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Geoelectrical Investigation of Aquifer Systems in Toro and Environs, Northeast Nigeria

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Abstract: *Aquifers in Toro and the surrounding area of northeastern Nigeria were characterized using fourteen (14) Vertical Electrical Resistivity Sounding (VES). The study's goal is to use Schlumberger configuration to describe the local aquifer system. The study is warranted due to the numerous unsuccessful wells and boreholes in the area. A maximum electrode spacing of 120 meters was used for the vertical electrical sounding (VES). These three-layer earth models (H, Q, and A) were used to derive the sounding curves. The following lithologies were identified in the area: surface soil having resistivity between 91Ωm - 154.21Ωm with thickness of 0.88m - 4.77m; fractured basement having resistivity of 11.52Ωm - 578Ωm with thickness of 4m – to depth infinite; and the fresh basement having resistivity of 1121.21Ωm - 1401Ωm with a thickness of 8m to depth infinite in thickness. The region's groundwater supply potentials were evaluated using the resistivity contrast (FC), transverse resistance (T), and longitudinal conductance (S). The area's groundwater potentials were classified as high to medium, and its aquifer protection capacity was rated as moderate to excellent. The results of the evaluated parameters indicate that the groundwater potential in the region is mainly high to moderate. Bad quality data, in proper expertise, poor drilled-hole development, and erroneous point selection that are very rampant Basement terrains might be the cause of the most failed/aborted wells incidents in the area. Clean water is essential in human for drinking, and its contamination or lack can have serious negative effects on public health, from disease to epidemics.*

Keywords: *Well; Resistivity; Section Borehole, Data, Drinking*

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1.0 Introduction

A basic human need is clean drinking water, and its contamination or lack can have serious negative effects on public health, from disease to epidemics. Rain, streams, and lakes are the main sources of water for humans. However, there are sources of drinking water that are unfit for human consumption because of contaminants and pollutants brought on through human actions (Yohanna et al., 2022a). Search for portable water in Toro and environs is hindered by dormant boreholes and Hand-drilled well failure brought on by inexperience knowledge of basement aquifers', technical expertise, and inadequate hole development (Abiola *et al.*, 2013). Groundwater exploration requires understanding of hydrogeological parameters because normally groundwater is been stored in fractures/weathered zones (Satpathy& Kanungo, 1976; Olorunniwo and Olorunfemi, 1987).

A geophysical technique that can be suitably adopted for groundwater search in the Basement terrain is the electrical resistivity method (Limaye, 1989). The fundamental significant resistivity comparison between highly resistive fresh bedrock and worn and/or fissured columns determines the technique's suitability. Groundwater is most likely to be found in the basement's weathered and fractured areas. Researchers have investigated the groundwater in the Basement Complex using the resistivity approach (Andarawus et al., 2022a; Nur and Ayuni, 2004; Edet and Okereke, 1997; Acworth, 1987; Nur and Kujir, 2006;Olurunfemi and Fasuyi, 1993, Zohdy et al., 1974; Olasehinde, 2010). Due to a lack of knowledge about basement aquifers, weathering and in-situ rock depletion cause borehole failure rates to be greatest in basement terrain. Communities, private citizens, and the government of Nigeria are expanding borehole projects to provide dependable drinking water (Nur, 2012). When compared to other geophysical methods in groundwater exploration. The resistivity technique is used in groundwater exploration far more frequently (Umar et al, 2025, Kaura et al., 2024; Nur and Ayuni, 2011, Nur and Afa, 2002). This work is aimed at carrying out geoelectrical search for groundwater development in Toro, Northeast, Nigeria, for the purpose of determining variation in resistivity with depth and aquifer vulnerability of subsurface rock materials in the area.

1.1 Study Area Description, Geology and Hydrogeology

The research area covers between latitudes 10^0 00' 00"N and 10^0 05’ 00"N and longitudes 09^0 00’ 00" E and 09^0 05’ 00" E (Fig. 1). It can be reached by the main road between Bauchi and Jos, in addition to the numerous towns, villages, and settlements connected by tarred and untarred roads. Topographic altitudes in the area range from 3250 to 3550 feet, and the landscape is gently sloping.

The Nigerian Basement Complex is made up of rocks that were form from the Precambrian in age, as well as crystalline rocks with a variety of metamorphism phases, that includes rocks such as phyllite, Schist gneisses, migmatite, quartzite and pegmatite. Organizations such as Conred Nigeria Limited (1978), Edok-Eter Mandilas Nigeria Limited (1976–1979), and the Bauchi State Agricultural Development Project (BSADP) played roles during the stated periods. carried out Survey of hydrogeological fields of the area to ascertain its hydrogeological condition (Shemang and Jiba, 2005). Alluvium is a mixture of silt lenses, sand, clay, boulders, and gravels that is created by weathering and nearby hills. It is deposited under water table conditions in groundwater sources and stream valleys (Carter *et al.*, 1963).

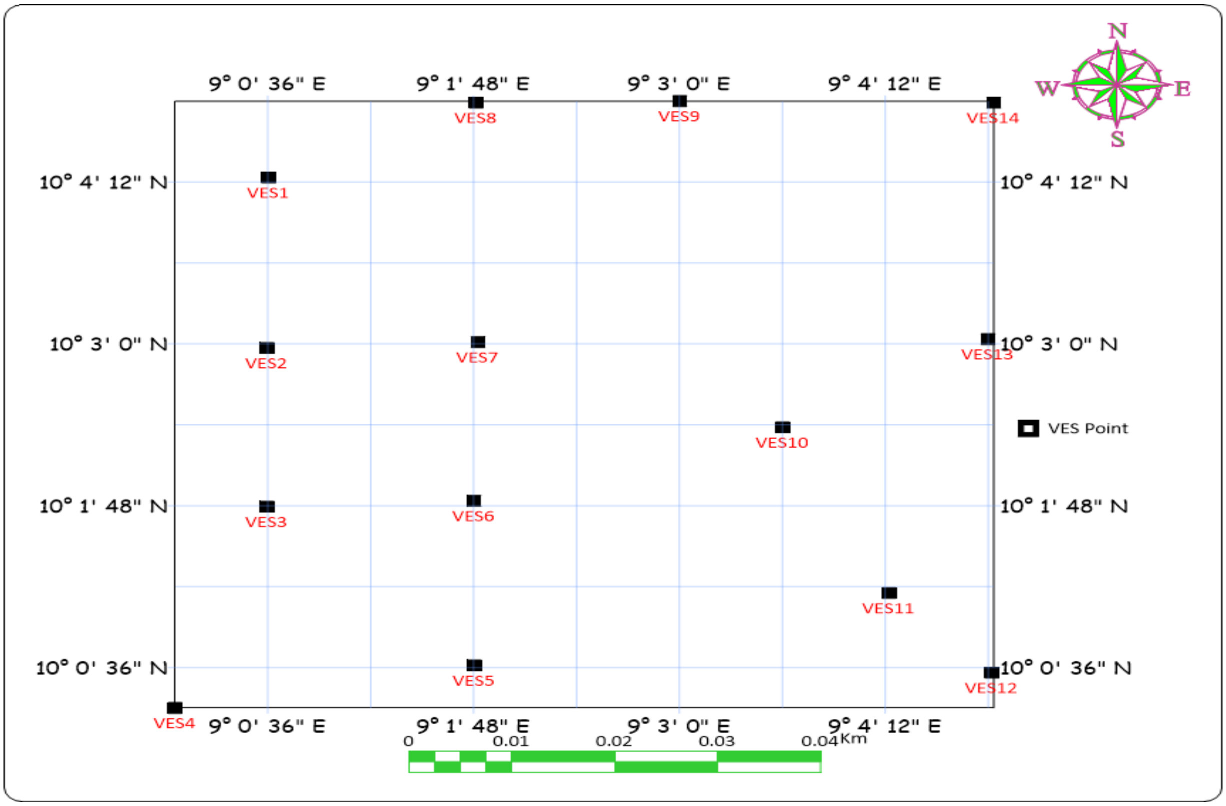

Fig. 1: The study location map with VES points

2.0 Materials and Method

The work is to identify lithology and rock types using topographical, geological, and reconnaissance data from the Nigerian Geological Survey Agency. Resistivity data obtained from the Schlumberger electrode configuration and ABEM SAS-2000B Terameter was adopted for the geophysical investigations. The apparent resistivity for the current and potential electrodes was determined by multiplying the meter's recorded resistance by its corresponding geometric factor. Sounding curves against AB/2 are then used to illustrate the apparent resistivity values on a bi-logarithm graph. Several master curves and partial curve matching were used to manually interpret the plotted sounding curves (Abdulbariu et al., 2023; Zohdy, 1965, Yohanna et al., 2022b; Aminu et al., 2022; Nanfa et al., 2022). The partial curve that corresponds to geoelectric properties was the model that was applied for iteration using software IX1D.

$$p_a = \left[\frac{(AB/2)-(MN/2)}{MN}\right].Ra \qquad (1)$$

where AB = Represent Interval between the two current electrodes' ρa is the apparent resistivity,

Ra is the measured apparent electrical resistance, and MN the distance between the potential electrodes.

Focusing on both parallel and perpendicular current flow, this study computed the electrical resistivity properties—including longitudinal conductance (S), transverse resistance (T), and resistivity contrast (FC)—in stratified subsurface formations (Telford et al., 1978). The conductance longitudinal unit values, which quantify the impermeability and hydraulic conductivity of the confining clay layer, are used to calculate the aquifer protection capacity of the research region (Tsepav et al., 2015). Equation (2) is used to determine the conductance longitudinal layer (S) of overburden station pointst (Henriet, 1976; Andarawus et al., 2022).

$$S = \sum_{i=1}^{n} (hi/pi) \quad (2)$$

Between i = 1… n, which hi is the thickness of layer and ρi is the resistivity of the layer, the ayers number extending to the aquifer's varies. From the surface to its top.

The values of longitudinal conductance units can be utilized to categorize the locations based on their aquifer protective capacity as poor, good, moderate, or weak. This classification follows the approach proposed by Akintorinwa and Oladapo (2007). Refer to Equation (3):

$$T = \sum_{i=1}^{n} (hipi) \quad (3)$$

T stands for transverse resistance, ρi indicates the resistivity of each layer, and hi represents the thickness of the respective layers. According to Bayewu et al. (2018), groundwater yield in basement terrain can be classified as high, medium, or low based on the overburden thickness and/or the reflection coefficient. When heavy overburden covers the cracked zone, the biggest groundwater output is known as the resistivity contrast (FC), and it may be calculated as follows: Formula (4):

$$FC = \frac{(pn)}{\rho n - 1} \quad (4)$$

where, pn represents the nth layer's layer resistivity and pn−1 represents the resistivity of layer on top of the nth layer.

2.1 Measurements of Hydraulic Head in the Study Area

The depths and static water levels (SWLs) of hand-dug wells and boreholes were measured using a dipper-T model water level meter. Site elevations and geographic coordinates (latitude and longitude) were obtained using a GPS device (Garmin e-Trex 20 model). Since households typically begin drawing water early in the morning, measurements were taken before usage commenced. To ensure even sampling distribution, the study area was divided into ten quadrants. The SWL data, along with topographic elevation above mean sea level, were used to compute the hydraulic head for each well. These values were then used to generate a hydraulic head map for the study area.

3.0 Results and Discussion

Sounding data in the area were displayed as sounding curves by plotting the apparent resistivity against AB/2 or halving the spread length on log-log paper. IX1D software is used to create sounding curves from smoothed data that is entered into a computer system. After smoothing the curves, smooth layer curves were produced. The layers are the general characteristics of the geological materials in the area as observed (Table 1). The H, Q, and A were found in the geological formations of the study area (Table 1). Type Q curves has resistivity attribute of ρ1> ρ2> ρ3, Type A curves have ρ1< ρ2< ρ3, and H type curves have ρ1> ρ2< ρ3. All sounding VES and their parameters (thicknesses, resistivities, errors in fiiting, and their respective curve types) are shown in Table 1. For every point sounded in the study area, this includes information on layer thicknesses, resistivities, and their fitting errors. The fitting errors for the general features of the sounding curves that were observed range from 0.98 percent to 0.215 percent. Since each type curve represents a distinct image of the subsurface electrostratigraphic layers. These curves were assessed for hydrogeological significance in order to provide a basis for describing the aquifer potentials in the area. Therefore, main aquiferous zone is at the base, where there are fractured basement/ weathered overburden thickness with high degree of conductivity. Which may produce portable water with high yield in the area.

3.1 The Area's Isoresistivity Map

A map that connects locations with equal electrical apparent resistivity is called an iso-resistivity contour map. AB/2 = 60 m was produced connecting points of equal resistivity. All sounding locations had iso-resistivity contour spacing of AB/2 = 60 m, and contours of locations with equal apparent resistivity Fig.

were made. This is interpretation was based on patter of the map. This only represents the general lateral variation in the area's electrical properties and does not reflect resistivity changes at specific electrode spacings. Fig. 2 shows resistivity values ranging from 200 Ωm to 650 Ωm. The estimated depth of investigation for AB/2 = 60 m is approximately between 15 and 30 meters. The map reveals a heterogeneous subsurface structure. Lower resistivity values are observed in the central and southwestern parts of the study area, whereas higher resistivity values are recorded in the northwestern and northeastern regions.

Table 1: Information about the resistivities, layer thicknesses, and fitting errors for each point sounded in the research area

VES Staion	Layer Thickness (m)		Layer Resistivity (Ohms-meter)			Error Fitting (%)	Type Curve
	H1	H2	ρ1	ρ2	ρ3		
VES1	3.87	21.60	546	61	1221	0.61	H
VES2	1.00	22.31	273.40	189.35	59.79	0.24	Q
VES3	1.00	19.74	120	37.23	1400	0.44	H
VES4	1.45	15.57	673.23	100	300	0.40	H
VES5	0.80	9.29	345.34	102	200	0.78	H
VES6	2.74	28.65	471.81	179.47	241	0.64	H
VES7	0.66	1.00	343.15	205	2218	0.88	A
VES8	1.55	22.31	692.23	120	1346	0.21	H
VES9	1.00	11.12	294.92	244.82	2043.75	0.81	H
VES10	1.00	20.53	229.80	40.51	2251	0.26	H
VES11	2.00	20.61	502	40	1000	0.43	H
VES12	2.50	7.00	858.72	80	1500	0.20	H
VES13	2.00	30.23	600.20	10.00	1300	0.81	H
VES14	1.00	20.00	200	100	1250	0.88	H
TOTAL	23.97	273.95	6350.8	1468.98	1771.54	7.81	

3.2 Area's Geoelectrostratigraphic Sections

The VES interpretation results were used to prepare geoelectric sections. This electro stratigraphic section was generated by interpreting data from numerous VES sites located along a profile. Before establishing the location of each VES point using the station interval the highest length of the traverse was measured and sketch to scale vertically and horizontally. Resistivity values of each VES at boundaries beneath were identified and their thicknesses were delineated. The total number of sections is three. The geoelectric sections identified the following underlying layers: fresh bedrock, weathered layer/fractured basement, topsoil, and laterite. This area has been found to have three geoelectric layers: fresh basement, weathered/fractured basement, and topsoil or laterite (Fig. 3). Topsoil resistivity ranges between 200 Ωm and 858 Ωm, with thicknesses varying from 0.56 to 3.77 meters. The weathered or fractured basement shows resistivity values between 10.62 Ωm and 200 Ωm, with thicknesses ranging from 2 meters to indefinite depths. Fresh bedrock has a resistivity range of 1225.44 Ωm to 2250 Ωm, and its thickness extends from 6.35 meters to an undefined depth (Fig. 3).

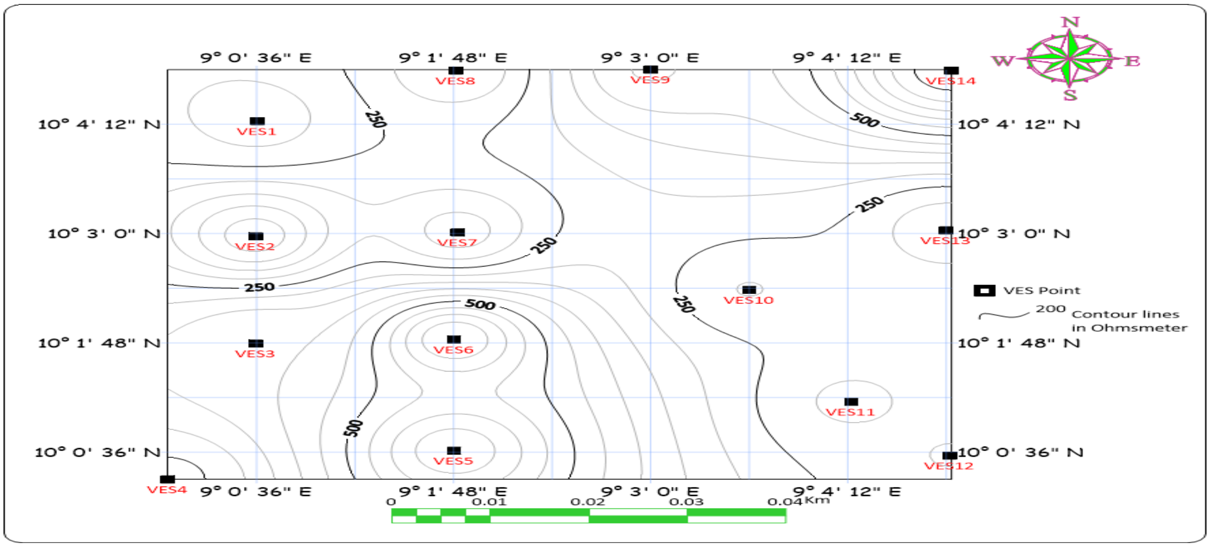

Fig. 2: Showing Isoresistivity map of AB/2= 60m in the area

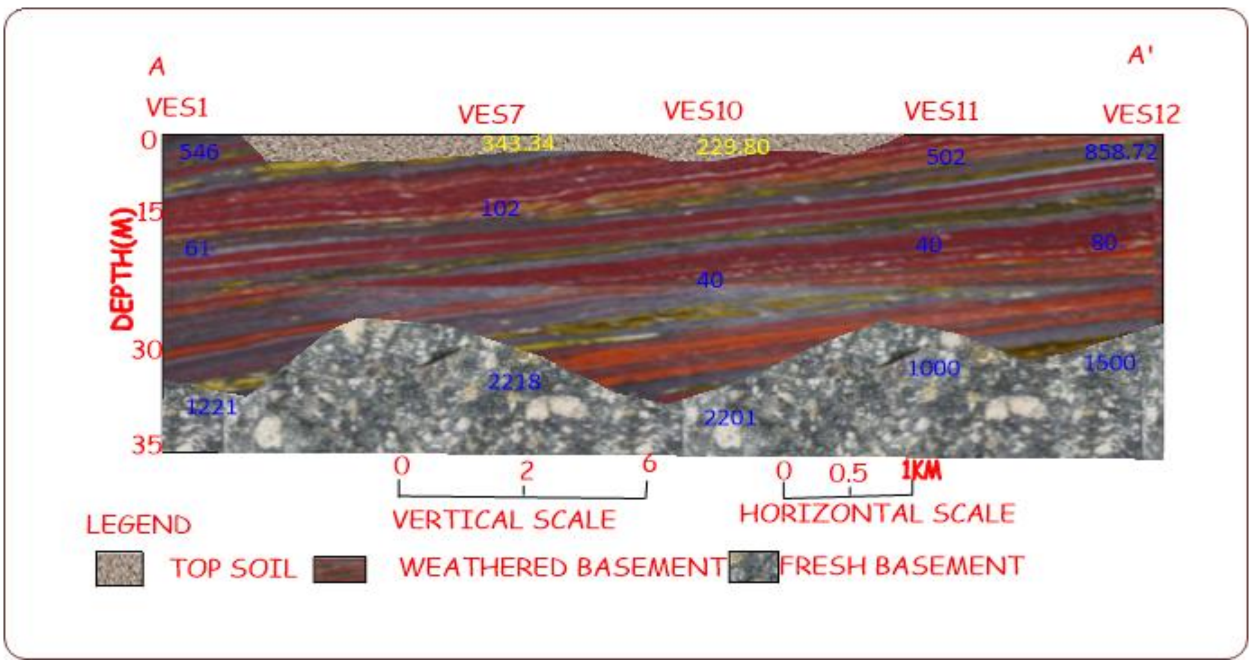

Fig. 3. Geo-electric section in the area

3.3 Evaluation of the Area's Groundwater Potential and Aquifer Protective Capacity

The study area's protective capacity has a good to moderate capacity rating, based on Aina et al. (2019) and Olusegun et al. (2016) (Table 2). The ability of the aquifer to safeguard rating in Table 2 and parameters like longitudinal conductance (S) and transverse resistance (T) were used to calculate the aquifer protective capacity in the research area. The overall thickness of materials with low resistance was shown to have changed based on longitudinal conductance variations between VES points (Worthington 1977; Glain 1979). One of the electrostratigrahic characteristics to identify potential groundwater potential zone is the total longitudinal conductance (S). A shallow basement and low-resistivity formations (like clayed soil) are indicated by low T values, while a deeper basement and high-resistivity formations are indicated by higher T values. Very resistive subsurface deposits are associated with particularly high transverse resistance values. Transverse resistance values can also help indicate the direction of groundwater movement within an aquifer. Total transverse resistance (T) is a geoelectric parameter used to pinpoint zones with the highest groundwater potential (Andarawus et al., 2022b). According to Olusegun et al. (2016), T is positively associated with transmissivity, where higher T values are likely to reflect aquifers or zones with greater transmissivity. In the study area, the longitudinal conductance values of the overburden materials range from 0.004648796 to 0.0473261 Siemens (Table 2). The longitudinal conductance and aquifer potential maps (Fig.s 4 and 5) reveal that infiltration from precipitation is relatively low in the northeastern and northwestern sections of the research area.

Table 2: Information about the study area's groundwater yield, overburden thickness (m), resistivity contrast, Ohms-meter transverse resistance and the rating of the overburden aquifer's protective capacity

VES Staion	Values of Longitudinal Conductance in the area (Siemens)	Values of Transverse Resistance in the area (ohms-meter)	Values of Overburden Thickness in the area (m)	Values of Contrast Resistivity in the area	Values of Aquifer protective capacity rating in the area	Yield Ground water
VES1	0.0139868	46380.870	25.47	28.02	Excellent	High
VES2	0.0473261	11478.182	23.31	21.00	Excellent	High
VES3	0.0131451	32296.950	20.74	17.00	Excellent	High
VES4	0.0158586	18266.3746	17.02	9.35	Excellent	High
VES5	0.01683813	6531.6606	10.09	3.44	Excellent	High
VES6	0.01583813	7531.8606	31.39	23.67	Excellent	High
VES7	0.0006001121	4591.809	1.66	9.1	Moderate	Moderate
VES8	0.0149898	37380.470	23.86	19.11	Excellent	High
VES9	0.004648796	31001.86	12.12	17.12	Excellent	High
VES10	0.0139895	36380.230	21.53	11.22	Excellent	High
VES11	0.0121351	32111.950	22.61	10.11	Excellent	High
VES12	0.0169885	46380.230	9.50	2.89	Excellent	High
VES13	0.01331351	30111.850	32.23	18.22	Excellent	High
VES14	0.01378689	46380.130	21.00	11.21	Excellent	High

The aquifer water potentials in the resrach area are classified as medium to high (Fig. 5). According to this study, areas with an overburden thickness of more than five meters are thought to have a high groundwater potential, whereas areas with an overburden thickness of less than thirteen meters are thought to have a very poor groundwater potential (Aina et al, 2019). The region has a high groundwater potential overall, though this is primarily limited to areas with wethered basements underneath them. This finding consistently emphasizes how crucial it is to carry out a comprehensive groundwater exploration in the area so that to delineate possible locations for productive boreholes.

The aquifer water potential of a place can be determined by measuring the resistivity contrast (Olusegun et al. 2016). The values of resistivity contrast varies from 2.89 to 28.02 (Fig. 6). The study found that the most promising VESs for groundwater exploration are 1 and 6 (Table 2). By connecting locations with equivalent hydraulic head and displaying the regions of groundwater flow direction with right-angled piezometric lines. The hydraulic head map of the area was produced (Fig. 7). The southwest and south receive regional groundwater from the northwest recharge area (Fig. 7). The northern portion of the region is the second discharge area. With a few spots in the middle and southern sections, the northern and northwest sections of the research area had the highest hydraulic head. Although the southeast of the area had lowest hydraulic heads, additionally, certain discharge zones were discovered at the northeast, central and southern parts of the area.

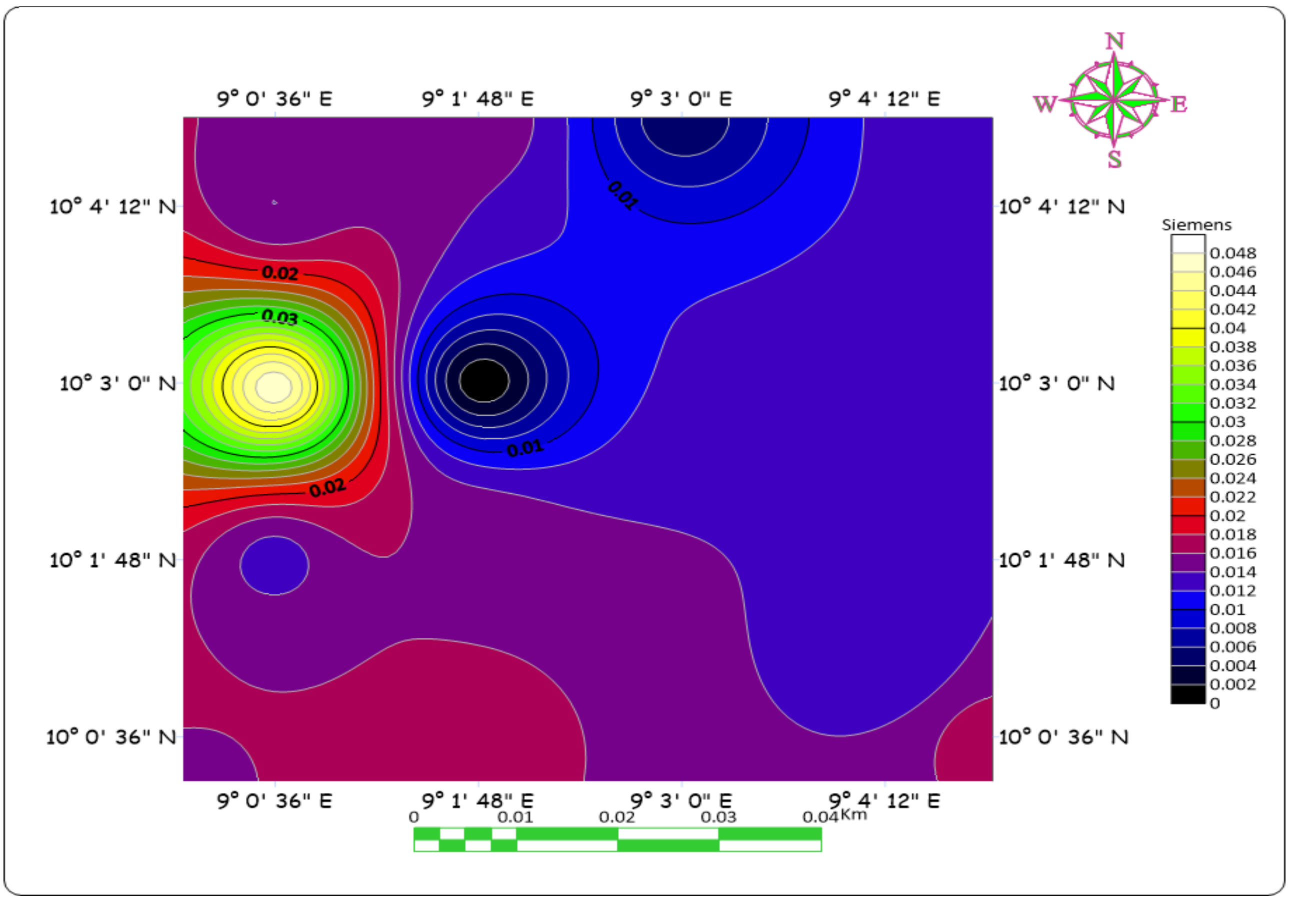

Fig. 4: Longitudinal conductance map of the area

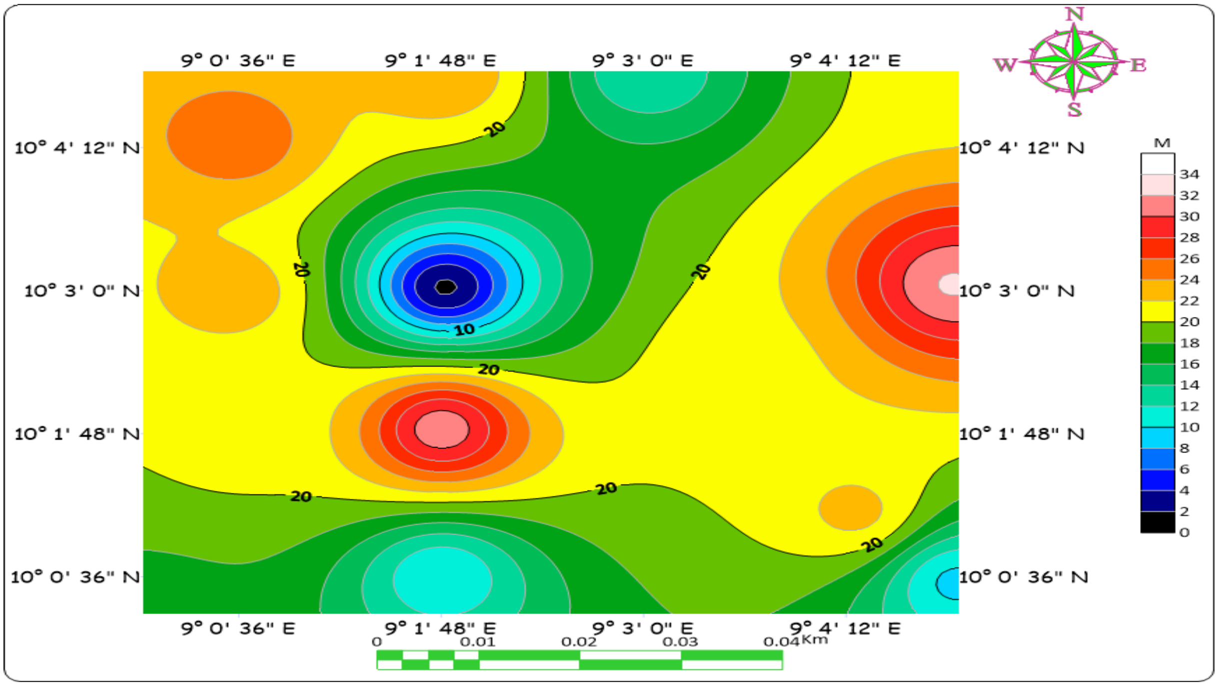

Fig. 5: Groundwater potential map of the area

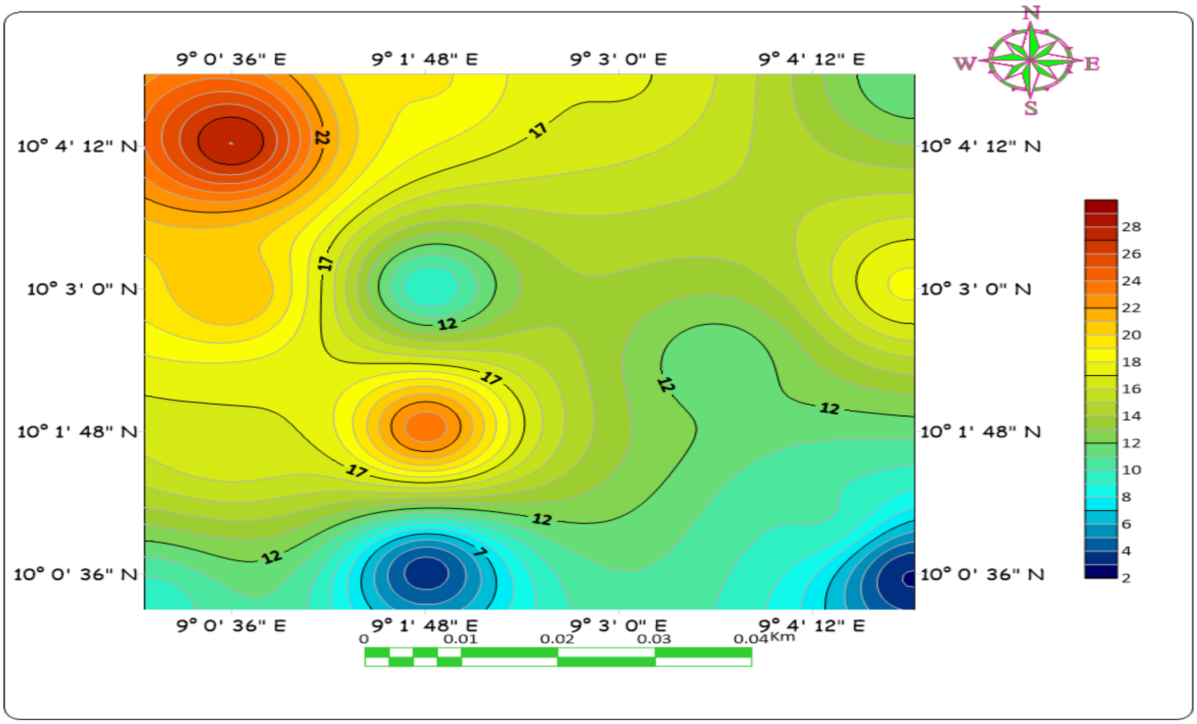

Fig. 6: Resistivity contrast map of the area

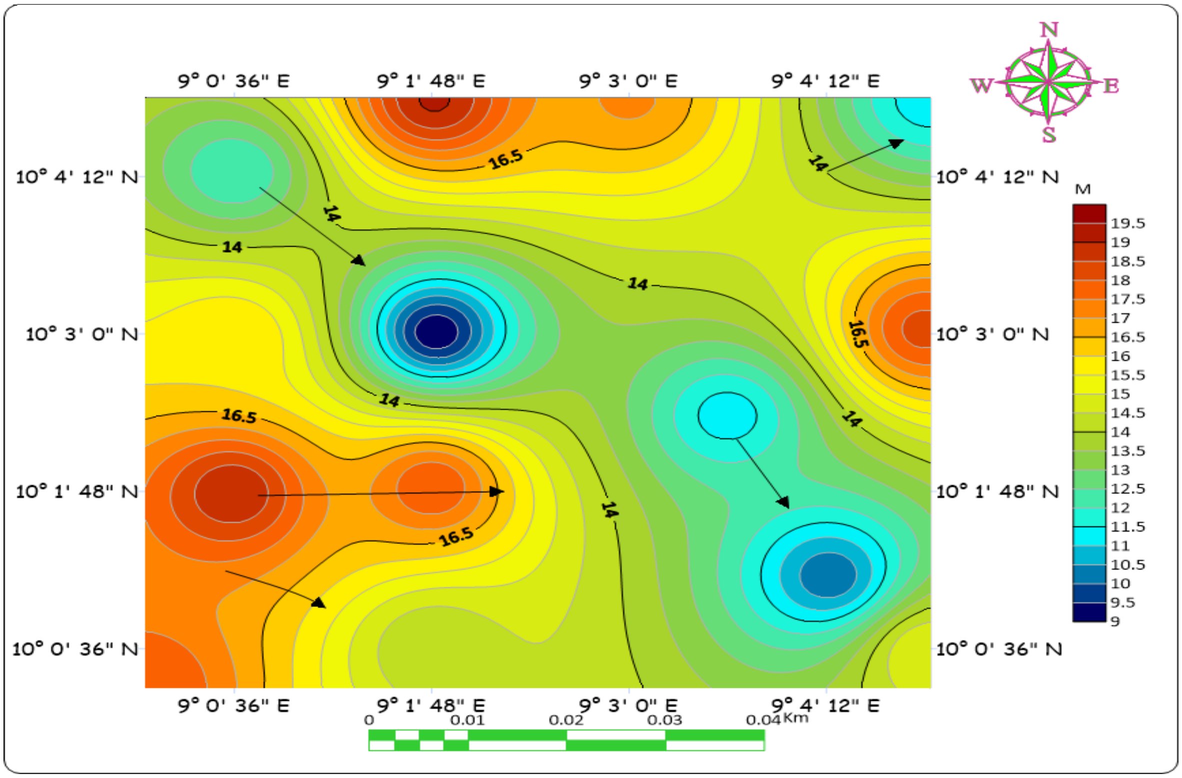

Fig. 6: Hydraulic head map distribution of the area

4.0 Conclusion

With an emphasis on resistivity variation with depth and aquifer layers, this paper concludes by offering priceless insights into the characterization of aquifers in Toro and the surrounding area. The region's aquifer system, which is mostly made up of weathered and fractured basement, has overburden thicknesses between 1.66 and 32.20 meters and resistivity values between 0- 1400Ωm. The aquifer's vulnerability is less and the groundwater potentials range from high to moderate. The formation parameters are explained in detail by the results. Throughout the investigation, 14 vertical electrical soundings were carried out in the research area. The results revealed three geoelectric layers. The majority of curves were found to be of H, Q, and A type, which are mainly of the terrains found on the Basement Complex. The implications of these findings are extensive. They stress the pressing need for national and international policymakers to integrate groundwater suitability and potential into development plans for economic planning. Additionally, the study contributes to the body of existing literature by highlighting the benefits of portable, safe drinking water for economic planning. This study acknowledges its limitations, such as instruments and the ambiguity in interpreting geophysical data. Several factors, such as inadequate quality data, lack of technological expertise, poor drilled-hole development, and incorrect point selection. This are common on terrains associated with Basement Complex could be responsible for the area's high number of failed/aborted borehole cases. In summary, human survival depends on having access to clean water availability and its contamination will negatively impact human health, leading to anything from diseases to epidemics.

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Consent for publication

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Data shall be made available on demand.

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C.A. Nanfa onceptualized the study, designed methodology, analyzed data, and prepared the original draft; C.S. Dalom conducted field data acquisition and processing; O.G. Olaseni performed software-based data interpretation and map generation; M.B. Aminu contributed to geological interpretation and manuscript review; and O.I. Millicent assisted with field data and manuscript review.