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RESEARCH ARTICLE

GEOELECTRICAL INVESTIGATION OF GROUNDWATER QUALITY THROUGH ESTIMATES OF TOTAL DISSOLVED SOLIDS AND ELECTRICAL CONDUCTIVITY IN PARTS OF AKWA IBOM STATE, SOUTHERN NIGERIA

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ABSTRACT

This paper presents the results of a geophysical investigation of groundwater quality in parts of Akwa Ibom State, Southern Nigeria. A total of 11 vertical electrical soundings (VES) was carried out in the study area using the Schlumberger electrode configuration. The results of the interpretation show that the area comprises 4 geoelectric layers. The third layer constitutes the major economic hydrogeological unit in the area and has resistivity of between 50.3 Ω m and 2088.9 Ω m and thickness of between 36.8 m and 149.0m respectively. The groundwater quality was assessed through estimates of the electrical conductivity and total dissolved solids in water. The conductivity ranges from 74.5 to 604.4 μ S/cm with an average value of 244.0 μ S/cm while the TDS values range from 47.7 to 386.8 ppm with an average value of 156.1 ppm. Based on these values, which are within the permissible limits, the water is considered to be fresh and suitable for drinking and other domestic/agricultural usages. The results show excellent correlation between the estimated TDS and the Dar-zarrouk parameters (longitudinal conductance and transverse resistance) on one hand and the aquifer bulk resistivity on the hand which demonstrate the ease of deriving TDS from surface resistivity data.

KEYWORDS

Aquifers, resistivity, water quality, VES, contaminations.

1. INTRODUCTION

Water is a good solvent and picks up impurities easily. Pure water is tasteless, colourless, and odourless and is often regarded as a universal solvent. Dissolved solids refer to any minerals, salts, metals, cations or anions dissolved in water. Total dissolved solids (TDS) comprise inorganic salts (principally calcium, magnesium, potassium, sodium, bicarbonates, chlorides, and sulphates) and some small amounts of organic matter that are dissolved in water. TDS in drinking water originates from natural sources, sewage, urban run-off, industrial wastewater, and chemicals used in the water treatment process, and the nature of the piping or plumbing. The resultant effects of these factors are unwanted taste, odour and colouration of water (Freeze and Cherry, 1979). Thus, the total dissolved solids test is used as an indicator test to determine the general quality of the water.

Water is very fundamental to life. Groundwater, a major source of potable water used today for domestic, industrial and agricultural purposes is often contaminated by many soluble chemicals (Oladunjoye, et al., 2011). Variations in the concentrations of these chemical constituents in groundwater, which may be natural or due to human activities, determine the geochemical character of water and thus, may affect its quality (Gowd, 2005; Odeyemi et al., 2011). One of the major challenges of the 21st century is that of ensuring potable water in adequate amounts to meet the needs of the growing human population. Obtaining useful information on

groundwater quality of an area is necessary for managing and sustaining the geo-resource to meet man's increasing water needs.

The resistivity and hence, conductivity of water is directly related to the amount of total dissolved solids (TDS) in the water. TDS in general, could be determined from electrical conductivity EC (Salufu and Akhirevbulu, 2015). Electrical conductivity and TDS are two physical parameters commonly used to assess the quality of water (Aweto, 2013; Rusydi, 2018). EC is very easy to measure by the use of a portable conductivity meter. However, measurements of TDS are expensive and more difficult because of their requirement of specialized equipment and time consuming (Rice et al., 2017). Electrical resistivity methods have been used for many years for groundwater studies (Bello and Makinde 2007, Yilmaz, and Koc, 2014; George et al., 2015; George et al., 2016). The Vertical electrical sounding technique (VES) for instance is sensitive to variations in electrical resistivity with depth and could be used to determine the aquifer bulk resistivity. Relationships exist for estimation of water resistivity from the aquifer bulk resistivity, from where the electrical conductivity could be estimated (Ibanga and George 2016; Ekanem, et al., 2019). Thus, the surface resistivity method can be used for the assessment of groundwater quality.

Pure water has an electrical conductivity of nearly zero. Allowable limits of TDS and EC, according to the world health organization are 500ppm and 400 μ S/cm respectively (USEPA., 2002; WHO, 2004). TDS levels greater

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than the above limits can have an effect on water taste and usually are indicative of high hardness or alkalinity (Wetzel, 2001). High levels of TDS in water alone are not indicative of health hazard. Nonetheless, high levels of certain ions which are included in the TDS, for example copper, nitrates, aluminium, lead or arsenic might be life threatening (Kurl et al., 2019). The aquifers in the study area are usually exploited without proper assessment of the groundwater quality as most of the boreholes in the area were completed without any geochemical analyses to ascertain the water quality. Consequently, this study was aimed at using the surface resistivity method to determine the electrical conductivity and hence, the total dissolved solids (TDS) in groundwater in parts of Akwa Ibom State. These parameters are useful in assessing the groundwater quality of the aquifers in the area.

2. LOCATION OF STUDY AREA AND ITS GEOLOGY

The study area comprises three Local Government areas in the Southern part of Akwa Ibom State. These local government areas are Onna, Ikot Abasi and Eastern Obolo (Figure 1). The area lies between latitudes 4°32'N and 5°00'N and longitudes 7°25'E and 8°25'E in the Niger Delta region of Southern Nigeria. The area has two main seasons, which are the rainy and the dry seasons respectively. The former usually starts from around March and ends around October while the latter usually spans from around November to February (George et al., 2014). However, slight changes sometimes occur in the upper and lower limits of these seasons as a result of global climatic changes (George et al., 2014).

Geologically, the study area is located in the Tertiary to Quaternary Coastal Plain Sands (CPS) (also known as the Benin Formation) and alluvial environments of the Niger Delta region of Southern Nigeria. The Benin Formation overlies the paralic Agbada Formation and covers up to 80% of the study area (George et al., 2014). The sediments of the Benin Formation comprise inter fringing units of lacustrine and fluvial loose sands, pebbles, clays, and lignite streaks of diverse thicknesses, while the alluvial units comprise tidal and lagoonal sedimentary sands, beach sands and soils which are mostly found in the Southern parts and along the river banks. The CPS constitutes the main aquifer units in the study area and comprises poorly sorted continental sands (fine, medium, and coarse) and gravels that alternate with lignite streaks, thin clay horizons, and lenses at several locations. The thin clay/shale horizons truncate the vertical and lateral extents of the sandy aquifers and in this way, build up multi-aquifer systems in the area (George et al., 2011, George, 2020).

Figure 1: Location map of the study area showing its Geology and VES points

3. BACKGROUND OF STUDY

3.1 Total dissolved solids (TDS) and electrical conductivity (EC)

The resistivity and hence, conductivity of water is directly related to the amount of total dissolved solids (TDS) in the water. TDS is the total amount of dissolved material present in water. It typically includes predominantly dissolved mineral ions such as sodium, chloride, potassium, calcium and magnesium, chloride, sulphate, nitrate and bicarbonate. TDS equally include other inorganic ions, dissolved organic material, and non-ionic matter such as dissolved silica. Although a relatively small amount of the TDS includes non-ionic matter, which carry no electrical charge, water with high values of TDS usually have lower values of resistivity or higher values of conductivity. For instance, water with a high concentration of dissolved salts will have a low resistivity or high conductivity.

The major application of TDS is in the area of assessment of groundwater quality (Salufu and Akhievbulu, 2015). TDS in water and electrical conductivity (EC) are physical parameters commonly used to assess the water quality (Rusydi, 2018). EC is easy to measure by the use of a portable

conductivity meter. However, measurements of TDS are expensive and more difficult since they require more equipment and take more time (Rice et al., 2017). Surface resistivity methods provide an easy and less expensive means of estimating TDS from resistivity data. Mathematically, TDS can be calculated in parts per million (ppm) from EC or water resistivity ρ_w by using equation 1 (Aweto, 2011; Aweto et al., 2018) (1):

$$TDS = 0.64 \times EC = \frac{6400}{\rho_w} \quad (1)$$

where $EC = \frac{1}{\rho_w}$. The water resistivity can be obtained from the formation

factor F , which according to Archie's equation is given in equation 2 (Archie, 1942).

$$F = \frac{\rho_b}{\rho_w} = a\phi^{-m} \quad (2)$$

where ρ_b is the aquifer bulk resistivity, a is the pore geometry factor, m represents the cementation exponent and ϕ is porosity.

3.2 Dar-zarrouk parameters

A given geoelectric layer is characterized by two primary parameters. These parameters are the layer resistivity (ρ) and thickness (h). Two other secondary parameters can be obtained from these two primary parameters. These secondary parameters are the longitudinal conductance (S) expressed in Siemens (S) and transverse resistance (T) expressed in ohmmeters squared (Ωm^2). These other parameters are jointly known as the Dar-zarrouk parameters (Maillet, 1947; Henriet, 1976).

For a given layer, the longitudinal conductance S is given mathematically as:

$$S = \frac{h}{\rho} \quad (3)$$

The transverse resistance of a given layer, on the other hand is defined as:

$$T = \rho \cdot h \quad (4)$$

For n layers, these two secondary parameters are respectively given by equations (5) and (6) respectively.

$$S = \sum_{i=1}^n \frac{h_i}{\rho_i} \quad (5)$$

$$T = \sum_{i=1}^n \rho_i \cdot h_i \quad (6)$$

where i is the number of layers ($i = 1, 2, 3, \dots, n$). The Dar-Zarrouk parameters particularly the longitudinal conductance, may be useful in the assessment of aquifer properties and protection studies (Henriet, 1976).

4. MATERIAL AND METHOD

The VES technique utilizing the Schlumberger electrode configuration was adopted in this study. A total of 11 soundings were made at select locations in the study area using a SAS 4000 model of ABEM Terrameter and its accessories. A maximum current electrode separation (AB) of 1400 m was used while maximum potential electrode spacing (MN) was 50 m. The apparent resistivity ρ_a were computed from the measured apparent resistance values R_a by the use of equation (7).

$$\rho_a = \pi * \left\{ \frac{\left(\frac{AB}{2} \right)^2 - \left(\frac{MN}{2} \right)^2}{MN} \right\} * R \quad (7)$$

The computed apparent resistivity values were manually plotted against half of the current electrode separation ($AB/2$) on log-log graph. Manual smoothening of each plotted curve was done where necessary to get rid of the effects of lateral heterogeneities and other forms of noisy signatures (Chakravarthi et al., 2007; George et al., 2015). The smoothening was achieved by either taking the mean of the two readings at the crossover

points or discarding any outlier at the crossover points, which was not in conformity with the prevailing trend of the curve. Data that stood out as outliers in the dominant curve trend for few VES points were also discarded as they could lead to high root mean square error (RMSE) values during the computer modelling stage. Discarding these outliers in any case did not change the dominant trend of the sounding curves especially as ten data were measured per decade.

Thus, the trends observed in the smoothened curves were considered to be due to the variation of the electrical resistivity with depth of investigation. The preliminary interpreted results were improved by the

use of computer based VES modelling software called WINRESIST. This software performs automated approximation of the initial resistivity model from the observed data to improve upon the results using the iterative least square inversion method. The depths and layer thicknesses were constrained by the use of the borehole data at the vicinity of the VES stations while the layer resistivities were allowed to vary. The modelling software uses the initial layer parameters to do a number of calculations and at the end produces theoretical curves in the process shown in figure 2. These curves allow the layer parameters (resistivity, thickness and depth) to be determined within the maximum depth of current penetration.

5. RESULTS, ANALYSIS, AND DISCUSSION

Table 1: Summary of VES data interpretation

VES NO	Name of Location	Longitude (Degrees)	Latitude (Degrees)	Bulk resistivity ρ (Ω m)				Thickness h (m)			Depth d (m)		
				ρ_1	ρ_2	ρ_3	ρ_4	h_1	h_2	h_3	d_1	d_2	d_3
1	Eastern Obolo	7.6611	4.5136	1423.0	210.0	860.5	8367.5	19.4	43.1	49.9	19.4	62.5	112.4
2	Eastern Obolo	7.5970	4.4970	210.7	397.9	1721.4	228.2	0.7	12.8	55.2	0.7	13.5	68.7
3	Eastern Obolo	7.7720	4.5600	1006.6	158.4	50.3	5566.4	18.3	44.1	53.2	18.3	62.4	115.6
4	Onna	7.8570	4.6222	1241.0	118.1	611.2	4893.0	21.6	56.7	36.8	21.6	78.3	115.1
5	Onna	7.8817	4.8218	1360.0	112.4	783.1	551.0	18.7	61.1	37.3	18.7	79.8	117.1
6	Onna	7.8931	4.7210	1063.3	1380.7	2088.9	372.5	7.0	54.0	149.0	7.0	61.0	210.0
7	Onna	7.8390	4.8300	1146.1	1400.1	1881.1	201.0	5.9	43.4	81.7	5.9	49.3	131.0
8	Ikot Abasi	7.5606	4.6500	120.0	223.3	1945.6	62.3	4.2	2.0	68.1	4.2	6.2	74.3
9	Ikot Abasi	7.6810	4.6370	999.8	4938.0	103.4	1789.0	10.4	32.2	57.7	10.4	42.6	100.3
10	Ikot Abasi	7.5666	4.5657	660.4	1488.6	549.2	1248.7	1.3	3.6	47.8	1.3	4.9	52.7
11	Ikot Abasi	7.5632	4.7100	115.8	577.7	115.9	46.1	4.3	6.0	105.3	4.3	10.3	115.6

The results of the interpretation of the VES data are summarized in table 1. The results show that the area under investigation is made of 4 geoelectric layers within the limit allowed by the current electrode separation employed. The first layer has resistivity ranging from 115.8 Ω m to 1423.0 Ω m with an average value of 849.7 Ω m. this layer, interpreted as the Motley topsoil has thickness ranging from 0.7 m to 21.6m and runs across the study area. For the second layer, the resistivity ranges from 112.4 Ω m to 4938.0 Ω m while the thickness ranges from 2.0 m to 61.1 m. This layer was interpreted as gravelly sand and also cuts across the entire study area. The third layer, interpreted as fine sand has resistivity ranging from 50.3 Ω m to 2088.9 Ω m with an average value of 973.7 Ω m and thickness of 36.8 m to 149.0 m. This third layer constitutes the economic aquifer from where the dwellers in the area tap their groundwater. The fourth layer has resistivity which ranges from 46.1 Ω m to 8367.5 Ω m and was interpreted as coarse sand. The thickness of this layer could not be ascertained as a result of the permissible depth allowed by the maximum current electrode separation used. Samples interpreted VES curves are shown in figure 2.

Figure 2: Sample interpreted VES curves (a) VES 4 at Eastern Obolo (b) VES 6 at Onna (c) VES 11 at Ikot Abasi

Figure 3 shows the variation of the aquifer bulk resistivity. Higher bulk resistivity values are observed in the North eastern and south western parts of the study area. This trend suggests that the aquifers in these parts with relatively higher resistivity values may have better water quality than those in the remaining parts with relatively lower values. The distribution of the water resistivity is shown in the contour map of figure 4. Again, the water resistivity follows the same trend as the aquifer bulk resistivity, with relatively higher values in the North eastern and south western parts of the study area.

Figure 3: Contour map showing the distribution of the aquifer bulk resistivity

Figure 4: Contour map showing the distribution of the water resistivity

To determine the TDS from the interpreted VES data, first the water resistivity needs to be determined. This was done by using the expression derived in parts of the study area (Ibanga and George, 2016). This expression is given in equation 8.

$$\rho_w = 0.0577 \rho_b + 13.643 \quad (8)$$

Finally, the TDS was estimated from equation 1. The Dar-zarrouk parameters for the aquifer unit were respectively calculated from equations 3 and 4. Table 2 shows a summary of these computed results. The distribution of the TDS in the study area is shown in figure 5. The TDS values vary from 47.7 to 386.8 ppm with an average value of 156.1 ppm. A comparison of Figures 4 and 5 indicates that areas of low water resistivity correspond to areas of high TDS as predicted by equation 1.

Table 2: Summary of aquifer/water properties

VES NO	Name of Location	Latitude (Degrees)	Longitude (Degrees)	Bulk Resistivity ρ_b (Ωm)	Thickness (m)	Water resistivity ρ_w (Ωm)	Water Electrical conductivity EC ($\mu S/cm$)	TDS (ppm)	Longitudinal conductance S (Ω^{-1})	Transverse resistance T (Ωm^2)
1	Eastern Obolo	7.6611	4.5136	860.5	49.9	63.29	158.0	101.1	0.058	42938.95
2	Eastern Obolo	7.5970	4.4970	1721.4	55.2	112.97	88.5	56.7	0.032	95021.28
3	Eastern Obolo	7.7720	4.5600	50.3	53.2	16.55	604.4	386.8	1.058	2675.96
4	Onna	7.8570	4.6222	611.2	36.8	48.91	204.5	130.9	0.060	22492.16
5	Onna	7.8817	4.8218	783.1	37.3	58.83	170.0	108.8	0.048	29209.63
6	Onna	7.8931	4.7210	2088.9	149.0	134.17	74.5	47.7	0.071	311246.1
7	Onna	7.8390	4.8300	1881.1	81.7	122.18	81.8	52.4	0.043	153685.87
8	Ikot Abasi	7.5606	4.6500	1945.6	68.1	125.90	79.4	50.8	0.035	132495.36
9	Ikot Abasi	7.6810	4.6370	103.4	57.7	19.61	510.0	326.4	0.558	5966.18
10	Ikot Abasi	7.5666	4.5657	549.2	47.8	45.33	220.6	141.2	0.087	26251.76
11	Ikot Abasi	7.5632	4.7100	115.9	105.3	20.33	491.9	314.8	0.909	12204.27

Figure 5: Contour map showing the distribution of the TDS in the study area

Figure 7: Contour map showing the distribution of the aquifer longitudinal conductance in the study area

The distribution of the water electrical conductivity is shown in the contour map of figure 6. The EC values ranges from 74.5 to 604.4 $\mu S/cm$ with an average value of 244.0 $\mu S/cm$. Lower values of the conductivity are observed in the central part and the far north eastern part of the study area. Figures 7 and 8 respectively show the distributions of the longitudinal conductance and transverse resistance in the study area. Higher values of longitudinal conductance are observed in the central part of the part of the study area while the reverse is the case with the transverse resistance. On the whole, the high values of the transverse resistance imply that the area has good groundwater potential.

Figure 6: Contour map showing the distribution of water conductivity in the study area

Figure 8: Contour map showing the distribution of the aquifer transverse resistance in the study area

Figure 9 shows a correlation of the estimated TDS with the aquifer bulk resistivity. The high coefficient of determination (0.97) implies that TDS can be estimated with high accuracy from bulk resistivity according to equation 9:

$$TDS = 4852.7 \rho_b^{-0.588} \quad (9)$$

The relation between TDS and the Dar-zarrouk parameters are shown in the regression plots of figures 10 and 11 respectively. Both plots show

power relations between TDS and longitudinal conductance and transverse resistance respectively. The power inverse relation of TDS and longitudinal conductance is given by equation 10 with a coefficient of determination of 0.82 while equation 11 given the relation between TDS and transverse resistance with a coefficient of determination of 0.94 respectively.

Figure 9: regression plot of TDS against aquifer bulk resistivity

Figure 10: Regression plot of TDS against aquifer longitudinal conductance

Figure 11: Regression plot of TDS against aquifer transverse resistance

6. CONCLUSION

The surface resistivity method was adopted in this study to estimate water conductivity and total dissolved solids with the sole aim of using these parameters to assess the water quality in parts of Akwa Ibom State, Southern Nigeria. The study area is shown to comprise of 4 geoelectric layers with the third layer as the major aquifer from where the inhabitants obtain their water for drinking and other purposes. The estimated water conductivity ranges from 74.5 to 604.4 μS/cm with an average value of 244.0 μS/cm while the TDS values range from 47.7 to 386.8 ppm with an average value of 156.1 ppm. These values, which are well within the permissible limits imply that the water in the aquifers could be considered to be fresh water and thus, is suitable for drinking and other domestic or agricultural purposes. The regression plots demonstrate that TDS could be predicted with high degree of confidence from the Dar-zarrouk parameters which are readily derivable from VES data. Although results show that the aquifers sampled have freshwater based on EC and TDS values, follow up research involving hydrogeochemical and microbiological analyses should be carried out in order to firm up the results obtained in this present study.

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