Identification and Characterization of Aquifers by the Electrical Measurement Method in the Villages of Nsele and Kikamba in the Kongolo Health Zone in the Democratic Republic of the Congo (DRC)

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Abstract: This study focuses on the identification and characterization of aquifers by the electrical measurement method, specifically vertical electrical sounding in the villages of Nsele and Kikamba in the Kongolo health zone in the Tanganyika province in the Democratic Republic of the Congo. The main objective is to locate potentially aquifer zones and to estimate their production capacity from hydrogeological parameters in order to guide the installation of water collection structures, especially since the need for drinking water is very great in this area where refugees fleeing wars in North Kivu and South Kivu are flocking. The methodology is based on the one hand on the interpretation of 6 electrical soundings carried out in these villages, supplemented by the geological and hydrogeological analysis of the study area and on the other hand on the estimated calculations of the hydrogeological parameters characterizing the different geological formations identified in this area. The results show that out of the 9 identified aquifer formations, 8 are sandy. For sands, the porosity varies between 0.129 and 0.329 while the storativity between 1.85×10^{-3} and 1.88×10^{-2} for confined aquifers, between 1.79×10^{-1} and 2.77×10^{-1} for unconfined aquifers. Hydraulic conductivity between 11×10^{-5} m/s and 303×10^{-5} m/s, transmissivity between 39 m^2/d and 49483 m/d. Considering the values of the parameters determining the storage function of an aquifer (porosity and storativity) and those determining the conduction function (transmission) of an aquifer (conductivity and transmissivity), out of the 9 identified aquifers, 3 aquifers can be theoretically exploited for at least about two years for water collection. The other aquifers do not store enough water to be exploited.

Keywords: *Aquifers, DRC, Electrical Survey, Health Zone, Kikamba, Kongolo, Nsele.*

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I. INTRODUCTION

Among the factors contributing to the high mortality rate in rural areas in the Democratic Republic of Congo (DRC) are waterborne diseases, that is to say, diseases linked to water quality and access to drinking water. Indeed, rural populations in the majority and those on the outskirts of cities have difficulty accessing drinking water. Due to the absence of a water distribution network, they settle for water from springs or artisanally dug wells which are clear in appearance but not potable because they come from unconfined aquifers (groundwater tables) sensitive to surface pollution because they are quickly recharged by infiltrating rains.

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According to the United Nations Environment Program (UNEP, 2011), despite the abundance of surface water, the vast majority of the Congolese population depends on groundwater and springs to supply themselves with drinking water. It is estimated that groundwater represents almost 47 percent (421 km /year) of the water resources renewable of the DRC. In addition to this general situation, particularly for the Kongolo territory, assessment missions (United Nations, 2021 and REACH DRC, 2022) have mentioned the arrival of several displaced persons coming from neighboring provinces and territories fleeing community violence and armed conflicts. This migration, which increases the number of households, increases the need for drinking water. Faced with this reality, several organizations in their mission to provide adapted responses to the problems encountered by these populations have adopted the drilling of drinking water as a solution. A safe borehole requires prior localization of the aquifer from which the water will be drawn as well as its capacity to mobilize and convey the water. Thus, this study aims to provide these organizations, for drilling, with information on certain aquifers available in these two villages.

The scientific interest of this study falls into two parts: On one hand, it adds specific information that does not exist concerning this study area to the information bank on water reserves in the world and on the other hand, the clear approach adopted for the identification and characterization of aquifers can constitute a source of inspiration for other researchers for certain prospecting (Oil, minerals, ...).

This study is based on two hypotheses: On one hand, taking into account the known geological and hydrogeological information of these villages, the electrical measurements carried out there could allow for the identification of aquifers. On the other hand, from these measurements we can specify certain physical characteristics of these aquifers such as: Thickness, depth, effective porosity, storage coefficient, permeability and transmissivity.

Some authors have conducted studies similar to ours (Chisugi, & al., 2018; Tabbagh, 1988; Onja, 2017; Boudoukha, 2008; Kouakou et al., 2012; Abé & Kouassi, 2018). While globally these other studies mainly aimed at the identification of aquifers by using electrical measurements, ours, in addition to this first objective, brings an additional dimension by explicitly evaluating the hydrodynamic properties of the aquifers (porosity, storage, hydraulic conductivity and transmissivity) as well as their real potential for exploitation for drinking water supply. It therefore presents a broader scientific and operational scope, since it allows not only to locate the aquifers, but also to evaluate their real capacity for storage, transmission and exploitation for drinking water supply.

II. PRESENTATION OF THE STUDY AREA

From an administrative point of view, our study area is located in the Kongolo territory (Figure 1), one of the six territories of the Tanganyika province which itself is part of the twenty-six provinces of the Democratic Republic of Congo (DRC). This province is located in the South-East of the Democratic Republic of Congo between 5° and 8.5° South latitude and 26° and 31° East longitude. It shares its borders with the Provinces of Maniema and South-Kivu to the North; the Province of Lomami to the West, those of Haut-Lomami and Haut-Katanga, as well as countries like Zambia to the South and to the East by Lake Tanganyika and Tanzania.

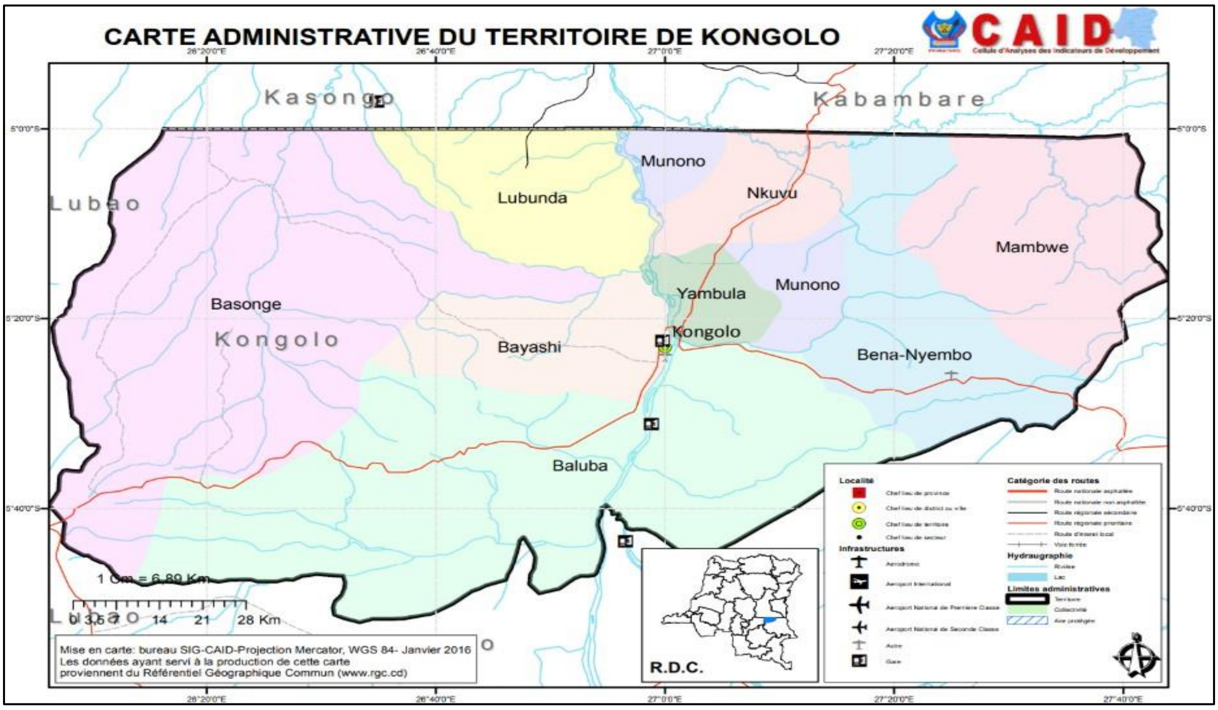

Fig 1 Administrative map of the Kongolo territory (Source: SIG-CAID-2016)

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Considering the health district, the two villages concerned by our study are located in the Kongolo health zone, one of the two health zones of the Kongolo territory, among the 11 health zones of the Tanganyika province (Figure 2).

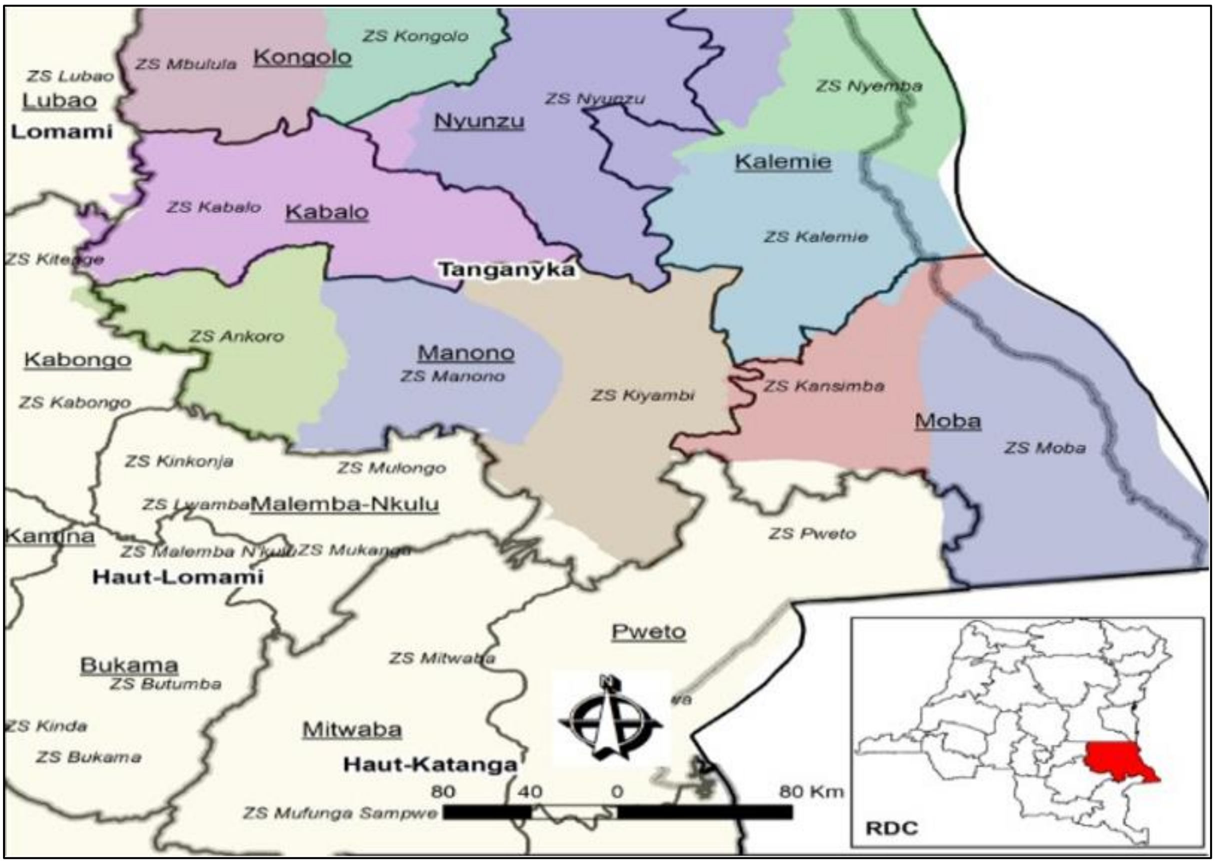

Fig 2 Map of the Health Zones of the Tanganyika Province. (Tanganyika Provincial Government, 2022)

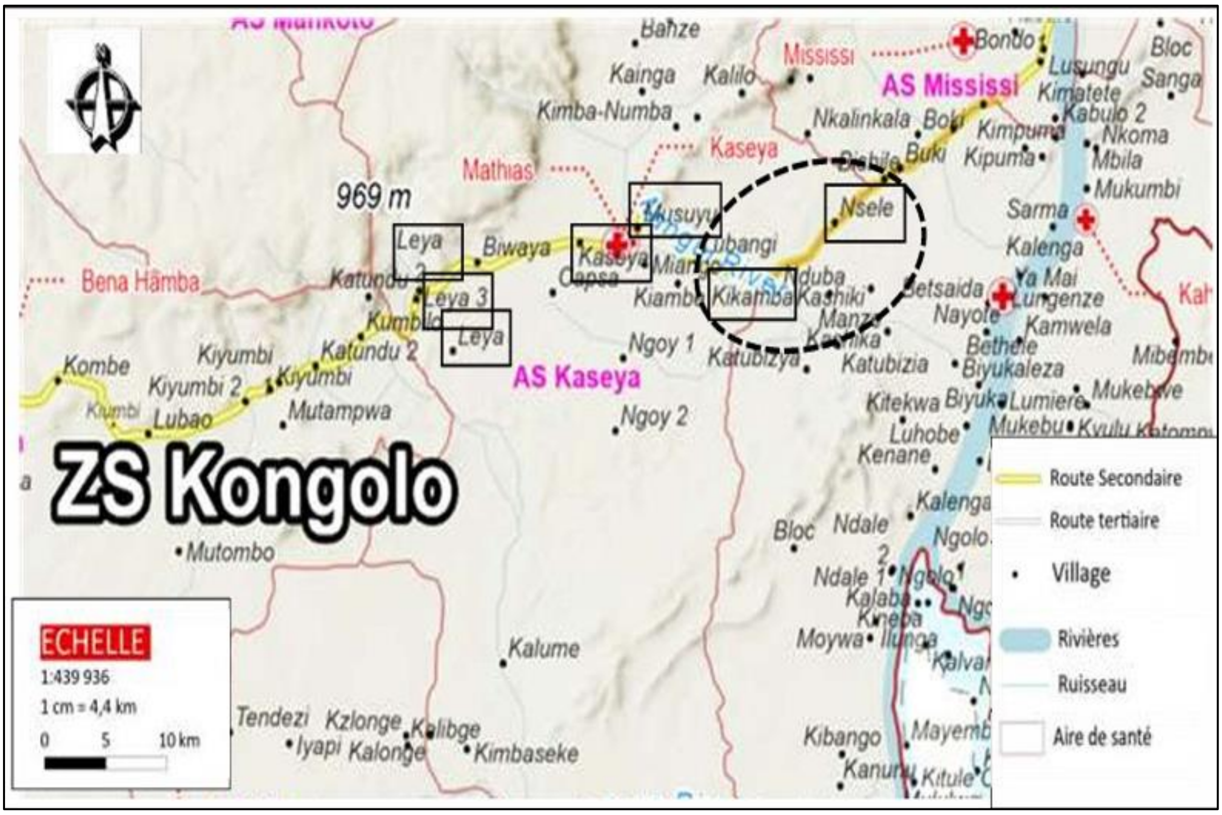

Fig 3 Extract of the Map of the Kongolo Health Zone: the Two Villages Kikamba and Nsele (Circled in Dotted Bold) Concerned by the Study. (Source: MSF, DR Congo-Tanganyika-Health Reference Map)

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➢ *Location of the Villages*

The NSELE village is located southwest of Kongolo (capital of the territory of the same name), on the Kongolo-Lubao Road, 22 km from Kongolo.

Between 5°32'0'' and 5°34'0'' S

26°52'0'' and 26°54'0'' E

The KIKAMBA village is located southwest of Kongolo, on the Kongolo-Lubao Road, 26 km from Kongolo.

Between 5°32'0'' and 5°34'0'' S

26°50'0'' and 26°52'0'' E

➢ *Geological and Hydrogeological Context*

- *Geological Context*

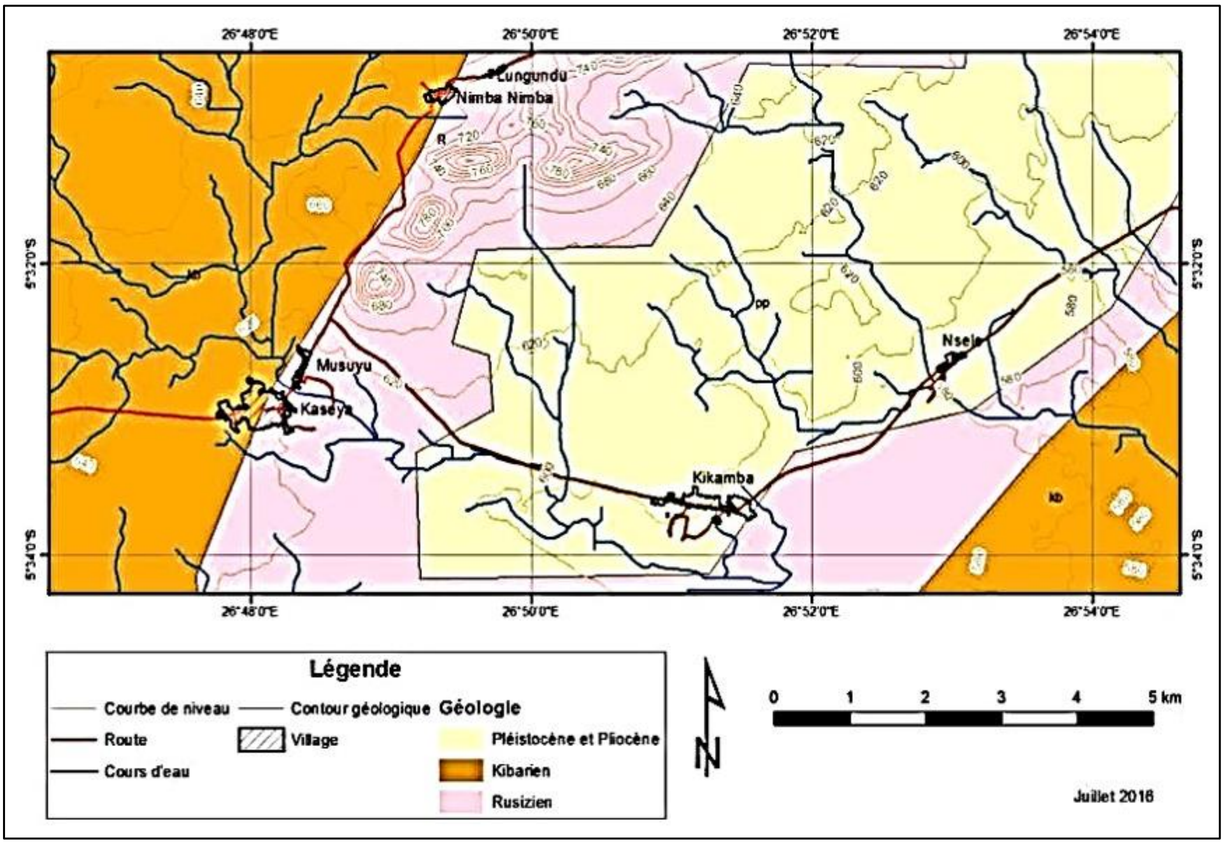

Fig 4 Geological Map Covering Both Villages (Manzuma Mpukuta et al., 2016)

The geological formations of these two villages are located in the Pleistocene and Pliocene periods resting on the Rusizian basement (Figure 4). Field observations show that in Nsele, we encounter alluvium consisting of yellow clayey sands which are predominant. In Kikamba, we find more or less clayey sands and silts, often red, sometimes associated with iron crusts or sheets of ferruginous pellets, often with gravel at the base, occupying plains and terraces.

- *Hydrogeological Context*

Generally speaking, among the 5 key hydrogeological units of the Democratic Republic of Congo, our study area is located in the unit "*Highly productive continuous aquifer rocks of the central basin and Oubangui and other alluvial plains*" composed of coarse alluvial sediments (UNEP, 2011). In this unit, the transmissivity values obtained using borehole test pumping are often 10 to 200 m / day, with yields of 0.2 to 0.6 l /s (15 to 50 m /day). Transmissivity values of 40 to 300 m / day andindividual borehole yields of 0.05 to 0.3 l / s (5 to 25 m per day) were recorded during borehole tests in various unconsolidated aquifers, mainly in the central basin (Chisugi et al., 2018). Particularly, following field observations, unconfined aquifers are encountered in Nsele in loose deposits, sometimes at a shallow depth, which are practically always polluted by organic matter at the surface. In Kikamba, the banks of the Munguyi stream located about 400 m south of the village are made up of thick layers of aquifer gravel.

III. MATERIALS AND METHODS

➢ *Data Collection*

Apparent resistivity measurements were carried out according to the resistivity method, by Vertical Electrical Sounding (VES), with the SCHLUMBERGER geometric device.

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The prospecting device used is an IRIS brand geo-resistivimeter, model SYSCAL with its accessories consisting of:

- 2 reels of electrical cables 300 m long each for current injection between the electrodes A and B;
- 2 reels of electrical cables 200 m long each for measuring the potential difference between electrodes M and N;
- 1 external 12 V battery
- 4 stainless steel electrodes.

Our device is represented by the installation drawing (figure 5) and its diagram (figure 6).

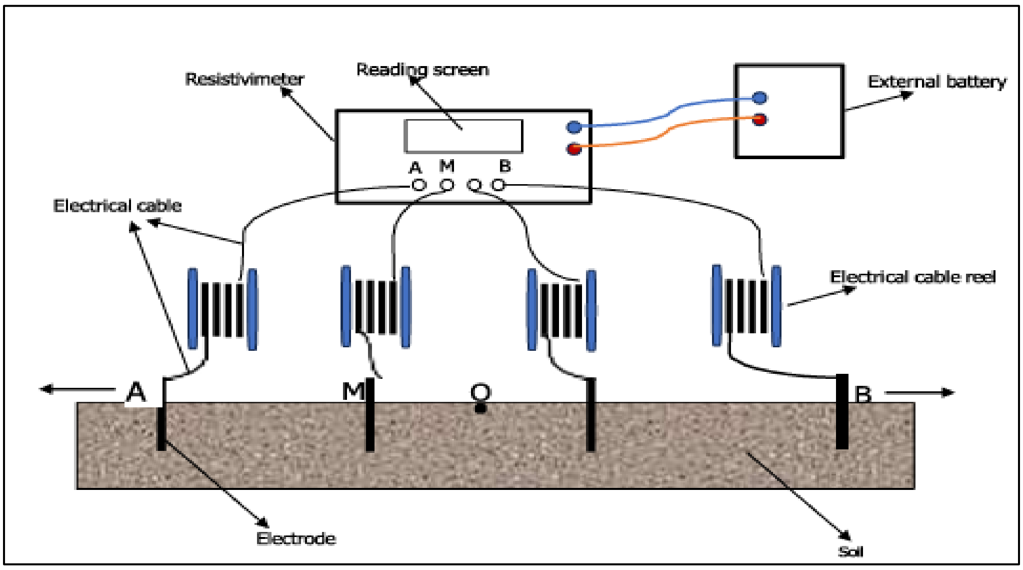

Fig 5 Drawing of the Complete Installation for the Vertical Electrical Sounding with the Schlumberger Device. (Drawing by Ourselves)

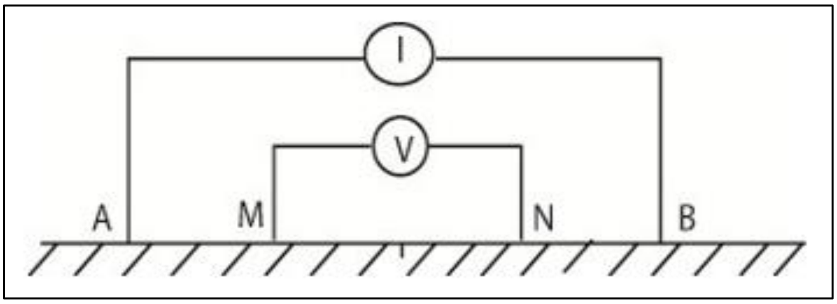

Fig 6 Diagram of the Schlumberger Device

For each village, three VES were carried out. (Table 1)

Table 1 Survey Points Location

No.	Village	Survey	GPS coordinates of the survey point		
			Longitude (x)	Latitude (y)	Altitude (z)
1	NSELE	SE1	26,88419°	-5,54401°	595 m
		SE2	26,88347°	-5,54449°	599 m
		SE3	26,88266°	-5,54497°	589 m
2	KIKAMBA	SE1	26,85196°	-5,56078°	604 m
		SE2	26,85498°	-5,56120°	598 m
		SE3	26,85770°	-5,56165°	604 m

- ➢ *Processing of Collected Data and Determination of Aquifers*

We used the IPI2WIN software for data processing.

To determine the aquifers from the data processing results, we took into account the following principles:

- Types of rocks that can become aquifers: Among the rocks that can contain water, there are also on one hand crystalline rocks (particularly plutonic rocks including the fractured granites of the Rusizian) and on the other hand alluvium, eluvium, sands and sandstones (from the Plio-Pleistocene).
- Typical weathering horizons of the Rusizian: The

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transformation of a parent rock, over time, under the influence of various physical, chemical and biological processes generates geological formations forming layers with different morphological, physical, chemical and biological characteristics. These layers are horizons whose set forms the profile. Comparing the values and succession of the resistivity layers of the electrical survey results with those of the different horizons of the profile allows a good interpretation. Considering their composition, some horizons are of an aquifer nature: Fissured or fractured horizon, coarse saprolite (Arena), crust dismantling zone.

- The most common aquifers are: Unconsolidated sands and gravels, permeable sedimentary rocks (sandstones, limestones) and highly fractured crystalline rocks.
- The most common aquitards are: Clays, shales and dense crystalline rocks. (Allan Freeze et al., 1979)
- Most sand and gravel aquifers are unconfined, with relatively shallow water tables (from a few meters to a few tens of meters), but confined aquifers are also found locally, particularly in multilayer aquifer systems (Margat & Van der Gun, 2013, p.49).
- The new aquifer model considers as basement aquifers the fissured or fractured rocks and the unconsolidated weathered materials or sandy saprolite ("Types of aquifers", 2026; Margat & Van der Gun, 2013, p.59).

The geological and hydrogeological data observed in the field complemented these principles.

➢ *Estimation of Parameters Characterizing Aquifers*

Based on the data describing the aquifers, we will estimate, using certain empirical laws of geophysics (Kozeny-Carmen law, Darcy's law, Archie's law), the hydrodynamic or hydrogeological parameters linked to the two main functions of an aquifer:

- The storage function (Role of the reservoir) of an aquifer, which designates its capacity to store groundwater and to release it when conditions change (pumping, natural drainage, variation of the piezometric level, etc.).This function allows on one hand to control the quantity of water available in the aquifer and on the other hand to determine its sustainability for the exploitation of a groundwater source (an aquifer). These parameters are:

✓ The *effective porosity* (n); proportion of the rock volume capable of containing and releasing water.
✓ The *storage coefficient* (S); it allows evaluating the mobilizable reserve of an aquifer (quantity of water available) and predicting the sustainability of withdrawals or exploitation.

- The conduction or transmission function of an aquifer (Role of channel) which explains how water is mobilized and transported in the aquifer. These parameters are:

✓ *Permeability* (k); Translates the ease with which water can circulate through the rock under the effect of a hydraulic gradient; allows evaluating the productivity of a well (sustainable flow, possibility of exploitation).
✓ *Conductivity* (K); Expresses the speed of water flow in the aquifer.
✓ *Transmissivity* (T): Capacity of an aquifer to transmit water in the horizontal plane; allows determining
✓ the exploitable flow rate in a borehole.

➢ *Porosity*

In our VES case, we calculated the porosity as a function of resistivity, using Archie's empirical law (Glover, 2017; Liu & Kitandis, 2013; Niu & Zhang, 2018; Telford, 1999) for a saturated geological formation with 1 as the value for the tortuosity factor (Grover, 2016):

$$n = (\rho_o/\rho)^{1/m} \tag{1}$$

Where, ρ: Resistivity of the soil or rock formation (resistivity obtained by the vertical electrical sounding), ρ_o: Resistivity of the fluid contained in the rock formation (in our case the fluid is water), m: Cementation factor; depends on the pore shape and the compaction of the rock. Based on the results of several studies (Glover, 2017; Liu & Kitandis, 2013; Niu & Zhang, 2018; Telford, 1999), we considered m = 1.8 for sands and 1.5 for fractured rocks.

➢ *Specific Storage (S_s)*

The specific storage of a saturated aquifer is defined as the volume of water that a unit volume of aquifer releases from storage under a unit decline in hydraulic head. (Freeze & Cherry, 1979). It is expressed by the following relation:

$$S_s = \rho^* g\, (\alpha + n\beta) \tag{2}$$

Where ρ^* is fluid (water) density (kg/m³), g is gravitational acceleration (m/s²), α is the aquifer matrix compressibility (m²/N or Pa⁻¹), β the water compressibility (m²/N or Pa⁻¹), n is the aquifer porosity (dimensionless) and S_s is the specific storage (m⁻¹).

For our calculations, we consider the following values:

- Water density (ρ*) : 10^3 kg/m^3
- Gravitational acceleration (g) : 9.81 m/s^2
- Water compressibility (β) : 4,4.10^{-10} m /N (Pa^{-1})
- Aquifer matrix compressibility (α) (Freeze & Cherry, 1979; Woessner, 2020): For sands 10 m/N (Pa) and 10 m /N (Pa) for fractured rocks.

The porosity *n* is calculated with formula (1) by taking as the value for water resistivity (ρ_o): 10Ωm.

➢ *Storativity or Storage Coefficient (S)*

The storage coefficient S being defined as the volume of water released per unit change in hydraulic head normal to the surface, per unit surface area

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(Woessner, 2020). In the practical case of vertical electrical sounding, we used the following relations according to the type of aquifer (Fetter, 2001; Freeze & Cherry, 1979; Heath, 1983; Woessner, 2020).

For a confined aquifer of thickness h (determined from the vertical electrical sounding), the storativity is determined by the following relation:

$$S = S_s h = \rho^* g\, h\, (\alpha + n\,\beta) \tag{3}$$

For an unconfined aquifer

$$n = S_y + S_r \tag{4}$$

Where n: Porosity, S_y: Specific yield and S_r: Specific retention or residual saturation.

The storativity corresponds to the specific yield, therefore:

$$S = S_y = n - S_r \tag{5}$$

For the calculation of specific yield, we used $S_r = 0.03$ (Heath, 1983; Fetter,2001). The porosity is calculated with relation (1).

- *Evaluation of the Volume of Water Mobilizable by an Aquifer*

The volume of mobilizable water is calculated with the relation (Fetter, 2001; Woessner,2020; Castellazzi et al.,2022):

$$V = S\, A\, \Delta h \tag{6}$$

Where S: Storativity (dimensionless), A: Surface area covering the drained aquifer (in m^2), Δh: variation of the hydraulic head that will cause water drainage.

If we theoretically consider that the volume of water released by the aquifer corresponds to the maximum drop in the water level, then Δh corresponds to the thickness h of the aquifer. As with the vertical electrical sounding (VES) we cannot determine the total surface area of the aquifer, we will consider the geophysical zone of influence from the investigation radius AB/2 of the VES. If we assume the medium is homogeneous, the mobilizable reserve in the zone of influence is worth:

$$V = S_y\, h\, \pi\, (AB/2)^2 \tag{7}$$

- *Estimation of the Sustainability of Withdrawals (Exploitation Duration)*

To estimate the exploitation duration, we start from the natural definition of the flow rate of a fluid: The volumetric flow rate Q of a fluid is its volume that passes through a given cross-section in a given amount of time (Moebs et al.,2016; Urone et al., 2012; Bonnin et al.,2018):

$$Q = V / t \tag{8}$$

Where Q is volumetric flow rate (m^3/s), V is the volume of water (m^3) and t the time (s).

This formula applied in our practical case:

- Q: Water withdrawal flow rate (m^3/h),

We used in our calculations an average flow rate of 3.5 m^3/h (Chisugi & al.,2018; OIM-RDC,2023; UNESCO,1987) to estimate the exploitation duration.

Knowing that 1day = 24 hours and 1year = 365 days, we can convert the flow rate into m^3/year:

$$Q = 3.5 \times 24 \times 365 = 30660\ m^3/\text{year}$$

- V: Volume of mobilizable water (m^3)
- t : Exploitation duration (years).

$$t = V/Q \tag{9}$$

- *Hydraulic Conductivity (K)*

Hydraulic conductivity is deduced from Darcy's law which is a fundamental equation used to describe fluid flow in porous media (Fetter, 2001; Freeze & Cherry,1979; Woessner & Poeter,2020). It is the proportionality constant in Darcy's law and is a function of the porous medium and the fluid contained in this medium:

$$K = (k\, \rho^* g)/\mu \tag{10}$$

Where μ is the dynamic viscosity of the fluid (Kg/m. s or Pa.s); it characterizes the resistance of the fluid to its flow.

For water, $\mu = 0.890 \times 10^{-3}$ kg/m·s (Haynes & Lide, 2016).

Hydraulic conductivity measures how easily water flows through the aquifer. It has the dimensions of velocity and is expressed in m/s.

- *Permeability (k)*

The permeability of a medium refers to its ability to be traversed by a fluid (liquid or gas) under the effect of a hydraulic gradient. Unlike hydraulic conductivity, permeability is a property that characterizes only the medium and is independent of the fluid (Todd & Mays, 2005).

To determine the permeability of the aquifers, we used the Kozeny-Carman law.

For granular formations (Freeze & Cherry, 1979):

$$k = (n^3/(1-n)^2)\,(D^2/180) \tag{11}$$

Where D: Average diameter of the grains comprising the medium, estimated according to Freeze & Cherry

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(1979) and Jeffress, Williams, et al. (2006) as 2.5×10^{-4} m for medium-grained sand n: Porosity calculated using equation (1) of Archie's law.

For basement aquifers, we use the second form of the Kozeny-Carmen law: For a parallel network of planar fissures of opening e, this law takes the following form (Freeze & Cherry, 1979; Hudson & Harrison, 2000; Jeffress Williams et al., 2006):

$$k = (n\, e^3)/12 \qquad (12)$$

➢ *Transmissivity*

Transmissivity (T) is the capacity of an aquifer to transmit water in its horizontal plane. Unlike permeability (which is an intrinsic property of the material), transmissivity depend on the saturated thickness. If permeability (k) describes the ease of water circulation in the material, transmissivity describes the actual and overall capacity of the aquifer to conduct water. For an aquifer of thickness h, transmissivity T is calculated by the following relation as a function of conductivity (Freeze & Cherry, 1979; Woessner & Poeter, 2020):

$$T = K\, h \qquad (13)$$

Transmissivity is expressed in m^2/s, in practice in m^2/d. Conductivity is calculated with formula (10) derived from Darcy's law.

IV. RESULTS

➢ *Data Collected by Electrical Sounding*

For each sounding, the resistivity meter records the values of $AB/2$, MN, the potential difference ΔV, the current intensity I, the geometric factor k, and the electrical resistivity ρ_a which are included in the following tables (Tables 2).

Tables 2 Tables of Data Collected by Electrical Surveys in the Villages of Nsele and Kikamba

(A) For the village of Nsele

SE1					
AB/2	**MN**	ΔV	I	k	ρ_a
3	2	69.299	2.32	12.566	375.36
4	2	50.511	2.71	23.562	439.17
5	2	46.768	3.55	37.699	496.65
6	2	52.495	5.65	54.978	510.81
7	2	53.172	7.95	75.398	504.29
8	2	53.392	11.57	98.96	456.67
10	2	57.244	20.84	155.51	427.16
15	2	54.703	53.55	351.86	359.43
10	6	52.304	5.76	47.647	432.67
15	6	52.829	16.69	113.1	357.99
20	6	55.599	26.64	204.73	427.28
30	6	56.119	66.54	466.53	393.46
35	6	57.254	109.3	636.7	333.52
40	6	46.706	125.6	833.05	309.78
50	6	56.243	264.02	1304	277.85
40	20	56.405	56.41	235.62	235.6
50	20	56.515	101.52	376.99	209.87
70	20	23.255	138.16	753.98	126.91
80	20	11.845	91.14	989.6	128.61
100	20	9.465	123.91	1555	118.79
120	20	1.655	33.94	2246	109.53
100	40	17.762	135.54	753.98	98.806
120	40	6.08	79.4	1100	84.198
150	40	10.428	230.04	1736	78.683
175	40	2.785	77.19	2374	85.649
200	40	0.925	30.5	3110	94.325

SE2					
AB/2	**MN**	ΔV	I	k	ρ_a
3	2	38.76	1.58	12.566	308.29
4	2	43.48	2.85	23.562	359.49
5	2	57.16	5.41	37.699	398.34
6	2	46.87	6	54.978	429.45
7	2	53.02	9.23	75.398	433.07
8	2	56.25	12.99	98.96	428.51

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10	2	54.37	19.75	155.51	428.13
15	2	54.61	50.55	351.86	380.1
10	6	56.13	7.25	47.647	368.88
15	6	57.22	18.73	113.1	345.52
20	6	56.74	43.61	204.73	266.38
30	6	36.15	58.51	466.53	288.23
35	6	56.56	125.26	636.7	287.48
40	6	45.22	142.83	833.05	263.74
50	6	34.19	226.96	1304	196.5
40	20	55.41	45.23	235.62	288.67
50	20	58.52	102.48	376.99	215.28
70	20	53.61	246.3	753.98	164.12
80	20	34.62	245.81	989.6	139.37
100	20	11.75	145.53	1555	125.6
120	20	4.95	100.26	2246	110.9
100	40	15.9	105.43	753.98	113.73
120	40	9.413	99.96	1100	103.54
150	40	3.395	48.11	1736	122.49
175	40	7.052	160.68	2374	104.19
200	40	4.435	104.1	3110	132.5
225	40	3.066	74	3945	163.44

SE3					
AB/2	**MN**	ΔV	I	k	ρ_a
3	2	49.56	2.6	12.566	239.55
4	2	53.72	4.76	23.562	265.89
5	2	55.28	7.21	37.699	289.02
6	2	53.67	8.47	54.978	348.35
7	2	56.52	10.9	75.398	390.93
8	2	55.8	12.73	98.96	433.81
10	2	54.57	17.31	155.51	490.23
15	2	54.18	36.34	351.86	524.62
10	6	53.64	5.58	47.647	458.03
15	6	50.7	11.34	113.1	505.62
20	6	55.41	23.09	204.73	491.28
30	6	36.31	69.76	466.53	242.8
35	6	9.885	28.67	636.7	219.52
40	6	6.523	26.58	833.05	204.44
50	6	19.26	134.8	1304	186.36
40	20	9.007	14.8	235.62	143.39
50	20	47.18	119.6	376.99	148.68
70	20	24.19	162.9	753.98	111.93
80	20	8.278	84.8	989.6	96.603
100	20	4.644	100.2	1555	72.11
120	20	2.236	89.36	2246	56.206
100	40	8.445	72.08	753.98	88.338
120	40	6.48	91.41	1100	77.947
150	40	2.995	57.98	1736	89.66
175	40	4.435	108.9	2374	96.677
200	40	3.009	86.43	3110	108.28

(B) For the Village of Kikamba

SE1					
AB/2	**MN**	ΔV	I	k	ρ_a
3	2	55.919	1.75	12.566	401.54
4	2	58.804	3.14	23.562	441.25
5	2	54.493	4.34	37.699	473.35
6	2	54.832	6.05	54.978	498.27

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7	2	56.644	8.51	75.398	501.86
8	2	55.032	10.72	98.96	508.02
10	2	55.018	16.96	155.51	504.47
15	2	56.753	34.01	351.86	587.15
10	6	56.186	6.36	47.647	420.93
15	6	54.674	12.27	113.1	503.95
20	6	55.709	27.87	204.73	409.23
30	6	54.073	74.9	466.53	336.8
35	6	55.566	102	636.7	346.88
40	6	55.103	135.2	833.05	339.57
50	6	14.83	93.03	1304	207.92
40	20	53.649	35.3	235.62	358.09
50	20	52.619	92.23	376.99	215.08
70	20	12.724	62.61	753.98	153.23
80	20	15.101	104.4	989.6	143.16
100	20	18.392	232.1	1555	123.24
120	20	15.941	296.4	2246	120.82
100	40	34.275	218.2	753.98	118.43
120	40	31.104	297.1	1100	115.13
150	40	9.246	129.5	1736	123.92
175	40	8.416	143.4	2374	139.35
200	40	1.965	37.52	3110	162.89

SE2					
AB/2	**MN**	ΔV	I	k	ρ_a
3	2	53.978	2.29	12.566	296.2
4	2	53.921	4.1	23.562	309.87
5	2	50.883	6.23	37.699	307.9
6	2	57.373	10.18	54.978	309.85
7	2	57.035	14.27	75.398	301.36
8	2	52.104	18.61	98.96	277.07
10	2	55.204	32.54	155.51	263.82
15	2	55.142	73.33	351.86	264.59
10	6	51.756	9.09	47.647	271.29
15	6	57.721	23.79	113.1	274.4
20	6	54.169	35.89	204.73	309
30	6	55.723	108.54	466.53	239.51
35	6	55.9	150.99	636.7	235.72
40	6	41.275	173	833.05	198.75
50	6	11.492	102.01	1304	146.93
40	20	55.704	65.27	235.62	201.09
50	20	37.699	100.17	376.99	141.88
70	20	33.889	206.17	753.98	123.94
80	20	21.229	206.63	989.6	101.67
100	20	6.342	115.43	1555	85.44
120	20	3.791	113.21	2246	75.219
100	40	18.253	187.14	753.98	73.541
120	40	6.866	116.99	1100	64.532
150	40	2.255	64.9	1736	60.309
175	40	3.405	124.77	2374	64.783
200	40	4.206	190.28	3110	68.748

SE3					
AB/2	**MN**	ΔV	I	k	ρ_a
3	2	48.89	1.37	12.566	448.45
4	2	53.816	2.54	23.562	499.22
5	2	54.636	3.92	37.699	525.44
6	2	51.851	4.98	54.978	572.42

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7	2	53.768	6.58	75.398	616.11
8	2	55.685	8.99	98.96	612.97
10	2	55.623	13.31	155.51	649.88
15	2	56.844	39.25	351.86	509.58
10	6	57.879	4.43	47.647	622.53
15	6	55.771	12.77	113.1	493.94
20	6	57.054	34.58	204.73	337.78
30	6	41.432	75.15	466.53	257.21
35	6	27.776	71	636.7	249.08
40	6	20.757	73.15	833.05	236.38
50	6	14	86.26	1304	211.69
40	20	54.703	65.26	235.62	197.5
50	20	40.803	87.27	376.99	176.26
70	20	13.571	85.72	753.98	119.37
80	20	16.484	138.61	989.6	117.69
100	20	9.766	146	1555	104.02
120	20	10.146	282.58	2246	80.651
100	40	40.889	288.51	753.98	106.86
120	40	21.238	281.89	1100	82.842
150	40	3.767	75.51	1736	86.591
175	40	9.789	276.21	2374	84.131
200	40	10.877	367.38	3110	92.083

➢ *Result of Survey Data Processing by IPI2WIN Software*

The processing of this data by the IPI2WIN software produced, for each electrical sounding (Figure 7):

- A real curve (a), a theoretical curve (b), and a histogram representing the layers (c)
- A table (d) with different columns (Layer number (N), layer resistivity (ρ), thickness of each layer (h), depth of the layer interface from the surface (d), altitude of the layer relative to ground level (Alt)).

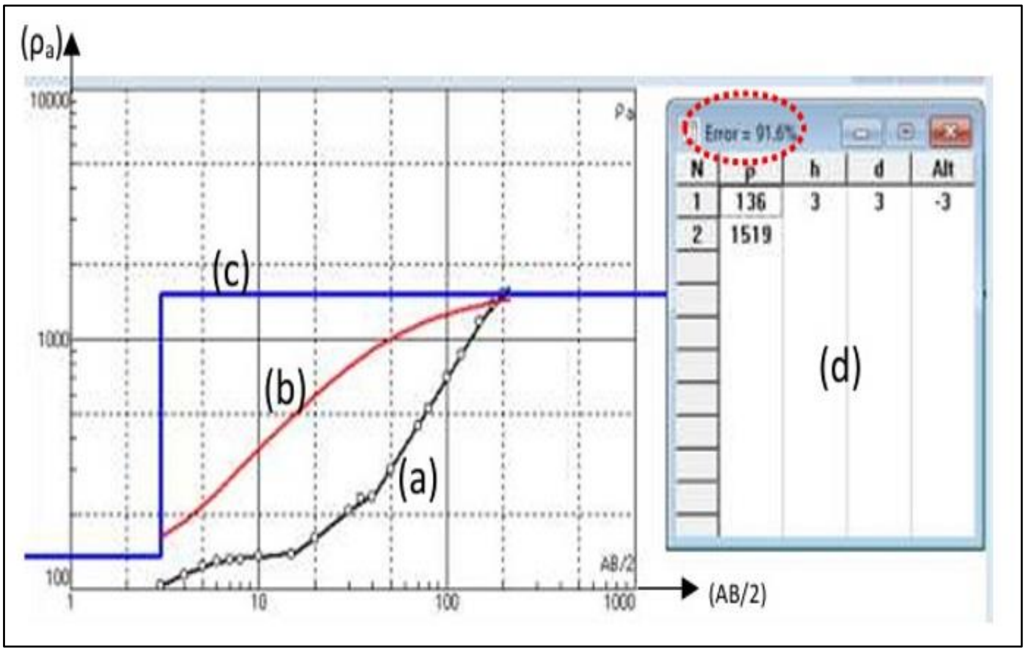

Fig 7 The Two Curves and the Layer Information Table (Excerpt from our Work). (a): Real Curve; (b): Theoretical Curve; (c): Histogram; (d): Table

Here we present the graphs and resistivity layer tables for each sounding point obtained with the software (with the graph elements as described in Figure 8).

➢ *Village of Nsele*

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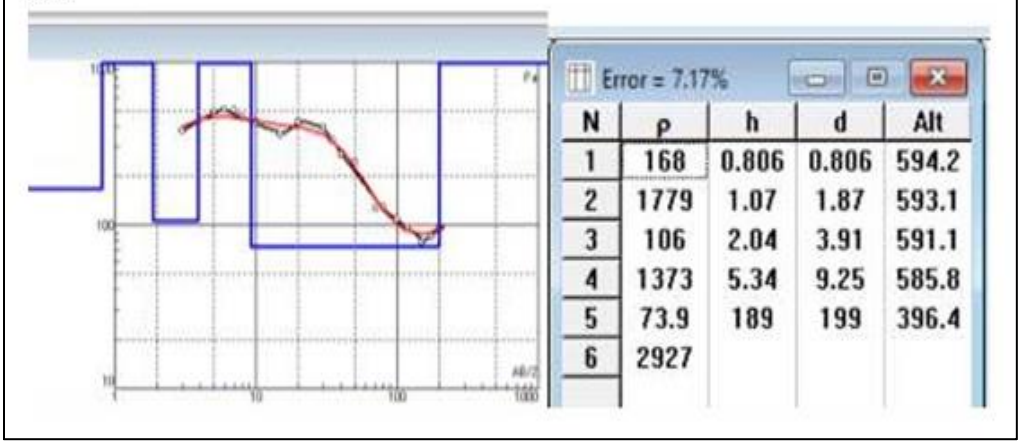
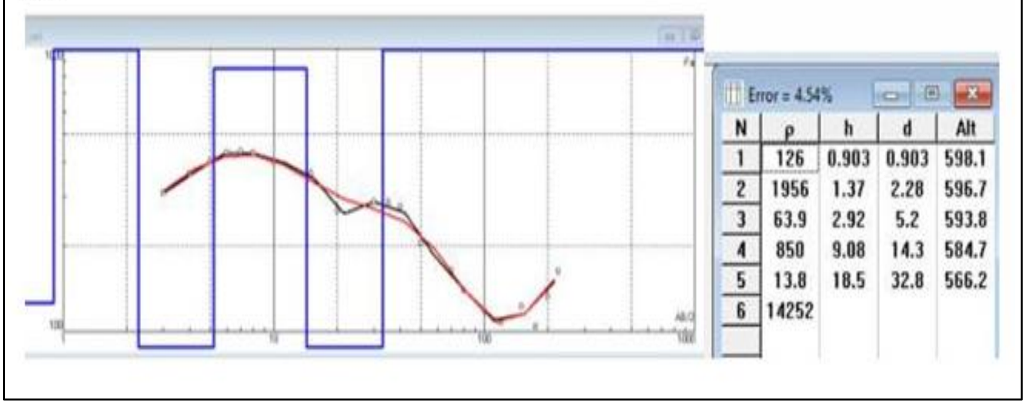
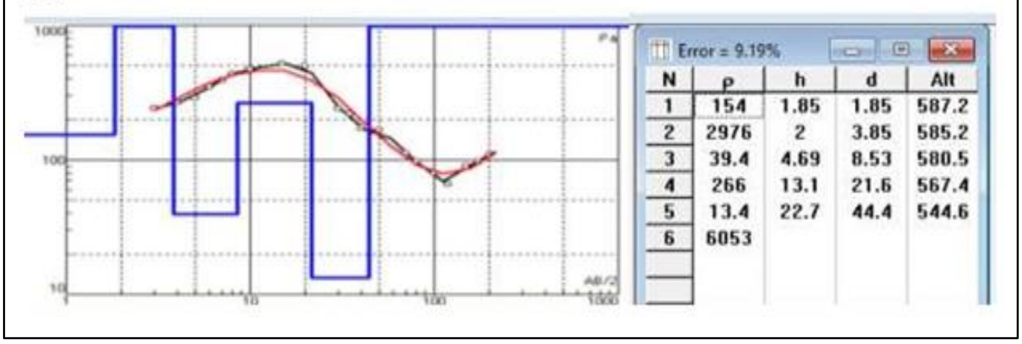
SE1



SE2

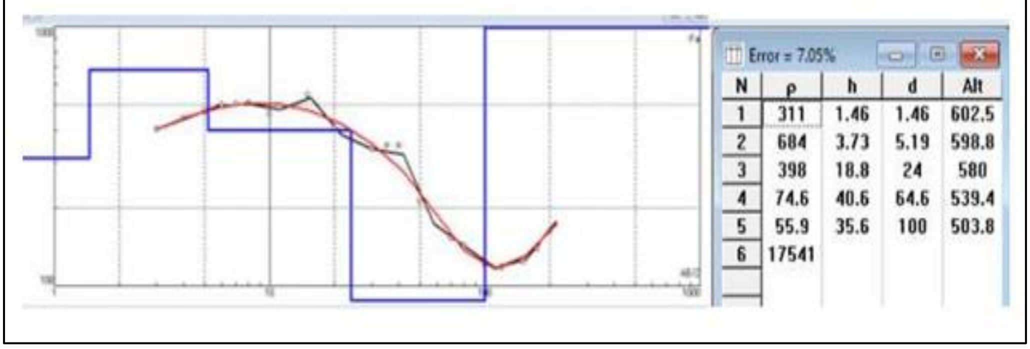


SE3



- *Village of Kikamba*

SE1



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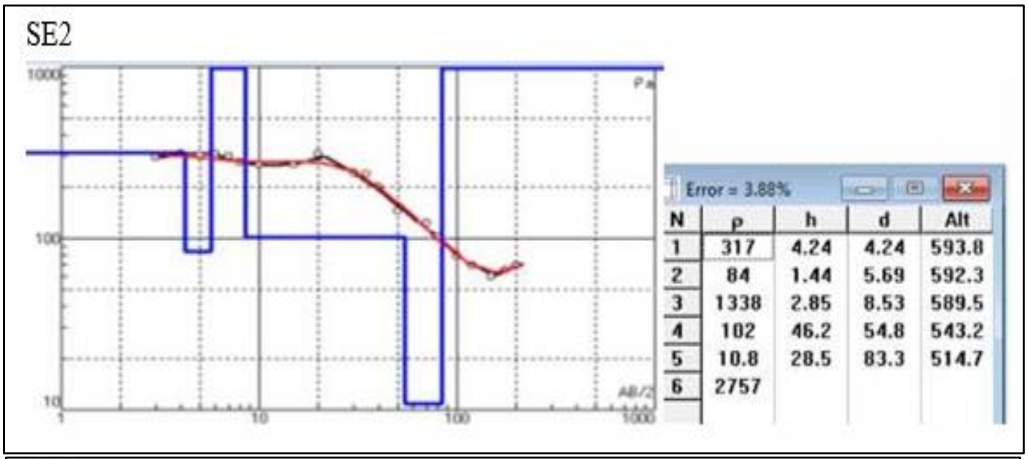

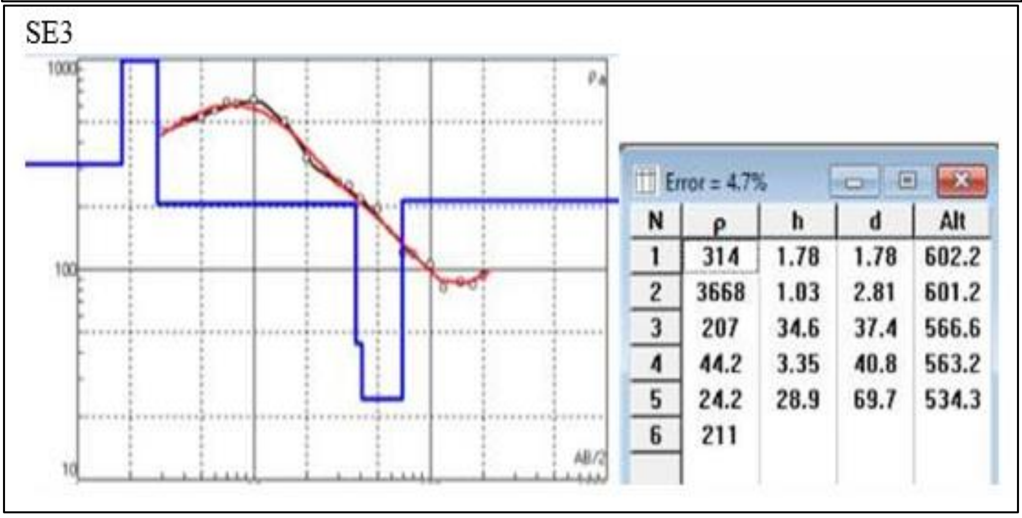

➢ *Result of the Interpretation of Resistivity Layers*

Considering the weathering horizons of the Rusizian, the rock types that can be aquifers as well as the geological and hydrogeological data observed in the field, we have identified the different geological formations represented by the resistivity layers (Table 3): formations that can store and transmit water (aquifers), those that can store water but transmit it with difficulty (aquitards), and impermeable formations (aquicludes). Among the aquifers, we have distinguished confined from unconfined (free aquifers), and sand aquifers from basement aquifers (fractures or fissures).

Table 3 Complete Interpretation of Sounding Data Processing Results

Village	Sounding	Resistivity layers				Interpretation		
		N°	ρ (Ω. m)	h (m)	d(m)	Nature of geological formation	Concl.	Observation
NSELE	SE1	1	168	0.806	0.806	Dismantled cuirass	Aquifer	free, sands
		2	1779	1.07	1.87	Ferruginous cuirass	Aquiclude	
		3	106	2.04	3.91	Saturated clayey sands	Aquitard	
		4	1373	5.34	9.25	Slightly fractured granite	Aquitard	
		5	73.9	189	199	Saturated sandy granitic arena	Aquifer	Confined, sands
		6	2927			Slightly fractured granite	Aquitard	
	SE2	1	126	0.903	0.903	Dismantled cuirass	Aquifer	free, sands
		2	1956	1.37	2.28	Ferruginous cuirass	Aquiclude	
		3	63.9	2.92	5.2	Saturated clayey sands	Aquitard	
		4	850	9.08	14.3	Moderately fractured granite	Aquifer	Confined, basement
		5	13.8	18.5	32.8	Clays or saturated lithomarge	Aquitard	
		6	14252			Sound granite		
	SE3	1	154	1.85	1.85	Dismantled cuirass	Aquifer	Free, sands
		2	2976	2	3.85	Ferruginous cuirass	Aquiclude	
		3	39.4	4.69	8.53	Saturated sandy clays	Aquitard	
		4	266	13.1	21.6	Slightly saturated saprolite	Aquitard	

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		5	13.4	22.7	44.4	Saturated clays	Aquitard	
		6	6053			Sound granite	Aquiclude	
KIKAMBA	SE1	1	311	1.46	1.46	Ferruginous gravels and nodules		Surface soil
		2	684	3.73	5.19	Ferruginous cuirass	Aquiclude	
		3	398	18.8	24	Dismantled cuirass at bottom	Aquifer	Confined, sands
		4	74.6	40.6	64.6	Saturated clayey sands	Aquitard	
		5	55.9	35.6	100	Saturated fine saprolite (Lithomarge)	Aquitard	
		6	17541			Sound granite	Aquiclude	
	SE2	1	317	4.24	4.24	Ferruginous gravels and nodules		Zone of non saturation
		2	84	1.44	5.69	Humid silty sands (saturated)	Aquifer	Free, sands
		3	1338	2.85	8.53	Ferruginous cuirass	Aquiclude	
		4	102	46.2	54.8	Saturated sands and gravels	Aquifer	Confined, sands
		5	10.8	28.5	83.3	Saturated fine saprolite (Lithomarge)	Aquitard	
		6	2757			Weakly fractured granite	Aquitard	
	SE3	1	314	1.78	1.78	Ferruginous gravels and nodules		Surface soil
		2	3668	1.03	2.81	Ferruginous cuirass	Aquiclude	
		3	207	34.6	37.4	Saturated sands and gravels	Aquifer	Confined, sands
		4	44.2	3.35	40.8	Saturated clayey sands (Bt horizon)	Aquitard	
		5	24.2	28.9	69.7	Saturated fine saprolite (Lithomarge)	Aquitard	
		6	211			Sandy arena	Aquifer	Confined, Sands

➤ *Calculation Results of Hydrogeological Parameters*

To calculate these parameters, we applied formulas 1, 3, 5, 7, 9, 10, 11, 12, and 13. The calculation results are presented in Table 4. As the purpose of this work is to identify aquifers, we calculated the hydrogeological parameters only for aquifer formations. For the calculation of the storage coefficient, the calculation procedure for unconfined aquifers (Formula 5) is different from that for confined aquifers (Formula 3). We excluded the last layers whose thickness and depth are unknown. The maximum value of AB/2 for each sounding is taken from the corresponding table (Table 4).

Table 4 Presentation of Hydrogeological Parameter Calculation Results

Village	**Sound.**	**n°**	**Poro. (n)**	**S_r**	**S**	**S_y**	**t**		**k (m^2)**	**K (m/s)**	**T (m^2/s)**	**K (m/d)**	**T (m^2/d)**	**k (darcy)**
							Years	**Months**						
NSELE	SE1	1	0,209	0,030		1,79E-01	1	7	5,03E-12	0,00055	0,000	48	39	5
		5	0,329		1,88E-02		15	7	2,75E-11	0,00303	0,573	262	49483	28
	SE2	1	0,245	0,030		2,15E-01	1	0	8,92E-12	0,00098	0,001	85	77	9
		4	0,052		9,10E-05		0	0	2,69E-12	0,00030	0,003	26	233	3
	SE3	1	0,219	0,030		1,89E-01	1	5	5,97E-12	0,00066	0,001	57	105	6
KIKAMBA	SE1	3	0,129		1,85E-03		0	2	9,87E-13	0,00011	0,002	9	177	1
	SE2	2	0,307	0,030		2,77E-01	2	8	2,08E-11	0,00229	0,003	198	285	21
		4	0,275		4,58E-03		1	10	1,38E-11	0,00152	0,070	131	6056	14
	SE3	3	0,186		3,42E-03		0	6	3,36E-12	0,00037	0,013	32	1105	3

V. DISCUSSION

Subsequently, we will use the following convention to identify the layers (aquifers):

- *Village, Electrical Sounding, Layer Number.*

- Example: *Nsele, SE2, C3* means: the third layer of the second electrical sounding in the village of Nsele.

Table 4 shows us the following information.

- *Storativity and Sustainability of Withdrawals (Exploitation).*

- Considering only the zones of influence of the electrical sounding points, of the 9 listed aquifers, 3 aquifers cannot reach 1 year of exploitation due to their very low storativity (they have overall a porosity of less than 20%).

- Six aquifers, have a porosity of more than 20%, can be exploited for at least one year:

- ✓ *Nsele, SE1, C1* (unconfined aquifer): 1 year and 7 months,
- ✓ *Nsele, SE1, C5* (confined aquifer): 15 years and 7 months,
- ✓ *Nsele, SE2, C1* (unconfined aquifer): 1 year,
- ✓ *Nsele, SE3, C1* (unconfined aquifer): 1 year and 5 months,
- ✓ *Kikamba, SE2, C2* (unconfined aquifer): 2 years and 8 months,
- ✓ *Kikamba, SE2, C4* (confined aquifer): 1 year and 10 months,

Among these aquifers, there are 4 unconfined (water table) despite their small thicknesses (less than 2m) which is compensated by their specific yields which are about 100 times more than the storage coefficients of the confined aquifers.

- A basement or fissure aquifer (*Nsele, SE2, C4*), despite its thickness, has a very low porosity (about 5%) and a very low storativity: Its storage coefficient is about 10 times less than that of confined sand aquifers. It cannot be exploited even for 1 month.

- *Transmission or Water Conduit*

- Transmissivities greater than $0.015 m^2/s$ or $1296\ m^2/d$ represent good aquifers for the exploitation of water wells (Freeze & Cherry, 1979). Thus, considering table 4, the productive aquifers regarding good water transmission are:

- ✓ *Nsele, SE1, C5* : 49484 m^2/d (Sand)
- ✓ *Kikamba, SE2, C4* : 6056 m^2/d (Sand)

It is noted that their high transmissivities are a consequence of their great thicknesses.

- Unconfined aquifers, despite their good storage capacities, do not have good transmissivity due to the smallness of their thicknesses.
- The best aquifers for exploitation are the two sand aquifers that combine good storage and good transmission:

- ✓ *Nsele, SE1, C5* : T= 49484 m^2/d ; exploitation duration : 15 years 7 months
- ✓ *Kikamba, SE2, C4* : T= 6056 m^2/d ; exploitation duration : 1 year 10 months.

Drilling results in our study area show a transmissivity interval of $10m^2/d$ to $300m^2/d$ (Chisugi et al., 2018), which corroborates the transmissivity values of six of the nine identified aquifers. The other three have very high values, certainly due to their thicknesses.

These results, obtained exclusively with VES data, are very estimative, especially since the VES does not allow for precise determination of the lateral extent of an aquifer (which is why we were content with the surface area obtained using the radius of influence of the sounding point) nor the variation of the hydraulic head (Δh). To obtain real results, it will be necessary to associate drilling data, lithological logs, or pumping tests. To obtain the extent of the aquifers, it will be necessary to associate electrical profiling or Electrical Resistivity Tomography with the electrical sounding to highlight lateral variations in resistivity.

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