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Geophysical Study of Groundwater Formation Systems Using Electrical Resistivity in Manga Area in Nyamira County, Kenya

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Abstract: *We report of a geophysical study that involved the use of the vertical electrical sounding (VES) technique with Schlumberger array using SSR-MP-ATS terrameter that was carried out in Manga area found in Nyamira County in Kenya. This aimed at investigating the subsurface formation and determining the corrosivity and protection capacity of the groundwater formation system. The results obtained revealed the existence of an average of five subsurface layers. The first layer forms the topsoil layer that is unlikely to be corrosive at VES 1 and VES 2 as well as can cause mild corrosion in metal and metallic structures buried in this layer at VES3 and VES 4.The overburden protection capacity is weak and the aquifer protection capacity is identified as having moderate protection in VES 1, VES 3 and VES 4 and being poor in VES 2.The area also has shallow aquifers and deep aquifers that are found in a highly fractured zones as revealed by aquifer transmissivity results.*
Keywords: *corrosivity, manga, protection capacity, resistivity, Schlumberger*

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I. Introduction

Geophysical methods have been used across the world to obtain information on groundwater formations [1,2].These include the determination of aquifer characteristics and parameters [2,3,4, 5, 6,7],identification of sites for borehole drilling [8,9,10,11] and lately in determination of aquifer protection capacity as well as aquifer vulnerability [12,13,14].This is because of population growth and its accompanying challenges like waste management [15],need for clean and enough water [16] for both domestic, agricultural and industrial uses. The information on aquifer protection capacity has in turn been useful in groundwater management and protection, [17].

Geophysical explorations, investigations and studies have also increased with time due to computerized software and systems that are very handy in data analysis [18, 19]. In Kenya, due to the establishment of the Kenya Groundwater Mapping Programme (KGMP) in 2014 with an aim of improving scientific knowledge on the nation's groundwater wealth and priority given to arid and semi arid lands, studies have been done in dry areas like Turkana [20,21] and Machakos [22] to determining groundwater potentials using vertical electrical sounding. However, this may be evidence enough that the knowledge and information on groundwater is either scarce or unavailable even on areas perceived to have reliable supply of water in the country but operating in times of uncertainty that include climatic changes, high population growth rate and unstable economy in Kenya today, Manga area being one of them. The need for conservation, protection and management of environmental resources, is the driving force to carrying out this research.

1.1 The study area

Manga area is located on the western side of Kenya between latitude $0^0$29'S to $0^0$45'S and longitudes $34^0$45'E to $34^0$57'E. This area is not only being a source of perennial springs; Kerongo and Tetema and seasonal springs; Kiangoso but also streams and rivers that serves the residents of both Nyamira and Kisii counties. Like any other place in the world, the area experiences climatic changes in that the distinct long rains and short rain seasons that used to exist, no longer does. Manga area has a Gini coefficient in the range of 0.24 to 0.35.This means that the gap between the rich and the poor in this area is very narrow and the available resources are shared fairly equally. The VES stations included ; Kiangoso as VES 1,Kerongo as VES 2,Kerora as VES 3 and Manga as VES 4.

Geologically, area consists of both Nyanzian and Kavirondian system of rocks which are isoclinally folded about axes that has an east – westerly trend. These are the oldest rocks in the country with ages over 2,500 million years. These rocks include conglomerates, granitic intrusions among others hence Fig. 1 shows the area of study.

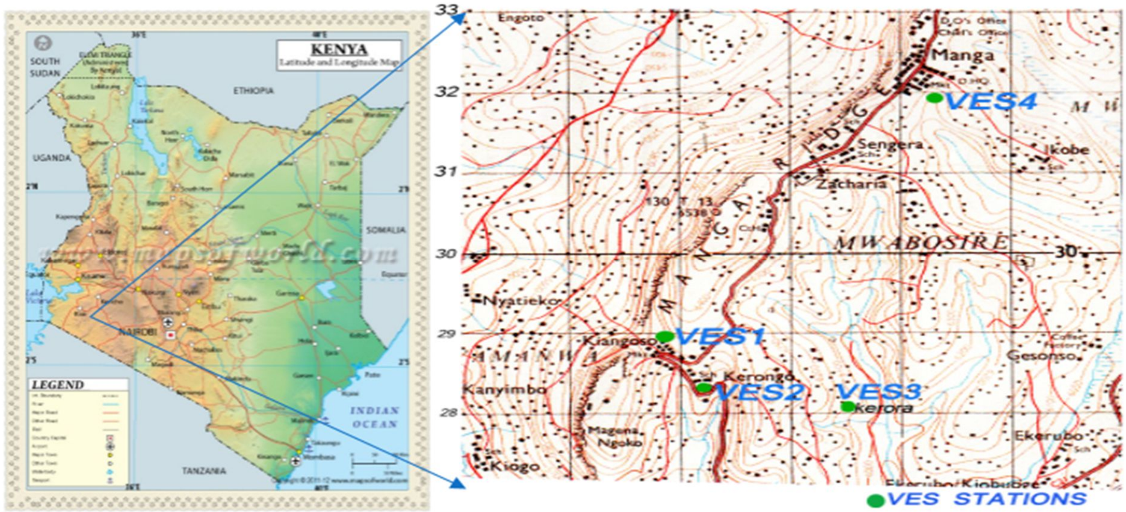

Figure 1: map of the area of study from the map of Kenya and as adapted from toposheet of Kisii district showing the VES stations in the study area.

1.2 Theory of electrical resistivity

Electrical resistivity is based on the flow of electric current through the ground and rock material. The resultant electric field, E produced is described in terms of electric potential U, as:

$$E = -\nabla U \qquad (1)$$

Rocks have resistance on the flow of current I, when it is induced across them. The current density J, is given by:

$$J = \frac{1}{\rho}\frac{dV}{dL} \qquad (2)$$

Where ρ is the resistivity of the material, $\boldsymbol{d}$V is the change in voltage and $\boldsymbol{d}$L is the change in length of the material.

In the three dimension, equation 2 therefore becomes:

$$J = -\frac{1}{\rho}(i\frac{\partial v}{\partial x} + j\,\frac{\partial v}{\partial y} + k\,\frac{\partial v}{\partial z}\,) \qquad (3)$$

Using (1) and (2) the current density J, is given by:

$$J = \frac{E}{\rho} \qquad (4)$$

Hence combining equations (3) and (4) we obtain:

$$J = -\frac{E}{\rho}(i\,\frac{\partial v}{\partial x} + j\frac{\partial v}{\partial y} + k\frac{\partial v}{\partial z}\,) \qquad (5)$$

But in three dimension, the equation of continuity which is the Dirac delta function that govern a point in this space is given as:

$$\nabla.J(x,y,z,t) = \frac{\partial q(x,y,z,t)}{\partial t}(\partial(x)\partial(y)\partial(z)) \qquad (6)$$

Therefore on combining (5) and (6), the resultant equation is:

$$\nabla.J(x,y,z,t) = -\nabla.\frac{E}{\rho}\frac{\partial q}{\partial t}\left(i\,\frac{\partial v}{\partial x} + j\frac{\partial v}{\partial y} + k\frac{\partial v}{\partial z}\,\right)$$

(7)

Hence (7) gives the relationship between the current density J, and electric field E, of a point charge in a three-dimension medium of resistivity ρ.

In vertical electrical resistivity, the resistivity is measured by injecting a direct current into the ground through two electrodes A and B as in Figure 2. Hence the direct current-resistivity method Maxwell's equation is given by:

$$\nabla.E = \frac{1}{\varepsilon_o}\,q$$

(8)

Where E is the electric field, ε_o is the permittivity of free space and q the charge density.

When a single electrode say A or B as in Figure 2, is located at a boundary of any semi-infinite and the medium is an electrically homogeneous ground and this electrode carry a current I, then the area A, and the potential in this medium at any point is given by:

$V = \frac{\rho L}{2\pi r}$
(9)
Where r is the distance from this electrode.
From (13), the electric potential U about r is given as:
$U(r) = \frac{I\rho}{2\pi r}$
(10)
Hence for a pair of electrodes A and B as in the Schlumberger array, the potential U according to [29] is therefore given by:
$U_{AB} = \frac{I\rho}{2\pi}\left[\frac{1}{r_a} - \frac{1}{r_b}\right]$
(11)
Where r_a and r_b are distances MA and MB respectively as shown in Fig. 2 below.

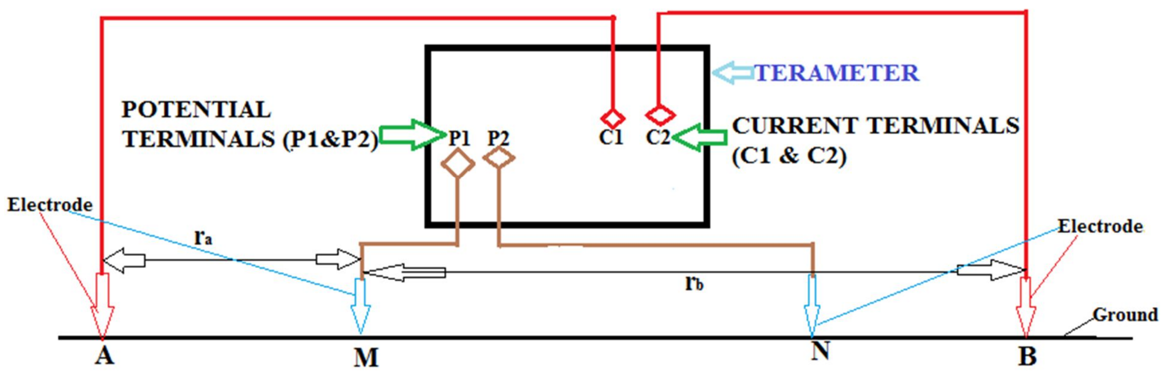

Figure 2: Schematic representation of four electrode arrangement in the Schlumberger array as connected to terrameter.

II. Materials And Method

The study entailed the use of vertical electrical sounding (VES) which is comparatively easier to perform with Schlumberger array that is a labour friendly in that it required a minimum of three people to carry out the study as compared to other methods. Four electrodes as in Figure 2, of which two electrodes on either side of SSR-MP-ATS terrameter were arranged in a straight line and connected to it. A current was injected into the ground through the current electrodes that were A and B distance of separation apart and received at the surface through the potential electrodes which were M and N distance apart, then SSR-MP-ATS terrameter automatically displayed apparent resistivity and resistance of the subsurface materials. The distance of separation AB was initially 3.2 metres, then increased in every subsequent sounding to a maximum of 500 metres which translated to AB/2 of 250 metres, which also represents the maximum depth of subsurface investigation. On the other hand, MN was initially 1m and increased when necessary. For every sounding, the AB/2, MN/2, apparent resistivity and resistance was recorded. This data was then used to generate field curves which were subjected to Gewin V1.04 and 1X1D unregistered version which are computerized iterative interpretation softwares for quantitative interpretation of the VES data was obtained.

III. Results and Data Analysis

Given the apparent resistivity and the thickness of a subsurface layer, the qualitative data analysis was then done using equation the Dar-Zarrouk parameter [12] that is longitudinal conductance, S, and transverse resistance, T were calculated by using
Longitudinal conductance:
$S = \frac{h}{\rho_a}$
(12)
Transverse resistance: $T = h\rho_a$
(13)
While the hydraulic conductivity of an aquifer:
$K = 386.40 R_{RW}^{-0.93283}$
(14)
Where R_{RW} is the aquifer resistivity
Transmissivity of an aquifer:

$$T = 386.40 h R_{RW}^{-0.93283} \tag{15}$$

Where R_{RW} is the aquifer resistivity and h is the thickness of the aquifer.

Further, contour maps for longitudinal conductance, transmissivity, hydraulic conductivity as well as topsoil corrosivity were drawn using the sigma plot computer software. Identification of curve types was done using the three layered sequence analysis technique.

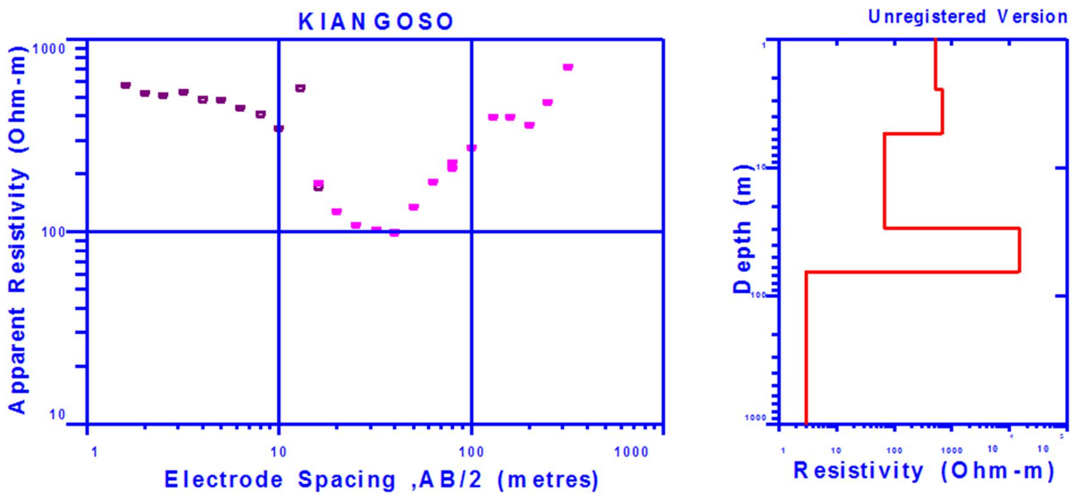

Figure 3: A curve showing the variation of apparent resistivity with electrode spacing AB/2, which represents the depth of investigation and model interpretation showing the depth, thickness and resistivity of each layer at VES 1

VES 1 consists of a six-layer subsurface which forms a KHKQ type of aquifer curve on a three layered sequence analysis. The first layer, which extends from the earth surface to 2.48 metres deep, has an apparent resistivity of 524 Ohm-metres. A 2.91 metres thick layer that extends to 5.39 metres deep underlies this layer. The apparent resistivity in this second layer is 676 Ohm-metres .The third, fourth and fifth layers have thickness of 24.36 metres, 35.42 metres and 8.38 metres respectively as shown in Fig. 3.

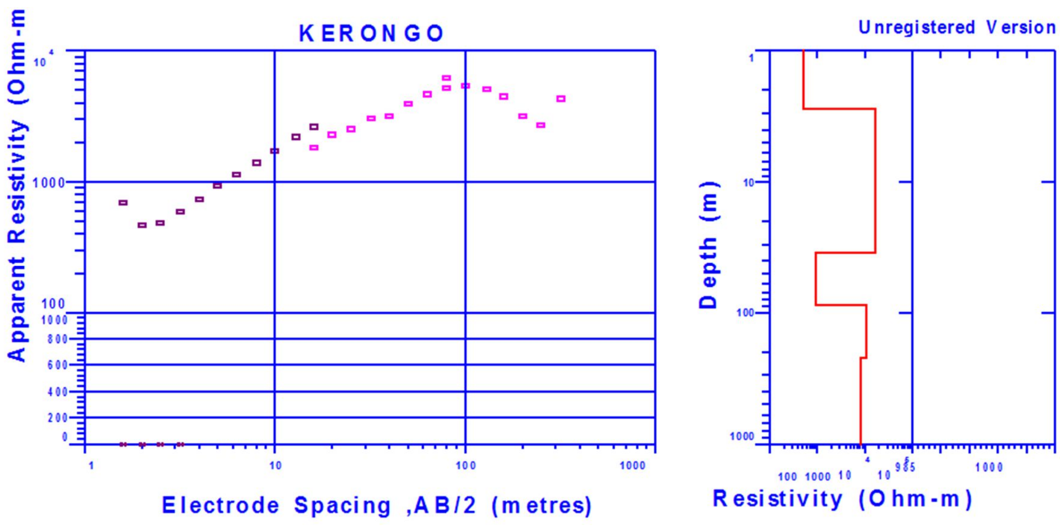

Figure 4: A curve showing the variation of apparent resistivity with electrode spacing AB/2, which represents the depth of investigation and model interpretation showing the depth, thickness and resistivity of each layer at VES 2

VES 2 consists of having six sub surface layers. The first layer starts from the earth's surface and extends to 2.80 metres deep. This layer has a resistivity of 513 Ohm-metres. The second layer underlies it with a resistivity of 16661Ohm-metres and 31.61 metres thick. The third layer extends from 34.41 metres deep to 87.91 metres deep. This layer is therefore 53.50 metres thick and has a resistivity of 924 Ohm-metres. The fourth and fifth layers are 134.4 metres and 29.29 metres thick respectively as shown in Fig. 4.From the descriptions of layers above, it is evident that the fourth layer is thicker while the first layer is thinner as compared to the other layers in VES 2.On a three layer sequence analysis, VES 2 forms a KH type of curve.

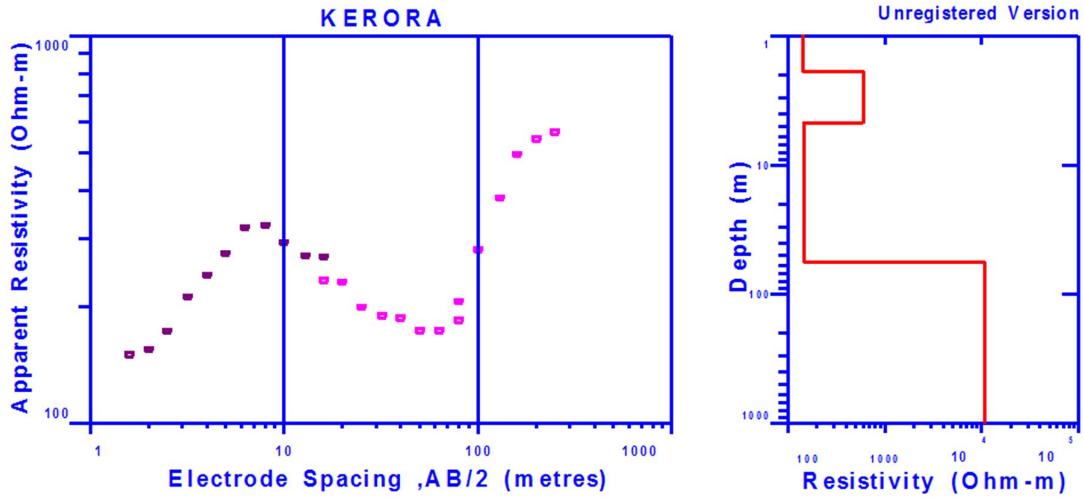

Figure 5: A curve showing the variation of apparent resistivity with electrode spacing AB/2, which represents the depth of investigation and model interpretation showing the depth, thickness and resistivity of each layer at VES 3.

VES 3 consists of 5 layered distribution of sub surface. The fourth layer is 64.50 metres thick, followed by the third layer with a thickness of 51.61 metres. The second and first layers are 2.81 metres and 1.87 metres respectively. The fifth layer starts at 120.79 metres deep as model shown in Fig. 5. The alternating low and high resistivities, in the order of low and high respectively forms a KHK type of curve on a three-layer sequence analysis.

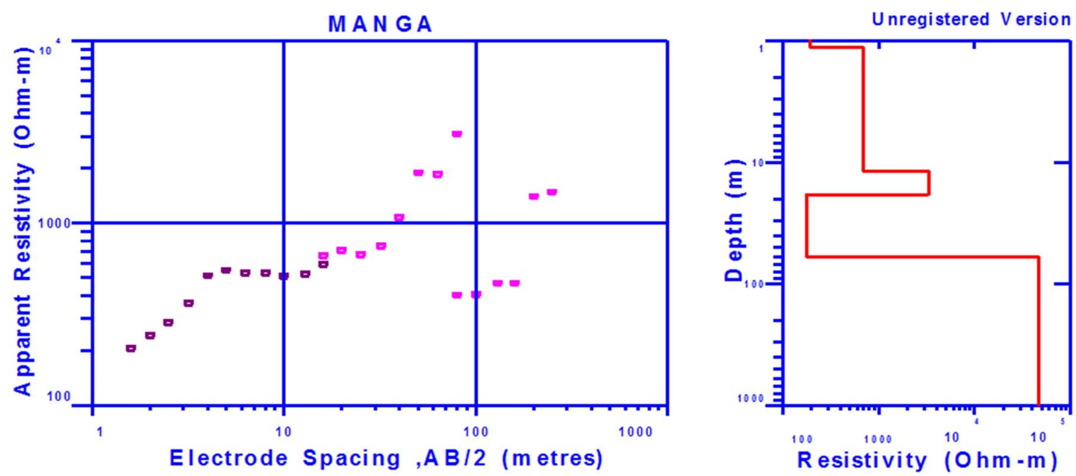

Figure 6: A curve showing the variation of apparent resistivity with electrode spacing AB/2, which represents the depth of investigation and model interpretation showing the depth, thickness and resistivity of each layer at VES 4

VES 4 consists of a six-layer subsurface, with resistivities increasing in the first three layers and from the third to sixth layer an alternating low and high resistivities pattern, in the order of low and high respectively which forms a AKHK type of curve on a three-layer sequence analysis is exhibited. The first layer, which extends from the earth surface to 1.14 metres deep, has an apparent resistivity of 191 Ohm-metres. A 10.58 metres thick layer that extends to 11.72 metres deep underlies this layer. The apparent resistivity in this second layer is 697 Ohm-metres. The third, fourth and fifth layers have thickness of 6.86 metres, 41.63 metres and 82.00 metres respectively. The sixth layer starts at 142.21 metres deep as shown in Fig. 6.

Layer 1 in VES 1 and VES 2 has resistivities of 524 Ohm-metres and 513 Ohm-metres respectively while VES 3 and VES 4 has the resistivities of 143 Ohm-metres and 191 Ohm-metres respectively. The lower resistivities are thus in VES 3 and VES 4 and ranges between 100 Ohm-metres and 200 Ohm-metres. The higher resistivities in the range of 500 Ohm-metres and 600 Ohm-metres are exhibited in VES1 and VES 2 as shown in Table 1.The first layer is also noted to be the thinnest of all the layers of the sub surface in all the VES stations.

The resistivity in layer 2 in all the VES stations is greater than the resistivity in layer 1. However, these resistivities decreases significantly in all the VES stations except in VES 4 where it increases in the third layer. An increase in layer thickness is also noted in layer 2 as compared to layer1 in all the VES stations. In layer 4, the resistivity increases in VES 1, VES 2 and VES 3 but reduces in VES 4 as shown Table 1.

Table 1: Layer thickness and layer resistivity

	Layers (h in meters and ρ in Ohm-metres)									
	L1		L2		L3		L4		L5	
	h1	ρ1	h2	ρ2	h3	ρ3	h4	ρ4	h5	ρ5
VES 1	2.48	524	2.91	676	24.36	69	35.42	14669	8.38	3
VES 2	2.80	513	31.61	16661	53.50	924	134.4	10902	29.29	8037
VES3	1.87	143	2.81	608	51.61	147	64.50	10734		
VES 4	1.14	191	10.58	697	6.86	3331	41.63	180	82.00	46581

The longitudinal conductance of layer 1,in VES 3 is greater than longitudinal conductance in VES 1, VES 3 and VES 4.However,all the values of longitudinal conductance of all the layers in all in all the VES stations is less than 1 Siemen except for layer 5 in VES 1 as shown in Table 3.On the other hand, the transverse resistance in layer 1 is greater than 1000 for VES 1 and VES 2 and less than 300 in VES3 and VES 4.In addition the higher values of transverse resistance are in VES2 layer 2 and layer 4 as shown in Table 2.

Table 2: Longitudinal conductance, S and Transverse resistance, T

	Layers(S in Siemen x10^{-3} and T in ohm-m^2)									
	L1		L2		L3		L4		L5	
	S1	T1	S2	T2	S3	T3	S4	T4	S5	T5
VES 1	4.733	1299.52	4.305	1967.16	353.0	1680.84	2.415	519575	2793.3	25.14
VES 2	5.458	1436.4	1.897	526654.21	57.9	49434	12.33	14652724	3.644	235403
VES 3	13.08	267.41	4.622	1708.48	351.1	7586.67	6.009	692343		
VES 4	5.969	217.74	15.18	7374.26	2.059	22850.66	231.3	7993.4	1.76	3819642

In VES 1 and VES 3, the aquifers are found at shallow depth at an average of 5m below the surface and have longitudinal conductance values of 0.3530 Siemens and 0.3511 Siemens respectively. On the other hand, VES 2 and VES 4 aquifers are at a depth of greater than 18 m and 34m respectively and have the longitudinal conductance of 0.05791 Siemens and 0.2313 Siemens respectively as presented in Table 3.

Table 3: Aquifer analysis

	ρ (ohm-m)	Depth(m)	H(m)	Longitudinal conductance(Siemens)	Hydraulic conductivity	transmissivity	Protection capacity
VES 1	69	5.39 - 29.75	24.36	0.3530	7.442	181.28	moderate
	3	65.17 - 73.55	8.38	2.7933	138.6641	1162.00	
VES 2	924	34.41 - 87.91	53.50	0.05791	0.6615	35.39	poor
VES 3	147	4.68 - 56.29 120.79-	51.61	0.3511	3.6753	189.68	moderate
VES 4	180	18.58 - 60.21 142.21 -	41.63	0.2313	3.0426	126.66	moderate

IV. Discussion

4.1 Overburden protection capacity

Overburden layers are layers that overlain the aquifers. In VES 1, VES 2 and VES 3, the first two layers forms the overburden layers while in VES 4 the first three layers forms the overburden layers. This layers form part of the earth with an ability to filter and slow down the movement of pollutants into the aquifers [6] and so is termed as the overburden protection capacity. According to [25], the overburden protection capacity is proportional to the overburden layer thickness and inverse to this layers hydraulic conductivity. In addition, it also has a direct relationship with longitudinal conductance [14]. An analysis of the layers thickness and their respective resistivity shows that, the values of the thickness at all the VES station is smaller than the respective resistivity. It follows therefore, that at every VES station, the longitudinal conductance of all layers is less than one as observed in Table 3. Further, an overburden layer with a longitudinal conductance value of less than one as of these VES stations, shows that these overlying strata will allow more contaminants to infiltrate into the aquifer. However distribution of the overburden protection capacity of this area is as shown in Fig.7.

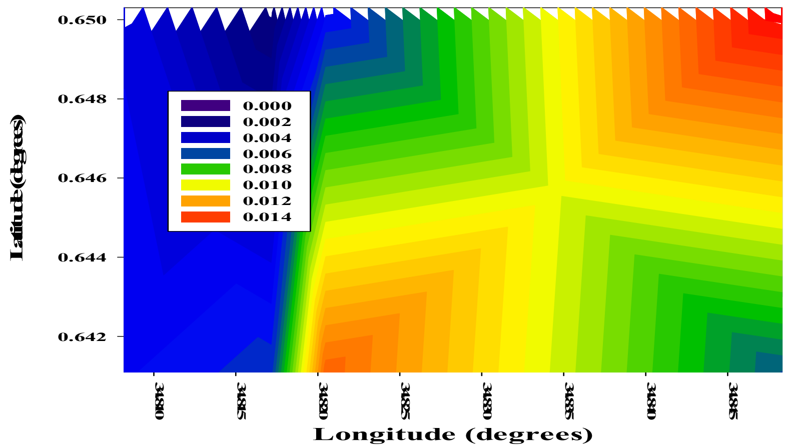

Figure 7: A generated contour map showing the distribution of overburden protection capacity levels in the Manga area

4.2 Aquifer protection capacity

Longitudinal conductance, transverse resistance and transmissivity are used in the evaluation of aquifer protection capacity. According to [13,26,27,28], VES 1, VES 3 and VES 4 were rated as having a moderate aquifer protection capacity since this rating is found in a category of values of aquifer protection of between 0.2 to 4.9.On the other hand, VES 2 has a poor aquifer protection capacity since its rating is less than one. According to [13], when the rating values of aquifer protection capacity is greater than 10, the aquifer provides an excellent protection capacity. It follows therefore that the values between 5 and 10 implies very good and those between 0.2 and 4.9 the aquifer offers a moderate protection capacity. In addition, a weak protection capacity has values that range from 0.1 and 0.19 while a poor aquifer protection capacity has values less than 0.1, [13] adds. Hence the aquifer transmissivity and hydraulic conductivity distributions is as shown in Fig. 8 and Fig. 9 respectively.

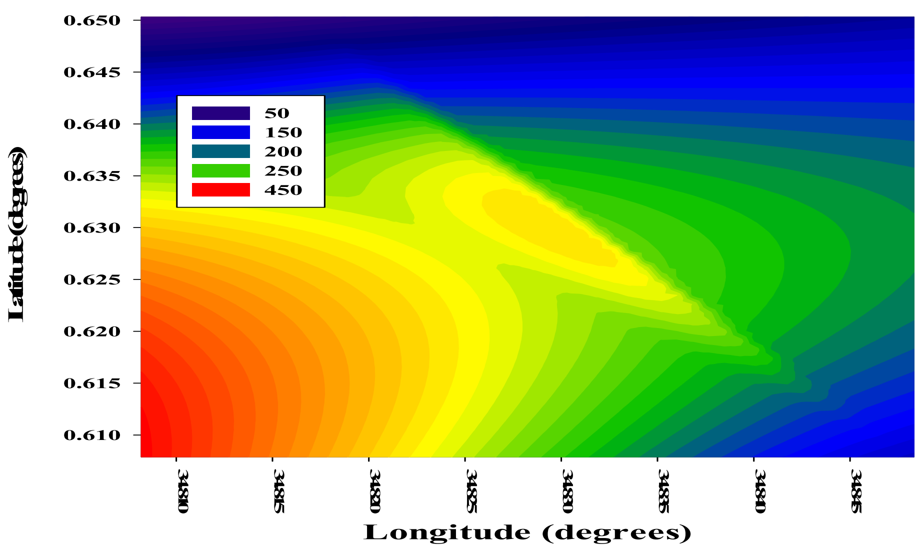

Figure 8: A generated contour map showing the distribution zones of Aquifer transmissivity across the Manga area.

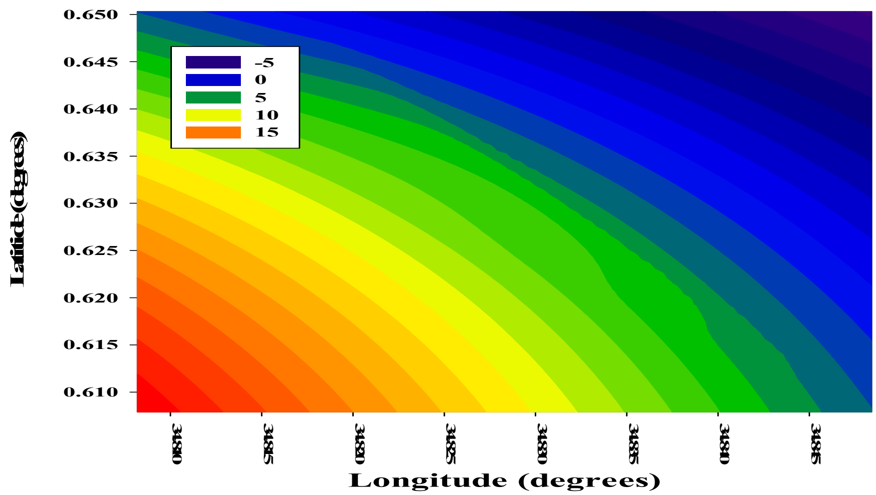

Figure 9: A generated contour map showing the distribution zones of Aquifer Hydraulic conductivity across the Manga area

4.3 Topsoil corrosivity

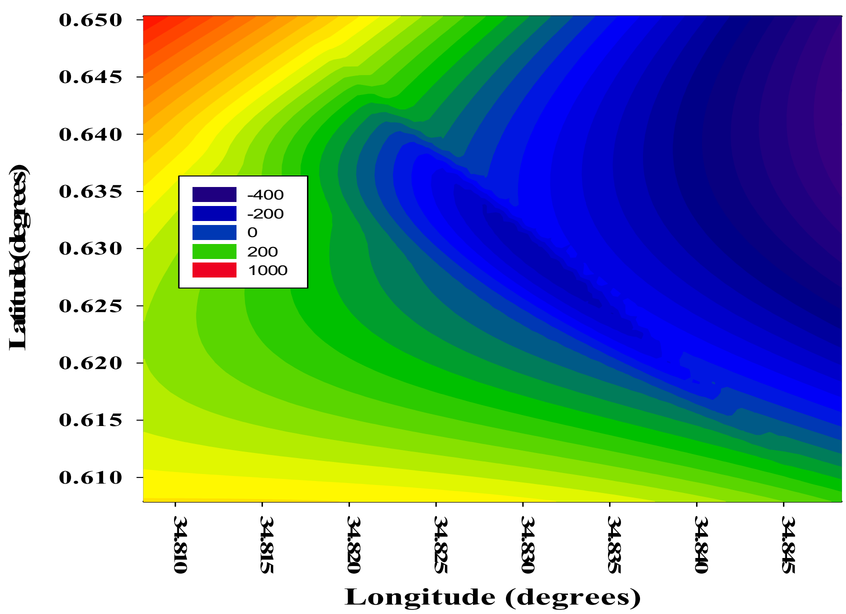

Figure 10: A generated contour map showing the distribution zones of topsoil corrosivity across the Manga area

The topsoil which essentially forms the first layer of the subsurface at every VES station, is important in that it is where all the water pipe networks are distributed and subsurface structures are constructed for either agricultural or environmental purposes [23]. Corrosivity of the topsoil means the tendency of the topsoil to react with metal pipes or metallic structures when in contact. Prior knowledge of topsoil corrosivity is important in both selection and protection of metal pipes that are used in the distribution networks for groundwater [23, 14] and prevents financial wastage on unrequired materials and maintenance of collapsed structures. According to [24,14] the resistivity values of the first layer of the subsurface determine the corrosivity level of the topsoil, high resistivity values are associated with areas that have dry soil with no moisture content and therefore are non-corrosive area. On the other hand, the low resistivity values are associated soil with moisture content hence areas that are corrosive. VES 1 and VES 2 have resistivity of 524 ohm-m and 513 ohm-m respectively hence rated as areas that are unlikely to be corrosive while resistivity of 143 and 191 ohm-m for VES 3 and VES 4 respectively causes mild corrosion as supported by [14]. However, the distribution of the topsoil corrosivity is as shown in Fig. 10.

V. Conclusion

The area has an average of five subsurface layers. The first layer forms the topsoil layer that is unlikely to be corrosive at VES 1 and VES 2 as well as can cause mild corrosion in metal and metallic structures buried in this layer at VES3 and VES 4.The overburden protection capacity is weak and the aquifer protection capacity is identified as having moderate protection in VES 1, 3 and 4 and being poor in VES 2.The area also has shallow aquifers and deep aquifers that are found in a highly fractured zones as revealed by aquifer transmissivity.

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Alice Makonjo Wekesa, et. al. "Geophysical Study of Groundwater Formation Systems Using Electrical Resistivity in Manga Area, Kenya." *IOSR Journal of Applied Geology and Geophysics (IOSR-JAGG),* 9(1), (2021): pp 25-34.