

Integrated Approach for the Characterization and Modeling of a Fractured Basement Aquifer: Application to the Pézouan Industrial Site, West-Central Côte d'Ivoire

Roland Bebo Tigboh^{1*}, Eric Germain Kouassi Kouakou^{1,2}, Mohamed Moustapha Ndam Njikam^{3,4}, Yacouba Lingadé¹

¹Departement of Geosciences, Université Péléforo Gon Coulibaly, Korhogo, Côte d'Ivoire

²Office National de l'Eau Potable (ONEP), Abidjan, Côte d'Ivoire

³Department of Mining and Geological Engineering, Advanced School of Mining and Energy Resources Transformation (ESTM), University of Bertoua, Bertoua, Cameroon

⁴Observation et imagerie innovantes, Université Côte d'Azur, CNRS, Observatoire de la Côte d'Azur, IRD, Geoazur, Valbonne, France

Email: *tigboh@gmail.com, ericgermainkouassi@gmail.com, lingadéyacouba@gmail.com, ndamnjikamm@gmail.com, ndam@geoazur.unice.fr

How to cite this paper: Tigboh, R.B., Kouakou, E.G.K., Ndam Njikam, M.M. and Lingadé, Y. (2026) Integrated Approach for the Characterization and Modeling of a Fractured Basement Aquifer: Application to the Pézouan Industrial Site, West-Central Côte d'Ivoire. *Open Journal of Geology*, 16, 272-292.

<https://doi.org/10.4236/ojg.2026.166015>

Received: May 10, 2026

Accepted: June 27, 2026

Published: June 30, 2026

Copyright © 2026 by author(s) and Scientific Research Publishing Inc.

This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).

<http://creativecommons.org/licenses/by/4.0/>



Open Access

Abstract

Groundwater resources play a strategic role in supporting industrial development in crystalline basement regions where surface water availability is often limited or highly variable. This study aimed to identify hydraulically productive structures and develop a conceptual hydrogeological model of the aquifer system supplying the SIPIC industrial site near Issia, western Côte d'Ivoire. An integrated methodology combining morphostructural analysis, electrical resistivity investigations, vertical electrical soundings (VES), borehole data analysis, and three-dimensional hydrogeological modeling was implemented to characterize groundwater occurrence and flow within the fractured crystalline basement. Structural mapping revealed a predominance of fracture orientations around N120°, while geoelectrical investigations highlighted several conductive zones interpreted as potential groundwater-bearing structures. The VES results identified favorable aquifer horizons mainly located between 50 and 110 m depth. Borehole validation confirmed the reliability of the proposed targeting criteria. The highest yields were recorded in boreholes drilled at the intersection of hydrogeological discontinuities and structural lineaments, associated with W-shaped geoelectrical anomalies and H-type sounding responses. Boreholes F2 and F3 yielded 35 m³/h and 40 m³/h, respectively, demonstrating the strong influence of structural controls on groundwater productivity. The

three-dimensional hydrogeological model revealed a multilayer aquifer system composed of an unconfined aquifer between 35 and 50 m depth and two deeper semi-confined to confined aquifers located between 55 and 70 m and between 80 and 105 m depth. Groundwater storage and flow are primarily controlled by the interaction between the weathered layer and hydraulically connected deep fracture networks. The results demonstrate that integrating structural, geophysical, and hydrogeological datasets significantly improves the identification of high-yield groundwater targets in fractured basement environments. The proposed conceptual model provides valuable support for future groundwater development and sustainable water resource management in crystalline basement regions of West Africa.

Keywords

Groundwater Exploration, Fractured Basement Aquifer, Electrical Resistivity, Vertical Electrical Sounding, Hydrogeological Modeling, Côte d'Ivoire

1. Introduction

Agriculture has played a predominant role in the economy of Côte d'Ivoire since the country's independence in 1960. In 2024, this sector accounted for approximately 15% of the gross domestic product and remained the leading provider of employment as well as a major driver of national exports [1]. Beyond its economic importance, agriculture also plays a key role in food security, rural poverty reduction, and the socio-economic stability of the country. As part of a strategy aimed at increasing the local valorization of agricultural raw materials, Côte d'Ivoire has experienced significant growth in agro-industrial processing units in recent years, particularly in the natural rubber sector, for which the country remains the leading producer in Africa. This industrial expansion has resulted in the establishment of several rubber-processing plants, such as Pakidié in Sikensi, SAPH in Soubré, and SIPIC in Issia [2].

The development of the rubber industry has led to an increasing demand for water resources. Water is required at several stages of the production chain, including plantation maintenance, latex extraction, industrial processing operations, transportation, fire protection systems, and domestic uses for staff. In a context characterized by population growth, increasing industrial demand, and the impacts of climate change, the sustainable securing of water resources has become a major challenge for the industrial and economic development of Sub-Saharan African countries ([3] [4]).

In this context, groundwater represents a strategic resource because of its generally good quality and its relative resilience to climate variability [5]. In Sub-Saharan Africa, weathered and fractured basement aquifers play a fundamental role in supplying water to rural populations and industrial infrastructures [6]. However, groundwater exploitation in crystalline basement environments remains

particularly challenging. Unlike continuous sedimentary aquifers, basement aquifers are characterized by strong spatial heterogeneity, where groundwater storage and circulation are mainly controlled by weathered zones, fractures, and structural discontinuities ([7]-[9]). In Côte d'Ivoire, crystalline formations cover approximately 97.5% of the national territory [10], giving fractured basement aquifers a critical role in meeting water demands. Nevertheless, the productivity of these aquifers generally remains low to moderate, and the identification of hydraulically productive structures is difficult due to the complex distribution of fracture networks and the anisotropy of groundwater flow systems ([6] [11]).

Despite the numerous studies conducted on basement aquifers in West Africa, the understanding of the geological and structural controls governing groundwater circulation remains limited, particularly in areas subjected to high industrial water demand. Recent studies have shown that basement aquifers exhibit complex hydraulic heterogeneities and that conventional groundwater exploration approaches do not always effectively identify deep productive fractures [12]. Furthermore, several authors have highlighted that uncertainties related to the geometry of fractured zones, hydraulic connectivity, and the spatial distribution of hydrodynamic properties still constitute a major scientific challenge for the sustainable management of crystalline aquifers [6]. In this context, the use of integrated hydrogeological characterization approaches appears essential to improve the understanding of fractured aquifer systems and to reduce the risks associated with the drilling of high-yield boreholes.

This study is part of the effort to secure the groundwater supply for the SIPIC industrial plant, whose water demand is estimated at approximately 100 m³/h. The study aims to identify hydraulically productive structures and to develop a conceptual hydrogeological model of the aquifer within the study area. More specifically, this work seeks to improve the understanding of the structural controls governing groundwater circulation in a fractured crystalline basement environment. The expected results will contribute not only to improving exploration strategies for basement aquifers, but also to the development of sustainable groundwater management approaches in tropical crystalline basement regions of West Africa.

2. Study Area

The study area is located near the town of Issia in west-central Côte d'Ivoire, approximately 2 km from the urban center, within a major agro-industrial zone dedicated to natural rubber production and processing (**Figure 1**). Geographically, the area lies within the Upper Sassandra region, which belongs to the humid tropical zone of Côte d'Ivoire. The climate is characterized by high annual rainfall ranging between 2100 and 2400 mm and an average annual temperature of approximately 26°C [6]. The region experiences two rainy seasons and two dry seasons under the influence of the equatorial transitional climate. These climatic conditions favor significant groundwater recharge and sustain a dense hydrographic network [6] [7].

Topographically, the study area is characterized by gently undulating terrain with elevations ranging from approximately 172 to 389 m above sea level. The landscape is dominated by low hills and shallow valleys, which locally influence surface runoff and groundwater infiltration processes. The hydrographic network is particularly dense and includes the Lobo River, one of the major tributaries of the Sassandra River basin, as well as numerous secondary streams and seasonal drainage channels. This hydrographic system plays an important role in surface water-groundwater interactions and contributes to the hydrological dynamics of the region [8].

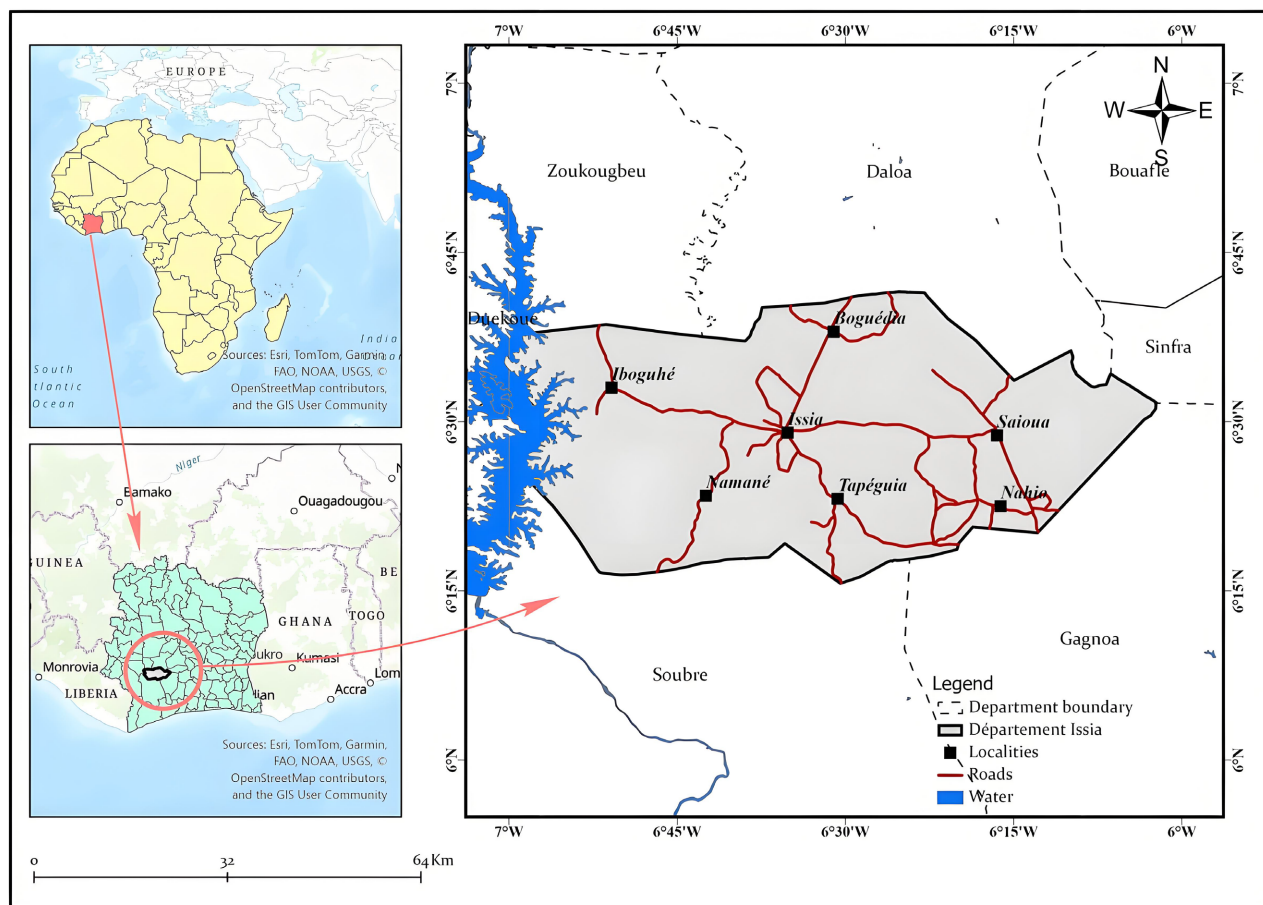


Figure 1. Location map of the study area.

From a geological perspective, the study area belongs to the Paleoproterozoic basement of the West African Craton, specifically within the Baoulé-Mossi domain of the Birimian terranes. This domain constitutes one of the principal geological units of Côte d'Ivoire and is known for its complex tectono-metamorphic evolution associated with the Eburnean orogeny ([13] [14]). The regional geological framework is structurally controlled by major shear zones and fault systems, including the Zouénoula fault to the west and the Komi fault to the east, which significantly influence the fracturing and hydraulic behavior of basement aquifers [15]. The basement formations in the region are predominantly composed of leu-

cogranites intruded into metavolcanic and metasedimentary formations, particularly schists and parametamorphic rocks. At the study site, the geological substratum mainly consists of chlorite-sericite and clayey schists (**Figure 2**). These lithological formations are generally characterized by low primary porosity, and groundwater occurrence is mainly associated with weathered horizons and secondary permeability induced by fractures, faults, and tectonic discontinuities [7] [8].

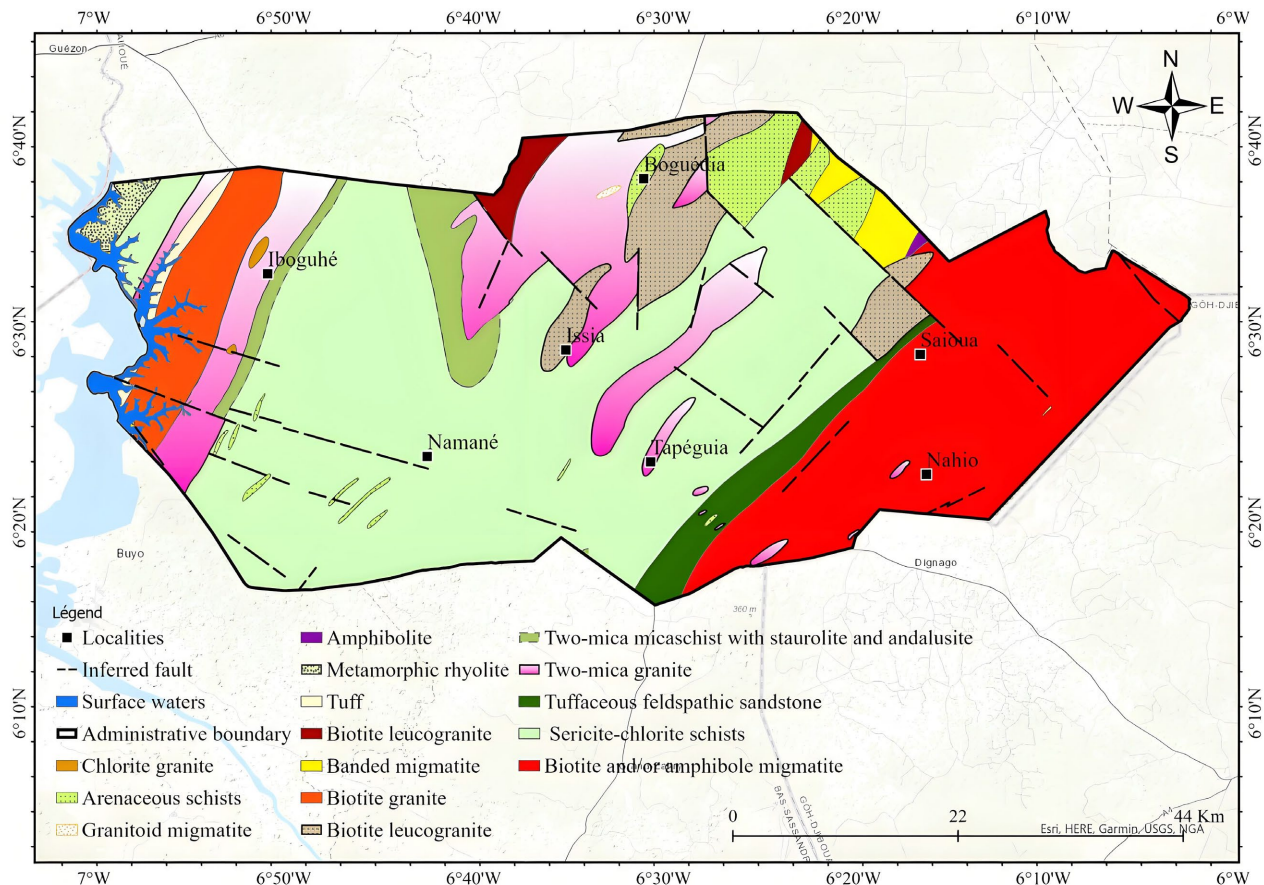


Figure 2. Geological map of the Issa division [14].

Hydrogeologically, the region belongs to the extensive crystalline basement aquifer system that covers most of Côte d'Ivoire. Groundwater circulation and storage are strongly controlled by the thickness of the weathered layer and the connectivity of fracture networks [6] [7] [9]. Previous studies conducted in crystalline basement environments in West Africa have demonstrated that productive boreholes are generally associated with intensely fractured zones, weathered contacts, and major tectonic lineaments [6]. However, the strong spatial heterogeneity of fractured basement aquifers makes the identification of high-yield groundwater reservoirs particularly difficult. In the Issia area, increasing industrial water demand associated with rubber-processing activities further emphasizes the need for improved hydrogeological characterization and structural analysis of groundwater-bearing formations.

3. Data and Methods

3.1. Materials

This study is based on the combined use of geological, geophysical, topographic, and hydrogeological data in order to characterize the aquifer structures of the study area and to develop a conceptual hydrogeological model of the fractured basement formations. Geophysical data acquisition was carried out using a Syscal Pro Switch 48 multi-electrode resistivity meter equipped with its associated accessories. This equipment was used for electrical resistivity investigations aimed at characterizing lithological variations, weathered horizons, and fractured structures likely to constitute productive aquifer reservoirs. The geographic coordinates of the profiles and measurement points were recorded using a Global Positioning System (GPS).

Several datasets were used in this study, including the geological and pedological maps of the Daloa sheet at a scale of 1:200,000, digital elevation models (DEM) employed for morphostructural analysis, as well as geophysical data acquired in the field between May 10 and 14, 2022. These acquisitions consisted of approximately 4.540 km of electrical resistivity profiling and 1.800 km of vertical electrical sounding surveys. Hydrogeological data from four boreholes, including total depth, weathered layer thickness, and pumping yield, were also used for result interpretation and validation.

Data processing and analysis were performed using several specialized software packages. ArcGIS was used for thematic mapping and spatial analysis, while MapInfo was employed for the extraction and analysis of structural lineaments. Geosoft Oasis Montaj was used for the processing and interpretation of geophysical data, Surfer was applied for spatial interpolation and preparation of modeling datasets, and RockWorks 17 was used to construct three-dimensional hydrogeological models.

3.2. Methods

The adopted methodology aims to improve the understanding of the hydrogeological functioning of fractured basement aquifers in the study area through an integrated approach combining morphostructural analysis, geophysical investigations, and hydrogeological modeling.

The first step consisted of a morphostructural analysis based on the use of digital elevation models (DEM). In this study, a lineament is defined as a linear geomorphological feature observable on topographic data that may reflect the surface expression of geological structures such as faults, fractures, joints, or lithological contacts. A hydrogeological discontinuity refers to any structural feature likely to influence groundwater flow by enhancing secondary permeability within the crystalline basement. The morphostructural analysis was performed using an ALOS PALSAR Digital Elevation Model (DEM) with a spatial resolution of 12.5 m. Prior to lineament extraction, the DEM was preprocessed through sink filling, noise reduction, and the generation of multi-directional shaded-relief images to enhance the expression of structural features. Automatic lineament extraction was then carried out using the LINE algorithm implemented in PCI Geomatica, which detects linear features through edge enhance-

ment, curve extraction, thresholding, and line-linking procedures. The extracted lineaments were subsequently validated through visual inspection and comparison with the regional geological framework, drainage network geometry, and topographic expressions observed on the DEM. This approach enabled the automatic extraction of lineaments and major structural discontinuities likely to control groundwater circulation within fractured crystalline formations. Conductive axes identified from electrical resistivity data correspond to elongated low-resistivity anomalies interpreted as weathered or fractured zones potentially favorable for groundwater circulation. The synthesis of the structural information obtained was used to preselect favorable zones for the implementation of geophysical profiles. Such an approach is widely applied in basement hydrogeological studies to optimize the identification of productive fractured zones ([10] [16] [17]).

In order to characterize the geometry of aquifer structures and fracture networks, eleven parallel geophysical profiles were carried out across the study area (**Table 1**). Electrical resistivity profiling was performed using the rectangular-gradient array, a configuration particularly suitable for mapping lateral resistivity variations and detecting conductive fractured zones in crystalline basement environments. The survey consisted of eleven parallel profiles, each 500 m long, with a spacing of 50 m between adjacent profiles. Measurements were acquired at 10 m intervals along the profiles. Based on the acquisition geometry, the estimated depth of investigation ranged from approximately 80 to 140 m, allowing the characterization of both the weathered horizon and the underlying fractured basement. Electrical resistivity measurements were used to identify lithological contrasts, weathered horizons, and potentially water-bearing fractured zones. Potential drilling targets were selected prior to drilling according to a combination of structural and geoelectrical criteria. These criteria included: i) the presence of major hydrogeological discontinuities identified from morphostructural analysis; ii) intersections between hydrogeological discontinuities and lineaments; iii) the occurrence of conductive axes revealed by electrical profiling; and iv) the presence of marked conductive anomalies interpreted as fractured and/or weathered zones favorable for groundwater accumulation. Areas satisfying several of these criteria were considered priority targets for subsequent vertical electrical soundings and drilling operations.

Vertical investigations using electrical sounding techniques allowed the establishment of one-dimensional (1D) geoelectrical models of the different subsurface formations. This method is commonly used in basement hydrogeological studies for the identification of zones favorable for high-yield borehole drilling ([16] [18] [19]). Vertical Electrical Soundings (VES) were subsequently conducted using the Schlumberger array configuration with a maximum current electrode spacing (AB) of 500 m. The interpretation of the apparent resistivity curves enabled the identification of geoelectrical layers, the estimation of layer thicknesses, and the delineation of potential aquifer horizons. The interpreted geoelectrical models were later correlated with borehole lithological logs to improve the reliability of aquifer characterization and drilling target selection. The VES data were interpreted using the WinSev software through a one-dimensional multilayer inversion approach. The interpretation pro-

cess consisted of fitting theoretical apparent resistivity curves to the field measurements by iteratively adjusting layer resistivities and thicknesses until an acceptable agreement was obtained between calculated and observed data. The resulting geoelectrical models provided estimates of the resistivity and thickness of the subsurface layers. Hydrogeological interpretation was subsequently performed by correlating the geoelectrical parameters with the local geological context and borehole information. Layers exhibiting resistivity values generally ranging from 20 to 100 $\Omega\cdot\text{m}$ were interpreted as saturated weathered formations, whereas zones characterized by resistivity values between 50 and 300 $\Omega\cdot\text{m}$ within the crystalline basement were interpreted as water-bearing fractured horizons. Aquifer depths and boundaries were therefore determined from the thickness and depth of these conductive to moderately conductive layers identified in the inverted geoelectrical models.

Finally, three-dimensional hydrogeological modeling was conducted to better understand the spatial organization of aquifer formations and the relationships between the different geological and hydrogeological units present within the site. This approach involved integrating geophysical, geological, and hydrogeological data to construct a coherent representation of the aquifer system. The 3D models were developed using apparent resistivity data, borehole coordinates, and information obtained from mechanical drilling surveys. Several previous studies have demonstrated the relevance of geological and hydrogeological modeling for the analysis of groundwater flow and the understanding of fractured aquifers in crystalline basement environments ([19] [20]). Following the geophysical investigations, four production boreholes were drilled to validate the proposed targeting criteria. Borehole productivity was assessed through 24-hour step-drawdown pumping tests conducted by the drilling contractor after borehole completion. The recommended exploitation yields reported in this study correspond to the operational discharge rates derived from these tests and considered suitable for sustainable groundwater abstraction. These yields were subsequently used to evaluate the reliability of the structural and geophysical criteria adopted for borehole siting.

Table 1. Details of the geophysical surveys conducted at the study site.

Site	Array	Profiles	Direction (°)	Length (m)	Electrical Soundings
SIPIC (PEZOUAN DOMAIN)	Rectangular Gradient Array	L1-0-00	N40°E	410	Se8
		L1-0+52		410	
		L1-0+101		410	Se9
		L1-0+146		410	
		L1-0+176		420	Se10, Se11, S12
		L1-0+33		420	Se6, Se7
		L1-0+190	N120°E	410	Se2
		L2-0+00		390	Se3
		L2-0+40		390	Se4
		L2-0+83		430	Se5
		L2-0-45		440	Se1

4. Results and Discussion

4.1. Morphostructural Analysis and Structural Control of Groundwater Flow

The morphostructural analysis conducted from topographic data enabled the identification of twenty-two (22) major lineaments exhibiting a preferential ESE orientation, predominantly represented by the N120° and N170° directional families (**Figure 3**). In parallel, the hydrogeological discontinuity mapping revealed fifty-two (52) structures distributed among several directional sets, mainly N20°, N45°, N70°, N80°, N110°, N120°, and N160°. The integration of lineament and hydrogeological discontinuity maps highlights a structural framework dominated by the N120° family, which represents the most prevalent orientation within the study area. This direction appears to constitute the principal fracture set controlling groundwater circulation. The predominance of this structural trend suggests a regional tectonic control inherited from the Eburnean evolution of the Baoulé-Mossi domain, which is characterized by a complex network of shear zones and fractures affecting the Birimian formations of Côte d'Ivoire ([14] [15]).



Figure 3. Lineament and hydrogeological structure map of the study area.

The identified structural orientations are broadly consistent with those reported in several fractured basement regions of West and Central Africa, where fractures striking between N110° and N130° frequently play a major role in groundwater drainage and aquifer productivity ([21]-[23]). Within the study area, the occurrence of a major N170° lineament intersected by a N20° hydrogeological discontinuity constitutes an additional favorable feature for the development of secondary fracturing and enhanced hydraulic connectivity. Such structural intersections are commonly recognized as preferential zones for groundwater storage and circulation in crystalline basement aquifers [7] [8]. The structural framework established from the morphostructural analysis therefore, provides a first-order understanding of the spatial organization of groundwater-bearing structures and constitutes a valuable basis for guiding subsequent geophysical investigations aimed at identifying the most hydraulically productive zones within the study area.

4.2. Geoelectrical Characterization of Fractured Structures

The geoelectrical investigations conducted within the study area provided a more detailed characterization of the fractured structures previously identified through morphostructural analysis. The eleven parallel electrical profiles revealed several low-resistivity zones interpreted as major geological discontinuities, predominantly located at the extremities of the profiles (**Figure 4(1)**). These conductive anomalies likely correspond to weathered and/or fractured zones that favor groundwater infiltration and circulation. In crystalline basement environments, low resistivity values are commonly associated with weathered horizons or water-filled fractures, whereas high resistivity values generally characterize fresh, compact, and poorly permeable bedrock formations [7] [8]. Consequently, the conductive anomalies identified across the study area represent potential indicators of hydraulically active structures that may play a significant role in groundwater storage and flow.

The analysis of the isoresistivity map (**Figure 4(2)**) highlighted several conductive axes trending predominantly N40°, N45°, and N120°. These orientations closely correspond to the structural families previously identified from lineament mapping and hydrogeological discontinuity analysis. This strong agreement between morphostructural and geoelectrical results reinforces the hypothesis that these structures effectively control groundwater circulation within the study area.

In addition, the geoelectrical mapping revealed other conductive structures oriented N70°, N80°, and N160° (**Figure 5(1)**), which were not always clearly expressed in the surface morphostructural data. These findings demonstrate the value of geophysical methods for detecting buried or weakly expressed subsurface structures that may nevertheless exert significant hydrogeological control. The structural framework derived from the integrated geoelectrical dataset (**Figure 5(2)**) confirms the predominance of N120°-oriented fractures throughout the study area. This structural trend appears to constitute the principal fracture family

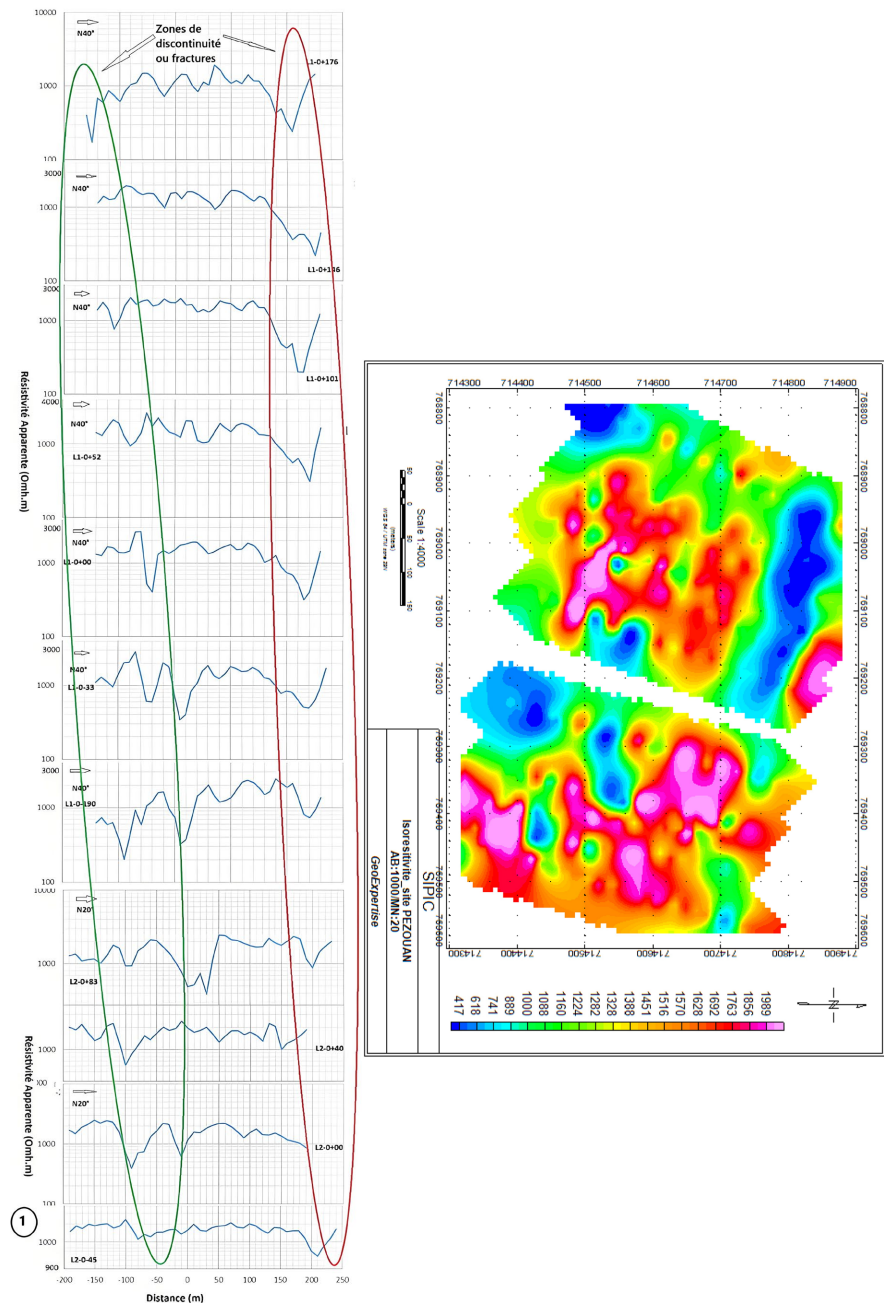


Figure 4. (1) Parallel electrical resistivity profiles; (2) apparent resistivity map of the study area.

controlling preferential groundwater flow. Such an organization is consistent with fracture patterns documented in several fractured basement settings across West Africa, where inherited tectonic structures commonly act as the main hydraulic conduits within crystalline aquifers ([6] [7] [21]). Furthermore, several intersections between the different fracture families were identified. These intersection zones are of particular hydrogeological significance because they generally promote enhanced fracture density and hydraulic connectivity. Numerous studies have demonstrated that the highest borehole yields in crystalline basement envi-

ronments are frequently associated with structural intersections, where groundwater storage and flow conditions are optimized [6] [8].

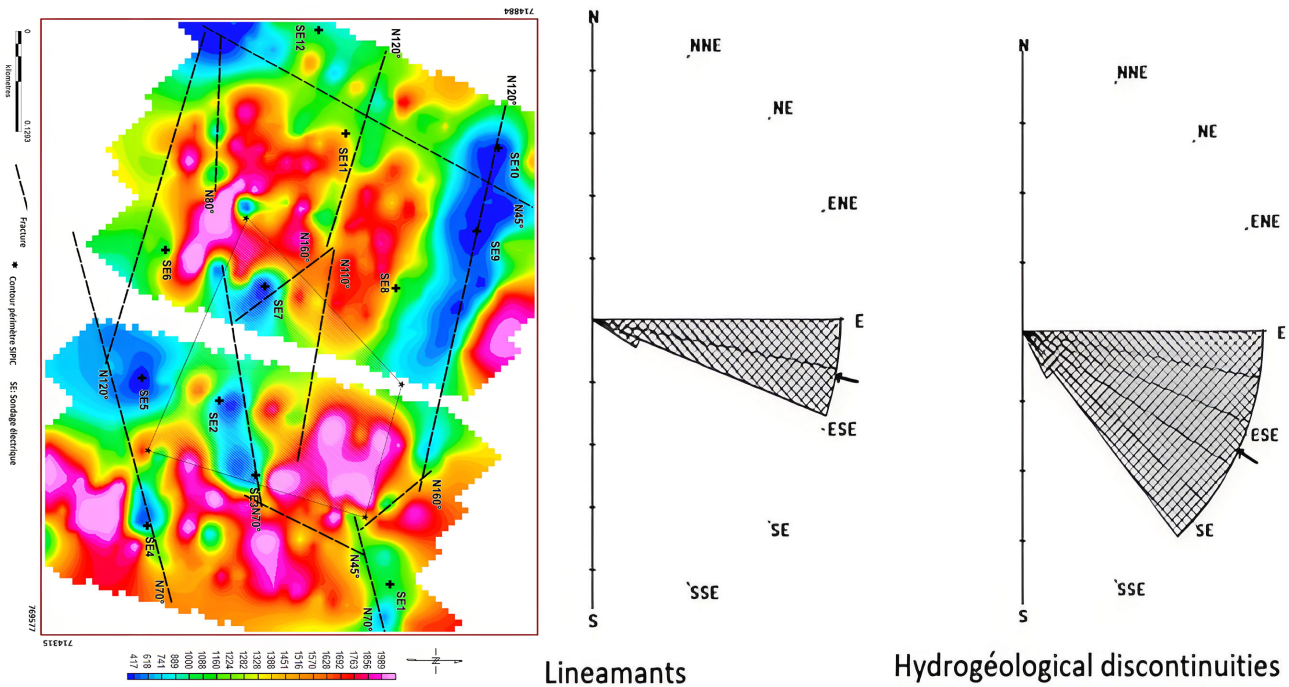


Figure 5. (1) Conductive axes interpreted from the apparent resistivity map; (2) directional rose diagram of the identified structural features.

Overall, the geoelectrical results confirm that the groundwater potential of the study area is strongly controlled by the fracture network and associated structural discontinuities. The consistency observed between the morphostructural analysis and the geoelectrical anomalies increases confidence in the selected target zones for detailed hydrogeological investigations and future groundwater development activities.

4.3. Interpretation of Vertical Electrical Soundings

The vertical electrical soundings (VES) conducted over the main anomalies identified during the previous investigation stages provided valuable insights into the vertical organization of the subsurface formations and the characterization of horizons likely to constitute productive aquifer reservoirs. The interpretation of the apparent resistivity curves revealed three main types of geoelectrical responses (**Figure 6**): H-type curves, K-type curves, and multilayer QH- and KH-type curves. For interpretation purposes, Type 1 responses correspond to H-type curves, Type 2 responses correspond to K-type curves, whereas Type 3 responses correspond to multilayer QH- and KH-type curves.

- H-type curves, characterized by a decrease in resistivity followed by an increase with depth, generally indicate the presence of a conductive layer bounded by more resistive formations. In the crystalline basement context of the Issia region, this response may be associated with a weathered or water-saturated frac-

tured zone overlying a more compact basement unit. The interpretations indicate that the potentially productive horizons related to this curve type are mainly located between 50 and 100 m depth. Such a configuration is commonly observed in basement aquifers, where deep fractured zones constitute the principal exploitable groundwater reservoirs [7] [8].

- K-type curves exhibit an increase in resistivity followed by a decrease at greater depth. This response generally reflects a succession of geological formations with marked lithological contrasts. Within the study area, the potentially water-bearing horizons associated with this geoelectrical signature are generally encountered at depths greater than 70 m. These results suggest the presence of deep fractured structures capable of sustaining groundwater circulation within the crystalline basement.
- The multilayer QH- and KH-type curves reflect a more complex geological organization characterized by the alternation of several layers with contrasting electrical properties. Their interpretation highlights the occurrence of multiple potentially productive groundwater horizons located between 40 and 60 m depth and between 90 and 110 m depth. The superposition of conductive layers may indicate the presence of several phases of weathering and/or fracturing that affected the basement rocks, thereby creating distinct hydraulic reservoirs.

The identification of aquifer horizons was based on the inverted multilayer geoelectrical models derived from the VES interpretation. For each sounding, conductive to moderately conductive layers interpreted as saturated weathered formations ($20 - 100 \Omega \cdot m$) or water-filled fractured basement zones ($50 - 300 \Omega \cdot m$) were identified. The depth to the top and bottom of these layers was calculated from the cumulative thicknesses of the overlying geoelectrical units. Consequently, the reported aquifer depths correspond to the vertical position of these interpreted water-bearing layers within the geoelectrical models rather than to the apparent resistivity curves themselves. The depths of the favorable groundwater-bearing horizons identified through the vertical electrical soundings are generally consistent with conceptual models of basement aquifers developed for West Africa. According to these models, groundwater resources are primarily concentrated within weathered layers and fractured zones located at the interface between the weathered mantle and the fresh basement, as well as within hydraulically connected deep fractures [6]-[8]. The depths identified in this study are also comparable to those reported by [17] and [18] in other crystalline basement regions of Côte d'Ivoire.

The integration of morphostructural analysis, geoelectrical profiling, and vertical electrical sounding results enabled the identification of several favorable drilling targets. Four boreholes were subsequently drilled to validate the selection criteria established from the geophysical investigations. The main characteristics of the boreholes, including their depth, weathered layer thickness, and recorded yields, are summarized in **Table 2**.

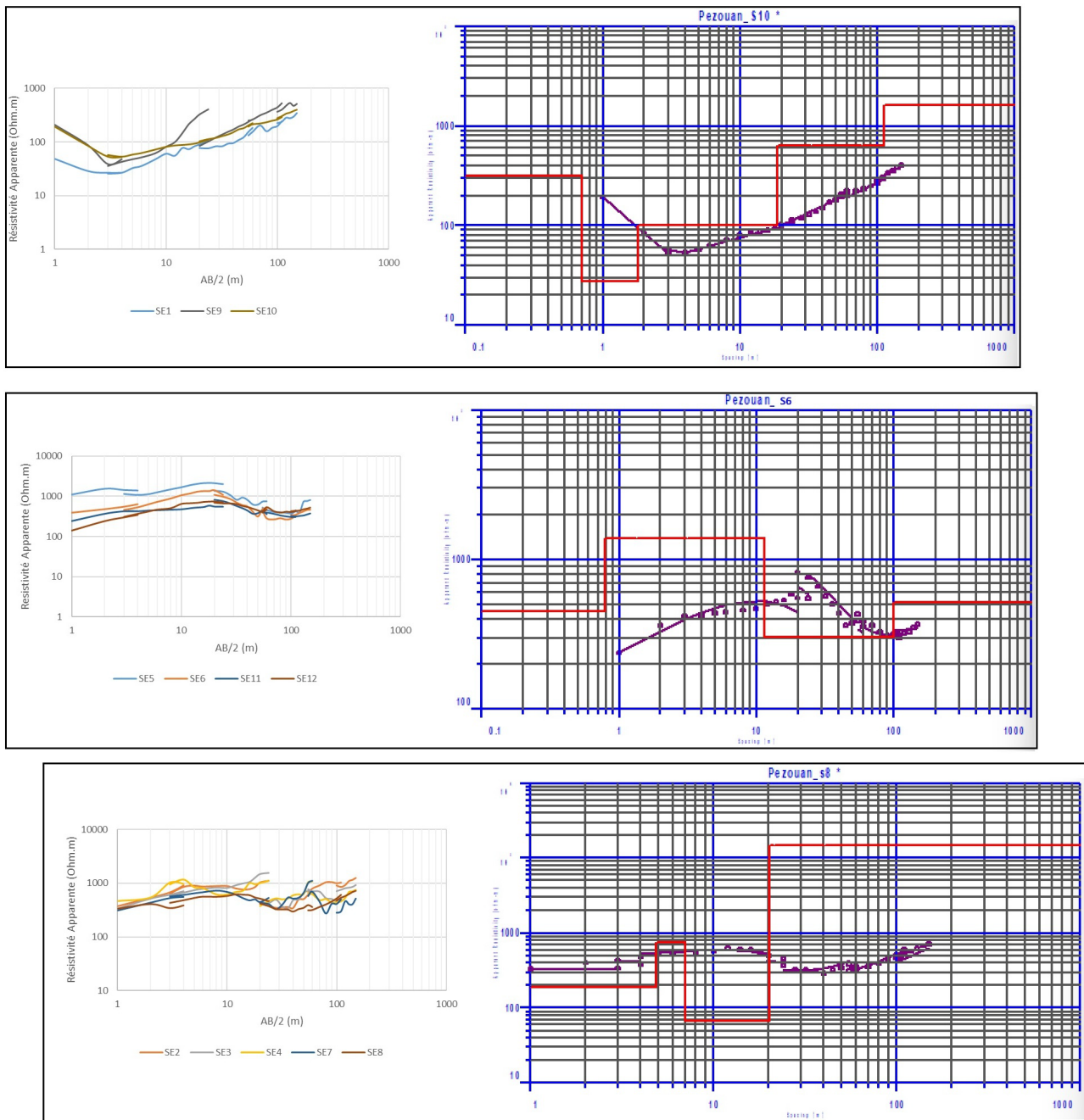


Figure 6. Typical vertical electrical sounding (VES) curve families and their interpreted geoelectrical responses.

Table 2. Characteristics of the drilled boreholes and corresponding hydrogeological performance.

Borehole	Depth (m)	Weathered layer thickness (m)	Hydrogeological discontinuity (Yes/No)	Lineament (Yes/No)	Anomaly shape	VES type	Yield (m ³ /h)
F1	100	25	Ouï	Non	V	Type 3	27
F2	110	28	Ouï	Ouï	W	Type 1	35
F3	100	24	Ouï	Ouï	W	Type 1	40
F4	110	29	Non	Non	U	Type 2	8

4.4. Validation of Productivity Criteria Using Borehole Data

The drilling of four production boreholes provided an opportunity to assess the reliability of the targeting criteria derived from the morphostructural analysis (**Figure 3**), geoelectrical investigations (**Figure 4** and **Figure 5**), and vertical electrical soundings (**Figure 6**). The characteristics of the drilled boreholes and their hydraulic performances are summarized in **Table 2**. The reported yields correspond to the recommended exploitation discharges determined from 24-hour step-drawdown pumping tests conducted after borehole completion.

The recorded borehole yields vary significantly, ranging from 8 m³/h for borehole F4 to 40 m³/h for borehole F3. This variability reflects the heterogeneous nature of the aquifer system and confirms the fundamental role of fractured structures in controlling groundwater productivity within basement aquifers. The highest yields were obtained from boreholes F2 and F3, which produced 35 m³/h and 40 m³/h, respectively. The W-shaped geoelectrical anomalies associated with these boreholes are interpreted as broad conductive zones resulting from the superposition or intersection of several fractured structures, whereas V-shaped anomalies generally indicate narrower conductive features. Such W-shaped anomalies are commonly considered favorable targets for groundwater exploration in crystalline basement environments because they may reflect enhanced fracture density and hydraulic connectivity. These two boreholes share several common characteristics: they are located at the intersection of hydrogeological discontinuities and structural lineaments identified through the morphostructural analysis (**Figure 3**), they are associated with W-shaped geoelectrical anomalies observed on the electrical profiles (**Figure 4**), and they correspond to H-type electrical sounding responses (Type 1). The convergence of these favorable indicators appears to constitute a key criterion for identifying zones with high groundwater potential.

In contrast, borehole F4 yielded the lowest discharge (8 m³/h). Unlike F2 and F3, this borehole is not associated with either a hydrogeological discontinuity or a major structural lineament. It is also characterized by a U-shaped anomaly and a K-type sounding response (Type 2). This difference in behavior suggests that the mere presence of a weathered horizon is insufficient to guarantee high productivity and that fracture connectivity plays a dominant role in groundwater circulation. Borehole F1 exhibits intermediate behavior, with a yield of 27 m³/h. Although it is located on a hydrogeological discontinuity, the absence of a nearby major structural lineament may explain its lower productivity compared with boreholes F2 and F3. This result highlights the importance of structural intersections in the development of zones with enhanced hydraulic transmissivity.

The weathered layer thicknesses observed in the four boreholes range from 25 to 30 m, indicating that weathering thickness alone cannot explain the differences in productivity. For example, borehole F3, with a weathered thickness of 25 m, yielded 40 m³/h, whereas borehole F4, with a weathered thickness of 30 m, yielded only 8 m³/h. This observation confirms that groundwater productivity depends more strongly on the organization and connectivity of fracture networks than on

the thickness of the weathered cover alone. These findings are consistent with the conceptual basement aquifer model proposed by [6]-[8], according to which the highest yields are generally obtained when boreholes intersect both weathered horizons and hydraulically connected deep fractures. Structural intersections play a particularly important role by enhancing groundwater storage, flow, and recharge within fractured basement systems.

Overall, the strong agreement between the mapped structures (Figure 3), the geoelectrical anomalies (Figures 4 and Figure 5), the electrical sounding signatures (Figure 6), and the measured borehole performances (Table 2) validates the integrated approach adopted in this study. The results demonstrate that the most favorable criteria for locating productive boreholes in the Issia region are the presence of structural intersections, the occurrence of W-shaped geoelectrical anomalies, and the identification of H-type geoelectrical signatures associated with hydraulically connected fractured zones.

4.5. Three-Dimensional Hydrogeological Modeling and Conceptual Aquifer Model

To integrate all information derived from the geophysical investigations and borehole data, a three-dimensional hydrogeological model was developed using Rock-Works software. This approach combined the results of the vertical electrical soundings, lithological borehole logs, and groundwater inflow observations recorded during drilling operations. The main objective was to reconstruct the sub-surface architecture and improve the understanding of the hydrogeological functioning of the aquifer system within the study area.

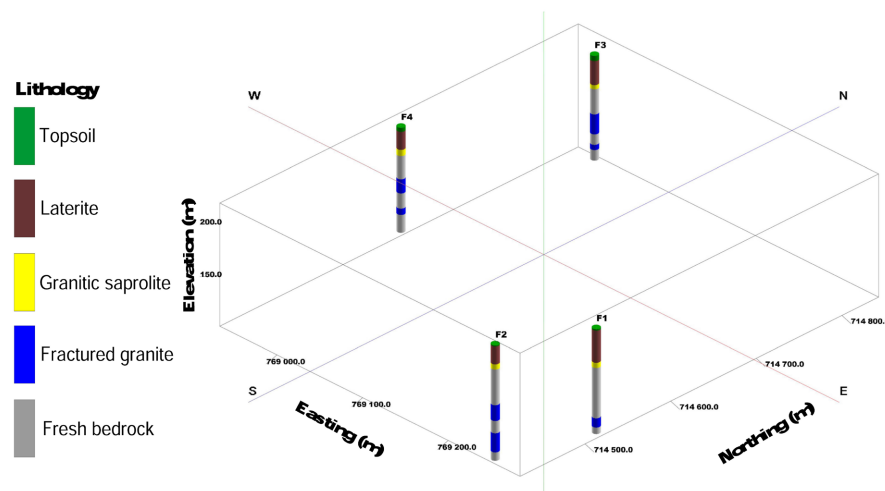


Figure 7. Three-dimensional distribution of lithological logs.

The first stage of the modeling process consisted of developing a three-dimensional lithological log model integrating borehole information and geoelectrical interpretations (Figure 7). This model highlights the spatial distribution of the different geological units and the location of the main aquifer horizons inter-

cepted by the boreholes. The observed groundwater inflow zones are unevenly distributed and appear to be preferentially associated with fractured basement horizons. This observation confirms the results obtained from the structural and geoelectrical analyses presented previously (**Figures 3 to Figure 6**), which indicated that groundwater occurrence is strongly controlled by the fracture network.

Based on these data, a three-dimensional geological model was constructed to visualize the spatial relationships between the subsurface formations encountered across the site (**Figure 8**). The model reveals a vertical organization typical of tropical crystalline basement aquifers, characterized by the succession of a superficial soil and lateritic cover, an underlying weathered horizon of variable thickness, and a fractured basement domain at depth. The results indicate that the main groundwater storage and flow zones are associated with the interface between the weathered layer and the fractured basement, as well as with deeper fracture networks. This organization is consistent with the conceptual basement aquifer model proposed by [6]-[8], according to which borehole productivity largely depends on the interaction between weathered horizons and hydraulically connected fractured structures.

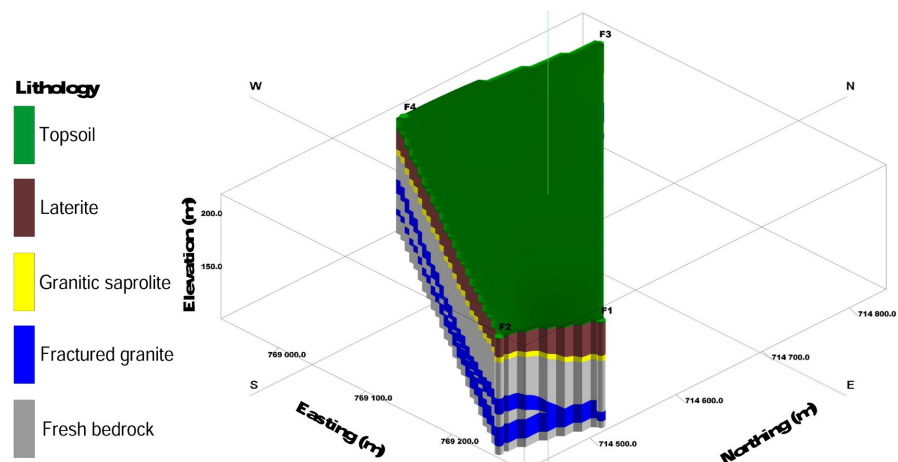


Figure 8. Three-dimensional geological model showing the spatial organization of the main subsurface units.

The correlation between the lithological models and the resistivity domains derived from the vertical electrical soundings also provided further insights into the hydrogeological architecture of the site. Areas characterized by low to moderate resistivity generally correspond to saturated weathered horizons or intensely fractured zones identified in the boreholes. This agreement confirms the reliability of the geophysical interpretations and highlights the value of integrating geophysical and hydrogeological datasets for the characterization of crystalline basement aquifers. The resulting three-dimensional hydrogeological model (**Figure 9**) highlights the presence of three main aquifer levels within the investigated system. The first corresponds to an unconfined aquifer located between approximately 35 and 50 m depth. Two deeper groundwater reservoirs

were identified between 55 and 70 m and between 80 and 105 m depth, respectively. These deeper units behave as semi-confined to confined aquifers, separated by relatively low-permeability layers acting as hydraulic barriers. Their depth provides greater protection from surface contamination and likely explains their significant contribution to the high yields observed in the most productive boreholes. The spatial organization of these aquifer levels suggests that groundwater flow is primarily controlled by the fractured structures identified through the morphostructural and geoelectrical analyses. Intersections between fractures and hydrogeological discontinuities appear to constitute preferential groundwater flow pathways, promoting both recharge and hydraulic connectivity within the deeper aquifer system. This interpretation is consistent with the results obtained for boreholes F2 and F3, which yielded the highest discharges and are located in areas where several favorable structural criteria converge.

Overall, the three-dimensional modeling enabled the development of a coherent conceptual model of the hydrogeological functioning of the study area. The model confirms that aquifer productivity is primarily controlled by fracture organization, hydraulic connectivity within deep structural networks, and the interaction between the weathered layer and the fractured basement. As such, it provides a valuable decision-support tool for future high-yield borehole siting and for the sustainable management of groundwater resources intended to supply industrial water demands within the study area.

Nevertheless, it is important to acknowledge that the model is subject to uncertainties related to the limited number of boreholes available and to the interpolative nature of three-dimensional modeling techniques. Consequently, the results should be regarded as a conceptual representation of the aquifer system that may be refined through the acquisition of additional geological, geophysical, and hydrogeological data in future investigations.

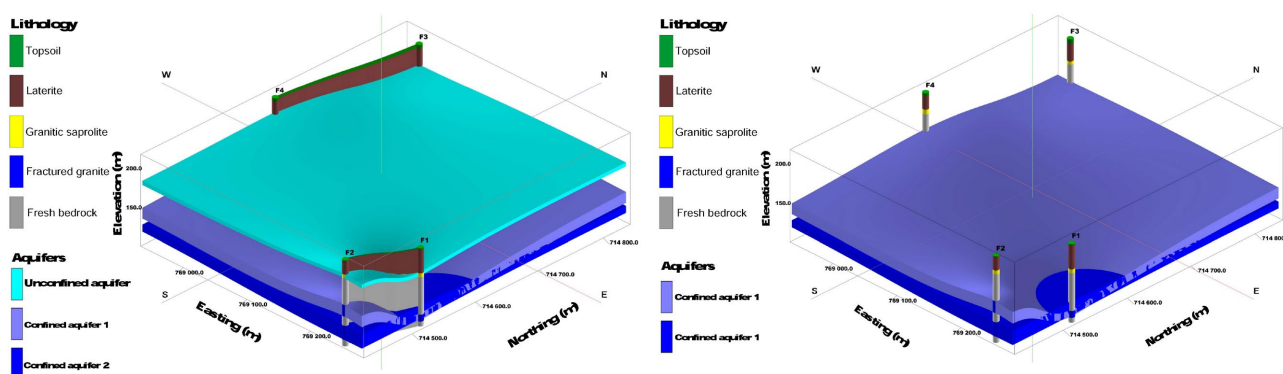


Figure 9. Three-dimensional hydrogeological model showing the distribution of unconfined and confined aquifers in the study area.

5. Conclusions

This study aimed to identify hydraulically productive structures and improve the

understanding of the hydrogeological organization of the subsurface in the Issia region in order to secure groundwater supply for the industrial activities of the SIPIC plant. The integrated approach combining morphostructural analysis, geoelectrical investigations, vertical electrical soundings, borehole data, and three-dimensional modeling enabled the characterization of the main geological controls governing groundwater occurrence and flow within this fractured crystalline basement environment.

Structural analysis revealed a predominance of fractures oriented around N120°, while geoelectrical investigations identified several conductive zones associated with potentially productive fractured structures. Vertical electrical soundings highlighted favorable groundwater-bearing horizons mainly occurring between 50 and 110 m depth. Borehole validation confirmed the relevance of the targeting criteria adopted in this study. The highest yields were obtained from boreholes located at the intersection of hydrogeological discontinuities and structural lineaments and associated with W-shaped geoelectrical anomalies and H-type sounding responses. Boreholes F2 and F3 yielded 35 m³/h and 40 m³/h, respectively, demonstrating the significant influence of structural controls on aquifer productivity.

Three-dimensional hydrogeological modeling allowed the development of a coherent conceptual model of the aquifer system. The model consists of an unconfined aquifer occurring between 35 and 50 m depth and two deeper aquifer levels located between 55 and 70 m and between 80 and 105 m depth, respectively. The results indicate that the most productive groundwater reservoirs are associated with the interface between the weathered layer and the fractured basement, as well as with hydraulically connected deep fracture networks.

Overall, this study demonstrates the effectiveness of an integrated structural, geophysical, and hydrogeological approach for identifying high-potential groundwater targets in crystalline basement environments. The findings provide a practical basis for future groundwater development and contribute to the sustainable management of groundwater resources in basement terrains of West Africa.

Acknowledgements

The authors are grateful to the reviewers for their help in improving the quality of this document.

Availability of Data

The data that support the findings of this study are available on request from the corresponding author.

Compliance with Ethical Standards

On behalf of all authors, the corresponding author states that there is no conflict of interest.

Conflicts of Interest

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

References

- [1] Banque mondiale (2024) Rapport sur la pauvreté, la prospérité et la planète 2024: Les pistes d'action pour sortir de la polycrise. Banque.
<https://openknowledge.worldbank.org/server/api/core/bitstreams/1a27dba2-d2fd-4d03-b786-68e4ae898991/content>
- [2] SIA (2023) Les atouts des filières hévéa et palmier à huile présenté aux investisseurs.
- [3] Cobbing, J. and Hiller, B. (2019) Waking a Sleeping Giant: Realizing the Potential of Groundwater in Sub-Saharan Africa. *World Development*, **122**, 597-613.
<https://doi.org/10.1016/j.worlddev.2019.06.024>
- [4] Tang, X. and Adesina, J.A. (2022) Integrated Watershed Management Framework and Groundwater Resources in Africa—A Review of West Africa Sub-Region. *Water*, **14**, Article 288. <https://doi.org/10.3390/w14030288>
- [5] Fornés, J.M., Hera, Á.I. and Llamas, M.R. (2005) The Silent Revolution in Groundwater Intensive Use and Its Influence in Spain. *Water Policy*, **7**, 253-268.
<https://doi.org/10.2166/wp.2005.0016>
- [6] Bianchi, M., Palamakumbura, R.N., MacDonald, A.M. and Macdonald, D.M.J. (2023) Assessing Regional Variation in Yield from Weathered Basement Aquifers in West Africa and Modelling Their Future Groundwater Development and Sustainability. *Hydrogeology Journal*, **31**, 257-274. <https://doi.org/10.1007/s10040-023-02594-w>
- [7] Dewandel, B., Lachassagne, P., Wyns, R., Maréchal, J.C. and Krishnamurthy, N.S. (2006) A Generalized 3-D Geological and Hydrogeological Conceptual Model of Granite Aquifers Controlled by Single or Multiphase Weathering. *Journal of Hydrology*, **330**, 260-284. <https://doi.org/10.1016/j.jhydrol.2006.03.026>
- [8] Lachassagne, P., Dewandel, B. and Wyns, R. (2021) Hydrogeology of Weathered Crystalline/Hard-Rock Aquifers—Guidelines for the Operational Survey and Management of Their Groundwater Resources. *Hydrogeology Journal*, **29**, 2561-2594.
<https://doi.org/10.1007/s10040-021-02339-7>
- [9] Jourda, P., Saley, M.B., Djaoua, E.M., Kouamé, K.J., Biémi, J. and Razack, M. (2006) Utilisation des données ETM+ de Landsat et d'un SIG pour l'évaluation du potentiel en eau souterraine dans le milieu fissuré précambrien de la région de Korhogo (Nord de la Côte d'Ivoire): Approche par analyse multicritère et test de validation. *Revue Internationale de Télédétection*, **5**, 339-357.
- [10] Doumouya, I., Dibi, B., Kouame, K.I., Saley, B., Jourda, J.P., Savane, I., *et al.* (2012) Modelling of Favourable Zones for the Establishment of Water Points by Geographical Information System (GIS) and Multicriteria Analysis (MCA) in the Aboisso Area (South-East of Côte d'Ivoire). *Environmental Earth Sciences*, **67**, 1763-1780.
<https://doi.org/10.1007/s12665-012-1622-2>
- [11] Oussou, F.E., Yalo, N., Ndehedehe, C.E., Oloukoi, J., Alassane, A., Boukari, M., *et al.* (2022) Fracture Aquifers Identification in the Zou Basin (West Africa) Using Remote Sensing and Gis. *Geocarto International*, **37**, 3199-3222.
<https://doi.org/10.1080/10106049.2020.1852613>
- [12] Kinglo, A.A., Hector, B., Galiez, C., Koita, M., Lachassagne, P., Lawson, F., *et al.* (2026) Are There Biases in Borehole Databases of Weathered Basement Aquifers Affecting Their Reliability to Estimate Aquifer Productivity? *Hydrogeology Journal*, **34**, 497-519. <https://doi.org/10.1007/s10040-025-02991-3>

- [13] Doumbia, S., Pouclet, A., Kouamelan, A., Peucat, J.J., Vidal, M. and Delor, C. (1998) Petrogenesis of Juvenile-Type Birimian (Paleoproterozoic) Granitoids in Central Côte-d'Ivoire, West Africa: Geochemistry and Geochronology. *Precambrian Research*, **87**, 33-63. [https://doi.org/10.1016/s0301-9268\(97\)00201-5](https://doi.org/10.1016/s0301-9268(97)00201-5)
- [14] Vidal, M., Gumiaux, C., Cagnard, F., Pouclet, A., Ouattara, G. and Pichon, M. (2009) Evolution of a Paleoproterozoic "Weak Type" Orogeny in the West African Craton (Ivory Coast). *Tectonophysics*, **477**, 145-159. <https://doi.org/10.1016/j.tecto.2009.02.010>
- [15] Pouclet, A., Doumbia, S. and Vidal, M. (2006) Geodynamic Setting of the Birimian Volcanism in Central Ivory Coast (Western Africa) and Its Place in the Palaeoproterozoic Evolution of the Man Shield. *Bulletin de la Société Géologique de France*, **177**, 105-121. <https://doi.org/10.2113/gssgfbull.177.2.105>
- [16] Kouakou, K.E.G., Lasm, T., Sombo, B., Sombo, C., *et al.* (2014) Contribution de la géophysique à l'étude structurale et à l'identification des aquifères de fissures dans le département de Dabakala (Centre-Nord Côte d'Ivoire). *International Journal of Innovation and Applied Studies*, **8**, 1752-1769.
- [17] Koïta, M., Yonli, H., Soro, D., Dara, A. and Vouillamoz, J. (2017) Taking into Account the Role of the Weathering Profile in Determining Hydrodynamic Properties of Hard Rock Aquifers. *Geosciences*, **7**, Article 89. <https://doi.org/10.3390/geosciences7030089>
- [18] Kouakou, K.E.G., Sombo, B.C., Kouadio, K.E., Kouassi, F.W., *et al.* (2013) Sondage et Profilage Électrique dans le District de la Vallée du Bandama (Côte d'Ivoire): Corrélation des Résultats Électriques et Sondages Mécaniques, Typologie et Modèles des Courbes Géoélectriques. *European Journal of Scientific Research*, **94**, 355-372.
- [19] Sombo, A.P. (2018) Electrical Soundings: Help Tools for Mapping Continuous Aquifer. Case of the Municipality of Cocody (South-East of Côte d'Ivoire). https://agris.fao.org/search/en/providers/124827/records/685179bf53e52c13fc7708aa?utm_source=chatgpt.com
- [20] Kouakou, K.E.G. and Lasm, T. (2015) Contribution of Electrical Resistivity Methods to Water Research in Cristalline Environnement: Case of Yakasse-Attobrou and Abié.
- [21] Youan Ta, M., Lasm, T., Jourda, J.P.J., Bachir Saley, M., Adja Miessan, G., Kouamé, K., *et al.* (2011) Cartographie des eaux souterraines en milieu fissuré par analyse multicritère. Cas de Bondoukou (Côte-d'Ivoire). *Revue internationale de géomatique*, **21**, 43-71. <https://doi.org/10.3166/geo.21.43-71>
- [22] Igrace, Y.M., Mubenga, K.W., Nkenge, L., Dieudonné, M.P. and Guylain, E.M. (2025) Contribution à l'étude structurale des formations situées entre les rivières Mbavu et Lukula dans les territoires de Tshela et Seke Banza, en République Démocratique du Congo. *Revue Internationale de Recherche Scientifique et Revue-IRS*, **3**, 6952-6965. <https://doi.org/10.5281/zenodo.17789168>
- [23] Baamar, B., Badra, L., Benyounes, G.A. and Souiah, M. (2017) Contrôle structural des minéralisations à fluorine d'El Hammam (Maroc Central). *Bulletin de l'Institut Scientifique, Rabat, Section Sciences de la Terre*, **39**, 1-24.