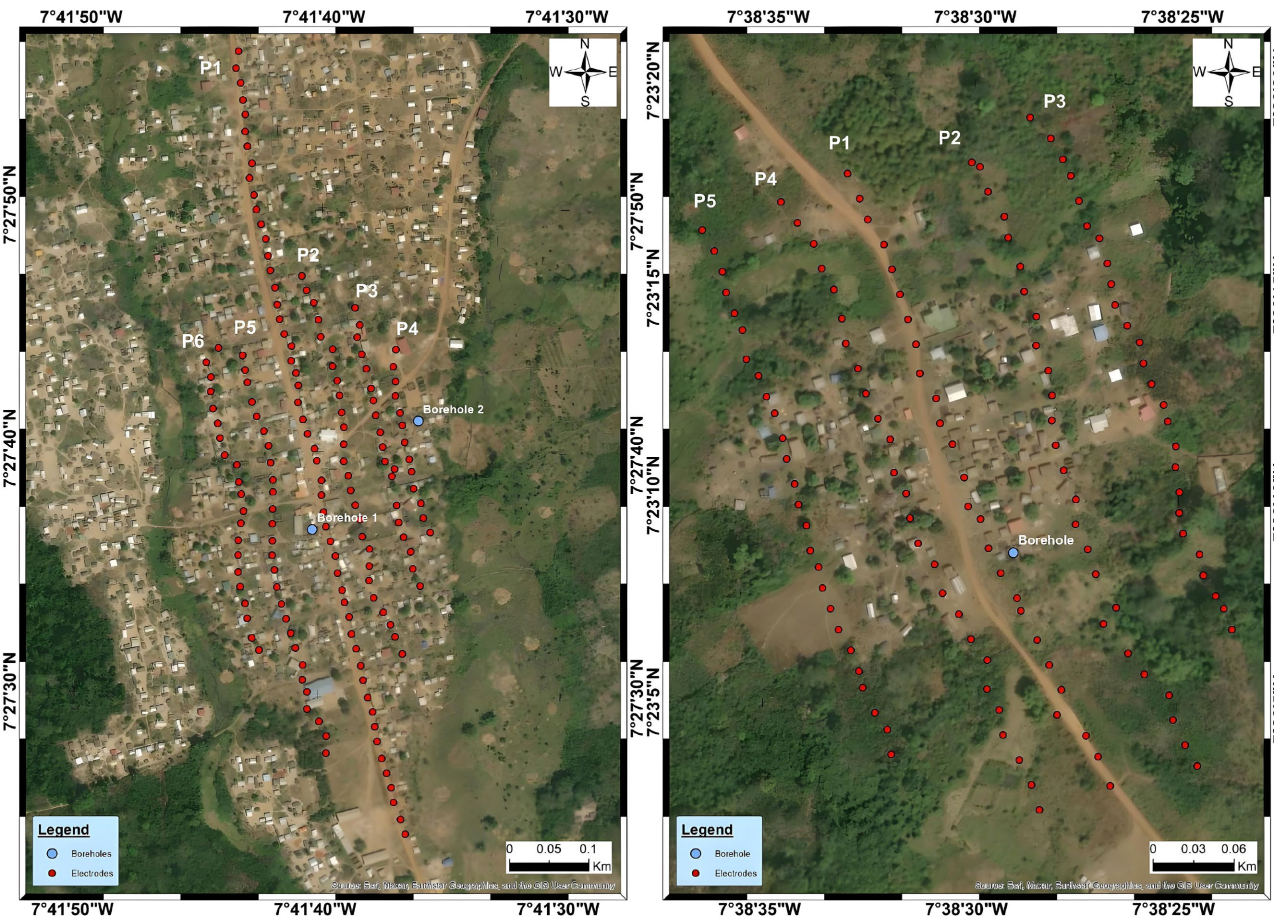
3.3.2. Horizontal Prospecting data Acquisition by Resistivity Profiling

The resistivity profiling survey involves the measurement of apparent resistivity data using the Schlumberger array along eight profiles. In Tiakeupleu village, five (5) profiles were carried out, with profiles P1, P3, and P5 conducted in a N160˚ direction, and profiles P2 and P4 conducted in the opposite direction, N340˚, and thus parallel to each other. In Biakalé village, six (06) profiles were carried out, with P1, P3, and P5 conducted in a N174˚ direction, while P2, P4, and P6 were in the opposite direction, N354˚. In practical field surveys, the choice of the Schlumberger array is made with the current injection electrodes A and B spaced at 200 m (AB = 200 m), the potential differences resulting from a spacing of 20 m between electrodes M and N (MN = 20 m) and a 20 m offset for all profile measurements.

A graph of the apparent resistivity as a function of the position of the stations on the profile was produced on a semi-logarithmic scale to highlight different types of anomalies along the profiles. Depending on the measurement step and the inter-profile distance, a mesh of the two localities was carried out, providing the necessary elements for an electrical resistivity map.

The apparent resistivity datasets were measured manually using a resistivity meter; the electrode positions were clearly marked and pegged before the commencement of the data measurements for each traverse and sounding. This ensured quality data measurements by minimizing electrode positioning error. Also, care was taken to ensure good connectivity between the electrodes and the connecting cables while maintaining effective contact between the ground and the electrodes before each measurement.

The injected current was automatically selected from a minimum of 1.0 mA to a maximum of 500.0 mA by the resistivity meter based on the subsurface conductivity. It was set for repeat measurements with a minimum data stacking of 3 and a maximum of 6; thus, each data point was sampled 3 - 6 times before displaying



(a) (b)

Figure 4. Measurement points locations in Biakale (a) and Tiakepleu (b).

the median. The root-mean-square error in the data measurements was generally less than 4%. However, isolated cases in which the root-mean-square error was up to 5% were repeated after ensuring the electrodes were maintaining good contact with the ground. Figure 4 presents the measurement points locations in Biakale and Tiakeupleu.

3.3.3. Vertical Prospecting by VES

For VES, surveys are carried out on the conductive anomalies detected previously during electrical profiling. Their purpose is to characterize the geometry of the ground under these measurement stations. VES is applied to a horizontally or approximately horizontally layered earth. Geological targets may include rocks of different lithologies, layered aquifers of different properties, rocks overlying igneous rocks, or the weathering zone of igneous rocks. In the most favorable case, the

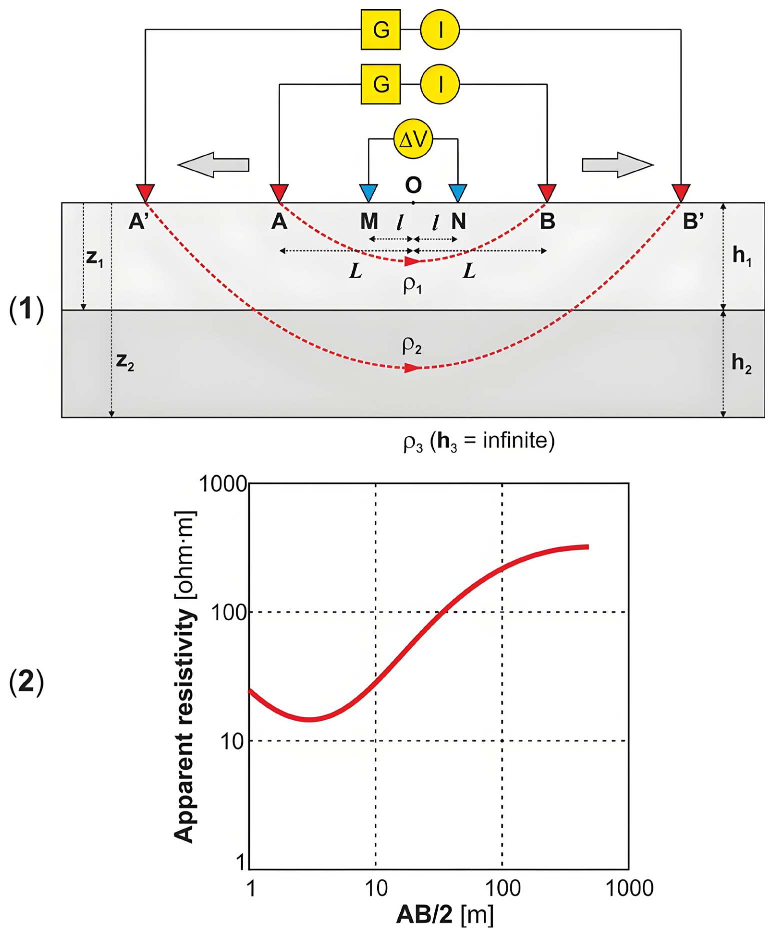


Figure 5. Principle of VES investigation of the subsurface. (1) Configuration of the electrodes for a Schlumberger sounding array; dashed curves represent current flow paths, l = MN/2 is the half-spacing of the measurement electrodes, L = AO = BO = AB/2 is the half-spacing of the current electrodes. (2) Example of apparent resistivity sounding curve obtained for a layered terrain, showing the variation of apparent resistivity with the current electrodes half-spacing. Electrodes M and N are placed in a fixed position with a short spacing between them, whereas A and B electrodes are placed symmetrically on the outer sides of the potential electrodes (with the spacing AB ≫ MN), [22]).

number of layers, their thicknesses, and resistivities are the outcome of a VES survey. The basic idea of resolving the vertical resistivity layering is to stepwise increase the current-injecting electrodes AB spacing, which leads to an increasing penetration of the current lines and, in this way, an increasing influence of the deep-seated layers on the apparent resistivity. The step-wise measured apparent resistivities are plotted against the current electrode spacing in a log/log scale and interpolated to a continuous curve. This sounding curve is the basis of all data inversion to obtain the resistivity/depth structure of the ground (**Figure 5**) [23].

We used Schlumberger linear electrode configurations for resistivity measurements. Because of practical and methodical advantages, VES mostly use the symmetrical Schlumberger configuration where the voltage electrodes M, N are closely spaced and fixed to the center of the array and the current electrodes A, B move outwards. The geometrical factor is (for AB ≫ MN). The interpretation was done using the WinSEV software, which represents the data in sounding curve form. These curves have different shapes, which make it possible to define several types of curves. They represent characteristic layer arrangements and juxtapositions under the stations.

$$K_{\text{Schlumberger}} = \frac{\pi}{MN}\left(\frac{AB}{2}\right)^2 \tag{3}$$

3.3.4. Data Processing and Inversion

The apparent resistivity datasets for the resistivity profiling were plotted against measurement station positions (distance) on a semi-logarithmic graph sheet. The resulting field curves obtained were analyzed to identify conductive anomalies for which electrical soundings will be carried out, and, additionally, to determine the conductive, resistive, or intermediate facies along the profiles.

The apparent resistivity datasets for the resistivity soundings were plotted against half-current electrode spacing (AB/2) on a bi-logarithmic graph sheet. The resulting field curves were then curve-matched with Schlumberger master curves to determine the geoelectric layers and estimate the corresponding geoelectric parameters. The estimated number of layers and their geoelectric parameters were then used as initial model parameters for computer iteration using the WinSEV program. The iterative procedure produced the model parameters for the delineated geoelectric layers.

3.3.5. Resistivity Mapping

Targets for resistivity mapping (or profiling) are near-surface resistivity anomalies, induced by fracture zones, cavities, or waste deposits. Any common electrode configuration can be utilized for mapping purposes. Typically, the chosen four-point configuration remains consistent and is traversed along profiles, while recording the apparent resistivity. In this study, the Schlumberger configuration was employed for conducting the electrical profiling along with vertical electrical soundings. Before fieldwork commences, the optimal electrode spacing of the configuration is determined through model calculations, provided assumptions regarding the resistivity and depth of the target, as well as the resistivity of the surrounding material, are feasible.

3.3.6. ERT Implementation

ERT surveys were conducted along a conductive axis identified on the resistivity map obtained in each village. The objective was to determine the lithostratigraphic structure (number of superimposed layers, thickness, depth, resistivity) beneath each conductive axis. For this purpose, the Wenner alpha array was utilized on a profile of 32 electrodes spaced 5 meters apart, resulting in a maximum line length of 155 meters. The profile orientation was N280˚ at Biakalé and N250˚ at Tiakeupleu.

With the array, line orientation, and materials defined, data acquisition was conducted by first preparing the measurement sequence using Electre II software, resulting in 155 quadrupoles, which are combinations of 4 electrodes, 2 for current injection (A and B) and 2 for measuring potential difference between electrodes M and N (see **Figure 6**). A sequence of 32 electrodes with an inter-electrode distance of 5 meters was defined for this purpose. Subsequently, Prosys II software was employed to upload the elaborated sequence from the computer to the resistivity meter. An automatic injection mode (multi-electrode mode) was then defined, as it optimizes injection to deliver the required current while conserving energy.

Following measurements, acquisition data stored in the resistivity meter were transferred to the field computer using Prosys II software for pre-processing (scanning, filtering) and processing (data inversion with BERT software). The purpose of ERT was to delineate different resistivity ranges according to depth and the characteristics of crossed formations, facilitating the creation of a 2D imagery of the ground.

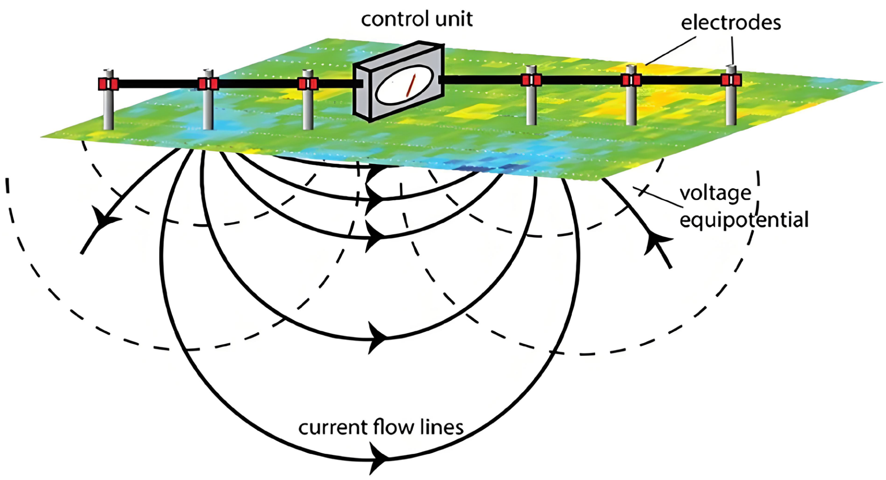


Figure 6. Example of ERT data collection.

Multiple electrodes are installed along the ground surface, and two electrodes at a time are used to drive current into the subsurface. The resulting voltage difference is measured between two or more potential electrodes. Flow and equipotential lines are analogous to those estimated from the groundwater flow equation, where current and fluid flux are mathematically parallel, as are voltages and heads, which are both potentials. The synthetic modeling workflow [23] is described in 4 main steps (**Figure 7**). These steps are: 1) assign best-guess physical properties for the hypothetical subsurface model; 2) forward model, *i.e.*, calculate the data that would result from the assumed 'true' model entered by the user in the first step and corrupt the data with random errors for realism, generating 'synthetic data'; 3) analyze the synthetic data by inverse modeling to produce an image, or tomogram; and 4) compare the inverted synthetic image with the assumed true model. If the synthetic image does not sufficiently resolve the target sought, *i.e.*, a light non-aqueous phase liquid plume in this schematic, field implementation of the method will likely fail and should be discouraged.

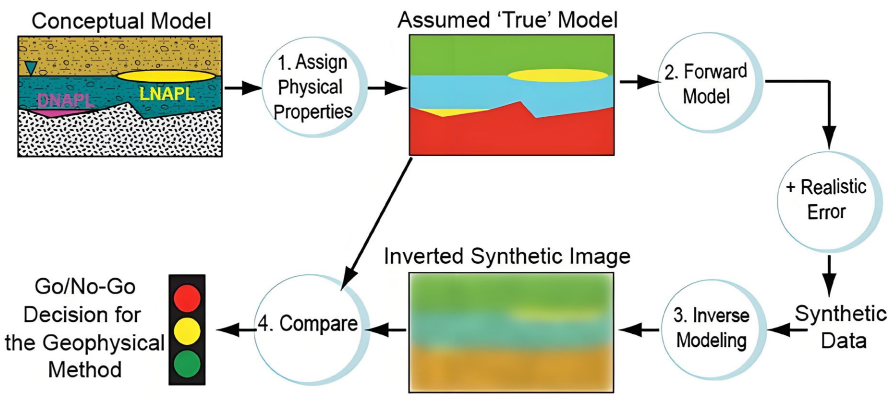


Figure 7. Synthetic modeling workflow [23] [24].

4. Results

4.1. Anomalies of Different Forms Identification

This study's various anomalies are V, U, W, M, K, and H types. **Figure 8** shows examples of resistivity anomalies in Tiakeupleu and Biakalé villages respectively at X = 120 m and X = 320 m. We respectively observe "U" type anomalies of 100 m wide with resistivity peaks from 1076 Ω·m to 1217 Ω·m and "V" type anomalies of 80 m wide with resistivities from 1430 Ω·m to 1134 Ω·m which could be assimilated to zones of faults, fractures, geological contact or cleavage zones at the level of the schistosity planes. A variant of this form of anomaly is the faulting anomaly in the crystalline basement evidenced by the electrical profile corresponding to "K" type anomalies (**Figure 9**). The fault zones are materialized on this profile by "H" type anomalies. This anomaly is inserted between 2 resistant facies. Directly above this anomaly, the SE2 sounding survey was carried out, proof that this type of anomaly is of hydrogeological interest in geophysical prospecting. At the center of P3 electrical profile in Biakalé, a resistivity peak is observed. On either side of this resistant zone occurs a level of low resistivity marked by "W" type anomalies. We observe "W" vein type anomalies of 80 m wide which materialize very fractured basement zones with resistivity peaks of 808 Ω·m to 1030 Ω·m. These resistivities could characterize cleavage zones at the level of subvertical schistosity planes, as observed around Biakalé, and could correspond to deep aquifer zones or to complex structures formed essentially of fractured quartz veins. The P5 profile in Biakalé highlights the type M anomaly, of 80 m wide as presented in **Figure 8**.

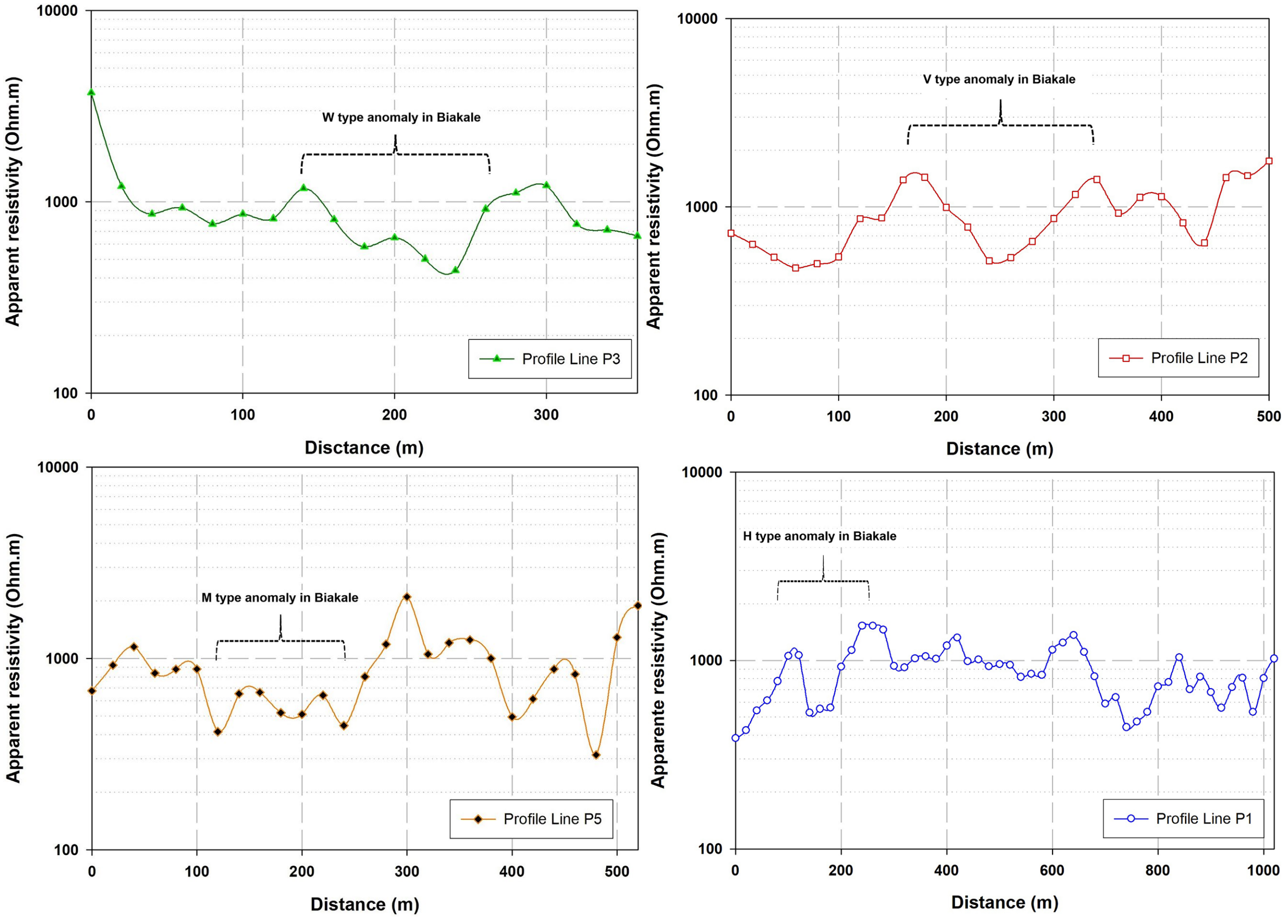


Figure 8. Electrical resistivity profiling graphics/anomaly types in Biakale.

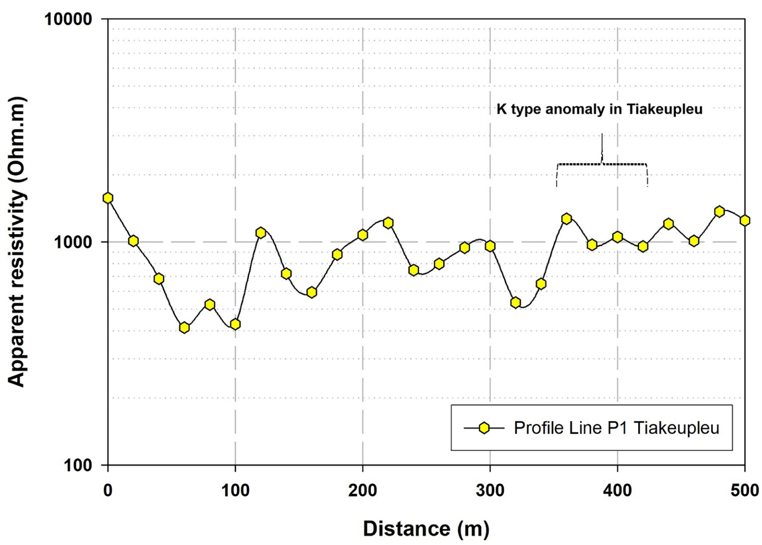


Figure 9. Electrical resistivity profiling graphic/anomaly type in Tiakeupleu.

4.2. Geoelectric Characterization

The obtained data made it possible to image the distribution of electrical resistivities. The presence of resistive facies and conductive facies on the prospected sites are observed. The resistive facies may be due to an abundance of sub-outcropping granite at Biakalé while at Tiakeupleu the indurated cuirass observed could explain it. An increase in clay content, grainy arenas, or water-bearing fissures may be evidence of a conductive environment in the study area. The resistivities reach 3800 Ω·m towards the North-East part in Biakalé (**Figure 10**), like the South-South-West zone of Tiakeupleu (**Figure 11**) where they reach 3400 Ω·m. Observation of the resistivity map makes it possible to detect a main conductive axis in Biakalé with of N280˚ direction, as well as several other secondary axes interspersed by resistive facies. At Tiakeupleu, 3 conductive axes are identified in the N250˚ direction. The conductive axis 1 in Tiakeupleu is located in a lowland. Near conductive axis 3 is drilled the only borehole of the village which supplies all the villagers.

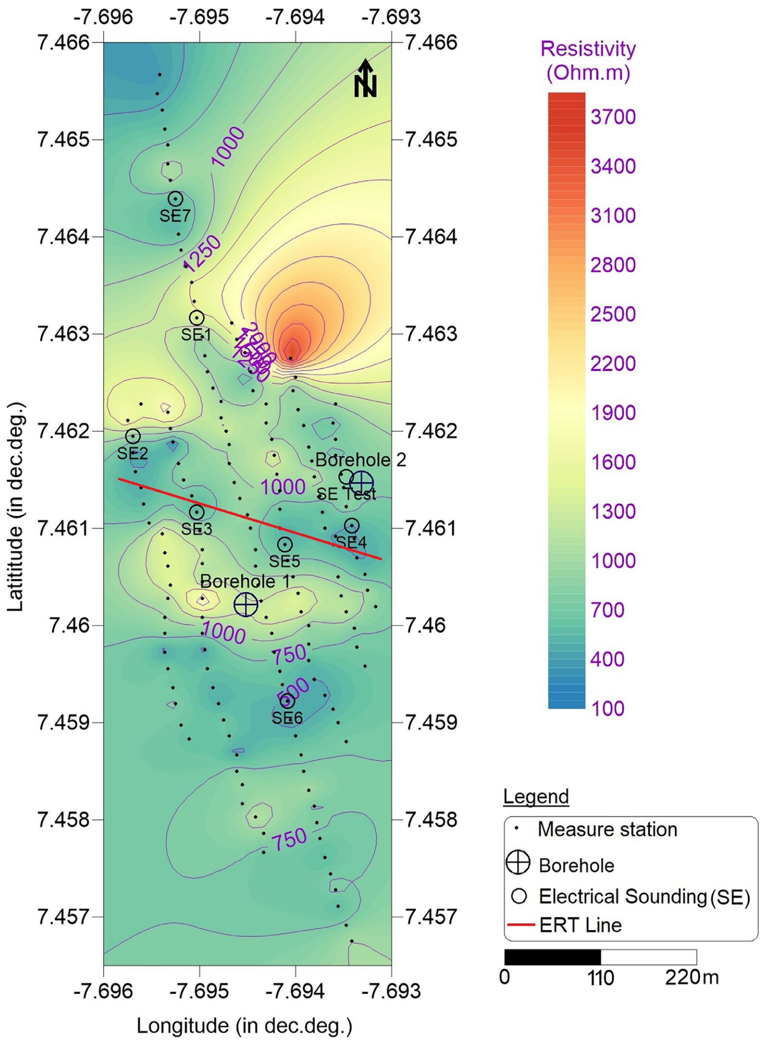


Figure 10. Resistivity map of Biakalé site.

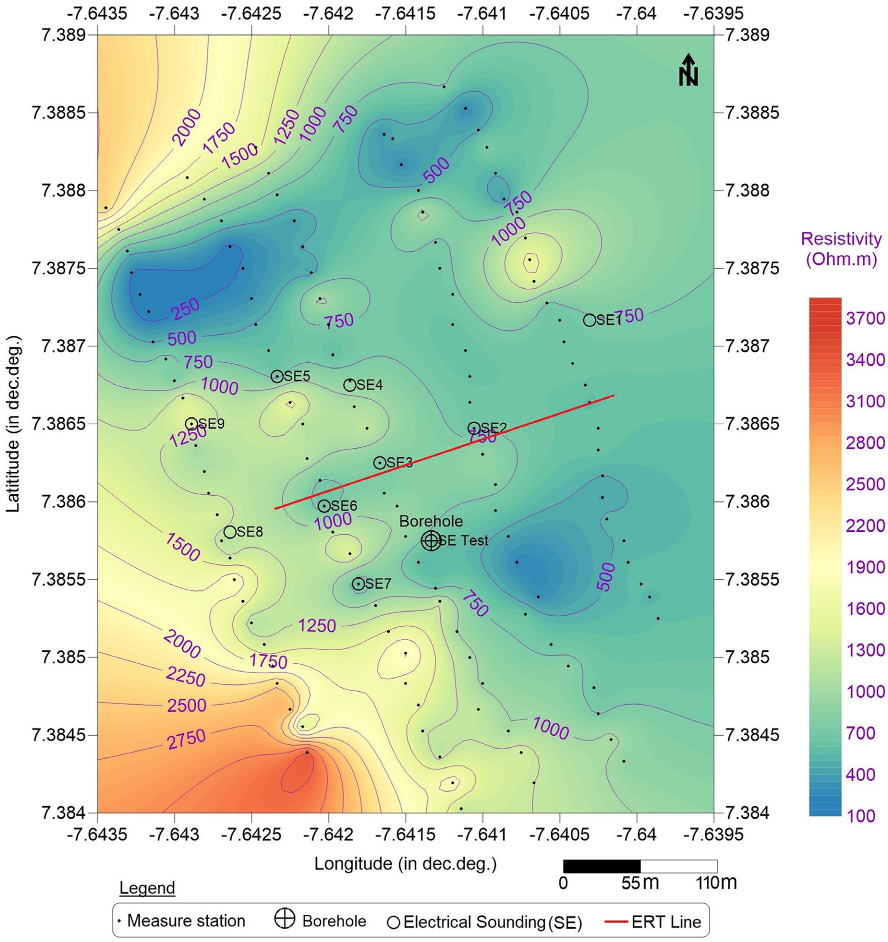


Figure 11. Resistivity map of Tiakeupleu site.

4.3. Lithostratigraphic Structure from Electrical Surveys

VES carried out in this study have made it possible to generally identify families of curves corresponding to aquifers layers successions or not. From all these established electrical sounding curves, three main types emerge: a "boat bottom" type, "a single rising branch", and a "dragging ascent".

4.3.1. Boat Bottom Type Sounding

The boat bottom type sounding carried out on the U-type anomaly in Tiakeupleu (Figure 12) corresponds to a three-layer model. The first layer's electrical resistivity varies from 146 Ω·m to 443 Ω·m. It corresponds to the lateritic shell, which is composed of the cuirass and lateritic clays, with a relatively small thickness of 3.2 m. The second layer corresponds to the very conductive complex and represents the clayey-sandy alteration with a thickness of 19 m. The resistivities of this complex are relatively low and vary between 113 and 154 Ω·m. The third layer corresponds to the resistive base: This is the part of the curve which rises with a slope of 45˚. This particular rise reflects the presence at depth of a very resistive rock of crystalline or crystallophyllian nature. The apparent resistivity of the latter is generally high, possibly reaching 1861 Ω·m.

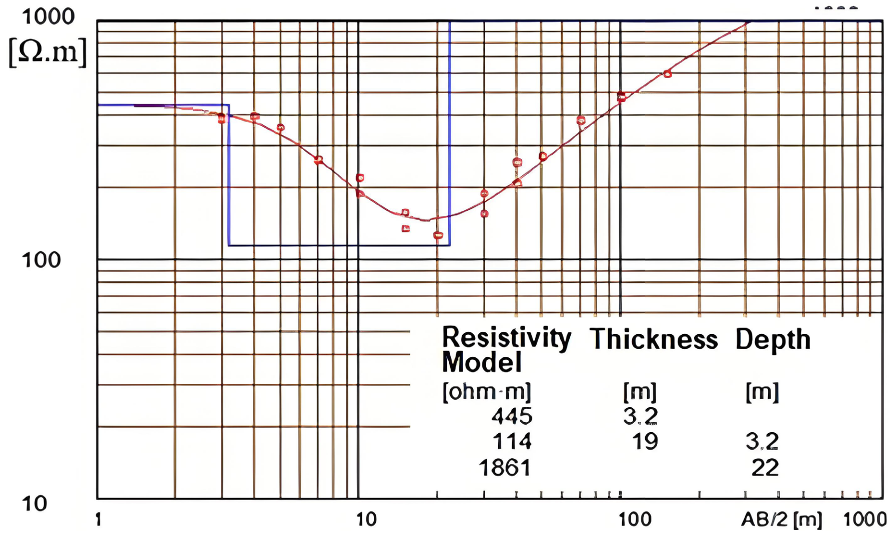


Figure 12. Boat bottom type sounding curve in Tiakeupleu.

4.3.2. A single Rising Branch Type Sounding

This type of curve generally reveals the presence of only two terrains. The first terrain is of clayey-sandy alterites (Figure 13). The second corresponds to the true resistivities of the clays which essentially constitute this level, vary between 27 to 53 Ω·m and their thickness reaches 6 m. Finally, this level is on a bedrock with a resistivity greater than 8170 Ω·m.

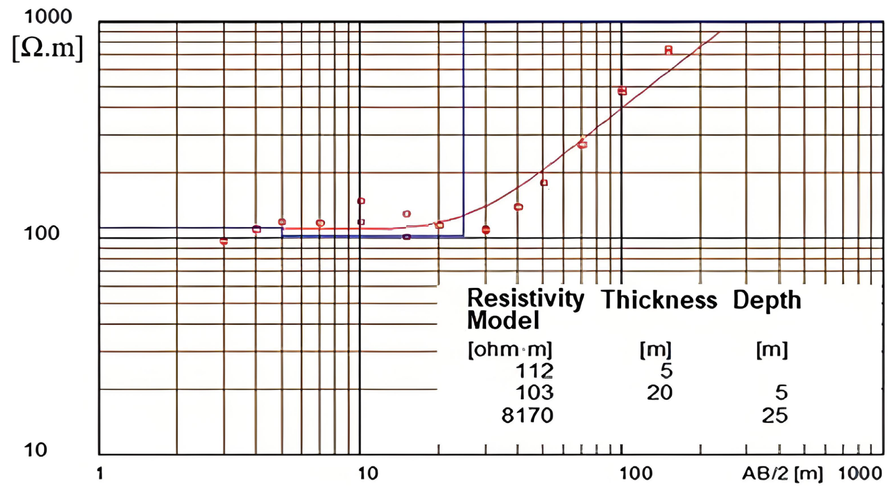


Figure 13. A single rising branch type sounding curve in Biakalé.

4.3.3. A Dragging Ascent Type Sounding

This type of curve generally reveals the presence of two terrains, only grainy arenas (gravelly horizon) and the fissured hard rock, between the conductive horizon and the basement. The staircase on the rising branch reveals the frequent variation of the conductivity in Figure 14. In this figure, we observe the presence of four different layers with different resistivities and thicknesses. The first three layers are relatively conductive as the fourth disc with a resistivity of 1512 Ω·m is very resistive.

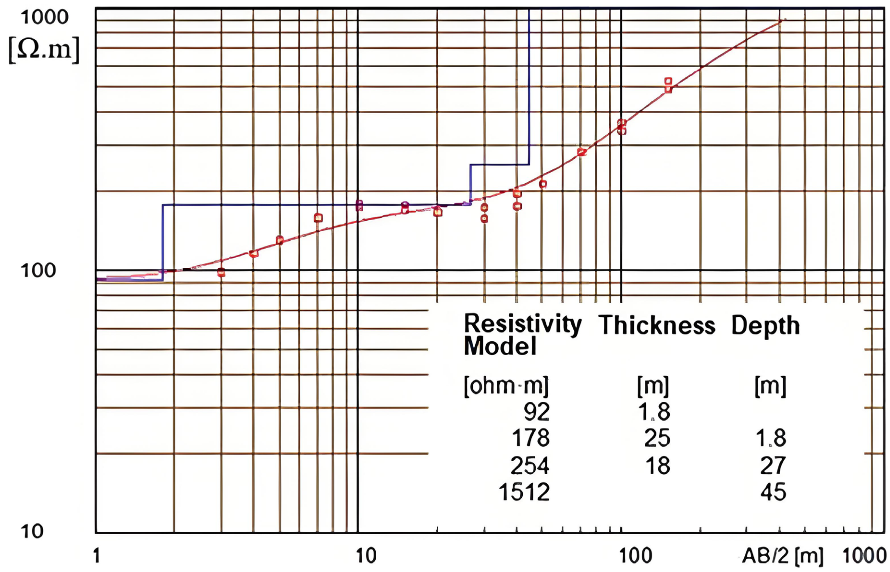


Figure 14. A dragging ascent type sounding curve in Biakalé.

4.4. Lithostratigraphic Structuring from Electrical Resistivity Tomography

These observations highlight the sensitivity of resistivity to hydrogeological compartments and consequently to the hydrogeological target, with an RMS of 2.22% in Biakalé and 6.96% in Tiakeupleu. The variation in resistivity behaviour allows for the distinction of horizontal and vertical heterogeneity within the study area. Initially, in terms of resistivities, it is evident for each site that there is clear discrimination, providing information about the ground. Three primary units are identified, with a highly conductive layer flanked by two resistive layers. Examination of the resistivities reveals the presence of a horizontally homogeneous matrix, with resistivities ranging from 31 to 99 Ω·m in Tiakeupleu and from 72 to 129 Ω·m in Biakalé, as depicted in Figure 15 and Figure 16 respectively. From top to bottom, a resistive layer is observed atop the conductive layer, which in

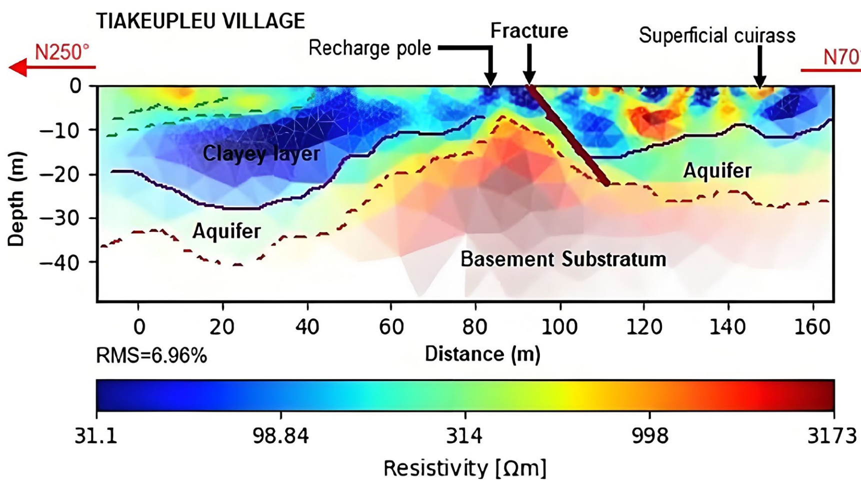


Figure 15. ERT Imagery of Tiakeupleu aquifer.

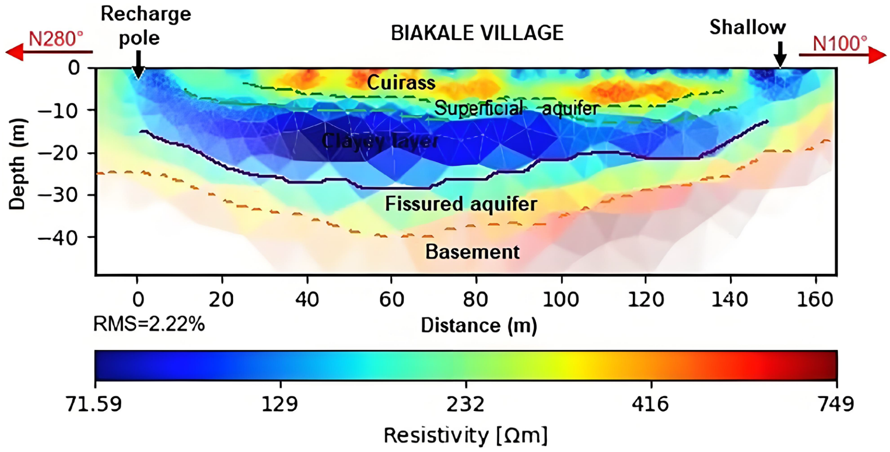


Figure 16. ERT Imagery of Biakale aquifer.

turn rests on a substratum. This conductive layer is approximately 10 m thick in both Biakalé and Tiakeupleu. In Biakalé, it is detectable from a depth of 10 m and is situated slightly higher in Tiakeupleu. This layer could potentially be the aquifer tapped by the hand-dug wells in the village of Biakalé, which remain consistently full throughout the year. In addition, infiltration poles are identified on each site, and a hard armor (cuirass) is also visible. In some areas, it is covered with a thin layer of topsoil. In Biakalé, this cuirass is approximately 7 m thick, while in Tiakeupleu, the bedrock is clearly visible at depths of less than 10 m.

5. Discussion

The study conducted in the villages of Tiakeupleu and Biakalé in the Tonkpi region enabled the determination of key geophysical parameters for the optimal location of boreholes. Geophysical methods of electrical resistivity are essential indirect reconnaissance tools for mapping underground geological formations. Consequently, the location of the boreholes was selected based on these geophysical parameters. Considering all our results, it is crucial to observe them carefully to ensure the successful establishment of productive boreholes. The interpretation of electrical profiles reveals the existence of six types of anomalies: narrow conductive compartment type anomalies and wide conductive compartment type anomalies. This is consistent with the findings of certain authors such as [25] and [26] in the northern province of Séno, North-East Burkina Faso, and the Tanda region in North-East Côte d'Ivoire, respectively.

At the level of conductive compartment type anomalies, various forms of conductive anomalies "V", "W", "K", "U", "H", and "M" have been identified, which have determined the choice of drilling sites. From a geophysical perspective, these forms indicate areas of low resistivity that can be attributed to fractures or cracks, which may act as water veins in the crystalline basement [27]. Therefore, these areas are suitable for the installation of boreholes. Other authors, such as [28] and [27], have also reached the same conclusion in the Sikensi Department and the Bandama Valley District in Côte d'Ivoire. Indeed, these forms of anomalies are often associated with zones of discontinuities (contact zones, faults, fractures, etc.).

In addition, on the electrical profiles, we observe in places the transition from areas of high resistivity values to areas of low values, which could correspond to geological structures such as faults, veins, or geological contact zones. However, the identification of anomaly types is linked to the measurement offset used during the survey. Indeed, a relatively large measurement offset masks the true anomaly type and has the disadvantage of confusing certain geological structures. Otherwise, it is sometimes difficult to discriminate a vein from a fault or a geological contact. The identification of a vein is only possible when the measurement offset allows it to be located in relation to the surrounding formation. Additionally, a fault can be mistaken for a geological contact. To differentiate them, the prospector must change the depth of investigation as soon as an anomaly is discovered. This precaution has the advantage of highlighting (depths and resistivities) the adjacent raised and sunken geological blocks. The classification of survey curve types encountered was determined based on the studies in the Seno region (Burkina Faso, [29]), and the Daloa region (Côte d'Ivoire, [30]), respectively. The "boat bottom" curves observed generally indicate that they are found in the tropical regions of West Africa. Their interpretation reveals a structure with three electrically distinct horizons (e.g. [31]). With regard to "single rising branch" sounding curves, they can reveal productive zones if the supply is good, as in the case of coarse tectonised granites or lowland zones. The presence of "dragging ascent" curves in the study area indicates that we are in a deformation zone. According to these authors, this type of sounding is linked to the influence of a megafracture, and the productivity of these sounding curves is always good (>2 m^3/h) and depends on the thickness of the fissured zone.

The resistivities are very well resolved by the inversion and vary between 31 and 3173 Ω·m. The resistivity increases with depth, and the last layer appears more resistive, as indicated by other geophysical methods [32]. The resistivity section exhibits variations in layer thickness, resulting in the compartmentalisation of aquifers, as described by the usual conceptual basement aquifer model, with several zones together forming the same reservoir [33].

ERT has allowed for better description of lateral variations in aquifer thicknesses (e.g., [13] [14] [16]) and identification of potential infiltration zones. This is very important for achieving good sustainable flow rates over time if the aquifers are not overexploited. Indeed, the presence of a significant thickness of weathered material is very important for obtaining good flow rates and maintaining them during exploitation. However, this weathered layer should be as sandy as possible, rather than clayey materials [14]. Unfortunately, ERT often does not allow distinguishing between humid clayey weathered materials and saturated sandy weathered. To overcome this limitation, complementary geophysical measurements such as proton magnetic resonance can be used (e.g. [33]).

6. Conclusions

The geophysical methods, in particular the lateral investigations techniques (electrical profiling) and VES, made it possible to locate and characterize the hard-rock aquifers in Tiakeupleu and Biakalé in the Tonkpi region. The work carried out has made it possible to identify indicators to install with success boreholes in crystalline areas.

With regard to electrical anomalies characterization, two types of anomalies have been identified: anomalies of narrow conductive compartment type and those of wide conductive compartment type. These types of normalities are expressed in various types which are "V", "W", "K", "U", "H" and "M". As for the vertical electrical soundings, it is the boat bottom type that is the most observed. The resistivity map revealed major conductive axes in the area. The electrical resistivity tomography made it possible to draw up a geophysical/geological layer model highlighting 3 main units, with a probable aquifer layer overcoming the bedrock. Electrical resistivity methods have effectively contributed to aquifers location and characterization in the study area. They make it possible to reduce the failure rate in the installation of boreholes. Thus, the integration of vertical electrical resistivity soundings with resistivity maps, and ERT enhances the characterization of the groundwater reservoir. Discontinuities in the ground are important features in near-surface characterization for groundwater exploration efforts in basement complex terrain as they possess hydrological implications.

Availability of Data and Material

Further study on the study area and the data is on going. The data can not be released to the public until the study is completed. The data can be released to the reviewers for verification purpose.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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