Original article

Assessment of Aquifer parameters in Imburu area, Northeast Nigeria, using the Vertical Electrical Sounding, GIS, and Remote Sensing techniques

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Abstract

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Abstract

Groundwater is gradually becoming the most feasible alternative to the expensive conventional surface water system in Nigeria, both for drinking and agricultural purposes. The focus of the present study was to evaluate aquifer parameters with a view to delineate the groundwater potential in Imburu, a farming area in Northeastern Nigeria, using vertical electrical sounding (VES), geographic information system (GIS), and remote sensing (RS) techniques. The three techniques were combined to have delineated groundwater potential, estimated aquifer transmissivity, and hydraulic conductivity using the aquifer's resistivities and Digital Elevation Model (DEM) data of the Shuttle Radar Topography Mission (SRTM) acquired from Landsat 7 Thematic Mapper (TM) imagery, and the concept of Dar Zarrouk (D.Z.) parameters. A total twenty-seven (27) vertical electrical sounding (VES) measurements were conducted across the study area with at least a 100 m distance from one VES point to another, using the Schlumberger electrode configuration, with current electrode spacing (AB/2) ranging from 2 m to about 200 m in each VES point. The summary of the results revealed that the area is characterizes by mostly five-layer lithology of AKH and KQQ. Quantitative interpretation of the third layer suggested that it is the aquifer layer with resistivity variation ranging from about 56.3 Ωm to about 221.6 Ωm, and with thickness varying from about 14 m to about 30.8 m. The groundwater potential in the study is generally good, though with weak aquifer protective capacity that suggested the vulnerability of the aquifer to infiltration from contaminants.

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Introduction

Naturally, Nigeria, just like many other countries across the world, has been endowed with considerable quantity of groundwater resources. The resource has since been playing an important role in the economic and social life of many people in terms of domestic and agricultural usage. Groundwater is gradually becoming the most feasible alternative in Nigeria to the expensive conventional surface water system, as the cost of exploitation by way of hand-dug wells and boreholes appeared far cheaper when compared to the later that will require construction of impounding reservoirs, piping network, and whole lots more of expenses to maintain the system. In general terms, groundwater has been a major source of water in many Nigerian communities in recent times, partly due its near perfect in terms of purity. In Nigeria for instance and owing to the ever increasing demand for water supplies due to increase in population growth, groundwater exploration is gaining more and more importance across the nation (Joseph, 2012).

Delineation of potential aquifer zones is an important aspect of groundwater prospecting (Choudhury *et al.*, 2017). Groundwater is a very important recourse for a sustainable development in many localities, having been the source of water in areas where planning and development of surface water tend to be economically not viable (Gouet *et al.*, 2020). In spite of that, a major constraint is the complex and erratic nature of groundwater occurrences in distinctive aquifers of distinct hydrological and lithological characteristics. In other maintain sustainability of groundwater in any area, groundwater potential of such area needs to be evaluated. The property of an aquifer to transmit water, which is termed as the transmissivity of the aquifer is an important parameter in that regard. Other aquifer parameters include hydraulic conductivity, storativity and permeability, and formation factor.

Groundwater has been a major source of water for sustaining human life throughout the world. It has generally been considered a stable and reliable resource. In recent times, the unprecedented improvement in rural electrification, culminating into efficient groundwater pumps, has made it possible for global groundwater extraction to have increased from, about 312 km3 per year in the 1960s to about 743 km3 per year in 2000, and approximately 70 % of this extraction is used for agriculture. About half of domestic human water consumption in urban areas is from groundwater (Wada *et al.*, 2010). Groundwater is therefore an important resource that requires careful planning, development and management, which could be achieved through multidisciplinary scientific researches. Groundwater resource, surface water, and ecosystems are all interconnected in ways that necessitate an integrated approach to management. To effectively manage in this way requires high-quality scientific data not only of the component aspects of the interconnections but also of aquifer parameters of the resource. Because groundwater has been out of sight, many assumed the recourse is unlimited, thus it is basically not underappreciated. Many are not mindful of the possible degradation of groundwater at any point in time, though the time for groundwater system degradation to reach thresholds of concern, even if recognized, is typically longer than many timeframes used in societal decision making.

Imburu area is a village in Numan Local Government of Adamawa State, Northeast Nigeria, and a port settlement that lies on the convergence of Benue River and Gongola River. The area is as well a farming community east of Numan, with its inhabitants engaging in rainy season farming and irrigation farming all year round. The Benue River has been especially responsible for irrigation around the area, accounting for about 80 per cent of annual farming activities. However, population growth in and around the area has put on much pressure on farmland used, with ever increasing demand for such produce grown under irrigation system. Continuous increase in population complemented the ever increasing water demand, which in turn, increased groundwater abstraction worldwide (Chand *et al.*, 2004; Nicholson *et al.*, 2000). These have necessitated the expansion of farmland for irrigation around Imburu, making it difficult for some farmer to access surface water from the Benue River because of distance. This resulted in many farmers looking elsewhere for alternative sources of water other than the conventional surface water. Groundwater appears cheap, an alternative to surface water for many farmers around the area. In areas with difficulty to access surface water, developing groundwater is an exceptional option sustainable water supply (Abimuku *et al.*, 2019). Groundwater resource has been historically out of sight, hence the need for stakeholders to constantly monitor the resource, such that it sustained both present and future need. Evaluation of groundwater resources is a developmental issue that requires elegant understanding of the geologic and hydro-geologic properties of the aquifers through topnotch scientific studies. Groundwater exploration is one of the most significant ways (techniques) to locate potential new water supplies, especially when combined with remote sensing and geographic information system techniques.

The focus of the present study was to evaluate aquifer parameters with a view to delineate the groundwater potential of the Imburu area, using geophysical – vertical electrical sounding (VES), geographic information system (GIS), and remote sensing (RS) techniques. The three techniques were combined to have delineated watershed, estimated aquifer transmissivity, hydraulic conductivity using the aquifer's resistivities and Digital Elevation Model (DEM) data of the Shuttle Radar Topography Mission (SRTM) acquired from Landsat 7 Thematic Mapper (TM) imagery. The concept of Dar Zarrouk (D.Z.) parameters was as well adopted and aquifer transmissivity, permeability, and hydraulic conductance were theoretically estimated.

A number of previous studies have employed the technique of the vertical electrical sounding using the Schlumberger array to study subsurface geologic layer with a view to delineate depth to the bedrock and thickness of the geologic layers (Kumar and Swathi, 2014; Babagana and Elnour, 2020; Sirhan and Hamidi, 2012; Olanrewaju and Abdulkadir, 2020). Olawuyi and Abolarin (2013); Aizebeokhai *et al.* (2010); Ali *et al.* (2014); and Babagana and Baba (2020), estimated a linear relationship between actual and predicted depth using the vertical electrical sounding technique. In their separate submissions, Roger *et al.* (2001) and Alabi (2010) estimated aquifer hydraulic conductivity using resistivities determined from Schlumberger electrical soundings. The VES technique has adjudged a viable geophysical method in delineation of groundwater potential aquifers in watershed (Gowd, 2004; Cardarelli *et al.*, 2010). Electrical resistivity method was adopted to study and characterize groundwater aquiferous zones (Olanrewaju and Abdulkadir, 2020; Olawuyi and Abolarin, 2013). Prolific groundwater aquifers were as well delineated using the VES technique (Raji and Adedoyin, 2020; Rincón *et al.*, 2018; Samanta *et al.*, 2018; Urrutia-Fucugauchi and Pérez-Cruz, 2018; Wada *et al.*, 2010; Wang, 2004; Olukemi *et al.*, 2014). Freshwater lens could be investigated using the VES technique (Costabel *et al.*, 2017; Babagana and Sharma, 2020). Characterization of the nature of subsurface infiltration zones is achievable using the vertical electrical sounding method (Sirhan and Hamidi, 2012). The Dar Zarrouk parameter concept was adopted using resistivity technique to estimate groundwater potential of aquifers (Asfahani, 2013).

The resistivity technique could be married with other techniques such as the Geographic Information System, and the Remote Sensing, to study groundwater aquifer potential (Boucher *et al.*, 2009; Dena O *et al.*, 2012; Domeneghetti *et al.*, 2019; Abarca *et al.*, 2011; Chormanski *et al.*, 2011). In the same vain, the GIS and RS based approach has become a key tool for mapping, assessment, and managing of groundwater resources in recent times (Joy and LU, 2004; Demir and Kisi, 2016; Albano *et al.*, 2018; Curebal *et al.*, 2016; Brivio *et al.*, 2002; Syifa *et al.*, 2019).

1.1. The Study Area

Imburu area lies between latitude 9^{0}29'24''N and 9^{0}29'31''N, and longitude 12^{0}04'20''E and 12^{0}14'08''E, on a flat terrain of average 150 m elevation. The area is characterized by two seasons, namely wet and dry seasons. The wet season is usually hot and overcast, while the dry season tends to be sweltering and partly cloudy. The annual temperature in Imburu area typically varies from about 60^{0}F to about 100^{0}F. The annual temperature is rarely below 56^{0}F or above 107^{o}F. The hot season in the area usually last between February and May each year, with average daily high temperature of above 99^{0}F. The wet season lasts between June and September each year, with average daily temperature below 91^{0}F. The rainy period in the present study area usually lasts between March and November in every year, with most of the rain falling in August and September, and with average total accumulation of about 6.8 inches annually. The area generally experiences high seasonal variation in perceived humidity, with muggier period lasting between March and November each year.

Imburu is an area situated in the lap of nature surrounded greenery during rainy season, and with the Benue River south of the area. The area is also abounding with vast stretches of pastures, making it even more easier farming, herding and other agricultural activities to thrived. The main occupation of the dwellers of the area is agriculture and manual labor. Fig 1 shows the georeferenced map of the area indicating positions of VES across the study area.

The area covers a landmass of about two square kilometers (2 sq. km).

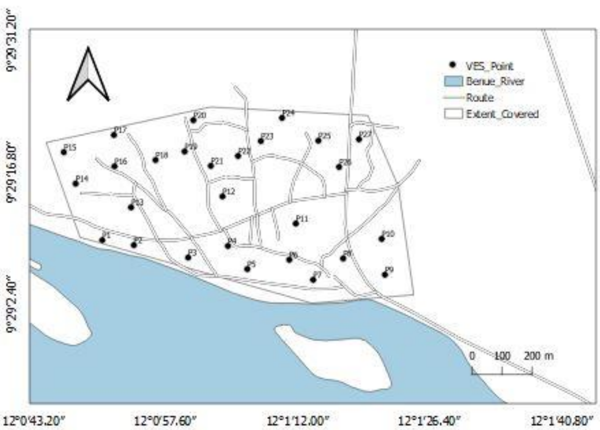

Figure 1: Georeferenced Map of the Study Area showing VES positions

1.2. Geological consideration

The geology of the study area is basically that of Bima Sandstone, unconformably overlies the Crystalline Basement Complex throughout the Upper Benue Trough (Obiefuna and Nggada, 2014; Obaje, 2009), with type section of the formation to the south in the Lamurde anticline. Based on the physical sedimentary structures, the area lies in the Middle Bima Sandstone Member of the Upper Benue Trough, consisting of very coarse-grained, felspathic sandstones, thin clays, shales, calcareous sandstone and impure limestone with a number of bivalves (Babagana and Elnour, 2020; Tukur *et al.*,2014). The area is a flat terrain.

Materials and Methods

ABEM SAS-1000 Terrameter (Resistivity meter), steel electrocdes, core cables, a DC Power Source, and a laptop computer were some of the hardware meterials used in the field for geophysical survey where in, resistivity data were generated. The softwares used for the generated geophysical data processing were IX1D Interpex, Surfer 13 Goleden, and QGIS analysis softwares. Aquifer features as Transmissivity and Hydraulic conductivity were estimated from the resistivity data using the concept of Dar Zarrouk paramenter. Landsat 7 Thermatic Mapper (TM) in combination with Digital Elevetion Model (DEM) data of the Shuttle Radar Topography Mission (SRTM) were used to investigate physiographic features such as topographic indwx and drainage direction.

Geophysical survey

A total twenty-seven (27) vertical electrical sounding measurements were conducted across the study area with at least a 100 m distance from one VES point to another (Fig 1). The vertical electrical sounding measurements were conducted using the Schlumberger electrode configuration, with current electrode spacing (AB/2) ranging from 2 m to about 200 m in each VES point. The potential electrode spacing (MN) ranged from 0.5 to 32 m. The sequential arrangement for the AB/2 was 2, 4, 6, 8, 10, 13, 16, 20, 25, 30, 35, 40, 50, 60, 80, 100, 120, 140, 160, 180, and 200 m. The MN sequential arrangement ranged between 0.5, 0.5, 1.5 1.5, 1.5, 2, 2, 2, 5, 5, 5, 8, 8, 8, 10, 10, 10, 13, 13, 16, 16, 16, 32, 32, and 32 m. The MN was normally changed (increased) whenever the AB/2 is stretched to a point of weaker signals. DC current were injected into subsurface through a pair of the current electrodes and the corresponding potential difference were recorded through a pair of the potential electrode. The injected current I and the measured potential difference V were automatically used by the resistivity meter generate apparent resistivity which was subsequently processed using the IX1D Interpex computer software to deduce layer resistivity and thickness. The Surfer 13 Golden software was used to process the aquifer layer resistivity and thickness to produce the contour maps of both the resistivity and thickness of the aquifer layer.

Theoretical Development

Using the concept of Dar Zarrouk (D.Z.) parameters – transverse resistivity (TR) and longitudinal conductance (LS), consider a lithology of n homogeneous and isotropic layers of resistivities $\rho_{1,}\rho_{2,}.....\rho_n$ and thicknesses of $h_{1,}h_{2,}.....h_n$.

Assuming a prism of unit square cross-sectional area cut out of the lithology, then the D.Z. parameters of the prism can be given by

$$TR = \sum_{i=1}^{n} h_i \rho_i \quad (1)$$

$$LS = \sum_{i=1}^{n} \frac{h_i}{\rho_i} \quad (2)$$

The geologic formation factor (F) can be deduced from;

$$F = a/\phi^m \quad (3)$$

Where:

ϕ is the porosity

m is a constant which depends on cementation

a is also a constant.

The permeability (k) of an aquifer can be determined in terms of the aquifer porosity as;

$$k = b\phi^c \quad (4)$$

Where b and c are constants.

Now assuming a uniform water quality, equations (3) and (4) can be combined to deduce a relation between hydraulic conductivity, k_h, (in cm/sec) and resistivity, ρ_0, (in ohm-cm), thus;

$$k_h = 386.4\rho_0^{-0.9328} \quad (5)$$

From the hydraulic conductivity relation, the transmissivity (T) of aquifer can be deduced as;

$$T = k_h h \quad (6)$$

Where h is the thickness of layers

Remote sensing survey

To visualize elevation model in 3-dimensional, elevation information of the study area was extracted from https://www.opendem.info from the Landsat 7 Thematic Mapper (TM) imagery. The extracted elevation information was processed using the QGIS analysis software with spatial resolution of 20 m to generate physiographic features of interest to the present study. These features included the topographic index in (a/tan (b)) and Drainage direction in the study area.

Results and Discussion

The summary of the geophysical investigation revealed that the area is characterizes by mostly five-layer lithology of AKH and KQQ. The topmost layer has resistivity variation between 200 Ωm and 1193 Ωm with thickness varying between 0.3 m and 2.1 m (Table 1). The second layer showed resistivity variation between 78 Ωm and 2281 Ωm, and thickness variation between 11.8 m and 23.6 m (Table 1). Quantitative interpretation of the third layer suggested that it is the aquifer layer with resistivity variation ranging from about 56.3 Ωm to about 221.6 Ωm, and with thickness varying from about 14 m to about 30.8 m (Table 2). The resistivity variation in the third layer, been the layer of interest in the present study, showed ranges of resistivity values of water bearing formations around the study area (Babagana and Sharma, 2022). The fourth layer is a layer of relatively high resistivity variation ranging from about 77.8 Ωm to about 2714 Ωm, with thickness variation between 17 m and 30 m, while the fifth layer, a layer of high resistivity variation ranging from about 231 Ωm to about 7143 Ωm (Table 1).

The hydraulic conductance and the transmissivity values estimated using the concept of the Dar Zarrouk parameter revealed a ‘good’ groundwater potential in the area of the present study. The hydraulic conductance varies between 2.51 m/day to about 9.0 m/day, with the transmissivity value ranging from about 1013.4 m^2/day to about 5605.6 m^2/day (Table 3). The longitudinal conductance of the aquifer, which is directly rating the protective capacity of the aquifer revealed weak to moderate protective capacity of the aquifer in the study area, with the longitudinal conductance varying from 0.08 S to about 0.32 S (Table 4).

Table 1: Summary of the geophysical survey with resistivities and thicknesses of layers

VES	Longitude (E)	Latitude (N)	Resistivity (Ωm)					Thickness (m)			
			ρ1	ρ2	ρ3	ρ4	ρ5	h1	h2	h3	h4
P1	12.01407	9.485929	287.9	123.5	101	245	1113	0.9	18	14	27
P2	12.01503	9.485779	338	78	132	1338	765	1.4	16	21.4	28
P3	12.01667	9.485403	518	312	133.6	2453	983	1.6	17	18	27.8
P4	12.01788	9.485755	200	987	132.8	112.8	-	1.2	21	20.3	-
P5	12.01847	9.485053	217.4	2281	87.5	382.9	556	1	16	18	17
P6	12.01974	9.485337	998	662	188	1132	881	1	13	18.6	29
P7	12.02046	9.484727	335.6	133.2	201	883	3318	1	18	17	23
P8	12.02137	9.485376	1193	145	144.3	987.8	667	1.2	19	21.7	30
P9	12.02264	9.484882	616	222	88	342	339	0.3	13	19	18
P10	12.02254	9.485969	770	303	98	983	5531	0.5	11.8	20	26
P11	12.01994	9.486434	750.3	327	56.3	637	5528	0.6	20	18	22.6
P12	12.01772	9.487258	300	318.6	165.8	1327	-	2.1	21	23.4	-
P13	12.01494	9.486926	207	200	182	2714	-	1.6	23	30.8	-
P14	12.01326	9.487645	881	122	221.6	231	-	1	23.6	19	-
P15	12.01291	9.488600	661.3	117.5	188.7	100	543	2	13.3	25	29
P16	12.01444	9.488171	405	881.3	172.8	211	348	2	20	26.8	27
P17	12.01442	9.489123	411.3	443.2	93.5	97	624	2	20	18	25
P18	12.01569	9.488363	420	133	100	341	835	1.7	20.8	18	26.3
P19	12.01657	9.488622	400	277	128	101.7	738	1.4	20.6	19.8	26
P20	12.01683	9.489572	534.2	718.3	145	217	3316	2	17.5	27	23
P21	12.01736	9.488186	229.4	603	175	77.8	999	2	19	23.8	24
P22	12.01819	9.488488	200	551	145.8	2137	4412	1	15	29	27
P23	12.01888	9.488938	231	531.3	76.6	231.8	-	1	17.4	18.3	-
P24	12.01952	9.489643	566	98.5	99.8	778	7143	2	16.6	23.6	25
P25	12.02062	9.488949	612.7	211.6	111.3	452	231	1.3	20	24	25.8
P26	12.02125	9.488153	818.6	333.2	131.7	291.7	4416	1.3	21	26.6	27
P27	12.02185	9.488992	800.3	111.6	203.4	188.8	817	1.3	15.6	26	27

Table 2: Aquifer thicknesses and resistivities

VES Point	Longitude (E)	Latitude (N)	Aquifer resistivity (Ωm)	Aquifer thickness (m)	VES Point	Longitude (E)	Latitude (N)	Aquifer resistivity (Ωm)	Aquifer thickness (m)
P1	12.01407	9.485929	101	14	P15	12.01291	9.488600	188.7	25
P2	12.01503	9.485779	132	21.4	P16	12.01444	9.488171	172.8	26.8
P3	12.01667	9.485403	133.6	18	P17	12.01442	9.489123	93.5	18
P4	12.01788	9.485755	132.8	20.3	P18	12.01569	9.488363	100	18
P5	12.01847	9.485053	87.5	18	P19	12.01657	9.488622	128	19.8
P6	12.01974	9.485337	188	18.6	P20	12.01683	9.489572	145	27
P7	12.02046	9.484727	201	17	P21	12.01736	9.488186	175	23.8
P8	12.02137	9.485376	144.3	21.7	P22	12.01819	9.488488	145.8	29
P9	12.02264	9.484882	88	19	P23	12.01888	9.488938	76.6	18.3
P10	12.02254	9.485969	98	20	P24	12.01952	9.489643	99.8	23.6
P11	12.01994	9.486434	56.3	18	P25	12.02062	9.488949	111.3	24
P12	12.01772	9.487258	165.8	23.4	P26	12.02125	9.488153	131.7	26.6
P13	12.01494	9.486926	182	30.8	P27	12.02185	9.488992	203.4	26
P14	12.01326	9.487645	221.6	19					

Table 3: Hydraulic conductance and Transmissivity values for the Aquifer layer

VES Point	Longitude (E)	Latitude (N)	Hydraulic conductance (m/day)	Transmissivity (m^2/day)	Ground water potential
P1	12.01407	9.485929	5.22	1414	Good
P2	12.01503	9.485779	4.06	2824.8	Good
P3	12.01667	9.485403	4.02	2404.8	Good
P4	12.01788	9.485755	4.04	2695.84	Good
P5	12.01847	9.485053	5.96	1575	Good
P6	12.01974	9.485337	2.92	3496.8	Good
P7	12.02046	9.484727	2.75	3417	Good
P8	12.02137	9.485376	3.74	3131.31	Good
P9	12.02264	9.484882	5.93	1672	Good
P10	12.02254	9.485969	5.37	1960	Good
P11	12.01994	9.486434	9.00	1013.4	Good
P12	12.01772	9.487258	3.29	3879.72	Good
P13	12.01494	9.486926	3.01	5605.6	Good
P14	12.01326	9.487645	2.51	4210.4	Good
P15	12.01291	9.488600	2.91	4717.5	Good
P16	12.01444	9.488171	3.16	4631.04	Good
P17	12.01442	9.489123	5.61	1683	Good
P18	12.01569	9.488363	5.27	1800	Good
P19	12.01657	9.488622	4.18	2534.4	Good
P20	12.01683	9.489572	3.72	3915	Good
P21	12.01736	9.488186	3.12	4165	Good
P22	12.01819	9.488488	3.70	4228.2	Good
P23	12.01888	9.488938	6.75	1401.78	Good
P24	12.01952	9.489643	5.28	2355.28	Good
P25	12.02062	9.488949	4.77	2671.2	Good
P26	12.02125	9.488153	4.07	3503.22	Good
P27	12.02185	9.488992	2.72	5288.4	Good

Table 4: Aquifer longitudinal conductance and protective capacity rating

VES Point	Longitudinal conductance (S)	Aquifer Protective Capacity	VES Point	Longitudinal conductance (S)	Aquifer Protective Capacity
P1	0.14	Weak	P15	0.13	Weak
P2	0.16	Weak	P16	0.16	Weak
P3	0.13	Weak	P17	0.19	Weak
P4	0.15	Weak	P18	0.18	Weak
P5	0.21	Moderate	P19	0.15	Weak
P6	0.10	Weak	P20	0.19	Weak
P7	0.08	Poor	P21	0.14	Weak
P8	0.15	Weak	P22	0.20	Moderate
P9	0.22	Moderate	P23	0.24	Moderate
P10	0.20	Moderate	P24	0.24	Moderate
P11	0.32	Moderate	P25	0.22	Moderate
P12	0.14	Weak	P26	0.20	Moderate
P13	0.17	Weak	P27	0.13	Weak
P14	0.09	Poor			

The contour map, as prepared from the aquifer resistivity using the Surfer 13 Golden software suggested an almost even distribution of groundwater in the area along all directions, N, E, S, and W (Fig 2). This is evidently so because ranges of resistivity of water bearing formation could be deduced from the contour map, in all parts of the study area. The aquifer thickness from contour map revealed high thickness of about 30 m in the western region of the study area (Fig 3). High concentration of hydraulic conductivity occurred towards southeast in the area (Fig 4). Aquifer transmissivity tends to be stronger in the west, and in the northeastern parts of the study area (Fig 5). The moderate aquifer protective capacity occurred towards southeast, with most parts revealing weak protective capacity (Fig 6). These different parameters in different locations and directions suggest that groundwater potential in the Imburu area is generally good, though with weak aquifer protective capacity.

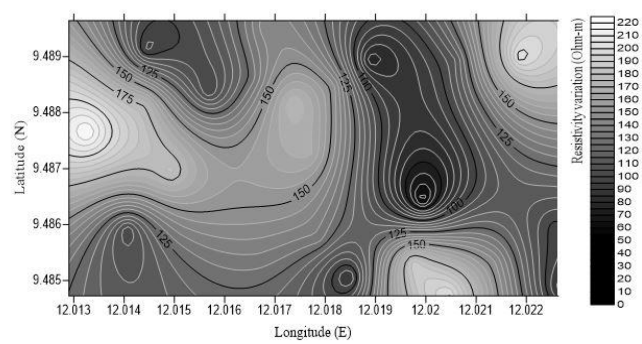

Figure 2: Contour map showing aquifer resistivity distribution across the area

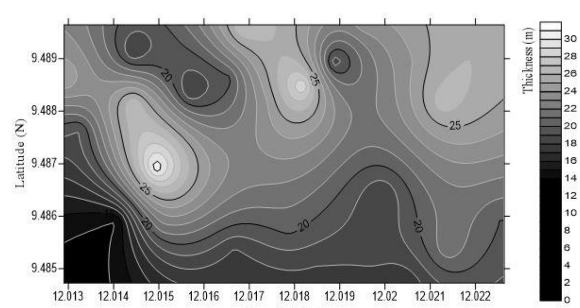

Figure 3: Contour map showing aquifer thickness distribution

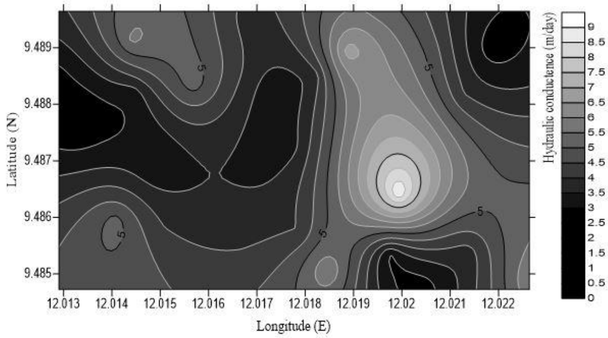

Figure 4: Distribution of Hydraulic Conductivity

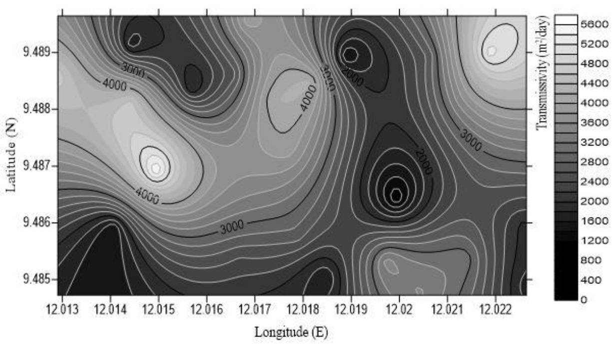

Figure 5: Contour map revealing distribution of aquifer transmissivity

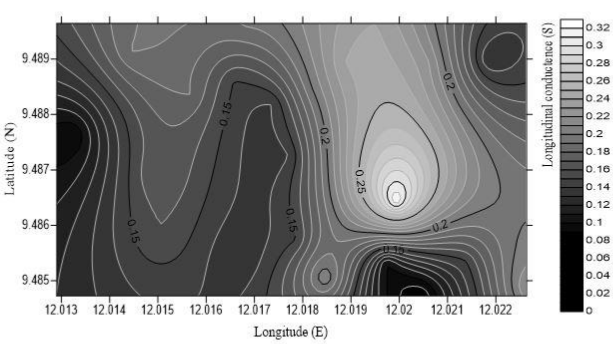

Figure 6: Distribution of Longitudinal conductance across the area

The remote sensing data processed in the present study revealed that the area is basically a flat terrain of about 150 m average elevation (Fig 7). The topographic index in (a/tan(b)) showed variation between 9.5 and about 16.0 (Fig 8). The drainage direction varies between negative 8 to positive 8 (Fig 9) that is in the direction of East, and towards Gongola River.

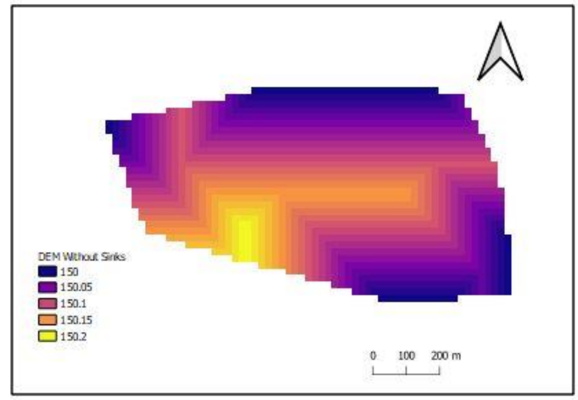

Figure 7: Digital Elevation Model (DEM) in the area

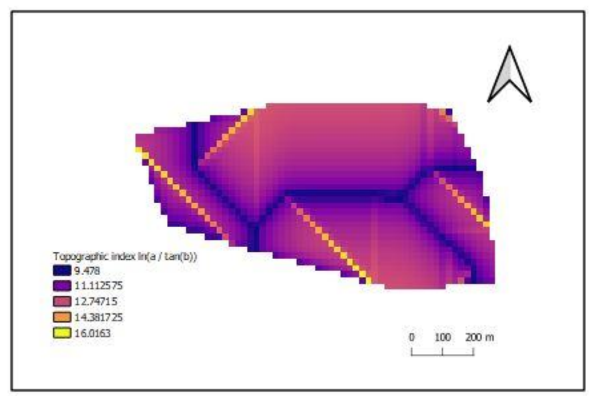

Figure 8: Variation of Topographic Index across the area

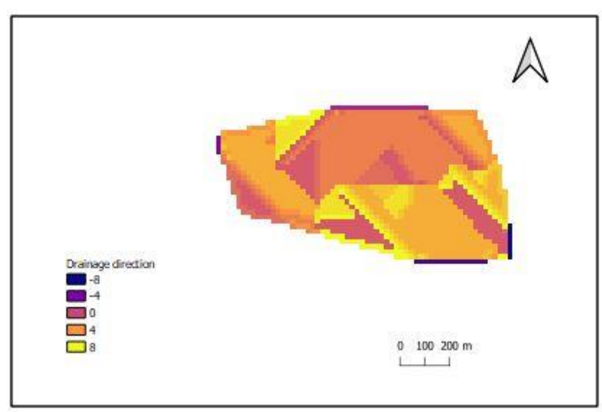

Figure 9: Drainage direction in the area

Conclusion

From the foregoing results and discussion, it is thus concluded that;

a) The study area is characterized by mostly five-layer lithology with the aquifer layer situated in the third layer.
b) The groundwater potential in the Imburu area is generally good, though with weak aquifer protective capacity.
c) The weak aquifer protective capacity suggested that the groundwater in Imburu area is vulnerable to contaminants infiltration, hence requiring collective efforts from all groundwater stakeholders to properly manage and maintain the resource.
d) The present study further affirmed that a combination of vertical electrical sounding (VES), GIS, and remote sensing techniques is a viable option for groundwater investigation.

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Conflict of interest

The authors have declared that no competing interests exist.

Authors' contributions

SMB conducted the research, collected the data, analyzed it and drafted the manuscript. SS supervised the research and manuscript.

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