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Original paper

Geo-electric assessment of groundwater potentials and vulnerability to contaminants for sustainable water management at Utue-Ogume, Delta State, Nigeria

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Abstract: Relevance. The study focuses on assessing groundwater potentials and the effectiveness of the overburden protective layer in preventing contaminant intrusion into the groundwater aquifer within a municipality in the Western Niger Delta. **Aim.** Employing Vertical Electrical Sounding (VES), 2-D resistivity imaging, and Dar-zarrouk parameters, the research aims to investigate the geoelectric characteristics of the subsurface layers, delineate the aquiferous layer, and assess the protective capacity of the overburden. **Methods.** Nine VES were conducted using the Mini-Res Resistivity Meter with the Schlumberger array. Data processing utilized IPI2win software, revealing seven to eight geoelectric layers. The aquiferous layer, situated between the fifth and sixth layers, exhibited varying resistivity (924.9Ωm to 1629Ωm), thickness (34.52 m to 79.20 m), and depth (55.95 m to 106.00 m). **Results.** Dar-zarrouk hydraulic parameters (hydraulic conductivity, longitudinal conductance, transverse resistance, and transmissivity) were derived from aquifer resistivity and thickness. Hydraulic conductivity ranged from 6.55 m/day to 6.80m/day, transmissivity from 228.5 m^2/day to 538.6 m^2/day, longitudinal conductance from 0.031Ω^{-1} to 0.076Ω^{-1}, and transverse resistance from 37385.1Ωm^2 to 129016.8Ωm^2. Zones with contrasting parameter values were identified. **Conclusion.** The overburden protective layer was rated as having poor capacity, rendering the aquifer highly vulnerable to contaminants. Conversely, the aquifer demonstrated potential for providing portable water, reflecting subsurface heterogeneity and ample hydraulic pressure. A recommended hydrochemical study will further assess water portability.

Keywords: aquifer, Dar-zarouuk parameters, hydraulic conductivity, protective overburden capacity, transmissivity.

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ГЕОФИЗИКА

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Оригинальная статья

Геоэлектрическая оценка потенциала подземных вод и уязвимости к загрязнителям для устойчивого управления водными ресурсами в Утуэ-Огуме, штат Дельта, Нигерия

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Резюме: Актуальность работы. Исследование посвящено оценке потенциала подземных вод и эффективности водоупорного слоя вскрышных пород в предотвращении проникновения загрязняющих веществ в водоносный горизонт подземных вод на территории муниципалитета в дельте Западного Нигера. **Цель**. Вертикальное электрическое зондирование (ВЭЗ), двухмерная резистивная визуализация и параметры Дар-Заррук использовались для исследования потенциала грунтовых вод и прочности пород водоупорного слоя. **Методы**. Девять профилей ВЭЗ были исследованы с использованием измерителя сопротивления Mini-Res установкой Schlumberger. Данные ВЭЗ были обработаны с помощью программного обеспечения IPI2win, которое оконтурило от семи до восьми геоэлектрических слоев. Водоносный горизонт, расположенный между пятым и шестым слоями, показал вариацию сопротивления от 924,9 Ом·м до 1629 Ом·м, мощность от 34,52 до 79,20 м и глубину от 55,95 до 106,00 м. **Результаты.** Гидравлические параметры Дар-Заррука (гидравлическая проводимость, продольная проводимость, поперечное сопротивление и пропускающая способность) были получены на основе удельного сопротивления и мощности водоносного горизонта. Гидравлическая проводимость варьировалась от 6,55 м/день до 6,80 м/день, пропускающая способность – от 228,5 $м^2$/день до 538,6 $м^2$/день, продольная проводимость – от 0,031 $Ом^{-1}$ до 0,076 $Ом^{-1}$ и поперечное сопротивление – от 37385,1 Ом·$м^2$ до 129016,8 Ом·$м^2$. Выявлены зоны с контрастными значениями параметров. **Заключение**. Защитные свойства водоупорного горизонта были оценены как низкие, что делает водоносный горизонт очень уязвимым для загрязнений. И наоборот, водоносный горизонт продемонстрировал потенциал для обеспечения питьевой водой, что отражает неоднородность недр и достаточное гидравлическое давление. Рекомендуемое гидрохимическое исследование позволит дополнительно оценить возможность переноса веществ воды.

Ключевые слова: водоносный горизонт, параметры Дар-Заррук, гидравлическая проводимость, защитные свойства пород водоносного горизонта, коэффициент фильтрации.

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Introduction

The United Nations' sixth agenda for Sustainable Development Goals emphasizes access to clean water and sanitation, as waterborne diseases are linked to unsafe, polluted water and poor sanitation. Around 1.1 billion people worldwide lack access to safe water, with 67% of the rural population lacking a safe water supply [Pandya, 2018]. Groundwater, a clean and portable water source, is under pressure due to regional population growth and urbanization. Around 2 billion people worldwide depend on underground water for daily consumption, and it can contribute to regional water crises if used sustainably [Owoyemi et al., 2019]. Groundwater promotes living standards, economic growth, food security, and livelihoods. However, less than 5% of the population has access to public water, and many rely on untreated water from shallow boreholes and dug wells [Ugbaja, 2021; Chinyem, Ovwamuedo, 2023; Mahdi, Khayyun, 2019]. Groundwater contamination from surface contaminants poses a significant challenge, and indiscriminate disposal of waste can harm the environment and health [Adimalla et al., 2020].

Electrical geophysical surveys are crucial for investigating potential geologic units and avoiding drilling abortive boreholes/wells. These surveys from primary electrical resistivity data estimate geo-hydraulic parameters like hydraulic conductivity, transmissivity, porosity, longitudinal conductance, and transverse resistance. The method involving vertical electrical sounding (VES) is helpful in groundwater study, determining depth to the water table, aquifer geometry, and groundwater quality [Eke, Ekpelu, 2021; Chukwudi et al., 2022]. This study uses surface electrical resistivity measurements for sustainable water management in Utue-Ogume, Delta State, Nigeria.

The Utue-Ogume community in Delta State, Nigeria, is underlain by the Benin Formation, a sedimentary rock formation deposited during the Cretaceous and Tertiary periods. The area is part of the Niger Delta Basin, a large sedimentary basin that covers parts of Nigeria, Cameroon, and Equatorial Guinea. The area's geology is characterized by sedimentary rocks deposited in marine environments, mainly sandstones, shales, and claystones. The Ndokwa area, which comprises Utue-Ogume, is underlain by modern and Holocene delta top deposits, which resulted in various physiographic landforms [Mgbolu et al., 2019]. The deposits of the Freshwater Swamps and the Sombreiro-Warri Deltaic Plain are considered recent expressions of and a continuation of the Benin Formation, which resulted from sediment-laden discharges of the River Niger. The sediment is an admixture of medium to coarse-grained sands, sandy clays, silts, and clays that settle in fluvial/tidal channels, tidal flats, and mangrove swamp environments. The Benin Formation, the youngest of three significant formations, is usually described as consisting of massive continental/fluvial sands and gravels [Anthony et al., 2019].

The hydrogeology of Utue-Ogume, located in the Ndokwa West Local Government Area of Delta State, Nigeria, is influenced by the area's geology. The sedimentary rocks are permeable, allowing for easy groundwater movement. The water table is shallow, and groundwater is recharged by rainfall and runoff from nearby hills. Groundwater flows generally towards the coast, where aquifers discharge into the Atlantic Ocean [Egbueri, Igwe, 2020; Salufu, Aigbedion, 2021]. The aquifers in the area are primarily unconfined, composed of unconsolidated sand and gravel deposits. Groundwater quality in the Niger Delta Basin is generally good, but concerns about contamination from agricultural activities and poor sanitation practices have been raised [Owoyemi et al., 2019]. Additionally, there have been reports of saltwater intrusion in some parts of the region due to excessive pumping.

Utue-Ogume is part of the physiographic province described as the Low Deltaic Plain and Freshwater Swamps, coinciding with the Upper and Lower Floodplain [Shaari et al., 2020]. The province is further subdivided into three distinct landform assemblages: the combined Ase River, River Niger floodplain, Sombreiro-Warri, and low ridged plain. Utue-Ogume is drained by four central river systems: the Adofi River to the north, the Ethiope River and Okumeshi River (Warri River) to the northwest, and secondary tropical lowland forests due to the loss of original primary forest due to farming and timber exploitation [McLachlan et al., 2020].

In conclusion, the geology and hydrogeology of Utue-Ogume are crucial factors that influence the availability and quality of groundwater in the area. Sustainable groundwater resource management and water supply protection are essential for the community's well-being.

Materials and methods

The electrical resistivity method involves injecting current into the subsurface via two current electrodes, AB. The potential difference created due to the passage of the electric current through the earth's materials is measured across a pair of potential electrodes, MN. The Schlumberger array was employed for the survey, and the data was acquired using the *Mini-res Resistivity Meter*, where consecutive readings are taken automatically and the results are averaged continuously. The continuously updated running average is displayed as resistance automatically.

Vertical Electrical Sounding (VES) was conducted in the NE-SW and NW-SE directions using random spot sampling of nine points. A maximum current electrode spread (AB/2) of 300m was used using the Schlumberger array due to its speed, cost-effectiveness, and sensitivity to lateral variation. A reading of resistance R of the earth material within the electrical space of the electrode configuration was obtained at each resistivity station. These values were converted into apparent resistivity (ρa) by multiplying with a geometric factor (K). The resulting apparent resistivity values were used to generate sounding curves interpreted qualitatively and quantitatively. Quantitative interpretation was done using partial curve matching and computer iteration techniques using the 1-D inversion IPI2WIN software. The software uses the least-squares optimization technique to adjust the starting model until the difference between field data and model output is minimized. The software also converts apparent resistivities obtained as a function of field spacing to true resistivities as a function of depth. The resulting true resistivities represent the best average bulk resistivity for the given layer.

Knowledge of aquifer hydraulic characteristics or parameters (also known as Dar-Zarrouk Parameters) is essential to ensure excellent and proper groundwater resource management. The Dar-Zarrouk parameters are hydraulic conductivity, transmissivity, permeability, longitudinal unit conductance and transverse unit resistance. These Dar-Zarrouk parameters are used to estimate aquifer hydraulic characteristics.

Moreover, [Hasan et al., 2018] and [Sanuade et al., 2018] opined that the hydrogeological characteristics of a site that is useful in the simulation of groundwater flow and in evaluating overburden protective capacity and transmissivity of an area are the Dar-Zarrouk parameters (i.e. longitudinal conductance (SL) and transverse resistance (Tr). The Dar-zarrouk parameters are calculated from the field values of the resistivities and thicknesses of the subsurface layering units. Thus, the derived values for hydraulic conductivities and transmissivities are used in evaluating the overburden rock's protective capacity and the aquifer's vulnerability to surface contaminants.

The longitudinal conductance of a geologic formation refers to its ability to conduct electrical current along its length. The electrical resistivity geophysical method is used to measure the electrical conductivity of these underground formations. The longitudinal conductance is also regarded as the medium's ability to retard and filter percolating fluid, which is considered the protective capacity of the aquifer overburden and is expressed as:

Longitudinal unit conductance,

$$SL = \sigma hi \quad (1)$$

Where σ is the aquifer conductivity and hi is the aquifer thickness

According to [Ahmed et al., 2020] and [Oguama et al., 2019] transverse resistance is a parameter that describes areas with high potential for groundwater exploration/exploitation such that high values of transverse resistance indicate that the area has a high potential for groundwater exploration and vice versa. The transverse resistance (Tr) in this study was computed using this relation as expressed:

$$Tr = h.\rho \quad (2)$$

Where h is the thickness of the aquifer and ρ is the aquifer resistivity.

The hydraulic conductivity (k) is a hydrogeologic property of the medium, which refers to the ease with which a fluid can flow through the medium. It depends upon the porous medium and flowing fluid [Oborie et al., 2018]. Apart from characterizing the dynamic behaviour of the hydrogeologic units that allow the groundwater flow, the hydraulic conductivity also affects the yield of wells and contaminant spread. [Tijani et al., 2021; Idris et al., 2018] opined that in areas with few or sparse pumping test information (spatial distribution of aquifer properties), applying the surface resistivity method can provide helpful information on aquifer properties. Thus, arising from a dearth of pumping test information in the research area, the hydraulic conductivity data was estimated from empirical relationship using the exponential law function by [Tartakovsky et al., 2020] and it is given as:

$$Ln k = 0.068 \ln \rho i + 6.02 \quad (3)$$

Where ρi is the aquifer resistivity, K is the hydraulic conductivity.

Results and Discussion

The 1D resistivity survey results show an AHK lithology in the area, with seven to eight geoelectric layers delineated. The first layer is ferrugenised topsoil, with resistivity ranging from 286.8Ωm to 3236Ωm. The layers include dried sand, sandy clay, clayey sand, dried sand/indurated, saturated sand (aquifer), clayey sand, and sandy clay. Primary aquifer parameters (resistivity and thickness) were determined from Table 1 and used to estimate Dar-zarrouk (hydraulic) parameters. The lithologic pseudo section of the aquiferous layer comprises saturated sand, with resistivity ranging from 924.9Ωm to 1629Ωm, similar to the reports of Enebeli et al., [2021]. This layer is less conductive. Figure 7 shows the variation of resistivity with depths, while Figure 8 shows the spatial distribution of the resistivity of the aquifer. The superposition of 1D and 2D cross-correlation along the NW-SE transverse line perfectly correlates the conductive zone, unsaturated vadose zone, and aquiferous phreatic zone with resistivity values and depth.

This study's hydraulic conductivity (k) ranges from 6.55m/day to 6.80m/day, which is high compared to Kransny's transmissivity standard rating. The conductivity value falls within the range of 4.6m/day to 8.8m/day, as found in previous studies on groundwater flow in Isoko South Local Government Area of Delta State and 6.8m/day in Ozoro, Nigeria, as determined by pumping test results. These results align with previous studies on aquifer hydraulic characteristics.

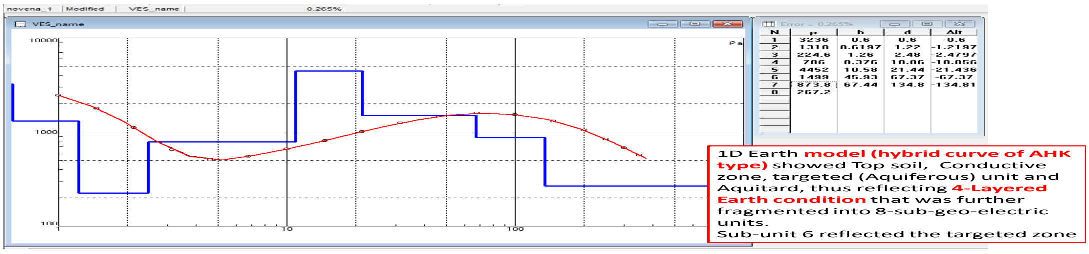

Fig. 1. VES Field Curves of the 1-D Resistivity Model

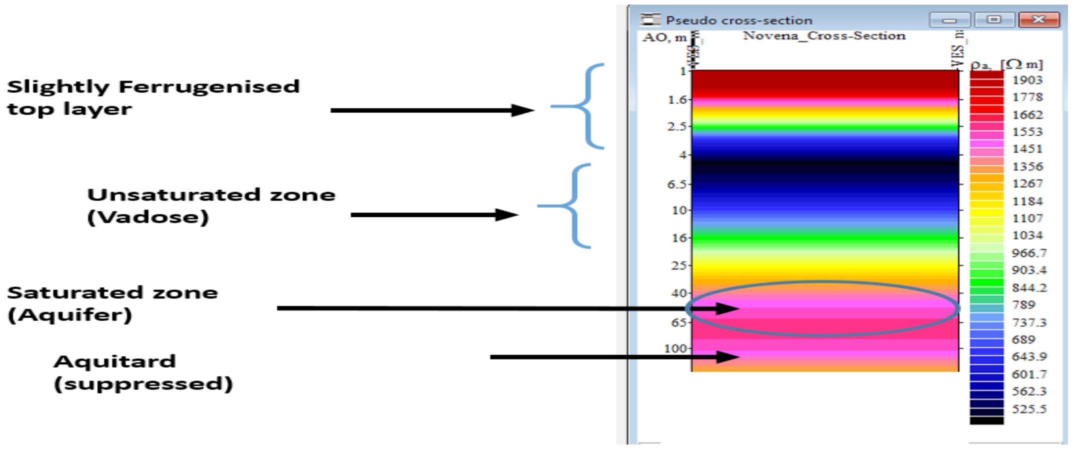

Fig. 2. VES LithologicPseudosection of the area showing Aquiferous Zone

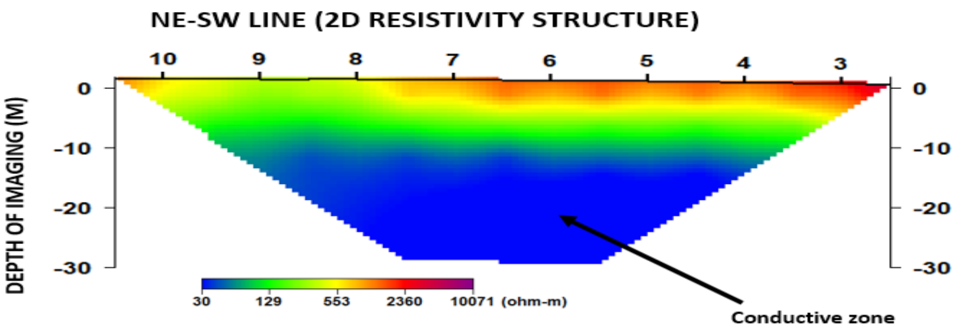

Fig. 3. 2-D Resistivity Imaging along NE-SW transverse line showing the thickness of the Conductive zone

The hydraulic conductivity (k) estimated from equation 5 ranged from 6.55m/day to 6.80m/day (table 2). The hydraulic conductivity is rated high (table 6) when compared to the transmissivity standard rating by Dewandel et al., (2017) as shown in table 5 since the transmissivity rating is between 100m-1000m^2/day. The hydraulic conductivity value of this study falls within the range from 4.6m/day to 8.8m/day in the works by Assouline and Selker [2017] on the hydraulic conductivity of modeled groundwater flow in Isoko South Local Government Area of Delta State. It is also in agreement with the hydraulic conductivity value of 6.8m/day calculated from the pumping test result in the works of Asfahani [2016] and Oguama [2020] in the determination of aquifer hydraulic characteristics from surface electrical and borehole measurements in Ozoro, Nigeria.

Table 1

Aquifer Hydraulic Parameters in the Study Area

VES Points	Aquifer Resistivity, ρ (Ωm)	Aquifer Thickness, h (m)	Aquifer Depth, d (m)	Aquifer Conductivity, σ = 1/ρ $(\Omega m)^{-1}$	Longitudinal Conductance, S = σh (Ω^{-1})	Transverse Resistance, R = hρ (Ωm^2)	Hydraulic Conductivity, K (m/day)	Transmis-sivity, T = Kh (m^2/day)
VES 1	1499	45.93	67.37	$6.67x10^{-4}$	0.031	68849.1	6.77	310.9
VES 2	1276	43.25	64.69	$7.84x10^{-4}$	0.034	55187.0	6.69	289.3
VES 3	1083	34.52	55.95	$9.23x10^{-4}$	0.032	37385.1	6.62	228.5
VES 4	1020	41.70	63.10	$9.80x10^{-4}$	0.041	42534.0	6.59	274.8
VES 5	942	64.60	86.10	$1.06x10^{-3}$	0.068	60853.2	6.56	423.8
VES 6	1340	60.00	81.50	$7.46x10^{-4}$	0.045	80400.0	6.71	402.6
VES 7	1629	79.20	106.00	$6.14x10^{-4}$	0.048	129016.8	6.80	538.6
VES 8	1010	75.18	102.00	$9.90x10^{-4}$	0.074	75931.8	6.59	495.4
VES 9	924.9	70.45	92.49	$1.08x10^{-3}$	0.076	65159.2	6.55	461.4

Table 2

Aquifer Protective Capacity and Vulnerability Ratings

Sum of Longitudinal Conductance (mho or Ω^{-1})	Overburden Protective Capacity Rating (Oladapo, and Akintorinwa, 2007)	Vulnerability Rating (Van Stempvoort et. al, 1992; Ofomola, 2014)
>10	Excellent	Extremely low Vulnerability
5-10	Very good	Low Vulnerability
0.7-0.49	Good	Moderate Vulnerability
0.2-0.69	Moderate	High Vulnerability
0.1-0.19	Weak	Extremely High Vulnerability
<0.1	Poor	

Table 3

Aquifer Overburden Protective Capacity to Surface Contaminants in the Study Area

VES Points	Aquifer Resistivity, ρ (Ωm)	Aquifer Thickness, h (m)	Aquifer Depth, d (m)	Longitudinal Conductance, S = σh (Ω^{-1})	Transverse Resistance, R = hρ (Ωm^2)	Aquifer Protective Capacity Rating	Aquifer Vulnerability Rating
VES 1	1499	45.93	67.37	0.031	68849.1	Poor	Extremely High Vulnerability
VES 2	1276	43.25	64.69	0.034	55187.0	Poor	Extremely High Vulnerability
VES 3	1083	34.52	55.95	0.032	37385.1	Poor	Extremely High Vulnerability
VES 4	1020	41.70	63.10	0.041	42534.0	Poor	Extremely High Vulnerability
VES 5	942	64.60	86.10	0.068	60853.2	Poor	Extremely High Vulnerability
VES 6	1340	60.00	81.50	0.045	80400.0	Poor	Extremely High Vulnerability
VES 7	1629	79.20	106.00	0.048	129016.8	Poor	Extremely High Vulnerability
VES 8	1010	75.18	102.00	0.074	75931.8	Poor	Extremely High Vulnerability
VES 9	924.9	70.45	92.49	0.076	65159.2	Poor	Extremely High Vulnerability

Table 4

Standards for Transmissivity (Krasny, 1993)

Transmissivity (m^2/day)	Designation	Groundwater Supply Potential
1000	Very High	Withdrawal of great regional importance
100-1000	High	Withdrawal of lesser regional importance
10-100	Intermediate	Withdrawal of local water supply (Small community, plants, e.t.c)
1-10	Low	Smaller Withdrawal for local water supply (Private consumption)
0.1-1	Very Low	Withdrawal for Local water supply (Private consumption)
<0.1	Impermeable	Sources of Local water supply are difficult

Table 5

Summary of Results of Aquifer Properties of VES Stations in the Study Area

VES Stations	Hydraulic Conductivity, K (m/day)	Transmis-sivity, T = Kh (m^2/day)	Transmissivity (m2/day) {Kransny, 1993}	Designation	Groundwater Supply Potential
VES 1	6.77	310.9		High	Withdrawal of Lesser Regional Importance
VES 2	6.69	289.3		High	Withdrawal of Lesser Regional Importance
VES 3	6.62	228.5		High	Withdrawal of Lesser Regional Importance
VES 4	6.59	274.8		High	Withdrawal of Lesser Regional Importance
VES 5	6.56	423.8	100-1000	High	Withdrawal of Lesser Regional Importance
VES 6	6.71	402.6		High	Withdrawal of Lesser Regional Importance
VES 7	6.80	538.6		High	Withdrawal of Lesser Regional Importance
VES 8	6.59	495.4		High	Withdrawal of Lesser Regional Importance
VES 9	6.55	461.4		High	Withdrawal of Lesser Regional Importance

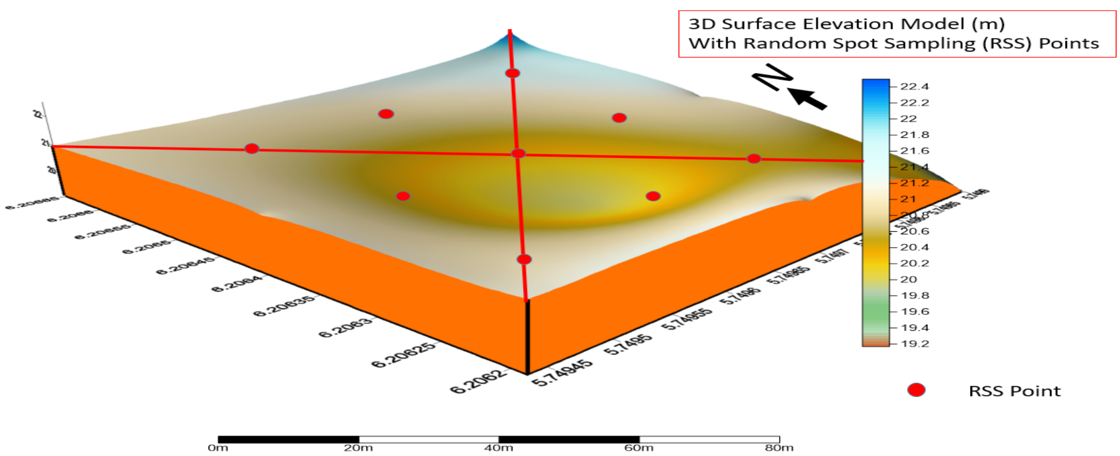

Fig. 4. 3-D surface Elevation Model with Random Spot sampling Points

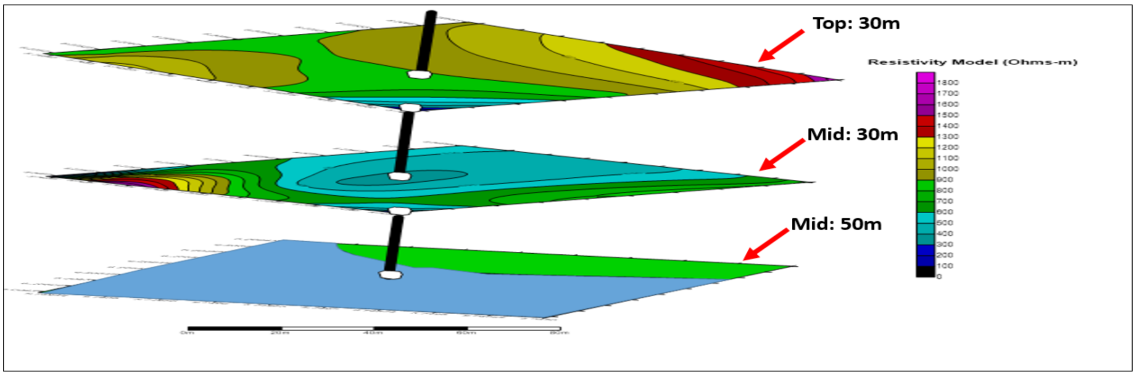

Fig. 5. Comparison between Cross Section of Random Spot Sampling and Horizontal Slice through Arithmetic Progressive Layers of Subsrface Formation in the Area

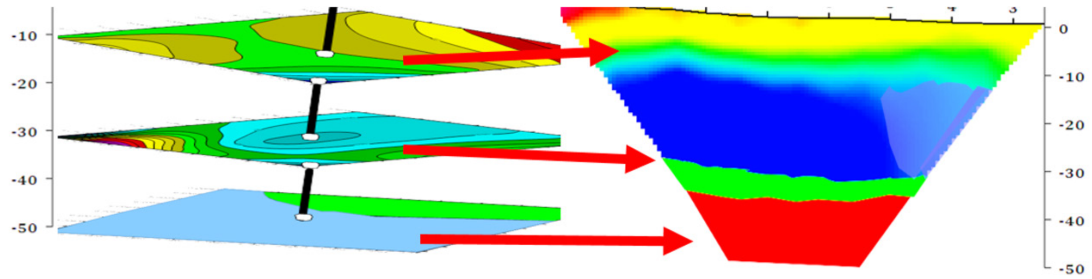

Fig. 6. Hydraulic Conductivity in the Lateral Electro-Facies from Cross Correlation of 1-D, 2-D and 3-D Earth Model

The study focuses on the hydraulic conductivity of a 3-D surface elevation model of an area, which was mapped using random spot sampling (RSS) points. The resistivity at 10m depth was observed to be erratic, indicating a near surface effect, while at 30m, the erratic effect became low with high conductivity, likely due to the effect of clay material. At 50m, a fairly uniform effect was observed, indicating profiling within the aquiferous unit.

The hydraulic conductivity of the Earth Model from Correlation of 1-D, 2-D and 3-D Surface Elevation showed consistency with the 1-D, 2-D, and 3-D dicer models within the study area. It was concluded that hydraulic conductivity becomes poorer towards the North-East section of the mapped area.

Transverse resistance is another important factor in determining areas with high potential for groundwater exploration. The values of transverse resistance ranged from 37385.1Ωm2 at VES 3 to 129016.8Ωm2 at VES 7, with the maximum at VES 7. High transverse resistance values correspond to high groundwater transmissivity, suggesting high potential yield of the groundwater in the area.

Longitudinal conductance varied from 0.031Ω-1 to 0.076Ω-1, with low values indicating high permeability, hydraulic conductivity, and low clay volume. These low values were compared to the Standards for rating aquifer overburden protective capacity and vulnerability ratings, revealing that the aquifer's protective capacity is rated poor/extremely high vulnerability, indicating it is unprotected from pollution and prone to contamination risk from surface contaminants.

Transmissivity values in the area ranged from 228.5m2/day to 538.6m2/day, with the maximum at VES 7. High transmissivity values indicate that the probability of good yield of groundwater is high, encouraging sinking of productive boreholes in the area. High transmissivity values also indicate that the area is underlain by relatively thick aquifer materials, and as transmissivity is a function of thickness, it increases with thickness.

The study found that regions of high hydraulic conductivity and transmissivity, such as VES 7, VES 6, VES 1, VES 2, and VES 5, have good aquifer productive potential but poor overburden protective layer, corresponding to regions of high transmissivity values. Portable groundwater can be harnessed sufficiently within the depth range of 40m -65m, but the distal end should be given preference to ensure better transmissivity.

Conclusion

The VES field data revealed that the subsurface lithology of the area is characterized by seven to eight geoelectric layers of topsoil, dried sand, sandy-clay, clayey sand, dried sand/indurated, saturated sand, clayey sand and sandy clay. Computer modeling software programme was used to obtain values of the subsurface resistivity, thickness and depth. The layer thickness, depth and their corresponding resistivity values were used to determine the Dar- Zarrouk parameters in order to estimate the hydraulic conductivity, longitudinal conductance, transverse resistance and transmissivity of the aquifer in the area. The results of the longitudinal conductance were used to characterize the aquifer overburden protective capacity which was rated as poor and extremely high vulnerability to contaminants. The area is characterized with high transverse resistance and high transmissivity values indicating a good groundwater yielding material that is capable of promoting adequate recharge from precipitation as well as having high groundwater supply potential to satisfy the needs of people living in the region. The VES gave the range of hydraulic conductivity from 6.55m/day to 6.80m/day and this would affect the direction and magnitude of groundwater velocity, groundwater flow as well as pollutants transport. The results of the aquifer hydraulic characteristics estimated from the Dar-zarrouk parameters revealed that the aquifer in the area contain adequate quantity of water sufficient to meet economic needs in the region and has enough hydraulic pressure to release portable water to serve the people living in the region. Thus, portable groundwater can be harnessed sufficiently within depth range of 40m to 65m but the distal end should be given preference to assure for better transmissivity. This is because a slice through the 10m, 30m and 50m geometrically showed variation in earth resistivity structure with hydraulic conductivity becoming poorer within the North-East section of the mapped area. Arising from the poor rating of the overburden protective capacity resulting to extremely high vulnerability to surface contaminants, it is recommended that a comprehensive hydrochemical study be carried out to determine the portability of the water. It is also advised that the groundwater be treated after abstraction before supply to the inhabitants in the area for consumption.

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