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Characterization of Transmissivity Attributes of Fractured Aquifers from Geo-electrical models: Matuu, Kenya

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Abstract
Vertical electrical soundings (VES) have been used to estimate transmissivity of aquifers in Matuu, Kenya.
The Schlumberger configuration was used for geo-electrical data acquisition. The half–currents electrode ($AB/2$) spacing ranged from 1.5m to 200m.The quantitative interpretation of the VES curves involved the use of partial curve matching and the 1-D computer iteration technique. The depth sounding interpretation results were used to generate geo-electric models from which the aquifer was delineated. The geo-electric sections mostly reveal a three layer formation of the A-type which comprises the topsoil, weathered/semi-weathered and fractured basement. The weathered/semi-weathered layers constitute the aquiferous zone in all the stations.
Transmissivity (T) is one of the most important parameters in determining groundwater potential; it is generally estimated from pumping tests. In this study the relation between hydraulic parameters and geo-electrical parameters using both experimental and theoretical data sets from Finland, Nigeria, India and Egypt, have been tested on data from Matuu.
Cross-plots of transmissivity and tranverse resistance for data sets generated for Matuu from these relationships showed good correlation. From the foregoing the relationships developed from data from Ondo state, Nigeria (theoretical) and West coast Goa, India (experimental) have therefore been used to estimate spatial variations of transmissivity. It is hoped that this information would serve as a useful guide to groundwater exploration in Matuu.

Keywords: *Aquifer, Groundwater, Hard Rocks, Matuu, Transmissivity, Transverse Resistance.*

1. Introduction
Hard rocks are characterized by various types of rock discontinuities varying from few millimeter size joints to major fault zones and lineaments. The main rock discontinuities are foliation, fractures (joints), faults and lineaments. However, weathering and fracturing can impart secondary porosity and permeability to varying extent [1]. The hydraulic properties of these rocks are mainly controlled by fracturing; hard rocks are by nature, therefore, anisotropic and heterogeneous media.
Transmissivity (T) is one of the most important parameters in groundwater potential evaluation; it is generally estimated from pumping tests, but this method is time consuming and expensive. However, geo-electrical methods, particularly those involving resistivity, can contribute considerably in estimation of transmissivity while delineating the aquifer and locating structural features.
Electrical resistivity technique is the most commonly applied method among all the geophysical methods for groundwater exploration, because of the large variation of resistivity for different formations and the changes that occur due to the saturated conditions, [2] used Dar-Zarrouk parameters to estimate transmissivity, [3] carried out geo-electrical sounding for groundwater studies,[4] studied correlation between geo-electrical and aquifer parameters while [5] evaluated the relationship between transverse resistivity and transmissivity.
In this study, experimental data obtained from previous studies in Finland, Nigeria and Egypt, with similar geological formations to that of Matuu have been tested to develop transmissivity attributes of the area using geo-electrical data models.

2. Geology
Geologically, Matuu is a hard rock zone characterized by Precambrian basement crystalline rock system of Mozambique belt segment (EMBS) which stretches in Kenya about 800 Km length and 200 Km width at 3^0 N and 4^0 S latitudes and between 37^0E and 39^0E longitudes [6]. These rocks have undergone cycles of metamorphism, exposure and erosion leading to surface rocks comprising of metamorphic rocks of granitic origin [6], the

surface rocks comprises of metamorphic rocks overlain by a Plateau (Yatta) to the south, the formation of Yatta plateau begun at the start of Miocene period by eruption of Phonolites. This resulted into large part sub-Miocene surface being covered by lava. The study area is described by meta-intrusive mafic and ultramafic rocks that include Diorites, Gabbros, Anorthosites, Peridotites and Picrites, the mafic and ultra-mafic rocks occur in the general Machakos area and its environs [7]. Figure 1 gives the projected topographic map of the study area as part of map of Kenya.

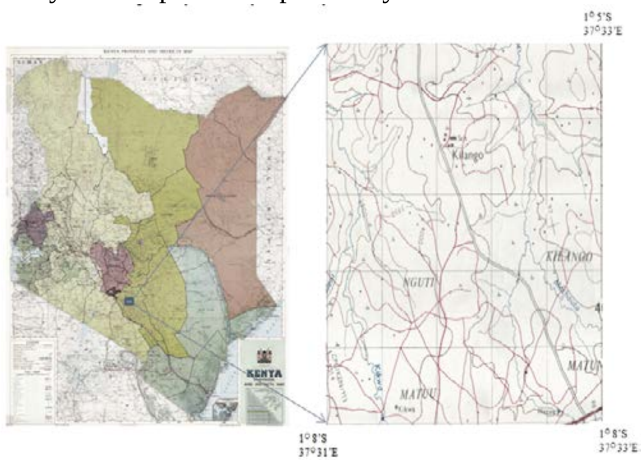

Fig. 1: Topographic map of the study area (Matuu)

3. Theoretical considerations

Generally aquifer transmissivity (T) can be determined using hydraulic conductivity (K) and aquifer thickness (h) as defined by Eq. (1) [2].

$$T = Kh \quad (1)$$

The value of hydraulic conductivity can be estimated by considering various relations between geo-electrical and hydraulic parameters, which could be developed empirically, theoretically or experimentally or directly from field hydrological measurements such as pumping tests [2].

Previous work involving transmissivity as a tool for aquifer characterization show ranges of calculated transmissivity values for aquifers (Table 1), showing that transmissivity values above 100 m^2/day is an indication of good yield aquifers with wider areas of groundwater supply, while that above 10 m^2/day indicate intermediate supply which is equally useful for local supply [8].

Table 1: Transmissivity ranges

Transmissivity magnitude	Class	Designation	Groundwater Supply potential
$T > 1000$	I	Very High	Withdrawals of great regional importance
$100 < T \leq 1000$	II	High	Withdrawals of lesser regional importance
$10 < T \leq 100$	III	Intermediate	Withdrawals for local water supply
$1 < T \leq 10$	IV	Low	Smaller withdrawals for local water supply
$0.1 < T \leq 1$	V	Very low	Withdrawals for local supply with limited consumption
$T \leq 0.1$	VI	Imperceptible	Sources for local water supply is difficult

[9] equally employed the resistivity method to characterize crystalline rock aquifer at Georgia with an attempt of groundwater potential evaluation. From a typically hard rock terrain found in the Jangaon sub-watershed, Andhra Pradesh, India, [10] carried out a related study that showed linear relationship between transmissivity and formation factor by employing resistivity method.

4. Methodology

Grids were established and 11 measurement stations were identified. A handheld Global Positioning System (GPS) was used to identify the coordinates for each station. Vertical investigations of geo-electrical sections at the stations were conducted using Schlumberger array method with half the spacing between current electrodes (AB/2) and potential electrode (MN/2) ranging from 1.5 m to about 200 m and 0.5 m to about 20 m respectively. The Vertical Electrical Soundings (VES) resistivity measurements were done using SARIS Terrameter. The measurement trends were monitored at the field by drawing logarithmic curves for every sounding. Forward and reversed measurements were conducted to help control polarization effects. VES data from the 11 stations were then subjected to digital inversion using IPI2Win software to generate geo-electric models.

5. Results, Analysis and Discussions

Fig. 2 shows a sample result of digital inversion for soundings conducted over the area. From digital inversion results, the following curve types (Table 2) could be associated with the VES soundings carried in study area. For groundwater potential evaluation based on aquifer characteristics, H-type curves are of interest [8]. It was evident that the soundings conducted at the western part of the study area had H curve type dominating i.e. 67% of the total H-type fall precisely at the west of Matuu area. This is an indication of an inferred aquifer, defined by low resistivity layer bounded by an overburden and resistive basement [8].

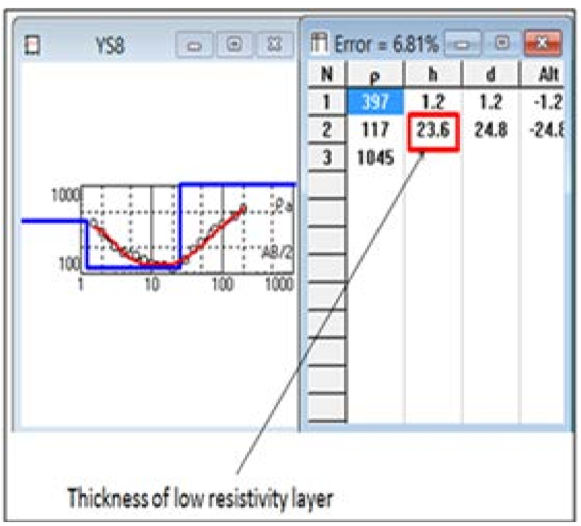

Fig. 2: Inversion result for sounding YS8

Table 2: Curve Types associated with VES analysis

VES Station Code	Curve Type analysis	
	Curve nature	Type
YS1	$\rho_1 > \rho_2 < \rho_3$	H
YS2	$\rho_1 > \rho_2 < \rho_3$	H
YS3	$\rho_1 < \rho_2 < \rho_3 < \rho_4$	AA
YS4	$\rho_1 < \rho_2 < \rho_3$	A
YS5	$\rho_1 > \rho_2 < \rho_3$	H
YS6	$\rho_1 > \rho_2 < \rho_3$	H
YS7	$\rho_1 > \rho_2 < \rho_3$	H
YS8	$\rho_1 > \rho_2 < \rho_3$	H
YS9	$\rho_1 < \rho_2 > \rho_3 < \rho_4$	KH
YS10	$\rho_1 < \rho_2 < \rho_3$	A
YS11	$\rho_1 < \rho_2 < \rho_3$	A

For comparative analysis of transmissivity, transverse resistance (R) for the geo-electrical sections generated for each VES was calculated using Eq. (2), with the results shown in table 3. High values of R is an indication of higher potentials for the groundwater values linked to VES displaying H-type curves were considered for analysis.

$$R = \sum_{i=1}^{n} (h_i \rho_i) \qquad (2)$$

Where h_i, ρ_i is thickness and resistivity of the i^{th} layer of n layered geo-electrical section respectively.

Table 3: Calculated results for transverse resistance

VES Station Code	ρ	h	Transverse Resistance (Ωm^2)
YS1	336	2.57	
	189	56.4	10659.6
YS2	803	1.31	
	160	13.9	2224.0
YS3	53.1	6.54	
	103	16.8	
	285	76.6	23908.67
YS4	86.7	1.23	
	107	9.71	1145.611
YS5	859	0.394	
	195	18.9	3685.5
YS6	510	1.54	
	119	17.5	2082.5
YS7	107	6.3	
	23.4	8.8	205.92
YS8	396	1.2	
	117	23.5	2749.5
YS9	524	0.426	
	1239	0.566	
	169	11.9	2011.1
YS10	3.56	1.27	
	53.2	12.2	653.5612
YS11	50.4	3.32	
	163	26	4405.328

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5.1 Transmissivity Attributes

Determination of transmissivity attributes of the aquiferous zones of Matuu is among the key aspects in evaluation of groundwater potential of the area. Three regions of hard rock formations namely, Ondo State of Southwestern Nigeria, Egypt, and Central Finland, where experiments were carried out and relationships between geo-electrical and hydraulic data developed, were considered for this research. The relationships developed for the above regions were tested for data sets from Matuu to estimate transmissivity. In table 4, T_i are the corresponding transmissivity values where i ranges from 1 to 3 for customized reference to case studies.

The experimental results of groundwater survey obtained from central Sinai fields in Egypt, with Cretaceous Sandstones forming its basement, a quadratic relationship between hydraulic conductivity and aquifer resistivity shown by Eq. 3 was developed [11], the estimated hydraulic conductivity values together with corresponding aquifer thicknesses were useful in calculation of transmissivity values (T_1) for aquifers in Matuu (Table 4). The transmissivity values obtained were relatively high i.e. many falling in class I with only one in class II, as far as aquifer classification is concerned (Table 1).

$$K = 0.012\rho^2 - 1.2\rho + 35 \tag{3}$$

A plot of transmissivity against transverse resistance is given in Fig. 3 from which a linear relationship shown by Eq. 4 with a correlation coefficient of 0.9843 was obtained showing a strong correlation between the parameters

$$T = 1.329R - 914.7 \tag{4}$$

From basement complex areas of Ondo State, Southwestern Nigeria a theoretical relationship between hydraulic conductivity and aquifer bulk resistivity shown by Eq. 5 was developed for fractured and faulted basement rocks made of granite gneiss, biotites gneiss, quartzite and Charnokite [12]. Eq. 5 was useful in estimation of hydraulic conductivity values which were used together with aquifer thicknesses to generate transmissivity values (T_2) shown in table 4.

$$K = 0.0538 \times e^{0.0072\rho} \tag{5}$$

From the product of Eq. 5 and aquifer thicknesses (h), the expression used to generate transmissivity values (T_2) shown by Eq. 6 was obtained;

$$T_2 = 0.0538he^{0.0072\rho} \tag{6}$$

The plot in Fig. 4 shows comparison of transmissivity with calculated transverse resistance for Matuu groundwater potential zone. A linear correlation (Eq. 7) with a correlation coefficient of 0.9991 was realized.

$$T = 0.001101R - 0.3074 \tag{7}$$

The transmissivity values (T_3) in table 4 shows values calculated using an experimental relation shown by Eq. 8 developed from measurements results for granitic area of central Finland [13]. The relation compares transmissivity with transverse resistance (R), this was directly applied to the data obtained for Matuu groundwater potential zone and a strong correlation, shown in Fig. 5 was realized (0.9788), however, the values of transmissivity realized were relatively low.

$$T = 0.0007661R + 0.9541 \tag{8}$$

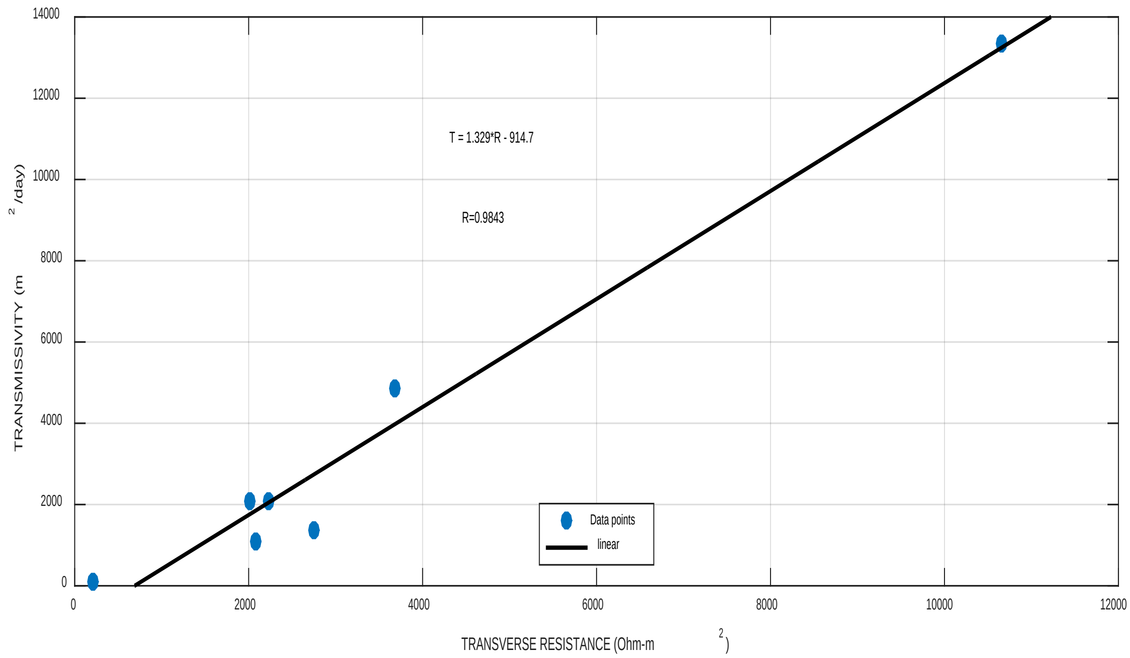

Fig. 3: Plot of Transmissivity against Transverse resistance relative to geological formation of Central Sinai, Egypt.

Table 4: Calculated Transmissivity Values for Matuu area

VES	***R*** (Ωm^2)	***ρ*** (Ωm)	***h*** (m)	***K*** *(Hydraulic conductivity relative to Ondo State)*	Transmissivity (m^2/day)		
					T_1 (Central Sinai)	T_2 (Ondo State)	T_3 (Central Finland)
YS1	10659.6	189	56.4	0.209782959	13358.45	11.83	9.259
YS2	2224	160	13.9	0.17025094	2087.78	2.37	2.282
YS5	3685.5	195	18.9	0.219044185	4862.97	4.14	3.103
YS6	2082.5	119	17.5	0.126731854	1087.31	2.22	2.873
YS7	205.92	23.4	8.8	0.063672545	118.72	0.56	1.445
YS8	2749.5	117	23.5	0.124919992	1383.40	2.94	3.858
YS9	2011.1	169	11.9	0.181648494	2081.70	2.16	1.954

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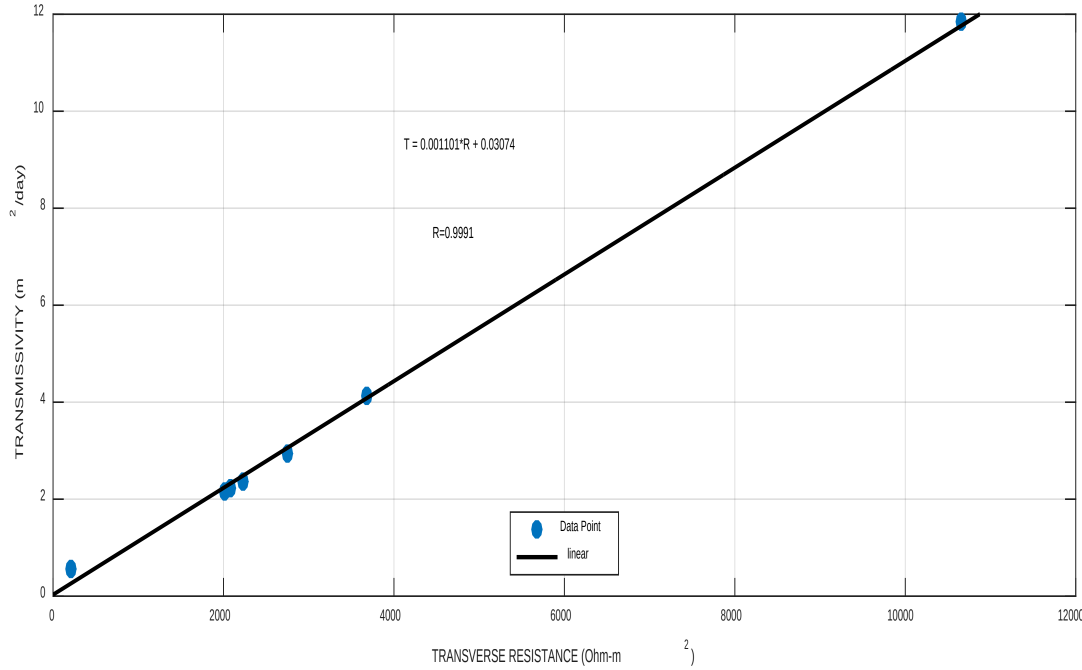

Fig. 4: Plot of Transmissivity against Transverse resistance relative to geological formation of Ondo State, Southwestern Nigeria.

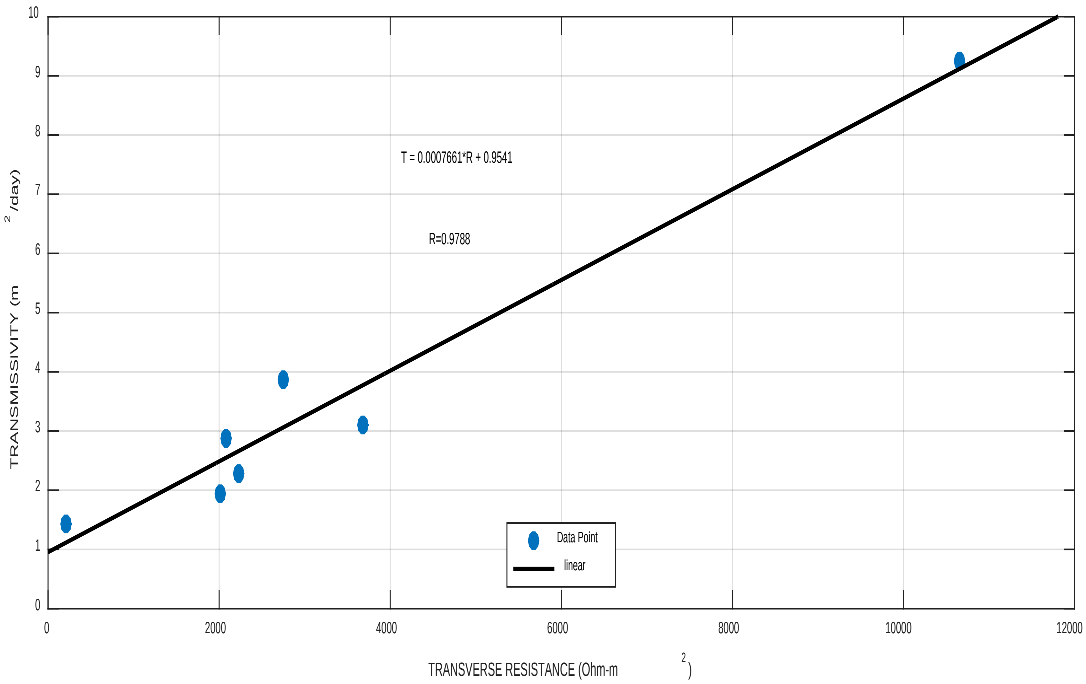

Fig. 5: Plot of Transmissivity against Transverse resistance relative to geological formation of Central Finland.

4. Summary

From the results obtained in all the three case study areas two aspects of comparison were considered, i.e. cases with relatively strong correlation coefficients as well as similar geological formation as that of Matuu. This consideration narrowed down to two cases, that is, Ondo State, Southwestern Nigeria and Central Finland, (Table 5). More specifically, the tested results for Ondo state revealed a stronger correlation with that of Matuu (0.9991), and is consistent with transmissivity value from well test in the nearby area (approximately 5.0 m^2/day). The results associated with the Ondo State case study was used to estimate transmissivity values for Matuu. The estimated result shows an average transmissivity of about 10 m^2/day, which is an indication of intermediate aquifer yield.

Table 5: Comparative analysis of case studies with similar characteristics as Matuu

Case Study Area/Field	Ondo State, SouthWestern Nigeria [8]	Central Finland [11]
Geological Formation	Fractured and faulted basement rocks made of granite gneiss, biotites gneiss, quartzite and Charnokite	2555.4 square kilometer granitic, other areas defined by mica gneiss among other crystalline magmatic units
Study Interest	Geophysical evaluation of rock type impact on aquifer characterization in hard rock terrain areas of Ondo State.	Investigation of hydraulic properties and drilled well yield with respect to factors related to well location in the Precambrian crystalline bedrocks of Central Finland.
Result summary for the case study area	Estimated average hydraulic conductivity for the aquifer units are 4.43, 0.96 and 4.58 m/day, while their mean transmissivity values are 13.0, 8.71 and 60.18 m^2/day respectively. Magmatites and Pegmatites were associated with confined aquifers with varying degree of fracturing while zones of minimal fracturing linked to biotites gneiss formations.	Yields are directly affected by topography and geological factors such as rock types and associated fault regimes. The median hydraulic parameters were found to be as follows: Transmissivity; $7.3x10^{-6}$ m^2/s, Hydraulic conductivity; $1.1x10^{-7}$ m/s, and Normalized yield; 12 L/hr/m.
Range of Transmissivity values for Matuu, relative to case study area	0.56 m^2/day-11.83 m^2/day	1.445 m^2/day-9.259 m^2/day
Aquifer classification based on calculated transmissivity ranges for Matuu	Up to class III, Intermediate yield, (Withdrawals for local water supply)	Class IV, Low yield, (Smaller withdrawals for local water supply)
Correlation coefficient between Transmissivity and Transverse resistance for Matuu relative to the case study areas	0.9991 (Strong Correlation)	0.9788 (Strong Correlation)

A contour map (Fig. 6) showing trends in estimated transmissivity attributes displays higher values (above 10 square meters per day) to the north west of Matuu, indicating a better yield at the zone as far as groundwater potential evaluation is concerned. The eastern zone displays poor transmissivity thus not recommended for siting boreholes.

4. Conclusions

Concluding on transmissivity analysis as a key groundwater primer, one out of three sites from which parameter relations were obtained gave values indicating high/very high groundwater yields i.e. above 100 m^2/day limits, when applied for the Matuu groundwater potential zone. Of the considered relations, 1 was theoretical and 2 were experimental cases from areas in Finland, Nigeria and Egypt. These sites are of hard rock basement system. Specifically, the experimental relation from Central Finland as well as the theoretical relation from Ondo State, Southwestern Nigeria gave relatively strong correlation, with granitic Gneiss, Biotite Gneiss, Quartzite and Chamokite as geological formations, which is a similar situation in Matuu, the aquifer characteristics can be confidently compared. Over 60% of the soundings which gave H-Type curves, considered in transmissivity calculations fall in the west of Matuu area. Linear relationships between transmissivity and transverse resistance over the area from all the three cases showed strong correlation with correlation coefficients ranging from 0.9843 to 0.9991, however, estimated results showed transmissivity attributes of West Matuu to be approximately 10 square meters per day which indicate moderate hydraulic transmissivity associated with intermediate aquifer yield that can support local supply.

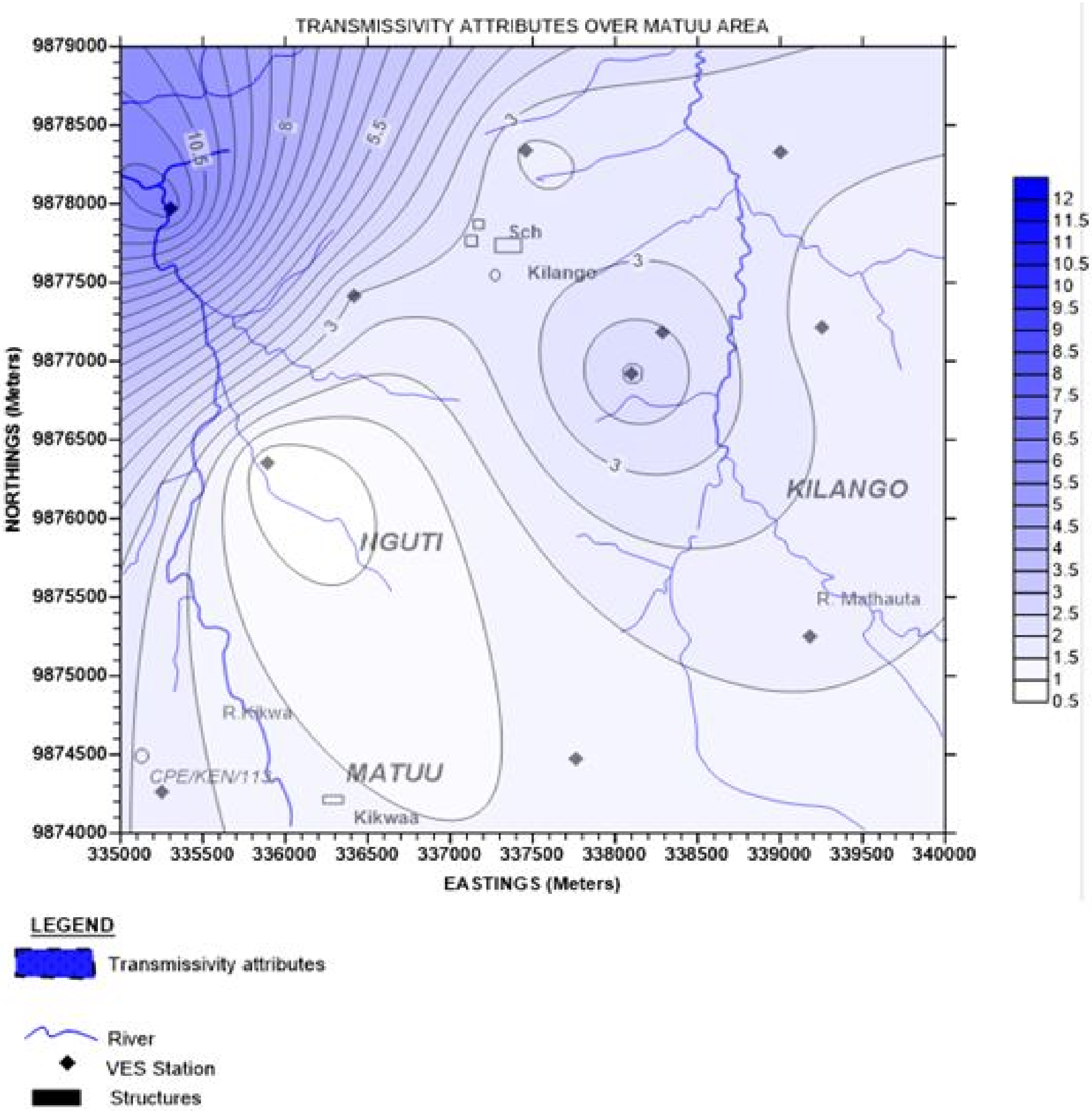

Fig. 6: Transmissivity attributes of Matuu groundwater potential zone

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