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Characterization of Aquifer wide hydraulic properties of the Miocene – Recent sediments of the Niger Delta from Transverse Resistance.

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ABSTRACT

Hydraulic properties characterizes the dynamic behavior of aquifers, they are vital parameters which strongly influences well yield. Attempt has been made in recent time to estimate aquifer hydraulic parameters at Orerokpe from resistivity soundings based on the established relationship between transmissivity, transverse resistance and diagnostic hydraulic and electrical conductivities constant ($K\sigma$). This study focuses on the integration of transverse resistance and pump test data to characterize hydraulic properties within the Benin Formation of the Niger Delta basin. Twenty – three (23) vertical electrical soundings from dc resistivity method was utilized using Schlumberger array. However, contrary to prevailing opinion that this approach can be applied to small areas and also, in order to ascertain the reliability of this approach; the hydraulic conductivity from a reference borehole located at Eku (10 km north of Orerokpe) was combined with electric conductivity obtained from one (1) sounding that was conducted close to the reference borehole. The established relationship between aquifer conductivity and transverse resistance was used to estimate transmissivity variations in the aquifer. Values of transmissivity obtained varied between 482.8 to 1888.3m²/day and was compared with transmissivity deduced with reference borehole located in Orerokpe. The results showed strong correlation ($R^2 = 0.9997$) between estimates of transmissivity with reference borehole in Orerokpe and 10 km away. Hence, this method can be reliably used for the estimation of transmissivity variations in areas with no pump tests on a large within the Niger Delta

Keywords: Aquifer, transmissivity, hydraulic conductivity, transverse resistance, pump test

Introduction

Groundwater is a finite but an abundant resource in the Niger Delta. Despite its widespread use as domestic and industrial water globally, groundwater resource is poorly understood (Solly *et al.*, 1998).

Adequate water supply has remained grossly inadequate; this challenge is further compounded with the rapidly increasing population in the Niger

Delta. There are several methods that can be used to estimate aquifers hydraulic properties; these properties include hydraulic conductivity, transmissivity and storativity. These properties characterize the dynamic behavior of aquifers for flow of groundwater to occur and as a result are vital parameters in hydrogeology which strongly influences yield of wells.

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In order for groundwater to be available to perform its main function for domestic and industrial use, a proper understanding of its hydraulic characteristics is required. Poor knowledge of aquifer hydraulic properties has adversely affected optimal exploitation of aquifers (Aweto and Akpoborie, 2015).

In the Niger Delta where water is commonly of critical economic significance, groundwater assessments and sustainability are of utmost importance. Sustainability of groundwater has often become a difficult task (Ngah and Eze, 2017). Because of increased water demand from the growing population, most groundwater development was done without prior hydrogeophysical investigation. Furthermore, estimation of aquifers hydraulic conductivity requires conducting pump tests which are capital and labour intensive (Hamil and Bell, 1986) and are often neglected. This has resulted in abortive groundwater development schemes. In order to pursue sustainable groundwater development, it is crucial to have reliable estimate of groundwater potential (Singh, 1984). Detailed knowledge of aquifer hydraulic properties will ensure maximum potential and utilization of the groundwater resources (Ataie-Ashtianii *et al.*, 1999). One way of determining the hydraulic properties is through pump test (Todd, 2004; Anomohunran, 2014; Aweto and Akpoborie, 2015). This test is however time consuming, expensive to conduct and is not usually included in most borehole drilling contracts in the Niger Delta. Hence, pump test is generally sparse in the Niger Delta to make any general statement on aquifers hydraulic characteristics.

The assumptions in pump test are seldom valid because errors may arise in results obtained due to occurrence of diverse field conditions. Also, according to Tizro *et al.* (2010) results of pump test are usually relevant to relatively small portion of an aquifer. However according to Aweto and Akpoborie (2015), a geophysical – hydrogeological approach integrating pump test and Dar Zarrouk parameters would give very credible estimates of hydraulic properties in the Niger Delta basin. This is because spatial variations in geology due to occurrence of extensive thick sand beds with little or no clay and water quality are negligible. Ungemach *et al.* (1969); Kelly (1977); Niwas and Singhal (1981) had established an empirical relationship between aquifer electrical resistivity/conductivity and hydraulic properties. Myriad of studies (Onuoha and Mbazi, 1988; Ekwe *et al.*, 2006; Massourd *et al.*, 2009) have shown that the combination of conductivity with pump test data can provide reliable estimates of transmissivity variations in an aquifer.

In this study an attempt was made at estimating hydraulic properties of the Benin Formation aquifer using analytical relationship between transmissivity and transverse resistance from geophysical data at Orerokpe and hydrogeological data from a reference well at Eku about 10 km north of Orerokpe.

Materials and Methods

Location and Geology

This study was carried out in Eku, Orerokpe, Afiesere and Ughelli all situated in the western Niger Delta (Fig. 1) located within longitudes 5° 53' E and 6° 28' E and latitudes 5° 43' N and 5° 55' N.

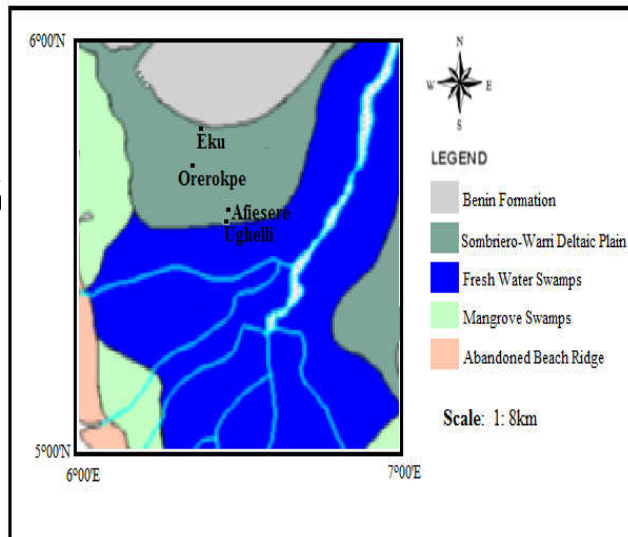


Fig. 1: Geologic map of Western Niger Delta showing study area.

The area is underlain by three geologic formations (Reijers, 2011). These include: the basal Akata Formation, Agbada (Eocene) Formation and the topmost Benin (Oligocene) Formation. The Akata Formation is made up of high-pressured marine shale; the Agbada is an alternating sequence of sand and shale while the Benin Formation consists predominantly of clay, silt, sand and gravel. Superficial expression of the Benin Formation related to series of interglacial marine transgression that occurred during the Quaternary is the Sombriero-Warri Deltaic plain deposits (Oomkens, 1974). The Sombriero-Warri Deltaic plain deposits overlie the Benin Formation everywhere south of River Ethiope and west of Abraka. They are between 40 – 150 m thick. The Benin Formation and the Sombriero-Warri Deltaic plain deposits constitute the aquifer in the Niger Delta basin.

Methodology

One (1) vertical electrical sounding (VES) was run near a reference borehole at Eku with the aid of ABEM SAS 4000 Terrameter. The Schlumberger electrode configuration using a maximum current electrode spacing of 300 m was employed. The measured apparent resistivities and corresponding

current electrode spacing were converted into resistivities and thickness of layer using winResist (Vander, 1988). Soundings from twenty (20) locations at Orerokpe from Aweto and Akpoborie (2015) as shown in fig. 2 also form part of this study. Two (2) soundings from Afiesere and Ughelli were also conducted near a reference borehole where hydraulic conductivity, K had been determined from pump test in a study by DTSG (1998) were used as a control in this study.

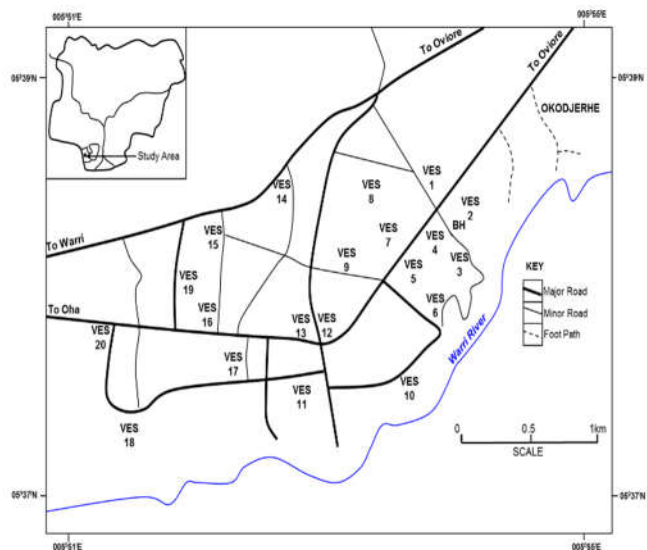


Fig. 2: Location map of Orerokpe showing geoelectric sounding stations (Aweto and Akpoborie, 2015)

Groundwater quality was determined from Total Dissolved Solids (TDS) measured in-situ with a conductivity/TDS meter at thirteen (13) locations in Eku. The value of TDS in mg/l displayed by the conductivity/TDS meter is calculated from the specific conductance of groundwater using the expression below:

$$\text{TDS} = \text{cFEC} \quad (\text{Lloyd and Healthcote, 1985})$$

where EC is electrical conductivity in μScm at 25°C (specific conductance).

cF is correlation factor (a correlation factor of 0.64 as used by Aweto, 2013; Aweto, 2018 was used in this study).

Pump test was performed in the reference well at Eku at a constant pump rate (Q) of 2200 m³/day for 5 hours and observation (drawdown) was observed at another well 42.5 m away. The drawdown ($h_o - h$) in meters was plotted pumping time (t) in minutes on a semi-logarithmic graph as shown in fig. 3. Pump test data was analyzed based on Cooper – Jacobs's straight-line method (Kruseman and De Ridder, 1983; Hiscock, 2006) which expresses transmissivity, T as:

$$T = \frac{0.183Q}{(h_o - h)}$$

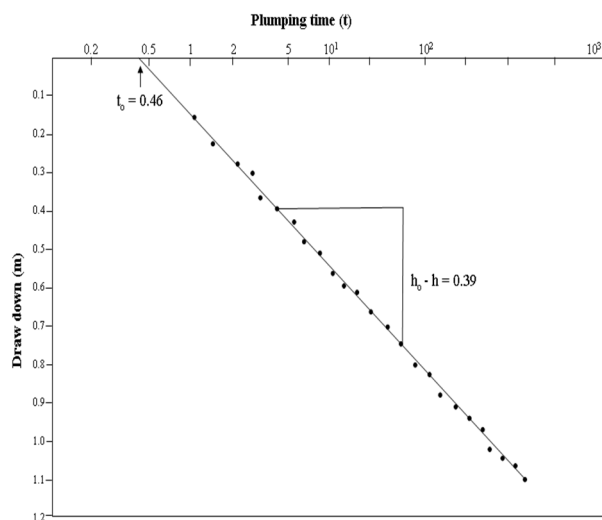


Fig. 3: Time against drawdown plot for reference borehole at Eku.

Two analogous and related phenomena take place in an aquiferous medium viz: flow of current and groundwater. The flow of current in an aquifer is regulated by Ohm's law while the flow of groundwater is regulated by Darcy's law. Groundwater flow is also determined by its transmissivity. According to Fitts (2002) a relationship exists between electric and hydraulic properties of an aquifer. Considering a prism of an aquifer with a unit cross sectional area and having a thickness b , Niwas and Singhal (1981) obtained an analytical relationship between transmissivity (T) and transverse resistance (R) for an isotropic and homogenous aquifer as given below:

$$T = K\sigma R$$

Transverse resistance is expressed as:

$$R = \rho b$$

Using the K value from pump test together with σ value inverted from the sounding near the reference borehole at Eku, the $K\sigma$ constant was calculated. The combination of this constant with transverse resistance at the sounding locations at Orokpe was used to determine transmissivity variations.

Results and Discussions

Lithology

Results of lithological study conducted by Aweto and Akpoborie (2015) at Orokpe and ditch cuttings recovered from borehole lithologic log (fig. 4) show a succession of fine – grained sand underlain by medium to coarse – grained sand that are typically angular to sub – rounded and well sorted quartz sand. Interpretation of resistivity sounding data from Eku, Afiesere and Ughelli reveal same fining upward sequence. Thus, a remarkable lithological similarity exists in the study area.

Pump test analysis

The result of pump test performed in the reference well at Eku indicates that the aquifer exhibits a transmissivity of 1032.3 m²/day and hydraulic conductivity of 29.5 m/day. On the basis of the $K\sigma$ constant calculated from the well at Eku using the K value of 29.5 m/day and the σ value of 0.0011525 for the aquifer extracted from the resistivity data ($\rho = 868 \Omega\text{m}$) near the well location. The $K\sigma$ constant was combined with transverse resistance to estimate transmissivity variations in the aquifer. The estimated transmissivity is presented in table 1.

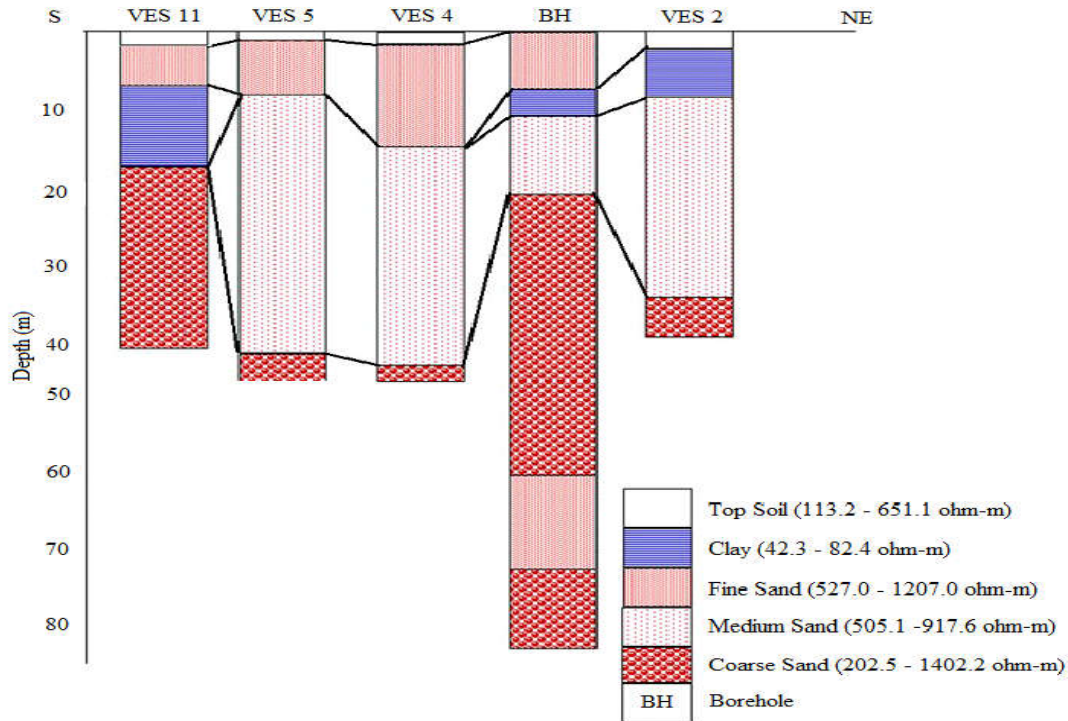


Fig. 4: Geoelectric section correlated with lithologic log (Aweto and Akpoborie, 2015)

Table 1: Estimates of aquifer transmissivity variation at Orerokpe

VES Stations	$\rho(\Omega m)$	b(m)	$R(\Omega m^2)$	K (m/day)	$K\sigma$	T(m ² /day)
1.	429.9	37.9	16293.2	29.5	0.034	553.97
2.	928.7	24.3	22567.41	29.5	0.034	767.29
3.	1084.2	39.4	42717.48	29.5	0.034	1452.39
4.	917.6	26.5	24316.40	29.5	0.034	826.76
5.	505.1	28.6	14445.86	29.5	0.034	491.15
6.	1047.9	18.3	19176.57	29.5	0.034	652.00
7.	771.0	20.7	15959.7	29.5	0.034	542.63
8.	1530.0	36.8	55539.0	29.5	0.034	1888.33
9.	355.9	42.0	14947.8	29.5	0.034	508.23
10.	604.0	26.3	15885.2	29.5	0.034	540.10
11.	1402.2	19.6	27483.12	29.5	0.034	934.43
12.	938.7	21.8	20463.66	29.5	0.034	695.76
13.	1384.2	15.1	20901.42	29.5	0.034	710.65
14.	968.0	31.2	30201.6	29.5	0.034	1020.85
15.	1621.8	20.6	33409.08	29.5	0.034	1135.91
16.	1550.6	21.9	33958.14	29.5	0.034	1154.58
17.	404.2	67.1	27121.82	29.5	0.034	922.14
18.	483.0	29.4	14200.2	29.5	0.034	482.81
19.	1165.0	24.7	28775.5	29.5	0.034	978.38
20.	1225.0	16.1	19722.5	29.5	0.034	670.67
21.	868	34	29512	29.5	0.034	1003.41
22.	459	25	11475	29.5	0.034	390.15
23.	658	27	117766	29.5	0.034	604.04

Location 21 – Eku

Location 22 – Afiesere

Location 23 - Ughelli

The result shows that transmissivity varied between 482.81 and 1888.33 m²/day. It is important to note that the estimated transmissivity and hydraulic conductivity values of 1003.41 m²/day and 29.4 m/day is identical to values of 1032.3 m²/day and 29.5 m/day obtained from pump test. Transverse resistance of any subsurface geological formation is given by the product of resistivity and thickness. A geological formation reflecting a predominantly high transverse resistance indicates that its resistivity is higher or has higher thickness indicating favourable aquifer condition. As the $K\sigma$ value is constant for the aquifer, the values of transmissivity estimated are expected to vary from location to location depending on the change in transverse resistance.

The aquifer in this study generally reflects high transverse resistance thus indicating high transmissivity and good groundwater potential. As shown in fig. 5, the transmissivity obtained in this study with the reference borehole located 10 km away was correlated with transmissivities determined by Aweto and Akpoborie (2015) with the reference borehole located at Orerokpe. The results show positive correlation ($R^2 = 0.9997$); the slope of fig. 5 is close to 1 (0.98) is an indication that transmissivity determined the two studies gave nearly similar results. Findings of Aweto and Akpoborie (2015) as shown in fig. 5 indicated that 4 locations were characterized by moderate transmissivity while results of this study (fig. 7) show that 2 locations were characterized by moderate transmissivity.

The suitability of combining transverse resistance and pump test data in estimating aquifer wide hydraulic properties is due to the homogeneity of the study area and similarity in water quality. The aquifer though about 10 km apart; subsurface lithological trend for the study as derived from geoelectric study revealed lateral homogenous system characterized by relatively similar resistivity values of 868 Ωm , 459 Ωm and 658 Ωm at Eku, Afiesere, Ughelli respectively and an

average of 966 Ωm at Orerokpe. Total dissolved solids distribution map at Eku (fig. 8) showed that TDS varied between 11.2 and 172 mg/l. Aweto *et al.* (2015) evaluated TDS in groundwater at Orerokpe from resistivity sounding data and found out that TDS level varied between 44.1 and 151.7 mg/l. This finding is consistent with results of this study which indicated a variation of 11.2 to 172 mg/l. The closeness in resistivity and TDS values can be considered as an indication of similarity in geology and water quality. The Louis *et al.* (2004) study showed that in an area of similar geological and hydrogeological conditions, it is possible to use its diagnostic $K\sigma$ constant to determine transmissivity at other locations with no pump test data from additional resistivity (conductivity) measurements. The diagnostic $K\sigma$ constant of the Benin Formation aquifer from Eku was also used to determine transmissivity at Afiesere (location 22) and Ughelli (location 23). The estimated transmissivity values of 390.15 m²/day and 604.04 m²/day closely matches values of 473.33 m²/day and 785.65 m²/day deduced from pump test data respectively (DTSG, 1998).

The scenarios above satisfy observations by Kelly and Reiter (1984); Mazac *et al.* (1985) that a direct relationship exist between hydraulic and electrical properties of an aquifer. Contrary to prevailing opinion that geophysical – hydrogeological approach in determining aquifer hydraulic properties can only be applied to small area. Heterogeneity and anisotropy in the subsurface due to faulting which may pose a problem in applying this on a larger scale is absent in this area. The area consists of predominantly clean sands that extends over long distances; characterized by the virtual lack of clayey numbers. The occurrence of clays with higher frequency towards the coast in the south has been reported by Etu – Efeotor and Akpokodje (1990).

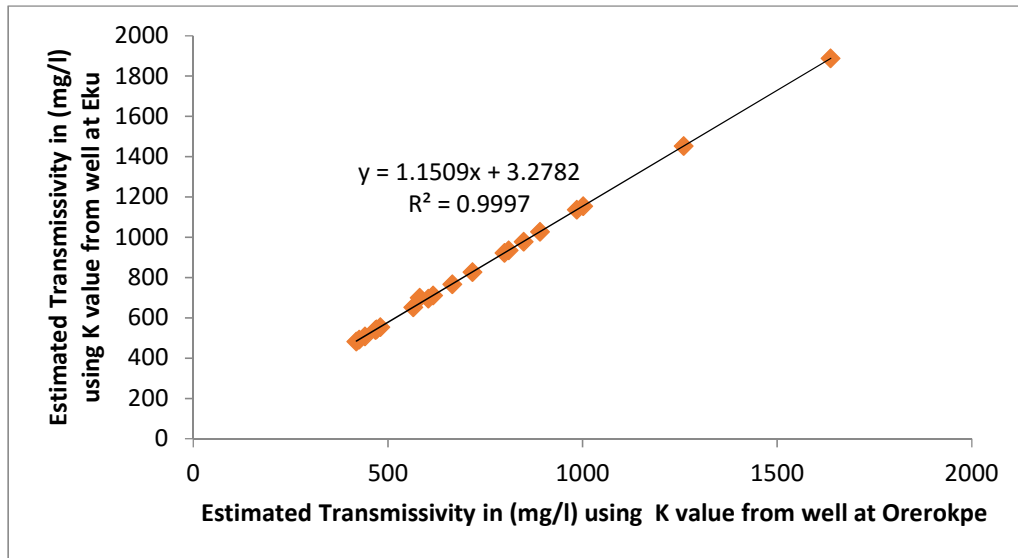


Fig. 5: Correlation of transmissivity estimated with reference well in and outside Orokpe

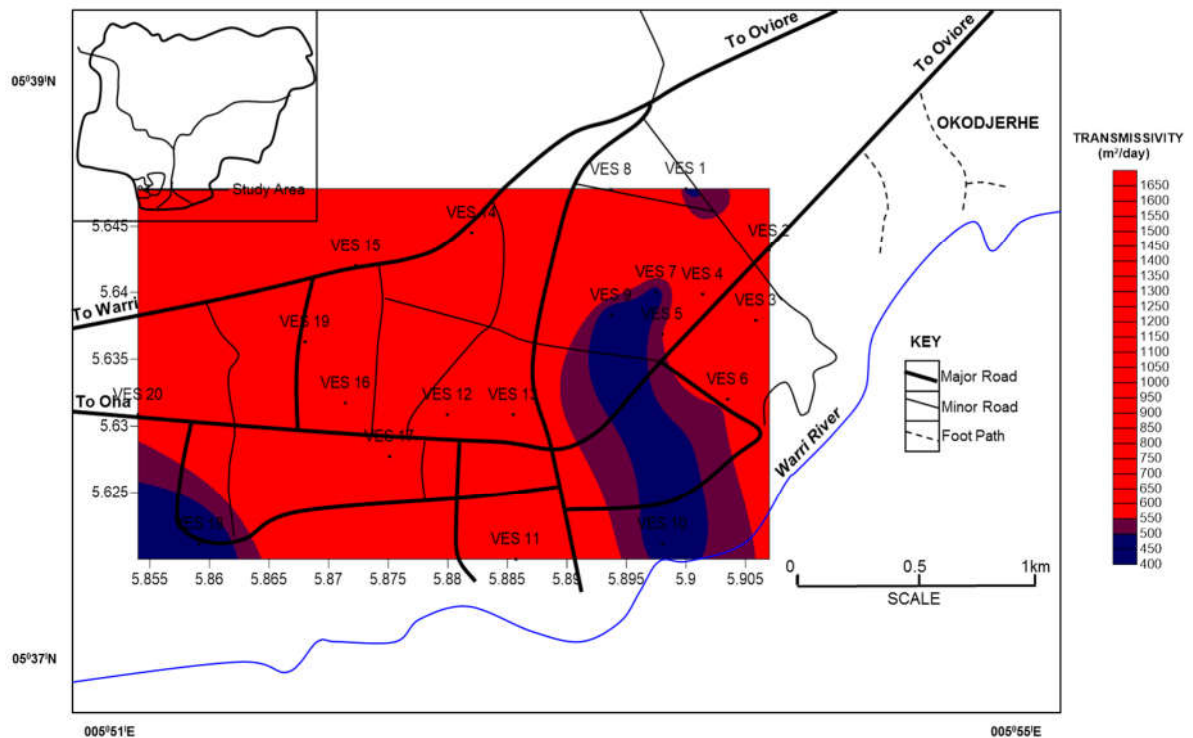


Fig. 6: Transmissivity variations at Orokpe (Aweto and Akpoborie, 2015)

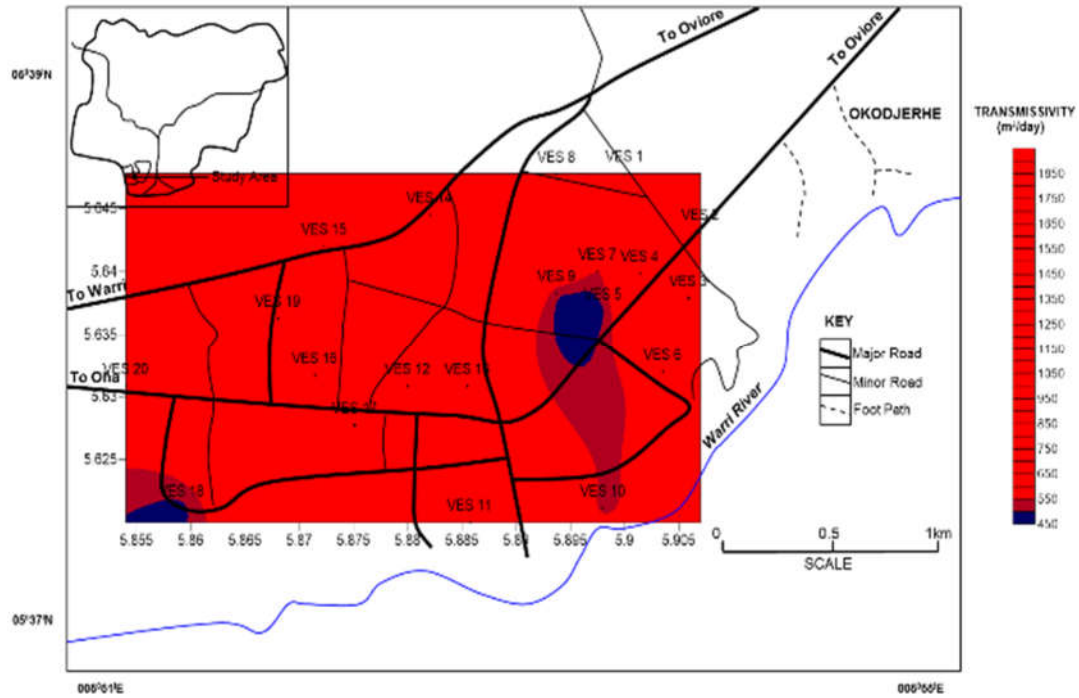


Fig. 7: Transmissivity variations at Ororokpe with reference borehole located at Eku

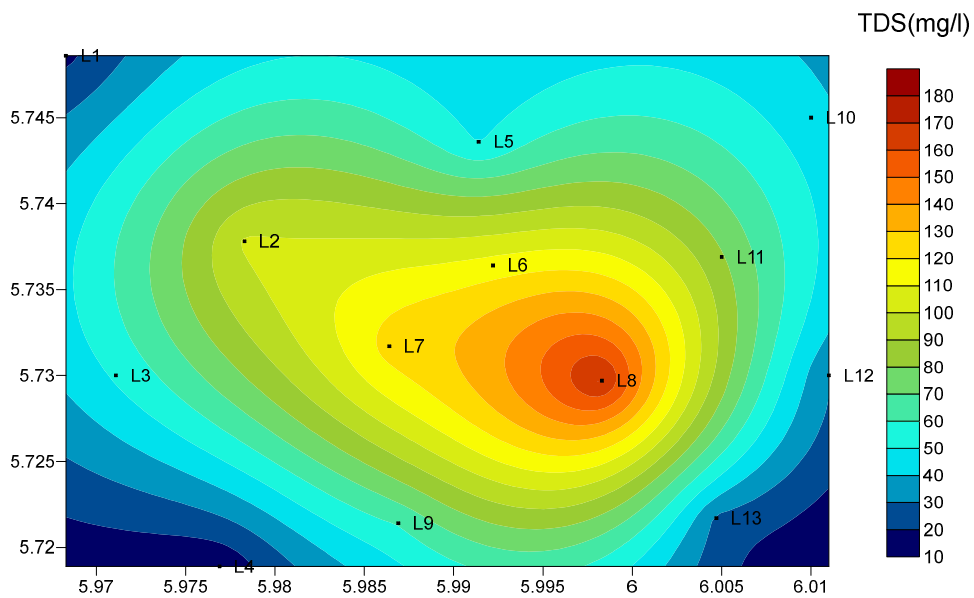


Fig. 8: Total dissolved solids variation at Eku

Conclusion

In this study, the results from geoelectric soundings conducted at Orerokpe had been combined successfully with pump test data from a reference borehole at Eku about 10 km away. The results gave useful and reliable estimates of transmissivity variation in the aquifer which varied between 482.81 and 1888.33 m²/day. The results show that transmissivity of aquifers are generally higher at locations with high transverse resistance. Resistivity distributions show that the geologic formation is the same; characterized by large lateral homogeneity. The negligible spatial variation in geology and groundwater chemistry within the aquifer indicated by its diagnostic constant $K\sigma$ product made this approach possible. Findings from this study show that values of transmissivity estimated with a reference borehole located at Orerokpe from a previous study by Aweto and Akpoborie (2015) show good agreement with estimates using a reference borehole located outside Orerokpe. Also, the closeness of transmissivity values obtained from transverse resistance and those obtained from pump test at Afiesre and Ughelli is a good indication of the reliability of this method. Hence, an integration of geophysical and hydrogeologic methods show promise in estimating reliable aquifer wide hydraulic properties.

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