Quest Journals
Journal of Research in Environmental and Earth Sciences
Volume 10 ~ Issue 1 (2024) pp: 26-33
ISSN(Online) :2348-2532
www.questjournals.org

Research Paper

Estimation of Aquifer Transmissivity Using Geoelectrical Sounding and Pumping Test

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Abstract: *The nexus between surface geophysical measurements and subsoil hydraulic properties is explored to estimate aquifer transmissivity in this study. The reseach objectives include: to map subsurface layer thicknesses, identify aquiferous zones within the probed depths, and establish empirical relationships between the aquifer properties and the geoelectric parameters. Thirty two Schlumberger vertical electrical soundings (VES) were carried out within reasonable distances to borehole sites where pumping tests were conducted. By linking transmissivities derived from pumping test data with Dar Zarrouk parameters (transverse resistance) generated from geoelectric data, a constant was determined to convert transverse resistance to transmissivity. Results indicated that transmissivity from pumping tests ranged from 4.84 x* 10^{-4} *to 1.63 x* 10^{-3} m^2/s*, while estimated transmissivity from transverse resistance ranged from 2.5 x* 10^{-4} *to 2.53 x* 10^{-3} m^2/s*. The association between transmissivity acquired through pumping tests and transmissivity computed from surface geophysical surveys exhibited a robust correlation, with an R-squared value of 0.85. This study provides a rapid and cost-effective alternative to the conventional and expensive pumping test method, offering a quick estimation of aquifer properties and potentials.*

Keywords: *Electrical sounding, Aquifer, pumping test, Dar Zarrouk parameters, transverse resistance, transmissivity*

R*eceived 25 Jan., 2024;* ***R****evised 05 Feb., 2024;* ***A****ccepted 07 Feb., 2024* *© The author(s) 2024.*
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I. INTRODUCTION

The rise in population and economic expansion has consistently heightened the strain on natural resources, leading to an increased demand for essential services like clean water. Currently, the focus has shifted from conventional water sources to groundwater, which is considered a reliable and safe option for potable water. Groundwater has gained widespread acceptance as a preferable alternative to surface water resources [1,2]. The research area's increased quest for drinkable groundwater is motivated by the prevalence of pathogens and coliform from open defecation, as well as the pollution of most surface water sources from crude oil exploration operations. This pressure has led to the creation of new hydrogeological and geophysical challenges relating to the need for detailed aquifer evaluation, as this is necessary in delineating aquiferous zones, effective groundwater monitoring and optimization [3,4].

The analysis of aquifer hydraulics is usually centered around transmisivity which defines the ability for fluid flow through porous media. Traditional hydrogeological and engineering investigations of aquifer transmissivity have been effectively carried out through the pumping test technique. However, this method comes with certain challenges, including both significant capital and labor requirements. The process involves the drilling of multiple boreholes, the deployment of numerous operatives, and the utilization of a considerable amount of equipment. This method focuses largely on the immediate vicinity of the test well as the result approximates only a small segment of the aquifer, areas not covered in many cases are grossly estimated which leads to erroneous results [5]. Given the potential correlation between hydraulic and electrical properties, attributed to their connection with pore space structure and heterogeneity [6], an alternative method for assessing aquifer characteristics involves employing surface geoelectrical methods. Specifically, the vertical electrical sounding (VES) method within geophysical investigations has gained broad acceptance for groundwater evaluation. This method is favored for its high subsurface resolution, non-invasive nature, relatively economical costs, and its capacity for quantitative assessment [2].

The assessment of aquifer potential, especially regarding transmissivity in groundwater hydrology, is guided by Henri Darcy's well-established rule of flow through porous materials. According to this rule, the discharge through porous media is exactly proportional to the product of the material's coefficient of permeability, the hydraulic gradient, and the cross-sectional area perpendicular to the flow [7]. Although the pumping test technique is widely popular and successful in estimating aquifer transmissivity, it has limitations, such as a lack of lateral continuity, a constraint effectively addressed by the resistivity method.

According to [6], a number of scholars have put forward theories for assessing aquifer potential by connecting resistivity readings to the outcomes of pumping tests. [8] demonstrated an empirical association between aquifer electrical resistivity and hydraulic characteristics, as well as a linear relationship between hydraulic conductivity and the resistivity of aquifer materials. Using Darcy's law of fluid flow and Ohm's law of current flow, [9] further estimated aquifer transmissivity from Dar-Zarrouk parameters in porous media and examined the relationships between transmissivity and longitudinal conductance as well as transverse resistance. The goal of this work is to combine obtained Vertical Electrical Sounding (VES) data to give an integrated and economical method of assessing aquifer transmissivity across a large region, even with a limited number of pump tests.

II. GEOLOGY AND HYDROGEOLOGY

The study area is situated between latitudes 4° 60′ N and 5° 05′ N, and longitudes 6° 20′ E and 6° 40’E (Figure 1). It falls within the Quaternary deposits of the Benin Formation, which has a thickness ranging from 40 to 120 meters. The formation is composed of unconsolidated sand with occasional clay/silt intercalations that tend to increase in silt content towards the seaward direction. The Benin Formation is highly productive and serves as the aquifer base for the Niger Delta region. It comprises fluvial and lacustrine deposits with variable thicknesses. The presence of clayey intercalations within the Benin Formation has resulted in a multi-aquifer system in the area [10].

The study area experiences an annual rainfall of approximately 3000 mm, and it is characterized by a network of rivers and streams, making direct precipitation the primary source of recharge. The water refills the aquifers when it seeps through the Benin Formation's very porous sands. Groundwater in the research region typically occurs under water table circumstances [10].

III. METHODOLOGY

Geoelectric Survey

In the geophysical investigation, the Schlumberger electric configuration was employed with a maximum current electrode spread (AB = 600 m). A total of thirty (30) vertical electric soundings (VES) and six pumping tests from existing boreholes were conducted in the study area. The field operations utilized the ABEM Terrameter SAS 1000 device, and data interpretation was performed through a computer-aided modeling technique using IP2Win software. A potential difference (ΔV) between the potential electrodes (M and N) was measured by delivering current to the ground via electrodes A and B in the field technique. Incremental expansion of the electrode spacing was utilised to collect data on the ground's depth and stratification, but the electrode array's center points remained constant.

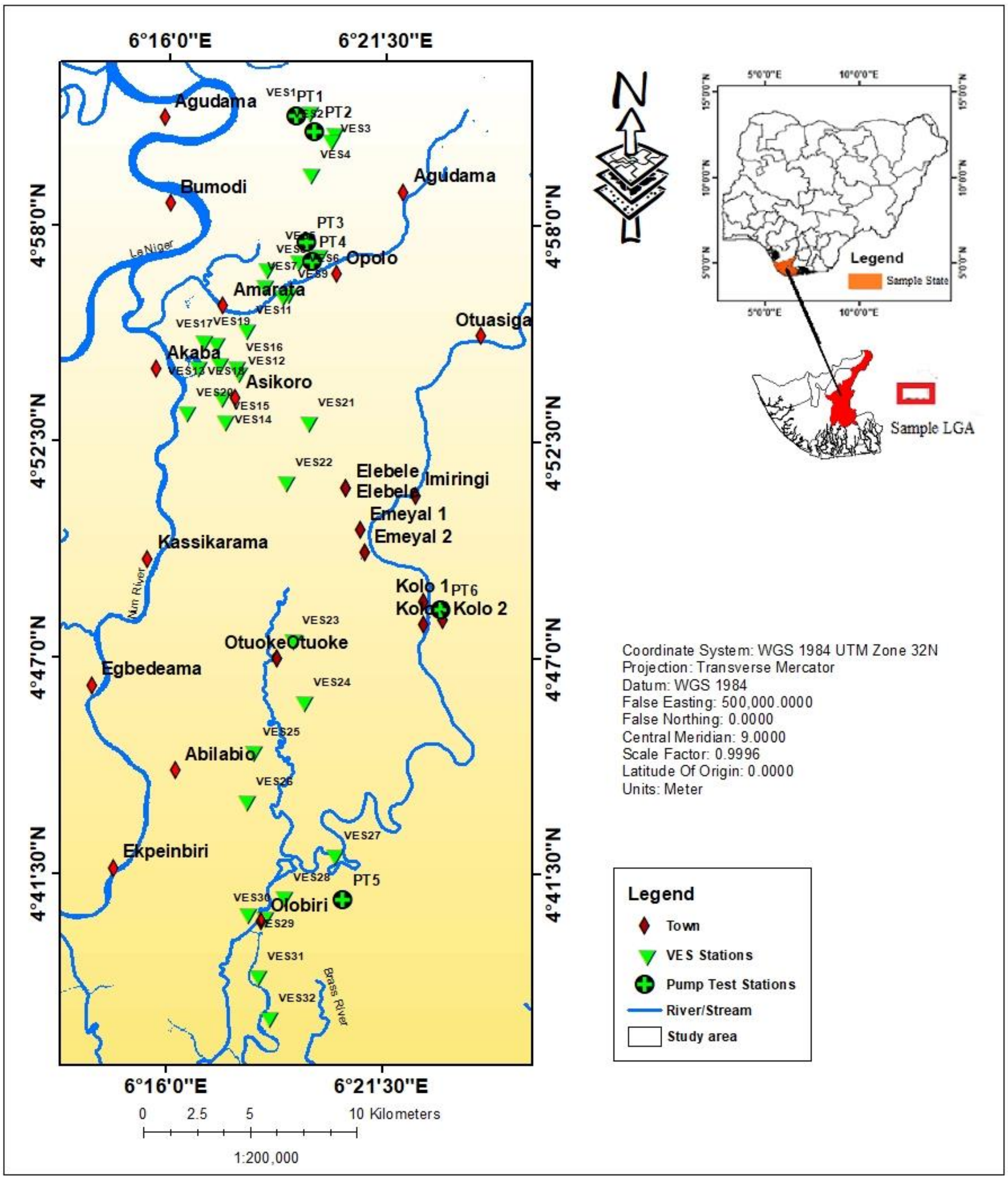

Figure 1: Study Area Showing VES and Pumping Test Points

Pumping Test

Pumping procedures were executed to ascertain the hydraulic properties of the aquifer. These assessments were conducted at designated sites employing the approach of a solitary well pumping test. The analysis of drawdown in relation to time, crucial for assessing transmissivity, utilized the Jacob's straight-line method. Measurements of drawdown in the well were taken at specific intervals during the pumping process. A receptacle with a known volume was employed to collect the discharged water. The estimation of transmissivity (T) involves fitting a straight line to drawdowns plotted on an arithmetic axis against time on a logarithmic axis. The quantitative determination of T is achieved through the application of Equation 1:

$$2.3Q/4\pi\Delta(h-ho) \qquad (1)$$

Where Q is discharge and $\Delta(h-ho)$ is the change in drawdown per log cycle.

Analytical Relationship of Geo‐ hydraulic Parameters

Combining layer resistivity and thickness—also known as the Dar Zarrouk parameters—offers a basis for evaluating aquifer characteristics (Niwas and Singhal, 1981). Based on studies by [11] and [12], analytical relationships between aquifer transmissivity and Dar Zarrouk characteristics have been developed. The terms transverse resistance (RT) and longitudinal conductance (LC) have the following quantitative meanings when referring to a homogeneous and isotropic layer:

$$R_T = \rho h \qquad (2)$$

$$L_C = h/\rho \tag{3}$$

where h is layer thickness (in meters) and ρ is the electrical resistance in ohm-metres. As to the findings of Niwas and Singhal (1981), there exists an analytical correlation between transmissivity and the Dar Zarrouk parameters hinged on Darcy's law of groundwater flow and Ohm's law of current flow:

$$T = K/\rho(R_T) \tag{4}$$

$$T = Kp L_C \tag{5}$$

where T is the transmissivity, which may be found by multiplying the hydraulic conductivity (K) of the aquifer by its thickness (h); that is,

$$T = Kh \tag{6}$$

Longitudinal conductivity is represented by L_C and transverse resistance by R_T, respectively.

Studies on the effect of clay content by [13] demonstrated that hydraulic conductivity of sediments containing clays could be related to electrical resistivity, and that low resistivities and hydraulic conductivity were often associated with high clay concentrations. According to this, hydraulic conductivity and resistivity in certain types of aquifers are linearly related. Therefore,

$$K/\rho = C_1 \tag{7}$$

According to [14], hydraulic conductivity and porosity in an unconsolidated, sandy, clay-free aquifer are directly correlated, whereas porosity and resistivity are inversely correlated. Therefore,

$$Kp = C_2 \tag{8}$$

where C_1 and C_2 are constants. Substituting Equation (7) into (4), and Equation (8) into (5) gives:

$$T = R_T C_1 \tag{9}$$

$$T = L_C C_2 \tag{10}$$

Consequently, Kp may be regarded as constant in sandy areas devoid of clay, but K/ρ would be constant in conditions containing clay. Niwas and Singhal (1981) state that differences in effective porosity (Equation 8) or changes in clay content (Equation 7) regulate the changes in resistivity and hydraulic conductivity throughout an aquifer. Given that there are few variations in the electrical conductivity of the groundwater in the aquifer.

IV. RESULTS AND DISCUSSION

The constructed geoelectric sections based the processed geoeelectric data shows a presentation of the various layers encountered with layer thickness and associated resistivity values (Figure 2).

Lithological Correlation

From the Yenagoa area, twenty (20) VES surveys with stations 1 to 20 were carried out. Fourteen (14) stations exhibited three (3) layers, while six (6) showed four (4) subsurface layers within the depth of investigation. In the Ogbia axis twelve (12) VES surveys were carried out with eight (8) stations exhibited three (3) layers, while four (4) stations showed four (4) layer structure.

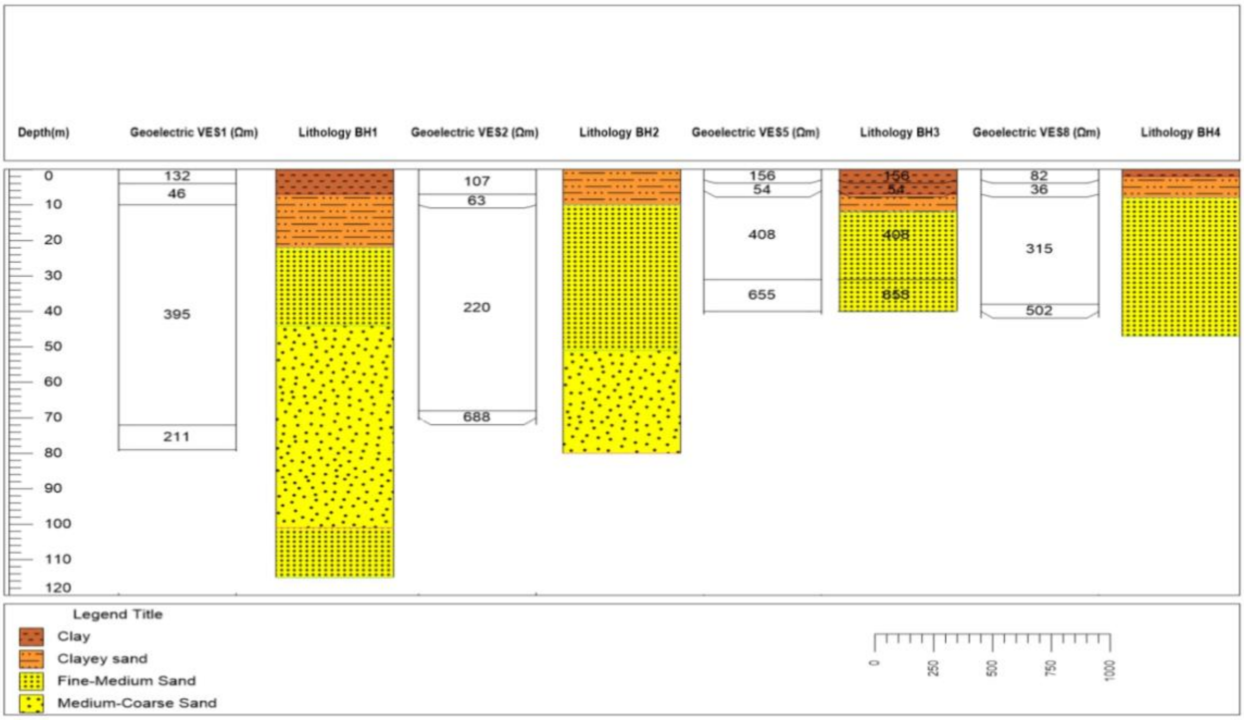

Figure 2: Geoelectric sections and bore hole litholog correlation within the study area.

In both areas, the borehole sections showed two (2) distinctive lithologies; fine grains (clay, slit grading into fine sands with depth) which occur as top units within the depth range of 0 to approximately 6m and the medium - coarse sands which are the base units. Constrained by borehole data, resistivity values ranging from 21 Ωm to 180 Ωm were interpreted as clay and slit grading into fine sands with increasing resistivity. While resistivity ranges above 180 Ωm are sands with increasing coarseness with depth. The sand units were observed to be thick and extensive; and serves as the aquiferous zones (Figure 3). In the Ogbia axis, clay units with variable thickness within depths 40 to 60 m were delineated which segments the aquifer into unconfined above and confined below. The unconfined aquifer is the source of groundwater for both hand dug wells and shallow boreholes within the study area.

Transmissivity

The resultant geoelectric layer parameters were used to determine the Dar-Zarrouk parameters shown in Table 2, the calculated transverse resistance which is directly proportional to the transmissivity (T) of the aquifers vary from 3840 Ωm^2 at VES 11 to 38829 Ωm^2 at VES 3 in Yenagoa, and 7410 Ωm^2 at VES 26 to 17836 Ωm^2 at VES 30 in Ogbia. The transmissivities of the aquifers were quantitatively determined by means of Equation 1. The measured transmissivity values (Figure 4) ranged from 4.84×10^{-4} m^2/sec -1.63×10^{-3} m^2/sec (41.82 m^2/day - 140.832 m^2/day) and is designated intermediate to slightly high as presented in Table 1 [15]. The lower values are indicative of low ground water yield reported in some of the study locations (VES 5, 8 and 29). The results thus explain why in the above mentioned locations seasonal or temporally functional bore holes are common place [16]. These occurrences confirm that the transmissivity of the aquifers is affected by the thickness and lithologic characteristics of the aquifer materials. Generally, the higher the transmissivity value of an aquifer, the better its productivity prospect.

In relation to the intrinsic rock properties of the study area, the calculation of modeled transmissivities incorporated the transverse resistance (Equation 9). The transmissivity results from pumping tests were graphed against the aquifer transverse resistance values obtained from six locations. This process yielded an equation that was subsequently employed to predict transmissivity at vertical electrical sounding (VES) locations where pumping tests were not carried out. The crossplots comparing both the pumping test and modeled transmissivity results demonstrated a strong correlation, with an R^2 value of 0.85.

The groundwater supply potential of the study area going by Krasny (1993), is fairly good ranging from low (13%) to Intermediate and high (87%) (Table 1). This shows a capacity to supply the local groundwater needs which is mainly for household/domestic purpose. Only few areas can sustain a continues groundwater flow even in the event of heavy discharge due to industrial use or population growth.

Table 1: Classification of Transmissivity Magnitude (After Krasny, 1993)

Magnitude of Transmissivity (m^2/day)	Designation	Ground Water Supply Potential
>1000	Very High	Regional Importance
100 – 1000	High	Lesser Regional Importance
10 – 100	Intermediate	Local water supply
1 - 10	Low	Private consumption
0.1 - 1	Very Low	Inadequate for local water supply

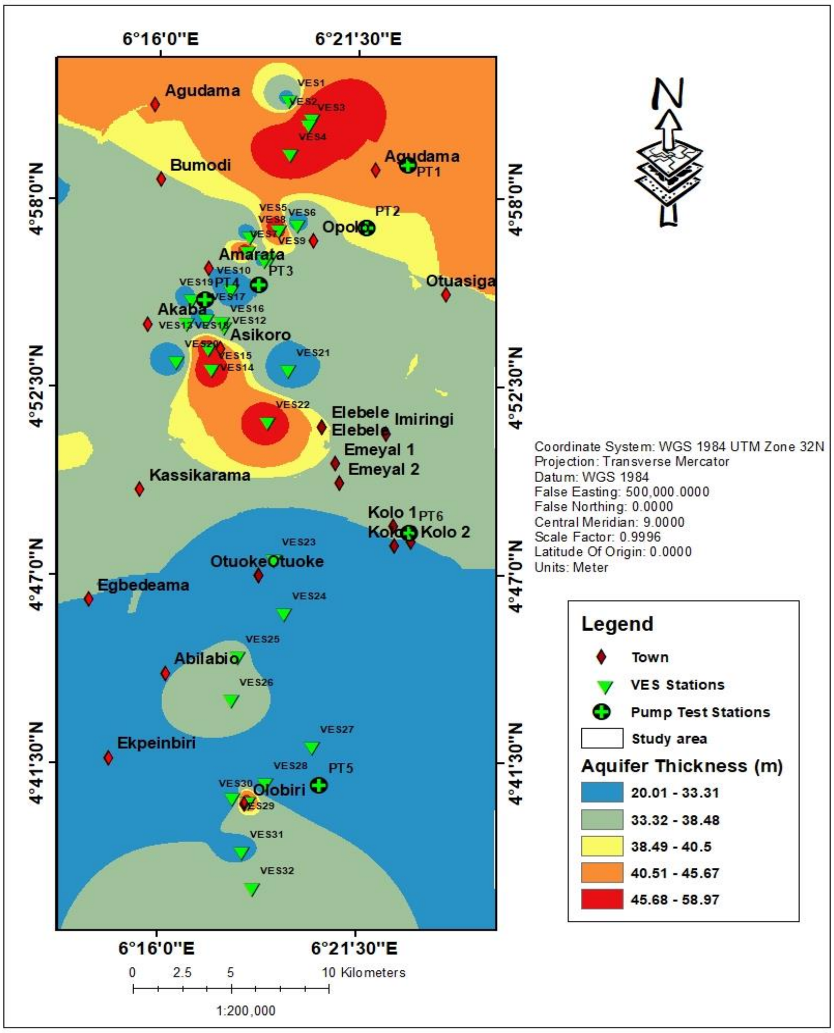

Figure 3: Aquifer zone within the study area.

Table 2: Summary of aquifer and Dar Zarrouk parameters across the study area

VES Station	Aquifer thickness (m)	Aquifer resistivity (Ωm)	Transverse resistance (Ωm2)	Longitudinal conductance (mhos)	Measured transmisvity (m2/sec)	Modelled transmissivity (m2/sec)
1	31	503	15593	0.0616	1.18x10^{-3}	1.02x10^{-3}
2	59	220	12980	0.2680	-	8.46x10^{-4}
3	43	903	38829	0.0476	-	2.53x10^{-3}
4	57	251	14307	0.2271	-	9.32x10-4
5	28	408	11424	0.0689	5.3x10^{-4}	7.45x10-4
6	55	87	4785	0.6322	-	3.12x10-4
7	51	534	27234	0.0955	-	1.77x10-3
8	27	315	8505	0.0857	6.15x10^{-4}	5.43x10-4
9	43	462	19866	0.0931	-	1.29x10-3
10	27	296	7992	0.0912	-	5.21x10-4
11	20	192	3840	0.1042	-	2.5x10-4
12	34	403	13702	0.0844	-	8.23x10-4
13	24	360	8640	0.0667	-	5.63x10-4
14	56	93	5208	0.6022	-	3.39x10-4
15	51	240	12240	0.2125	-	7.98x10-4
16	38	486	18468	0.0782	-	1.2x10-3

17	46	413	18998	0.1114	-	1.23x10-3
18	34	615	20910	0.0553	1.63x10-3	1.36x10-3
19	29	745	21605	0.0389	-	1.41x10-3
20	26	285	7410	0.0912	-	4.83x10-4
21	26	634	16484	0.0410	-	1.07x10-3
22	52	314	16328	0.1656	-	1.06x10-3
23	27	279	7533	0.0968	-	4.91x10-4
24	22	414	9108	0.0531	-	5.94x10-4
25	34	191	6494	0.1780	-	4.34x10-4
26	37	212	7844	0.1745	-	5.11x10-4
27	32	524	16728	0.0611	9.21x10-4	1.09x10-3
28	25	440	11000	0.0568	-	7.17x10-4
29	24	380	9120	0.0632	4.84x10-4	5.94x10-4
30	49	364	17836	0.1346	-	1.16x10-3
31	27	184	4968	0.1467	-	2.19×10^{-4}
32	33	281	9273	0.1174	-	4.08×10^{-4}

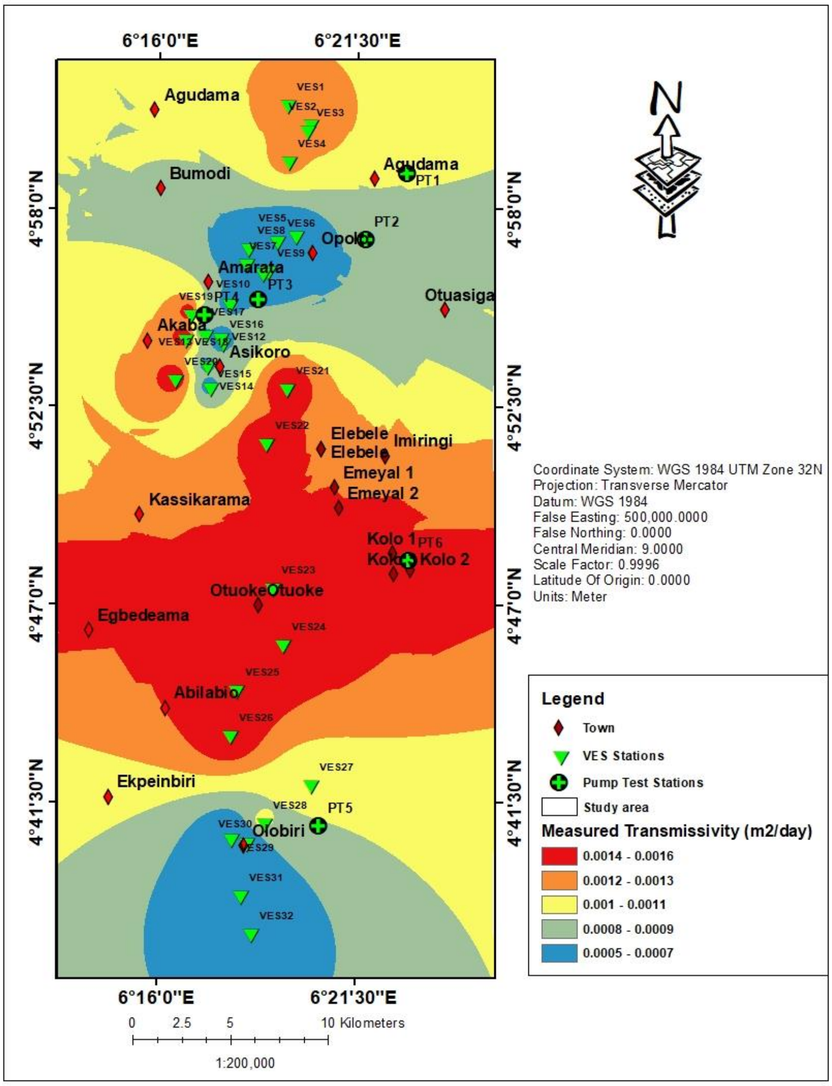

Figure 4: Measured Transmissivity (m^2/day)

V. CONCLUSION

A valuable, economical, and practical method for estimating aquifer hydraulic parameters like the aquifer transmissivity is to analyze the secondary derivatives of the geoeletric sounding data, especially the transverse resistance. This is due to the connection between the electrical and hydraulic characteristics, which are both influenced by the subsurface's lithology and pore space structure. The results of the investigation show that the measured transmissivity values in the study area ranged from 4.84×10^{-4} m^2/sec -1.63×10^{-3} m^2/sec (41.82 m^2/day - 140.832 m^2/day) and is designated intermediate to slightly high. The lower values are indicative of low ground water yield zones that exist in some sections of the study. A good connection (R^2=0.85) can be seen between the transmissivity determined from the surface geophysical survey and the transmissivity obtained from the pumping test.

The results of the study thus give a quick estimation of aquifer properties and potentials that are not solely based on the relatively rigorous and expensive pumping test method but on an alternative rapid and cost effective geoelectric technique.

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