Contribution of IoT to The Execution of Hydro-Agricultural Projects: Electrical Resistivity Tomography as A Decision-Making Tool for Determining Geophysical Targets, Nganda Site-Senegal.

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Summary - The hydrogeophysical study conducted at the Nganda site, using a connected (IoT) ADMT kit, is based on the interpretation of resistivity panels and the application of petrophysical laws. Electrical imaging reveals a stratified sedimentary system characterized by a very low resistivity zone (8 to 16 Ω·m) located between -60 and -95 meters in depth. The application of Archie's Law at this level allows for an estimated high effective porosity, ranging between 30% and 39%, which is characteristic of clean sands or saturated detrital formations. Correlation with Darcy's Law and permeability models (such as Kozeny-Carman) indicates high transmissivity ($T \approx 2 \cdot 10^{-3}$ m^2/s), suggesting significant freshwater production potential. A theoretical pumping flow rate of approximately 45 m^3/h is feasible, subject to controlled drawdown. Beyond 100 meters, the increase in resistivity (>100 Ω·m) indicates the presence of bedrock or an impermeable base isolating the aquifer. For the borehole implementation, prospecting should target the horizontal window between distances 6 and 10 of Profile 1 to intercept the maximum thickness of the aquifer. Technical Recommendations: Recommended Total Depth: 105 meters. Screening Intervals: Concentrated between -65 and -95 meters. Mandatory Testing: A resistivity well logging must be performed before casing, followed by a long-term pumping test to definitively calibrate permeability and the sustainable exploitation flow rate. The studied site shows excellent potential for a high-yield borehole intended for irrigation or water supply.

Keywords: hydro-geophysics, IoT, resistivity, petrophysical laws, flow rate

INTRODUCTION:

In a global context marked by climate instability and growing demographic pressure, the sustainable management of natural resources has become one of the major challenges of the 21st century. Achieving the Sustainable Development Goals (SDGs), particularly "Zero Hunger" (SDG 2) and "Sustainable Management of Water" (SDG 6), relies on our ability to accurately characterize aquifers in a non-invasive and economically viable manner. Among surface geophysical tools, Electrical Resistivity Tomography (ERT) stands out as a breakthrough technology to meet these imperatives (FAYE et al., 2022).

Electrical Resistivity Tomography is based on the injection of a direct current into the ground and the measurement of the resulting potential difference. It allows for a two-dimensional or three-dimensional image of the electrical resistivity distribution of an aquifer's substratum (DIOUF et al., 2026). This physical property is extremely sensitive to water content, salinity, and the porosity of geological formations, making ERT an unparalleled diagnostic tool for aquifer imaging (DIALLO et al., 2025).

Food security intrinsically depends on the availability and quality of water resources. By enabling precise mapping of recharge zones and early detection of saline intrusion or aquifer depletion, ERT secures irrigation systems. It provides farmers and decision-makers with a scientific basis to optimize groundwater use, thereby preventing waste and ensuring stable harvests in the face of recurrent droughts.

Beyond its technical advantages, ERT meets the imperative of economic efficiency (SDG 12). Unlike traditional exploratory boreholes, which are costly, site-specific, and sometimes unsuccessful, ERT offers extensive spatial coverage at a reduced cost. By minimizing the risk of drilling failure and precisely guiding the installation of hydraulic infrastructure, this technique allows for a strategic and responsible allocation of financial resources, particularly in developing economies.

It is within this broad perspective that this research article is situated, aiming to demonstrate how the systematic integration of electrical resistivity tomography into development programs can serve as a catalyst for integrated water resource management.

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Through various case studies, we will explore how this geophysical target, once reserved for fundamental research, is now becoming an operational pillar for food security and the economic resilience of territories.

MATERIALS AND METHODS

- Study Location

The geophysical study conducted at the Nganda site is part of a research and characterization effort focused on aquifer formations, aimed at the installation of hydro-agricultural boreholes.

The approach adopted is based on electrical geophysical methods, which are suited to the local geological context and widely used for hydrogeological investigations in sedimentary zones, basement rock, and weathered formations.

The study was carried out in Nganda, a commune in the Kaffrine Department and Region, established in 2008 and located near the Gambian border. It is an active agricultural hub with a population of over 14,000 (ANDS, 2023), accessible via a 35 km road from Kaffrine. The figure 1 below presents the study area.

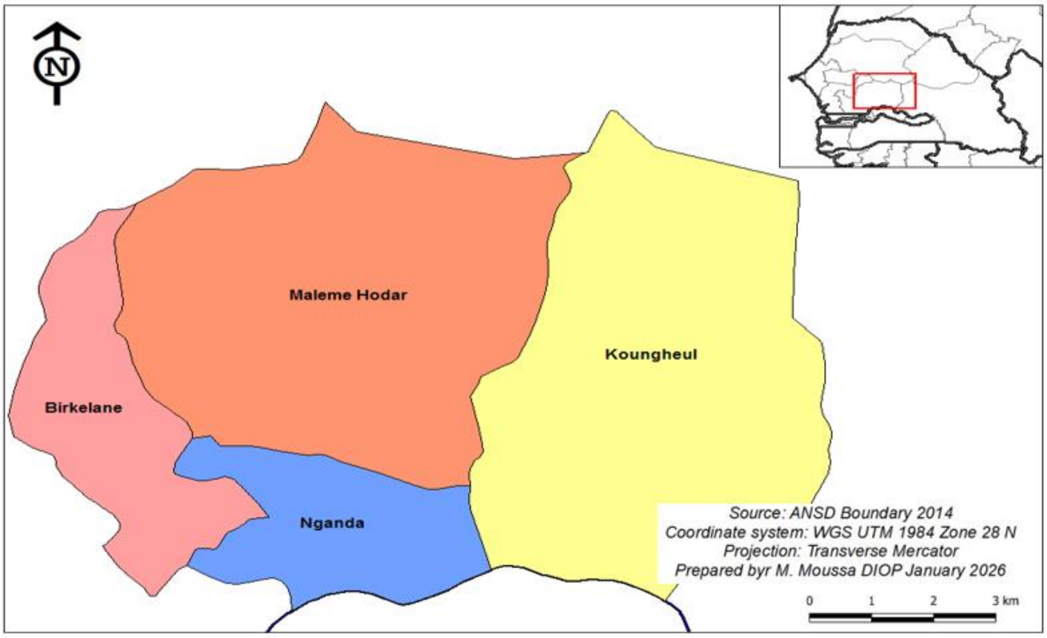

Figure 1: The study area

- Study Area Characteristics

The area is renowned for its economic potential. From an administrative and geographical perspective, the Kaffrine region constitutes a transition zone between the Sahelian domain to the north and the Sudano-Sahelian domain to the south. The relief is generally monotonous, characterized by moderate altitudes and low topographic energy, which promotes rainwater infiltration when pedological and structural conditions are favorable.

The climate is of the Sudano-Sahelian type, marked by:

- A long dry season, dominated by hot and dry winds;
- A short rainy season, concentrated between June and October, with irregular and often insufficient rainfall.

These climatic conditions make surface water resources scarce and temporary. Consequently, local populations depend primarily on groundwater for drinking water supply, livestock watering, and agricultural activities. In this context, identifying favorable zones for borehole installation constitutes a major challenge for local development, justifying the conduct of an in-depth geophysical study.

- Geological Setting

The Ganda study area, located in the Kaffrine region, belongs to the Senegalo-Mauritanian sedimentary basin, specifically its central part corresponding to the "Groundnut Basin" (Bassin Arachidier). This basin is characterized by a thick Cenozoic sedimentary cover resting on older Upper Cretaceous formations.

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According to the 1/500,000 geological map of Senegal and BRGM summaries, the regional stratigraphic sequence is presented, from top to bottom, as follows:

a. Quaternary and Continental Terminal

These surficial formations consist of a highly heterogeneous sandy to sandy-clay set, locally capped by lateritic duricrust (ironstone). Their thickness generally varies from a few meters to several dozen meters. They constitute the dominant loose cover in the Kaffrine region.

b. Eocene (Lutetian – Ypresian) Eocene formations are represented by: Lutetian limestones (locally absent or discontinuous in the central Groundnut Basin); Ypresian marls and sandy marls, which are widely developed and act as the regional impermeable substratum. These marly levels are systematically identified in geophysical interpretations as conductive horizons, marking the base of exploitable aquifers.

c. Paleocene – Maastrichtian At depth, the following are encountered: The Paleocene, consisting of limestones, sometimes marly and locally karstified; The Maastrichtian, composed of sands, sandstones, and sandstone-limestone levels. In the Kaffrine region, these deep formations are generally only reached by high-depth boreholes and do not constitute the priority target for rural hydraulic projects.

- Structural Context

Tectonics are generally weak in the central Groundnut Basin. The structures recognized at a regional scale show dominant NNE–SSW and ENE–WSW orientations, inherited from the deep basement, but without major discontinuities significantly affecting the geometry of the aquifers in the Ganda area.

- **Hydrogeological Setting**

From a hydrogeological perspective, the Ganda region belongs to the Senegalo-Mauritanian basin aquifer system, one of the most exploited in Senegal for water supply in rural and semi-urban areas. The work of the BRGM and the hydrogeological atlas by Collignon (2018) identify three major aquifer units relevant to the study area:

a- Superficial Aquifer of the Quaternary – Continental Terminal

This aquifer is developed within the Quaternary and Continental Terminal sands and clayey sands. It features:

- Dominant intergranular porosity;
- Direct recharge through precipitation infiltration;
- Variable thickness, generally ranging from 20 to 50 m in the central Groundnut Basin.

From a geophysical standpoint, this aquifer corresponds to medium to high resistivities when the sands have low clay content and low mineralization, and lower resistivities when clay content or mineralization increases.

b- Eocene Marly Substratum (Regional Aquitard) The Lutetian and Ypresian marls constitute a continuous impermeable level, acting as the hydrogeological substratum. This level is systematically identified in geophysics by:

- Low resistivities (conductive horizon);
- A sharp contrast with the overlying sandy formations.

It marks the lower limit of exploitable aquifers in most hydraulic projects in the Kaffrine region.

c- Deep Aquifers (Paleocene – Maastrichtian)

Deep aquifers, developed in:

- Paleocene limestones;
- And locally in Maastrichtian sands and sandstones; present variable potential and are generally reserved for high-depth structures.

Their exploitation requires specific geophysical investigations and strict water quality control, particularly regarding mineralization.

d- Water Quality and Hydrogeological Constraints

According to Collignon's atlas, groundwater in the central Senegalo-Mauritanian basin presents:

- Generally moderate mineralization;
- Spatial variability related to lithology, depth, and recharge conditions.

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The Kaffrine region is little affected by saline intrusion, a phenomenon mainly limited to coastal areas. The primary constraints are instead related to:

- The limited thickness of the sandy aquifers;
- The local presence of clays;
- And the lateral variability of the formations.

Equipment:

Following geological and hydrogeological analysis, geophysical prospecting was conducted using the electromagnetic induction method. An electrical sounding establishes a curve of apparent resistivity variation measured at the surface as a function of depth using an AMNB quadripole. Investigation depth increases with the spacing between current electrodes A and B. The study used an ADMT ZN-series rapid groundwater detector, launched in 2023, representing AIDU's latest innovation in groundwater exploration technology. This device supports single-channel configurations as well as 12, 24, 36, 48, and 60 channels. Compared to traditional multi-channel instruments, it offers significantly faster measurement speeds and higher accuracy, acquiring up to ten times more data in the same time span. We also used a handheld GPS for referencing measurement points.

Figure 2: ADMT ZN and pocket GPS

- **Methodology**
  - **Data Collection**:

The ADMT system uses the Helmholtz wave propagation equation and exploits natural electromagnetic fields of the Earth (frequencies 0.1 Hz–5 kHz) to investigate the subsurface. These waves propagate through the ground and are influenced by electrical resistivity (ρ), allowing detection of geological structures such as water-bearing layers and mineralized zones.

Measurements were carried out down to depths of 300 m at all sites. Profile lengths were 60 m, with repeated measurements. When significant discrepancies appeared between two measurements, a third or fourth reading was performed if necessary. Measurements were taken using two electrodes, moved after each reading until the 60 m profile was completed. The measured values do not directly represent material resistivity but correspond to geo-electrical logs used to produce iso-value maps.

  - **Mathematical Equations:**

Helmholtz equation (1)

The Helmholtz equation is a partial differential equation describing the propagation of harmonic waves in space. For the magnetic field (H) and electric field (E), with Laplacian operator (∇) and complex wave number (k), it is expressed as:

$$\nabla^2 H + k^2 H = 0 \qquad (1)$$

$$\nabla^2 E + k^2 E = 0 \qquad (2)$$

Porosity Estimation: Archie's Law (2)

To determine whether the rock can contain water, we use the relationship between the measured formation resistivity (from the profile) and the resistivity of the water. Archie's Law is a fundamental empirical relationship in petrophysics and geophysics. It allows for the estimation of a reservoir rock's water saturation by linking its electrical resistivity to its porosity.

$$\phi = \left(\frac{a \cdot \rho_w}{\rho_b} \right)^{1/m} \qquad (3)$$

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- a: tortuosity factor
- m: cementation exponent
- ρw: water density
- ρb: bulk density

Permeability Estimation (K): Kozeny-Carman Relation (3)

Permeability (the capacity to allow water flow) is linked to resistivity through an empirical power law. A well's flow rate depends on the hydraulic conductivity (or permeability, K). Empirical relations exist (such as the Kozeny-Carman equation) that link Archie's parameters to permeability:

$$K \approx C \cdot \phi^m \cdot d^2 \qquad (4)$$

Flow Rate Calculation: Darcy's Law (4)

Once Archie's law has helped us estimate porosity and, by extension, permeability (K), Darcy's law is applied to predict the flow rate (Q):

$$Q = \frac{-KA}{\mu}\frac{\Delta P}{L} \qquad (5)$$

- Q : Flow rate (Volumetric flow rate)
- K : Permeability
- A : Cross-sectional area
- Delta P : Pressure drop (ou Pressure difference)
- µ : Dynamic viscosity
- L : Length (Flow path length)

In hydrogeology, this is a form of the Thiem equation for steady-state flow to a well in a confined aquifer. It calculates the flow rate (Q) based on the transmissivity (T) of the medium and the drawdown (Δs) observed between two radial distances. The simplified Dupuit or Thiem formula is used:

$$Q \approx \frac{2\pi \cdot T \cdot \Delta s}{\ln(R/r)} \qquad (6)$$

Data Interpretation and Software:

Interpretation was performed using the embedded AiduWater application, which generates subsurface maps down to the desired depth. These maps represent soil nature; some materials are difficult to distinguish at early stages of saturation, while water-bearing zones are more readily identifiable. Interpretation therefore considers even minor variations in measured values.

Interpreting the values - from measurement to target:

The hydrogeological "target" is generally an area of low resistivity relative to its surroundings, but with crucial nuances. Table 1 presents references to facilitate the interpretation of electrical resistivity tomography results.

Table 1: Standards – Interpretation of Electrical Resistivity

N°	Type of Ground	Resistivity (Ω.m)	Hydrogeological Potential
1	Clay/marl	1 – 30	Impermeable screen/poor target
2	Saturated sand/gravel	30-150	Excellent target
3	Fissured limestone	100-500	Good target

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N°	Type of Ground	Resistivity (Ω.m)	Hydrogeological Potential
4	Crystalline rock	≥ 1000	Sterile/no porosity
5	Bedrock	20-100	Classic target/storage zone above the bedrock

Source: BRGM, Senegal - 1981

ArcGIS and Surfer software were used for cartography and data processing.

RESULTS AND DISCUSSION

The set of resistivity pseudo-sections (Profiles 1 and 2) reveals a consistent vertical organization, which is characteristic of the central Groundnut Basin.

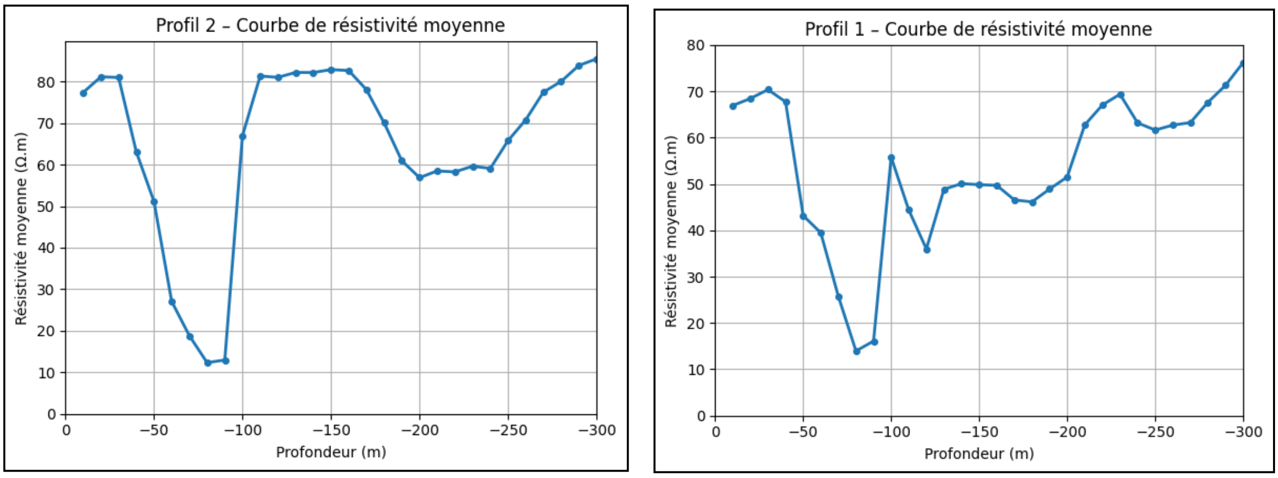

Figure 3: Apparent resistivity curve

Graphs 1 and 2 represent a Vertical Electrical Sounding (VES). They show the evolution of average resistivity as a function of depth for profiles 1 and 2. From the analysis of the electrical horizons, three major zones can be distinguished, corresponding to the structures identified in the figures:

- A superficial zone (0 to -40 m): the resistivity is stable around 70 and relatively high (~80). This corresponds to dry or low-porosity terrain at the surface.
- A conductive anomaly (-50 to -100 m): A sharp drop in resistivity is observed, reaching a minimum of 12 at approximately -80 meters. This is a very clear signature of a clay-rich layer or a highly conductive aquifer. This marks the "top" (roof) of the hydraulic system.
- A heterogeneous substratum (-110 to -300 m): the resistivity rises abruptly to over 80 Ω.m, indicating more compact rock. However, a second drop (a plateau around 60) is noted between -200 and -240 meters. This plateau at -200 m is very interesting as it indicates a fractured zone or slight weathering within the bedrock.

Unlike profile 2, which rose very high, the resistivity on profile 1 remains low and fluctuating, between 35 and 55. This is an excellent sign suggesting a more fractured and better-weathered zone than on the other profiles. The rock is not "fresh" (compact); it features voids or fissures filled with water. Between depths of -200 to -300 m, the resistivity gradually rises toward 75, indicating that the harder, less porous basement is being reached.

Profiles 3 and 4 represent Electrical Resistivity Tomography (ERT) cross-sections. They translate color variations (resistivity values) into geological structures and exploitable hydrogeological targets.

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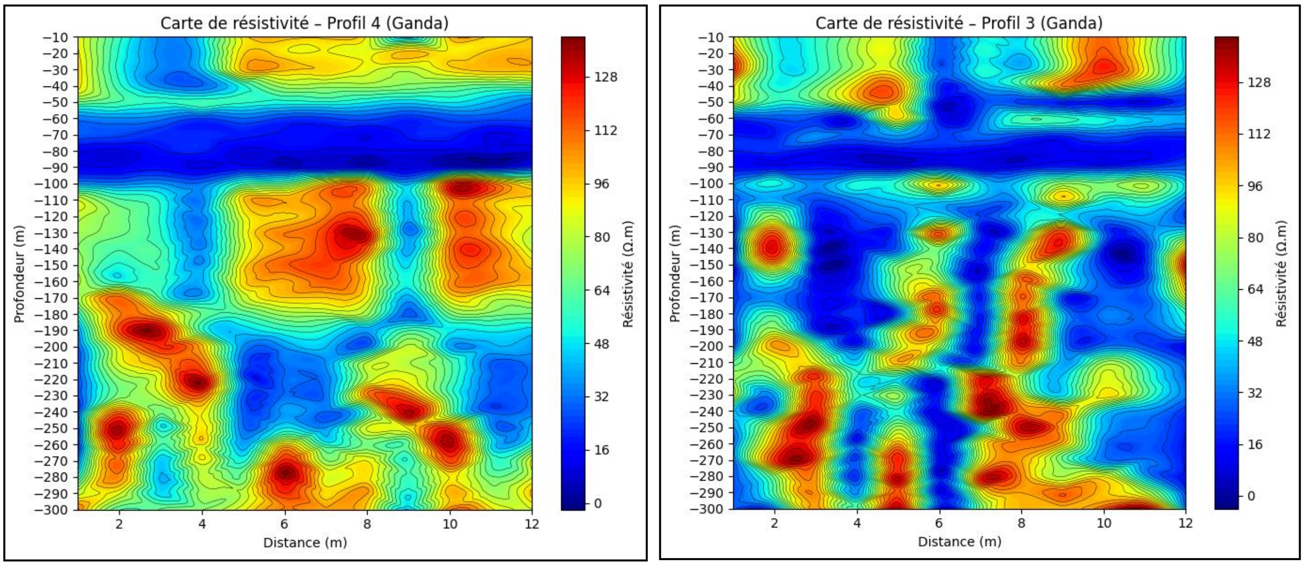

Figure 4: Apparente Apparent resistivity maps

Detailed analysis of profiles 3 and 4 reveals a vertical structure characterized by three main horizons:

- 0 to -40 m (Surface Horizon): Yellow and orange zones (60-90 Ω·m). This consists of a mixture of soils and semi-permeable formations (clayey sands or dry weathered rock/aluerites).
- -50 to -100 m (Conductive Level): A very continuous dark blue band with very low resistivity (≤16 Ω·m). In hydrogeology, this is the typical signature of a clay layer (impermeable) or a highly mineralized water-saturated zone.
- -100 to -300 m (Bedrock or Substratum): A heterogeneous medium with red/brown "cores" (≥120 Ω·m). These zones represent fresh, compact, and low-porosity rock (such as granite or massive limestone).

Identification of Borehole Targets:

The hydrogeological target is the zone where water can be stored and circulate. On the four profiles (1, 2, 3, and 4), two types of targets are distinguished:

- Contact Aquifer (Primary Target): The zone located just below the blue band (at approximately -110 m). The blue layer is clay and caps a confined aquifer under pressure within the fissures at the top of the bedrock.
- Fracture Zones (Secondary Targets): The green/light blue corridors separating the deep red blocks are reservoirs that allow for groundwater storage. These vertical anomalies indicate fractured or weathered rocks where water can accumulate at depth.

Potential Assessment (Flow Rate) Key Positive Findings:

The continuity of the conductive layer (blue) suggests a well-structured hydrogeological system at the local scale. The predominance of red zones (resistive) at depth shows that the rock is generally compact. Therefore, the success of a borehole will depend on precise positioning to intercept a vertical fracture.

Graphs 3 and 4 confirm that to obtain a significant flow rate, it is imperative to penetrate the impermeable barrier located between -50 and -100 m to reach the fissure zones located lower down, at approximately -105 meters, where the curve begins to rise. The optimal catchment zone is located between -200 and -240 meters, where the curves indicate a weakness in the hard rock.

Analysis of the results shows that **Profile 1 is the most promising for flow rate**. The zone between -60 m and -90 m is much less resistive compared to profiles 2, 3, and 4, indicating potentially higher permeability. The small peak at -100 m, followed by a decline, suggests an alternation of rocky layers and fissure zones. The **-60 to -90 meter interval represents the most favorable zone for groundwater catchment** in the study area. This is where the electrical contrast suggests the best water storage (transmissivity). Substratum analysis shows an impermeable zone at -100 m. Consequently, stopping the borehole at approximately -110 meters is sufficient; beyond this depth, the rock becomes too resistive (compact), and the chances of finding water decrease.

Scientific Justification for the Estimated Project Flow Rate (45 m³/h) on Profile 1:

The scientific justification for the estimated flow rate of 45 m³/h on Profile 1 is based on the combined analysis of three fundamental geophysical parameters: induced transmissivity, the volume of the fractured reservoir, and the role of the impermeable cover. Indeed, the fracture zone is thick (~70 m) and well-protected by an impermeable "roof" (overburden), which guarantees a confined aquifer with a significant rise in the static water level.

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Transmissivity (T) Analysis via Resistivity Contrast: A borehole's flow rate is directly linked to its transmissivity, defined by T=K·e.

- Effective Thickness (e): On Profile 1, the low-resistivity zone (40 - 55 Ω·m) extends from -20 m to -90 m, representing a thickness of 70 meters. This is a significant reservoir thickness for a fractured medium.
- Permeability (K): A resistivity of 50 Ω·m in a basement rock (which normally exceeds 1,000 Ω·m when fresh) indicates a high fracture rate and significant weathering. The more the resistivity drops relative to the parent rock, the larger the pore space (filled with water), thereby increasing the hydraulic conductivity.

Role of the Impermeable "Roof" (Confined Aquifer):

Graph 1 shows a highly conductive layer (14 Ω·m) between -50 and -90 m. This layer acts as an upper confining bed (aquitard). In hydrogeology, a confined aquifer is often associated with more stable and higher flow rates than an unconfined aquifer because the water is stored under pressure. During drilling, the water level will rise within the borehole (piezometric level), increasing the available drawdown for the pump.

Empirical Calculation Synthesis:

In crystalline basement or indurated sedimentary zones, a 70 m fracture zone with a resistivity 20 times lower than the fresh rock allows for flow rates of this magnitude (approaching 45 m^3/h). If the resistivity had dropped below 20 Ω·m in this zone, it would suggest an excessive presence of clay that could clog the water inflows. Here, at 50 Ω·m, we are in the "ideal window" for clean sands or well-fissured rocks. This calculation is purely theoretical. The red zone (highly resistive, >120 Ω·m) at depth suggests a parent rock or sound (dry) basement that will not produce water. The borehole must imperatively stop at, or be screened within, the blue zone.

Table 2: Summary of output parameters:

Parameter	Estimated Value	Source
Producing Zone	-60 to -95 m	Image Interpretation (Blue)
Porosity (phi)	30%	Archie's Calculation
Transmissivity (T)	$9.4\ 10^{-4}\ m^2/s$	Layer Calculation
Potential Flow Rate	High	45 m^3/h

Source: Study results

In hydrogeology, a flow rate above $10^{-3}\ m^2/s$ is considered to be world-class. This means that water flows very easily. During pumping, the water level in the well (the drawdown) should remain moderate, which reduces the electricity costs for the pump.

Conclusion:

This Electrical Resistivity Tomography (ERT) geophysical study at the Nganda site confirms favorable hydrogeological potential, particularly between depths of 60 and 95 meters.

The analysis reveals a clear stratification of the subsurface:

- 0 to -50 m: Heterogeneous zone, likely unsaturated or composed of surface sediments.
- -60 to -95 m: Target zone (Aquifer). The very low resistivity (8 to 16 Ω·m) indicates a porous zone saturated with fresh water. The application of Archie's Law suggests a high effective porosity (approximately 30% to 39%).
- Beyond -100 m: Increase in resistivity (red zones). This indicates a lithological change towards a more compact rock (basement or compact clays), which is unfavorable for water circulation.

For the location of the abstraction structures, we recommend prioritizing the area between distances 6 and 10 of Profile 1 (horizontal distance), where the blue lens is thickest and most homogeneous. Drilling should stop at approximately 100-110 meters. Drilling deeper would not increase the flow rate and might reach sterile or poor-quality layers. The projected operating flow rate is 45 m3/h. This flow rate was determined using the results of mathematical equations used in hydrogeophysics.

It is also advised to provide a 2 to 3-meter sump (blank pipe) at the bottom to collect fine sediments and to use a calibrated quartz gravel pack around the screens to prevent fine sand from entering the borehole, given the high calculated porosity.

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