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Geoelectrical Application to Well Site Boreholes for Groundwater Exploration on White Bandama Watershed in Crystalline Zone of Korhogo Region (Ivory Coast)

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Abstract— Basement aquifers, which occur within the weathered and fractured zones of crystalline bedrocks, are important groundwater resources in tropical region. The complexity of hard rock aquifers, the lack of exhaustive studies regarding these aquifers lead to bad siting of boreholes drilling points. Geophysical investigations are used to obtain information about the weathered and fractured zones of the crystalline basement rocks, which relates to the occurrence of groundwater. Knowledge of the spatial variability of basement aquifers is useful in siting wells and boreholes for optimal and perennial yield. The electrical resistivity method is one of the most widely used geophysical methods for characterizing the spatial variability of the weathered and fractured zones in groundwater exploration efforts in basement complex terrains. This work deals with combining electrical resistivity profiling, vertical electrical sounding with surface two-dimensional (2D) geoelectrical resistivity imaging to characterise the weathered and fractured zones in a crystalline basement complex terrain of the white Bandama watershed in Korhogo (northern Ivory Coast). The study shows that a Schlumberger array for vertical electrical soundings integrated with the resistivity imaging is efficient and enhances the aquifer characterisation in basement complex terrain.

Index Terms— Aquifers, Cristalline basement, Geophysics, Groundwater exploration, Hard-rocks, Ivory Coast

1 Introduction

IN West Africa, due to the climate change coupled with the growing demography, drinking water supply, particularly in rural areas, is a problem that is becoming more and more acute. In Ivory Coast, a significant proportion of the population does not have access to drinking water and still drinks water from hypothetical sources. They are thus exposed to numerous diseases. This is the consequence of a low coverage rate of drinking water in rural areas, unlike in urban areas where the number of production centers has increased. In view of this observation, the control of the availability of water resources, particularly groundwater, which is also dependent on the climate in a little studied basin but with a high human density, remains a vital need. Basement terrains are areas underlain largely by impermeable crystalline igneous and metamorphic rocks, characterised with low porosity and permeability. Basement aquifers are important groundwater resources in tropical region due to their widespread extent and accessibility but with large spatial variability. In addition, there is often no readily available alternative source of water supply in basement complex areas, particularly for rural populations [1]. In West Africa in general, hard-rock aquifers are particularly important, in particular in Ivory Coast where groundwater resource development is often in small scale and usually for domestic water supply, due to the dispersed rural populations. Groundwater is largely potable as it is relatively less vulnerable to surface pollutants, and contains few suspended solids, small concentrations of bacteria and viruses, and minimal concentrations of dissolved mineral salts.

The upstream watershed of White Bandama, northern Ivory Coast, where the study area is located, is on a hard-rock aquifer which geometry and potentiality is not yet well characterized. The frequent high failure rate of dug wells and boreholes was observed when performing wells and boreholes for groundwater. One of the causes is a weak scientific knowledge on the environment.

Appreciable and perennial yield of wells or boreholes in basement aquifers require adequate storativity, effective transmissivity and sufficient drawdown, which can only be achieved by siting wells and boreholes in areas where they can penetrate the maximum thickness of the weathered and fractured bedrock.

To ensure precise siting of dug wells or boreholes and optimise the utility of groundwater resource in hard-rock, a proper understanding of the hydrologic characteristics of the basement aquifers and their spatial variability is required. This can be achieved by conducting geophysical surveys, which provides the spatial and/or temporal distribution of subsurface electrical conductivity [2]. The effectiveness of geoelectrical resistivity survey in groundwater exploration is mainly due to the correlation that generally exists between the electrical properties of the subsurface rocks and their fluid content, and the hydrologic properties of the formations as both electrical current and groundwater flow are channelled through the interconnected pore spaces [3] , [4] , [5]. In this study, the near-surface in a crystalline basement terrain in White Bandama watershed of northern Ivory Coast was characterised by integrating vertical electrical soundings with 2D surface geoelectrical resistivity imaging, whereby Schlumberger array was used for the resistivity data measurements. The goal of the characterisation was to delineate the weathered overburden and fracture zones in the study site with the intention of assessing the groundwater potential of the hard-rock aquifer and consequently locate optima points for siting productive boreholes or dug wells. The methodology used in this study is based on the use of an efficient strategy of combined hydrogeophysical prospecting methods, allowing a good characterization of the groundwater reservoirs.

2 Material and Methods

2.1 Site Description and Geological Settings

The study area is located in the white Bandama watershed, between latitudes 9°25' and 9°30' North and longitudes 5°43' and 5°37' West. The site under investigation is located in Korhogo region, which is within the crystalline basement of northern Ivory Coast (Fig. 1).

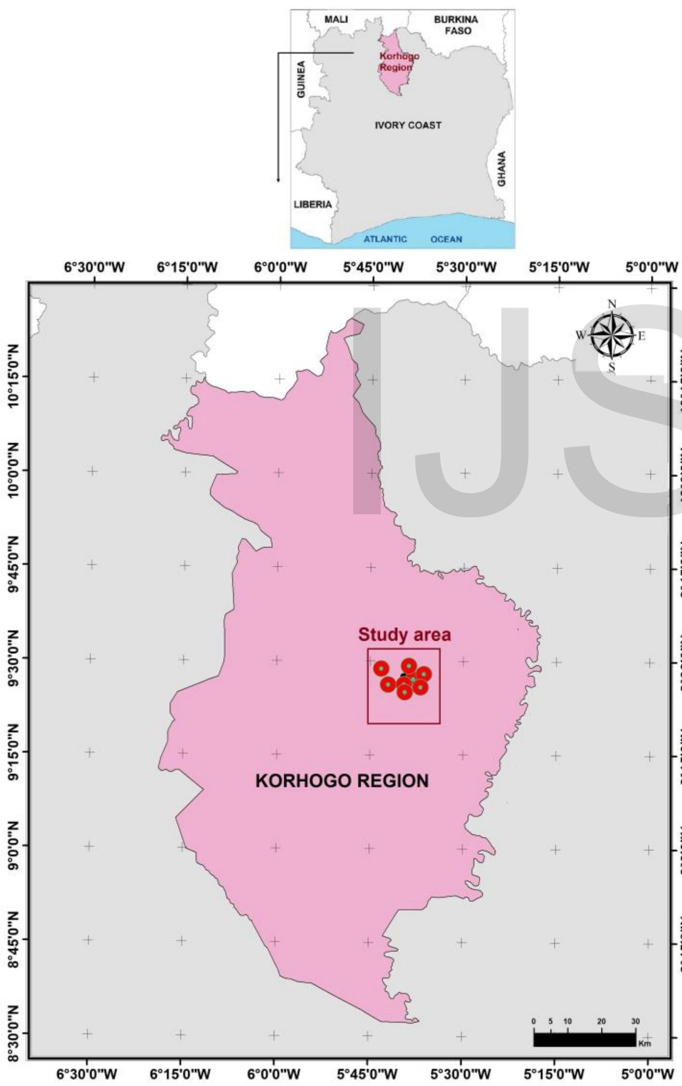


Fig. 1. Location of the study area

The geological substratum is made up of granite, granodiorites and post-birimean migmatites [6]. The topography of the area is largely characterised by sparsely distributed hills and knolls, which has a mean elevation of about 400 m above mean sea level. The underground water reserves are therefore to be sought in the mantle of alteration and in the cracks and fractures that affect this bedrock. This region benefits from higher precipitation, which allows the aquifer to be recharged despite the slow percolation of infiltration water. Drainage is provided by tributary rivers of the Bandama, and flooding occurs from August to September. Low water occurs from January to May. From 1970 to 2012, the average annual rainfall is 1,364 mm. The highest temperatures are recorded in April and May, while the lowest are observed in the period from December to January, with an annual average of 26.7°C. Groundwater reserves are stored in the upper weathered part, but are drained by underlying cracks and fractures, sometimes open to great depths. Discontinuous aquifers with fissure permeability are present almost everywhere. They are associated with the granitic basement. Their hydraulic characteristics depend on their lithology, thickness and granulometry of the overlying formations, which are closely related to the geomorphological and rainfall conditions. The climate is tropical humid characterised by two marked seasons (dry and rainy seasons). The dry season is usually between the months of November and May, while the rainy season is between June and October. The mean annual rainfall is greater than 1,400 mm and the average monthly temperature ranges from 23.2 °C in July to 32.7 °C in February.

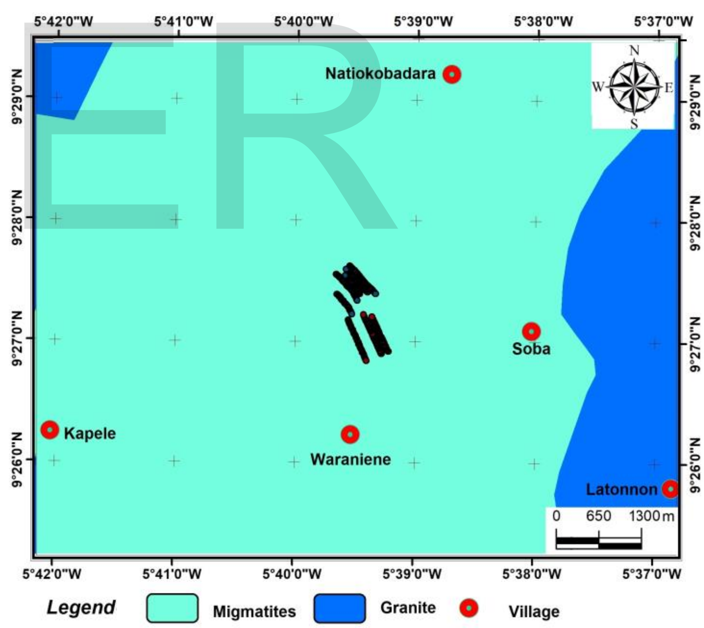


Fig. 2. Geological map of the study area

2.2 Data measurements

Geoelectrical 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.

Resistivity of the ground 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.

For a inhomogeneous ground (with real geological conditions) and arbitrary electrode arrangement, the apparent resistivity ρ_A (unit: Ohm meter, Ω.m) as the relevant petrophysical parameter can be calculated from the current I and the potential difference U by:

$$\rho_A = K \cdot \frac{U}{I} \qquad (1)$$

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:

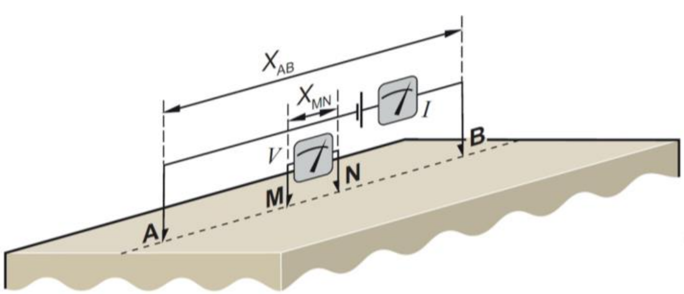
$$K^{-1} = \frac{1}{2\pi} \cdot \left[\left(\frac{1}{AM} - \frac{1}{BM} \right) - \left(\frac{1}{AN} - \frac{1}{BN} \right) \right] \qquad (2)$$

This data set is computer-processed with the aim to get the underground resistivity distribution, which has to be interpreted in terms of geological structures.

The geophysical data acquisition equipment consists of a Syscal Junior resistivity-meter with its accessories (connection cables, electrodes, decameters, hammers, masses, a compass, a GPS, etc.). The data processing system is composed of mapping software (Surfer 10) and geophysical processing software (WinSEV). Two (2) sites were investigated, with eight (8) profiles in N319° direction and six (6) vertical electrical soundings.

2.3 Resistivity profiling

The profile electrical resistivity survey involves the measurements of apparent resistivity data using Schlumberger array along eight traverses (Fig. 3). On the site 1, traverses L1, L2, L3, L4 and L5 were conducted in N319° direction and thus parallel to each other, while on site 2 traverse L1, L2 and L3 were conducted in the same direction (N319°) direction, the profile length going from 500.0 m to 720.0 m.



In practical field surveys, the choice of Schlumberger configuration is made with the currents injection electrodes A and B spacing of 200 m (AB=200 m), the resulting differences potential electrodes M and N spacing of 20 m (MN=20 m) and an offset of 20 m for all the profiles surveys.

Fig. 3. The used electrode arrays for Schlumberger configuration

The survey was conducted during the second week of October when the ground was relatively hard; however, watering of electrodes positions to ensure good contact between the electrodes and the ground was not required.

The apparent resistivity data sets were measured manually using SYSCAL Junior 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 minimising 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. The SYSCAL Junior was set for repeat measurements with minimum data stacking of 3 and maximum of 6; thus, each data point was sampled 3–6 times before displaying the median. The root-mean-squares error in the data measurements was generally less than 4%; however, isolated cases in which the root-mean-squares error was up to 5% were repeated after ensuring the electrodes were maintaining good contact with the ground.

2.4 Vertical electrical soundings VES

Vertical (1D) electrical soundings are applied to a horizontally or approximately horizontally layered earth. Geological targets may be, e.g., rocks of different lithologies, layered aquifers of different properties, rocks overlying igneous rocks, or the weathering zone of igneous rocks. In the most favourable case, the 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 to an increasing influence of the deep-seated layers on the apparent resistivity ρ_A. 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 base of all data inversion to obtain the resistivity / depth structure of the ground (Fig. 4).

We used Schlumberger linear electrode configurations for resistivity measurements. Because of practical and methodical advantages, vertical electrical soundings 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):

$$K_{\text{SCHLUMBERGER}} = \frac{2\pi}{MN} \cdot \left(\frac{AB}{2} \right)^2 \qquad (3)$$

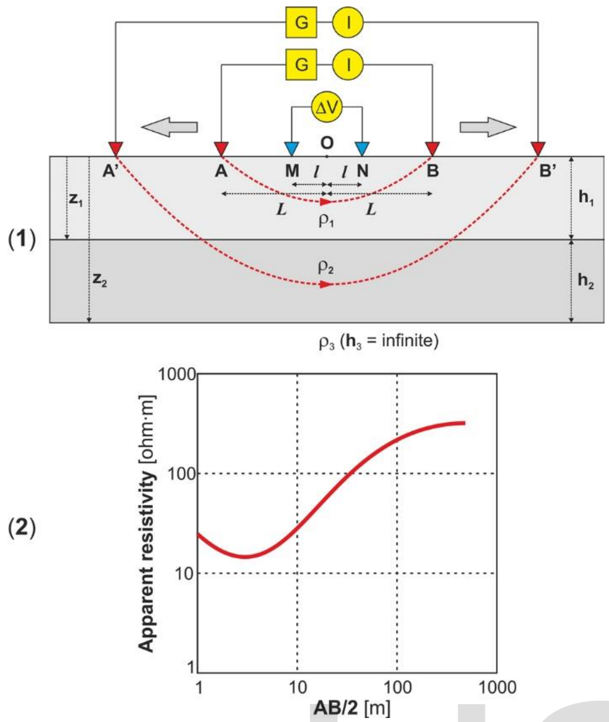


Fig. 4. Principle of Vertical Electrical Sounding (VES) investigation of the subsurface. (1) Configuration of the electrodes for a Schlumberger sounding array; dashed curves represent current flow paths, l = MN/2 is the half-spacing of the measurement electrodes, L = AO = BO = AB/2 is the half-spacing of the current electrodes. (2) Example of apparent resistivity (ρA) sounding curve obtained for a layered terrain, showing the variation of ρA 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) [7].

2.5 Data processing and inversion

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

The apparent resistivity data sets 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 so as 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 WinSEV program. The iterative procedure produced the model parameters for the delineated geoelectric layers.

2.6 Resistivity mapping

Targets of resistivity mapping (or profiling) are near surface resistivity anomalies, caused by fracture zones, cavities or waste deposits. Any common electrode configuration can be used for mapping purposes. In general, the chosen four-point configuration is kept constant and moved along profiles, while apparent resistivity is recorded. In this study, the Schlumberger configuration was used to carry out the electrical profiling as well as the vertical electrical soundings. Prior to field works, optimum electrode spacing of the configuration is determined by model calculation, if assumptions on resistivity and depth of the target and on resistivity of the surrounding material are possible.

3 Results and Discussion

The study strategy consisted of horizontal prospecting by electrical profiling to highlight lateral variations, followed by vertical prospecting by electrical sounding on conductive anomalies identified on the profiles (Fig. 5). On site 1 of the study area, a total of five profiles were completed. The profile line L1 of N319° direction characterized the ground over 500 m length, with resistivity values ranging from 320 to 1050 Ωm. On the northeast side of L1, and separated by 60 m, the L2 profile was conducted over a length of 600 m. The resistivities obtained range from 390 to 1020 Ωm. Both electrical resistivity profiles show the same pattern. In the first half part of the profile, L1 shows a much more conductive area and then becomes more resistive in the second half part. Anomalies are observed on these profiles, the most significant of which highlight discontinuities in N230° direction. These anomalies are targets to be characterized by electrical soundings and could be recharge poles of the underlying aquifer.

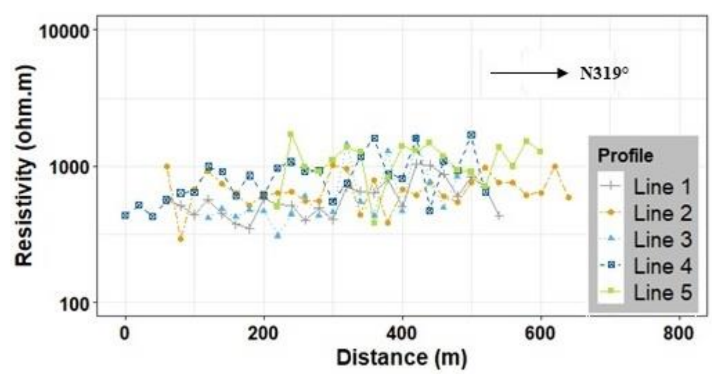


Fig. 5. Electrical resistivity profiling graphics on the site 1 of the study area

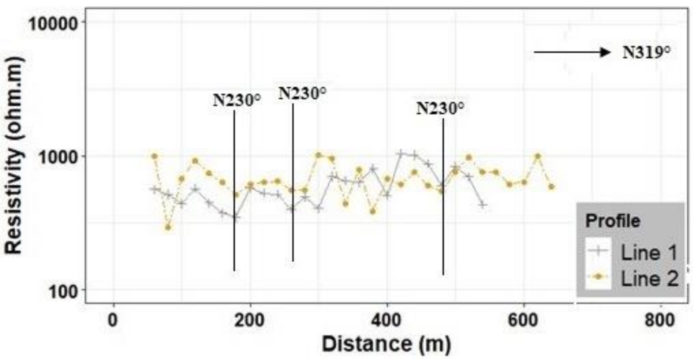


Fig. 6. Electrical resistivity profiling graphics for Line 1 and Line 2 on the site 1

On the southwest side of profile L1, L3 and L4 were completed with an inter-profile distance of 60 m. Profile L3 shows a more conductive zone with resistivity values of 300 to 1400 Ωm versus 430 to 1700 Ωm for profile L4. These profiles highlight conductive anomalies over which discontinuities in the subsurface, with N220° and N205° directions, could be observed (Fig. 7). These discontinuities may be similar to fractures to be investigated for the implementation of water drilling, after characterization by electrical sounding.

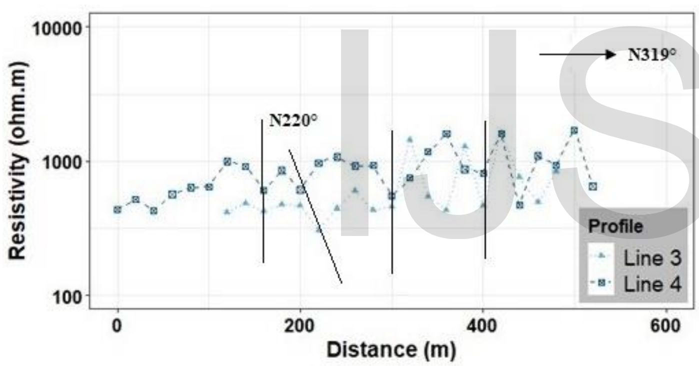


Fig. 7. Electrical resistivity profiling graphics for Line 3 and Line 4 on the site 1

Measurements carried out on site 1, with profiles of 500 m average length and more than 120 stations in the study area. These measurements allowed us to obtain a resistivity map (Fig. 8) which characterizes the site and shows a resistive facies in the eastern and northeastern sectors. On the other hand, a conductive facies is located in the central and southern part of the site, defining North-South and SW-NE conductive axes. The rest of the site is located on an intermediate facies. The sector favorable to the implementation of groundwater catchment is located in the southern and central part, where the existing traditional and modern wells are perennial. In addition to this sector, there are isolated areas on conductive SW-NE axes interspersed with resistive facies (Fig. 8).

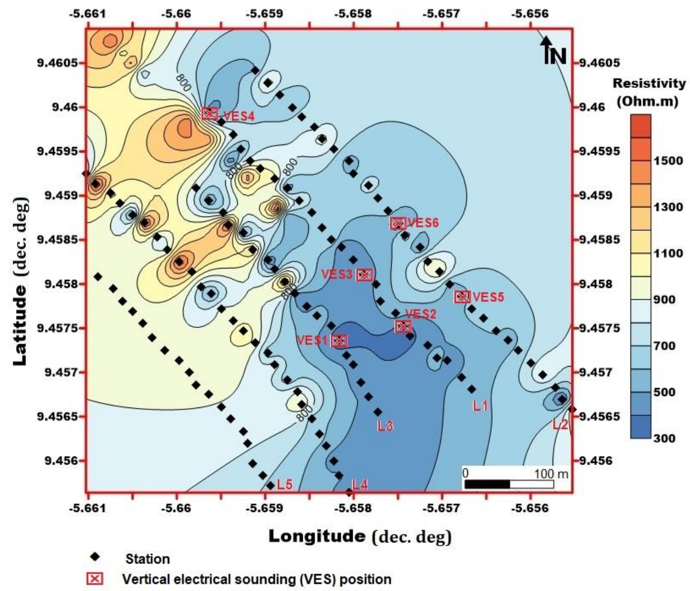


Fig. 8. Electrical resistivity map of site 1 of the study area

On the site 2, located in the southern part of site 1, 3 profiles of more than 700 m in length were carried out in N319° direction, with the same configuration. The results obtained show much higher resistivities compared to those of site 1. We note resistivity values ranging from 650 to 1450 Ωm for profile L1, from 600 to 1600 Ωm for profile L2, and from 950 to 4000 Ωm for profile L3. The first half part of site 2 identifies resistivity values close to those of site 1, especially for the L2 profile. In the second half of site 2, between 300 and 750 m from the beginning, the resistivity increases significantly from profile L1 to profile L3. This part of site 2 of the study area is marked by an increasingly resistive facies and characterized by fresh rock outcrops and the proximity of Mount Korhogo. No productive wells or boreholes have been drilled in this part of the study area, and our investigations did not reveal any significant anomalies that could be drilled for the groundwater catchment structures (Fig. 9). Also, an inversion artefact characterised with a low resistivity anomaly is observed in some part of the resistivity zones on the resistivity map; such low resistivity anomalies are characteristics of fractured zones in crystalline basement rocks as shown by [8], [9], [10], [11] and potentially serve as preferential flow path for groundwater within the basement rocks.

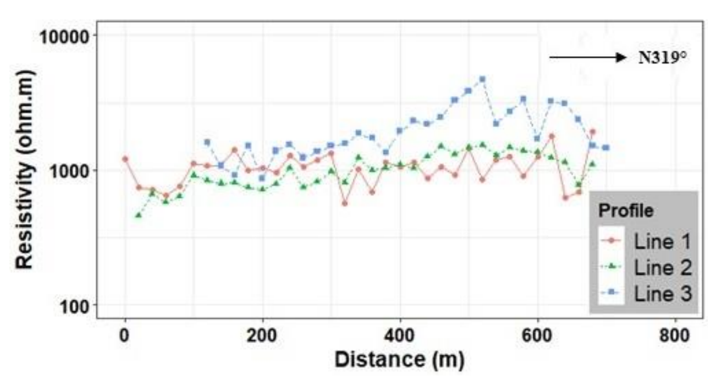


Fig. 9. Electrical resistivity profiling graphics on the site 2

In general, the resistivity map obtained on site 2 of the study area highlights a more resistive ground than on site 1. In detail, we note a conductive facies in the northern sector, constituting an extension of the conductive facies of site 1. The eastern sector of site 2 is strongly characterized by a highly resistive facies, due to the increasingly healthy rock outcrop, as we approach Mount Korhogo (Fig. 10).

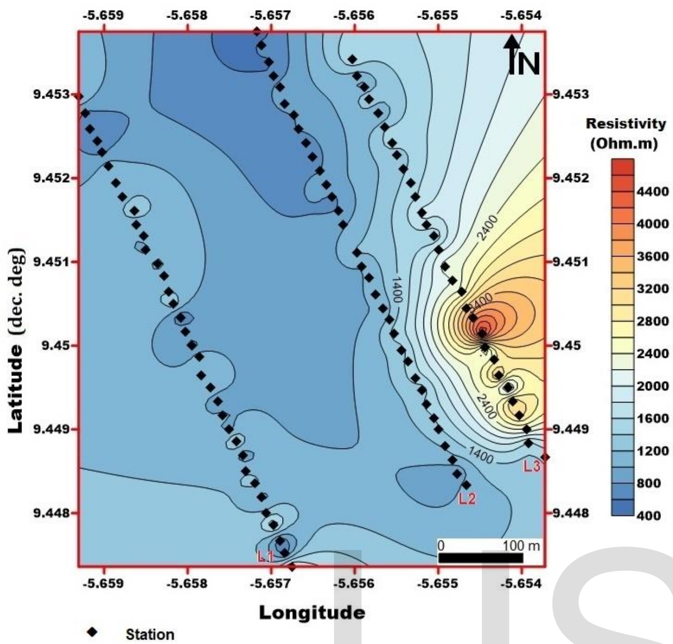


Fig. 10. Electrical resistivity map of site 2 of the study area

Data inversion from the six vertical electrical soundings over conductive anomaly zones (Fig. 8) provided a plot of electrical resistivity versus depth. The geoelectrical resistivity obtained from the resistivity sounding curves are presented in figs. 11, 12, and 13. Interpretation of the sounding curves allows us to identify 3 groups according to their shape and the number of layers.
The first group regards the three-layer model, which refers to a sounding curve with 2 inflection points corresponding to three terrains. A first layer composed of top soil with lateritic clays of 95 Ωm and 3.1 m thickness. The second terrain corresponds to conductive arenas of 655 Ωm and thickness 8.7 m. The third terrain corresponds to the subcrop basement of migmatites (Fig. 11). Such soundings can be productive if the drainance is good as in the case of tectonized coarse granites or lowland areas. Although a three-layer model comprising the top soil, regolith and fresh basement is commonly used for the interpretation of electrical resistivity sounding curves in basement complex environment, studies show that the regolith is essentially made up of the collapsed zone and saprolite as in [12], [13].

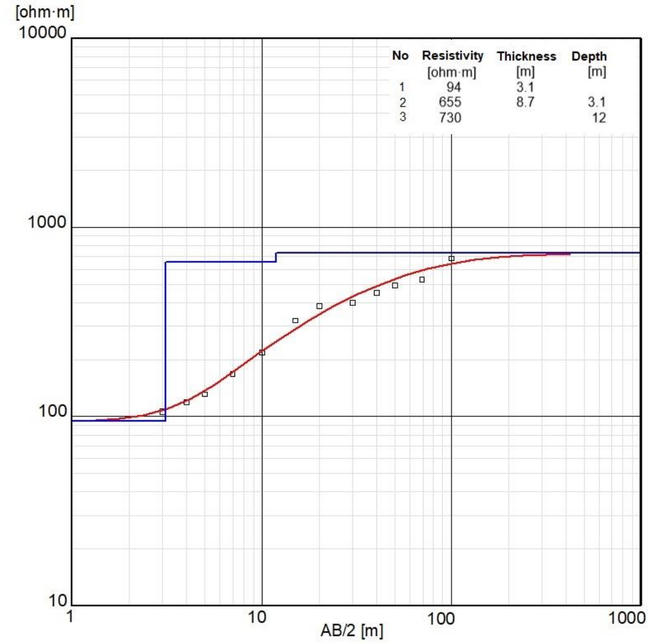


Fig. 11. Vertical electrical sounding (VES4), with resistivity and layer model

The second group concerns a four-layer model used for the interpretation of apparent resistivity data sets for VESs 3 and 6 (Fig. 12). It prensents the “dragging upwelling branch” of vertical electrical sounding curves (VES 3 and VES 6). In this case, the two branches of the curve are asymmetrical. The decrease in the upward slope is related to the existence of a very important terrain in hydrogeology and civil engineering, namely the gravelly arenas (gravelly horizons) and the fissured basement, between the conductive horizon and the sound basement [14], [15]. Indeed, Samé [16], Jourda [17], and Kouakou et al. [18] have shown that this type of curve is due to the presence of a thick fissured horizon between the conductive horizon and the fresh basement. When the thickness of the cracked horizon is significant, the upwelling branch becomes hesitant or dragging. This type of sounding is related to the influence of a major fracture [14], [19]. The productivity of this type of sounding is always good and depends on the thickness of the cracked fringe.
The VES 3 and VES 6 carried out on anomalies respectively profile line L1 and L2 (Fig. 8) show numerous inflection changes. From top to down, the first layer is composed of relatively loose lateritic clays of 55 Ωm and 2.5 m thickness, a second saprolite layer of clayey sand (300 Ωm, 26 m thickness), a third saprock layer of weathered / fractured basement (100 Ωm, 11 m thickness), and the bedrock layer 4 which is a basement more and more fresh with the depth. The geoelectrical model developed indicates an estimated alteration thickness of 37 m and 42 m, respectively and an underlying fissured horizon (Fig. 12). The strength of the alteration thickness (averaging over 30 m) and the presence of saturated levels appear to influence the productivity of boreholes. The hydraulically active fractures in the region are mostly encountered beyond

the 30 m drilling threshold, as is the case in several basement regions of Ivory Coast [20]. Following [21], [22], and [23], hydraulically active fracturing is optimal in the upper part of the fractured horizon located in the first thirty meters below the saprolites.

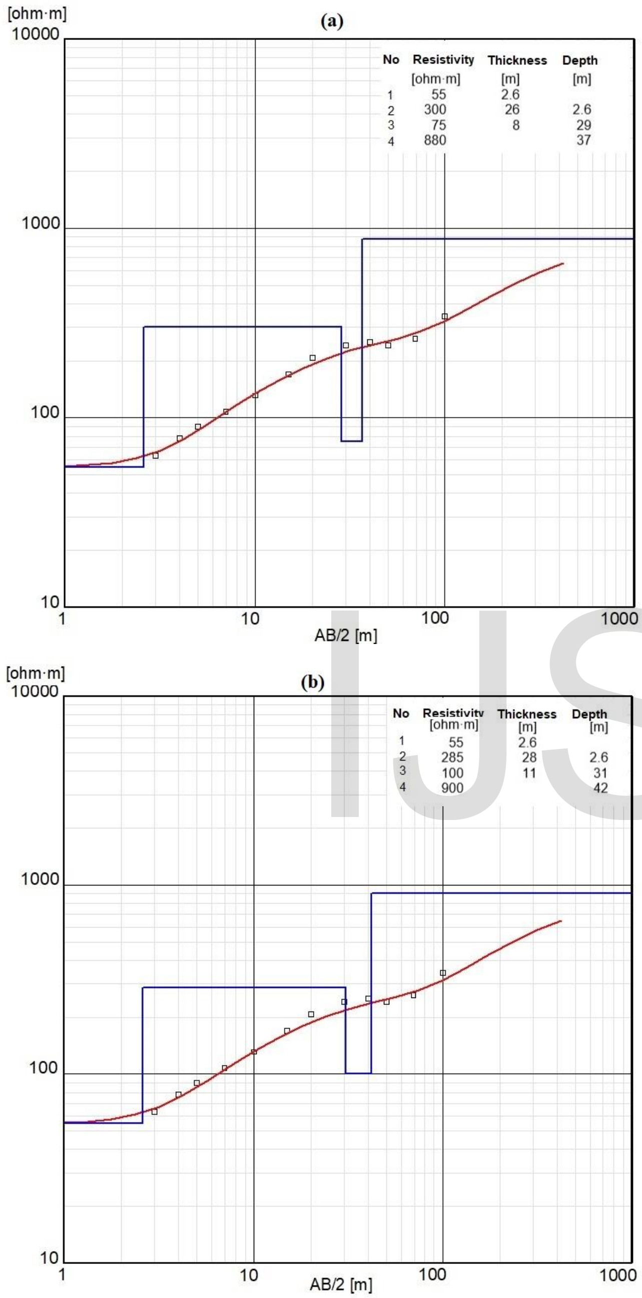
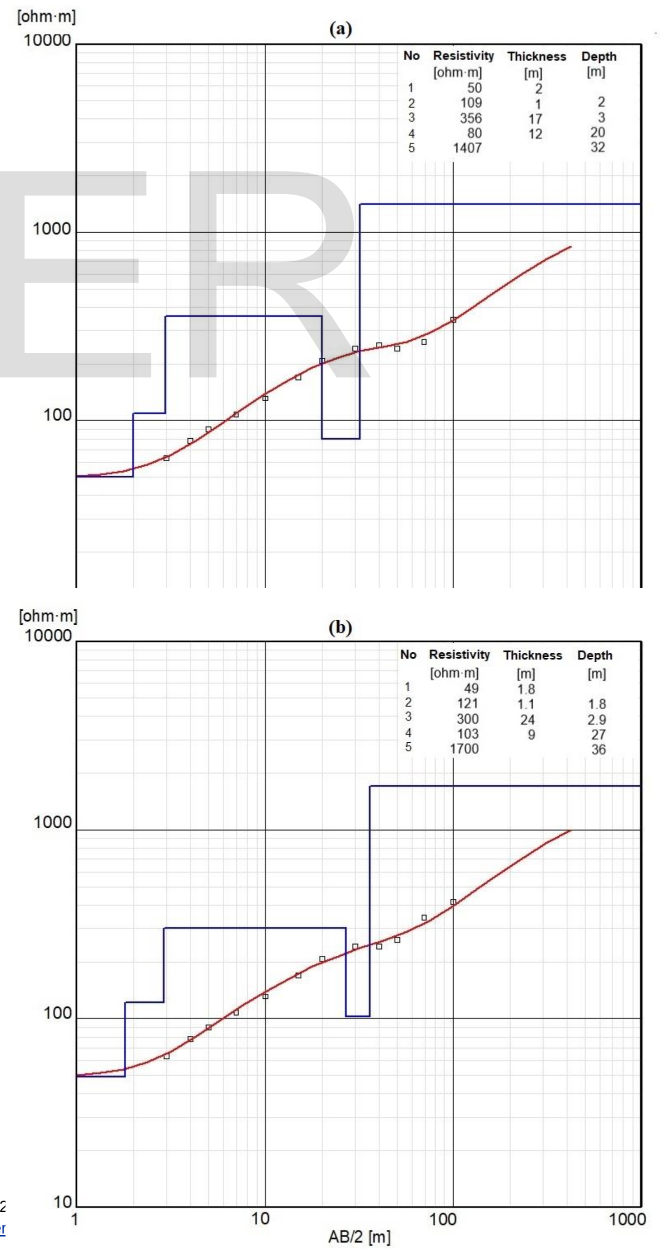


Fig. 12. Vertical electrical sounding, with resistivity and layer model for a) VES 3, b) VES 6

The third group is similar to the second group with a "dragging upwelling branch", but refers to a five-layer model. Here, the saprolite may be divided into upper and lower units; these units usually exhibit different electrical properties arising from changes in the degree of weathering and mineralogical composition of the constituent material in the zone. Consequently, a five-layer model was used to interpret the resistivity sounding curves of VES1, VES 2 and VES 5 (Fig. 13), as this fits the observed apparent resistivity data more reasonably than the traditional three or four layers models commonly adopted for the interpretation of geoelectrical resistivity sounding curves in crystalline basement complex terrain. From top to down, the first layer is composed of top soil with lateritic clays, a second layer of collapsed zone of clayey unit, a third layer of consolidated sand, a fourth layer corresponding to the weathered / fractured basement, and the fifth layer which is a fresh basement.

Curve shapes in fault zones as well as field observations (water boreholes, modern wells, traditional wells) confirm the importance of the deformations undergone by the Birimian and ante-Brimian formations. Thus, we can see shallow surface formations separated by thick alteration layers in fault zones. The calibration of the geophysical data with boreholes data shows a good correlation with the nature of the terrain and its thickness.



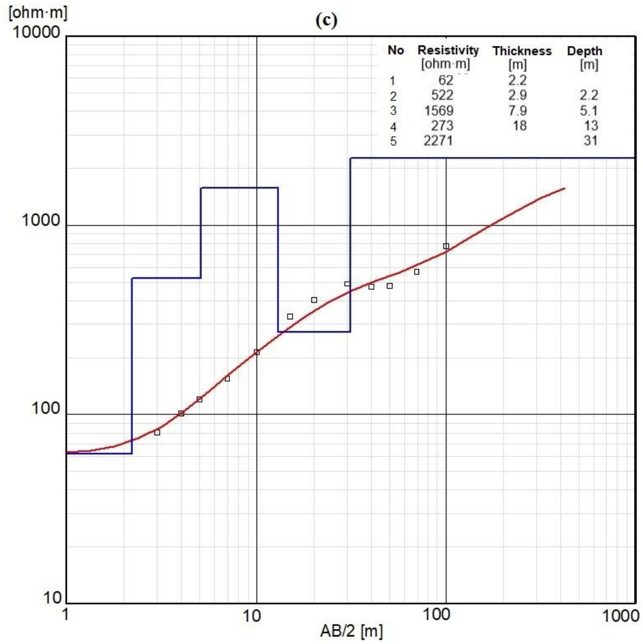


Fig. 13. Vertical electrical sounding, with resistivity and layer model for a) VES 1, b) VES 2 and c) VES 5

The geoelectric parameters obtained from the resistivity sounding curves are presented in Table 1. The geoelectric parameters for the resistivity sounding curves correlate reasonably well with each other.

Table 1. Parameters of the geoelectrical models resulted from the quantitative interpretation of apparent resistivity data recorded on vertical electrical soundings, with ρ and h respectively the resistivity and the thickness of layers

	VES1	VES2	VES3	VES4	VES5	VES6
ρ1 (Ωm)	50	48	55	94	52	55
ρ2 (Ωm)	109	121	300	655	522	285
ρ3 (Ωm)	356	300	75	730	1569	100
ρ4 (Ωm)	80	103	880	-	273	900
ρ5 (Ωm)	1407	1700	-	-	2271	-
h1 (m)	2	1.8	2.6	3.1	2.2	2.6
h2 (m)	1	1.1	26	8.7	2.9	28
h3 (m)	17	24	8	∞	7.9	11
h4 (m)	12	9	∞		18	∞
h5 (m)	∞	∞			∞	

The weathered and fractured basement overlies the fresh basement and is characterised with high inverse model resistivity. The fresh basement was penetrated by all the soundings conducted in the site; the minimum and maximum depths of penetration of the fresh basement are respectively 12.0 m in VES 4, and 42.0 m in VES 6, where the overburden is relatively thicker. This aquifer unit occurs at an average depth of about 31 m. Since groundwater occurrence in crystalline basement rocks is largely due to the development of secondary porosity and permeability resulting from weathering and fracturing of the crystalline basement rocks, groundwater is thought to preferentially accumulate or flow in regions with greater overburden thickness as well as regions with high fracture density and connectivity [1]. Thus, the regions characterised with low resistivity anomalies in the resistivity maps together with the delineated weathered and fractured zones are thought to be the preferred locations for borehole or dug well siting for optimum yield. Also, areas characterised with thin overburden should be preferred sites for engineering constructions. Taking this situation into account, the shallow occurrence of the basement aquifer as well as the weathered / fractured zones makes the hard-rock superficial aquifer exposed to surface pollution.

4 Conclusions

The results and interpretations obtained from this study, it appears that the strength of the alteration thickness (greater than 30 m) and the presence of a saturated level influence the productivity of boreholes. In addition, hydraulically active fracturing is optimal in the upper part of the fissured horizon located in the first thirty meters under the saprolites. The profiling identified structures such as fractures, oriented preferentially around N220° and N230° in general. The 1D cross-sections from the vertical electrical soundings provided numerous results regarding the thickness of the alteration zones, fissures and probable fracture depths of the proposed drilling points.

The geoelectrical resistivity imaging based on measurements made with Shlumberger array has been integrated with vertical electrical sounding to characterise the spatial distribution of near-surface features in a crystalline environment in Korhogo region. The resistivity soundings provide point information of the subsurface features, while the resistivity imaging gives the spatial distribution of subsurface resistivity which depicts the basement features. Thus, the integration of vertical electrical resistivity soundings with resistivity maps enhances the characterisation of the hard-rock aquifer. Discontinuities in the ground are important features in near-surface characterisation for groundwater exploration efforts in basement complex terrain as they possess hydrological implications. The spatial variability of the weathered and fractured zones was used to delineate the hard-rock aquifer and to well site perennial wells or boreholes in the investigated area.

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