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Exploration for Groundwater using integration of Aeromagnetic and Electromagnetic geophysical methods with Hydrogeologic Pumping Test in Uburu-Okposi Salt Lake Areas, Southeast Nigeria

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Abstract: *The study area is groudwater problematic due to being dominantly underlain by aquicludes formed by shales of Asu River group of Albian age and a small member of Turonian sediments of Ezeaku Formation. The study aimed at delineating potential structures for groundwater development using remotely sensed data from aeromagnetic survey that detected structural lineaments. Two pole profile modes of audio frequency magnetotelluric (AMT) targeted on the lineaments, indicated low amplitudes anomalies as aquifer forming structures. The aquifers are confined at depth ranging from 45 to 85 meters, where full scale aquifer properties were evaluated via constant rate of pumping tests, conducted at four (4) locations with average flow rate of 50.4*m^3*/day. The pumping resulted to minimum and maximum steady drawdowns of 1.80m and 4.60m respectively. Interpretion of the data using standard graphical techniques showed ranges of hydraulic conductivity from* 2.37×10^{-1}*m/day to* 4.56×10^{-1}*m/day, transmissivity from 1.73* m^2*/day to 5.28*m^2*/day, recovery test transmissivity from 2.13*m^2*/day to 5.93*m^2*/day and specific capacity from 11.59*m^2*/day to 19.92*m^2*/day.The results indicated low aquifer properties, implying lower rates of groundwater recharge than the rate abstracted, thereby inducing saline water insurgence that pollutes the groundwater, especially with high amount of TDS,* Na^+*,* K^+*,* Cl^- *and Fe. Thus, groundwater development in the area would only serve for local use.*

Key Words: *Fractures, Groundwater, Pumping Test, Asu River Group, Aquifer Vulnerability, Saline Water*

I. Introduction

Water is indispensable for agriculture, household and industrial processes for food, health and overall economic development of the world (Asian Development Bank, ADB, 2013). Water is life (United Nations Environment Programme, UNEP,2010).This means that Life would be impossible without Water (Castro and Huber, 2005). The water sector, particularly in developing countries is prone to enormous challenges of climate change, rapid population growth and increasing pollution sources. Rapid population growth has resulted to rising demand for water. According to UNESCO (2014), access to water should be human right as it is essential for meeting basic needs of mankind. Groundwater and surface water resources are major hydrologic sources for water supply. The surface water resources namely; oceans, rivers and lakes, although abundant and easily accessible, are heavily vulnerable to natural and anthropogenic pollutions, and hence, less potable than the groundwater supply.Generally, groundwater is less cheap to explore and exploit, yet it attracts more global attention because of the belief that it is purer in quality due to the protection of earth cover. Although groundwater is believed to be common, its occurrence is not easily determined, especially in groundwater problematic terrains. For example, areas underlain by christalline basement rocks and shales have often proved difficult for groundwater exploration and exploitation. One of the areas in Nigeria that have proved difficult for grounwater exploitation is the area geologically underlain by the Asu River Group of the Albian age. Many boreholes drilled in the areas have been unproductive due to inability to identify aquifers zones. Bayode and Akpoarebe (2011) have however shown that groundwater can be explored and exploited successfully in shaley terrains that have discontinuities which can occur in the form of shear zones, faults, and fractures. Along this line, Teme and Oni (1991) have found out that quantity of groundwater present within fractured rocks depends on width of openings, lateral extent, frequency of occurrence and depth of the fractures from the surface. This study was undertaken for the Uburu-Okposi area in southeastern Nigeria underlain by the Asu River Group. Tijani et al, (1996) who worked in adjacent areas had noted that faults and fractures were emplaced regionally during a tectonic episode of Santonian age. This work therefore aimed at identifying these regional and perhaps local structures that could be targeted for groundwater explotation. The study involved the integration of remotely sensed data from aeromagnetic survey and two pole profile mode of audio frequency magnetotelluric of electromagnetic method, both supported by pumping tests.

Regional Geology and geography of Lower Benue Trough

Sedimentation started within the entire Benue Trough in the early Cretaceous era as a result of south Atlantic sea-level rise. Consequent upon the high sea level, there was transgression that resulted to deposition of marine sediments into the entire Trough in the mid-Albian age. The transgressive period culminated to series of sedimentsary rocks, comprising shales, sandstones, ironstones and mudstones of Asu River Group. According to Obaje (2013), the Asu River Group of sediments dominates the Lower Benue Trough with the type locality at Asu River valley near Uburu and Okposi salt Lakes area (Fig1). The sedimentary fill of the lower BenueTrough was affected by two sets of tectonism, one in pre Turonian and the other in the Santonian time (Uma and Lohnert, 1992). The Santonian tectonism affected the part of the lower Benue Trough under investigation, resulting to a compressional movement along NE-SW trend that produced some parallel folds with NE-SW and N-S trending fractures.Topographically, the area ranges from 100m in the lowlands to 600m in the highlands, with annual rainfall of 2000mm during rainy season and about 250mm during dry season (Ekwere and Ukpong, 1994).The extent of infiltration from the rainfall is generally limited by the Asu River shale, which also prevents regional groundwater flow.

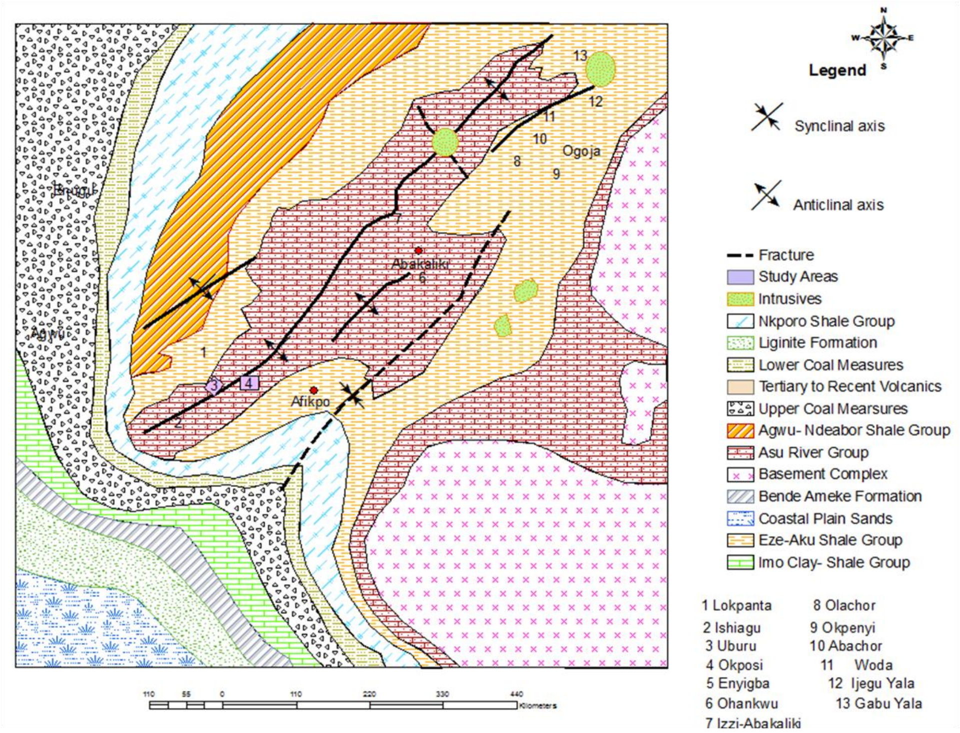


Fig 1: Geologic map of Lower Benue Trough regions and adjoining areas (modified from Zaborski, 1998)

Local Geology/Hydrogeology

The studied area is dominantly underlain by the shale of the Asu River Group of Albian age, with some Turonian sediments of the Ezeaku Formation in the northwestern and southwestern parts. Uburu-Okposi salt lakes are located in the area (Fig 2). Within the Turonian sediments is a sandstone member intercalated with siltstones and shales. Borehole logs revealed that the sandstone is about 25m thick and fine to medium-grained (Fig 3a). Egboka and Uma (1986) had reported the presence of well-indurated and argilliceous sandstone in the area. The sandstone could be traced along the East-West direction and towards the northwest of the studied area (see Fig 2). The Eze-aku Formation comprises generally of dark grey to black shales with frequent facie changes to sandstones. Borehole log (Fig 3b) confirms shales typical of the Asu River Group which has been hydrogeologically described as an aquiclude. Dip measurments in the northwestern and southern parts of the study area signify presence of synclines while they depict presence of an anticline towards the northeast. All these confirm that the area had been tectonically disturbed. Strike directions in both Asu River and Eze-aku sediments generally trend NE-SW

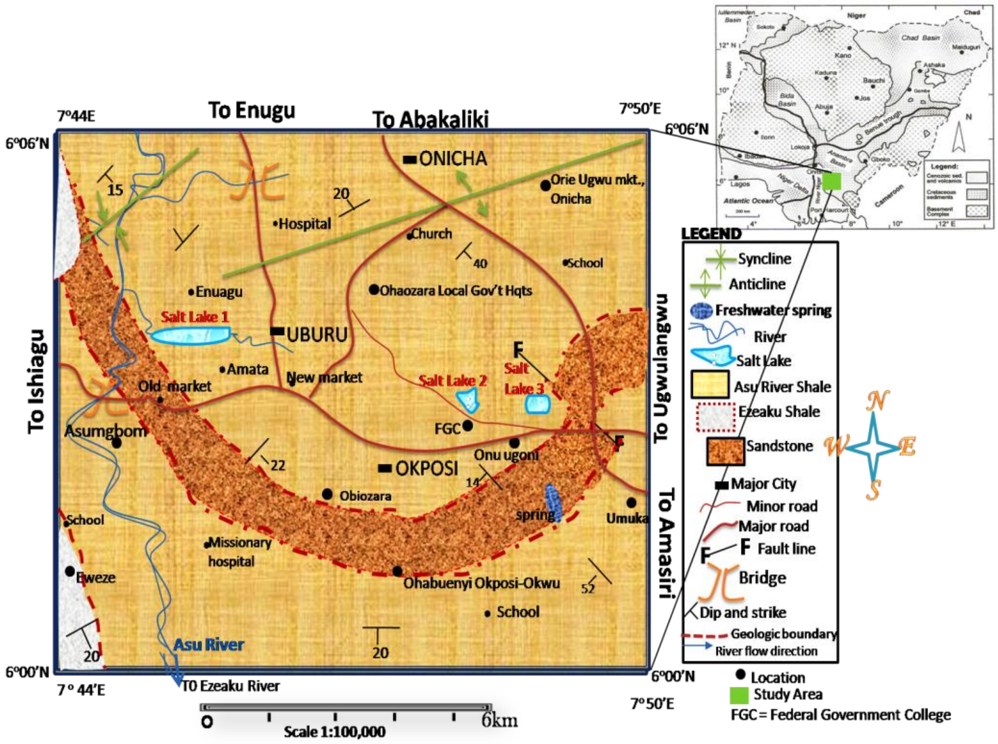


Fig 2: Geologic Map of Uburu-Okposi Salt Lakes and Environs

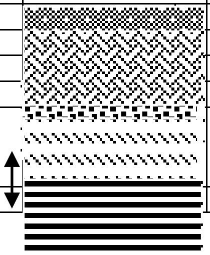
Drilling and Casing Program			**Depth (m)**	**Lithology data**	
Drill Bit size	**Casing size and screen size/length**			**Log**	**Definition of Lithology**
	Casing	**Screen**			
8" Trcone Bit	125mm	13 m	‹ 1		Lateritic overburden
			12		Mudstone with clayey Siltstone
6" Hammer Bit			20		Hard /Fine-medium grained sandstone
			32		Micaceous sandstone
			58		Weathered shale
			85		Hard and Shale wedge.

Fig 3a: Drilled and logged borehole data for Ohabuenyi Okposi-Okwu (N06^{0} 01' 067", E07^{0} 48' 373")

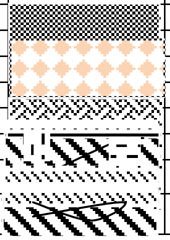
Depth (m)	**Lithology data**	
	Log	**Definition of Lithology**
3		Top soil overbrden
6		Clayey laterites
9		Damped mudstone
12		Blue-Black weathered shale (perched water table)
18		Dry hard shale
33		Fractured inhomogeneous shale pellets
42		Weathered shale (issues colloidal water, clears after short period)
45		Fractured shale (saturated with clean groundwater)

Fig 3b: Drilled and logged borehole data for Umuka Health Centre;(N06^{0} 01' 787", E07^{0} 49' 866")

II. Materials And Methods

Local structural lineaments were mapped by processing a regional remotely sensed aeromagnetic data from Nigeria Geological Survey Agency's database map number 302 of Nkalagu sheet. The data was further filtered via digital filtering technique using Oasis Montaj 7.5 application software to extract the local trend of the lineaments (Fig 4).Twelve (12) profiles were undertaken via"Two pole" profile measurement mode of audio frequency magnetotelluric electromagnetic survey, which was carried out with ADMT-2 Natural Electric field Geophysical equipment (NEF800 model). The equipment uses earth's natural current to measure different resistances of rock layers and transforms the parameters to voltage in milli volts (mV), producing anomaly changes on the basis of structural resistivity variation. It adopted change rule of electromagnetic field at five frequency series, namely; 500Hz, 170Hz, 67Hz, 25Hz and 10Hz. Data were collected at discrete intervals of 10 meters along each profile line through two non polarising electrodes, **M** and **N** plugged into the earth at 20 meters separation, such that **MN**=20m. Profile distances ranged from 300 meters to 800 meters for minimum and maximum profile length respectively. Compass of Brunpton model was used to keep the profile lines straight and perpendicular to the NE-SW trends of the lineation under investigation. Quantitatively, the voltage (potential differece [mV]) from the telluric current was plotted as a function of profile distance [m] using Grapher 8 software. It produced five successions of graphs from the five transmitting frequency series for every profile line.

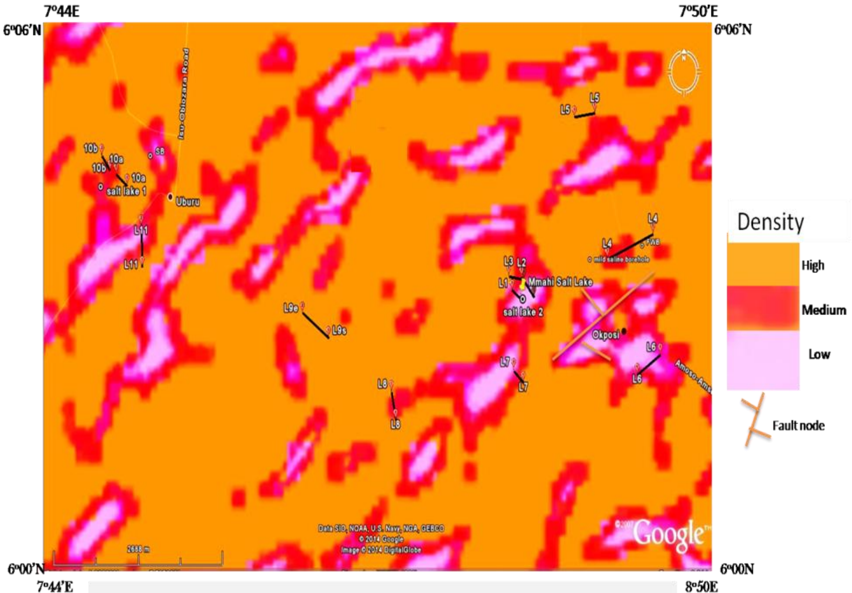


Fig 4: Magnetotelluric profiles across locally detailed lineaments

Prior to investigation of aquifer characteristics by pumping tests, boreholes to be surveyed were screened up to or greater than 85% of the aquifer thickness. The screen length interval covered the saturated part fully, thus, approximating the thickness of each local aquifer (Gautam, 2013). According to Kruseman and deRidder (1991), this makes it possible to obtain maximum discharge from horizontal flow, thus satisfying the basic assumption that underlies all flow to any pumped well. Observation wells were not used for the investigation because the area is not characterized by regional groundwater flow.With this idea therefore, each pumping test was carried out using constant rate method with all measurments from production boreholes.

The pumping test was in two compartments, the pumping part to generate drawdown data, and recovery part to produce residual drawdown data from spontanous recharge. Flow rate for each of the pumping tests was established following the Domenico and Swartz (1998) guideline by which borehole diameter is associated with a particular pumping rate. Thus, the pumping rate was established vis-avis the size of pumping apparatus such as 1.5 submersible pumps of Grandfos model used. The Pumping rate/discharge or flow rate was designed at the beginning of each pumping test by observing the time required to pump-fill a container (or calibrated bucket) of a known volume. Thus, twelve (12) litre gallon was filled in 20 seconds for pumping test location 1, coded as PMT1; ten (10) litre gallon was filled in 18 seconds for pumping test locations 2 and 3 of PMT2 and PMT3 respectively, while ten (10) litre gallon was filled in 16 seconds for location 4 (PMT4). A maximum flow rate of 38lit/min or 0.038m^3/min (54.7m^3/day); a minimum rate of 33lit/min or 0.033m^3/min (47.5m^3/day) and an average rate of 35lit/min or 0.035m^3/min (50.4m^3/day) were established for the groundwater discharge and these rates were sufficiently steady throughout the pumping phase. Each pumping test was powered using electric moveable generators and three parameters monitored during the pumping process, namely, time (using stopwatch), water level in the casing (using dip meter) and the established flow rate of discharged water. Resulting drawdowns were recorded on aquifer test data sheet as differences between the water levels during pumping and pre pumping water level (static water level, SWL) measured before pumping started. The pumping test period lasted until pseudo-steady state or equilibrium state was attained, that is, when the water level in the casing stabilized. At this stage, the water was filtered and sampled into 1 litre bottle and moved to laboratory within 12 hours where disolved elements of interest were analyzed using ICP-MS. The pump was thereafter turned off (shut down) and the recovery phase commenced immediately. The aim of the recovery test was to provide an independent check on the pumping test results. The water levels in the casing were timely monitored and measured as the groundwater recharged spontaneously. Differences in recharged water levels and the SWL were recorded on aquifer recovery data sheet as residual drawdown. The measurment lasted until the attainment of equilibrium state of the residual drawdown. Precaution was taken to ensure accurate results by discharging the pumped water far beyond suspected areas of drawdown influence. Analysis of the data commenced by manual plotting of drawdown on arithmatic scale as a function of time on logarithmic scale, using semi-log of 4-cycle graph paper following Cooper and Jacob (1946). Steady drawdown ($h-h_0$) being a drawdown per log cycle of time (t) was determined.The same graphical solution was used for the recovery test, although, the residual drawdown was plotted as a function of logarithm of t/t´, by which residual drawdown ($h-h_0$)’ per log cycle of t/t´ produced the slope, where

t = time since recovery started and

t´= time since pumping commenced.

Degree of accuracy was considered significant with pumping and recovery drawdown difference of (≤1.0m).The resulting data were subjected to mathematical treatment of Theis (1935) standard fomulae as simplified by the nonequilibrium formulae of Cooper and Jacob (1946) for confined aquifers. With the formulae, the aquifers' behavior was characterized numerically. Residual drawdown was used to determine the aquifer parameters, following Michael et al (2011) principle, as such would provide independent check on the pumping test result.

III. Results And Discussion

Detection of the aquifer forming structures

Results of the processed remotely sensed data from aeromagnetic survey provided information on structural lineaments (see Fig 4). The figure shows enhanced features represented in colour bands of different tones and contrasts.The colours grade from high contrast yellow background to low contrast grey band, confined by lenses of red bands. The lineaments fall on some surface hydro-geomorphologic units such as synclines and anticlines. From qualitative visual analysis of the lineaments, the grey bands are suspected to represent high moisture zone (Gautam, 2013).These zones trend NE–SW, thus, corresponding to the strikes directions. Relating the present study with the geodynamic history of the studied area as outlined by Uma and Lohnert (1992), the lineaments denote groundwater bearing structures, such as the NE–SW trending fractures that were emplaced during tectonic episode of Santonian age. A lineament intersection node is observed in the eastern part of the lineament map (see Fig 4), and is suspected to represent a fault when superimposed on the geologic map of the area (Fig 2).Structural significance of the lineaments was verified further using audio frequency magnetotelluric of electromagnetic survey according to guidelines of Foundation for Water Research, FWR (2002).

Figures 5, 6 and 7 are typical results from the electromagnetic profiles, each delineating anomalous curves at five different frequency amplitudes and showing five stratigraphic layers. From the graphical modeling, low amplitudes of anomalies signify terrains of low voltage within the subsurface and indicate zones for groundwater prospects. The zones are more delineated where the curves form ‘L’ or ‘V’ shapes (Figs 5 and 6).Vertical interconnection of the V- shaped curves were observed at distance of 280m in Profile 1 (see Fig 5), which falls at the edge of salt lake 2 (see Fig 2) towards northeast of Federal Government College (FGC),Okposi. Similarly, figure 6 shows some vertically correlated L–shaped curves, which are more prominent at distances of 100m and 230m within frequencies 67Hz and 25Hz across profile line 3. The typical shapes according to AIDU instruments (2012) denote fissure controlled saturation zone and represent vertical configuration of fractures. Horizontal alignments of the fractures are observed at depth relative to 170Hz where minimum amplitudes of anomalies dot evenly along the horizontal baselines of the profiles, with typical examples in figures 6 and 7. Extensive U - shaped depression-like anomalies are observed at 67Hz, 25Hz and 10Hz in figure 7, possibly indicating weathered zones within depths relative to the frequencies (Hz) along profile 11, northwards from the old Uburu market (see Fig 2). The fracture diagnostic curves are narrower with sharp edges unlike the extensive sinusoidal curves that discriminated the weathered zone. Comparison with the borehole logs (Figs 3a and b) from the same locality shows that the depths to the fractured and weathered zones range from 33m and increases southeastwards to about 85m. The depth range corresponds to saturation zones where groundwater occurs in the area, and thus signifies general aquifer depths.

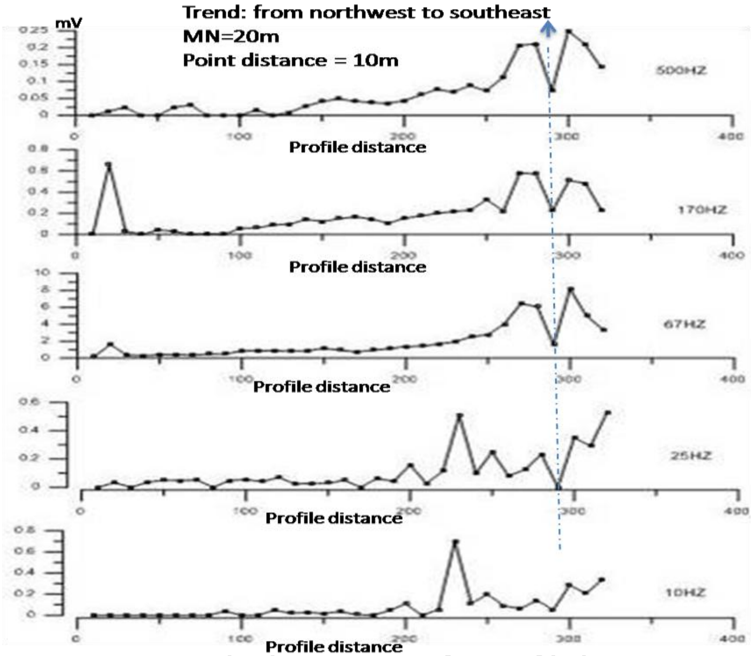


Fig 5: Anomaly change curve for profile line 1

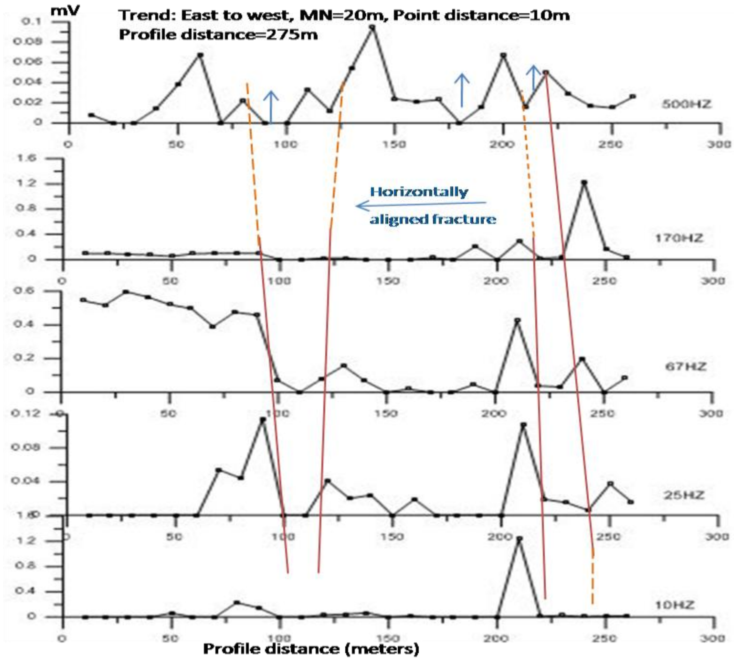


Fig 6 Anomaly change curve for profile line 3

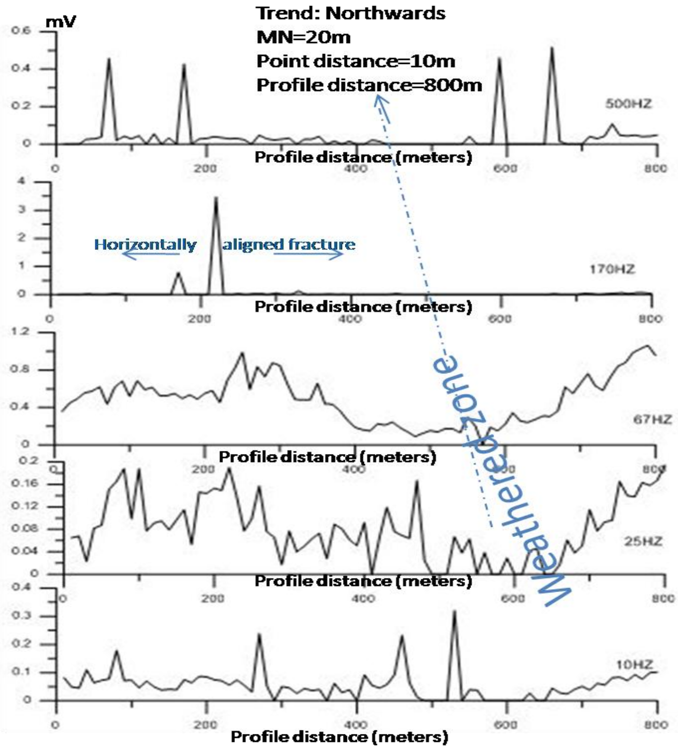


Fig 7: Anomaly change curve for profile line 11

The Aquifer Characteristics

Table 1 presents results of borehole screening that involved the saturated part of the aquifers.The screen lengths are equivalent to various aquifer thicknesses and are requisite in evaluation of aquifer characteristics via pumping test. Tables 2a and 2b present typical results for the pumping and recovery tests respectively.The results show straight line curves that produced drawdown per log cycle, h-h_0 for the pumping phase (Figs 8a and 9a) and residual drawdown per log cycle $(h - h_0)'$ for recovery phase (Figs 8b and 9b).

Table 1:Borehole drilling and screening report

Location number	Drilling Location	GPS reading:		Elevation (meter)	Total drilled depth (meter)	Screen length (meter)	Borehole diameter (millimeter)
		Longitude	Latitude				
	Ohabuenyi Okposi	E07^{0} 48’ 063”	N06^{0} 01’ 373”	78	45.1	13.0	125
	Orie Ugwu mkt., Onicha	E07^{0} 49’ 288”	N06^{0} 05’ 240”	64	48	9.0	115
	Divisional Hqt., Obiozara	E07^{0} 46’ 198”	N06^{0} 02’ 516”	56	51	10.0	112
	Onu ugoni Okposi	E07^{0} 49’ 013”	N06^{0} 03’ 384”	-	47	9.5	120

The drawdown curves show decrease towards a diagonal straight line, signifying drawdown increase with increasing period of pumping (Cooper and Jacob, 1946), a situation that can establish cone of depression (drawdown influence) around the vicinity of the aquifers tapped. According to Kruseman and deRidder (1991), drawdown curve makes it possible to evaluate parameters, such as Transmissivity (T), Hydraulic conductivity (K) and specific capacity when characterizing aquifers of an area. Table 3a presents summary results of some analyzed aquifer parameters in the study area. The results show average recovery transmissivity as 2.23 x 10^{-3}m^2/min (3.21m²/day), average hydraulic conductivity as 2.95 x 10^{-1}m/day, and average specific capacity as 14.38m²/day for the boreholes.The results show that magnitudes of transmissivity in all the surveyed locations are within low range of (1-10m^2/day) as classified in Table 3b. Thus, groundwater tapped from these aquifers can only serve for local or domestic water supply (Krasny,1993). Furthermore, values for the specific capacity indicate low productivity for the boreholes. This implies meager groundwater supply from the aquifers. From the results obtained, it is safe to say that the study area is indeed a groundwater problematic area. This is obviously due to the underlying geology which is mostly made up of poorly bedded shales that form aquicludes, which is a problem to groundwater occurrence. The shales substantially favour high runoff that hampers recharge of meteoric water due to little or no infiltrations (Fetters,2007). Aquifers where they exist as noted in the borehole logs are limited only in fractures and weathered zones which have limited hydraulic conductivity and transmissivity.

Table **2a: Constant Rate -Draw-Down sheet** for PMT2

S/No	T – time since pumping started (minutes)	Water Level (meters)	Draw – down (meters)	Comments and pumping rate (m^3/min)	S/No	t – time since pumping started (minutes)	Water Level (meters)	Draw – down (meters)	Comments and pumping rate (m^3/min)
1.	0.5	5.29	0.41		31.	55	14.50	9.63	
2.	1.0	5.69	0.81		32.	60	14.57	9.69	
3.	1.5	5.11	0.23		33.	65	14.67	9.79	
4.	2.0	6.51	1.66		34.	70	14.70	9.82	
5.	2.5	6.88	2.00		35.	75	14.76	9.88	
6.	3.0	7.23	2.35		36.	80	14.87	9.93	
7.	3.5	7.56	2.68	36 Litres/min	37.	85	14.87	9.99	36 Litres/min
8.	4.0	7.91	3.03		38.	90	14.94	10.06	
9.	4.5	8.26	3.38		39.	100	14.99	10.11	
10.	5.0	8.62	3.74		40.	105	15.04	10.16	
11.	6.0	9.04	4.16		41.	110	15.08	10.20	
12.	7.0	9.44	4.56		42.	115	15.11	10.23	
13.	8.0	9.80	4.92		43.	120	15.14	10.26	
14.	9.0	10.14	5.26		44.	130	15.17	10.23	
15.	10.0	10.48	5.57		45.	140	15.20	10.32	
16.	11.0	10.80	5.92		46	150	15.22	10.34	
17.	12.0	11.12	6.24		47.	160	15.24	10.36	
18.	13.0	11.44	6.56		48.	170	15.26	10.38	
19.	14.0	11.75	6.87		49.	180	15.25	10.37	
20.	15.0	12.06	7.18		50.	190	15.25	10.37	
21.	16.0	12.34	7.86		51..	200	15.26	10.38	
22.	18.0	12.64	7.76		52.	210	15.25	10.37	
23.	20.0	12.93	8.05		53.	230	15.25	10.37	
24.	23.0	13.24	8.36		54.	250	15.25	10.37	
25.	26.0	13.75	8.67		55.	270	15.26	10.38	
26.	30.0	13.83	8.95		56.	290	15.26	10.38	
27.	35.0	14.10	9.22		57.	310	15.26	10.38	
28.	40.0	14.23	9.35		58.	330	15.26	10.38	
29.	45.0	14.23	9.35		59.	350	15.26	10.38	
30.	50.0	14.41	9.53		60.	360	15.26	10.38	

(Note: All Water Levels were measured from the same spot (Static Water Level (Including shoot-out): ***4.88m)***

Table **2b: Constant Rate -Recovery sheet for PMT2**\

S/N	**t´ – time since pumping stop or start of recovery (minutes**	**t – time since pumping started (mi**	**t/t´ – time ratio**	**Water Level (meter)**	**Recovery in meter (m)**
1.	0.5	350.5	701	10.5	5.62
2.	1.0	351.0	351	10.49	5.61
3.	1.5	351.5	234.33	10.48	5.60
4.	2.0	352.0	176	10.37	5.49
5.	2.5	362.5	141	10.13	5.25
6.	3.0	363.0	117.67	10.12	5.24
7.	3.5	353.5	101	9.81	4.93
8.	4.0	354	88.5	9.77	4.89
9.	4.5	354	78.78	9.5	4.62
10.	6.0	356	59.33	9.37	4.49
11.	7.0	357	51.0	8.91	4.03
12.	8.0	358	44.75	8.90	4.02
13.	9.0	359	39.89	8.56	3.68
14.	10.0	360	36.0	8.25	3.37
15.	11.0	361	32.81	8.16	3.28
16.	12.0	362	30.17	7.77	2.89
17.	13.0	363	27.92	7.35	2.47
18.	14.0	364	26	6.88	2.00
19.	16.0	366	22.88	6.43	1.55
20.	18.0	368	20.44	5.79	0.91
21.	20.0	370	18.50	5.59	0.71

22.	25.0	375	15.00	5.51	0.63
23.	30.0	380	12.67	5.47	0.59
24.	35.0	385	11.00	5.40	0.52
25.	40.0	390	9.75	5.33	0.45
26.	45.0	395	8.78	5.29	0.41
27.	50.0	400	8.00	5.24	0.36
28.	55.0	405	7.36	5.22	0.34
29.	60.0	410	6.83	5.20	0.32
30.	65	415	6.38	5.20	0.32

Pump shut-down at t = **350mins**

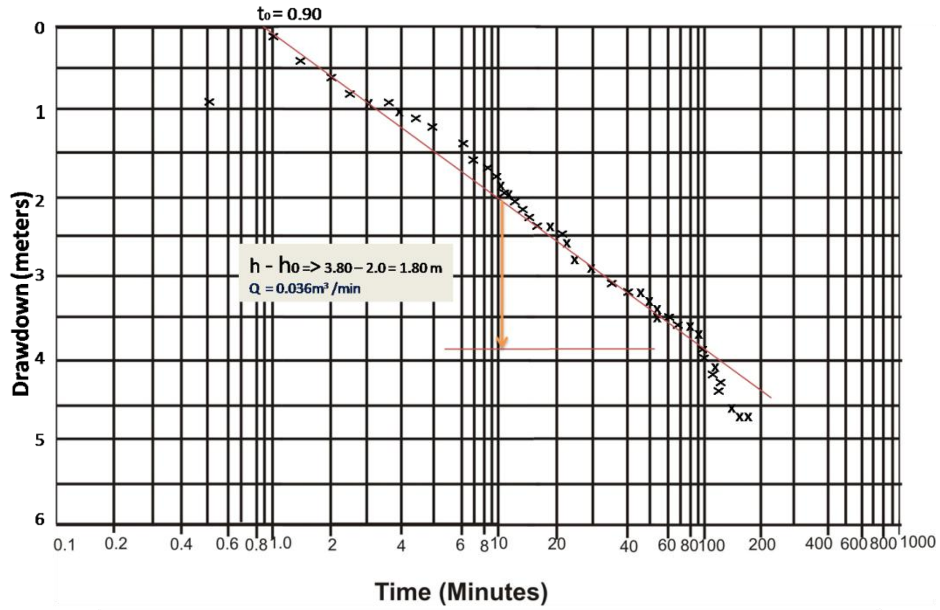


Fig 8a: Pumping Test(PMT) 1- Ohabuenyi-Okposi Okwu: 06° 01’ 373’’N, 07° 48 063’’E

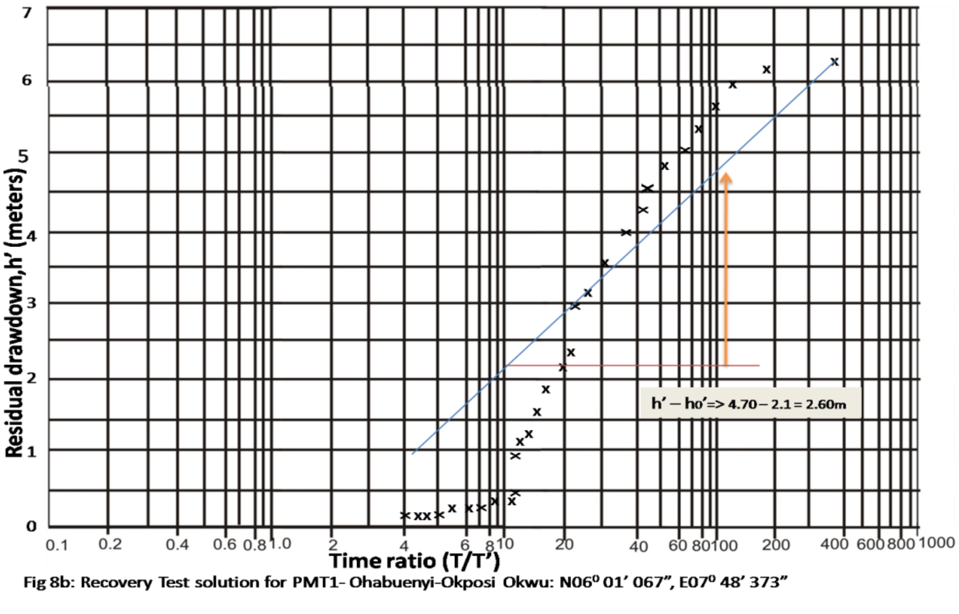


Fig 8b: Recovery Test solution for PMT1- Ohabuenyi-Okposi Okwu: N06⁰ 01’ 067”, E07⁰ 48’ 373”

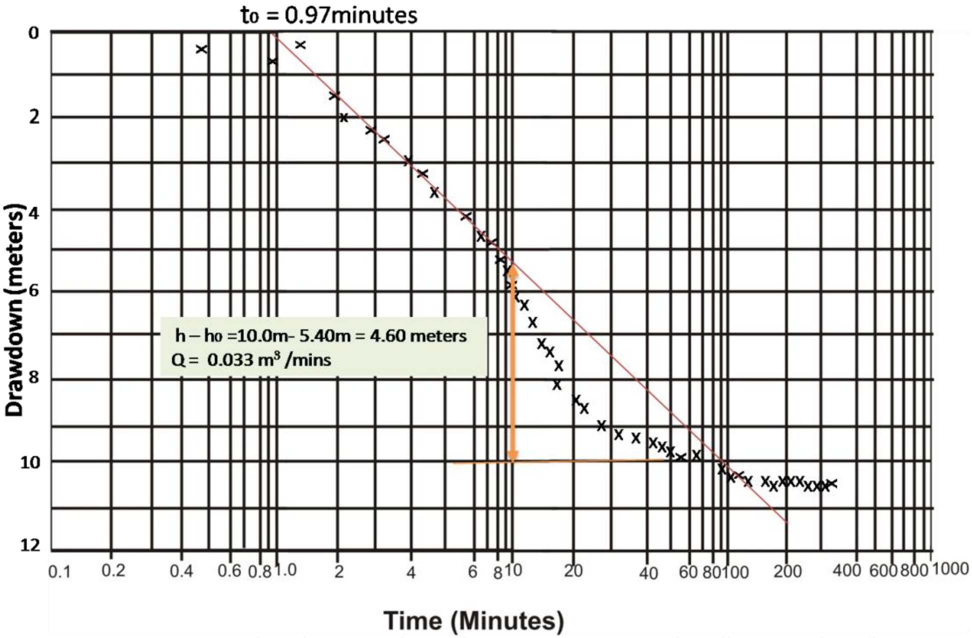


Fig 9a: Pumping Test (PMT) 2 -Orie-Ukwu mkt sq, ONICHA;N06º 05' 240''; E07 º 49' 288''

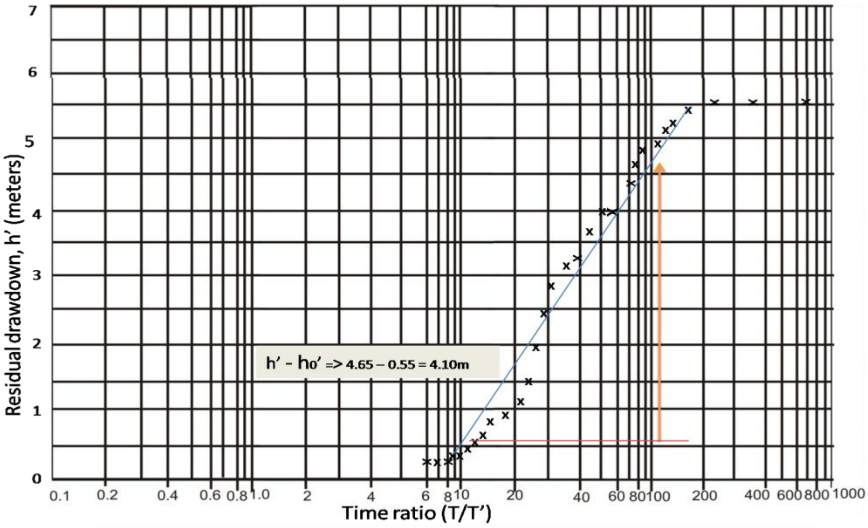


Fig 9b: Recovery Test for PMT 2 -Orie-Ukwu mkt sq, ONICHA: N06º 05' 240''; E07 º 49' 288''

The Aquifer potential and vulnerability

From the figure 8a, a parabolic form of drawdown curve is observed, indicating that aquifers of the study area were recharged with intermittent volumes of groundwater during the pumping test. The irregular volumes denote groundwater recharging from fractures of diverse hydraulic conductivity which ranges from minimum of 2.37 x 10^{-1}m/day to maximum of 4.56 x 10^{-1}m/day (see Table 3a). This type of hydraulic conductivity can be classified as anisotropic and heterogeneous (Todd and Mays, 2011). As discussed by Snow (1969), heterogeneity and anisotropy trends of aquifers depict point and directional properties in joint aperture, by which Freeze and Cherry (1979) highlighted to have been prompted by fracture concentration. The typical fracture forming aquifers in the study area (see Figs 5 and 6) are vertically interconnected, signifying high propensity to subsurface pollutions, especially when rate of abstraction is not compensated with equal recharge rate. Offodile (2002) noted that fractured aquifers across the Lower Benue trough, comprising regions of the study area cannot recharge with equal rates exploited, thereby resulting to steep drawdown. In Uburu-Okposi salt Lakes and environs, poor infiltration rate due to the underlying shales (aquicludes) has resulted to low rate of groundwater recharge, and can be attributed to the high rate of drawdown in boreholes after short period of pumping. Consequently, saltwater of connate origin migrates into the near surface freshwater aquifers through the vertically oriented fractures inorder to balance the quantity of the abstracted water, thus, mineralizing the groundwater system. According to Obaje (2009), salinized connate water was entrapped within the Asu River shale during deposition in the localities of Lower Benue Trough. The situation therefore, has degenerated to polluting groundwater of the study area by saltwater and some associated disolved elements.

Table 3a: Summary results of the aquifer parameters.

Sample Number	Pumping test Location (PMT)	Location code	Flow rate, Q (m^3/min)	Flow rate, Q (m^3/day)	Drawdown $(h – h_0)$ in meters	Residual draw-down $(h-h_0)´$ (m)	Transmissivity, **T** due to pumping Test		Transmissivity, **T** due to RecoveryTest		Hydraulic Conductivity (m/day)	Specific Capacity (m²/day)
							m²/min	m²/day	m²/min	m²/day		
1	Ohabuenyi-Okposi	**PMT1**	0.036	51.8	1.80	2.60	3.67×10^{-3}	5.28	4.12×10^{-3}	5.93	4.56×10^{-1}	19.92
2	Orie Ugwu, Onicha	**PMT2**	0.033	47.5	4.60	4.10	1.20×10^{-3}	2.88	1.48×10^{-3}	2.13	2.37×10^{-1}	11.59
3	Obiozara	**PMT3**	0.033	47.5	2.50	3.50	2.42×10^{-3}	3.48	1.72×10^{-3}	2.48	2.48×10^{-1}	13.57
4	Onu ugoni Okposi	**PMT4**	0.038	54.7	5.40	4.40	1.29×10^{-3}	1.86	1.58×10^{-3}	2.28	2.40×10^{-1}	12.43
Minimum			**0.033**	**47.5**	**1.80**	**2.60**	$\mathbf{1.20 \times 10^{-3}}$	**1.73**	$\mathbf{1.48 \times 10^{-3}}$	**2.13**	$\mathbf{2.37 \times 10^{-1}}$	**11.59**
Maximum			**0.038**	**54.7**	**4.60**	**4.10**	$\mathbf{3.67 \times 10^{-3}}$	**5.28**	$\mathbf{4.12 \times 10^{-3}}$	**5.93**	$\mathbf{4.56 \times 10^{-1}}$	**19.92**
Average			**0.035**	**50.4**	**3.58**	**3.65**	$\mathbf{2.14 \times 10^{-3}}$	**3.08**	$\mathbf{2.23 \times 10^{-3}}$	**3.21**	$\mathbf{2.95 \times 10^{-1}}$	**14.38**

Note: Hydraulic conductivity and specific capacity were estimated from **T**-value due to Recovery Test and residual drawdown respectively.

Table 3b: Classification of Transmissivity Magnitude (according to Krasny, 1993)

Magnitude (m^2/day)	**Class**	**Designation**	**Capacity (m^2/day)**	**Groundwater supply potential**	**Expected Q (m^3/day) at drawdown within 5m**
> 1000	I	Very high	> 864	Regional Importance	> 4320
100-1000	II	High	86.4 – 864	Lesser regional importance	432 – 4320
10-100	III	Intermediate	8.64 – 86.4	Local water supply	43.2 – 432
1-10	**IV**	**Low**	**0.864 – 8.64**	**Private consumption**	**4.32 – 43.2**
0.1-1	V	Very low	0.0864 – 0.864	Limited consumption	0.423 – 4.32
<0.1	VI	Imperceptible	< 0.0864	very difficult to utilize for local water supply	< 0.432

Table 4: Results of geochemical analysis of disolved ions

Sample Number	Sample Location	Sources	pH	Turbidity (NTU)	EC (µS/cm)	TDS (Mg/l))	Na (Mg/l)	K (Mg/l)	Ca (Mg/l)	Mg (Mg/l)	$HC0_3^-$(Mg/l)	NO_3^-(Mg/l)	Total Hardness	Cl (Mg/l)	Fe (Mg/l)	Floride(mg/l)	Temperature (°C)
1	Ohabuenyi	BH	6.50	1.29	470	233	21.2	09.2	16.5	11.8	32.2	10	120	10	0.08	0.34	31
2	Orie Ugwu	BH	6.41	2.63	216	112	34.0	28.0	30.6	20.0	34.6	18	98	206	0.31	0.05	28
3	Obiozara	BH	8.00	0.18	105	155	18.0	20.8	12.5	16.4	28.0	04	105	215	0.70	0.10	33
4	Eweze-Uburu	BH	7.13	1.10	111	69.5	27.8	08.1	18.2	14.5	44.4	35	214	06	0.09	0;08	30
5	Onu-ugoni	BH	6.70	1.15	624	509	16.4	10.2	15.0	18.0	30.5	06	266	291	0.11	0.30	29
6	Umuka	BH	7.3	0.93	465	133	6.3	3.0	14.8	29.4	32.0	Nd	269	106	0.07	0.60	30
Minimum			**6.41**	**0.18**	**105**	**69.5**	**6.3**	**3.0**	**14.8**	**11.8**	**28.0**	**04**	**98**	**06**	**0.07**	**0.05**	**28**
Maximum			**8.0**	**2.63**	**624**	**509**	**34.0**	**28.8**	**30.6**	**29.4**	**44.4**	**35**	**269**	**291**	**0.31**	**0.60**	**33**
Mean			**7.01**	**1.73**	**332**	**202**	**20.6**	**13.2**	**17.9**	**18.4**	**33.6**	**12**	**179**	**139**	**0.23**	**0.25**	**30**
WHO (2004) standard			**6.5-8.5**	**5**[*]	**1400**	**500**	**-**	**12**[*]	**75**	**50**	**-**	**50**	**100**[**]	**250**	**0.30**	**-**	**31**

BH= Borehole sample, *= USEPA, 1975, **=Pratt,1972

As seen in Table 4, potential pollution of the groundwater is indicated with mean values of electrical conductance (EC) as 332µS/cm, TDS as 202mg/l, Na^+ as 20.6mg/l, K^+ as 13.2mg/l, Ca^{2+} 17.9mg/l, Mg^{2+} as 18.4mg/l, $HC0_3{}^-$ as 33.6mg/l, $N0_3^-$ as 12mg/l, Total Hardness as 179mg/l, Cl as 139mg/l, Fe as 0.23mg/l, Flouride as 0.25mg/l, pH as 7.01 and Temperature as 30^0C. About 67% of all the samples are hard whereas other results signify that the groundwater is slightly acidic and alkalinic at normal range of temperature, with which elements rarely disolve in groundwater. Thus, the pollution of groundwater with some elements can be related to intrusions of fluids from a chemical sedimentary layer. For instance, TDS and Chloride ion in the representative sample 5 (Onu-ugoni) are polluting with 509mg/l and 291mg/l respectively. Correspondingly, the polluting level of sodium (Na) and potassium (K) in some of the samples indicates pollutions from saline sources, possibly NaCl and KCl salts. Although, the mean values of the ions are somewhat below WHO (2004) standard, the general concentrations are alarming, such as iron (Fe) with concentrations above the criteria limit in Orie-Ugwu and Obiozara areas. Comparison of results of Table 3a and Table 4 shows that the pollution increases with the high rate of drawdown. As opined by Kruseman and De Ridder (2000), low recharge rate accelerates high rate of drawdown, and can be detected by slanting of the drawdown curve out and below theoritical drawdown curve.

The low recharge rate is observed after 8 minutes of pumping (Fig 9a) where drawdown curve slanted downwards but curved towards the theoritical straight line after 30 minutes and eventually at horizonal plane of equilibrium after 100 minutes of pumping. The equilibrum phase denotes that drawdown influence (cone of depression) have encountered a prolific aquifer zone, possibly a weathered zone where the amount of discharged groundwater was recharged with equal amount. Thus, the quantity of groundwater abstracted can potentially (artificially) be recharged if adequate recharge source is available to the local aquifers by a rehabilitation scheme, such as surface ponding. Todd and Mays (2011) emphasized that recharge from potential infiltration by freshwater ponding is greater than those from actual (natural) infiltration. On a similar note, Ambroggi (1978) states that rate of replenishment of groundwater can be greater than the discharge rate if steady recharge source (ponding) is available. In a consolidated shaley terrain like the study area, where groundwater occurs in fractures, the surface ponding is necessary to enhance recharge, especially at the weathered zone. The steepness of residual drawdown curves indicated from 100 to 10 minutes of induced recharge (Fig 8b) and from 150 to 10 minutes (Fig.9b) imply the possibilility of high infiltration rate and signify that the recharge enhancement is feasible.

It was observed from the graphical analysis that steep slope observed in some parts of the curves denotes high rate of drawdown and near vertical cone of depression during pumping; gentle slope denotes gradual discharge and more expansive cone of depression, whereas horizontal dotting curve for equilibrium level denotes minimal disharge and produces flat and smooth cone of depression. According to Kruseman and De Ridder (2000), the transmissivity of an aquifer is high when the cone of depression is wide and flat but low when the cone of depression is steep and narrow. Results showed that low transmissivity case affects the study area, which would indicate steep and narrow cone of depression if constructed to suggest the low aquifer parameters. The lowest of the aquifer parameters from locations surveyed was observed at PMT1 (Onu-Orie Mkt, Onicha), hence, lateral variation follows that PMT1 > PMT3 > PMT4 > PMT2 (see Table 3a). The aquifers, although localized, they are influenced by fractures and faulting intensity with which the prospect for groundwater decreases northwards as shown in the transmissivity distribution map (Fig.10).

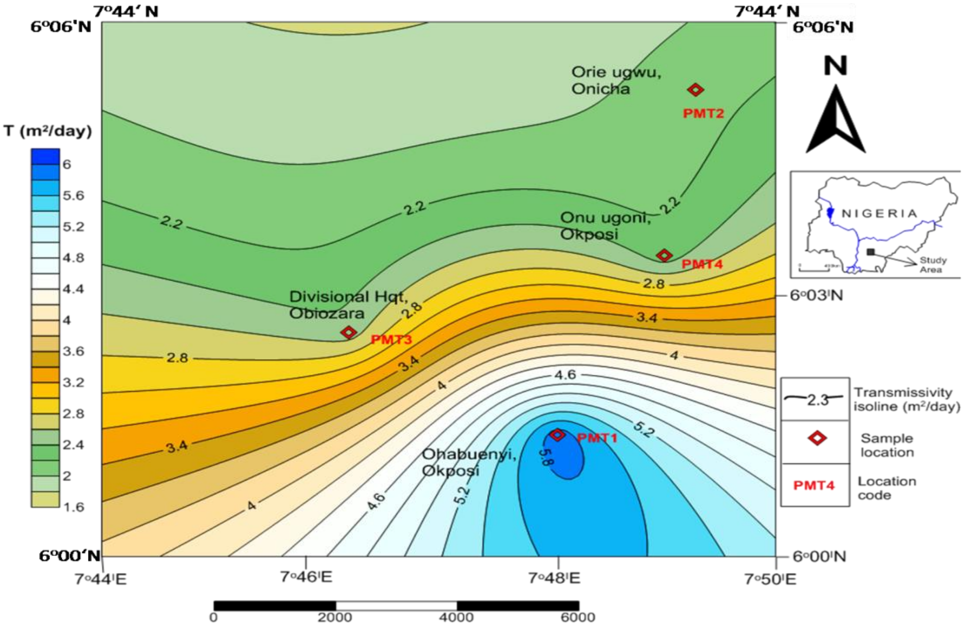


Fig 10: Iso transmissivity map showing aquifer potential and distribution.

IV. Conclusions

The following conclusions are drawn from this study:

(1) The studied area is hydrogeologically problematic because of the underlying geology which comprises mainly of shales that are aquicludes.

(2) Secondary porosity and permeability created few aquifers which can be explored through lineament mapping by the use of Audio-frequency magnetotelluric of electromagnetics (AMT) that delineates weathered and fracture zones through low amplitude anomalies.

(3) All the aquifers are characterized by low aquifer parameters such as transmissivity and hydrualic conductivity, as well as low specific capacity, indicating that groundwater supply in the area is low and can serve only private (domestic) or local use.

(4) Groundwater development through boreholes in the area fails because of steep drawdown caused by groundwater abstraction without equal recharge rates.

(5) The steep drawdown has influenced the intrusion of saline fluid into freshwater aquifers after some periods of pumping. The salinity emanates from a suspected deep saline rich sedimentary layer through some vertically oriented porous media. Thus, pollution of groundwater in area increases with increase in drawdown and vice-versa.

(6) Aquifers formed from weathered areas are more prolific than those formed from fracture because recharge rate in the former is eqaul to discharge rate and can offset the effect of drawdown in the boreholes.

(7) Groundwater rehabilitation is possible through artificially enhanced recharge. Such recharge will involve surface water ponding towards the weathered and fractured zones, especially in the southern parts of the area where there are more groundwater prospects.

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