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ADVANCED TECHNIQUES FOR DEFINING OPTIMAL BOREHOLE SITES IN LOKOJA'S BASEMENT COMPLEX

[1]**Ekweueme, K. J.,** [2] **Nwakwo, J.U.,** [1] **Uloko, D. M. and** [1] **Ayuba, N. I.**

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Abstract

The best borehole location has been pinpointed using empirically derived aquifer hydraulic parameters. Geoelectric properties were obtained by analyzing seventeen VES data points through partial curve matching and 1D Forward modeling. The study area displayed various geo-electric earth-layer models, with H-type and HA-type curves being most predominant. The conceptual aquifer model revealed a majority of Weathered/fractured systems common in basement complex environments. Aquifer resistivity ranged from 5.6 - 751.6 ohm-m, with lower values corresponding to clay materials. Aquifer layer thickness varied from 1.6 m to 48.3 m, averaging 13.6 m. Hydraulic conductivity in the study area ranged from 0.005 - 11.99 m/day, while transmissivity spanned from 0.03 - 141.6 m2/day. The study area was divided into five groundwater potential zones using the Krasny Classification Scheme. Results indicated that 80% of the area had Very Low and Low transmissivity, appropriate for small water withdrawals only. The optimal borehole location was identified in a small, high-transmissivity area, suitable for regional water abstraction purposes.

Introduction

As human populations grow, the pressure on resources such as water, increases and man has to search wider and deeper; with more sophisticated tools and better technologies to find them. Water is essential to human survival and thriving of civilizations. It finds application both for domestic and industrial uses. Although the quantity of water on earth is large, very little percentage of it is available for human consumption. Only about 2.5% of water found on earth is fresh water and of this amount, more than 98% is stored as ice in arctic regions and as groundwater (nearly 30% of freshwater) and only a little more than 1.2% flows as surface water in rivers, streams and lakes (Shiklomanov, 1993).

Additionally, water is unevenly distributed both temporally and spatially. All forms in which water is stored suffer from this temporal-spatial unevenness (Akaamaa et al, 2014; Falebita and Ayua, 2022). In some regions

[1]Department of Physics, Federal University Lokoja, Lokoja Kogi State
[2]Department of Physics, Michael Okpara University of Agriculture, Umudike

such as arid and semi-arid locations, the situation is dire surface water sources are unavailable and rainfall is insignificant both in frequency and quantity and as such man must rely only on the elusive groundwater.

In Lokoja, ample amount of fresh water exists as the river Niger is met by its main tributary the Benue, giving the town the appellation Confluence city. However, the problem of river pollution, inadequate technology and costs of purification, storage and distribution juxtaposed with the increasing population and lack of government will to get the public water-works adequately running means that residents must find alternative water sources (Omali, 2014; Efenji et. al., 2022).

For the majority of inhabitants, groundwater is the ideal source of drinkable water as it is presumed to be cleaner and easier to treat than surface water (Efenji, et. al., 2022) compared with other sources of water - untreated surface water, hand-dug and shallow wells - also available (Omali, 2014).

To access groundwater however, boreholes must be drilled. The study area majorly lies within a basement complex terrain and the geology notably correlates with poor groundwater yields. Several published literatures have shown that groundwater abstraction in basement complex terrain is problematic (Ofodile 1983; Olorunfemi and Fasuyi, 1993; Abiola et al., 2009; Omali, 2014; Naiyeju, et. al., 2021; Falebita and Ayua, 2022) and often results in borehole failure.

The issue of borehole failure is further exacerbated by siting boreholes without recourse to the location's likelihood for hosting and transmitting water. Drillers may sometimes overestimate the expected yield of water either by design (unscrupulous business practices) or mistakenly. Decisions for borehole locations may also be made based on political or other non-geologic factors. All these add to the existent difficulty in groundwater abstraction in basement complex regions.

The solution to this problem rests on delineating geologic conformations that have the potential to hold and transmit groundwater (Aquifers) and siting boreholes therein. An Aquifer then must have high porosity and permeability but in a typical basement complex, rocks have negligible primary porosity. Secondary porosity may develop as fractures, faults and shear zones and thus takes primary importance in groundwater exploration. The task therefore of delineating optimal borehole sites in a basement complex terrain is reduced to locating zones of increased secondary porosity and estimating fluid flow within the aquifers. These can be achieved by using geophysical surveying methods such as Electric Resistivity Sounding (VES).

VES Data can be interpreted to provide information on the geoelectric parameters (resistivity and thickness) of subsurface layering and hence identification of aquifer units on their basis. Furthermore, hydrogeoelectric parameters such as transmissivity and hydraulic conductance can be derived from the data using experimental relations already established in literature (Singh 2005; Mogaji *et al.*, 2011; Ehirim and Nwakoro, 2016; Terhemba *et al.*, 2016; Ayua and Falebita, 2018). These two parameters in particular are indicative of the flow of electric current within the subsurface which in turn is controlled by fluid flow. They can therefore be used as an indirect measure of the permeability of groundwater. VES data has the added advantage of being comparatively cheaper to acquire and the equipment for data acquisition more readily available than other geophysical methods that can also be employed for such studies.

The spatial distribution of these parameters is indicative of the likelihood of groundwater occurrence and on this basis borehole drilling sites may be delineated. The optimal borehole drilling site will be the one that correlates with the most preferred rating of these parameters. The study therefore aims at using VES derived parameters to classify Lokoja metropolis on the basis of suitability for borehole drilling sites.

Location and Regional Geological Setting

Lokoja (Fig. 1), located in the plains of River Niger at its confluence with River Benue, falls within both sedimentary and crystalline provinces (Ekwueme and Onyeagocha, 1988; Omali, et al. 2011; Ayuba, et.al., 2013; Osokpor and Okiti, 2013; Madukwe et al., 2014; Omali, 2014; Ayuba et.al 2015). The northern part of Lokoja is *located within* the Southern Bida Basin (Lokoja Sub- Basin) (Osokpor and Okiti, 2013) and rocks within Felele, Sarkkin Noma, Karaworo, Nataco, G.R.A and Mount Patti falls within the domain (Omali, et al. 2011). The Lokoja sub–basin is a NW – SE trending shallow gently down-warped trough (Osokpor and Okiti, 2013; Madukwe et al., 2014) that was formed due to the wrench fault movement related to the tectonic context of the Nigerian sedimentary basins (Jones, 1953; Braide, 1992). Campanian – Maastrichtian sediments subsequently filled this basin as has been established from sedimentology and palaeontologic researches (Jan Du Chene et al., 1979; Ojo, 1992; Abimbola 1993). The study area is predominantly underlain by the Precambrian Basement Complex (Fig. 2) which is comprised of migmatites, granite, gneisses and schists (Omali, 2014; Ayuba et.al 2015). Migmatite-biotiteGneiss covers a majority of the study area and outcrops at the southwest, west, northwest and central parts of the area. Undifferentiated older granite occurs south and southeast of the area. The older granites consist mainly of porphyroblastic granite, granite gneiss, porphyroblasticgneissandfine-grainedbiotitic

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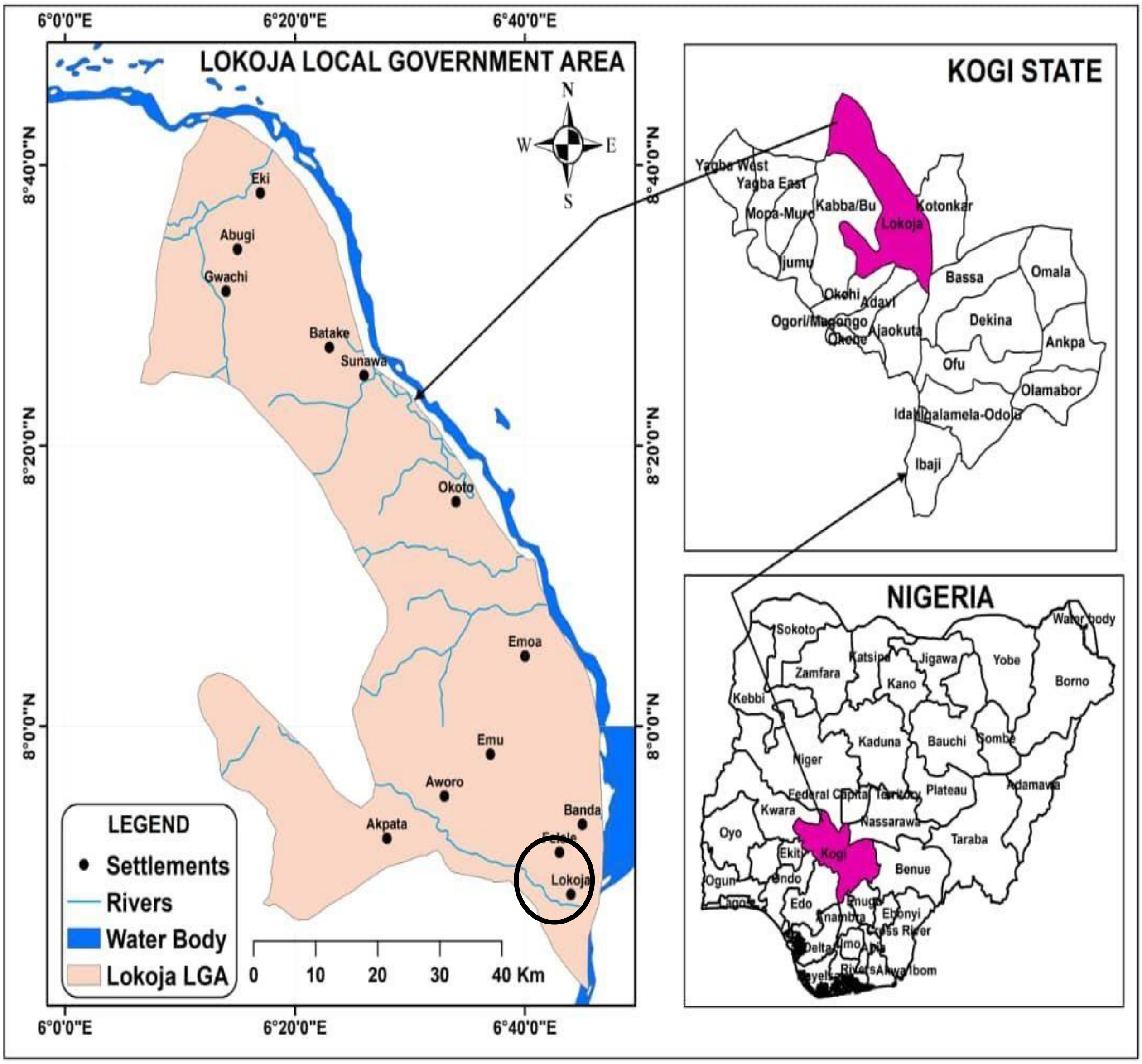

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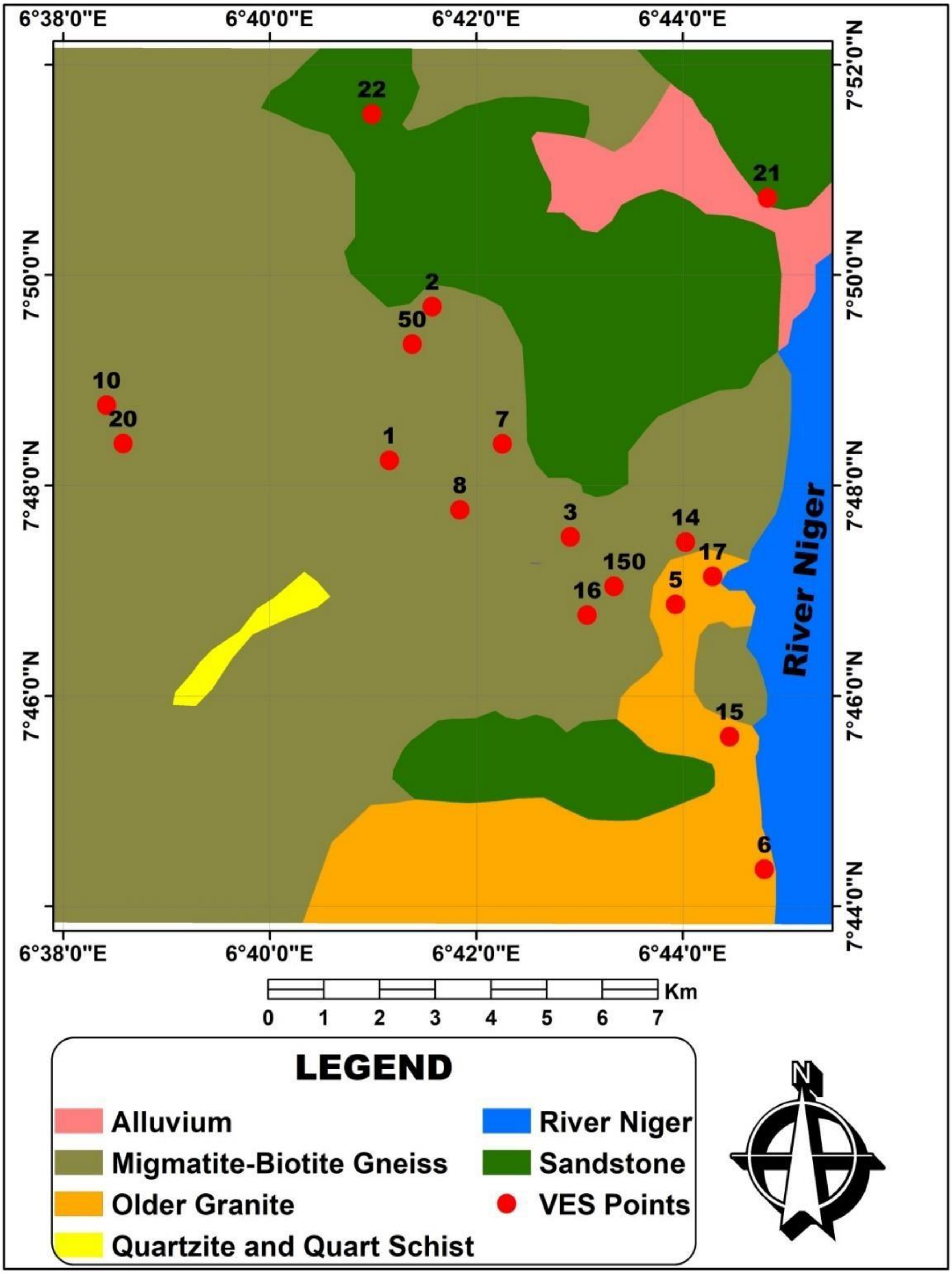
granite (Ayuba, et al., 2013).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VES Points
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Fig 1: Administrative Map of Lokoja LGA showing the Study Area in Black Circle

Fig 2: Geologic Map of the Study Area Showing locations of VES (Adapted from NGSA, 2006)

The gneisses are characterized by alternating light and dark bands with individual bands showing variation in thickness. The schists include mica-schists, quartz-schists, and quartz-muscovite schist, with quartz usually dominant over muscovite. The quartz-muscovite schists are relatively well exposed and form rounded hills or ridges due to resistant intercalated quartzite bands.

Hydrogeology

The chief property of basement complex rocks that controls presence and transmission of groundwater is the presence of joints and fractures and the degree of their interconnectedness. These properties increase the secondary porosity and permeability of the rocks thus improving the capacity of the rocks to store and transmit water.

Two aquifer types have been delineated in the area from previous studies. They are the weathered layer aquifer and weathered/fracture basement rock aquifer. Aquifer parameter data of the study area are relatively sparse, but based on aquifer test data depth to water table varies between 5.9 m and 41 m (Ige et al., 2018)

MATERIALS AND METHODS Data Acquisition

Seventeen VES Stations (Fig. 2) were occupied within the study area and survey carried out using Schlumberger array with SAS 300C Digital Terameter. Maximum half current electrode spread (AB/2) of 80 m to 100 m was used with the half potential electrode spread (MN/2) maintained between 1 m and 5 m respectively.

Data Processing

The Data was processed manually by plotting apparent resistivity (ρ_a) values against half current electrode spacing (AB/2). Partial Curve matching technique was employed using master and auxiliary curves to obtain layer parameters which were used as starting model for 1-D forward modeling. WinRESIST computer program (Vander, 2004) was used to invert the Starting model in an iterative procedure to obtain the 1-D geoelectric parameters (true layer resistivity and thickness) beneath the VES station. Interpretation was then undertaken to identify subsurface lithology, delineate aquifer layers, identify aquifer type and estimate transmissivity on the basis of the geoelectric parameters.

Transmissivity

Transmissivity is a major property of an aquifer and aids in the characterization of rocks as water conducting media or strata (Ehirim and Nwakoro, 2010;). Using empirical relation (Singh 2005, Mogaji et al., 2011; Ehirim and Nwakoro 2016; Ayua and Falebita 2018), the transmissivity for each aquifer layer was obtained using empirical equation as shown in Equation 1.0 below:

$T = (0.0538)\, e^{0.0072\rho} \times h$ …………………….. (1.0)

Where T = Transmissivity; ρ = aquifer resistivity; h = thickness. The transmissivity is expressed 2 in dimension of Length-squared per time (m^2/s or m^2/day).

Log Transmissivity Transform

Transmissivity values were log-transformed into logarithmic transmissivity index Y in order to 5 decrease the large order of magnitude difference into a form more easily characterized on maps 6 (Terhemba *et al.*, 2016). The Transformation was affected using the relation after Krasny (1993):

$= \log\left(\frac{T}{86400}\right) + 8.96$ ……………………….. (2.0)

The log-transformed transmissivity was plotted as Logarithmic transmissivity Map.

Hydraulic Conductivity

The hydraulic conductivity assesses the ability of a material to let fluids flow through it when 12 hydraulic pressure is applied. The unit of Hydraulic is m/s or m/day. Hydraulic conductivity is 13 related to transmissivity by the equation.

Hydraulic Conductivity = $\frac{T}{h}$ (3.0)

Where T = Transmissivity and h =aquifer thickness

Hydraulic Conductivity can therefore be estimated using empirical relation (Eqn 1.0) as

Hydraulic Conductivity = $(0.0538)^{0.0072\rho}$ (4.0)

RESULTS AND DISCUSSION

VES Results

21 Figure 3 (a-f) shows the results of typical VES sounding interpretation within the study area. The 22 resistivity depth sounding results obtained from the study area indicate presence of varying geo23 electric earth-layer models, ranging from 3-layer to 5-layer models. A variety of curve types which 24 can be interpreted in terms of the subsurface lithology (Olayinka *et al*. 2004) were encountered, 25 ranging from the 3-layer H and A type curves, to the 4-layer HA and KH type curves and the 526 layer HAK and HKH type curves respectively. The H-type and HA-type curves are predominant 27 in the study area making up 41% and 23% of the total curve types respectively figure 4 (a, b). The 28 variation in curve type found in the study area is an indication of the heterogeneity of the 29 subsurface (Akinlalu *et al.*, 2017; Gaikwad, et al., 2021).

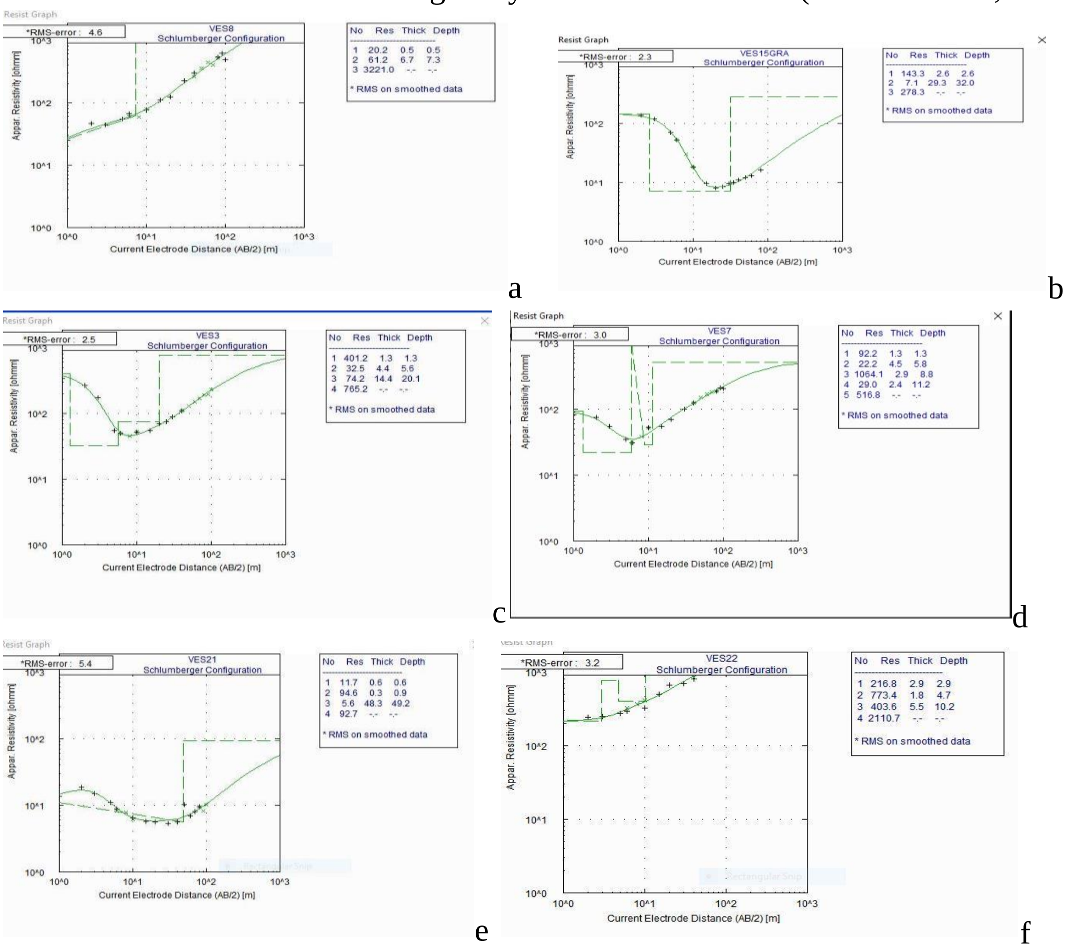

Fig 3 (a – f): shows sample result obtained from the 1D forward modeling with iteration

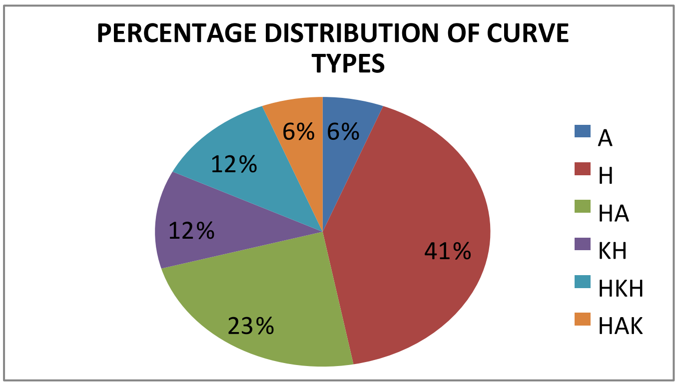

Fig 4: Percentage distribution of curve types in the study area

Aquifer Delineation and Characterization of Lithology

Electrical resistivity methods primarily reflect variations in ground resistivity (Omosuyi et *al.* 2008). These variations in ground resistivity exist across lithologic and or geo-electric boundaries in the subsurface. Their difference is the benchmark on which the aquifer and non- aquifer units where delineated. A synopsis of the geo electric parameters and classification of the resistivity sounding curves are presented in Table 1.

Conceptual Model of Aquifer

Aquifer units within the study area are predominantly made up of the Weathered/fractured basement complex rocks consistent with literature. They have wide variation in resistivity ranging from 5.6 to 751.6 ohm-meters. They tend to be localized and vary greatly in thickness, with a standard deviation of 12.7 m. The Aquifers in the three-layer models are largely unconfined and are generally thin. Aquifers within the four- and five-layer earth models are confined either by a clayey overburden or fresh basement rocks overlying fracture zones within the basement (VES 14 and 16 on Table 1).

Aquifer Resistivity

The resistivity of the aquifer unit varies widely (Table 2). It ranges from about 5.6 – 751.6 ohm-m. Aquifer units are made of heterogenous lithological materials as evidenced by the large standard deviation of their resistivities (212.95 ohm-meter). Resistivity is an important groundwater conditioning factor because high clay content generally corresponds with low resistivity (Okiongbo and Akpofure, 2012). Low values between 41 ohm-m and 58 ohm-m are typical of clay which may be continually saturated but impervious to the interstitial formation water and thus problematic for abstraction (Abiola *et al.*, 2009). An aquifer with high clay content will have a relative low groundwater potential. Very low resistivity values may also indicate zones with high salt content due to seepage of pollutant into aquifers. This also lowers the suitability of such aquifers as groundwater sources. The map of the aquifer unit resistivity distribution of the study area is presented as Figure 5.

Aquifer Thickness

The values are shown on Table 2. The aquifer layer thickness in the study area varies from 1.6 m to 48.3 m, with a standard deviation of 12.7 m. According to Omosuyi *et al.*, 2008; Adiat *et al.*, 2009, areas characterized by thickness between 10.6 – 32.8 m should be accorded more preference in groundwater development. Based on the foregoing, more than 50% of the study areas is observed to have aquifer thickness that can be significant for water development with an average thickness greater than 13 m. The map of the aquifer unit thickness distribution of the study area is presented as Figure 6.

Table 1: synopsis of the geo electric parameters and the geological type curve models

S/N	STATION	LAYER RESISTIVITY (Ω)	LAYER THICKNESS (M)	CURVE TYPE	INFERRED LITHOLOGY
1	VES 8	ρ_1=20.2 ρ_2=61.2 ρ_3=3221	h_1=0.5 h_2=6.7	A	Top Soil (Clay) Weathered Basement (Aquifer) Competent Basement
2	VES 15	ρ_1=143.3 ρ_2=7.1 ρ_3=278.3	h_1=2.6 h_2=29.3	H	Top Soil (Clay/Laterite) Weathered Basement (Aquifer) Competent Basement
3	VES 3	ρ_1=401.2 ρ_2=32.5 ρ_3=74.2 ρ_4=765.2	h_1=1.3 h_2=4.4 h_3=14.4	HA	Top Soil (Laterite) Clay Weathered Basement (Aquifer) Competent Basement
4	VES 7	ρ_1=92.2 ρ_2=22.2 ρ_3=1064.1 ρ_4=29 ρ_5=516.8	h_1=1.3 h_2=4.5 h_3=2.9 h_4=2.4	HKH	Top Soil (Clay/Laterite) Clay Competent Basement Fractured Basement (Aquifer) Competent Basement
5	VES 21	ρ_1=11.7 ρ_2=94.6 ρ_3=5.6 ρ_4=92.7	h_1=0.6 h_2=0.3 h_3=48.3	KH	Top Soil (Clay) Clay/Laterite Weathered Basement (Aquifer) Competent Basement
6	VES 22	ρ_1=216.8 ρ_2=773.4 ρ_3=403.6 $\rho4$=2110.7	h_1=2.9 h_2=1.8 h_3=5.5	KH	Top Soil (Laterite) Laterite Weathered Basement (Aquifer) Competent Basement
7	VES 5	$\rho1$=220.7 ρ_2=77.4 ρ_3=263.1 ρ_4=5682.1	h_1=0.3 h_2=3.5 h_3=26.6	HA	Top Soil (Laterite) Clay/Laterite Weathered Basement (Aquifer) Competent Basement
8	VES 10	ρ_1=458.5 ρ=104.1 ρ_3=10964.9	h_1=1.4 h_2=15.4	H	Top Soil (Laterite) Weathered Basement (Aquifer) Competent Basement
9	VES 6	ρ_1=548.7 ρ_2=83.3 ρ_3=3445.1	h_1=1.4 h_2=13.3	H	Top Soil (Laterite) Weathered Basement (Aquifer) Competent Basement
10	VES 2	ρ_1=71.6 ρ=43.2 ρ_3=257.2	h_1=1.4 h_2=1.6	H	Top Soil (Clay/Laterite) Weathered Basement (Aquifer) Competent Basement
11	VES 50	ρ_1=23.6 ρ_2= 5.9 ρ_3=36.5 ρ_4=881.7	h_1=1.0 h_2=2.9 h_3=14.9	HA	Top Soil (Clay) Clay Weathered Basement (Aquifer) Competent Basement
12	VES 1	ρ_1=122.5 ρ_2= 38.0 ρ_3=794.0	h_1=1.2 h_2=8.8	H	Top Soil (Clay/Laterite) Weathered Basement (Aquifer) Competent Basement
13	VES 150	ρ_1=197.2 ρ_2= 8.3 ρ_3=357.9	h_1=0.4 h_2=2.5	H	Top Soil (Clay/Laterite) Weathered Basement (Aquifer) Competent Basement

14	VES 14	ρ_1=291.6 ρ_2= 46.7 ρ_3=440.8 ρ_4=76.5 ρ_5=1118.6	h_1=1.0 h_2=2.4 h_3=3.9 h_4=17.4	HKH	Top Soil (Laterite) Clay Fresh Basement Fractured Basement (Aquifer) Competent Basement
15	VES 17	ρ_1=163.6 ρ_2= 8.3 ρ_3=145.6	h_1=0.6 h_2=3.1	H	Top Soil (Clay/Laterite) Weathered Basement (Aquifer) Competent Basement
16	VES 16	ρ_1=170.9 ρ_2= 18.2 ρ_3=751.6 ρ_4=2281.3 ρ_5=118.3	h_1=1.0 h_2=1.1 h_3=0.71 h_4=11.8	HAK	Top Soil (Laterite) Clay Weathered Basement (Aquifer) Competent Basement Weathered/Fractured Basement (Aquifer)
17	VES 20	ρ_1=2702.7 ρ_2= 111.6 ρ_3=161.3 ρ_4=3890.9	h_1=1.5 h_2=0.5 h_3=5.0	HA	Top Soil (Laterite) Clay/Laterite Weathered Basement (Aquifer) Competent Basement

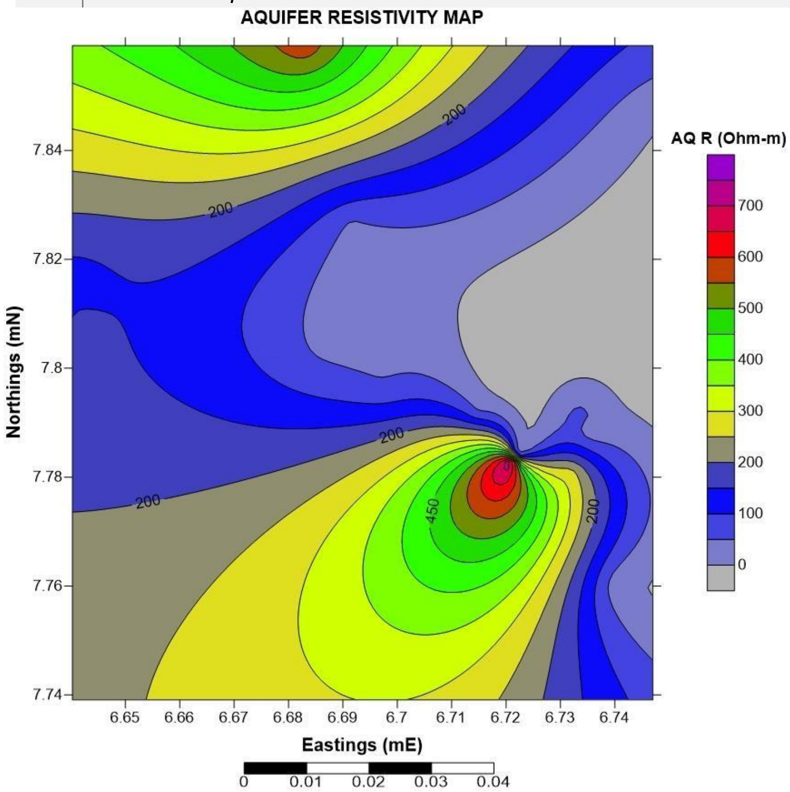

Fig 5: Aquifer Resistivity Distribution Map

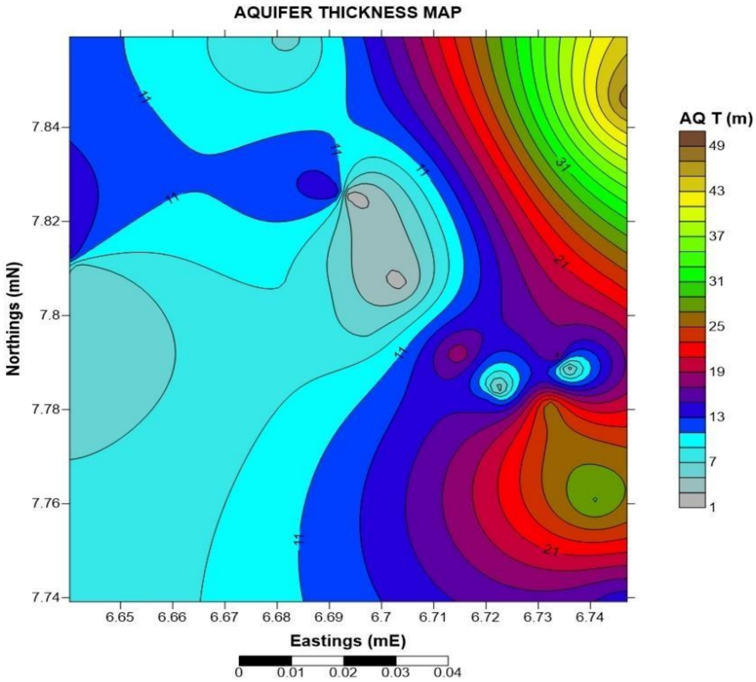

Fig 6: Aquifer Thickness Distribution Map

Table 2: Summary of VES Interpretation Results showing Groundwater Potential Classification

S/N	VES STATION NUMBER	AQUIFER RESISTIVITY	AQUIFER THICKNESS	TRANMISSIVITY	LOG TRANSFORMED TRANSMISSIVITY	GROUNDWATER PROGNOSIS (After Krasnny, 1993)
1	VES8	61.2	6.7	0.0301	2.5024	Very low
2	VES15	7.1	29.3	1.659	4.2433	Low
3	VES3	56.4	18.8	1.5181	4.2048	Low
4	VES7	29	2.4	0.1591	3.2252	Very low
5	VES21	5.6	48.3	2.7055	4.4557	Low
6	VES22	588.6	6.3	23.459	5.3938	Intermediate
7	VES5	263.1	26.6	9.51386	5.0018	Intermediate
8	VES10	104.1	15.4	1.75314	4.2673	Low
9	VES6	83.3	13.3	1.30345	4.1386	Low
10	VES2	43.2	1.6	0.11749	3.0934	Very low
11	VES50	36.5	14.6	1.02156	4.0326	Low
12	VES1	38	8.8	0.62243	3.8176	Very low
13	VES150	8.3	2.5	0.14278	3.1782	Very low
14	VES14	76.5	17.4	1.62383	4.234	Low
15	VES17	8.3	3.1	0.17705	3.2716	Very low
16	VES16	751.6	11.8	141.573	6.1745	High
17	VES20	161.3	5	0.85926	3.9576	Very low

Hydraulic Conductivity

Hydraulic conductivity controls the behavior of groundwater flow within an aquifer (Obiora *et al.*, 2015). Hydraulic conductivity values for the study area ranges from about 0.005 – 11.99 m/day. From the hydraulic conductivity distribution map (Figure 7) of the area, three regions of very low, intermediate and high conductivities can be delineated. The study area is however dominated by low hydraulic conductivities. The low hydraulic conductivity observed across the study area is an indication of possibly high clay content (Ehirim and Nwakoro, 2016) and thus low permeability (Obiora *et al.*, 2015). High hydraulic conductivity is therefore a more important conditioning factor for groundwater potential and thus areas of high hydraulic conductivities may be considered as possible sites for borehole siting.

Transmissivity

Transmissivity within the study area ranged from 0.03 m^2/day to 141.6 m^2/day, corresponding to log transformed values of transmissivity ranging from 2.50 m^2/day to 6.20 m^2/day. The results of the transmissivity is presented as Table 2. The mean log-transformed transmissivity value is 4.1 m^2/day indicating that the regional trend of transmissivity is low. This corresponds with the Log transmissivity map (Figure 8) which shows that more than 80% of the study area can be classified as having low transmissivity. A profile AB is drawn across the map in a NW-SE direction and fitted with a regional trend line by visual inspection. The trend line corresponds to about 4.2 m^2/day and is consistent with the regional obtained through statistical means. The profile shows two anomalies of interest. A positive, asymmetrical anomaly in the South-Eastern region of the map corresponding to the intermediate zone of transmissivity, whose peak is centered over the high transmissivity region and a negative anomaly in the center of the plot whose peak is centered over the zone of imperceptible transmissivity.

Optimal Borehole Site Delineation

The classified log transmissivity map (Figure) shows that the study area can be classified into four categories based on the Krasny classification scheme (Terhemba, 2016), namely Very Low, Low, Intermediate and High groundwater potential zones and the optimal borehole site of the study area can be assessed on that basis.

Areas around with Transmissivity value of less than 0.1 m^2/day (less than 3 m^2/day on the log transmissivity) is classified as imperceptible on the Krasny schemen. Within that region, aquifers for local consumption are difficult to locate and siting boreholes for groundwater abstraction within this zone is discouraged. More than 80% of the study area falls within two classifications; Very Low and Low transmissivity classification. They have transmissivity values of 0 – 10 m^2/day

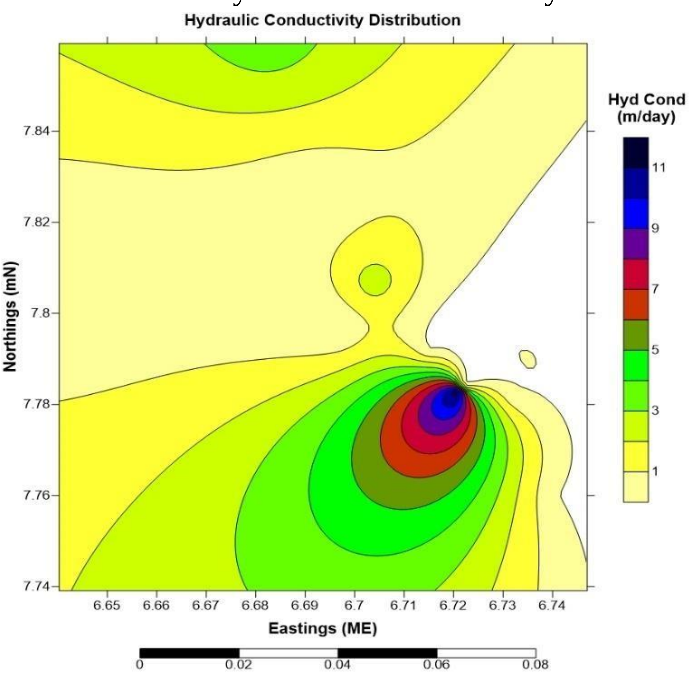

Fig 5: Aquifer Hydraulic Conductivity Distribution Map

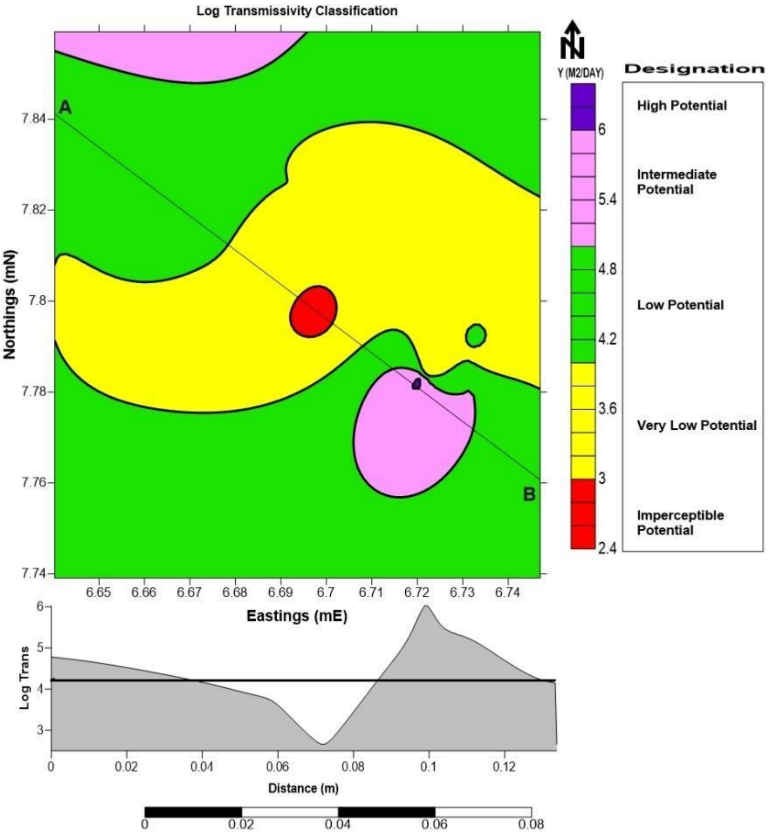

Figure 8: Log Transformed Transmissivity Map of the study area showing Profile

(Corresponding to 3 – 4 m^2/day on the log transformed scale). Within this region, aquifers can only supply water for limited consumption and boreholes sited here can only sustain small withdrawals for sequestered consumption. Since most of the study area falls within this classification, mechanized borehole installation may be carried out with the proviso that pumping should be done periodically and in tandem with the rate of aquifer recharge to aid sustainability. About 11% of the study area is classified as having intermediate transmissivity. Aquifers in this zone have transmissivity ranging from 10 – 100 m^2/day (corresponding to 5 m^2/day on the log transformed scale). Aquifers within this zone may be suitable for siting boreholes sufficient to discharge water for local water supply adequate for small communities and limited irrigation purposes. A small region, with areal extent of about 3.5 m^2 (colour code deep blue) with high transmissivity of about 140 m^2/day (corresponding to 6 m^2/day on the log transformed scale) is classified as having high transmissivity. Aquifers within this zone can support withdrawals of lesser regional importance and is identified as the optimal site for borehole location. This region may be considered for further geophysical survey and is best for siting boreholes that may serve in designing and construction of a public water works system.

CONCLUSION

The optimal borehole site delineation for Lokoja has been undertaken from the empirical estimation of aquifer hydraulic parameters from variables obtained from the 1D Forward modeling of VES data. Hydraulic conductivity values for the study area ranges from 0.005 – 11.99 m/day while Transmissivity within the study area ranged from 0.03 - 141.6 m^2/day, corresponding to log transformed transmissivity ranging from 2.50 m^2/day to 6.20 m^2/day. The study area can be classified into five zones based on Krasny Classification Scheme; Imperceptible (< 3 m^2/day), Very Low (3 m^2/day), Low (4 m^2/day), Intermediate (5 m^2/day) and High (6 m^2/day) groundwater potential zones. The findings showed that 80% of the study area falls within Very Low and Low transmissivity classification (3 – 4 m^2/day), correlating with zones of Low hydraulic conductivity. It is expected that boreholes sited within these areas can only sustain small withdrawals for sequestered consumption therefore borehole pump installation be carried out only on the condition that pumping is periodical and not exceed aquifer recharge rate to ensure sustainability. Additionally, a small region, with areal extent of about 3.5 m^2 is classified as having high transmissivity. It follows that aquifers within this zone can support withdrawals of lesser regional importance and is therefore identified as the optimal site for borehole location. It is recommended that this region be considered for further geophysical survey and may serve in designing and construction of a public water works system.

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