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Delineation of aquifer potential zones using hydraulic parameters in Gombe and environs, North-Eastern, Nigeria

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A R T I C L E I N F O

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A B S T R A C T

This research is aimed at delineating the groundwater potential zones in Gombe and environs using Dar Zarrouk parameters. The study area is located within longitudes 11°7′0″E to 11°14′0″E, and latitudes 10°15′0″N to 10°21′0″N, it is basically underlain by basement Complex rocks represented by Diorite and Granites, and Cretaceous sedimentary rocks represented by Bima, Yolde, Fika and Gombe Formations. Thirty two (32) vertical electric soundings (VES) using Schlumberger array method with the aid of ABEM Signal Averaging System (SAS) Terrameter was used for the data acquisition. The result of the interpretation shows four to six geo-electric layers. The geo-electric section revealed the major aquifers to be confined and semi confined and consist of Medium grain sandstones, with varying thicknesses. The aquifer hydraulic characteristics indicated that the transverse resistance, ranges from 235.2Ωm^2 to 6317.87Ωm^2 with an average value of 1789.50Ωm^2. The Longitudinal conductance, S, ranges from 0.1415Ωm to 31.933Ωm with an average of 2.002Ωm. The Hydraulic conductivity value range from 2.62m/day to 138.66 m/day with a mean value of 20.662 m/day. The transmissivity values obtained for the various layers range from 78.34 m^2/day to 13284.02m^2/day, with the average value been 893.57 m^2/day. Four groundwater potential zones were delineated including medium grain sandstones, Sandstones, clayey sand and shaly sand.

1. Introduction

Increased demands for water by the world's fast-growing population have stimulated the need to identify and establish the source of safe drinking water. Groundwater is that water found within the saturated voids beneath the ground (Abdulrahman et al., 2017). The source of groundwater is chiefly from precipitating atmospheric moisture which has percolated down into the soil and subsoil layers (Kwami et al., 2018).

The availability, quantity, and exploitability of groundwater depend on the porosity and permeability of the host rocks. Both parameters play important roles in ground water movement and recovery. The porosity of a geologic material is the amount of water (fluid) the material can hold. It is the volume ratio of the pore spaces to the total volume of soil, rock or sediment (Obiora et al., 2015). Geophysical investigations provide a rapid and cost-effective means of acquiring information on subsurface hydrogeology (Helaly, 2017). The application of electrical resistivity survey method using vertical electrical sounding was applied for the purpose of this research. Vertical electrical sounding is a geo-electrical method commonly used to measure vertical alterations of electrical resistivity. This method has been recognized to be more suitable for a hydro-geological survey of sedimentary basins than the other resistivity methods (Chambers et al., 2013).

The Dar Zarrouk Parameters derived from primary parameters (layer resistivity, and thickness) surface geo-electric soundings have proven to be important in understanding the spatial distribution of aquifer hydraulic parameters. Maillet (1947) first introduced the concept of Dar Zarrouk parameters, when the thickness and resistivity of subsurface layer is known, its transverse resistance and longitudinal conductance can be estimated. Nwosu et al., 2014 derived analytical relations between aquifer transmissivity and transverse resistance. Also, Heigold et al.

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(1979) established the association of aquifer hydraulic conductivity with resistivity measurements.

2. Study area

The study area is located in Gombe State North eastern part of Nigeria, between longitudes 11°7′0″E to 11°14′0″E and latitudes 10°15′0″N to 10°21′0″N of the equator of the Greenwich meridian (Fig. 1). The topography of the area is generally hilly with some parts having elevations more than the other surroundings. The elevation of the study area ranges from about 400m to 600m above sea level and falls within the Upper Benue Basin. The outcrops generally consist of rocks which are made up of sandstones. Surface drainage systems in the study area comprises of numerous streams channels flowing in the direction of the river basin towards the southeast. The climatic condition in the study area is characterized by two seasons; a rainy season, which starts in May

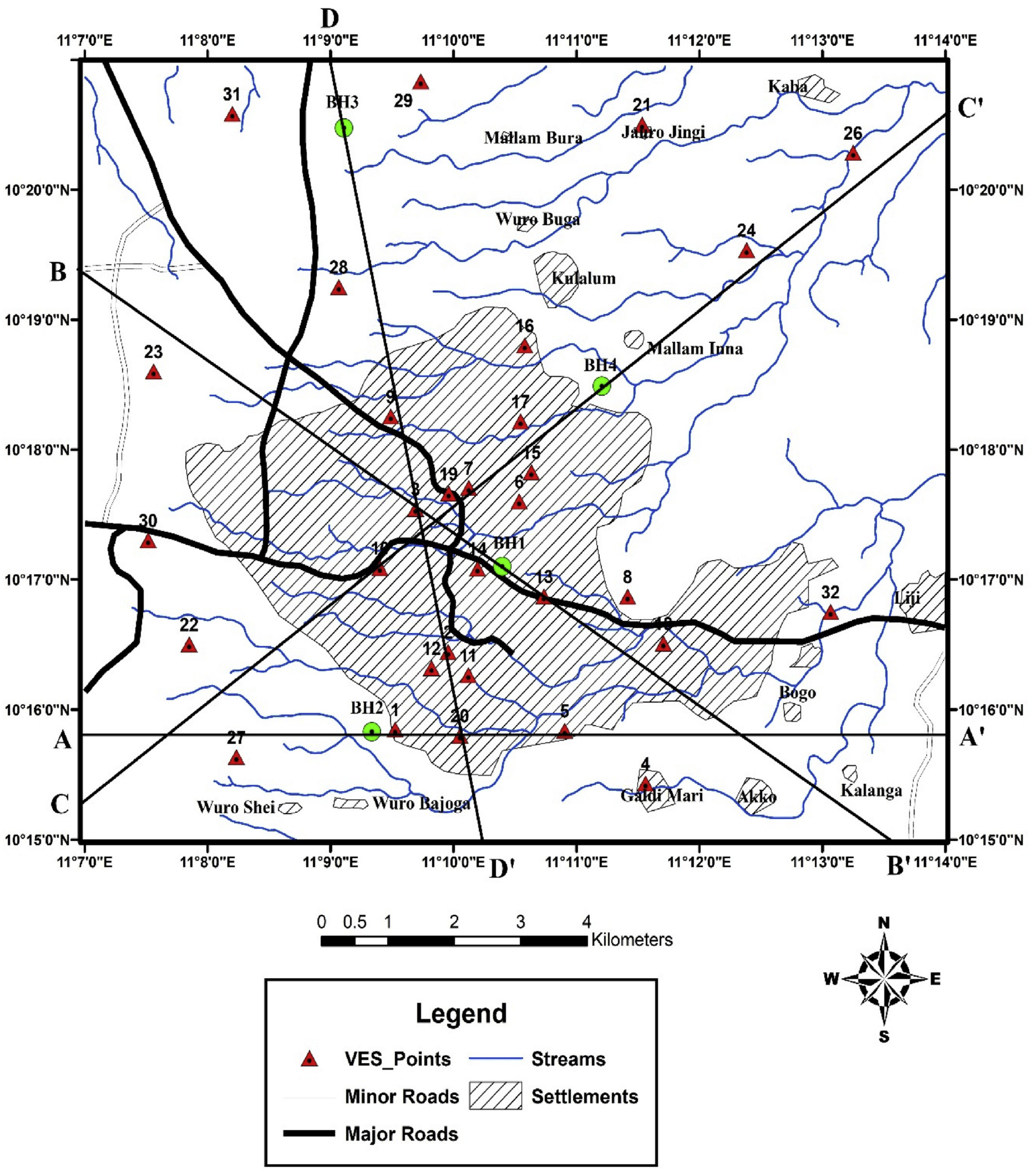

Fig. 1. Base map of the study area showing cross section of VES Points and Borehole points.

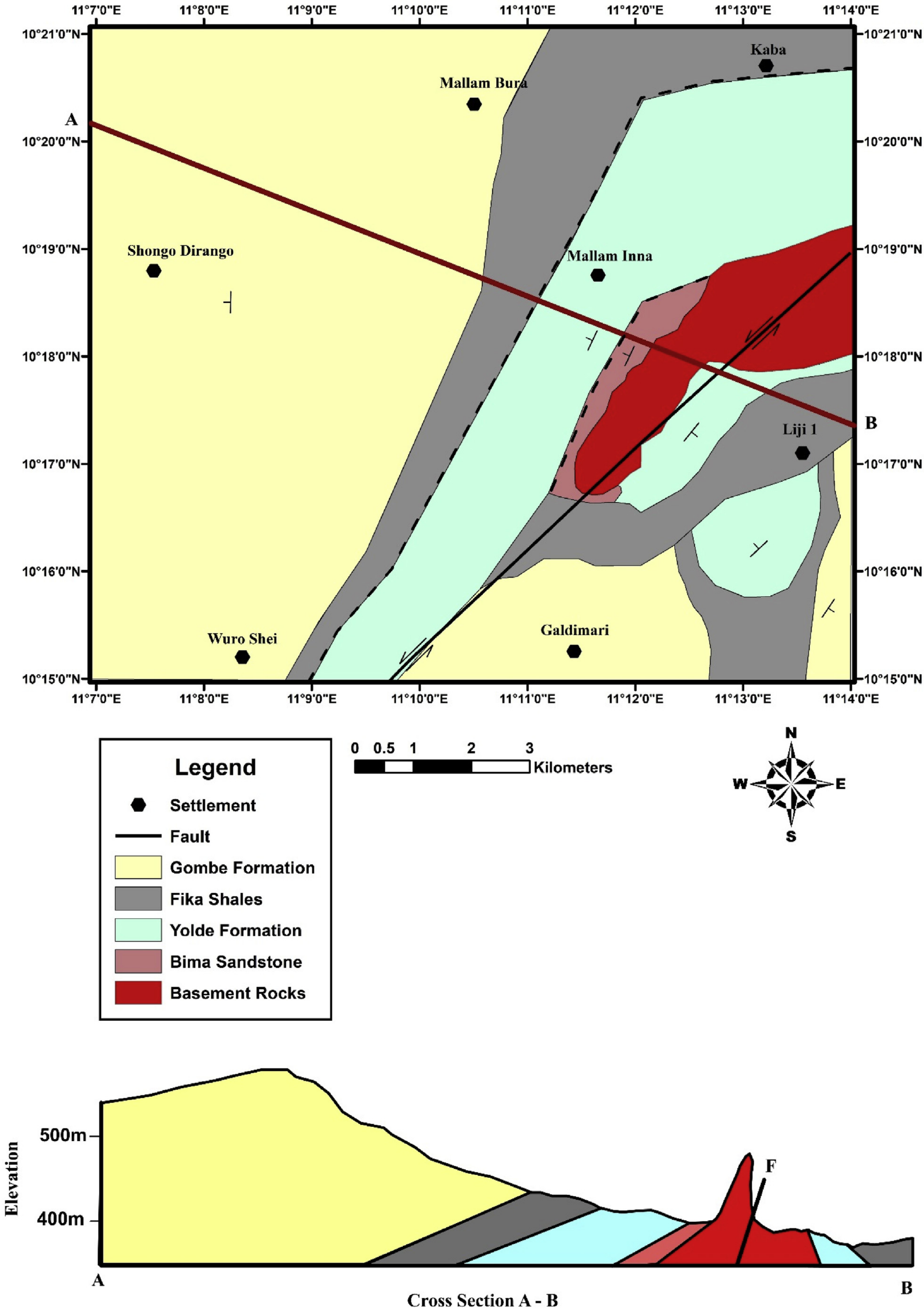

Fig. 2. Geologic map of the study area (modified from Zaborski et al., 1997).

Table 1
Geoelectric parameters, litholgic delineation and aquifer systems in the study area.

VES No.	Location	Coordinates & Elevations	Layer No.	Resistivity (ohm-m)	Thickness (m)	Inferred Lithology	Curve Type	Aquifer System
VES01	METTAKO	N10°15′50.7″ E 11°09′31.5″ ELEV. 477m	1	34.8	2.5	Clayey SandTop Soil	HKH	Medium Grained Sand
			2	14.0	14.0	Clay		
			3	70.9	34.7	Radish Brown Sand		
			4	27.3	20.2	Medium Grained Sand		
			5	64.5	…	Clay		
VES02	JAURO ABDUL PANTAMI	N10°16′26.5″ E 11°09′57.4″ ELEV. 462m	1	35.2	2.3	Clayey Sand Top Soil	KHK	Medium Grained Sand
			2	119.9	12.0	Radish Brown Sand		
			3	47.1	37.1	Sandy Shale		
			4	55.1	16.6	Medium Grained Sand Stone		
			5	242	…	Compacted Sand Stone		
VES03	JEKADAFARI JANKAI	N10°15′25.77″ E 11°09′41.5″ ELEV. 485m	1	8.0	10	Clayey Top Soil	QH	Silty Sand
			2	41.3	11.0	Clayey Sand		
			3	89.5	51.9	Silty Sand		
			4	47.3	…	Clay		
VES04	GALDIMARI AREA II	N10°15′25.77″ E 11°11′33.7″ ELEV. 432m	1	79.2	2.2	Sandy Top Soil	HKH	Silty Sand
			2	15.7	6.8	Clay		
			3	54.5	22.2	Sandy Clay		
			4	17.7	22.6	Silty San		
			5	21.4	…	Sand Stone		
VES05	BY PASS BARUNDE	N10°15′50.2″ E 11°10′52.4″ ELEV. 435m	1	32.4	2.9	Clayey SandTop Soil	HKH	Medium Grained Sand
			2	4.2	4.3	Clay		
			3	67.7	23.5	Radish Brown Sand		
			4	12.5	60.5	Medium Grained Sand		
			5	16.8	…	Clayey Sand		
VES06	AJIYA I	N10°17′35″ E 11°10′32″ ELEV. 450m	1	29.0	2.1	Clayey SandTop Soil	HKH	Medium Grained Sand Stone
			2	3.8	7.3	Clay		
			3	490.6	63.1	Silt/Dry Sand Stone Intercalation		
			4	59.9	19.3	Medium Grained Sand Stone		
			5	171.0	…	Sand Stone		
VES07	AJIYA II	N10°17′42.2″ E 11°10′7.4″ ELEV. 469m	1	11.0	12.8	Clayey Top Soil	QKH	Medium Grained Sand Stone
			2	53.7	10.0	Clayey Sand		
			3	93.5	36.4	Silty Sand		
			4	22.5	28.3	Medium Grained Sand Stone		
			5	42.5	…	Clay		
VES08	KASUWAN KATAKO	N10°16′52″ E 11°11′25″ ELEV. 432m	1	8.4	5.3	Clayey Top Soil	KQH	Medium Grained Sand Stone
			2	219.9	19.0	Compacted Sand Stone		
			3	37.1	28.9	Sand Stone		
			4	20.8	15.8	Medium Grained Sand Stone		
			5	38.1	…	Sandy Silt		
VES09	NEAR SPECIAL EDUCATION CENTRE	N10°18′15.2″ E 11°09′29.3″ ELEV. 505m	1	84.8	0.7	Lateritic Top Soil	HKH	Medium Grained Sand Stone
			2	39.6	2.3	Clayey Sand		
			3	114.1	7.2	Sand Stone		
			4	72.4	22.8	Medium Grained Sand Stone		
			5	131.3	…	Sand Stone		
VES10	NEAR TASHAN GONA	N10°17′05.2″ E 11°09′24.1″ ELEV. 491m	1	69.5	2.3	Sandy Top Soil	HKH	Medium Grained Sand Stone
			2	7.7	10.5	Clay		
			3	21.2	24.7	Clayey Sand		
			4	17.0	28.7	Medium Grained Sand Stone		
			5	23.7	…	Clay		
VES11	MALAMKURI	N10°16′15.8″ E 11°10′07.2″ ELEV. 459m	1	89.5	1.2	Sandy Top Soil	HKH	Medium Grained Sand Stone
			2	11.3	17.2	Clayey Sand.		
			3	106.4	31.8	Silty Sand		
			4	46.6	19.1	Medium Grained Sand Stone		
			5	104.0	…	Sand Stone		
VES12	GABUKKA PRI. SCH.	N10°16′19.05″ E 11°09′49.21″ ELEV. 468m	1	15.1	2.4	ClayeyTop Soil	HKH	Shaley Sand
			2	2.0	5.0	Clay		
			3	42.3	33.8	Clayey Sand		
			4	14.6	34.3	Shaley Sand		
			5	17.6	…	Clayey shale		
VES13	RAFINSANYI	N10°16′52.1″ E 11°10′44.1″ ELEV. 442m	1	80.7	4.6	Sandy Top Soil	QHA	Medium Grained Sand Stone
			2	15.7	9.5	Clay		
			3	10.4	18.7	Clayey Sand		
			4	20.2	13.8	Medium Grained Sand Stone		
			5	57.8	…	Clayey Sand		

(*continued on next page*)

Table 1 (*continued*)

VES No.	Location	Coordinates & Elevations	Layer No.	Resistivity (ohm-m)	Thickness (m)	Inferred Lithology	Curve Type	Aquifer System
VES14	KUMBIYA KUMBIYA	N10°17′04.93″ E 11°10′11.66″ ELEV. 458m	1	32.7	2.9	Clayey SandTop Soil	HKH	Medium Grained Sand Stone
			2	12.8	12.6	Clay		
			3	48.1	41.4	Shale Intercalation		
			4	18.6	24.4	Medium Grained Sand Stone		
			5	41.8	…	Sand Stone		
VES15	OPP. ALH. MANGA HOUSE	N10°17′49.5″ E 11°10′38.0″ ELEV. 442m	1	56.6	1.6	Sandy Top Soil	QQH	Shaley Sand
			2	11.2	38.9	Clay		
			3	10.6	14.8	Shale		
			4	8.0	29.4	Shaley Sand		
			5	23.2	…	Sandy Shale		
VES16	ARAWA	N10°18′48.0″ E 11°10′34.7″ ELEV. 442m	1	27.8	6.8	ClayeyTop Soil	HKH	Medium Grained Sand Stone
			2	17.4	14.7	Clay		
			3	64.7	42.3	Clayey silt		
			4	24.4	22.4	Medium Grained Sand Stone		
			5	54.8	…	Sand Stone		
VES17	GSU ZOO	N10°18′12.93″ E 11°10′32.72″ ELEV. 444m	1	91.0	5.9	Sandy Top Soil	HKH	Medium Grained Sand Stone
			2	29.2	8.1	Clayey Sand		
			3	215.9	22.8	Compacted Sand Stone		
			4	39.0	35.0	Medium Grained Sand Stone		
			5	62.6	…	Sand Stone		
VES18	YALANGURUZA	N10°16′30.45″ E 11°11′42.39″ ELEV. 417m	1	31.8	1.3	Top Soil, Sandy Clay	HKH	Sandstone
			2	3.7	16.1	Clay		
			3	177.6	107.5	Sandy Clay Intercalation		
			4	16.5	24.2	Shale		
			5	36.1	…	Sandstone		
VES19	NEAR UBAN DOMA HOUSE	N10°17′39.55″ E 11°09′57.62″ ELEV. 472m	1	20.0	5.8	ClayeyTop Soil	HKH	Silty Sand
			2	5.3	10.6	Clay		
			3	154.3	56.8	Sandy Clay		
			4	23.8	18.1	Silty Sand		
			5	59.3	…	Sand tone		
VES20	BAGADAZA	N10°15′47.9″ E 11°10′3.1″ ELEV. 472m	1	82.3	1.4	Sandy Top Soil	HKH	Medium Grained Sand
			2	13.5	5.5	Clay		
			3	192.1	28.4	Reddish Brown Sand		
			4	36.6	25.6	Medium Grained Sand		
			5	76.2	…	Clay		
VES21	JAURO JINGI	N10°20′30″ E 11°11′32″ ELEV. 465m	1	40.1	3	ClayeyTop Soil	HKH	Shaley sand
			2	8.4	5.3	Clay		
			3	78.8	25.3	Silt Stone		
			4	18.2	37.9	Shaley sand		
			5	17	…	Shale		
VES22	NAYINAWA	N10°16′30″ E 11°07′51″ ELEV. 483m	1	241	1.4	Sandy Top Soil	HKHA	Sandstone
			2	34.6	2.8	Clayey Sand		
			3	300.9	11.7	Compacted Sand Stone		
			4	36	27.6	Shale.		
			5	60.9	57.9	Sand Stone intercalation.		
			6	71.6	…	Sand Stone		
VES23	NEW GRA	N10°18′36″ E 11°07′33.6″ ELEV. 508m	1	231.7	1.5	Lateritic Sand Top Soil	HKH	Sandstone
			2	45.3	28.0	Sandy Clay		
			3	233.4	75.2	Sand, Silt Stoneintercalation		
			4	61.6	18.7	Sand Stone		
			5	134.4	…	Sand Stone		
VES24	NEAR RUNDE	N10°19′32″ E 11°12′23″ ELEV. 438m	1	227.4	6.3	Sandy Top Soil	HKH	Silty Sand
			2	114.4	17.8	Radish Brown Sand		
			3	152.6	19.7	Sandy Clay		
			4	132.6	27.4	Silty Sand		
			5	212.0	…	Sand Stone		
VES25	LIJI	N10°17′2″ E 11°30′52″ ELEV. 390m	1	173.9	9.1	Sandy Top Soil	HA	Silty Sand
			2	54.7	23.5	Clayey Sand		
			3	111.8	39.1	Silty Sand		
			4	208	…	Sand Stone		
VES26	KABA	N10°20′17″ E 11°13′15″ ELEV. 463m	1	36.7	4.9	Clayey Sand Top Soil	HKH	Medium Grained Sand Stone
			2	2.0	9.3	Clay		
			3	352.0	93	Compacted Sand Stone		
			4	46.3	25.6	Medium Grained Sand Stone		
			5	128.3	…	Sand Stone		
VES27	TUMPURE BASHAR	N10°15′38″ E 11°08′14″ ELEV. 504m	1	521.0	7.1	Top Soil Laterite	HKQH	Sandstone
			2	197.8	19.5	Lateritic Sand		
			3	475.5	80.3	Compacted Sand Stone		
			4	423.2	50.3	Compacted Sand Stone		
			5	211.3	29.9	Sand Stone intercalation.		

(*continued on next page*)

Table 1 (*continued*)

VES No.	Location	Coordinates & Elevations	Layer No.	Resistivity (ohm-m)	Thickness (m)	Inferred Lithology	Curve Type	Aquifer System
			6	378.5	…	Compacted Sand Stone		
VES28	ZAGAINA	N10°19′15″ E 11°09′04″ ELEV. 502m	1	292.3	1.7	Sandy Top Soil	HKH	Sandstone
			2	95.1	8.2	Sandy Clay		
			3	280.2	38.5	Compacted Sand Stone		
			4	119.6	22.5	Sand Stone		
			5	270.8	…	CompactedSand Stone		
VES29	ALKAHIRA	N10°20′50″ E 11°09′44″ ELEV. 478m	1	384.8	3.2	Top Soil Laterite	HKH	Sandstone
			2	152.6	9.0	Sandy Clay		
			3	765.6	35.8	Loose Sand		
			4	105.2	54.3	Sand Stone		
			5	294.0	…	Compacted Sand Stone		
VES30	LEGISLATIVE QTRS	N10°17′18″ E 11°07′31″ ELEV. 596m	1	530.6	3.9	Top Soil Laterite	HKQH	Silty Sand
			2	172.3	12.1	Lateritic Sand		
			3	631.6	38.9	Loose Sand		
			4	211.5	39.7	Sand Stone		
			5	84.4	58.8	Silty Sand		
			6	186.2	…	Shale		
VES31	BEHIND GRAVE YARD	N10°20′35″ E 11°08′12″ ELEV. 481m	1	316.2	14.6	Top Soil Laterite	AKQH	Medium Grained Sand Stone
			2	504.0	10.1	Compacted Lateritic Sand		
			3	947.2	30.5	Loose Sand		
			4	279.8	41.8	Sand Stone intercalation.		
			5	75.7	68.3	Medium Grained Sand Stone		
			6	253.0		Sand Stone		
VES32	NASARAWO	N10°16′45″ E 11°13′04″ ELEV. 395m	1	26.3	1.3	Clayey Top Soil	HKQH	Shaley sand
			2	4.7	4.4	Clay		
			3	100.1	14.9	Sandy Clay		
			4	16.7	17.9	Sandy Shale.		
			5	3.0	95.8	Shaley Sand		
			6	10.7	…	Shale		

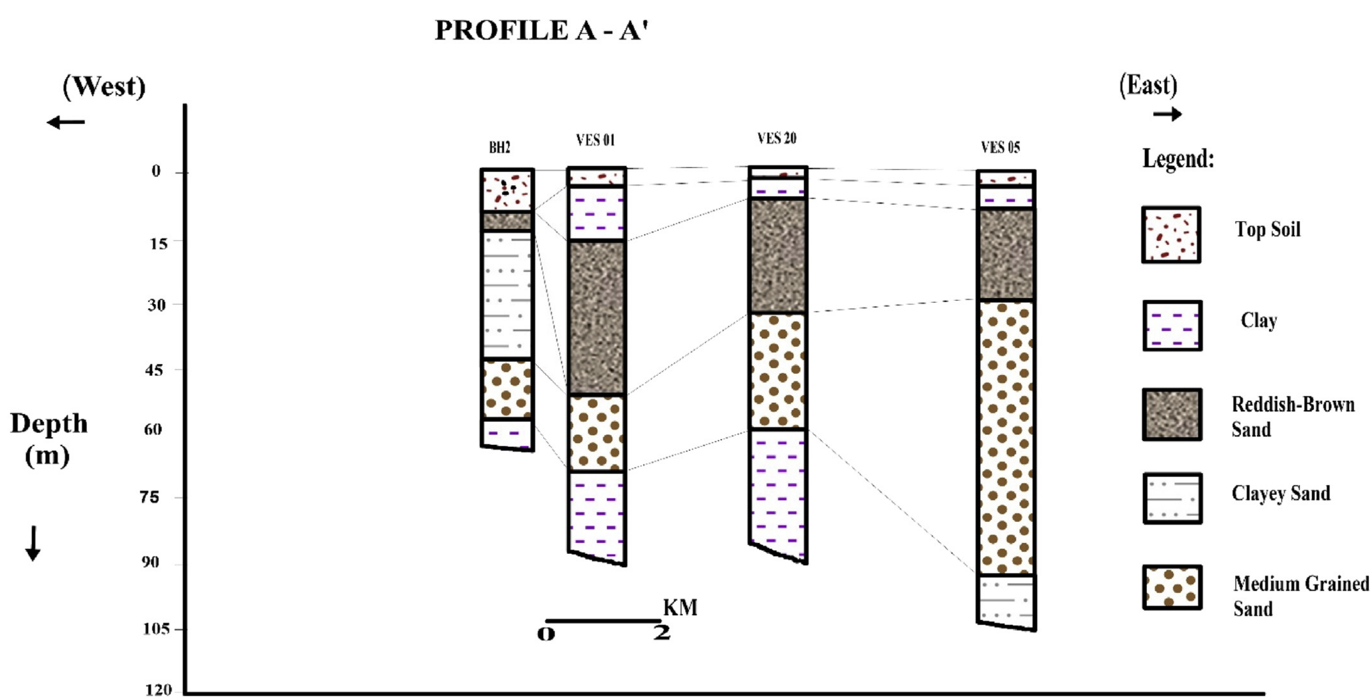

Fig. 3. Cross section along Profile A-A′.

and ends in October and the dry season, which normally spans between October and April. Most of the streams are seasonal overflowing their banks during rainy season. The rainy season is the period when tropical maritime air mass travels northwards over the study area from the Gulf of Guinea.

The mean annual rainfall is 1015mm for Gombe where the study area is situated while the dry season is characterized by an arid wind or tropical continental air mass originating from the Sahara Desert. During the period, there is little cloud cover and the temperature ranges from 14 °C–32 °C. The study area is mainly classified as a Sudan savannah region, which is characterized by grasses, shrubs and trees with large trunks. The grasses dry and trees shade off their leaves during dry season and flourish again when wet season returns.

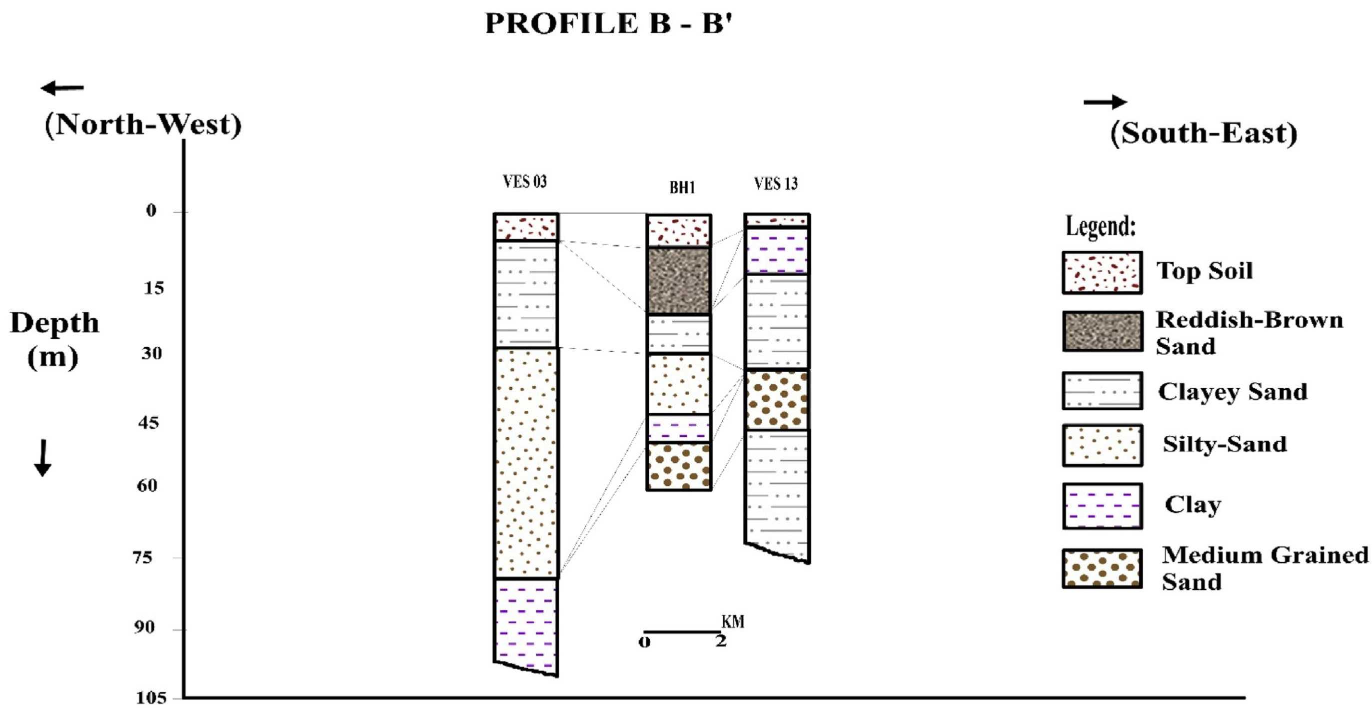

Fig. 4. Cross section along Profile B–B′.

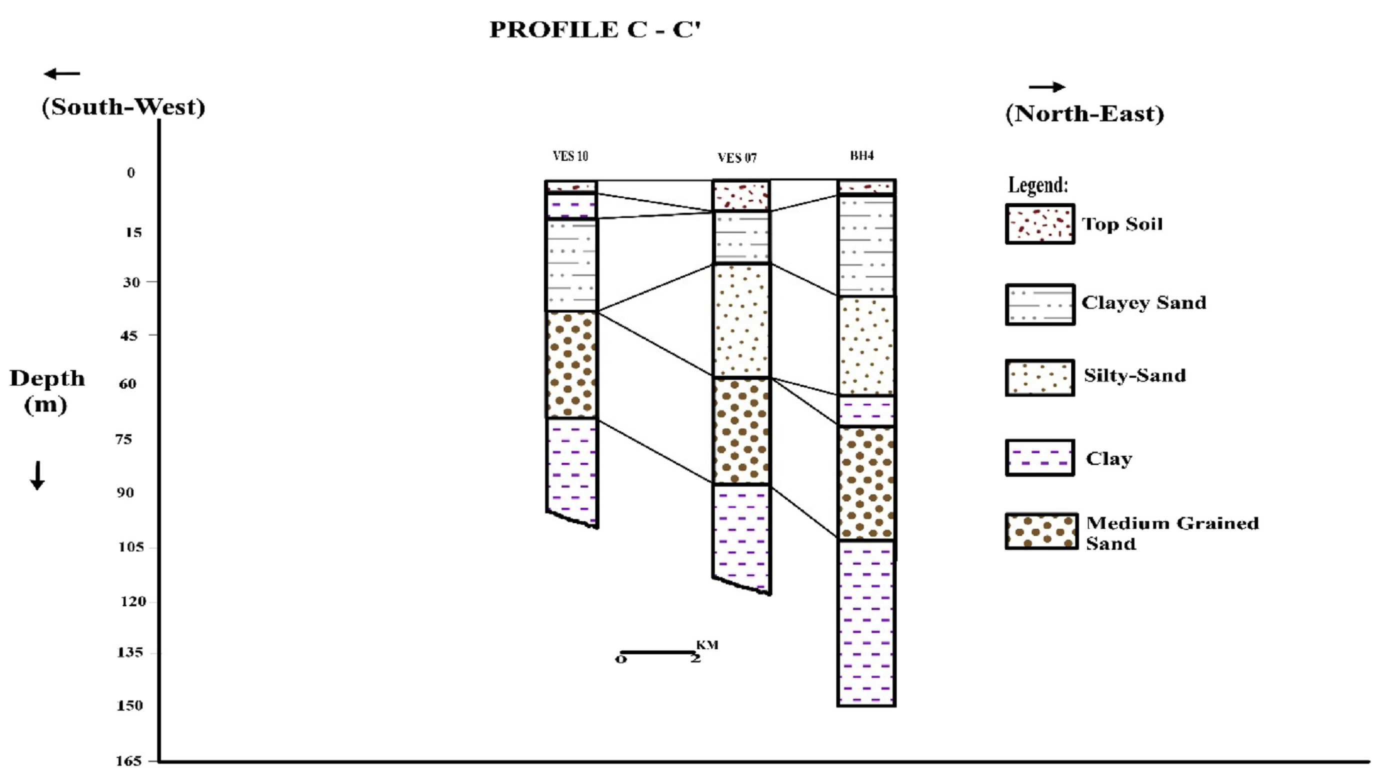

Fig. 5. Cross section along Profile C–C′.

2.1. Geology of the research area

The study area is underlain by Pre Cambrian Basement Complex rocks and Cretaceous sediments. The basement Complex rocks are represented by Diorite and Granites while the Cretaceous sediments are represented by Bima, Yolde, Fika and Gombe Formations (Fig. 2). Studies indicate that the rocks in the area were subjected to a wide range of tectonic disturbances involving Faulting. The orientation of the fault is mainly trending NW-SE.

The cross section A-B (Fig. 2) indicates (in younging order), the area constituted Basement rocks, Bima Formations, Yolde Formation, Fika Shales and Gombe Formation.

The Bima Sandstone, a continental Formation, is the basal part of the sedimentary successions in the study area. It lies unconformably on the

Table 2
Aquifer parameters of the study area (Dar-zarrouk parameter).

VES No	Locations	Layer Resistivity	Layer Thickness	Aquifer Conductivity	Longitudinal Conductance	Transverse Resistance	Hydraulic Conductivity (m/day)	Transmissivity (m^2/day)
1	METTAKO	27.3	20.2	0.036630037	0.73992674	551.46	17.67427124	357.0202791
2	JAURO ABDUL PANTAMI	27.3	20.2	0.036630037	0.73992674	551.46	17.67427124	357.0202791
3	JEKADAFARI JANKAI	55.1	16.6	0.01814882	0.301270417	914.66	9.17991525	152.3865932
4	GALDIMARI AREA II	89.5	51.9	0.011173184	0.579888268	4645.05	5.838725201	303.0298379
5	BY PASS BARUNDE	17.7	22.6	0.056497175	1.276836158	400.02	26.47830715	598.4097416
6	AJIYA I	12.5	60.5	0.08	4.84	756.25	36.62743871	2215.960042
7	AJIYA II	59.9	19.3	0.016694491	0.322203673	1156.07	8.491805826	163.8918524
8	KASUWAN KATAKO	22.5	28.3	0.044444444	1.257777778	636.75	21.16804253	599.0556035
9	NEAR SPECIAL EDUCATION CENTRE	20.8	15.8	0.048076923	0.759615385	328.64	22.77760708	359.8861919
10	NEAR TASHSN GONA	17	28.7	0.058823529	1.688235294	487.9	27.49396974	789.0769317
11	MALAMKURI	46.6	19.1	0.021459227	0.409871245	890.06	10.73289012	204.9982012
12	GABUKKA PRI. SCH.	14.6	34.3	0.068493151	2.349315068	500.78	31.68727805	1086.895932
13	RAFINSANYI	20.2	13.8	0.04950495	0.683168317	278.76	23.40810192	323.0318065
14	KUMBIYA KUMBIYA	18.6	24.4	0.053763441	1.311827957	453.84	25.281181	616.8608164
15	OPP. ALH. MANGA HOUSE	8	29.4	0.125	3.675	235.2	55.54023144	1632.882804
16	ARAWA	24.4	22.4	0.040983607	0.918032787	546.56	19.62629245	439.628951
17	GSU ZOO	39	35	0.025641026	0.897435897	1365	12.67197538	443.5191382
18	YALANGURUZA	16.5	24.2	0.060606061	1.466666667	399.3	28.27037505	684.1430761
19	NEAR UBAN DOMA HOUSE	23.8	18.1	0.042016807	0.760504202	430.78	20.08745121	363.5828669
20	BAGADAZA	36.6	25.6	0.027322404	0.699453552	936.96	13.44544117	344.203294
21	Jauro Jingi	18.2	37.9	0.054945055	2.082417582	689.78	25.79911004	977.7862705
22	Nayi Nawa	60.9	57.9	0.016420361	0.950738916	3526.11	8.361661237	484.1401856
23	New GRA	61.6	18.7	0.016233766	0.303571429	1151.92	8.272990812	154.7049282
24	Near Runde	132.6	27.4	0.007541478	0.206636501	3633.24	4.046363013	110.8703465
25	Liji	111.8	39.1	0.008944544	0.349731664	4371.38	4.744485789	185.5093943
26	Kaba	46.3	25.6	0.021598272	0.552915767	1185.28	10.79774836	276.4223579
27	Tunfure bashar	211.3	29.9	0.004732608	0.141504969	6317.87	2.619998966	78.33796908
28	Zagaina	119.6	22.5	0.008361204	0.18812709	2691	4.455199349	100.2419854
29	Alkahira	105.2	54.3	0.009505703	0.516159696	5712.36	5.021577563	272.6716617
30	Legislative Quarters	84.4	58.8	0.011848341	0.696682464	4962.72	6.16718666	362.6305756
31	Behind Grave Yard	75.7	68.3	0.01321004	0.902245707	5170.31	6.825902938	466.2091707
32	Nasarawo	3	95.8	0.333333333	31.93333333	287.4	138.6641193	13284.02263
	MIN	**3**	**13.8**	**0.004732608**	**0.141504969**	**235.2**	**2.619998966**	**78.33796908**
	MAX	**211.3**	**95.8**	**0.333333333**	**31.93333333**	**6317.87**	**138.6641193**	**13284.02263**
	AVERAGE	**50.890625**	**33.33125**	**0.044643251**	**2.015656914**	**1755.152188**	**20.62289268**	**899.6572411**

Precambrian Basement Complex. It ranges in age from Upper Aptian to Lower Albian (Allix et al., 1981). The sediments consist of poorly sorted, angular, highly arkosic pebbly sandstones, granulestones and pebble conglomerates (Zaborski et al., 1997). The Yolde Formation is indeed a transitional sequence between continental Bima Formation and the marine deposits of the lower part of Pindiga Formation (Fika Shales). The lower portion of Yolde Formation consists of sandstone-mudstone whereas the upper portion represents thinly and regularly bedded bioturbated sandstones. The exposure of Fika shales mostly revealed shaly mudstones. Dark grey when fresh but weathered to lighter blue-green to grey colour. Gombe Formation consists of pebbly coarse grained sandstone with indistinct cross bedding. In the lower part the sandstones are fine to medium grained and generally show tabular cross bedding which is highlighted by layers and streaks of white sandstone.

3. Materials and methods

3.1. Resistivity sounding

A total of 32 vertical electrical soundings were carried out (Fig. 1). The electrode configuration used for the work was Schlumberger array. Field data acquisition was carried out rapidly since it requires mainly the movement (adjustment) of the current electrodes. Electrodes were laid out with non-conducting measuring tapes. The field procedure consists of expanding the current electrodes ‘AB’ while keeping the potential electrodes ‘MN’ relatively fixed. For each reading, the current was sent into the ground through A and B which setup the measured potential difference between the potential electrodes M and N, the magnitude of the potential difference developed is a measure of the electrical resistance between probes. The resistance is in turn a function of the geometrical configuration of the electrodes and the electrical parameters of the ground (Dobrin, 1976). The electrode separation (AB/2) is varied from 1 to 300 m. The SAS 4000 Terrameter was positioned half way between the potential electrodes M and N, and was connected to terminals P1 and P2 and to terminals M and N. The current electrodes A and B was connected to terminals C1 and C2 respectively, these cables were run in parallel adjacent to the SAS 4000 Terrameter and was arranged symmetrically with respect to the potential electrodes.

3.2. Hydraulic parameters

The term "Dar Zarrouk" was introduced into the literature on electrical prospecting by Maillet (1947) for describing a relationship between the longitudinal unit conductance (Eq. 1) and transverse resistance (Eq. 2)

$$Si = hi/pi \tag{1}$$

And the transverse unit resistance,

$$Ti = hipi \tag{2}$$

Where ρi and hi are the electrical resistivity and thickness of the ith layer, respectively.

DZ (Dar Zarrouk) curve for an n-layer section is a plot of the DZ

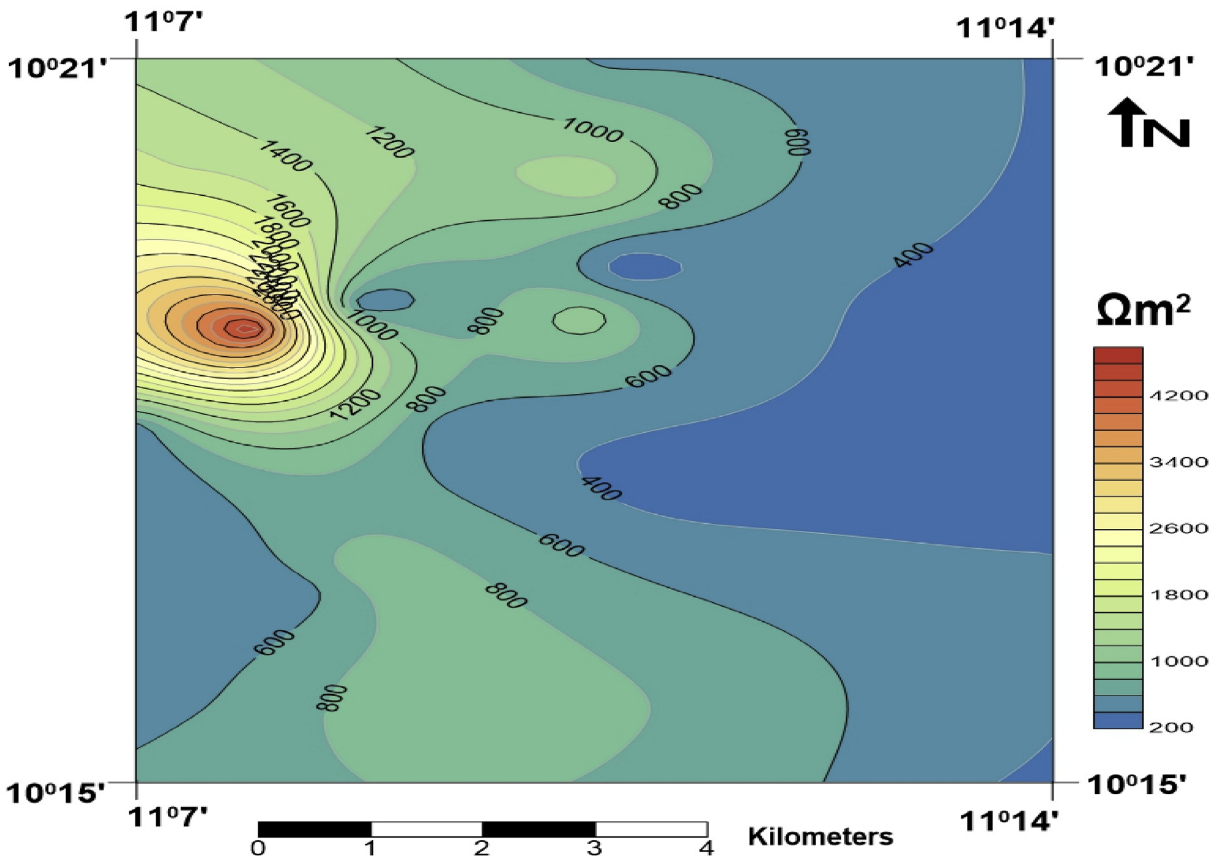

Fig. 6. Map of the study area showing variation in Transverse resistance.

Table 3
Rating of protective Capacity of Aquifers (After Oladapo and Akintorinwa 2007).

Longitudinal Conductance (Ω^{-1})	Protective Capacity Rating
>10	Excellence
5–10	Very good
0.7–4.9	Good
0.2–0.69	Moderate
0.1–0.19	Weak
0.1	Poor

resistivity.

$$\boldsymbol{Pmj} = \sqrt{\sum_{i=1}^{j} Ti \Big/ \sum_{i=1}^{j} Si} \tag{3}$$

Against the DZ depth

$$\boldsymbol{Lmj} = \sqrt{\sum_{i=1}^{j} Ti \sum_{i=1}^{j} Si} \tag{4}$$

An *n*-layer DZ curve is composed of n branches, each of which terminates at a point whose coordinates, Lm and pm, represent the thickness and resistivity of a fictitious layer that replaces all the overlying layers. According to Eqs. (3) and (4), the coordinates of any given point on a DZ curve are a function of the thicknesses and resistivities of layers that exist above a given depth, D, but they are not related to the thicknesses and resistivities of layers beneath that depth. In contrast, on a VES (vertical electrical sounding) curve, the coordinates of a given point are calculated from an integral expression (Stefanesco et al., 1930) that involves all the thicknesses and resistivities in the section, and, therefore, they are not related to a particular depth.

The longitudinal conductance (S) is a measure of the impermeability of a rock layer (Billing, 1972). Electrical anisotropy is a measure of stratified rock which is generally more conductive in the parallel plane than in the perpendicular plane (Malick et al., 1973; Cihan et al., 2014). For a sequence of horizontal, homogeneous and isotropic layers of resistivity $e1$ and thickness hi. Eqs. (5) and (6) defined the Dar Zarrouk parameters (longitudinal conductance S and transverse resistance TR) as follows:

$$S = h_1/e_i + h_2/e_2 + h_3/e_3 + \ldots\ldots h_n/e_n = \sum_{i=0}^{n} hi/ei \tag{5}$$

$$T_R = e_1h_1 + e_2h_2 + \ldots\ldots e_2h_2 = \sum_{i=0}^{n} eihi \tag{6}$$

Eq. (7) shows the relationship between aquifer transmissivity, and longitudinal conductance as proposed by Todd (1980).

$$Tr = K\delta R = Kh \tag{7}$$

Where Tr = Aquifer Transmissivity, K = Hydraulic Conductivity, σ = Electrical Conductivity (reciprocal of resistivity), R = Traverse Resistance, S = Longitudinal Conductance and h = Aquifer Thickness.

The Hydraulic conductivity K was determined using Eq. (8) as given by Heigold et al. (1979).

$$K = 386.40R_{rw}^{-0.93283} \tag{8}$$

Where, K is the hydraulic conductivity and R_{rw} is the aquifer resistivity (Resistivity of the inferred aquiferous layer from the interpreted curves).

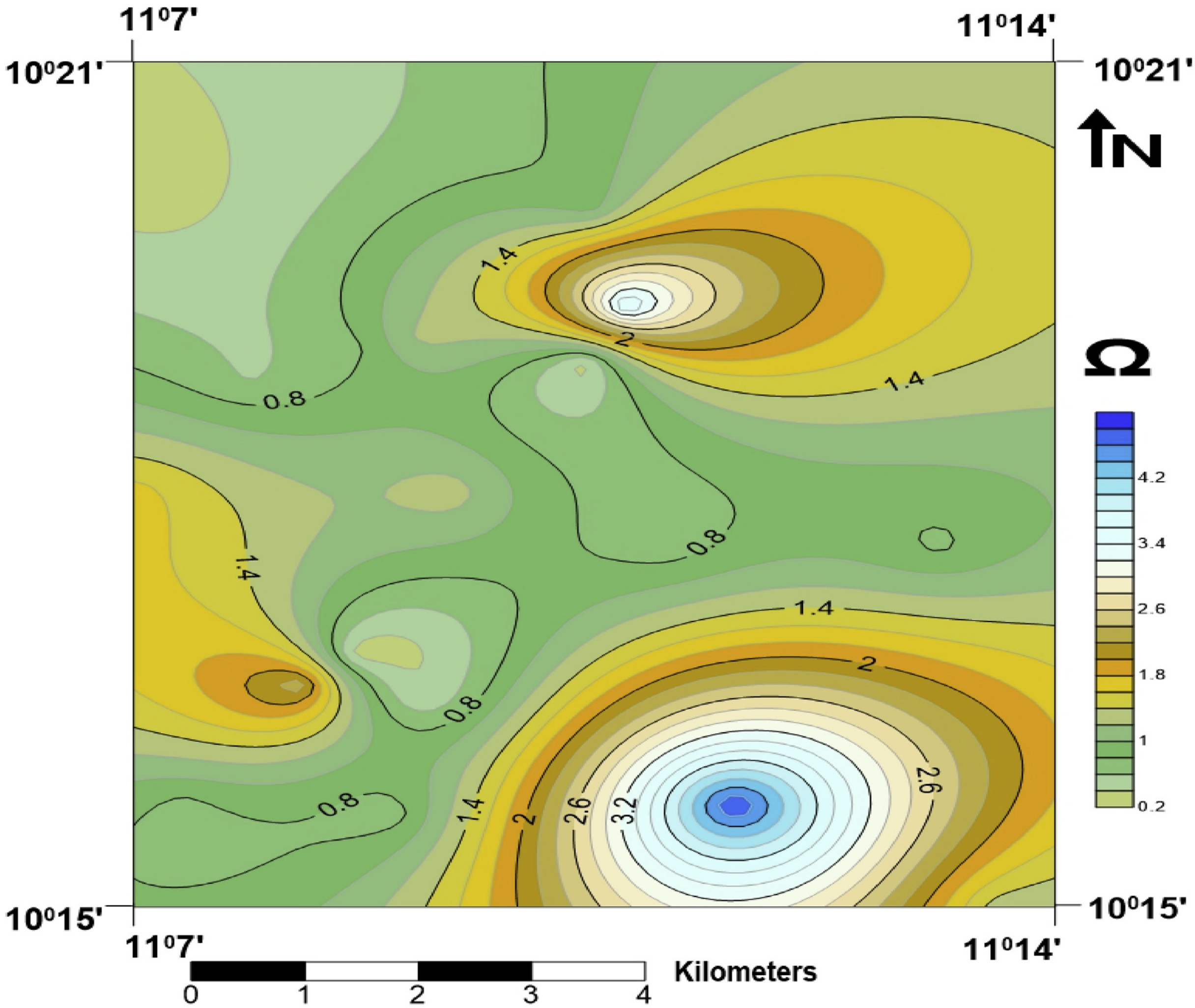

Fig. 7. Map of the study area showing variation of aquifer protective capacity.

4. Result and discussion

Geo-electric parameters are interpreted from geophysical (electrical) resistivity survey data. Interpretations of vertical electrical sounding data using WIN-Resist2 software lead to the generation of geo-electrical layers. The information from these geo-electric layers enhances the identification and interpretation of layer parameters which includes number of layers and their apparent resistivities, thicknesses, depth, curve type and aquifer systems (Table 1).

About11 curve types were identified in the study area (Table 1). Ground water is known to accumulate in the interconnected pores spaces within the Lithologic units. The shape of the VES curves (Appendix I) depends on the thickness of each layer, the number of layers in the subsurface and the ratio of the resistivity of the layer. The geo-electric characteristics give the respective layer resistivity values and thickness. The section gives a maximum of 9 layers with varying resistivity and thicknesses across each VES point. The first layer (Top soil) which composed of soil, loose sand and clay has resistivities ranges from 8 Ωm to 530.6 Ωm, and thickness varying from 0.7m to 14.6m. The second layer is composed of clay, clayey sand and sand silt intercalation in some places. This layer is characterized with resistivity values varying from 2Ωm to 504Ωm with thickness varying between 2.3m to 38.9m, the third layer which composed of clay sandstone intercalation, sandy clay, sandy silt and medium grained sandstones in some areas is characterized by resistivity values ranging between 10.4 Ωm to 947.2Ωm and thickness between 7.2m to 107.2m.

The fourth layer consists of Silty Sand and mostly medium grain sandstone with resistivity values ranging from 8 Ωm to 423.2Ωm and thickness ranging from 13.8m to 60.5m whereas the fifth layer consist of also clay and mostly sandstones characterized with resistivity values from 3 Ωm to 394 Ωm and thickness 29.9m–95.8m, also the sixth layer which is mostly clay has resistivity ranging from 10.7 Ωm to 378.5 Ωm.

The aquifer system comprises mostly of Medium grain sandstone accounting for about 16 VES locations, Sandstone 6 VES, Shaly and 4 VES points, and Silty Sand 6 VES points. This is inferred due to the high porosity and permeability characteristics of these Lithologic Formations attributed to their resistivity values.

4.1. Delineation of aquifer systems

A cross section of 3 bore holes with some VES points in the study area were used to correlate the borehole lithologic sections with the inferred lithologies observed from the Vertical Electrical Sounding interpretations (Fig. 1, above).

The profile A-A' (Fig. 3) along East-West trends of the study area encountered 1 borehole (BH2) and 3 VES points (VES01, VES20 and VES05). The Lithologic log of the bore hole was correlated with the geoelectric sections, the aquiferous layer (medium grain sandstone) show thickness ranging from 20.2m to 60m with an average of 32.2m (Fig. 3). The second layer of the borehole lithologic section (reddish-brown sand) with thickness of about 4m appear in the sections of VES01 and VES20 and VES05 as third layer with 34.7m, 28.4m and 23.5m thickness

Table 4
Protective capacity rating of aquifers in the study area using Oladapo and Akintorinwa 2007 rating.

VES No.	VES locations	Longitudinal conductance	Protective capacity rating
1	METTAKO	0.73992674	Good
2	JAURO ABDUL PANTAMI	0.301270417	Moderate
3	JEKADAFARI JANKAI	0.579888268	Moderate
4	GALDIMARI AREA II	1.276836158	Good
5	BY PASS BARUNDE	4.84	Good
6	AJIYA I	0.322203673	Moderate
7	AJIYA II	1.257777778	Good
8	KASUWAN KATAKO	0.759615385	Good
9	NEAR SPECIAL EDUCATION CENTRE	0.314917127	Moderate
10	NEAR TASHSN GONA	1.688235294	Good
11	MALAMKURI	0.409871245	Moderate
12	GABUKKA PRI. SCH.	2.349315068	Good
13	RAFINSANYI	0.683168317	Moderate
14	KUMBIYA KUMBIYA	1.311827957	Good
15	OPP. ALH. MANGA HOUSE	3.675	Good
16	ARAWA	0.918032787	Good
17	GSU ZOO	0.897435897	Good
18	YALANGURUZA	1.466666667	Good
19	NEAR UBAN DOMA HOUSE	0.760504202	Good
20	BAGADAZA	0.699453552	Moderate
21	JAURO JINGI	2.082417582	Good
22	NAYI NAWA	0.950738916	Good
23	NEW GRA	0.303571429	Moderate
24	NEAR RUNDE	0.206636501	Moderate
25	LIJI	0.349731664	Moderate
26	KABA	0.552915767	Moderate
27	TUNFURE BASHAR	0.141504969	Weak
28	ZAGAINA	0.18812709	Weak
29	ALKAHIRA	0.516159696	Moderate
30	LEGISLATIVE QUARTERS	0.696682464	Moderate
31	BEHIND GRAVE YARD	0.902245707	Good
32	NASARAWO	31.93333333	Excellent

Table 5
Inferred aquifer potential rating using Transmissivity values.

VES Locations	Transmissivity	Aquifer Potentials
METTAKO	357.0202791	Moderate Potential
JAURO ABDUL PANTAMI	152.3865932	Moderate Potential
JEKADAFARI JANKAI	303.0298379	Moderate Potential
GALDIMARI AREA II	598.4097416	High Potentials
BY PASS BARUNDE	2215.960042	High Potentials
AJIYA I	163.8918524	Moderate Potential
AJIYA II	599.0556035	High Potentials
KASUWAN KATAKO	359.8861919	Moderate Potential
NEAR SPECIAL EDUCATION CENTRE	162.2377961	Moderate Potential
NEAR TASHSN GONA	789.0769317	High Potentials
MALAMKURI	204.9982012	Moderate Potential
GABUKKA PRI. SCH.	1086.895932	High Potentials
RAFINSANYI	323.0318065	Moderate Potential
KUMBIYA KUMBIYA	616.8608164	High Potentials
OPP. ALH. MANGA HOUSE	1632.882804	High Potentials
ARAWA	439.628951	Moderate Potential
GSU ZOO	443.5191382	Moderate Potential
YALANGURUZA	684.1430761	High Potentials
NEAR UBAN DOMA HOUSE	363.5828669	Moderate Potential
BAGADAZA	344.203294	Moderate Potential
JAURO JINGI	977.7862705	High Potentials
NAYI NAWA	484.1401856	Moderate Potential
NEW GRA	154.7049282	Moderate Potential
NEAR RUNDE	110.8703465	Moderate Potential
LIJI	185.5093943	Moderate Potential
KABA	276.4223579	Moderate Potential
TUNFURE BASHAR	78.33796908	Moderate Potential
ZAGAINA	100.2419854	Moderate Potential
ALKAHIRA	272.6716617	Moderate Potential
LEGISLATIVE QUARTERS	362.6305756	Moderate Potential
BEHIND GRAVE YARD	466.2091707	Moderate Potential
NASARAWO	13284.02263	High Potentials

Table 6
Aquifer classification based on Transmissivity values (Offodile, 1983).

Transmissivity (m^2/day)	Classification of well
>500	High Potentials
50–500	Moderate Potential
5–50	Low Potential
0.5–5	Very low Potential
<0.5	Negligible potential

respectively. The third layer in the borehole lithologic section (Clayey Sand) with 30m thickness did not appear in all the VES points on the cross section. The 5th layer in the borehole lithologic section (Clay) has thickness of 10m and appear in VES01 and VES20 as the 5th layer. Clayey sand only appeared in VES05 as 5th layer. The aquifer system delineated is semi confined to confined and have thickness ranging from 20.2m to 60m with an average of 32.2m.

The profile B–B' (Fig. 4) along NW-SE trends of the study area encountered 1 borehole (BH1) and 2 VES points (VES03 and VES13). The Lithologic section of the borehole was correlated with the geoelectric sections, the aquiferous layer (medium grain sandstone) show thickness ranging from 10m to 51.9m, with an average of 25.2m (Fig. 4). The second layer of the borehole lithologic section (reddish-brown sand) with thickness of about 4m did not appear in geoelectric sections.

The third layer in the borehole lithologic section (Clayey Sand) with 10m thickness appeared as second layer in section of VES03 and 3rd layer in section of VES13 with thickness of 11m and 18.7m respectively. The 4th layer in VES 03 (Silty sand) with thickness of 51.9m did not appear in both VES13 and the lithologic section. The 5th layer in the borehole lithologic section (clay) with 7m thick did appear as 4th layer in section of VES03. The aquifer system delineated is semi confined to confined with thickness ranging from 10m to 51.9m, with an average of 25.2m.

The profile C–C' (Fig. 5) along SW-NE trends of the study area encountered 2 VES points (VES10 and VES07) and 1 borehole (BH4) and the lithologic section was correlated with the geo-electric sections, the aquiferous layer (medium grain sand) show thickness ranging from 28.3m to 30m with an average of 29m (Fig. 5). The second layer of the borehole lithologic section (Clayey sand) with thickness of about 27m appear also as a second layer in VES07 and third layer in VES 10 geo-electric sections with thickness of 10m and 24.7m respectively. Clay appear as second layer in VES10 with 10.5m thickness. The third layer in the borehole lithologic section (Silty Sand) with thickness of 27m appeared as a third layer in VES07 with thickness of 36.4. The 4th layer (clay) with 10m thickness did not appear in the geoelectric sections. Whereas the last layer in the bore hole (clay) did appear in both the VES10 and VES07. The aquifer system delineated is confined to semi confined to semi-confine and ranges in thickness from 28.3m t0 30m with an average of 29m.

4.2. *Dar-zarrouk parameters*

Aquifer parameters such as Transmissivity, Hydraulic conductivity, longitudinal conductance, and transverse resistance were determined from the VES interpretation results using Dar Zarrouk Parameters (Table 2).

4.3. *Transverse resistance and longitudinal conductance*

The transverse resistance in the study area varies from 235.2Ωm^2 to 6317.87Ωm^2 with an average value of 1789.50Ωm^2. Thus indicating very low ground water development class (Ezeh, 2012). Ezeh (2012) went further to state that values of transverse resistance of less than 200, 000Ωm^2 may not indicate absence of aquifer but may imply inadequate aquifer thickness or high mixed aquifer materials with finer sediments. The variation of transverse resistance in the study area is shown in Fig. 6 Thus areas of high transverse resistance occur in the western part of the

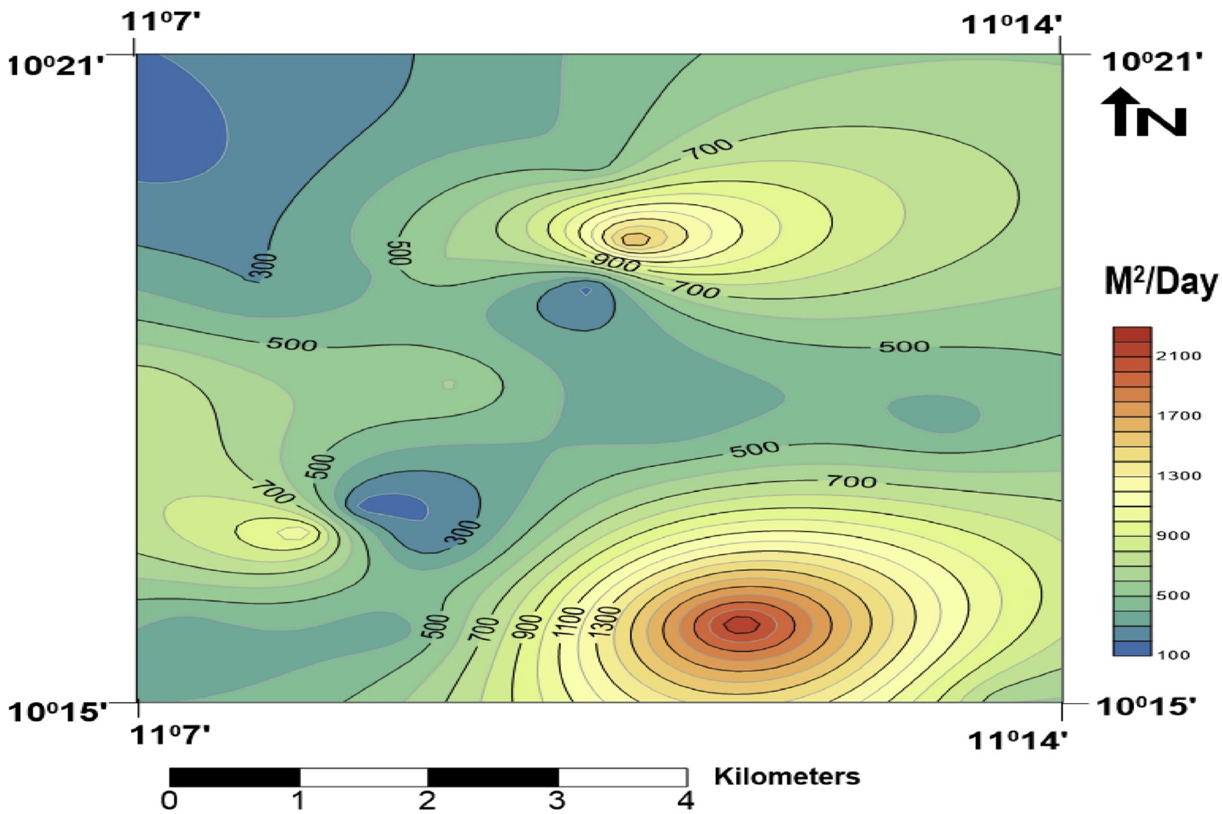

Fig. 8. Map of the study area showing variation in Transmissivity.

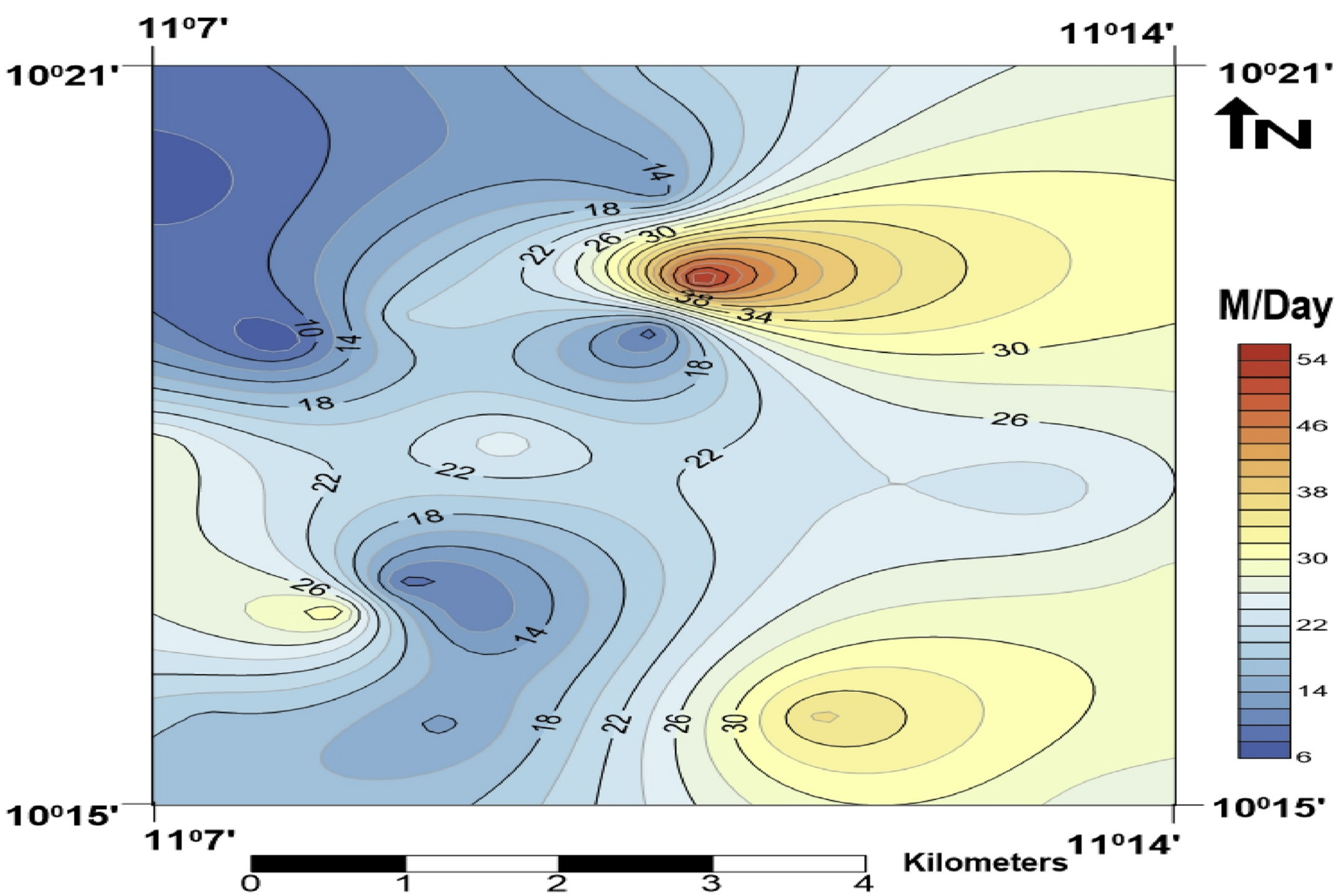

Fig. 9. Map of the study area showing variation in Hydraulic Conductivity.

study area.

4.4. Protective capacity

The values of the longitudinal conductance were used to evaluate the protective capacity of the aquifer using Oladapo and Akintorinwa 2007, protective capacity rating (Table 3). Values of longitudinal conductance in the study area ranges from 0.1415Ω to 31.933Ω with an average of 2.002Ω (Fig. 7). It revealed that in the study area Fifty percent 50% (VES 1, VES 4, VES 5, VES 7, VES7, VES10, VES12, VES 14, VES 15, VES 16, VES17, VES 18, VES19, VES21, VES 22, and VES 31) of the VES points have good protective capacity, Forty percent 40% (VES 2, VES 3, VES 6, VES 9, VES 11, VES 13, VES 20, VES 23, VES 24, VES 25, VES 26, VES 29 and VES 30) have Moderate Protective capacity, Six percent 6% (VES 27 and VES28) have Weak protective capacity, and Four percent 4% (VES32) have Excellent protective capacity (Table 4). Most of the VES points in the study area have values of Moderate to good protective capacity, thus indicating that the aquifers are protected. This is a good indication that wells located at these points are not susceptible to contamination because of the presence of good natural filter to percolating fluids in the regions. Fig. 7 shows the variation of aquifer protective capacity within the study area, good to excellent protective capacity is dominant around the southern and northern parts of the area.

4.5. Transmissivity and hydraulic conductivity

The Transmissivity of the aquiferous layer in the study area were calculated and presented in Table 5. The Transmissivity values ranges from 78.34 m^2/day to 13284.02m^2/day, the average value been 893.57 m^2/day. The Variation of the Transmissivity values in the study area was interpreted using Table 6 and it was observed that sixty nine percent (69%) of the VES points show Moderate Potential, thirty one percent (31%) show High Potentials (Table 5). Also the map of the study area showing variation in Transmissivity values is presented (Fig. 8). Fig. 8 shows that high aquifer potentials occur in the southern and northeastern part of the study area. The aquifer of the study area is generally of moderate to high potentials (Table 5).

The hydraulic conductivity values of the area range from 2.62m/day to 138.66 m/day at Tunfure Bashar and Nasarawo respectively, with mean value of 20.29 m/day, thus indicating hydraulic conductivity of fine, coarse sand and gravel (Bouwer, 1978). Fig. 9 shows map of the study area with variation of hydraulic conductivity values. Area with high hydraulic conductivity (around Nassarawo) would be highly permeable to fluid flow. Spatial distribution map of hydraulic conductivity (Fig. 9) shows that high hydraulic conductivity occurs in the southern and northeastern part of the study area, which correlates with areas of high transmissivity.

5. Conclusion

The resistivity soundings results revealed that about11 curve types were identified in the study area namely HKH, KHK, QH, QKH, KQH, QHA, QQH, HKHA, AH, HKQH, and AKQH with the lithologic layers varying from four 4 to 6 consisting of varying resistivity and thicknesses across each VES point. The geo-electric sections revealed that the major aquifer systems in the area range from confined to semi-confined aquifers consisting of Medium grain sandstones with varying thicknesses. The longitudinal conductance computed indicates that the aquifers in the area have moderate to good protective capacity whereas transverse resistance indicates very low ground water development class. Hydraulic conductivity and transmissivity values moderate to high aquifer potentials. Four groundwater potential zones were delineated including medium grain sandstones, sandstones, clayey sand and shaly sand.

Declarations

Author contribution statement

I.A. Kwami: Conceived and designed the experiments; Performed the Experiments; Analyzed and Interpreted the data; Wrote the Paper.

J.M. Ishaku: Conceived and designed the experiments; Analyzed and Interpreted the data.

S. Mukkafa: Performed the Experiments.

B.A. Ankidawa and I. A. Haruna: Contributed reagents, materials, analysis tools or data.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

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