Geostatistical Assessment of Aquifer Characteristics and Identification of Groundwater Development Priority Zones: A Case Study of Owerri and Some Selected Towns in Imo State

Kennedy O. Achilike
Department of Industrial Physics
Abia State University Uturu, Nigeria.

Abstract:- The aim of the study is to estimate the hydraulic characteristics of the aquifer units based on geostatistical parameters from surface geophysics. A total of seventeen (17) Vertical Electrical Sounding data were acquired to identify groundwater development priority zones in Owerri and some selected towns in Imo State. Five key factors that affect and control groundwater potential and vulnerability were utilized in the development of the geostatistical models which are groundwater potential index (GWPI), groundwater vulnerability index (GWVI) and groundwater development index (GWDI). These factors are depth to water (d), aquifer thickness (h), Mean Resistivity of aquifer (ρ_m), Transverse unit Resistance (R_T) and Protective capacity (P_C) of the overburden units of the aquifers. The geostatistical parameters estimated values for the study area are GWPI, 14 to 34, GWVI, 19 to 36 and GWDI 0.48 to 1.60. The rating of the study area based on the geostatistical parameters of GWDI revealed that the study area can be classified into six groundwater development priority zones: excellent (GWDI $\geq$ 1.60), very high ($1.60 <$ GWDI ≥ 1.28), high ($1.28 <$ GWDI ≥ 0.96), intermediate ($0.96 <$ GWDI ≥ 0.64), low ($0.64 <$ GWDI ≥ 0.32), very low ($0.32 <$ GWDI ≥ 0.10), negligible (GWDI < 0.10) designations. The geostatistical parameters would help to reduce the additional expenditures of carrying out pumping tests and offer an alternative approach for estimating hydraulic parameters, as it would give the estimation of the yield and quality/protective capacity of a prospective borehole in the area.

Keywords:- *Groundwater Potential; Groundwater Vulnerability; Groundwater Development; Transmissivity and Hydraulic Conductivity.*

I. INTRODUCTION

Depletion of water levels in aquifers and decline in design yield of wells due to excessive pumping in the absence of adequate knowledge on groundwater availability are becoming a major concern across the globe (Babiker et al., 2005; Kendy et al., 2003). As a response to the problems, approaches like artificial aquifer recharge, managed aquifer recharge, recharge area protection, and construction of underground storage dams are being discussed and practiced to some extent (Bouwer, 2002, Dillon, 2005 and Kumar et al., 2008). For an effective planning of the activities aimed at recovering aquifer depletion and maintaining the health of groundwater ecosystem, estimates of groundwater storage volume and its spatial distribution could be useful. The estimated volume, if analyzed together with other hydrogeologic characteristics, may help delineate potential areas for groundwater development. Such estimates could further be used for the development of management strategies aimed at sustainable use of the groundwater resources.

The existing techniques for the delineation of potential areas for groundwater development are based either on a single indicator that may not be adequate to reflect several aspects of groundwater development or too many indicators which may not be readily available for a target area. For example, the existing methods may be based on the length of screened sections in the aquifer (Kharel et al.,1998), groundwater storage volume (Johnson and Njuguna, 2002; Wahyuni et al., 2008), hydrogeomorphology and existing bore wells characteristics (Puranik and Salocke, 2006), multi-parameters data on groundwater comprising of land use, Hydrogeomorphology, lithology, soil rainfall, water level, aquifer thickness, permeability, suitability of groundwater (for drinking and irrigation) measured either in the field or from remote sensing (Jaiswal et al., 2003; Krishanamurthy et al., 1996 and murthy, 2000). Several factors are considered in those studies. Therefore, there is need for a method that can delineate the potential area for groundwater development from a reasonable number of logically relevant hydrogeologic parameters.

The objective of this study is to propose a geostatistical technique to delineate potential areas for groundwater development based on hydrogeophysical analogues of the relevant hydrogeologic parameters. In the proposed method, several parameters related to groundwater yield potential used in the earlier approaches are represented by five parameters, thus reducing greatly the number of parameters to be used in the analysis. The proposed geostatistical techniques are termed groundwater potential index, (GWPI), groundwater vulnerability index (GWVI) and groundwater development index (GWDI) models. The groundwater potential index (GWPI) and groundwater vulnerability index (GWVI) proposed in this study integrated all the relevant factors of availability and protection of groundwater resources. Taking the ratio of GWPI to GWVI, a groundwater development priority index called groundwater development index (GWDI) has been proposed for the evaluation of the groundwater resource availability and vulnerability.

The GWPI and GWVI geostatistical models are point count indexes modified after some existing methods such as DRASTIC and CALOD to produce groundwater potential and vulnerability maps of aquifers. DRASTIC is an acronym for the seven factors considered in the generation of groundwater vulnerability maps: Depth to water, Net recharge, aquifer media, soil media, Topography, Impact of the vadose zone media, Hydraulic conductivity of the Aquifer. CALOD is derived from clay layer thickness, Aquifer media, lateritic layer thickness, overlying layer character, Depth to groundwater level. The DRASTIC and CALOD models were developed from hydrogeologic and anthropogenic factors (Aller et al., 1987).

As is the case with any model, more parameters also meant that more data are necessary to calibrate and ultimately use the model. Additionally, uncertainties in the relative weights in the model would make it extremely difficult to calibrate. For these reasons, a simpler model is preferred to a complicated model for the practical application.

The GWPI, GWVI, and GWDI are the alternative models proposed in this study that could provide guidance for estimating groundwater characteristics on a regional or local level.

II. THE STUDY AREA

The study area (fig. 1) is located on latitudes $5^{0}40'$N – $5^{0}17'$N and longitudes $6^{0}55'$E – $7^{0}12'$E.
It is comprised of selected towns and villages around Owerri within a radius of 10 km.

The terrain of the study area is characterized by two types of land forms: high undulating and nearly flat topography. Borehole lithologic logs reveal that the undulating hills and ridges are under lain by a succession of thick unconsolidated sand stones and relatively thin clay units belonging to the Benin formation.

The sediments of the Benin formation are lenticular, unconsolidated, coarse to medium fine-grained sands with localized beds of fine sands and clayey sand. The sand units are mostly coarse grained, pebbly, poorly sorted and contains lenses of fine – grained sands (short and stauble, 1967; Onyeagocha, 1980).

The very porous and permeable character of the Benin formation (coastal plain sands), the overlying lateritic earth and the weathered top of this formation as well as the underlying clay/shale member of the Bende Ameke Series provides the hydrologic conditions contributive to aquifer formation in the area.

Some of the towns and villages within the southern part of the study area include: Irete, Obinze, Mgbirichi, Umuokanne, Umuagwo, and located in the northern parts are Orogwe, Ohii, Akwakuma, Orji, Mbieri Nworieubi, Ihuo, Atta, Orodo and Amaraku. Network of motorable roads, both tarred and untarred, as well as footpaths make access to most parts of the area possible (fig. 1).

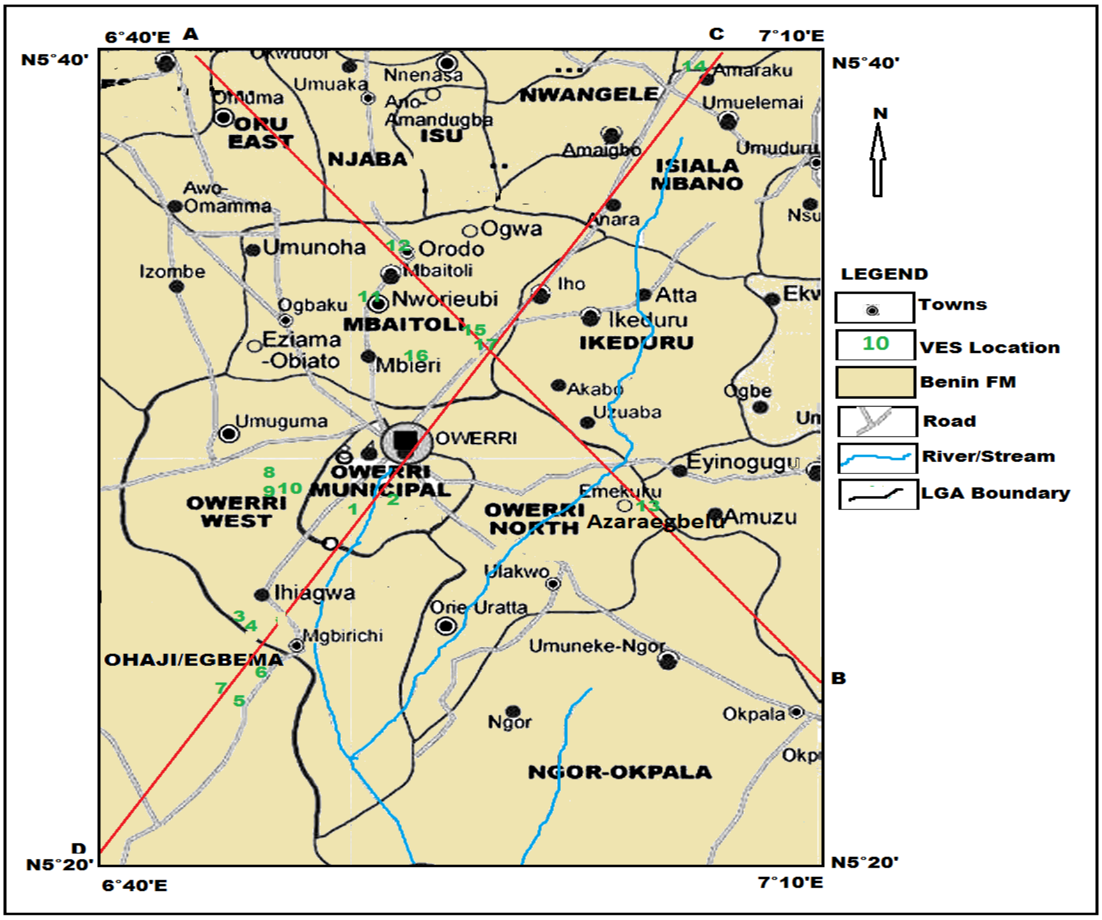


Fig 1:- Map of Study Area Showing Access Roads and the Location of Sounding Stations

III. METHODOLOGY

The modes of study include:

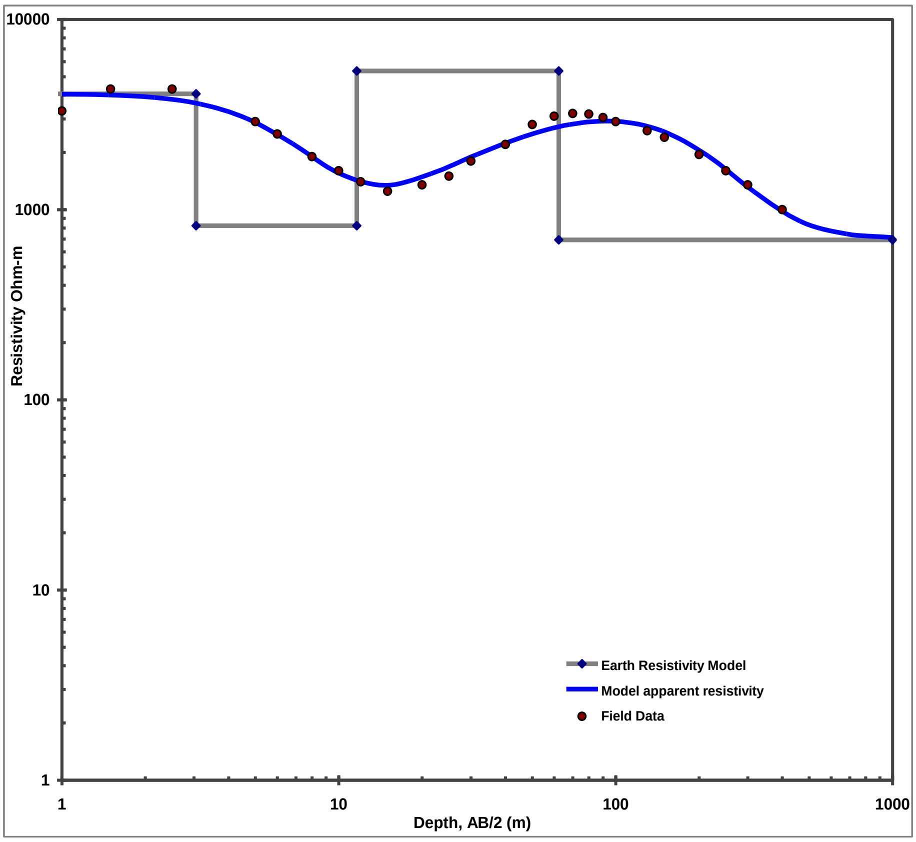
- Acquisition and interpretation of VES data
- Determination of aquifer parameters from the VES results
- Geostatistical models for the delineation of groundwater development priority zones.

A. Acquisition and Interpretation of VES Data

The data employed in this study, is a summary of aquifer parameters at 17 stations in the study area. A total of seventeen (17) VES stations were sampled and the summary of the results of the quantitative interpretation from the computer modeling of the VES data is shown in table 1. In the qualitative interpretation of the field results, the shape of the field corves (H, K, A, Q) was observed to get an idea quantitatively about the number of layers and the resistivities of the layers. Figures 2 shows a typical geoelectric type curve obtained in the study area.

Number of Layers	4		
Layer NO	Thickness (m)	Depth (m)	ρ (Ω-m)
1	3.05	3.05	4069.60
2	8.55	11.60	822.60
3	50.68	62.28	5363.90
4	-		693.50
-	-		
-	-		
-	-		
-	-		

FIELD DATA	
AB/2 (m)	ρa (Ω–m)
1.0	3300.00
1.5	4300.00
2.5	4300.00
5.0	2900.00
6.0	2500.00
8.0	1900.00
10.0	1600.00
12.0	1400.00
15.0	1250.00
20.0	1350.00
25.0	1500.00
30.0	1800.00
40.0	2200.00
50.0	2800.00
60.0	3100.00
70.0	3200.00
80.0	3180.00
90.0	3050.00
100.0	2900.00
130.0	2600.00
150.0	2400.00
200.0	1950.00
250.0	1600.00
300.0	1350.0
400.0	1000.0



VES NUMBER:	1	DIRECTION LAYOUT:	N - S	DATE:	March 24, 1991
LOCATION:	OWERRI MUNICIPAL, IMO STATE				
COORDINATES:	5°28'15.3"N	7°01'58.3"E		ELEVATION :	61m
PROJECT	RESEARCH WORK				

Fig 2:- Typical iterated sounding curve of the study area at VES 1

S/N	VES TOWN	Curve type	h	d	ρ_m	GWP1	GWV1	GWD1	$K\sigma$	P_c	R_T	λ
1	OWERRI	HK	50	62	3769	91	31	0.61	2.38	0.011	271868	1
2	OWERRI	HK	72	85	6950	25	27	0.92	3.56	0.008	494723	1.41
3	OBINZE	KQQQ	419	425	2186	16	19	0.84	8.60	0.085	442610	1
4	OBINZE	KQHK	208	211	2493	14	26	0.53	26.70	0.037	373573	1
5	OHAJI	AAKH	142	143	783	14	29	0.48	2.75	0.022	39573	1
6	OHAJI	HKHK	87	88	1616	16	27	0.59	2.95	0.027	154887	1
7	OHAJI	AKHK	205	207	2852	17	26	0.65	5.07	0.043	412312	1
8	IRETE	KHK	191	202	2641	17	27	0.65	6.58	0.036	505183	1
9	OROGWE	HK	28	393	5726	25	34	0.73	1.42	0.004	223896	1
10	OROGWE	HK	69	85	7053	28	24	1.16	3.71	0.009	741180	1
11	NWAORIEUBI	HK	176	185	7263	32	20	1.60	9.33	0.013	1600000	1
12	ORODO	HK	162	177	7550	32	20	1.60	8.91	0.020	1900000	1.41
13	AZARAEGBELU	HAAK	65	68	6399	25	30	0.83	1.99	0.011	452965	1
14	AMARAKU	HK	138	154	4685	20	36	0.76	6.85	0.024	954135	1
15	MBIERI	AK	106	118	4951	25	30	0.38	5.40	0.008	632792	1
16	MBIERI	KHK	71	75	4667	22	30	0.73	3.27	0.014	484001	1
17	MBIERI	KHK	48	53	9061	34	24	1.41	2.69	0.017	1400000	3

Table 1:- Groundwater development index for Owerri and some selected Towns in Imo State

B. Determination of Aquifer Parameters from the VES Results

The general shape of the resistivity curves from the qualitative results of the VES interpretation suggests that the transverse resistance of the aquifer is the dominant Dar zarrouk parameter for the estimation of transmissivity (T) in the study area

$$T = K\sigma R_T \qquad (1)$$

The results of the qualitative interpretation as shown in table (1) above, indicates that majority of the field curves are terminated by the K – type and Q – type shapes while minority of the field curves ended in the H -type and A - type segments. Frollick and Kelly (1985) observed that the transverse unit resistance (R) is the dominant Dar – Zarrouk parameter for a layer where the electrical current tends to flow perpendicular to the bedding plane and therefore controls the shaped of a K – shaped sounding curves . But when the electrical current flows parallel to the bedding plane as in a H – type curve, the longitudinal unit conductance (L_c) is the dominant Dar zarrouk parameter for estimation of transmissivity.

C. Development of Geostatistical Models

The geostatistical models are point count index method modified after some existing aquifer vulnerability methods such as DRASTIC and CALOD to produce groundwater potential/vulnerability maps. These maps are designed to show respective areas of greatest potential for prolific groundwater availability and/or extreme contamination on the basis of hydrogeologic and anthropogenic (human) factors (Amah et al., 2008). DRASTIC is an acronym for the seven factors considered in the method: Depth to water (D) Net Recharge (R), Aquifer media (A), Soil media (S), Topography (T), Impact of vadose zone media (I), and Hydraulic conductivity of the aquifer (C), (Aller et al, 1987). CALOD is derived from clay layer thickness (C), Aquifer media character (A), lateritic layer thickness (L), Overlying layer character (O), and the depth to groundwater level (D) (Edet, 2004). The factors which influence groundwater availability are most likely to influence its pollution potential. DRASTIC and CALOD have been modified by the five hydrogeophysical factors to produce GWPI and GWVI used as site evaluation model and groundwater quality assessment method respectively.

The geostatistical models adopted in this study are an integration of five input parameters namely: depth to water (d), aquifer thickness (h), mean resistivity of aquifer (ρ_m), transverse units resistance (R_T) and protective capacity (P_c) of the overburden units of the aquifer. The GWDI model is the groundwater development priority rating based on the ratio of GWPI/GWVI.

D. Development of GWPI and GWVI Models

The method of computing the groundwater potential index (GWPI) and groundwater vulnerability index (GWVI) involve three steps. The first step was to assign weightings to the relevant geoelectric parameters with their total units summed up to 10. The second was to divide the parameter value into ranges and third was to computer the index.

E. GWPI and GWVI Weightings

GWPI and GWVI parameters were assigned weightings ranging from 1 to 3 on the basis of their relative importance in groundwater exploration and evaluation.

S/N	**Parameters**	**Weightings (units)**
1	Thickness, h	1
2	Depth, d	3
3	Transverse Resistivity, R_T	3
4	Means resistivity ρ_m	3

Table 2:- Assigned Weightings (w) to the GWPI Parameters.

S/N	**Parameters**	**Weightings (units)**
1	Thickness, h	1
2	Depth, d	3
3	Protective capacity, P_C	3
4	Means resistivity ρ_m	3

Table 3:- Assigned weightings (w) to the GWVI parameters.

The thickness of the aquifer h is characterized by approximately uniform thickness (Amah et al., 2008). Besides aquifer thickness is limited to screen length of the abstraction borehole. Thus, it was assigned the least weighting factor of 1. The depth d, transverse resistance (R_T) and mean resistivity (ρ_m) play a significant role in groundwater utilization (Aller et al., 1987). The protective capacity P_c is a measure of the impermeability of the overburden layers of the aquifer which affects the vulnerability of aquifer to surface contaminants. Consequently, the four parameters were assigned a weighting factor of 3 since they determine the hydrogeologic properties which affect the availability and quality of groundwater.

F. GWPI and GWVI Ratings

The GWPI and GWVI parameters were divided into different class intervals and a rating assigned to each class interval (table 4,5, 6 and 7).

	ρ_m	R_T	d	H
Max	9061	1600000	425	419
Min	783	39573	39	28
Range	8278	1560427	386	391

Table 4:- Ranges of the various categories of the hydrogeoelectric parameters for GWPI.

		A **Prolific**	B **High**	C **Medium**	D **Low**
S/N	**Parameters**	**4**	**3**	**2**	**1**
1	ρ_m (ohm-m)	≥ 6991	≥ 4922	≥ 2852	< 2852
2	R_T (ohm-m^2)	≥ 1209893	≥ 819786	≥ 429679	< 429679
3	d (m)	≤ 39	≤ 135	≤ 232	> 232
4	h (m)	≥ 321	≥ 223	≥ 125	< 125

Table 5:- Assigned GWPI rating to various categories of hydrogeoelectric parameters

Class – rating
A – prolific
B – High
C – Medium
D- Low

GWP1 $\propto R_T \propto \frac{1}{d} \propto \rho_m \propto$ h (2)

The most significant interval is a rating of 4 and the least is a rating of 1.

	ρ_m	P_C	D	H
max min	9061 783	0.085 0.004	425 39	419 28
Range	8278	0.081	386	391

Table 6:- Ranges of the various categories of the hydrogeoelectric parameter for GWVI.

		A **Extreme**	B **High**	C **Medium**	D **Low**
S/N	**Parameters**	**4**	**3**	**2**	**1**
1	ρ_m	≤ 2852	≤ 4922	≤ 6991	> 6991
2	Pc	≤ 0.004	≤ 0.024	≤ 0.044	> 0.044
3	D	≤ 39	≤ 135	≤ 232	> 232
4	H	≤ 28	≤ 125	≤ 223	> 223

Table 7:- Assigned GWVI rating to various categories of hydrogeoelectric parameters

Class – rating
A - Extreme
B - High
C - Medium
D – Low

GWV1 $\propto \frac{1}{P_c} \propto \frac{1}{d} \propto \frac{1}{h} \propto \frac{1}{\rho_m}$ (3)

The groundwater potential index GWPI and GWVI, was then computed by taking the sum of the products of weightings with ratings over all the four geoelectric parameters. Mathematically,

GWPI = $\rho_{mw}\rho_{mr} + R_{Tw}R_{Tr} + d_w d_r + h_w h_r$ (4)
GWVI = $\rho_{mw}\rho_{mr} + P_{cw}P_{cr} + d_w d_r + h_w h_r$ (5)

Where w = weighting and r = rating for the different GWPI and GWVI parameters.

GWDI = $\frac{GWP_i}{GWV_i}$ (6)

The computed GWPI, GWVI and GWDI values were then used to develop a semi quantitative overall rating scale (R) for the classifications of groundwater at a borehole site (table 8 - 10).

Class	**GWP1 (R)**	**Groundwater potential**
A	> 30	Prolific
B	≤ 30	High
C	≤ 20	Medium
D	≤ 10	Low

Table 8:- Classification of Groundwater Potential at a Borehole Site

Class	**GWVI (R)**	**Groundwater vulnerability**
A	> 30	Extreme
B	≤ 30	High
C	≤ 20	Medium
D	≤ 10	Low

Table 9:- Classification of Groundwater Vulnerability at Borehole Site

Class	**GWDI (R)**	**Groundwater development**
A	≥ 1.35	Excellent/Very High
B	≤ 1.30	Very High/High
C	≤ 1.05	High/ Intermediate
D	≤ 0.80	Intermediate/Low
E	≤ 0.55	Low

Table 10:- Classification of Groundwater Development at Borehole Site

Sulfer 12 GIS software was used to contour the distribution pattern of the relevant parameters employed in this study. The thematic maps of GWPI, GWVI and GWDI provided the means to identify areas suitable for groundwater development. The results of GWPI, GWVI and GWDI thematic mapping applied to the entire area of study are presented in figure 3, 4 and 5.

➢ *GWPI*

Fig. 3 is the groundwater potential map of the study area. The groundwater potential map presents the groundwater prospects of the area which is zoned into A (GWPI $\geq$ 30), B ($29 < GWPI \leq 25$), C ($24 < GWPI \leq 21$) D ($20 < GWPI \leq 16$) and E ($15 < GWPI \leq 14$).

Zone A with red colour on the map constitutes the prolific groundwater potential zone (i.e. VES 11, VES 12 & VES 17). While zone B with yellow colour represents the high groundwater potential zone (i.e. VES 2, VES 9, VES 13, VES 10 &VES 15). Zone C with green colour is the medium groundwater potential zone (i.e. VES 16). The other zones include zone D with blue colour which is the low groundwater potential zone (i.e. VES 1, VES 6, VES 3, VES 7 & VES 8), Zone E with violet colour represents the very low groundwater potential zone (i.e. VES 4 & VES 5)

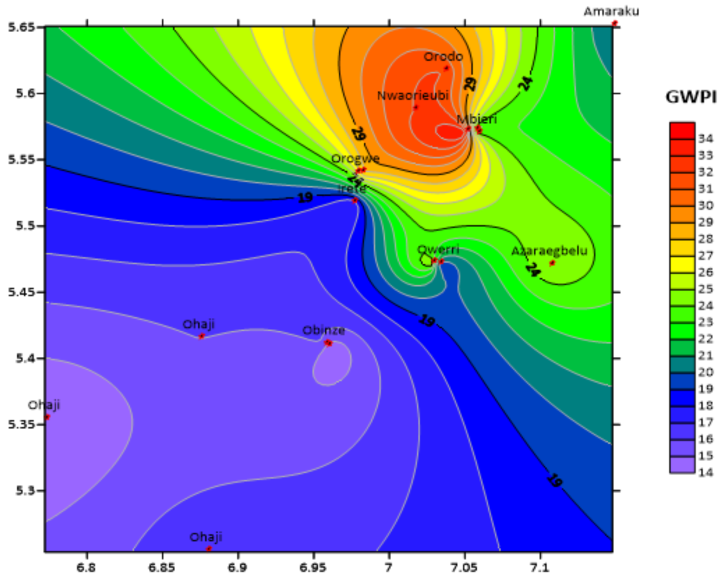


Fig 3:- Map of GWPI

➢ *GWVI*

The study area as shown in fig. 4 has been zoned into five classes according to their vulnerability to near surface contaminants: zone A ($GWVI \geq 32$) Extreme; zone B ($31 < GWVI \leq 29$) very high/extreme; zone C ($28 < GWVI \leq 25$) Very High; zone D ($24 < GWVI \leq 22$) High; zone E ($21 < GWVI \leq 19$) medium / high.

The $GWVI$ obtained from the study area range from 19 to 36 and according to table 9 and fig 4 the area could be zoned as Extreme (VES 9 & 14), Very High / Extreme (VES 1, 5, 13, 15 &16), Very High (VES 2 , 4, 6, 7, & 8), High (VES 11 & 17) and Med/High (VES 3, 10 & 12) groundwater vulnerability.

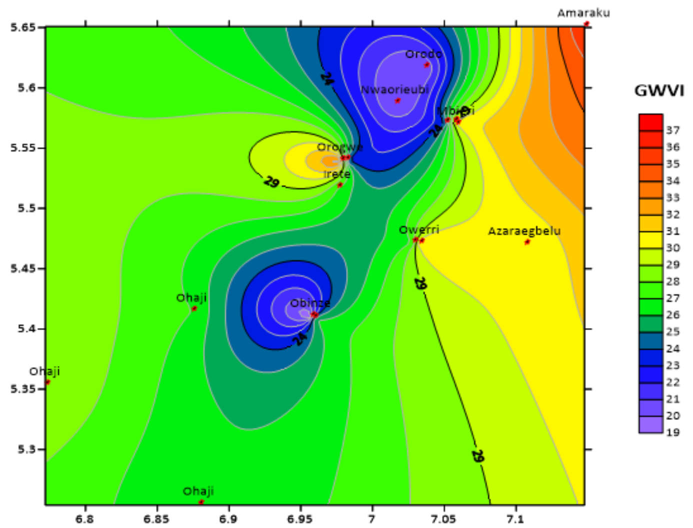


Fig 4:- Map of GWVI

➢ *GWDI*

Fig. 5 is the groundwater development map of the study area. The GWDI of the study area is zoned into five classes: zone A (GWDI ≥ 1.35) Excellent / Very High; zone B (1.34 < GWDI ≤ 1.10) Very High / High; zone C (1.09 < GWDI ≤ 0.85) High/Intermediate; zone D (0.84 < GWDI ≤ 0.60) Intermediate/Low; zone E (0.59 < GWDI ≤ 0.40) Low. Table 10 shows the GWDI rating. The GWDI obtained from the study area range from 0.48 to 1.60 and according to table 10 and fig. 5 the area could be zoned as A (VES 17, 11, 12); Zone B (VES 10); zone C (VES 3, 2, 13, 15); zone D (1, 7, 6, 8, 9, 14, 16); zone E (4, 5).

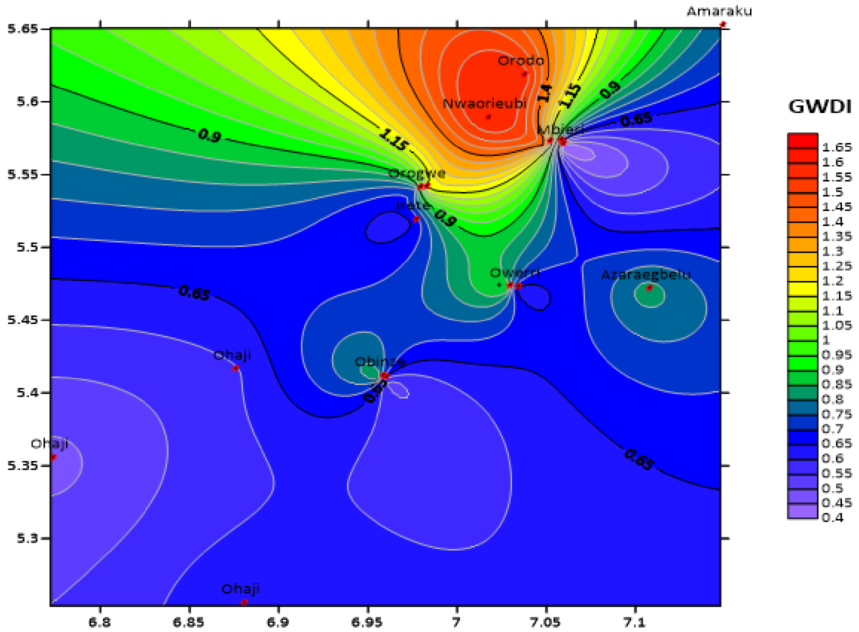


Fig 5:- Map of GWDI

IV. CONCLUSION

In this study, the groundwater potential and vulnerability to surface contaminants of the aquifers in Owerri and some selected towns in Imo state were undertaken using (17) schlumberger vertical electrical soundings (VES). The curve type varied from HK, AK, KHK to KQQQ, KQHK, AAKH, HKHK and AKHK. About fifteen (15) VES which is about 88% of the curve types terminated in K shape segment. This suggests that the predominant Dar-zarrouk parameters for estimation of the transmissivity values in the study area is the transverse unit resistance.

The study also revealed that the abnormally high values of aquifer thickness and depth recorded at VES 3 may be due to an anisotropic effect associated with the principle of suppression of intermediate layers in the interpretation of VES curves. The abnormally high aquifer resistivity values at VES 2, 12, 17 and overestimation of aquifer layer thickness at VES 3 may be due to the effect of anisotropy on the interpretation of vertical electrical sounding. Based on the geostatistical estimation of groundwater development priority, it was observed that VES 11 has the highest GWDI value of 1.60 indicating excellent groundwater development priority rating while VES 5 with GWDI value of 0.48 has the lowest GWDI priority rating.

It is envisaged that the results of this study would provide reliable information for an elaborate groundwater abstraction and environmental factors necessary for planning and development of residential and industrial estates by the urban planning authorities. For effective groundwater development programmes in the study area, it is recommended that pre-drilling geophysical investigations be carefully conducted for economic and environmental purposes.

ACKNOWLEDGEMENT

Special thanks to GEOPROBE INTL` NIG. LTD Owerri, for helping in acquisition of the VES data. Author is grateful to Okezuonu Patrick Chinedu for his immense support in this research work.

REFERENCES

[1]. Babikar S., Mohammed M., Hiyama T., Kato K. (2005). A GIS based drastic model for assessing aquifer vulnerability in Kahamighara heights, Gifu prefecture, central Japan. Sci total Environ **345**: 127 – 140.

[2]. Bouwer H. (2002). Artificial recharge of groundwater: hydrogeology and engineering hydrogeology **10(1)**: 121 – 142.

[3]. Kharel B. D., Shrestha N. R., Khadka M. S., Shrestha M. P. (1998). Hydrogeological conditions and potential barrier sediments in the Kathmandu valley. Final report of the technical cooperation project-Environment. Geology between Kingdom of Nepal, HMG and Federal republic of Germany.
[4]. Johnson T. A. & Njuguna W. M., (2002) Aquifer storage calculation using GIS and MODFLOW, LOS Angeles county, California. In ESRI user conference proceedings, San diego, USA.
[5]. Wahyuni S., Oishi S., Sunada K. (2008). The estimation of the groundwater storage and its distribution in Uzbekistan. Ann J hydraulic Eng **52**: 31 – 36
[6]. Puranik S. C. & Salokhe S. V. (2006). Delineating groundwater potential areas based on bore well characters in Kodoli Basin, Panhala Tahika, Kohalpur district, Maharash tra. In: Rejan S, Pandey P. C (eds). Antartic geoscience, Ocean-atmosphere interaction and Paleoclimatology, PP 307-317. National center for Antartic and ocean research (NCAOR), Goa, India.
[7]. Jaiswal R. K., Mukharjee S., Krishnamurthy J., Saxena R. (2003). Role of remote sensing and GIS techniques for generation of groundwater prospect zones towards rural development: an approach. Int J. remote sense. **24(5):** 993 -1008
[8]. Aller L., Bennet T., and Petty R. J. (1987): Drastic: 9 standardized system for evaluating groundwater pollution potential using hydrogeologic settings. US Environmental protection Agency, Washington D. C, 455.