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Estimates of Aquifer Hydraulic Characteristics and Vulnerability from Surface Resistivity Data: Case Study of Ugep and Environs, Southeastern Nigeria

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Abstract- Detailed hydrogeophysical study of Ugep and environs was carried out to determine the aquifer hydraulic parameters using Dar-zarrock parameters. Forty (40) vertical electrical sounding (VES) data were acquired using the digital Terrameter, SAS 4000 model. The Schlumberger configuration with a maximum current electrode spacing (AB) of 1000 meters was used for data acquisition. Twelve (12) parametric soundings were carried out near existing boreholes where pumping test data were available for correlative purposes and to constrain model predictive parameters. The VES data were interpreted using the conventional partial curve matching technique to obtain initial model parameters which were later used as input data for computer iterative modelling. The layer parameters thus obtained from the analysis were combined with information from litho-logs and pumping test data from existing boreholes to estimate aquifer hydraulic parameters using Dar-Zarrouk parameters. Results of the study revealed the aquifer resistivity in the study area ranges from 34.9Ωm at VES 3 to 3920Ωm at VES 32.The depth to the water table range from 12.4m - 147m with a mean value of 67.96m, while aquifer thickness varies from 5.7m to 123m with a mean value of 47.3m.The values of the Dar-Zarrock parameters revealed that the transverse resistance varies between 84992Ωm^2 to 1106.33Ωm^2 with a mean value of 19,817Ωm^2 while the longitudinal conductance has a mean value of 0.2848mhos/m. Similarly, hydraulic conductivity in the area ranges from 0.06m/day to 83.37m/day with a mean value of 12.75m/day, while the transmissivity values ranges from 2.233m^2/day to1784.83m^2, with an average of 375.93m^2/day. Estimates of aquifer vulnerability rating indicates that about 2.5% of the study area has a low class of groundwater vulnerability to contamination, whereas 55% of the study area indicated moderate aquifer vulnerability with DRASTIC index ranges of 107 to 140. It was also revealed that about 42.5% of the study area falls within the high aquifer vulnerability zone with a DRASTIC index value of between136-177.

Keywords: Aquifer hydraulic parameters, Dar- Zarrock parameters, DRASTIC, Vulnerability, Resistivity, Ugep, Calabar Flank, Vertical Electrical Sounding.

1.0 INTRODUCTION

Sedimentary basins worldwide have been shown to generally possess enormous hydrological and hydrogeological potentials due to their good porosity, permeability and hydraulic conductivity [1], [2], [3].The sedimentary sequences of southeastern Nigeria are known to contain several aquiferous units [3]. Several authors have over the years successfully estimated aquifer hydraulic characteristics from Dar-Zarrouk parameters in many parts of Southeastern Nigeria from surface electrical resistivity sounding data [4],[5],[6],[7],[8]. Studies carried out by [1], [9],[10], have helped to improve proper management and optimization of the hydrogeological potentials of basins in order to enhance safe discharge of the groundwater resources and for appropriately safeguarding the quality status of the groundwater resources. Nevertheless, the features of these aquifers such as transmissivity, hydraulic conductivity and storage potentials are yet to be fully understood because of the complex geology. The determination of aquifer hydraulic characteristics (hydraulic conductivity, transmissivity, and storage potentials) is best made on the basis of data obtained from well pumping test[1]. These properties are important in determining the natural flow of water through an aquifer and its response to fluid extraction. However, in the case of paucity of pumping test data, these characteristics may be estimated using the Dar-Zarrouk parameters from geophysical sounding. Estimation of aquifer hydraulic parameters using Dar-Zarrouk parameters is well known and has been extensively discussed by earlier scholars [10], [11],[12],[13].

Similarly, effective groundwater protection is guaranteed by protective layers with sufficient thickness and low hydraulic conductivity leading to high residence time of percolating water. Surface water percolates through the protective layers leading to groundwater recharge. During this percolation process, degradation from surface contaminant can occur by mechanical, physicochemical, and microbiological processes. These protective layers are most often regarded as homogenous bodies which are characterized by bulk properties like hydraulic conductivity. However, inhomogeneities in the protective layers

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such as sand bodies or fissures in clay which may lead to preferred pathways for percolation of contaminants are not often taken into account, although they are quite common[14] .

Groundwater has been considered as an important source of water supply due to its large storage capacity and relatively low susceptibility to pollution in comparison to surface water [15]. However there are significant sources of diffuse and point source pollution of groundwater from land use activities particularly agricultural practices. The intrusion of these pollutants to groundwater alters the water quality and reduces its portability. Prevention of contamination is therefore critical for effective groundwater management. Aquifer vulnerability assessment to delineate areas that are more susceptible to contamination from anthropogenic sources has therefore become an integral and important element for sensible water resource management and land use planning. This concept was first introduced in France by the end of the 1960's to create awareness to groundwater contamination [16]. The concept of vulnerability assessment is based on the assumption that the system, involving soil, rock, and groundwater, can offer a degree of protection against contamination of the groundwater by "natural attenuation". Vulnerability is an intrinsic property depending on the sensitivity the system shows to impacts, both natural and human .Intrinsic groundwater vulnerability can be explained as the systems incapability of protecting its water against contamination. There are numerous approaches for assessing groundwater vulnerability. However, the most widely used and well known is DRASTIC; a qualitative rating model.

DRASTIC is an index model designed to produce vulnerability scores for different locations by combining several thematic layers. The DRASTIC model has been the most commonly used aquifer sensitivity assessment method [15]. DRASTIC is an Index model designed to produce vulnerability scores for different locations by combining several thematic layers. The model was developed by the US Environmental Protection Agency (EPA) to evaluate groundwater pollution potential for the entire United States [17]. This model is based on the concept of the hydrogeological setting that is defined as a composite description of all the major geologic and hydrogeologic factors that affect and control groundwater movement into, through and out of an area [17]. The DRASTIC model rates relative sensitivity of land units by integrating information on depth to groundwater, impact of vadose zone, soils, recharge, hydraulic conductivity, topography (slope), and aquifer media in determining a ranking of groundwater sensitivity.

The Ugep area geologically belongs to the Calabar Flank of Southeastern Nigeria. Geomorphologically, it was classified as part of the Cross River hydro-geological zone [18]. (It is a basement area overlain by a thick sedimentary overburden. The groundwater recharge is good due to high yearly average rainfall and high porosity and connectivity of the aquifer zones. However, there have been incessant borehole failures in parts of the study area mainly at Nko, Idomi and parts of Ugep town. Much of the wells drilled in these areas have become abortive or dried up due to poor or lack of scientific investigation. These wells are associated with very high drawdown during the dry season resulting in outright failure of wells leading to inadequate water supply in the areas. The present study summarizes the hydro-geophysical assessment of the aquifer system of Ugep area, Southeastern Nigeria. It hopes to appraise the nature of the aquifers, their distribution, characteristics and thus, provides data to assess the productivity of the aquifers.

1.1 Location , Physiography and Geology of the Study area

1.1.1 Location, climate and physiography

The project area is located within latitudes $5^0 59^1$N - $5^0 42^1$N and longitudes $8^0 00^1$E - $8^0 25^1$E. The study areas is Ugep with a land mass of 87.8 km^2 (Fig.1).

The study area is part of the Cross River plain with undulating topography. It has highest relief of about 350ft (170m) and the lowest relief of approximately 100ft (30.48m) especially in the northeastern part in the direction of slope. Generally, there are low lying ridges which trend from the north to east and north to west of the study areas. Most of the ridges have been dissected by streams. The sandstone form dome structures. Other positive relief features are due to igneous intrusions at various locations in the study area. Temperatures in the study area range from 24.5^{0}C to 34.5^{0}C. The study area is characterized by an equatorial climate with a rainfall of between 2000 and 2500mm per year. The hottest month of the year is February and March whose mean daily temperature exceeds 32^{0}C, while the coolest period is between July and August where mean daily temperature is about 260C. The relative humidity is usually high throughout the year; values above 70% are recorded for places like Nko while Ijiman, Idomi and Ntankpo have theirs slightly lower than 70%.

The study area is drained by four major rivers which include Okwo, which drains from east to west, the Uhuru which runs north through south of the mapped area, Lokpoi, which trends in the northeast direction and the major one being

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the Cross River running in the northeast - southwest direction of the study area (Fig. 3). The drainage density in the area is 0.53 with a drainage frequency of 0.87.The drainage pattern in the study area varies from dendritic, rectangular and angular, with dendritic been dominant due to the characteristically inhomogeneous lithology. The coastal plains (Benin Formation) are observed to have low drainage density due to high infiltration rate, of the sandstones. Stream flows occurs along structural planes and other planes of weakness.

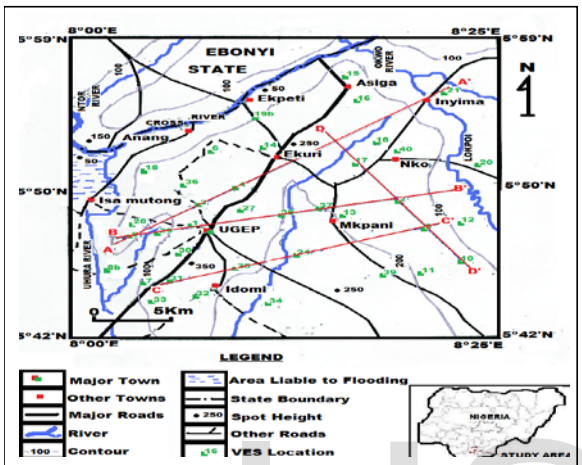

Fig 1: Location/topographic map of the study area

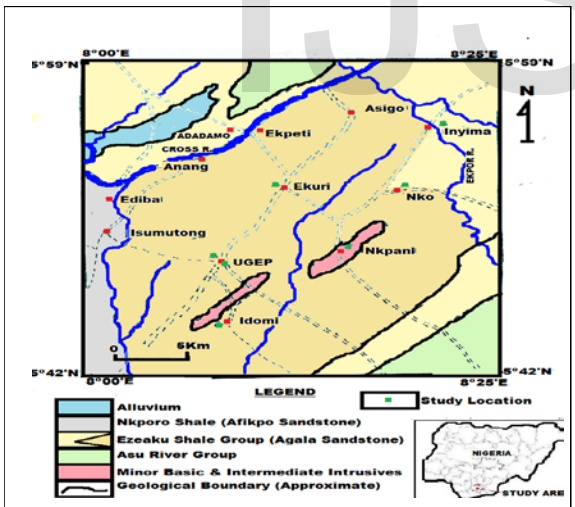

Fig.2. Geology map of the study area

1.1.2. Geology of the study area

Geologically, the area consists of a Precambrian crystalline basement and a sedimentary cover ranging in age from Cretaceous to Tertiary. Sedimentary rocks cover more than 80 percent of the area, while igneous intrusion cover less than 20 percent of the total area under investigation (Fig.2).The basement complex consists predominantly of migmatites, and banded granitic gneisses. Relics of the meta-sedimentary and meta-volcanic rocks are widely distributed within the migmatite-gneiss complex [19]. Generally, the basement complex rocks have been extensively intruded by volcanic, granitic and charnockitic rocks of Pan-African age.

Ugep is underlain by sedimentary rocks which belong mainly to the Asu River group and Ezeaku Formation (Fig.2). The Asu River group is of Albian age and comprises of bluish black shale with minor sandstone units. The shales are fissile and highly fractured. The sedimentary formations consist mostly of conglomerate, sandstone, shale, siltstone, mudstone, limestone, marl, clay and loose sand. The Eze-Aku Formation consists of flaggy calcareous shale thin sandy or shaley limestone and calcareous siltstone indicating the renewal of marine deposition in the Benue Trough.

Hydrogeology of an area emphasizes the occurrence, distribution, movement and geological interaction of water in the earth's crust. The hydrogeology of an area is therefore largely dependent on the lithology of the area. Edet[20] identified three potential aquiferous units in the study area as lenticular sandstone beds in shale and siltstone, fractured sedimentary rocks at contact zones between the sediments and intrusives and finally fractures and joints in the intrusives. The major hydrogeologic group in the area is the Shale-Siltstone-Sandstone group. The broad and thick shale family reduces the groundwater potential herein. However, the intercalation and fingering of sandstone –siltstone family creates for increase permeability within the group. Yields of 1-2.0 litres/second are known in most parts of the study area Idomi area (Edet, 1993). In Ugep area, rocks that underlain the area are mainly shale, sandstone and siltstones. The shale is laminated and partially baked. The sandstone and siltstones form the major aquifer in the area. Areas like Mkpani are covered and underlain by cretaceous indurated sediments of sandstone, siltstones, shale and doleritic/granodioritic rocks [20]. The aquiferous bodies are regolith, and fractures of sediments/igneous rocks; and interstices of poorly compacted sands. Fractures of small apertures are the major aquiferous structures identified within the subsurface of the area. Groundwater yield is small, and will only sustain low–moderate scale groundwater schemes. Aquiferous properties are low-moderate in rating with drawdown from pump wells being gentle with abstraction /discharge rate lower or equal to 1.0 litres/second.

Generally, the groundwater potential in the area is rated good to fair. Okereke, et al [21] in the study to determine the potential ground - water sites using geological and geophysical techniques identified the following

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hydrogeological units; in the crystalline basement complex, the water bearing units include the decomposed zone, the partially decomposed zone (overburden) and the fractured bedrock. The water table in this zone is highly variable. The yields are in the range of 10-200m^3/day, within the second lithological unit, the water bearing formations vary considerably from siltstones through sandstones to limestones. The depth to the water table averages 6.32m and the well yields range from 10-200m^3/day. The aquifer thickness exceeds 100m in places such as Edor, Mfum and Mkpani. From the hydrogeological point of view, shales constitute the thickest and most extensive aquitards in most sedimentary basins. According to [2], the porosities could range between 5-20%, while the hydraulic conductivities are rarely larger than 10-9m/s and commonly in the range 10-12 to 10-10ms-1. However, where these shales are extensively cracked, they can form good groundwater reservoirs. The groundwater recharge is prolific due to high yearly average rainfall and high porosity and connectivity of the aquiferous zones. The aquifer is characterized by medium to high yield (I500-2000 m^3/day). The soil and rock types present in the study area combine with the distinct wet and dry seasons to produce a characteristic hydrogeology. The major hydrogeological units are the crystalline basement; sandstone-siltstone-limestone-intrusive; shale-intrusive; shale; coastal plain sand and alluvium [20], [21].

2.0 MATERIALS AND METHODS

Vertical Electrical Sounding [VES] using the Schlumberger array with maximum current electrode separation of 1000m was used in acquiring the resistivity data. The Schlumberger electrode array was used to carry out a total of forty vertical electric soundings, utilizing a maximum electrode spread of 1000m. Seven of the stations were sited near existing boreholes to enhance interpretation and for comparative purpose and for quality control of the data. The current electrode spacing was increased symmetrically along a straight line about the fixed point while the potential electrodes were kept fixed but increased only when the measured signal became very small. Measurements were taken at increasing current electrodes distance such that in principle, the injected electric current should be penetrating at greater depths. The end result of the field measurement is the computation of the apparent resistivity (ρ_a). For Schlumberger array, apparent resistivity is given by [13]:

$$\rho_a = \pi\left(\frac{a^2}{b} - \frac{b}{4}\right)R \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where a = half current electrode separation and b is the potential electrode spacing.

The data obtained is usually plotted as a graph of apparent resistivity against half electrode spacing for the Schlumberger array. The electrode spacing at which inflection occurs on the graph provides an idea of the depth to the interface. A useful approximation is that the depth of the interface is equal to two thirds (2/3) of the electrode spacing at which the point of inflection occurs [22]. This approximation has found useful applications in computer iterative modeling.

2.1. Aquifer Hydraulic Characteristics from Geo-electric Data

The concept of Dar- Zarrouk parameters are used as a basis for the evaluation of aquifer hydraulic properties in the study area. These Parameters defined by the longitudinal unit conductance in Ω^{-1} (S, i.e layer thickness over resistivity), and transverse unit resistance in Ωm^2 (R, layer thickness times resistivity) have been found useful for the estimation of aquifer hydraulic characteristics. Niwas and Singhal [11] established an analytical relationship between transmissivity and transverse resistance on one hand and between transmissivity and longitudinal conductance on the other hand as follows:

$$T = K\sigma R = KS/\sigma \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where T= aquifer Transmissivity, K= hydraulic Conductivity, σ = Electrical Conductivity (inverse of resistivity), R = Transverse Resistance = hρ, S = Longitudinal Conductance =h/ρ, h =aquifer thickness, and ρ = aquifer resistivity.

In areas of similar geologic setting and water quality, the product Kσ remains fairly constant [11]. Thus knowledge of K from existing boreholes and σ from VES data can be used to estimate Kσ values for areas without boreholes. This relationship was found useful in this work.

2.2. Aquifer Vulnerability Estimation from the DRASTIC model

The DRASTIC model has been the most commonly used aquifer sensitivity assessment method [15]. The model was developed by the US Environmental Protection Agency (EPA) to evaluate groundwater pollution potential [17]. DRASTIC is an index model designed to produce vulnerability scores for different locations by combining different thematic layers. The model is based on the concept of the hydrogeological setting that is defined as a composite description of all the major geologic and hydrogeologic factors that affect and control groundwater movement into, through and out of an area[17]. The acronym

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DRASTIC corresponds to the initials of the seven parameters used in the model which are: Depth to water, Net Recharge, Aquifer media, Soil media, Topography, Impact of the vadose zone and Hydraulic Conductivity.

The significant media type of each of these parameters is assigned a subjective rating varying from 1 to 10 based on their relative effect on the aquifer vulnerability. Every parameter in the model has affixed weight multiplier indicating the relative influence of the parameter to contaminant transport [17]. Several information extracted from litho-logs, geo-electric logs and electric logs in this study were used as a guide for assigning ratings and weights. Thus, the net recharge was taken to be about 12 percent of the average annual rainfall [23]. The annual average rainfall for Ugep area is 2,250 mm; 12% of 2,250mm is equivalent to 270mm.The ratings and weights were therefore assigned according to [17],[23]. Similarly, estimates of hydraulic conductivities from this study were used as inputs for estimating the drastic index. The hydraulic conductivities were converted from meter per day (m/day) to gallons per day per square feet (gpd/ft²) before using them to calculate the DRASTIC index [17]. Aquifer vulnerability rating is then done based on the respective DRASTIC index as shown in table 1 below.

DRASTIC Index(Di)	Vulnerability Class
1-100	Low
101-140	Moderate
141 -200	High
>200	Very high

TABLE 1. AQUIFER VULNERABILITY CLASSIFICATION BASED ON DRASTIC INDEX [24], [16].

The final DRASTIC index (Di) is the weighted sum overlay of the seven parameters using the following equation:

$$D_i = D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w \quad \ldots(3)$$

Where *D, R, A, S, T, I, C* are the seven parameters, and the subscripts r and w are the corresponding ratings and weights respectively.

3.0 PRESENTATION OF RESULTS

3.1. Aquifer resistivity

The results of the field estimate were carefully analyzed. A qualitative estimate of the relationship between electrode spacing and the depth of penetration was made using curve matching technique to obtain initial model parameters which were used as input for computer iterative modelling using the OFFIX 3.1 software. Results of the curve matching were studied; the shape of the curve for each sounding gave an insight on the character of the beds or layers between the surface and the maximum depth of penetration. This is because the shape of a VES curve depends on the number of layers in the subsurface; the thickness of each layer, and the ratio of the resistivity of the layers [25]. Table 2 is the summary of layer parameters interpreted from the study area. The study area is characterized by ten (10) major sounding curve types. Fig. 3 shows a typical geo-electric curve type obtained in the study area.

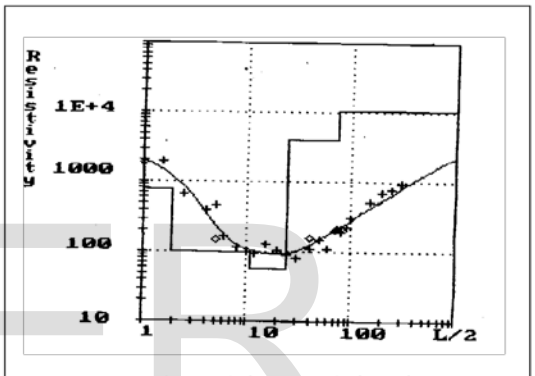

Fig. 3: Typical curve type in the study area

The resistivity map of the study area shows that the resistivity is high towards the Southern region, while low resistivity is recorded towards the Northern part of the map. Maximum resistivity is 3920 Ωm at the vicinity of Ugep(VES 1) which corresponds to the region having red and pink colours (Fig.4.). The minimum resistivity was recorded at Idomird 2(VES 32) about 34.9Ωm purple-blue coloured region (Fig. 4)

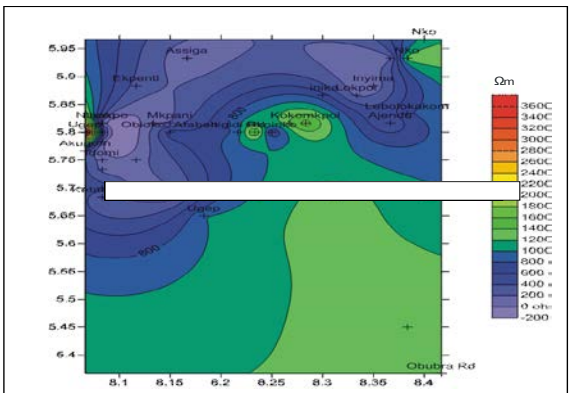

Fig.4. Contour map of aquifer resistivity (Ωm) map of Ugep and environs

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3.2 Aquifer conductivity

The minimum aquifer conductivity is 0.00025mhos at VES 40 while the maximum aquifer conductivity is 0.02083mhos at VES 16 (Table 1) with a mean value of 0.005822mhos. Aquifer conductivity for all the location is contoured (Fig. 5) with the blue color corresponding to the area having low conductivity value. The map of the study area reveals conductivity increasing towards the northwestern axis.

3.3 Aquifer Depth and thickness Estimation

The depth to water table in the study area ranges from 12.4m at Ugep point 3(VES 3) to 147m at Assiga 2 (VES 16) with a mean value of 67.96m.

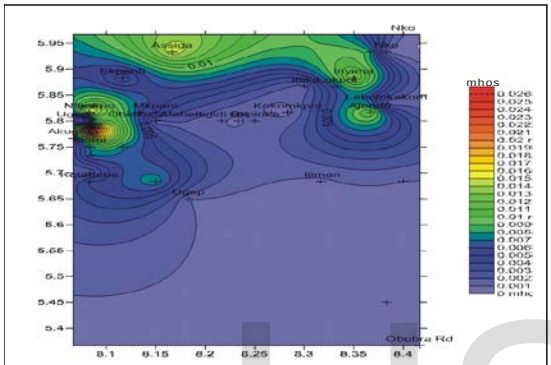

Fig.5. Contour map of Aquifer Conductivity (σ^{-1}) of the study area

Similarly, the result of the study revealed a strong spatial variation of aquifer thickness in the study area with values ranging between 5.7m near Lokpoi (VES 20) and 123m near Itigidi Road 4 (VES 9) with a mean aquifer thickness in the study area is 47.3m. Figures 6 and 7 are maps of the spatial variation of aquifer depth and thickness respectively.

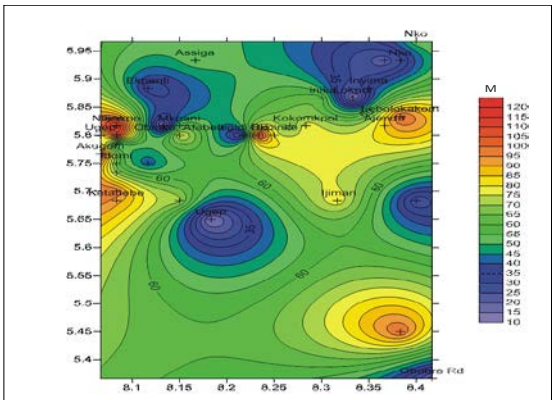

Fig.6.Contour map showing spatial variation of depth (m) to water table across the study area

3.4. Dar-Zarrock Parameters: Longitudinal conductance and transverse resistance

The Longitudinal Conductance was estimated by dividing the aquifer thickness by the aquifer apparent resistivity. The longitudinal conductance values vary between 0.0053mhos/m (VES 28) and 0.0053mhos/m (VES 40), with a mean value of 0.2848mhos/m. Longitudinal conductance(S) value decreases from the northwestern region of the study area towards the south and eastern part of the study area. The study reveals an increasing longitudinal conductance, towards the northwestern flank while the southeastern, northeastern and the entire southern part of the study is underlain with low conductive materials (Fig. 8)

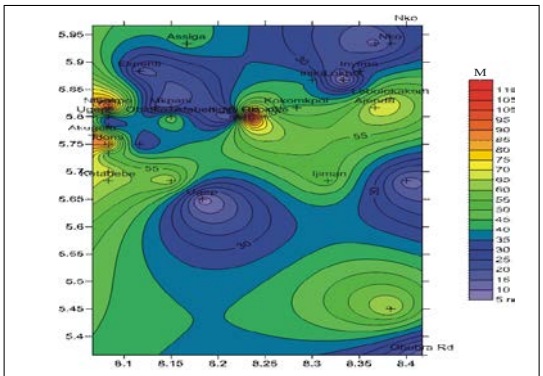

Fig.7. Contour map showing spatial variation of aquifer thickness (m)

The transverse resistance (R) is one of the parameters used to define target areas of good groundwater potential. It has a direct relationship with transmissivity such that highest transverse resistance values reflect most likely the highest transmissivity values of the aquifers or aquiferous zones and vice versa. High transverse resistance was recorded at Obubrard 3(VES 6) being 84992Ωm². The lowest transverse resistance was recorded at Idomird 2 (VES 32) being 1106.33Ωm2. The transverse resistance increases from the northwestern region to the southeastern region (Fig. 9). The area has a mean transverse resistance of 19819.3Ωm².

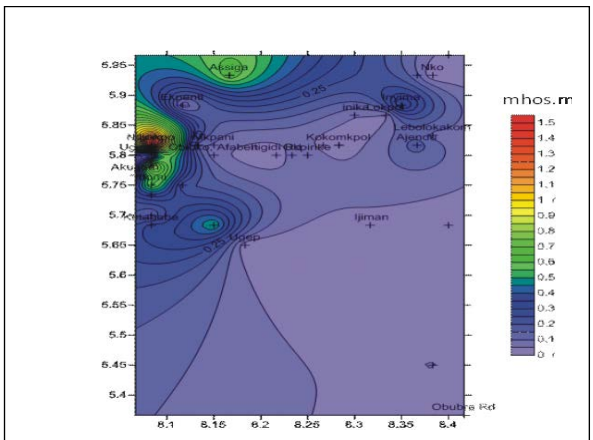

Fig. 8.Contour map of aquifer longitudinal conductance of the area

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3.5 Aquifer hydraulic conductivity and transmissivity estimation

The diagnostic constant is the product of the measured hydraulic conductivity from pump testing and aquifer conductivity. For the available twelve (12) hydraulic conductivity values (K), seven (7) belonged to the Asu River Group while five (5) falls within the Ezeaku Formation and is termed Zone B.

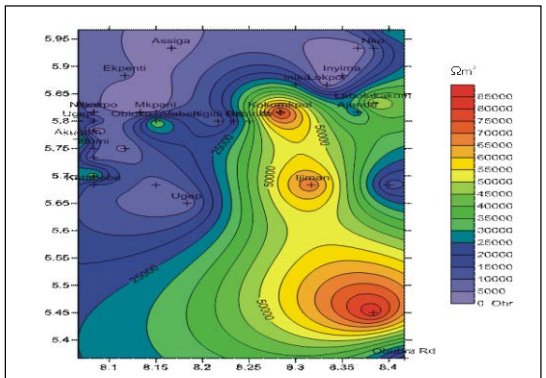

Fig. 9.Spatial variation of transverse resistance (Ωm²) across the study area

The diagnostic constant is the product of the measured hydraulic conductivity from pump testing and aquifer conductivity. For the available twelve (12) hydraulic conductivity values (K), seven (7) belonged to the Asu River Group while five (5) falls within the Ezeaku Formation and is termed Zone B. The average of the K values for zone A was used to generate the diagnostic parameter for all the VES locations in the zone (which includes VES 1, 3, 4, 6, 7, 8, 9, 20, 21, 22, 23, 24,25,27,31,32,33,34,35,36,&38).Similarly, the average of the K values for zone B was used to generate the diagnostic parameter for all the VES locations in zone B(which includes VES 2,5,10,11,12,13,14,15,16,17,18, 19,26, 28,29,30,37,39 &40). The estimated aquifer hydraulic parameters (hydraulic conductivity, transmissivity and storativity) from Dar-Zarrouk parameters are shown in table 3 below. In the present study, hydraulic conductivity was estimated from the product of the aquifer apparent resistivity and the diagnostic constant (the term diagnostic is used to indicate that it is the only model parameter that is directly related to the subsurface).

Results of the study revealed that the hydraulic conductivity in the study area ranges from 3.176m/day near (VES 1) to 33.672m/day near VES 9 with a mean value of 5.329m/day. Hydraulic conductivity in the area increases from the southern region to the northwestern region with the highest hydraulic conductivity values observed near Obioko Afaben (Fig. 10).Similarly, aquifer transmissivity in the area was estimated by taking the product of diagnostic constant and transverse resistance of the aquifer. The estimated transmissivity values ranges from 15.61m²/day near VES 1 to 1501.77m²/day near VES 9 with a mean of 645m²/day. Transmissivity was observed to increase from the southern region to the northeastern part of the study area with the highest transmissivity value observed near Lebolokakom Ajendu (Fig. 11).

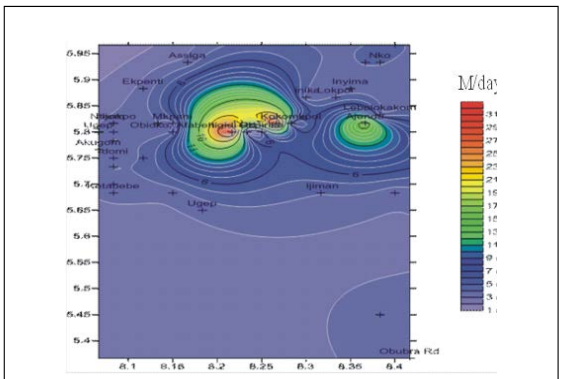

Fig.10.Map showing spatial variation of hydraulic conductivity across the study area

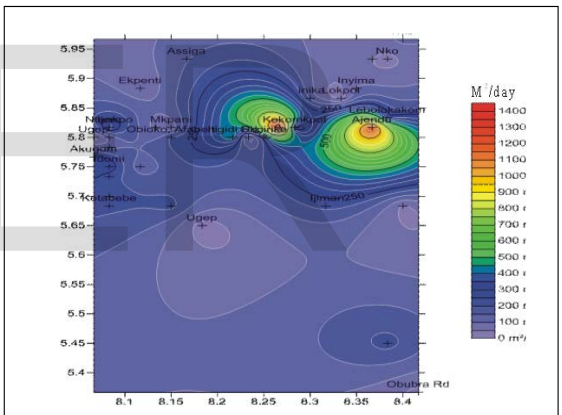

Fig.11.Map showing spatial variation of transmissivity across the study area

3.6 Aquifer Vulnerability Assessment using DRASTIC Index

Table 4 shows the DRASTIC Indices generated from the study area. The assigned weights and ratings are according to [17]. The aquifer vulnerability map based on the DRASTIC Index clearly indicates that about 55% of the study area falls within the moderate vulnerability zones with DRASTIC Index (Di) values ranging from 107 to 140. The high vulnerability zones contribute to about 42.5% of the study area with a Di range of 143 at VES 36 to 177 at VES 13.High vulnerability rate in these areas may be attributed to shallowness of their aquifer and the fact that most of the aquifers in the areas may be unconfined. The remaining 15% of the study area have low vulnerability rating with a Di range from 89 at VES

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38 to 99 at VES 11. Other areas with low aquifer vulnerability includes VES 9, 11,19,23, 30 and 38.The low vulnerability index in these areas may be attributed to deep water table.

implying good groundwater potential. The high transmissivity values are consistent with the finding of [20], [26], that the aquifer is composed of unconsolidated fine-medium-coarse grain sands. Hydraulic conductivity (K) values ranges from 3.176m/day to 33.672m/day with a mean value of 5.329m/day. Hydraulic conductivity in the area decreases from the northern axis to the southern axis of the study area. The low Hydraulic conductivity in the southern axis of the study area is an indication of the fact that most parts of the area are underlain by less thick and less conductive aquifer materials having relatively fair hydraulic conductivity thus making the area have a fair prospect for groundwater.

The thickness of the aquifer in the area was found to vary between 5.7m and 123m with a mean value of 47.3m.This anomaly could be as a result of the differences in elevation of the different places investigated since water table usually follows the ground surface. This study revealed a variation in the depth to water table across the area. Depth to water table range from 12.4m to 147m with a mean value of 67.96m

4.0 Discussion and conclusion

The evaluated aquifer parameters revealed that the transmissivity values ranges from 15.61m^2/day to 1501.77m^2/day with a mean of 645m^2/day. The transmissivity values are high over the entire area

The result of the aquifer vulnerability assessment using DRASTIC model clearly reveal that the area is generally moderately vulnerable to groundwater contamination with the depth to water table and vadose zone inflicting the largest impact on the intrinsic vulnerability of the aquifer systems in the area.

Finally, this study has helped to provide data on the aquifer hydraulic conductivity (K), Transmissivity (T), aquifer thickness (h), depth to water table, and the Dar Zarrouk parameters: longitudinal unit conductance (S) and the transverse resistance (R) of the aquiferous zones. Drilling of wells to determine aquifer hydraulic parameters is often prohibitively expensive, thus the use of Dar Zarrouk transmissivity technique outlined in this study in determining the aquifer transmissivity from resistivity data is a cost effective alternative. The advantage of using Dar Zarrouk parameters to estimate transmissivity is that the non-uniqueness of interpreting resistivity data is minimized.

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TABLE 2. SUMMARY OF LAYER PARAMETERS INTERPRETED FROM THE STUDY AREA

VES No	Location	Longitude	Latitude	No of layers	Curve type	Layer resistivity ρ (ohm-m)						Layer depth d (m)						Layer thickness t (m)				
						ρ1	*ρ2*	*ρ3*	*ρ4*	*ρ5*	*ρ6*	*d1*	*d2*	*d3*	*d4*	*d5*	*d6*	*t1*	*t2*	*t3*	*t4*	*t5*
1	Ugep 1	N5^{0}48′01.5″	E8^{0}04′16.8″	6	KH	2560	779	102	56.1	3970	10300	0.7	1.9	11	24	73		0.7	1.2	9.9	13	49.2
2	Obioko Afaben	N5^{0}48.436′	E8^{0}09.723′	5	AK	14.8	21..4	66.7	28.9	720		0.7	6.5	35	78			0.7	5.8	28	43	
3	Ugep 3	N5^{0}39′39″	E8^{0}31′30″	6	KH	2360	415	60.9	990	62	46	1.4	2.4	6.5	12	38		1.4	1	4.9	5.9	25.3
4	Obubra rd 1	N5^{0}51′15″	E8^{0}05′15″	6	HA	66800	328	123	44	1030	5090	0.2	1.3	6.7	14	25	126	0.2	1.1	5.5	5	11.6
5	Obubra rd 2	N5^{0}52′32″	E8^{0}05′ 18″	8	HA	1860	440	65.1	624	1200	127	0.7	1.8	5.3	7.6	17	42	0.7	1.1	3.5	2.5	9.5
6	Obubra rd 3	N5^{0}54′15″	E8^{0}05′22″	7	HKH	8200	181	64.7	337	1280	580	0.4	3.6	17	35	101	155	0.4	3.2	13	18	66.4
7	Itigidi rd 2	N5^{0}48′01.5″	E8^{0}04′16.8″	6	KH	4350	136	54	850	4100	3930	0.5	5.3	14	28	140		0.5	4.8	8.7	14	112.4
8	Itigidi rd 3	N5^{0}48′01.5″	E8^{0}04′16.8″	7	KH	4650	206	107	1380	2110	1310	0.5	1.2	20	65	135	178	0.5	0.7	19	45	70.5
9	Itigidi rd 4	N5^{0}48′01.5″	E8^{0}04′16.8″	7	KH	4550	267	111	46	75	42	0.5	1.1	25	47	74	114	0.5	0.6	24	22	27
10	Lebolokakom	N5^{0}49.599′	E8^0 09.538′	6	HK	125	18.2	48.3	148	790	73	0.5	1.5	4.7	37	103		0.5	1	3.2	32	66.4
11	Ajendu	N5^{0}49.538′	E8^0 09.647′	6	HA	70.4	29.1	60.6	380	86	47	0.5	3.3	16	85	162		0.5	2.8	13	69	76.8
12	Afaben	N5^{0}49.409′	E8^0 09.485′	6	HKH	30.8	17.6	125	169	14.7	10.9	0.9	4.8	7.9	13	48		0.9	3.9	3.1	19	21.2
13	Kokomkpol	N5^{0}49.606′	E8^0 09.688′	7	HKH	338	16.2	357	66	1210	1730	0.9	4	8.6	18	33	79	0.9	3.1	4.6	9.4	14.7
14	Okpirike	N5^{0}49.259′	E8^0 09.462′	5	AK	15.2	23	80	27	529		0.9	8.3	30	71	77	82	0.9	7.4	22	41	63.2
15	Ekori - Ekpenti	N5^{0}53.006′	E8^0 07.022′	7	HQ	1410	204	86	336	5.1	9.9	0.9	2.2	13	31	99	163	0.9	1.3	11	18	68.6
16	Assiga 1	N5^{0}56.23.3′	E8^{0}10′14.1′′	6	KH	90	31.3	6	66.8	48.7	36.1	0.7	1.9	11	54	142		0.7	1.2	8.6	44	81.7
17	Assiga 2	N5^{0}56′3.8′′	E8^{0}10′03.4′′	6	HKH	57.3	3.6	15.8	43.9	28.4	4.8	0.8	3.3	43	89	147		0.8	2.5	40	46	58.3
18	Nko 2	N5^0 58′3.8′′	E8^0 21.0″	6	HKH	760	407	1070	143	84	38.1	1	2.6	5.4	13	40		1	1.6	2.8	7.3	27.3
19	Nko 1	N5^{0}56′20.9″	E8^{0}10′31.9″	6	HA	543	31	118	9.6	91	80	1.1	8.4	22	43	73		1.1	7.3	13	22	30
20	Ekori inika	N5^{0}52.50.0′	E8^{0}07′03.4″	6	HQ	188	170	681	116	142	16.3	0.9	2.4	6.3	37	82		0.9	1.5	3.9	30	45.9
21	GSS Ugep	N5^{0}48′01.5″	E8^{0}04′16.8″	6	KQQ	271	36..5	25.5	327	76.2	59.4	0.6	5.7	19	58	92		0.6	5.1	13	39	33.6
22	Lokpoi	N5^{0}52′11.5′	E8^{0}18′01.0″	6	HKH	398	31.8	151	54	22.4	167	0.4	4.3	10	66	170		0.4	3.9	5.7	56	104.4
23	Inyima	N5^{0}53′23.7″	E8^{0}21′03.5″	6	HKK	129	48	72.7	54.7	66.7	22.4	0.8	5.4	37	77	98		0.8	4.6	31	40	20.6
24	Ketabebe 1	N 5^{0}48^{1}39.	E 8^{0}05^{1}04.	5	HKH	69.66	148.2	128	190.8	37.8		4.27	9.2	29	92			4.3	4.9	20	63	
25	Ketabebe 2	N5^{0}48^{1}37.9	E 8^{0}05^{1}04.6	5	KH	202.8	107.9	53.5	505.6	71..4		2.14	9.93	31	100			2.1	2.8	37	69	

26	PCN Ijiman	N5^{0}48^{1}38.1	E 8^{0}05^{1}01.2	4	HKH	1524	377.4	467	548.2			1.21	3.84	83				1.2	2.5	42		
27	Obioko Ijiman 1	N5^{0}48^{1}40.8	E 8^{0}04^{10}55.	6	KH	454.5	70.2	142.1	270	416.4		1.31	2.83	6.1	89	112		1.3	1.5	4.6	83	87.2
28	Obioko Ijiman 2	N5^{0}49^{1}33.4	E 8^{0}05^{1}04.	6	KH	910	44.42	129	50.55	52.5	61.5	1.46	3.14	6.8	99	101	110	1.5	1.7	3.6	26	42.3
29	Akugom Ijom	N5^{0}48^{1}31.8	E 8^{0}04^{1}49.1	6	KH	96.94	7.55	49.41	54.5	180.8		0.8	4.54	22	77	87		0.8	3.7	17	55	63
30	Ijom 1	N 5^{0}414 24	E 8^{0}09^{1} 34	6	KH	249	55.08	41.8	73.24	127.2		1.4	7.92	22	66			1.4	6.5	14	44	65.2
31	Ijom 2	N5^{0}45^{11}22.	E8^{0}05^{1}09.9	4	KH	335.2	33.5	53.01	141.9			0.89	9.83	52				0.9	8.9	42	89	
32	Idomi; 1	N5^{0}45^{11}27.	E8^{0}25^{1}21.0	4	HKH	259.1	67.65	34.9	18.2			1.47	26.2	46	132			1.5	25	32	100	
33	Idomi; 2	N5^{0}45^{11}24.	E8^{0}05^{1}27.0	4	QH	288.9	800	136.9	12.9			1.93	15.1	41	111			1.9	13	28	82	
34	Adim rd,Idomi	N5^{0}45^{11}20.	E8^{0}05^{1}24.1	5	KQH	193.6	48.95	142.9	103.1	32.37		1.66	9.34	24	69	214		1.7	7.7	17	52	162.6
35	Kowo st ,Idomi	N5^{0}49$'$35$''$	E8^{0}05^{1}02.4	5	KHK	1727	99.9	22.63	44.1	79.0.8		0,97	4.02	18	45	135		1	3.1	14	31	94.52
36	Ntankpo 1	N5^{0}49$'$33$''$	E 8^{0}25$'$10.5$'$	3	HA	53.07	125.4	74.32				4.61	67.7					4.6	63			
37	Ntankpo 2	N5^{0}49$'$49$''$	E8^{0} 09$'$ 48.	4	HA	52.33	35.52	183.3	107.6			1.46	27.7	60				1.5	1.7	18		
38	Afaben rd,Mkpani	N5^{0}41$'$42$''$	8^{0} 09$'$ 34$''$	5	HKH	370.7	35.59	108.2	130.9	52.71		1.16	5.38	25	79			1.2	4.2	20	54	
39	GPS Mkpani	N5^{0}49$'$32$'$	E8^{0} 09$'$47.4	4	HKH	34.5	27.76	34.21	82.78			2.62	26.2	83				2.6	24	57		
40	Nko	N5^{0}56$'$21$''$	E8^{0}23$'$31.9$''$	6	KH	2140	175	59.7	489	1320	19700	1.3	6.6	16	21	28		1.3	3.5	9.2	5.3	7.3

TABLE 3. AQUIFER HYDRAULIC PARAMETERS INTERPRETED FROM THE GEO-ELECTRIC SECTIONS IN THE STUDY AREA.

VES NO	Aquifer Depth (m)	Aquifer Thickness (m)	Aquifer Resistivity (Ωm)	Aquifer Conductivity (mhos)	Transverse Resistance (Ωm^2)	Longitudinal Conductance (Ωm)	Hydraulic Conductivity from pump testing from wells (m/day)	Diagnostic Parameter (kσ)	Estimated Aquifer Hydraulic Conductivity(m/day)	Estimated Aquifer Transmissivity (m^2/day)	Estimated Aquifer Storativity
1	73.2	49.2	3970	0.00025	19532	0.0124	11.05	0.0008	3.176	15.61	0.000147
2	77.9	51.0	720	0.00139	36720	0.0708	1.423	0.00573	4.126	210.41	0.000153
3	12.4	5.9	990	0.00101	5841	0.0060	1.001	0.0034	3.366	19.86	0.000177
4	25.3	11.6	1030	0.00097	11948	0.0113		0.0032	3.296	38.23	0.000348
5	17.1	9.5	1200	0.00083	11400	0.0079		0.0027	3.24	30.78	0.000285
6	101	66.4	1280	0.00078	84992	0.0519		0.0026	3.328	220.98	0.000199
7	27.6	13.6	850	0.00118	11560	0.016		0.0394	33.49	455.46	0.000408
8	64.5	44.6	1380	0.00073	61548	0.0323		0.0244	33.672	1501.77	0.000134
9	114	123	1710	0.00059	21033	0.0719		0.00197	3.369	41.44	0.000369
10	103	66.4	790	0.00127	52456	0.0841	4.2	0.00523	4.132	274.35	0.000199
11	85.2	69.0	380	0.01163	26220	0.1816		0.0479	18.2	1255.94	0.000207
12	12.8	18.9	169	0.00592	3194.1	0.1118		0.0244	4.124	77.94	0.000567
13	78.8	46.1	1730	0.00058	79753	0.0267		0.00239	4.135	190.61	0.000138
14	77.0	63.2	529	0.00189	33432.8	0.08715		0.00779	4.121	260.44	0.000190
15	30.7	17.6	336	0.00298	5913.6	0.0524		0.00995	3.343	58.84	0.000528
16	54.2	43.7	66.8	0.01497	2919.2	0.6515		0.05	3.34	145.96	0.000131
17	147.0	58.3	48	0.02083	2798.4	1.2146		0.0696	3.341	194.77	0.000175
18	54	28	1070	0.00094	29960	0.02617		0.0349	4.141	115.95	0.000840
19	21.6	13.2	118	0.00848	1557.6	0.11186		0.0349	4.118	54.36	0.000396
20	63.0	39	681	0.00147	26559	0.05727		0.00491	3.344	130.41	0.000117
21	58.0	38.9	327	0.00306	12720.3	0.119		0.0102	3.335	129.75	0.000153
22	10	5.7	151	0.00662	860.7	0.03775	0.072	0.0273	4.122	23.5	0.000171
23	36.8	31.4	72.7	0. 01376	2282.78	0.43191	0.019	0.049	3.562	111.85	0.000942
24	92 .0	62.9	190.8	0.00524	12001.3	0.3297		0.0175	3.339	210.02	0.000153
25	100.0	68.6	505.6	0.00198	34684.2	0.1357		0.0066	3.337	228.92	0.000189
26	110.0	32.0	548.2	0.00182	17542.4	0.0584	1.086	0.00608	3.333	106.66	0.000960
27	112.0	87.2	416.4	0.0024	36310.08	0.2094	0.92	0.008	3.331	290.48	0.000262
28	121.0	99.4	61.5	0.01626	6113.1	1.6163	0.84	0.0543	3.339	331.94	0.000298
29	87.0	63.0	180.8	0.00553	11390.4	0.3485		0.0185	3.345	210.72	0.000189
30	72.0	65.2	127.2	0.00786	8293.44	0.5126		0.0263	3.345	218.12	0.000196
31	62.0	89.4	141.9	0.00705	12685.9	0.63	5.14	0.0235	3.335	298.12	0.000268
32	46.42	31.7	34.9	0.02867	1106.33	0.9083		0.1181	4.121	130.66	0.000951
33	41.39	28.27	136.9	0.00731	3870.2	0.2065		0.0301	4.121	116.49	0.000848
34	68.9	52.4	141.9	0.007	7487.96	0.3667		0.02884	4.211	215.95	0.000157
35	135.0	94.52	79.08	0.0126	7474.64	1.1953		0.0519	4.104	387.94	0.000284
36	67.7	63.1	125.4	0.00797	7912.74	0.5032		0.0266	3.335	210.48	0.000189
37	59.6	18.26	183.3	0.00546	3347.06	0.0996		0.0182	3.336	60.92	0.000547
38	79.0	53.5	1309	0.00076	70031.5	0.04087	10.8	0.0031	4.058	217.1	0.000859
39	91.0	62.2	82.8	0.01208	5150.6	0.7512		0.0498	4.123	256.5	0.000187
40	28.4	7.3	1320	0.00076	9636	0.0055	8.426	0.0031	4.092	29.87	0.000219

TABLE 4. SUMMARY OF AQUIFER DRASTIC VULNERABILITY RATINGS USING DRASTIC INDEX

VES NO	Dr	Dw	Rr	Rw	Ar	Aw	Sr	Sw	Tr	Tw	Ir	Iw	Cr	Cw	DRASTIC INDEX	VULNERABILITY RATING
1	1	5	9	4	5	3	8	2	10	1	3	5	6	3	135	Moderate
2	10	5	9	4	2	3	7	2	10	1	3	5	1	3	134	Moderate
3	2	5	9	4	8	3	7	2	10	1	8	5	2	3	140	Moderate
4	1	5	9	4	8	3	8	2	10	1	8	5	2	3	137	Moderate
5	5	5	9	4	3	3	5	2	10	1	3	5	2	3	111	Moderate
6	7	5	9	4	5	3	8	2	10	1	3	5	1	3	130	Moderate
7	5	5	9	4	8	3	8	2	10	1	8	5	2	3	157	High
8	3	5	9	4	8	3	8	2	10	1	8	5	1	3	144	High
9	1	5	9	4	3	3	7	2	10	1	3	5	1	3	92	Low
10	1	5	9	4	5	3	7	2	10	1	8	5	2	3	126	Moderate
11	1	5	9	4	2	3	7	2	10	1	5	5	1	3	99	Low
12	1	5	9	4	5	3	7	2	10	1	8	5	1	3	123	Moderate
13	10	5	9	4	8	3	7	2	10	1	8	5	1	3	177	High
14	1	5	9	4	8	3	9	2	10	1	8	5	2	3	139	Moderate
15	2	5	9	4	8	3	3	2	10	1	5	5	2	3	117	Moderate
16	5	5	9	4	8	3	5	2	10	1	8	5	1	3	148	High
17	1	5	9	4	3	3	5	2	10	1	8	5	2	3	116	Moderate
18	1	5	9	4	3	3	8	2	10	1	5	5	2	3	107	Moderate
19	1	5	9	4	2	3	7	2	10	1	3	5	1	3	89	Low
20	1	5	9	4	8	3	7	2	10	1	3	5	4	3	116	Moderate
21	1	5	9	4	8	3	7	2	10	1	5	5	2	3	120	Moderate
22	1	5	9	4	8	3	7	2	10	1	8	5	2	3	135	Moderate
23	1	5	9	4	3	3	7	2	10	1	5	5	1	3	92	Low
24	1	5	9	4	3	3	5	2	10	1	3	5	1	3	102	Moderate
25	10	5	9	4	3	3	5	2	10	1	3	5	1	3	133	Moderate
26	2	5	9	4	3	3	7	2	10	1	5	5	1	3	107	Moderate
27	10	5	9	4	8	3	5	2	10	1	8	5	1	3	173	High
28	7	5	9	4	3	3	7	2	10	1	8	5	1	3	147	High
29	1	5	9	4	8	3	9	2	10	1	1	5	4	3	110	Moderate
30	1	5	9	4	2	3	5	2	10	1	3	5	1	3	85	Low
31	1	5	9	4	8	3	8	2	10	1	8	5	6	3	149	High
32	1	5	9	4	5	3	8	2	10	1	3	5	6	3	115	Moderate
33	1	5	9	4	9	3	7	2	10	1	9	5	4	3	149	High
34	1	5	9	4	3	3	8	2	10	1	5	5	2	3	107	Moderate
35	1	5	9	4	8	3	8	2	10	1	8	5	4	3	143	High
36	1	5	9	4	8	3	8	2	10	1	8	5	4	3	143	High
37	1	5	9	4	3	3	8	2	10	1	5	5	2	3	107	Moderate
38	1	5	9	4	3	3	8	2	10	1	2	5	1	3	89	Low
39	9	5	9	4	8	3	7	2	10	1	8	5	1	3	173	High
40	5	5	9	4	8	3	8	2	10	1	8	5	1	3	154	High