GEO-ELECTRIC INVESTIGATION OF THE AQUIFER CHARACTERISTICS AND GROUND WATER POTENTIAL OF THE LAKE CHALA WATERSHED, TAITA TAVETA COUNTY

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Geo-electric Investigation of the Aquifer Characteristics and Ground Water Potential of the Lake Chala Watershed, Taita Taveta County

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other University.

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DEDICATION

I dedicate this thesis to my husband Mathew Kigomo and my son Herbert Lionel Kigomo and to my parents from whose support have drawn all my motivation and strength this far

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LIST OF ACRONYMS AND ABBREVIATIONS

WWAP	World Water Assessment Programme
UN	United Nations
UNEP	United Nation of Environmental Programme
FAO	Food and Agricultural Organization
GIS	Geographical Information System
VES	Vertical Electrical Sounding
ρa	Apparent Resistivity
masl	Meters Above Sea Level
RMSE	Root Mean Square Error
IGRAC	International Groundwater Resources Assessment Centre
CPK	Church Province of Kenya
GPS	Geographical Positioning System
DEM	Digital Elevation Model
ME	Mean Error
MSE	Mean Standardized Error
UN	United Nation
UNEP	United Nation Environmental Programme
UTM	Universal Traverse Mercator
RMSSE	Root Mean Squared Standardized Error
WGS84	World Geodetic System

ABSTRACT

Groundwater systems are composed of complex set of interactions between physical environment such as soils, geology, precipitation, vegetation and topography and social economic activities exerting pressure on the physical environment. The interactions between these elements influence the hydrological cycle directly or indirectly and pose complex uncertainties to occurrence, movement and storage of groundwater. Lack of knowledge about the geographical unit responsible for groundwater occurrence, movement and storage within and around the Lake Chala watershed poses a major uncertainty in the analysis of and thus casts a dilemma in the management and conservation of groundwater within the watershed. This study was therefore carried out to evaluate the hydrogeological characteristics of the aquifers responsible for the recharge of Lake Chala so as to better understand the groundwater system of its watershed. The aim of the study was to identify the locality of groundwater potential zones, determine the hydrogeological characteristics of the groundwater potential zones and to quantify groundwater potential of the Lake Chala watershed. This was achieved by; locating surface groundwater potential zones through integrating factors influencing groundwater occurrence, movement and storage into Geographical Information Systems (GIS) and Remote Sensing platform, determining hydrogeological characteristics using Vertical Electrical Soundings (VES) and groundwater quantification using Darcy's Law. The results revealed that Lake Chala watershed is composed of relatively high groundwater potential zones with the very high and high potential zones occurring near the Lake. These potential zones contained high yielding water bearing layer that is made up of highly weathered ryholite to moderately weathered basalt and volcanic ash. The results revealed that the water bearing layer had a mean, minimum and maximum resistivities of 93, 43 and 182 ohm, depths of 0.8, 142, and 48.30 m, thicknesses of 0.8, 91, and 32.09 m, aquifer elevation of 507, 1017, and 798 m.asl, transmissivity of

0.00024, 0.0273, and 0.00963m^2/day and porosity of 23, 49, and 35% respectively. This layer is located within Lake Chala ground watershed which covers an area of 23.6km^2. It has a recharge zone that contains recharge aquifer covering 13.85 km^2, the discharge zone which contain discharge aquifer covering 5.55km^2 and the lake covering an area of 4.2 km^2. The mean groundwater flow within the Lake Chala ground watershed was estimated at 0.46m^3/s for recharge and 0.32m^3/s for discharge; while the equivalent mean annual recharge and discharge were 14.28Mm^3/year and 10.16Mm^3/year respectively. In conclusion, the study showed that Lake Chala watershed has a high groundwater potential with a thick and a high water bearing layer. This water bearing layer is a good reservoir as well as a good conduit system. These results are instrumental in providing information on the potential for groundwater resources within Lake Chala watershed which are useful in sustainable exploitation and conservation of the resource.

CHAPTER ONE
INTRODUCTION

The water environment and development are strongly interdependent. The state of the hydrological regime, its water quality and ecosystems are major factors contributing to human well-being (WWAP, 2006). While water is needed in all aspects of life, it is necessary that adequate supplies of water of good quality are maintained for the entire population of this planet. At the same time the hydrological, biological and chemical functions of ecosystems, adapting human activities within the capacity limits of nature and combating vectors of water-related diseases must be preserved (UN Water, 2007). In addition, the past 20 years, water use for food and energy production has been increasing in order to meet the demands of a growing population and to enhance human wellbeing (WWAP, 2006). Further withdrawals are predicted to increase by 50 per cent by 2025 in developing countries, and 18 per cent in developed countries (WWAP, 2006). Since nearly all industrial and manufacturing activities require adequate water supplies, this situation is likely to impede socio-economic development, and increase pressures on freshwater ecosystems. Available water resources continue to decline as a result of excessive withdrawal of both surface and groundwater (UNEP, 2007). Water shortages are among the most important global problems, linking issues as diverse as food security, international diplomacy, poverty alleviation, public health, energy production, and ecosystem protection (Douglas *et al*., 2006). Since 1950, world population has doubled but water use has tripled and as a consequence, a third of all nations are suffering from water stress (Donkor, 2006). In addition water scarcity, in its qualitative and quantitative manifestations, is emerging as a major development challenge for many countries (Donkor, 2006). Further deriving indicators of water resources (availability, water stress and scarcity) is essential to the development and proper management of these resources (Douglas *et al.,* 2006). Furthermore, it is estimated that, by the year 2025, 1.8 billion people will be living in countries or regions with absolute water scarcity, while two-thirds of the world population could be under conditions of water stress, the threshold for meeting the water requirements for agriculture, industry, domestic purposes, energy and the environment (UN Water, 2007). Therefore measures must be taken to investigate the possibilities of providing alternative sources of water to meet the challenges of water scarcity emanating from increased population pressure.

In Kenya, water is important for the survival of its citizens and the economic development since the country relies heavily on agricultural production. However, with an increasing population and expanding industrial sector, demand for water is constantly rising and this poses the challenge of managing the available water resources in a sustainable and integrated manner in order to meet this demand (Kithiia, 2012). Kenya is currently classified as a net water deficit country with an estimated 33.7Bm^3/year of total renewable water resources, 30.2Bm^3/year total renewable surface water, and 3.5Bm^3/year total renewable groundwater (FAO, 2014). This amount is projected to reduce by 2020. Only an estimated 40% of the renewable fresh water has potential for development as the remaining 60% is required for maintenance of the ecosystems and for future development (WRMA, 2009). Access to clean water is relatively low in the country estimated at 45% with 33% in the rural areas. Low access to water resources is exacerbated by poor distribution of the existing sources and the variable quality of ground water sources (WRMA, 2009). It is therefore necessary to establish the availability of more water resources especially in water scarce areas.

Water resources in Kenya are categorized as Surface or Ground Water. The surface sources include rivers, dams, lakes, ponds, wetlands, and water pans among others while ground water sources comprise the drilled boreholes and wells (UN Water, 2006). The surface water resources are grouped into five basins namely the Lake Victoria, Rift Valley, Athi/Sabaki River, Tana River and Ewaso Ngiro North River. Only Tana River and Lake Victoria basins have surplus water. The other three basins have water deficits and often rely upon inter-basin transfers to meet basic water demands (Kithiia, 2012). The ground water resources, on the other hand, vary in both quantity and quality and from basin to basin (UN Water, 2006).

The capacity for water resources to meet the various needs has been over-stressed and this has led to scarcity. Various reasons can be advanced for this and they include; population increase, climate change, environmental degradation, weak and inadequate institutional capacities, and the growing poverty levels in the country. The rapid population increase has subjected the limited water available to a lot of pressure in efforts to meet the challenges in water demands. Climatic variability and change has also significantly altered the rainfall patterns and amounts thereby affecting the rate of replenishment of water bodies (Kithiia, 2012). The above factors, coupled with wanton environmental degradation which is prevalent in the main water catchments, changing land use patterns, wastage, misuse and pollution, the water problem has become even more critical. This is evidenced by the drying up of rivers, receding or dwindling lake levels, siltation of dams such that they cannot hold the expected capacities, and degradation of water qualities in many sources (UN Water, 2006).

In most semi-arid regions, surface water resources are considerably unreliable due to the high inter- and intra-annual variability in rainfall. In addition, surface water bodies are highly vulnerable to contamination due to natural alteration and anthropogenic intervention. In the long term, groundwater resources are reliable, consistent, safe, and more importantly accessible to people. Groundwater is often the sole water resource in arid and semi-arid regions; therefore the assessment of quantity and quality of groundwater is vital (Anayah & Kaluarachi, 2009). Groundwater systems are composed of complex set of interactions between physical environment (soils, geology, precipitation, vegetation and topography) and social economic activities exerting pressure on the physical environment. The interactions between these elements influence the hydrological cycle directly or indirectly and pose complex uncertainties to occurrence, movement and storage of groundwater. The lack of knowledge about the geographical unit responsible for groundwater occurrence, movement and storage poses a major uncertainty in its analysis and thus casts a dilemma on management and conservation of groundwater in such environment (Anayah & Kaluarachi, 2009). There is therefore the need for groundwater occurrence, movement and storage assessment in order to provide better understanding of the dynamics of groundwater for sustainable use and helps planning and management of the available resources

Similar to most developing countries, groundwater data are not readily available in Kenya. This is most prevalent in arid and semi arid regions such as the Lake Chala water shed which is one of the areas faced with these challenges. Proper management of groundwater resources in the face of a changing climate and land use requires a reliable knowledge of their availability, recharge and demand. Given the data scarcity, detailed hydrogeological regional studies need to be carried out to provide the necessary groundwater data which will help in effective planning and management of the resources and prevent over exploitation and degradation of such resources.

1.1 Problem Statement

The Lake Chala watershed is located in a relatively semi arid region which has a high groundwater potential. The watershed has been experiencing high water demand for domestic, irrigation and other competing uses thus posing a challenge to the surface water which is the major source of water within the watershed. There is therefore a need to provide an alternative source of water to meet the ever increasing demand of water in the Lake Chala watershed and groundwater resources and Lake Chala is one of these alternatives. Lake Chala, a fresh water Lake fed by groundwater and has no surface water inflow or outflow, is located at Lake Chala watershed in a semi arid but groundwater rich area, on the Kenya Tanzania borders in Taita Taveta County. The Lake's elevated position means that its water could be conveyed by gravity for use within the watershed and its vicinity. However, available information on recharge and discharge system of the Lake and on groundwater resources in the area are grossly inadequate. In addition, the geographical unit and its components responsible for groundwater occurrence, movement and storage are unknown. These adequacies pose serious challenges in the analysis, management and conservation of the groundwater resources. Therefore this study focused on the analysis of the occurrence, movement and storage of groundwater resource in the Lake Chala watershed in order to guide its management and conservation.

1.2 Research Objectives

The main objective of this study was to determine the hydrogeological characteristics of aquifer and groundwater potential in the Lake Chala watershed.

1.2.1 Specific Objectives

The specific objectives of this study were:

1. To identify the locality of groundwater potential zones in the Lake Chala watershed.
2. To determine the hydrogeological characteristics of the groundwater potential zones in the Lake Chala watershed.
3. To quantify the groundwater potential of the Lake Chala watershed.

1.3 Justification of the Study

Water has traditionally been regarded as an inexhaustible gift of nature. However the population growth accompanied by agricultural development and increasing world industrialization is straining water resources. In addition there will be a critical shortage of water of suitable quality to sustain future growth unless water management is substantially improved. Further, there is need to manage the groundwater resources sustainably in order to stop further over-exploitation (Sanjeev, *et al.*, 2011). Groundwater management must be based on the right understanding of the groundwater characteristics at the scale of the total groundwater system and river basin if necessary. Depending on the specific situation, groundwater systems may be of relatively small, localized scale measuring a few hectares or square kilometers. The understanding of groundwater system requires substantial amounts of data from groundwater investigations and monitoring, interpretation by hydrogeologists, and groundwater flow modeling. The characterization of a groundwater system, as a basis for proper groundwater management, requires knowledge of hydrogeological parameters such as recharge, hydraulic conductivity (K), transmissivity (T), the extent or boundaries of the aquifer system; the aquifer properties; the sources of recharge to the system; the discharges from the system - including extractions from bores and changes of these characteristics with time (Swarzenski, & Mundorff, 1977). The Lake Chala watershed is located in a relatively semi arid region which has a high groundwater potential. With the increase in demand for domestic, irrigation, industrial other competing water uses, it has become difficult to meet the entire demand from a single source. However the potential of groundwater resources in the area is not well known and the extent and characteristic of the aquifers have not been determined. Lack of such information limits any rational economical development and management of groundwater resources in the study area as well as poses the risks of degradation of the groundwater resources. To meet these challenges, detailed hydrogeological studies should be conducted to evaluate the Lake recharging system which will results in accurate prediction of groundwater availability.

Geophysical methods are applied in groundwater studies. These are generally used to determine physical rock characteristics, geologic structures such as faults/fractures, lithological changes, and variations in thickness that will be the basis of identifying the presence of an aquifer and ultimately in establishing its characteristics and boundaries (Pastor, 2001). Therefore this study applied geophysical methods in the exploration of groundwater within Lake Chala watershed so as; to provide information on the groundwater system in the study area, assist in groundwater exploration for domestic, irrigation and industrial purposes. The generated information will also provide a suitable platform for sustainable management of groundwater resources in the Lake Chala watershed.

1.4 Scope of the Work

The study was conducted in Lake Chala watershed which is located on the Kenya and Tanzania border. It involved identification of groundwater potential zones using GIS and Remote Sensing, to aid in the identification of suitable locations for carrying out Vertical Electrical Sounding (VES) so as to determine the depth to groundwater. Determination of the hydrogeological characteristics such as conducting conductivity and extent of the groundwater potential zones in the Lake Chala watershed was achieved by undertaking geophysical survey using Vertical electrical sounding (VES) method.

CHAPTER TWO
LITERATURE REVIEW

2.1 Groundwater Occurrence

The origin of groundwater is precipitation which is conveyed to aquifers through the mechanical process of infiltration and conductivity through porous media. However, several factors influence infiltration and conductivity of precipitation water in the ground. These factors include lithology, precipitation, land cover/ use, slope and drainage network. The lithology is important in that it defines the porosity and permeability by precipitation water. In addition precipitation is the amount of water reaching the ground surface. Further, land cover /use influences the amount of precipitation available for infiltration. Slope influences infiltration rates and ground water storage potential. Steep slopes lead to reduced infiltration rate and reduced groundwater storage potential. Flat terrains enhance infiltration rate and lead to increased ground water storage potential (Bruijnzeel, 2004).

The type and density of vegetation cover directly determines the quantity of water intercepted and retained by the soil. For instance, forest retains a certain part of the precipitation by the tree canopy. Vegetation regularizes the runoff in conditions that are meteorologically normal. Its action in extreme conditions (floods and droughts) is relatively reduced. In cases of soils without vegetation the capacity of water retention is reduced, which leads to torrential runoff and to apparition of riverbed erosion phenomena (Barten, 2006 ; Underhill, 2003).

The geology of the watershed must be known in order to estimate the watershed hydrological reaction as it influences both the runoff and the groundwater flow. For the runoff the main geologic characteristic is the permeability of the soil substrate. In case of rainfall a watershed that has an impermeable substrate presents a faster and more violent increase of the runoff in comparison to a watershed with a permeable substrate. A watershed with a permeable substrate will provide a base runoff during dry periods that will last longer. Watershed geology is essential for groundwater flow, through the identification of the karst areas. These karst areas may modify even the real watershed delimitation (Lashkaripour, 2003).

2.2 Theory and Application of Geophysics

Geophysical surveys are useful in the study of most subsurface geological problems. They involve the application of physical principals such as density, magnetism, resistance/conductivity and seismic velocity to study the subsurface characteristics of the earth (Gressando, 1999). A number of geophysical methods are used in groundwater investigations as summarized in Table 1.

Table 1: Geophysical methods used in groundwater investigations

Geophysical method	Physical parameter	Application in groundwater prospecting
Electrical resistivity	Resistivity/conductivity	Resistivity/conductivity contrast
Electromagnetic	Resistivity/ conductivity	Resistivity/conductivity contrast
Gravity	Density	Density contrast e.g. fractures, basins, buried channels, dykes
Magnetic	Magnetization	Magnetization contrast especially in basaltic aquifers and contact zones
Seismic	Velocity	Variation in propagation of seismic waves

Source: (Zohdy *et al.*, (1990)

Electrical resistivity method is the most popular of all geophysical methods in groundwater exploration and investigations because it provides a good contrast between resistivity of water bearing zones and water-devoid zones, structural and lithological information of the sub-surface. This information include; thickness of aquifer overlying resistive bedrock, the quality of groundwater which could be saline, fresh, contaminated with toxic waste or brackish, strata thickness, depth to bedrock, hydrogeological units, aquifer hydraulic properties, fault zones and types of subsurface materials (Sabet, 1975 ; Ratnakumari, *et al.,* 2012,). Its diverse use is mainly because, the ability of a rock to conduct an electric current depends almost entirely on the amount, distribution and salinity of the water in the rock and horizontal changes in the subsurface resistivity (Sabet, 1975; Zohdy, *et al.,* 1990). Electrical resistivity involves Vertical Electrical Sounding (VES) and Horizontal Electrical Profiling (HEP). The resistivity measurements and interpretation of the data obtained using electrical resistivity methods work under basic assumptions that; the sub-surface is made of a sequence of horizontally stratified layers, each layer is homogeneous and isotropic and the field is generated by a point source of current that is located at the surface of the earth (Zohdy, *et al.,* 1990).

2.3 Relationship between Geology and Resistivity

Knowledge of typical resistivity values for different types of subsurface materials and the geology of the area surveyed is important in interpretation of resistivity results (Loke, 2001). Table 2 shows resistivity and conductivity of common rocks and minerals

Table 2: Resistivity of some common rocks and minerals

Material	Resistivity (Ω•m)	Conductivity (Siemen/m)
Igneous and metamorphic rocks		
Granite	$5*10 - 10^6$	$10^{-6} - 2*10^{-4}$
Basalt	$10^3 - 10^6$	$10^{-6} - 10^{-3}$
Slate	$6*10^2 – 4*10^7$	$2.5*10^{-8} - 1.7*10^{-3}$
Marble	$10^2 - 2.5*10^8$	$4*10^{-9} - 10^{-2}$
quartzite	$10^2 – 2*10^8$	$5*10^{-9} - 10^{-2}$
Sedimentary rocks		
Sandstone	$8 - 4*10^3$	$2.5*10^{-4} - 0.125$
Shale	$20 - 2*10^3$	$5*10^{-4}$ 0.05
limestone	$50 - 4*10^2$	$2.5*10^{-3} - 0.02$
Soils and waters		
Clay	1 -100	0.01 -1
Alluvium	10 -800	$1.25*10^{-3} - 0.1$
Groundwater (fresh)	10 -100	0.01 -0.1
seawater	0.2	5
Brackish water	0.3 – 1	

Source: Loke, (2001)

The electrical properties of most rocks in the upper part of the earth's crust are dependent primarily upon the amount of water, distribution of the water in the rock and the salinity. Resistivity of rocks generally depends on the water content (porosity), the resistivity of the water, the clay content and the content of metallic minerals (Mbiimbe, *et.al*, 2010). Saturated rocks have lower resistivity than unsaturated and dry rocks. The higher the porosity of the saturated rock, the lower its resistivity and the higher the salinity of saturating fluids, the lower the resistivity. Fractured and weathered rocks have lower resistivity than un-fractured and un-weathered rocks. The presence of clays and conductive minerals also reduces the resistivity of the rock (Ewusi, 2006).

According to Ewusi (2006), electrical resistivity method applies basic principles in determining the resistivity of different rocks within the earth subsurface. A hard rock without pores or fractures is very resistive to the flow of electric current. This is generally observed in hard fresh Precambrian rocks. Dry sand without water is very resistive. Porous or fractured rock bearing free water has resistivity, which depends on the resistivity of the water and on the porosity of the rock. Impermeable clay layer, which is wet, has low resistivity but may not contain enough yields for successful groundwater exploitation. Mineral ore bodies such as iron and sulphides have very low resistivity due to their electronic conduction; usually lower or much lower than 1 Ω .m.

2.4 Principles of the Geophysical Electrical Resistivity

Resistivity is measured by inducing an electrical current into the ground through two current electrodes and measuring the potential difference between potential electrodes. Electrical current is conducted through the subsurface by the electronic conductivity of the matrix grains and the electrolytic conductivity of the pore water (Al-Bassam & Tahir, 1996). The distance between the electrodes and the potential difference measured at the potential electrodes is used to calculate apparent resistivity of the subsurface geological units (Zohdy *et al.,* 1990). The apparent resistivity is the resistivity of a homogenous ground which will give the same resistance value for the same electrode arrangement. The apparent resistivity is a function of the electrode configuration, electrode spacing, applied current, true earth resistivities, number of layers, layer thickness, potential gradient and anisotropic earth properties. Figure 1 shows the basic principle of the electrical resistivity measurements. Depth of investigation is a function of the electrode spacing A &B current spacing and potential electrodes (M&N). The greater the spacing between the outer current electrodes, the deeper the electrical currents will flow in the earth, hence the greater the depth of exploration (Zohdy *et al.,* 1990)

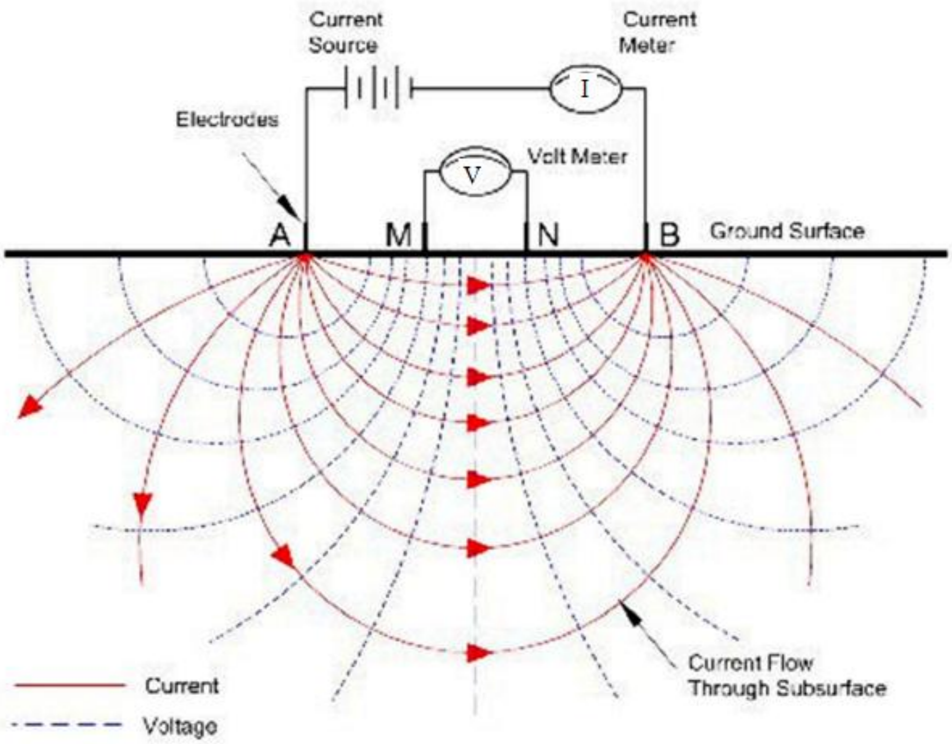

Figure 1: The basic principle of electrical resistivity measurements

The relationship between the "apparent" resistivity and the "true" resistivity is a complex relationship in which the true subsurface resistivity, an inversion of the measured apparent resistivity values using a computer program (Zohdy *et al.,* 1990). In the case of a homogenous medium the measured apparent resistivity is equal to the actual or true resistivity (Al-Bassam & Tahir, 1996).

2.5 Electrode Arrangements

The most commonly used electrode configurations are the Schlumberger (Figure 2) and Wenner (Figure 3). In each configuration the four electrodes are collinear but their geometers and spacing are different (Sisay, 2008). In the Schlumberger array, the current electrodes A and B are at equal distances and *L* is in opposite directions from the center of the array. The potential electrodes M and N are between A and B at equal distance *b* from the center of the array. A current is injected into the earth through A, and the circuit is closed at B. The resulting potential difference (ΔV), between M and N is measured together with applied current I. The measured values of I and ΔV together with L and b are used to calculate the apparent resistivity (ρ_a) as in Equation 1. This configuration minimizes the distance between the potential electrodes to the point where variations in the gradient are recognizable. Apparent resistivity is defined as the resistivity of an electrically homogeneous and isotropic half-space that would yield the measured relationship between the applied current and the potential difference for a particular arrangement and spacing of electrodes (Sisay, 2008).

$$\rho_a = \pi\left[\left(\frac{L}{2}\right)^2 - \left(\frac{b}{2}\right)^2\left(\frac{1}{b}\right)\right]\left(\frac{V}{I}\right) \quad \text{..........(1)}$$

Where

ρ_a = apparent resistivity (Ω-m)

L = current electrode spacing (m)

b = potential electrode spacing

V = voltage (volts)

I = applied current (A)

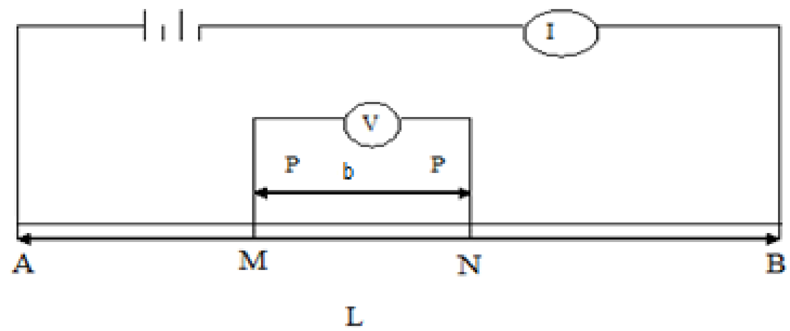

Figure 2: Schlumberger configuration

The apparent resistivity value is the product of the geometric factor and the resistance recorded in the resistivity meter. In each station, geoelectric soundings and apparent resistivity values are obtained by expanding the current electrode spacing after each reading as required by Schlumberger array for deeper penetration into the earth and structural responses (Alile, *et al*, 2008). The measured apparent resistivity values are normally plotted on a semi-log graph paper. To interpret, it is normally assumed that the subsurface consists of horizontal layers. In this case, the subsurface resistivity changes only with depth, but does not change in the horizontal direction. A one-dimensional model of the subsurface is used to interpret the measurements (Loke, 2001).

In the Wenner configuration, each potential electrode is separated from the adjacent current electrode by a distance of "*a*" which is one third the separation of the current electrodes. Wenner array is used for both resistivity profiling and depth sounding (Loke, 2001).

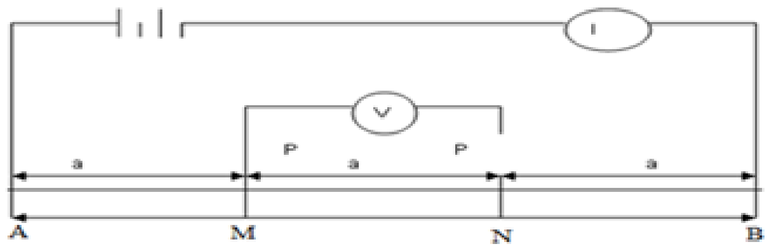

Figure 3: Wenner configuration

The array is relatively sensitive to vertical changes in the subsurface resistivity below the centre of the array and more sensitive to horizontal changes in the subsurface resistivity. The array is best used for horizontal structures, but is relatively poor in detecting narrow vertical structures. The Wenner array has large signal strength. The advantage of this array is that it is popular and widely used so it has a vast amount of interpretational material. The arrays also require much smaller data than the others to construct a pseudo-section. However, all four electrodes are moved making it less time efficient for profiling, but since the distances between the electrodes are small mistakes are less likely (Sisay, 2008). Apparent resistivity $\rho_a(\Omega)$ is calculated as shown in equation 2.

$$\rho_a = 2\pi a \frac{V}{I} \quad \text{..........} \quad (2)$$

Where

ρ_a = apparent resistivity (Ω)

a = probe spacing (m)

V = voltage measured (volts)

I = injected current (A)

2.6 Types of Electrical Sounding Curves

Sounding curves are generated when the field data are plotted on a semi-logarithmic scale showing ρ_a versus the separation AB/2. If the ground is composed of a single homogenous and isotropic layer of infinite thickness and finite resistivity, the apparent resistivity curve will be a straight horizontal line. If the ground is composed of two layers, the curve rises or falls depending on whether p2 > p1 (ascending type) or p2 < p1 (descending type). If the ground is composed of three layers, there are four possible combinations between the resistivities values, figure 4. These are; p1 > p2 < p3 (H – type), p1 < p2 < p3 (A – type), p1 < p2 > p3 (K – type), p1 > p2 > p3 (Q – type) (Shewa, 2007).

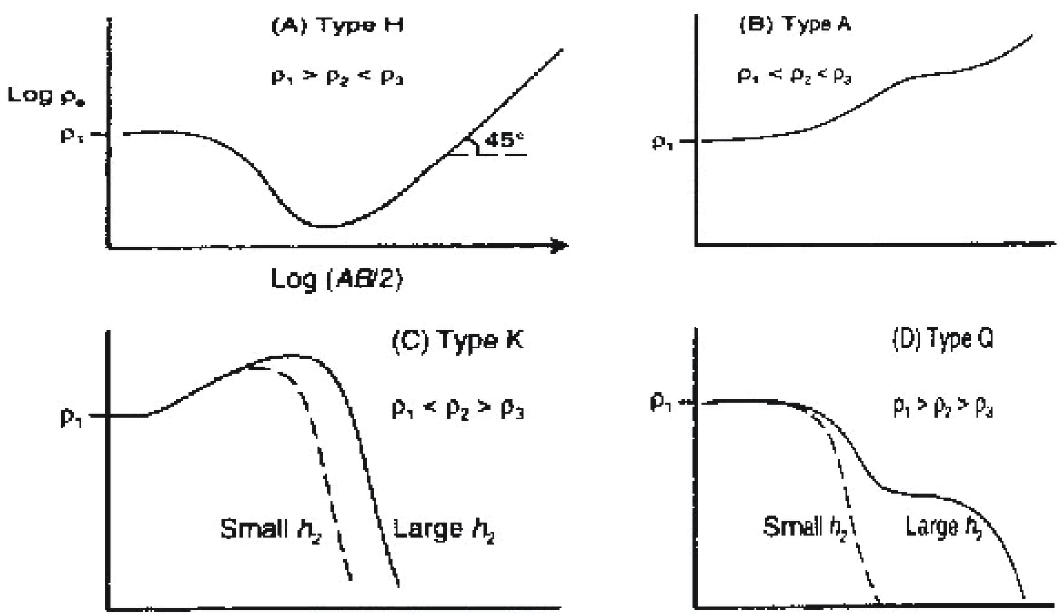

Figure 4: Three layer resistivities curve

If the ground is composed of more than three horizontal layers; the letters H, A, K and Q are used in combination to indicate the variation of resistivity with depth. In a four layer, there are eight possible combinations between the resistivities. HK – type (p1 > p2 < p3 > p4 is an example of a four layer curve. In a five layer curves, there are sixteen possible combinations of three letters. For example; a HKH- type (p1 > p2 < p3 > p4 < p5) (Elzein, 2007).

2.7 Interpretation of Resistivity Data

The aim of interpretation of the resulting curves is to determine the resistivity and thickness of each layer from the observed sensitivities and to use these results to obtain a complete geological picture of the area under investigation (Zohdy, *et al.*, 1990). To get more accurate quantitative results the data must be processed to give true resistivity distribution (Elzein, 2007). Interpretation of resistivity measurements therefore must be carried out with regards to the available geologic information of the area including geologic maps and borehole logs (if available). Interpretation of the resistivity data is done by; graphical curve matching method (which is rather obsolete technique) or computer based techniques (Zohdy, *et al.*, 1990).

In graphical curve matching, the field curve to be interpreted is plotted on transparent logarithmic paper with the same modulus as the master curve. It is then shifted over the master curve keeping the coordinate axes parallel, until a reasonable match is obtained with one of the master curves or with an interpolated curve. Layer resistivity values can be estimated by matching to a set of master curves calculated assuming a layered Earth, in which layer thickness increases with depth (Shewa, 2007).

2.8 Inversion and modeling

Modeling is the most popular method for interpretation of electrical resistivity geophysical data. The use of high speed digital computer is almost always necessary for the calculation of theoretical sounding curves. These are iterative methods where an initial model for the subsurface is improved by comparing the calculated anomaly with the observed anomaly. The model parameters are then adjusted to reduce the difference between the calculated and observed anomalies, (Elzein, 2007). The inversion routine used is based on the smoothness constrained least square method (Loke, 2001). If the calculated anomaly does not fit the observed anomaly, the subsurface model is changed until the Root Mean Square Error (RMSE) is reduced below 5%. The model is considered to be appropriate when the calculated values and the measured ones are best fitted (Elzein, 2007).

2.9 Application of Electrical Resistivity Techniques

Resistivity techniques have been used extensively in the past to detect groundwater and to delineate aquifers. Gressando (1999) used resistivity method to investigate groundwater in Lake Naivasha area. The investigation utilized Schlumbergher arrangement for vertical electric resistivity and Wenner arrangement for horizontal profiling. The schlumberghe array involved twenty five vertical electrical resistivity soundings (VES) which were spread out from Lake Naivasha shore (swamp zone) to Suswa in the southeast and Malewa catchment in the northeast of the study area. Horizontal profiling was used to obtain the lateral variations of the subsurface lithology.

Lashkaripour (2003) carried out VES resistivity surveys in Korin aquifer, southeast of Iran, to study the groundwater conditions such as depth, thickness, location of the aquifer and quality of the groundwater. VES using Schlumberger array technique were conducted at 596 positions for 26 profiles in the range of 200 to 400 m of half current electrode spacing. The field curves obtained were interpreted with the aid of Russian software, IP17.63. The results were compared with the lithological data obtained from 16 dug wells and were found in good agreement with the VES interpreted layers. He concluded from VES tests that there were four subsurface geoelectric layers: thin surface layer, alluvium, aquifer and the bed rock. The boundary and zones of the high groundwater yield potentials were delineated for the well sites.

Pastor, 2001, used geophysical studies to investigate groundwater system on the South of Lake Naivasha. The study involved the use of DC Schlumberger sounding method and TEM sounding method to determine physical rock characteristics, geologic structures such as faults/fractures, lithological changes, and variations in thickness, so as to identify groundwater potential in the study area. Pastor found out that two aquifers, shallow and deep exist in the study area. The shallow aquifer exists close to the lake stretching from Sulmac Farm towards Obsidian ridge while the deeper aquifer occurred south of the Lake towards Mt. Longonot at around 1400 m.a.s.l extending towards the geothermal area at deeper levels.

Batayneh (2007) conducted geoelectrical measurements using VES method on the eastern Red sea coast in Jordan using the PYSCAL-R2 resistivity meter and used the Schlumberger electrode array with outer electrode spacing AB/2 ranging from 15 to 600 m and potential electrode separation from 1 to 40 m. He interpreted the data using a 1-D inversion program (RESIX-IP), to obtain final earth models. In order to determine electrical characteristics of rock units, correlation between two VES stations and borehole lithology was developed. Resistivity measurements showed a dominant trend of decreasing resistivity due to increasing salinity with depth and westward toward the Red Sea. Accordingly, he detected three zones with different resistivity values corresponding to three different formations: (i) a water-bearing formation in the West containing saltwater presumably from the Red sea; (ii) a transition zone of clay and clayey sand thick formation and (iii) strata saturated with fresh groundwater in the east disturbed by the presence of clay and clayey sand horizons. He concluded that the VES surveying technique was useful to map the subsurface of structurally complex area where little geologic information was available due to lack of drill holes and it can also be used to locate bodies of groundwater and zones with anomalous electrical properties.

David and John, (1997), used electrical resistivity to investigate for a Supplemental municipal groundwater supply in Danville, Illinois. A total of 73 electrical earth resistivity profiles were obtained in a 35-square-mile part of the study area northwest of Lake Vermilion. The electrical earth resistivity surveys, using the Wenner array, were used to measure the electrical potential of earth materials from the land surface to some depth below it.

They were able to identify the areas with groundwater potential which can be explored. They also determined the thickness and nature of the water-bearing sands and gravels, and the relief of the underlying impervious layer.

Park *et al.* (2007) conducted 20 profiles of vertical electrical soundings (VES) in the riverside alluvium at the Buyeo area, South Korea, to examine the variations of subsurface geology and the associated groundwater chemistry. They utilized a combination of VES and borehole data, which provided useful information on the subsurface hydrogeologic conditions. They observed two types of aquifers in the riverside alluviums of the study area: the perched aquifer and the main aquifer. The perched aquifers occurred at shallow depths (1–5 m) in the central and southwestern parts of the study area and the main aquifer in the central part was observed below the perched aquifer. They interpreted from the distribution of water resistivity correlations with that of measured total dissolved solids concentration in groundwater and the earth resistivity of the aquifer. They observed a significant spatial variation. They concluded that the earth resistivity of the aquifer was mainly controlled by the soil type rather than by the water chemistry in the study area.

Sisay (2008) carried out a geophysical survey at Ada'a and Becho plain in Addis Ababa Ethiopia. The study mainly focused on the evaluation of the groundwater potential of Ada'a and Becho plains and was designed for the purpose of pressurized irrigation development. The methods employed were electrical resistivity sounding, electrical resistivity imaging and magnetic mapping alongside with the existing electrical sounding data in order to map the possible paths of fluids, to determine the aquifer properties of the areas, including depth to the saturated zones, degree of weathering and fracturing of the water-bearing zone, to delineate the most promising areas for future ground water development by studying the kind and thickness of the overlying strata and the lithology encountered. The study revealed that the main water bearing horizons in the area were fractured and weathered volcanic rocks (Volcanic sands, basalts, ignimbrites and tuffs), lacustrine and alluvial sediments. The study also showed that groundwater flows from the northern to the southern direction of the study area and concluded that southern part have a potential of groundwater.

Shanker (1994) carried out VES surveys using resistivity meter at many selected points in villages of Bellariu, Padupanamber and Tokur in Mangalore-Karnataka, South India, by employing Schlumberger electrode arrangement. The field curves obtained were interpreted using the curve matching technique. He concluded that the resistivities of the 1st and 2nd layer varied from 100 to 400 ohm-metres and 10 to 100 ohm-metres, respectively. The resistivity increased in deeper zones sometimes above 1000 ohm-metres. Therefore, he interpreted the 2nd layer as saturated from where sufficient groundwater can be tapped based on the VES results.

CHAPTER THREE
MATERIALS AND METHODS

3.1 Location

The Lake chala watershed lies on Kenyan Tanzania border on the southern slopes of Mt Kilimanjaro in Taita Taveta County between 740 m.a.s.l and 4000 m.a.s.l. The watershed is located 9.654 kilometers North of Taveta Town between longitude 037^0 30’ 0” E and 37^0 45’ 0” and latitudes 03^0 5’ 0” and 03^0 25’ 0” (Figure 5). The watershed has a transboundary water resource Lake Chala which is shared between Kenya and Tanzania. Lake Chala is a Crater Lake formed from a paroxysmal volcanic outburst (CPK 1955). It has a surface area of 4.2 km^2. The Lake has no surface inflow and outflow and it is fed by groundwater. According to CPK (1955), the floor of the Lake is level, the inner walls are inclined at an angle of 45^0 and the depth is estimated at 91.44 metres. The level of the water at the surface is 837 metres above sea level while the level of water at the floor is estimated at 730.139 metres above sea level.

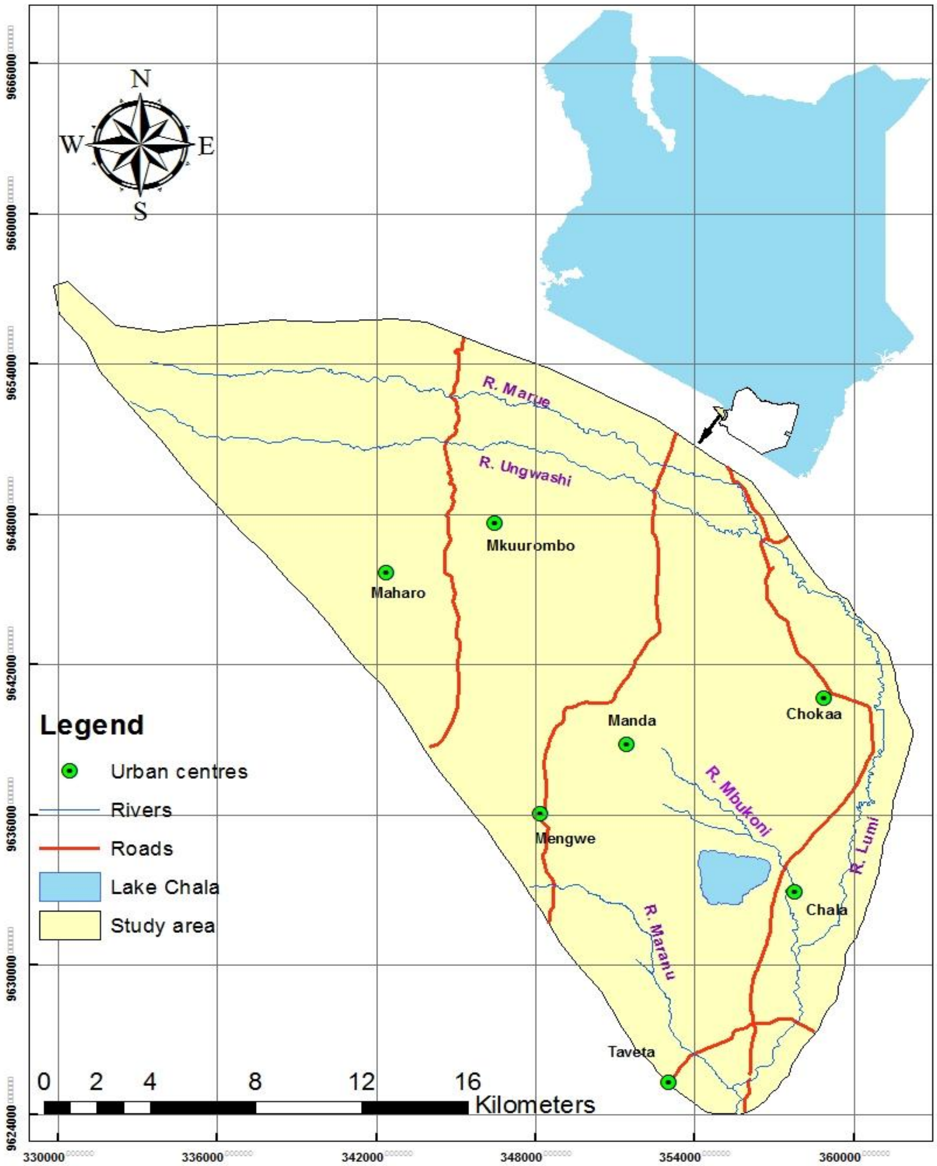

Figure 5: Map showing Lake Chala Catchment

3.1.1 Climatic Conditions of Lake Chala Catchment Area

Lake Chala watershed forms part of the southern slopes of Mt Kilimanjaro (Rohr & Killingtveit, 2003). Rohr and Killingtveit (2003) investigations on annual rainfall distribution on the slopes of Mt Kilimanjaro indicated an increase with altitude up to 2100 metres above sea level (m.asl) and then the rainfall decreases with an increase in the altitude (Figure 6). The annual rainfall on the southern slopes is high and reaches a maximum of 3,000 mm at 2,100, m.a.s.l. in the forest belt. Lake Chala Catchment area falls between 740, m.a.s.l and 4000 m.a.s.l and the annual rainfall is between 500– 4000 mm.

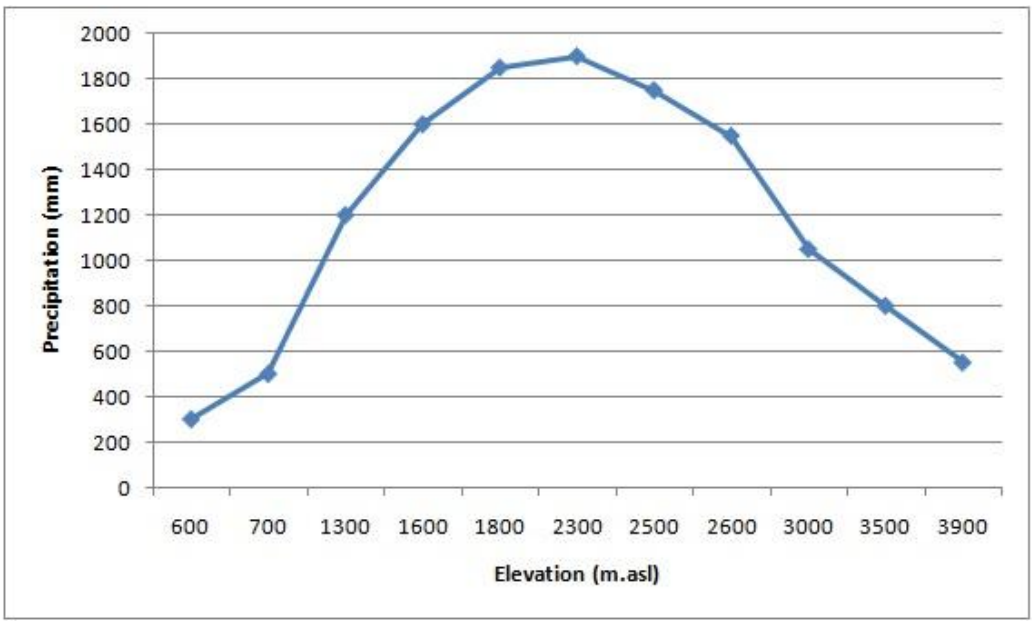

Figure 6: Rainfall distribution on the slope of Mt Kilimanjaro

3.1.2 Vegetation Cover

The Lake Chala Watershed vegetation cover is composed of forest, bush land and scrubland. The vegetation, according to Rohr and Killingtveit (2003), intercept rain drop, prevent, surface runoff, minimize surface evaporation and enhance infiltration. This has significant influence on the ground water recharge considering that the Lake has no surface inflow.

3.1.3 Hydro-geological setting of Lake Chala Watershed

Hydro-geology of Lake Chala catchment area is defined by the Kilimanjaro aquifer delineated by Alker et al., (2008). The aquifer (Figure 7) includes the volcanic pyroclastic and volcanic alluvium deposits found at the base of Mount Kilimanjaro and extending across the Kenyan-Tanzanian border. These deposits form basins which extend outward from the mountain and are limited by the surrounding Precambrian basement rocks. Occurrence of groundwater in the surrounding basement plains is limited to faults, fractures and small parts of weathered zones and also to the bottom layers of wide alluvial valleys which are recharged by natural flood spreading (Alker *et al*., (2008). The basement rocks are an aquaclude for a large regional groundwater flow system emanating from Kilimanjaro. It extends into the volcanic alluvium at the base of the mountain and forms major aquifers. These basins are filled by alluvium deposits composed of sand clay and gravel, with calcerous deposits with some lava and pyroclastic volcanic rocks, as well as fractured and weathered basalts (Figure 8).

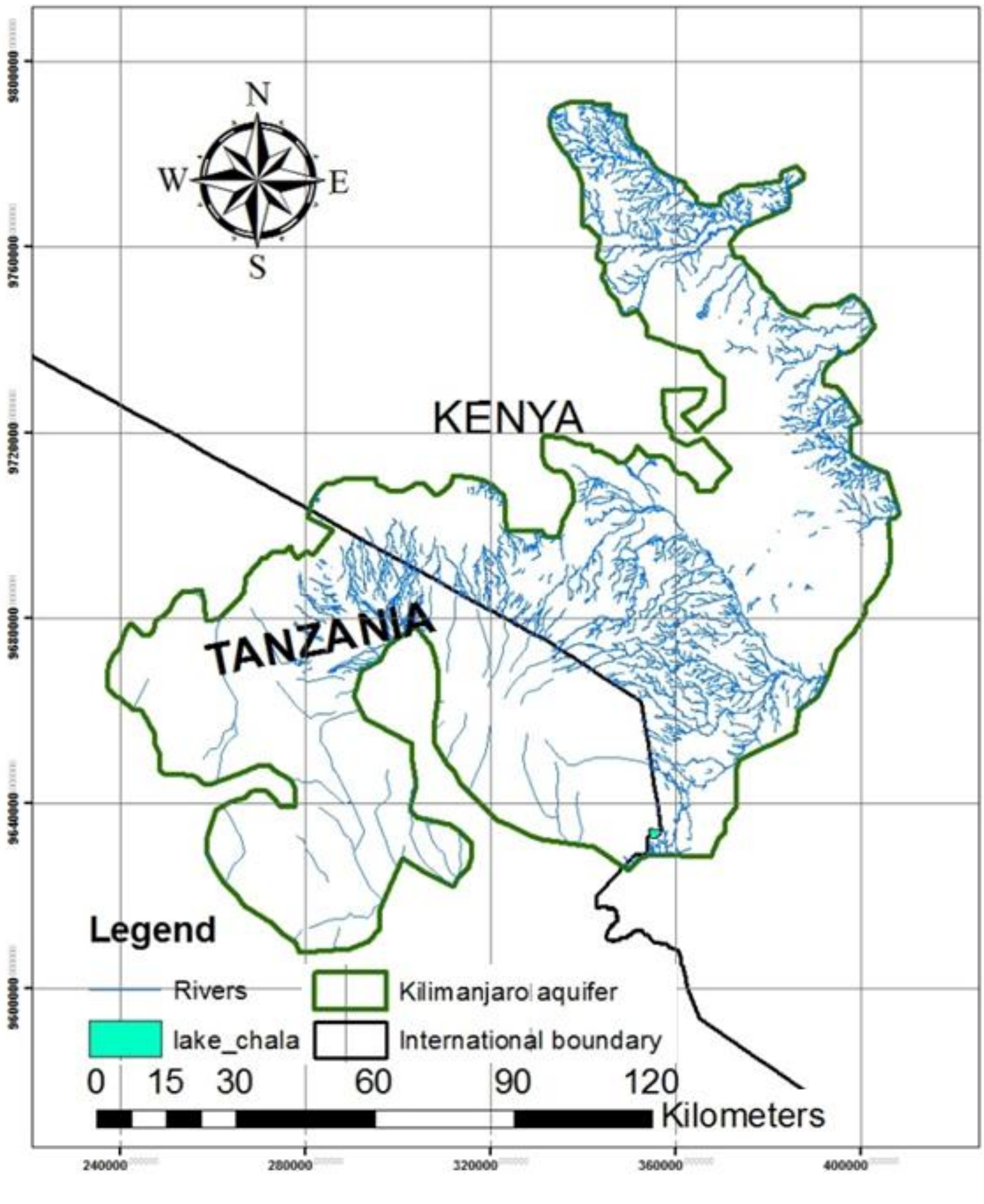

Figure 7: Kilimanjaro aquifer

Figure 8: Rocks and geology of Lake Chala Watershed

Lake Chala is part of the aquifer and although it does not have a visible inlet or outlet its recharge and discharge is strongly linked to the volcanic pyroclastics and volcanic alluvium deposits and fractured and weathered basalts which allow percolation through the faults, fractures and weathered zones.

3.2 Materials

3.2.1 Data for Generating Thematic Maps

The dataset used for generation of thematic maps and for the identification of groundwater potential zones of Lake chala watershed were; topographical map of Kenya of 2012 on 1:50,000 scale remote sensed data satellite images from Landsat-7 Thematic Mapper, DEM data of 1996, geological map of the area of 1952 from mines and geology, rainfall data of 2009, and river data of 2007, from World Resource Institute. The selection of the images and datasets was based on the availability. Vertical electrical soundings were conducted to generate resistivity data and subsequently aquifer thickness, depth, porosity and transmissivity data.

3.2.2 Instruments and Softwares

SYSCAL R2 Electrical Resistivity Meter and it accessories, a hand held 12 channel Garmin Etrex Global Positioning System (GPS) and digital camera were the main instruments used for data collection and generation. Table 3 shows the instruments and their accessories that were used for the purpose of this study. Syscal R2 Electrical Resistivity Meter was used to perform Vertical electrical sounding while the hand held 12 channel Garmin Etrex Global Position System (GPS) was used to locate vertical electric sounding positions. The camera was used to document the field surveys, topography, geology and vegetation in the form of photos for illustration purposes.

Table 3: Instruments and their accessories required for the study

Type of equipment	Accessories
SYSCAL R2 Electrical Resistivity Meter	4 Reels of wires (Two for current and two for Potential) 4 Non-polarizable steel metal stakes 4 wire clips 2 wire connectors for powering the SYSCAL R2 Electrical Resistivity Meter
GPS	
Digital camera	

The softwares used in the study were ArcGis10, Global Mapper 7, IP12win+IP and Spreadsheet Microsoft Excel 2007. Global Mapper 7 was used to generate a digital elevation model (DEM) of the study area. ArcGis10 was used to prepare and integrate different thematic layers used in the identification of suitable groundwater potential areas, and to perform groundwater analysis for estimation of recharge and discharge of the lake. Spreadsheet Microsoft excel 2007 was used to organize and analyze the resistivity sounding data. IP12win+IP were used to model and subsequently to interpret the resistivity sounding data and to generate and present geo-electric models of the study area.

3.3 Methods

3.3.1 Identification of groundwater potential zones in the LCW

In order to identify and delineate groundwater potential zones, rainfall, land cover, lithology, slope and drainage density themes were prepared from the acquired toposheets, geological map, Landsat images, rainfall and river data

The data themes were converted into raster format using the Arc Map convert commands under image analysis for integration in GIS analysis. Integration and analysis of these factors on a GIS platform aided in locating ground water potential zones where further groundwater investigations were conducted. For uniformity, the raster data were then registered to WGS84 Geographic Coordinate System using the projection and transformation tool in Arc Catalog version 10.

To guide the identification of the locality of the groundwater potential zones, a surface watershed was delineated by manual digitization from an overlay of digital elevation model and drainage network data. The delineated surface watershed was used to clip the slope, land use/cover, rainfall, drainage and lithology data layers using the extract tool under Arc Map 10 Analysis tools. Using the reclassify command under spatial analyst tools, all the data layers were assigned rank values with a rating scale range of 1 to 5 depending upon their suitability and capability to hold, store and transmit groundwater, (Table 4 and figure 13, 14, 15, 16 and 17). In the rank, a scale value of 1 means that the specific class of a particular factor has the highest weight to groundwater potential while a rank value of 5 means that the specific class of a particular factor has the lowest weight to groundwater potential (Muheeb & Mohammed, 2001, Sarkar *et al.,* 2001). Weighted overlay analysis was performed to generate groundwater potential zones map of the surface watershed Saraf *et al.,* 1998; Nag 2005), (Figure 18).

Table 4; Thematic layers, classes, ranks, influence and weights

Thematic layers	Classes	Rank	Groundwater Potential
Rainfall	1400-2400	1	Very high
	1200-1400	2	High
	800-1200	3	Moderate
	700-800	4	Low
	500-700	5	Very Low
Land cover	Forest	1	Very high
	Bushland	2	High
	Agriculture	3	Moderate
	Scrubland	4	Low
	Urban areas	5	Very low
Lithology	Sedimentary rocks	1	High
	Igneous rocks	2	Moderate
	Metamorphic rocks	3	Low
Slope (%)	0-3	1	Very high
	3-8	2	High
	8-16	3	Moderate
	16-27	4	Low
	27-50	5	Very low
Drainage density (per km)	0-0.3	1	Very high
	0.3-0.9	2	High
	0.9-1.5	3	Moderate
	1.5-2.3	4	Low
	2.3-3.9	5	Very low

The water table of an area is mainly controlled by variations in groundwater recharge, discharge and rainfall. Rainfall influences subsurface water sources in that part of the rainwater which falls on the ground is infiltrated into the soil to recharge groundwater (Todd and May, 2005). Areas with the highest rainfall (1400-2400) were categorized as areas of high potential for groundwater with areas receiving low rainfall (500-700mm) as low potential zones Table 4 and Figure 13.)

Land cover/use is another parameter that influences the occurrence of groundwater in Lake Chala watershed. The effect of land cover /use is manifested either by reducing runoff and facilitating, or by trapping water on their leaf. Water droplets trapped in this way go down to recharge groundwater. Land use/cover may also affect groundwater negatively by evapotranspiration, assuming interception to be constant (Sener *et al.*, 2005). Land cover/use map was generated and ranked figure 14. Very high ranking was assigned to the forest class and very low ranking was assigned to the urban areas class Table 4

Permeability and porosity controls the groundwater occurrence and recharging of an area and porosity and permeability directly depend on the lithology of the area (Loffler, 1974). Highest ranking was assigned to unconsolidated rock types of the study area, which were sedimentary rocks and low ranking to the consolidated rock type, metamorphic rocks Table 4 and Figure 15.

Drainage density is also an important parameter for groundwater occurrences and recharging. With respect to groundwater occurrences the higher drainage density is related to less infiltration of water to the ground which in turn leads to higher runoff and vice versa (Sener *et al.,* 2005). Based on this fact drainage density map was generated and ranked Figure 16 Table 4. Highest ranking was assigned to areas with low drainage density and low ranking was assigned to the areas with high drainage density Table 4.

Slope is also a crucial parameter for occurrence and recharging conditions of groundwater in a particular area; runoff will be more and infiltration is less in steep slope areas (Saraf & Chounhury, 1998). Therefore; highest ranking was given to areas with the lowest slope (0-3%) and highest ranking to the areas with highest slope (26-50%) respectively Table 4 and Figure 17.

3.4 Determination of hydro geological characteristics of the groundwater potential zones in the Lake Chala watershed

Based on the groundwater potential zones map of the surface watershed, 50 sites (Figure 18) were identified and located using Global Positioning system (GPS) for vertical electrical sounding (VES). The vertical electrical soundings were performed to determine the resistivity of the aquifer layers which was then used to generate aquifer thickness, depth, porosity and transmissivity. These hydrogeological characteristics were then used to estimate recharge and discharge of Lake Chala.

The coordinates of the stations where vertical electrical soundings were conducted were guided by groundwater potential zones map (Figure, 18). The exact locations of the VESs were adjusted based on the topography and vegetation. The VESs were concentrated within a 10 by 10 km area (approximately 5 km radius) around the lake. They were conducted along five horizontal profiles (A, B, C, D, and E) with each having between 6 and 7 VESs with the distance between the VESs and profile being between 1 and 2 km. (Figure 19). A total number of 50 Vertical electrical soundings were conducted using the Schlumberger configuration (Figure 2 and 9). The Schlumberger electrode configuration employed for the survey was carried out with measurements beginning with current electrode spacing (AB/2) of 1.6 to 320 and varying potential electrode spacing (MN/2) of 0.5m to 25m. The VESs data (mainly resistivity, current electrode spacing (AB/2) of 1.6 to 320 and varying potential electrode spacing (MN/2) of 0.5m to 25m) were entered in resistivity tables and plotted on semi-log graph paper (Appendix 1). The resistivity data was then entered into the IP2+win software to generate resistivity curves (Appendix 3) which were then analysed, modeled and interpreted to generate aquifer thickness, depth, bottom elevation, porosity and transmissivity (Appendix 4) of the water bearing layer in the Lake Chala ground watershed.

Figure 9: Field data collection activities

Porosity was derived from Archies formula (Benard, 2006) calculated as in equations 3 and 4 below.

$$R_r = FW_r \text{ --(3)}$$

Where

R_r = rock resistivity (ohms)

F = formation factor

W_r = water resistivity (ohms)

The formation factor F is evaluated as in equation 4, in which *a* is a constant, p is porosity and *n* is a constant. The values of *a* and *n* are normally taken as 1 and 2, (Benard, 2006) respectively

$$F = \frac{a}{p^n} \text{ -- (4)}$$

The transmissivity of an aquifer is defined as the hydraulic conductivity K times the saturated aquifer thickness b, as units of length squared over time. The hydraulic conductivity K for this study was estimated at 0.0003 m/s based on literature review by (Glenn, 2013) and the resistivity of the geological media of the Lake Chala watershed.

The aquifer bottom elevation, porosity and transmissivity values were converted through kriging (Figure 10) into effective aquifer bottom elevation raster, formation porosity raster and formation transmissivity raster and were used to calculate Darcy flow. Kriging is an advanced geostatistical analysis that generates an estimation of information where there is no data with a minimum interpolation error using neighbouring information. The model uses observations $z(s_1)$ at location s_1 to estimate the values $z(s_0)$ at point s_0, where the observation is not available (Goral & Kumar, 2013). Kriging applies (Equation 5) for the interpolation (DeMarsily, 1986).

$$\hat{Z}(s_0) = \sum_{i=1}^{N} \lambda_i Z(s_i) \qquad (5)$$

Where:

$Z(s_i)$ = the measured value at the *i*th location;

λ_i = an unknown weight for the measured value at the *i*th location;

s_0 = the prediction location;

N = the number of measured values

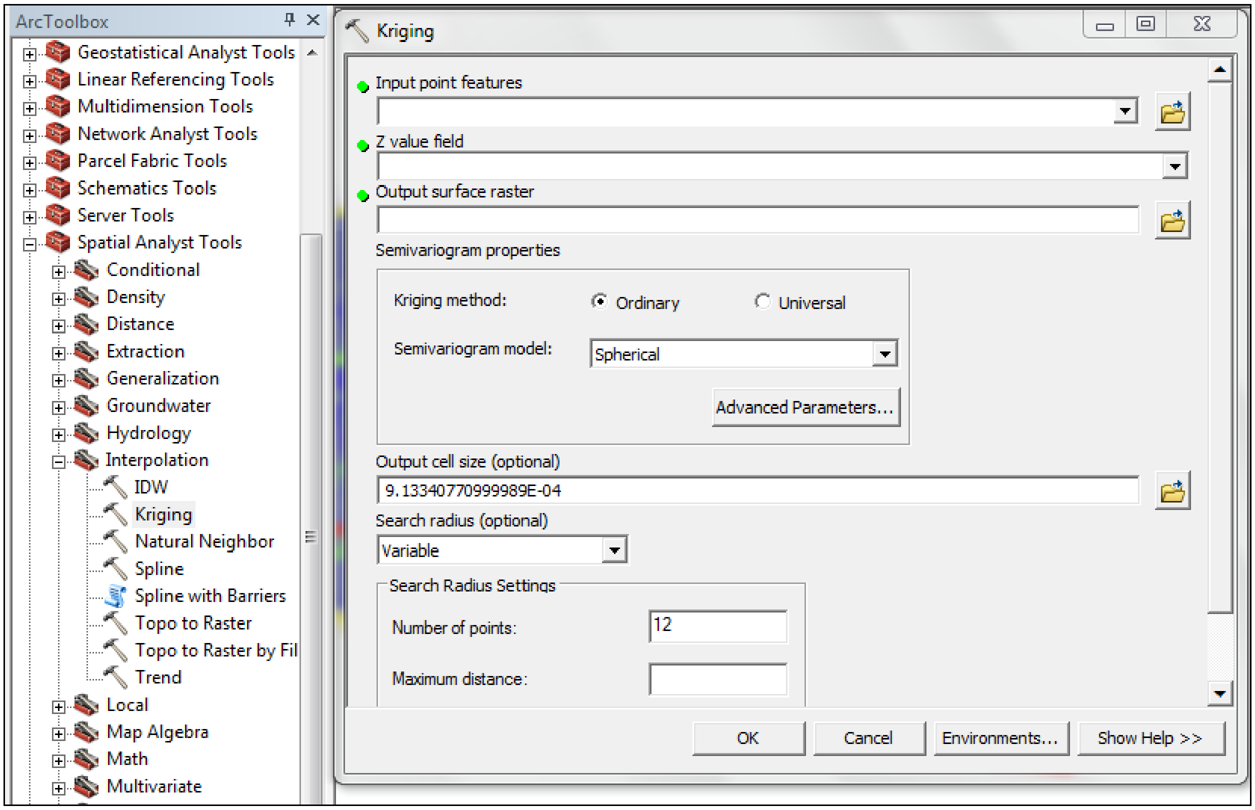

Figure 10: Kriging tool in Arcmap version 10

3.5 Groundwater quantification

To quantify groundwater potential it was important to delineate the real ground watershed which shows the flow direction and accumulation. This was accomplished by subjecting the aquifer bottom elevation to flow direction and flow accumulation analysis (Figure 11).

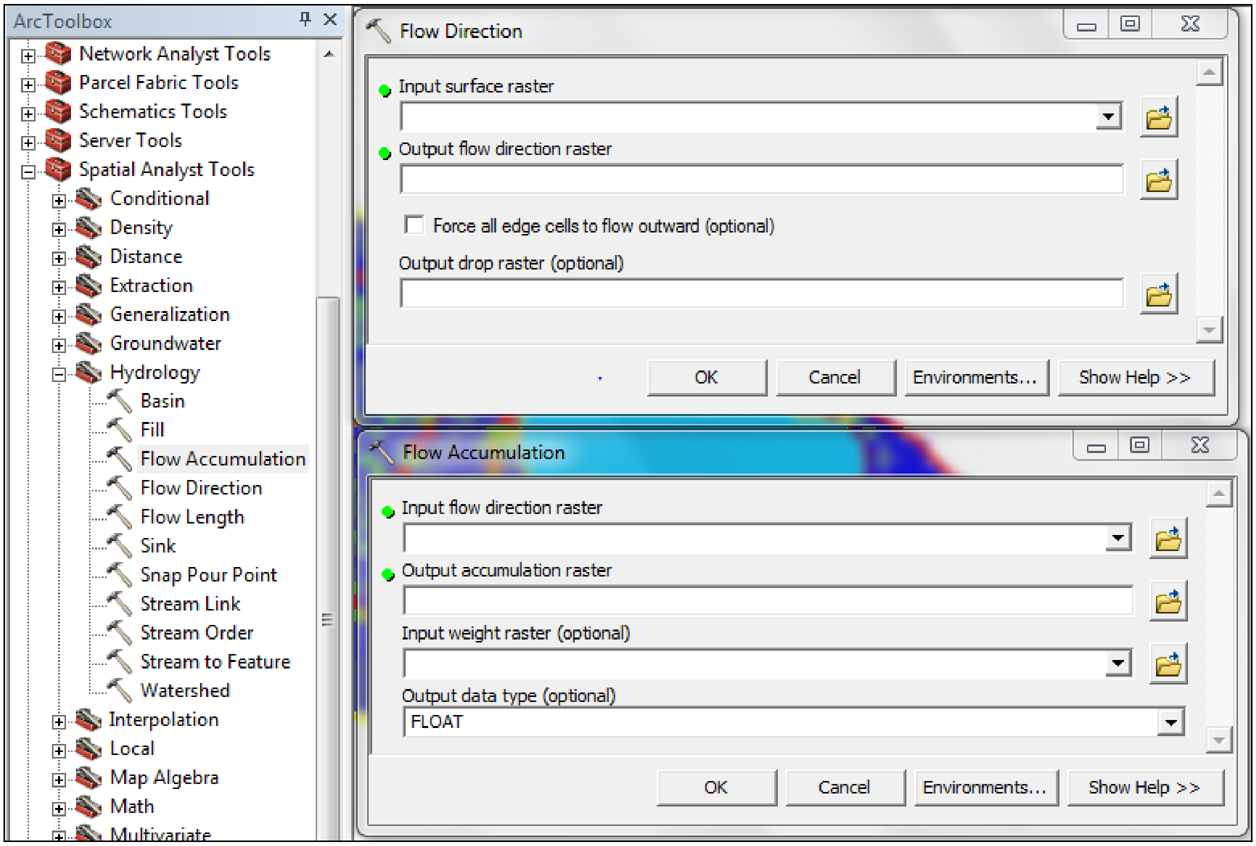

Figure 11: Flow direction and accumulation tool in Arcmap version 10

Flow direction was used to generate flow accumulation which calculates accumulated flow as the accumulated weight of all cells flowing into each down slope cell in the output raster resulting in watershed stream networks (Figure 21). The watershed stream networks were then used to delineate the real ground watershed (Figure 22). The real ground watershed was used to extract areas of interest from aquifer bottom elevation, effective formation porosity and formation transmissivity raster layers.

ArcGIS version 10 Darcy Flow analysis in Groundwater tools was then used to model recharge and discharge of groundwater in the Lake Chala watershed based on the extracted area of interest from aquifer bottom elevation, effective formation porosity and formation transmissivity raster layers (Figure 12).

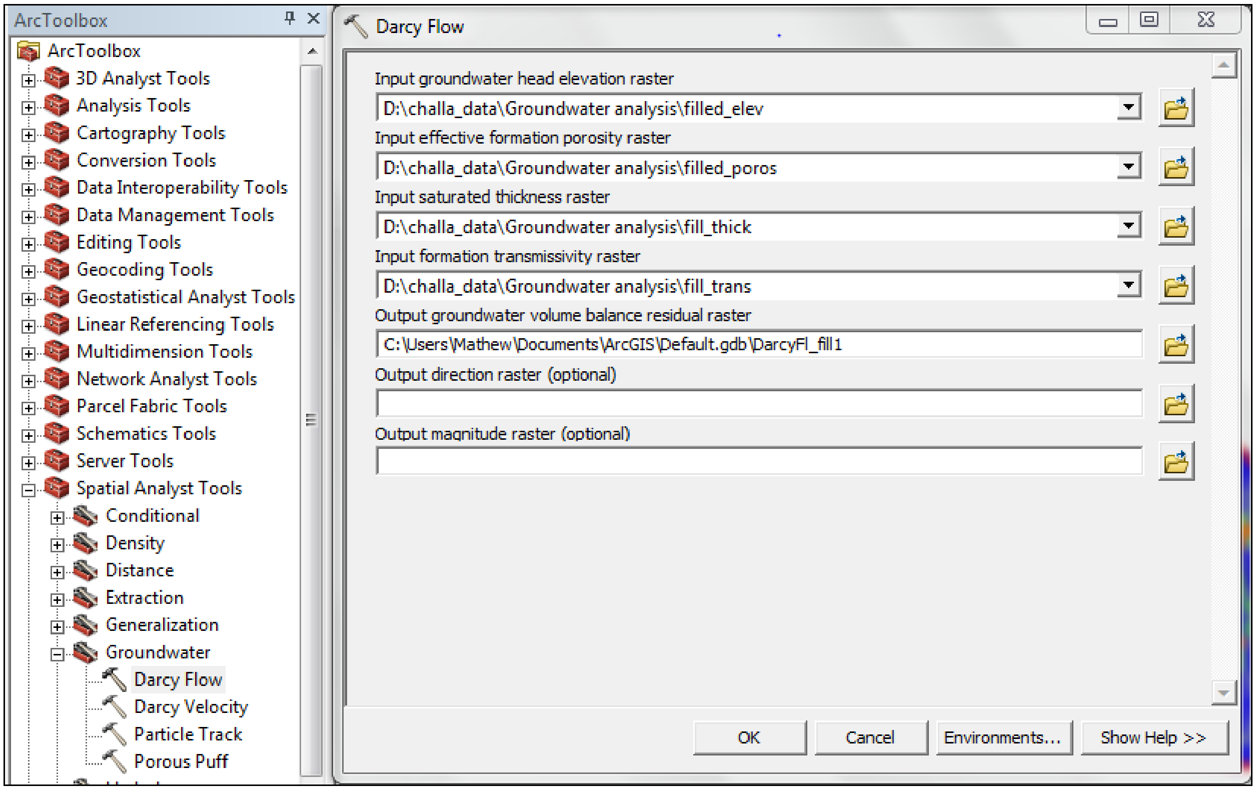

Figure 12: Darcy flow tool in Arcmap version 10

Groundwater inflow and outflow through a porous media can be determined using Darcy Law. To quantify groundwater flowing into and out of Lake Chala watershed, through recharge and discharge aquifer, Darcy equition was applied (Equition 6)

$$Q = KiA \text{ .... } 6)$$

Where

Q = Volume of water flowing through an aquifer m^3/day/s

K = Hydraulic conductivity (m/s)

i = Hydraulic gradient

A = Cross sectional area of the aquifer through which flow occurs (m^2) (aquifer thickness * width)

Several researchers; Simpkins, (2003), Oppong-Boateng, (2001), Pennequinn and Anderson, (1983), Shaw *et al.*, (1990), LaBaugh *et al*, (1997), Harvey *et al.*, (2000) and Hunt *et al.*, (2003), have applied Darcy equition in quantifying groundwater flow through aquifers.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Locality of groundwater potential zones in the Lake Chala watershed

Weighted overlay analysis of groundwater predictor factors in the Lake Chala watershed; mainly rainfall, land cover, lithology, slope, and drainage density are presented in Figures 13, 14, 15, 16 and 17 and these were used to generate groundwater potential map with various zones (Figure 18).

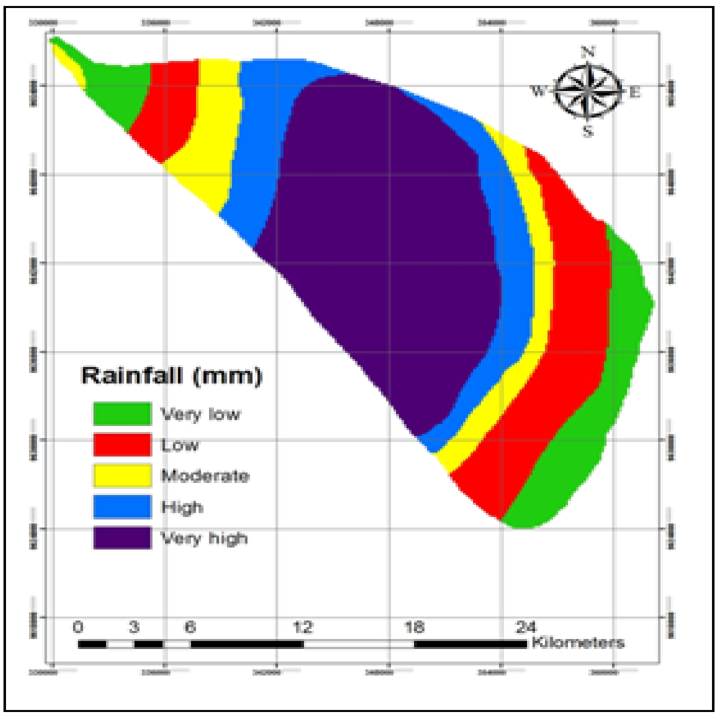

Figure 13: Ranked rainfall zones

Figure 13 shows classified and ranked rainfall map zones. Areas receiving 1400-2400mm were ranked as very high potential zones for groundwater while areas receiving

1000-1400mm as moderate potential zones and those areas receiving 500-800mm as low potential zones.

Figure 14 shows the classified and ranked land cover/use map of the Lake chala watershed. Forested areas were ranked as very high potential zones, bush-land as high potential zones, agricultural areas as moderate potential zones, scrubland as low potential zones and urban areas as very low potential zones respectively.

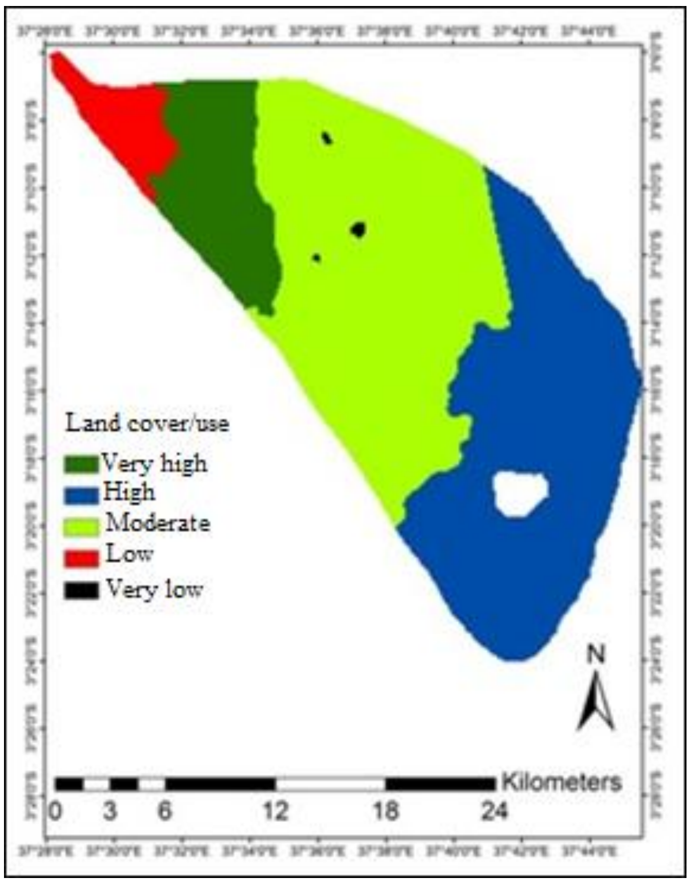

Figure 14: Ranked land cover/use zones

The Lake Chala watershed mainly comprises of three geological zones as shown in Figure 15. High potential zones were found in areas with sedimentary rocks, moderate potential in areas with igneous rocks and low potential in areas with metamorphic rocks.

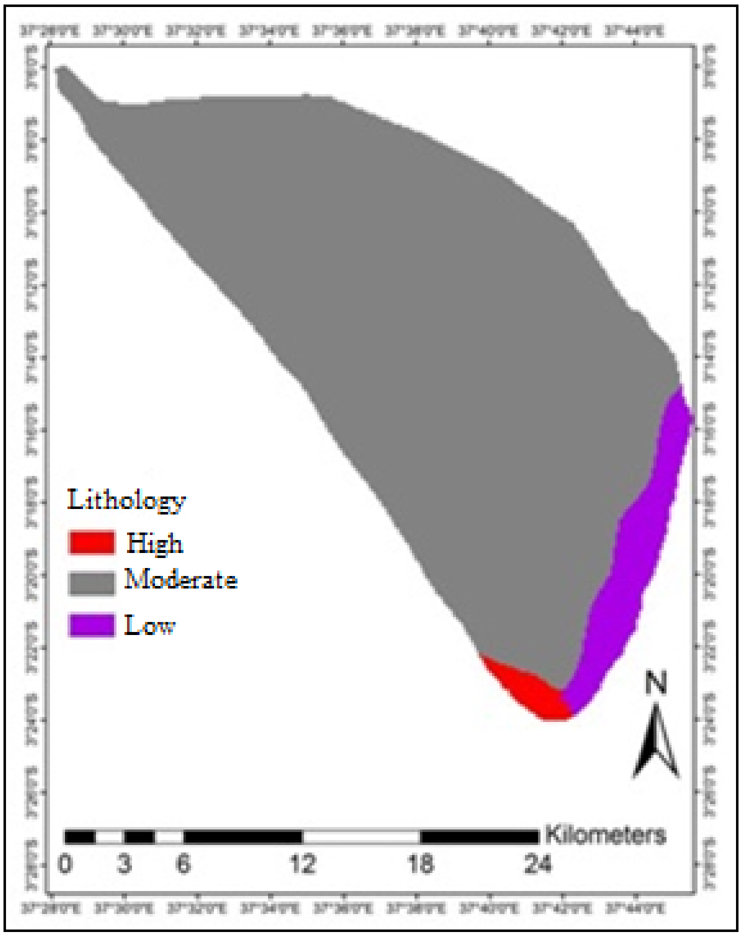

Figure 15: Ranked lithology zones

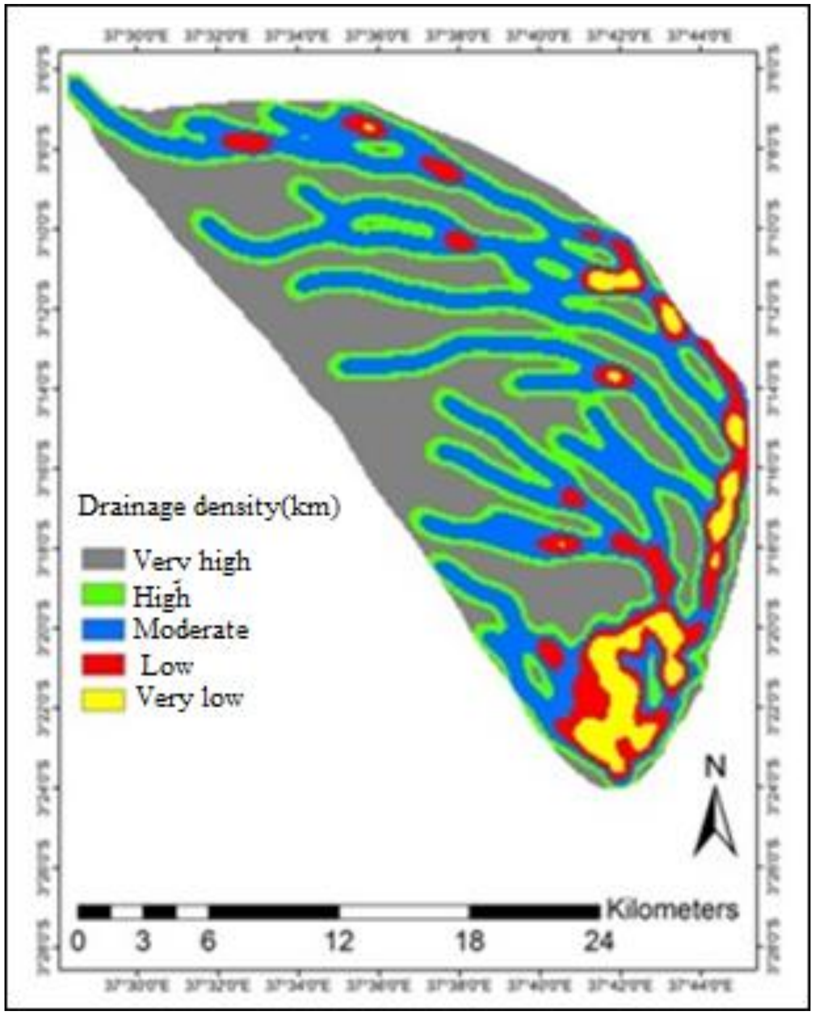

Figure 16: Ranked drainage density zones

Classified and ranked drainage density zones of the study area are shown in Figure 16. Based on the map, drainage density of the area is grouped into five classes. Areas covering 0-0.2km were ranked as the zone of very high potential and areas covering 1.8-3.06km were ranked as areas of very low potential.

Figure 17 shows slope classification and ranking. 0-3% slope represented zones of very high potential, 3-8% as zone of high potential, 8-16 % as zone of moderate potential, 16-27 % as zone of low potential and 27-50 % as zone of very low potential respectively.

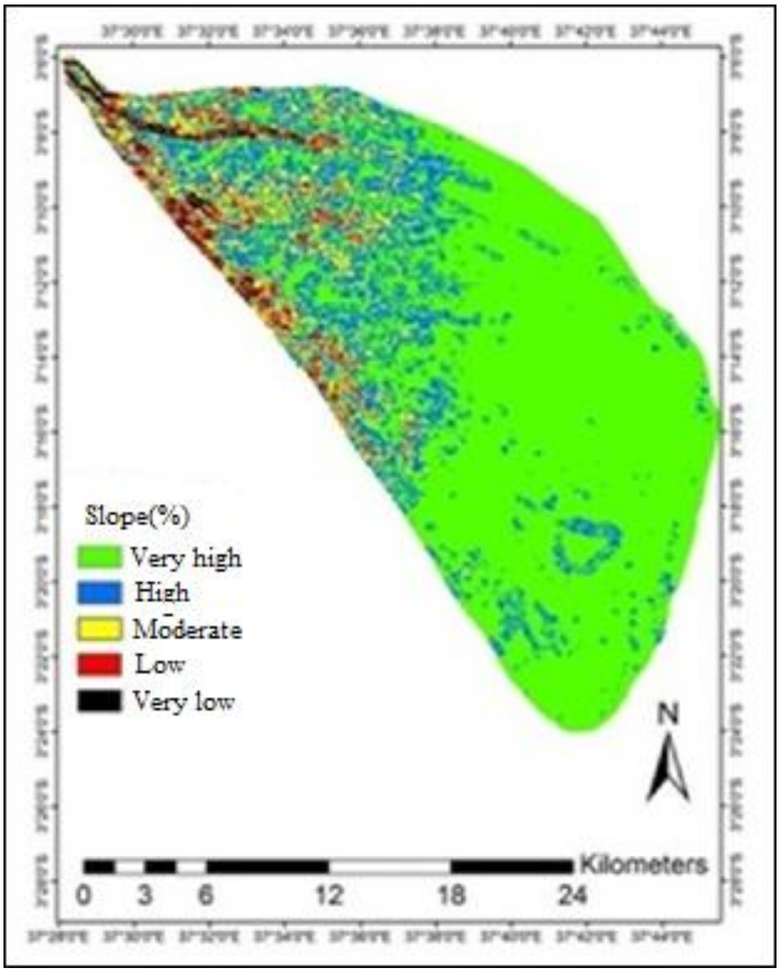

Figure 17: Ranked slope zones

Integration of rainfall, lithology, land use /cover, drainage density and slope as the major factors influencing the occurrence, movement and groundwater storage in Lake Chala watershed indicated that the study area is dominated by very high and high groundwater potential zones (Figure 18).

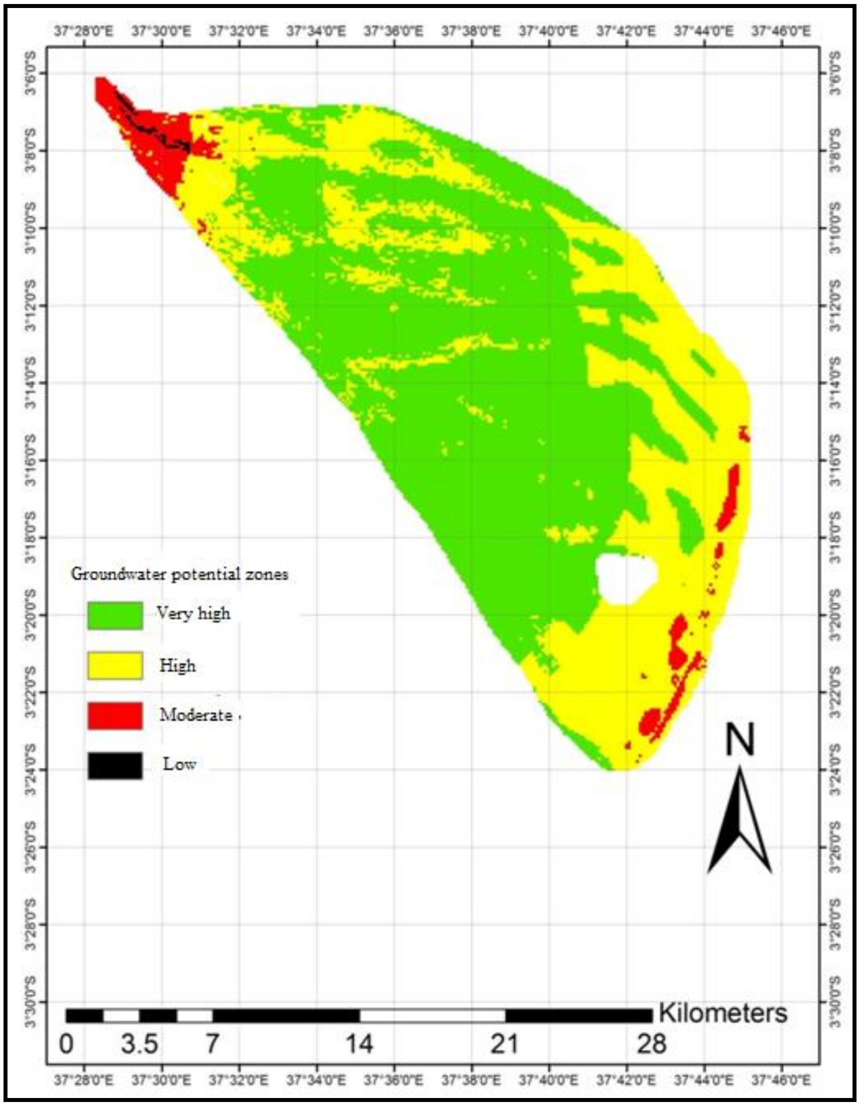

Figure 18: Groundwater potential in Lake Chala Watershed

Areas of high groundwater potential zones cover the largest area followed by areas of very high potential and low potential while very low potential cover the least area respectively. The integration also revealed that the very high and high groundwater potential zones occurred around the Lake and hence the locations for the conducting vertical electric soundings were concentrated around the lake (Figure 19)

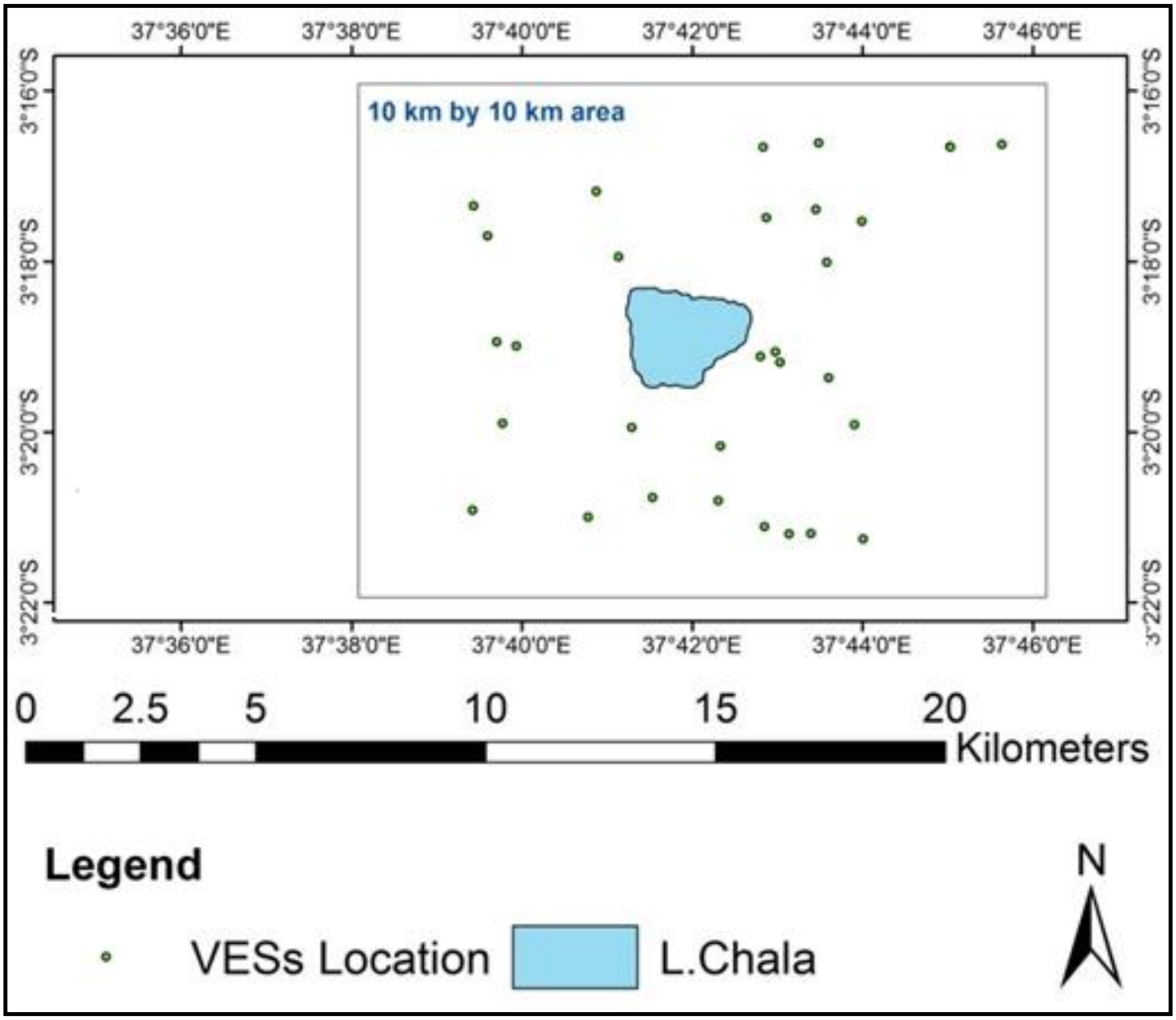

Figure 19: Vertical electrical soundings location

4.2 Hydrogeological characteristic of the groundwater potential zones in the lake Chala watershed

In harmony with WWDSE (2007) resistivity interpretation shown in Table 5, the water bearing layer of the Lake Chala ground watershed showed mean, minimum and maximum resistivities of 93.17, 42.6 and 182 ohm respectively, an indication that the water bearing layer is a high yielding aquifer true to the prediction in figure 18 which shows that the very high and high groundwater zones occur around the Lake.

Table 5; Resistivity of geological materials

Resistivity (Ώ.m)	Materials	Water bearing
1-40	Clay and sandy clay soil intercalated with silt, sand and gravel	Occasionally water bearing
40-200	Highly weathered ryholite, moderately weathered basalt and volcanic pyroclastic ash	Water bearing (high yielding aquifer)
200-500	Highly weathered fractured basalt	Less saturated and water bearing (low yielding aquifer)
500-1000	Weathered basalt	Dry to slightly water bearing
1000- 5000	Slightly fractured dry and fresh basalt	dry
5000	Basalt basement rock	Very dry.

(Modified from WWDSE, 2007)

Analysis and interpretation of the resistivity results generated mean, minimum and maximum aquifer thickness, depth, head elevation, porosity and transmissivity summarized in Table 6 and appendix 4. The results showed that the watershed have a thick water bearing layer with a mean depth and thickness of 48.30m and 32.09m respectively.

Table 6: Summary of hydro geological characteristics of the water bearing layer in the LCW

Hydrogeological characteristics	Minimum	Maximum	Mean
Resistivity	42.6 ohm	182 ohm	93.17 ohm
Depth	0.8m	142m	48.30m
Thickness	0.8m	91m	32.09m
Aquifer elevation	507masl	1017.03masl	798.87masl
Transmissivity	0.00024m^2/day	0.0273m^2/day	0.00963m^2/day
Porosity	23%	49%	35%

The characteristic depict a high yielding aquifer that slopes from North West to South East with the minimum, maximum and mean slopes being 0^0, 10.66^0 and 1.17^0 respectively. This enables free flow of groundwater through the aquifer. In Figure 20, the highest elevations occur to the North West of the lake while the lowest elevations occur to the South East of Lake.

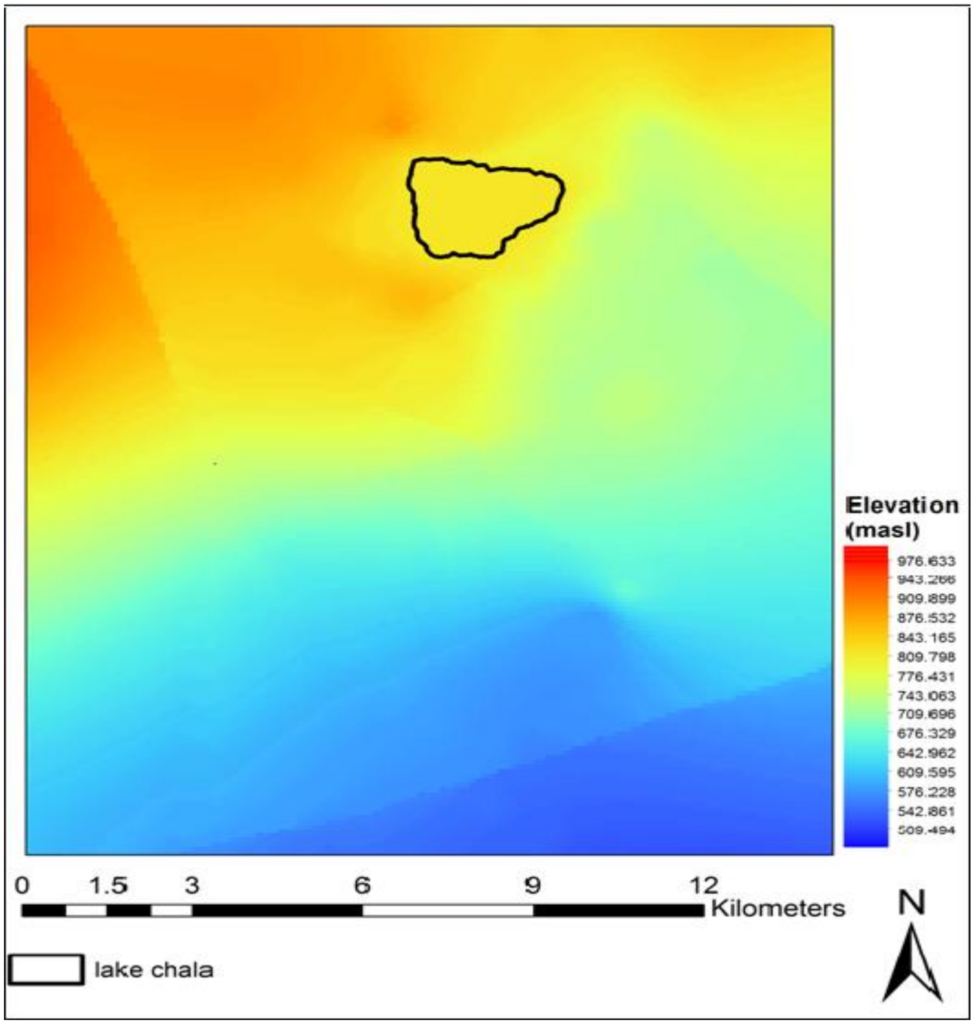

Figure 20: Aquifer bottom layer

The transmissivity and porosity revealed an aquiferous layer that is made up of highly weathered ryholite to moderately weathered basalt and volcanic ash. The hydro geological characteristics are a clear indication of a high yielding aquifer that is recharged from the slopes of Mount Kilimanjaro and discharges further below Lake Chala as illustrated in (Figure 20).

4.3 Groundwater potential of the Lake Chala watershed

Flow direction and accumulation show the accumulated weight of all cells flowing into each down slope cell. Figure 21 illustrates flow direction and accumulation using watershed stream networks. High accumulation occurs downstream while low accumulation occurs upstream. Accumulation increases downstream as more and more stream converge into one stream with a defined flow direction. The watershed stream networks indicate the water divide for the groundwater flow and thus are important for the delineation of the ground watershed defined as the area that appears, on the basis of elevation, to contribute all the water that passes through a given cross section of a stream. Figure 21 shows that there is a direct flow accumulation into the lake running from the North West and Western side of the lake and out of the lake running from South eastern side of the lake. The watershed stream networks form a defined watershed for the lake Chala groundwater flow.

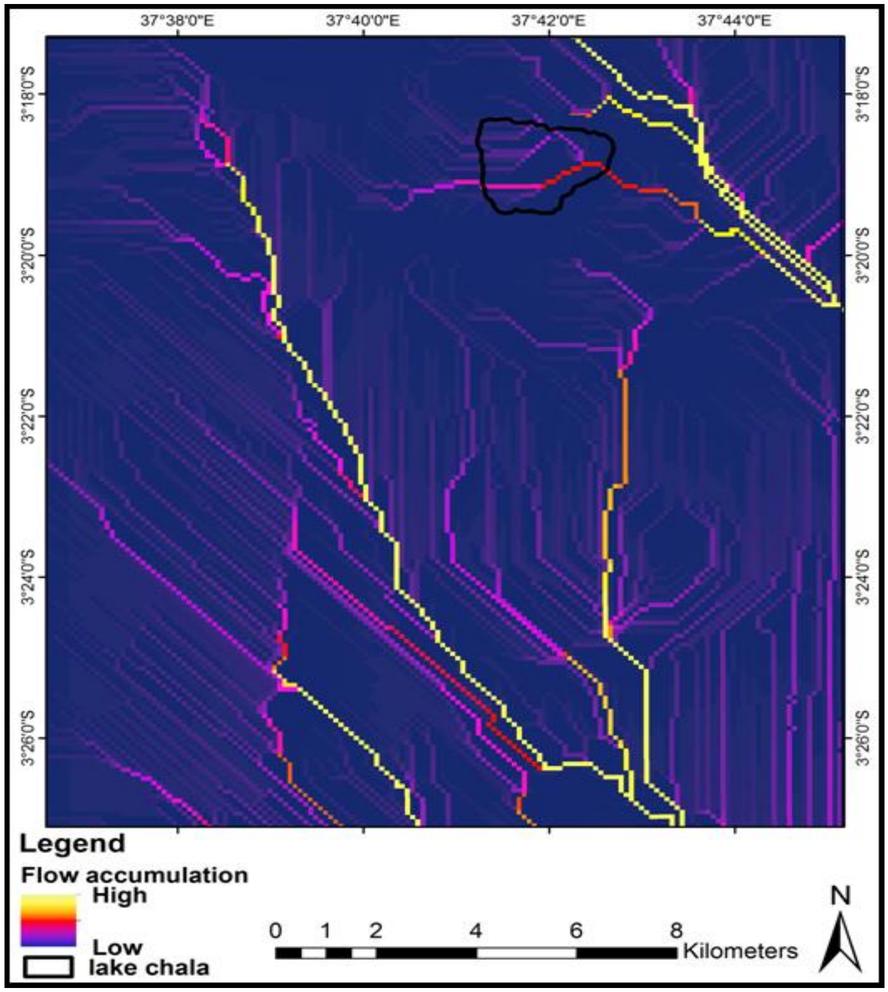

Figure 21: Groundwater flow accumulation map

The watershed which contain the recharge and discharge aquifer as indicated by the (Figure 22) formed around the Lake extending from the North Western side of the lake to South Eastern side of the lake. Based on the elevation, flow accumulation and flow direction, the part occurring on the North West of the Lake form the recharge zone, while the one occurring on the Southeastern part form the discharge zone. Water to and from the lake is through free flow and is facilitated by the porosity and transmissivity ranges defined in Table 6. The recharge occurs at mean elevation of 809 and discharges at a mean elevation of 743 meters above sea level. In agreement Grossmann (2005), the study investigation as illustrated in figure 22 reveal that groundwater within the Lake Chala watershed occurs in a localized aquifer. Similar results by Alker, et al., (2008) found out that occurrence of groundwater within Kilimanjaro aquifer was limited to faults, fractures and small parts of weathered zones. The results of this study confirm that the Lake Chala formed from a localized aquifer facilitated by high permeability of the highly weathered ryholite to moderately weathered basalt and volcanic ash.

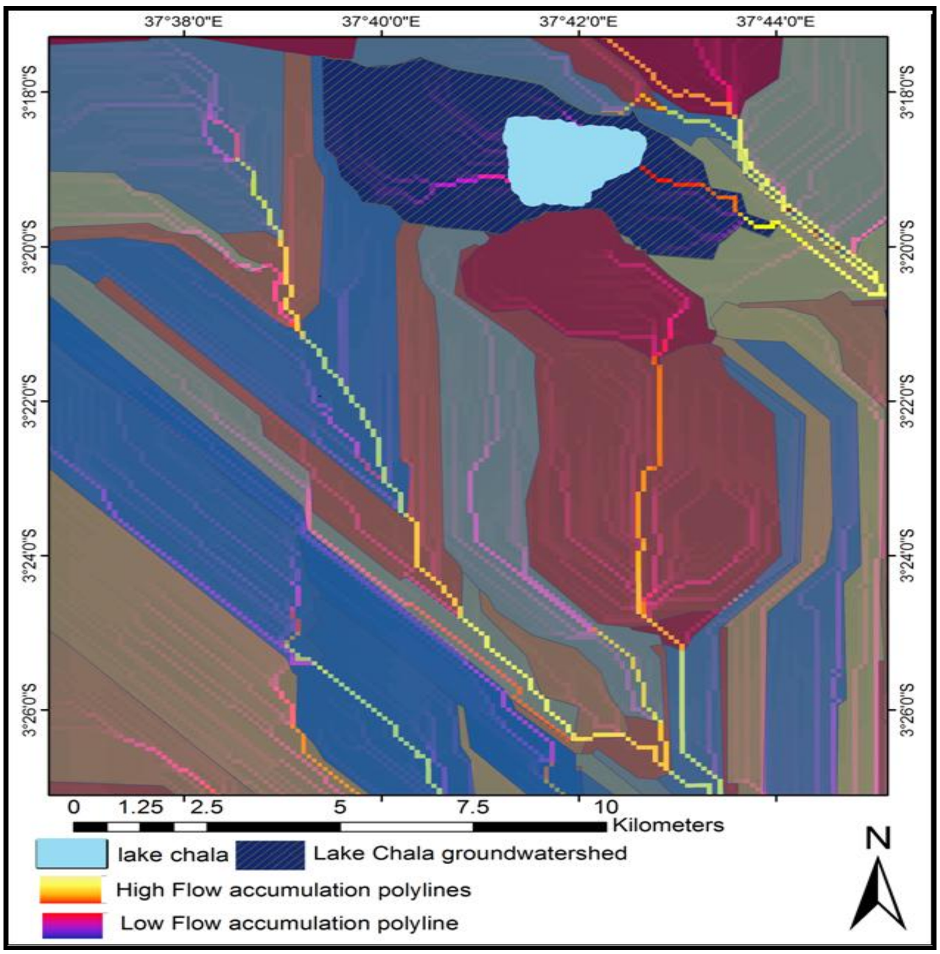

Figure 22; groundwater flow accumulation and watershed

The integration of hydrogeological characteristics namely aquifer bottom elevation, effective formation porosity and formation transmissivity generated from geophysical survey into Geographical Information Systems (GIS) is one of the most accurate and reliable methods of modeling and quantifying groundwater flow. Figure 23 shows the groundwater flow model of Lake Chala watershed generated from aquifer bottom elevation, effective formation porosity and formation transmissivity.

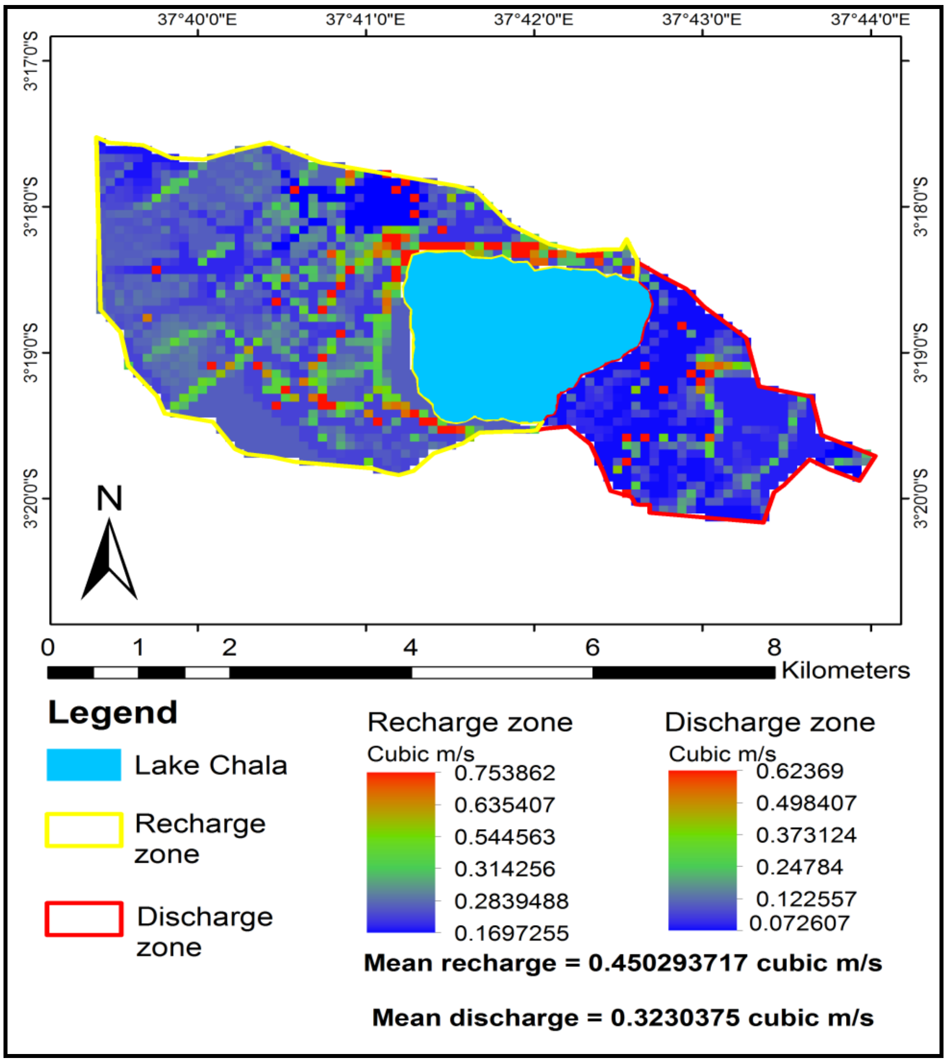

Figure 23: Lake Chala watershed Groundwater model

The Lake Chala ground watershed covers an area of 23.6km^2 with the recharge zone covering 13.85 km^2, the discharge zone covering 5.55km^2 and the lake covering an area of 4.2 km^2. The mean groundwater flow within the Lake Chala ground watershed was estimated at 0.45m^3/s (recharge) and 0.32m^3/s (discharge); equivalent to mean annual recharge and discharge of 14.28Mm^3/year and 10.16Mm^3/year respectively. The Lake Chala recharge and discharge results of this study was found to be close to (Payne, 1970) study results of 1967 which estimated mean annual groundwater inflow and outflow within the Lake Chala watershed to be 12.5 million m^3 and 8.2 million m^3 respectively.

CHAPTER FIVE

CONCLUSION AND RECOMMEDATION5.1 Conclusion

The research revealed that Lake Chala watershed is composed of high groundwater potential zones and that the occurrence, movement and storage of groundwater in Lake Chala watershed are controlled by a combination of factors such as rainfall, geological structures, land cover/use, drainage density and slope. The groundwater potential map depicts the high potential zone because of suitable surface and subsurface conditions like occurrence of high drainage density, permeable aquifers and nearness to streams that create conducive environment for higher water yield as well as favorable discharge. Low potential zones include rocky areas, which act as runoff zones and have deep and low yielding aquifers. The results further showed that GIS and Remote Sensing; provide a fast, cost effective and less time consuming assessment of occurrence, movement and storage of groundwater resources. Remote sensing based groundwater prospect zone map serves as a base for further exploration using hydro geological and geophysical methods. GIS and Remote Sensing are powerful tools in identifying the occurrence and understanding of groundwater systems which would provide firsthand information to students, researchers, local authorities, engineers, hydrogeologists and planners about the areas suitable for further groundwater exploration. GIS and Remote Sensing are realistic approach and therefore may be used for the optimum utilization of groundwater resources, preparation of better management plans and in protection and conservation of groundwater resources.

The analysis of vertical electrical sounding results showed that lake chala watershed was composed of high yielding water bearing aquifer that is made up of highly weathered ryholite to moderately weathered basalt and volcanic ash. This layer consists of recharge and discharge layer that run from North west side and South East side of the lake respectively. The layer covers an area of 23.6km^2 with the recharge zone which contain recharge aquifer covering an area of 13.85 km^2, the discharge zone which contain discharge aquifer covering an area of 5.55km^2 and the lake covering an area of 4.2 km^2 respectively. The mean recharge groundwater flow of the water bearing layer within the Lake Chala ground watershed was estimated at 0.45m^3/s and 0.32m^3/s (discharge); equivalent to mean annual recharge and discharge of 14.28M m^3/year and 10.16Mm^3/year respectively. The study has therefore shown that Vertical electrical sounding (VES) technique of the electrical resistivity method has proven to be successful and highly effective in determining the hydrogeological characteristics of the water bearing layers within Lake Chala watershed. The study has also shown that the watershed consist of a high yielding aquifer which is composed of volcanic ash and basaltic which are highly permeable, have high water retention capacity and are good groundwater potential zones. The VES surveys in conjunction with the GIS have been successful used to locate the lake chala watershed groundwater bearing layers which are responsible for recharging and discharging Lake chala as well as quantifying the amount of water from each water bearing layer.

5.2 Recommendation

Realizing that the groundwater potential in the lake chala watershed is dependent on precipitation patterns, lithology, land use and topography, this study recommends the following;

Creating public awareness on soil and water conservation degradation of the soils and vegetation cover within Lake Chala watershed is likely to adversely affect groundwater recharge. There is need therefore to ensure that natural forest and soils are conserved

The occurrence of extreme and erratic weather events is likely to cause adverse impacts on groundwater recharge. Changes in precipitation and prolonged dry spells are likely to affect the recharge capacity of the lake chala watershed. There is need therefore to integrate mechanisms for climate change mitigation to ensure that the processes of recharge and discharge are balanced.

GIS and Remote Sensing techniques is a powerful tool that help in locating groundwater potential areas. It also minimizes the areas where detail groundwater exploration activities are to be carried out to study sub surface aquifer condition through geophysical investigations. I therefore recommend the application of these techniques in other areas.

The Vertical Electrical Sounding survey has the potential to provide reasonable accurate results that can be used to understand the subsurface layers in groundwater exploration and should be applied in other areas for groundwater explorations

5.3 Further studies

Other methodology like horizontal electrical profiling two dimensional (2D) and three dimensional 3D should be carried out to further study the water bearing layer within lake Chala watershed

Other methodology like isotopes should be employed in future works for analysis of groundwater flow system along the corridor to confirm the output of this work.

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APPENDICES

Appendix 1: Resistivity Survey Sheet

Location ____

VES Ref ___________ Operator___________ Date ___________Mapsheet__________

Coord   X :___________Y:___________ Azimuth__________ Elevation ____________

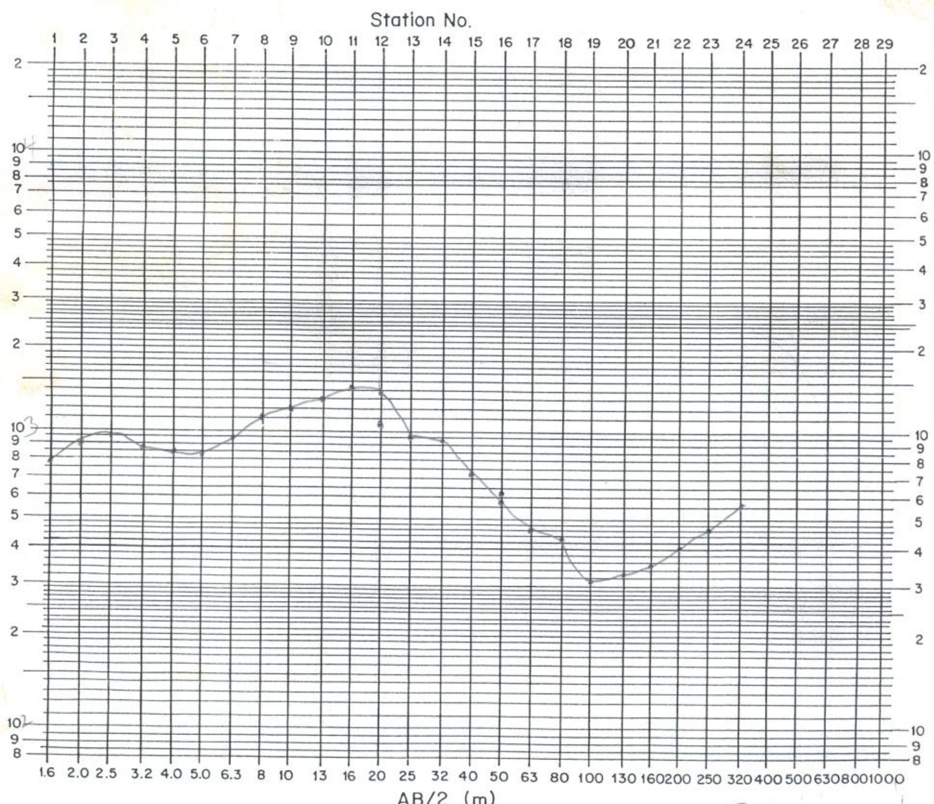
MN/2	AB/2	K	ΔV/I	ρ
0.5	1.6	7.26		
0.5	2.0	11.8		
0.5	2.5	18.8		
0.5	3.2	31.4		
0.5	4.0	49.5		
0.5	5.0	77.8		
0.5	6.3	124		
0.5	8.0	200		
0.5	10	313		
0.5	13	530		
0.5	16	803		
0.5	20	1260		
0.5	25	1960		
0.5	32	3220		
10	32	145		
10	40	236		
10	50	377		
10	63	608		
10	80	990		

10	100	1560		
10	130	2640		
10	160	4010		
10	200	6270		
25	250	9800		
25	250	3890		
25	320	6370		
25	400	10000		
25	500	15700		

Appendix 2: Sample of Field Resistivity Curves

Location: Kalambani Date: 16/01/2013
Mapsheet: ______ Coord. X: 0357916 Y: 9636777 Azimuth: E-W
VES/Profile No: Ves 2 Station interval: ______ m Operator: Beatrice Wambui

MN/2	AB/2	K	ΔV / I	ρ	MN/2	AB/2	K	ΔV / I	ρ	MN/2	AB/2	K	ΔV / I	ρ
0.5	1.6			797.2		25			981.2		320			567
	2.0			900.3		32			914.6					
	2.5			977.8		40			746.6					
	3.2			877.1	5	50			630.0					
	4.0			852.6	10	50			570.5					
	5.0			867.7		63			478.3					
	6.3			980.7		80			418.1					
	8.0			1126.1	10	100			341.3					
	10			1212.3	25	100			334.4					
	13			1327.3		130			322.1					
	16			1344.5		160			354.0					
0.5	20			1309.0		200			402.1					
5	20			1014.9		250			466.8					

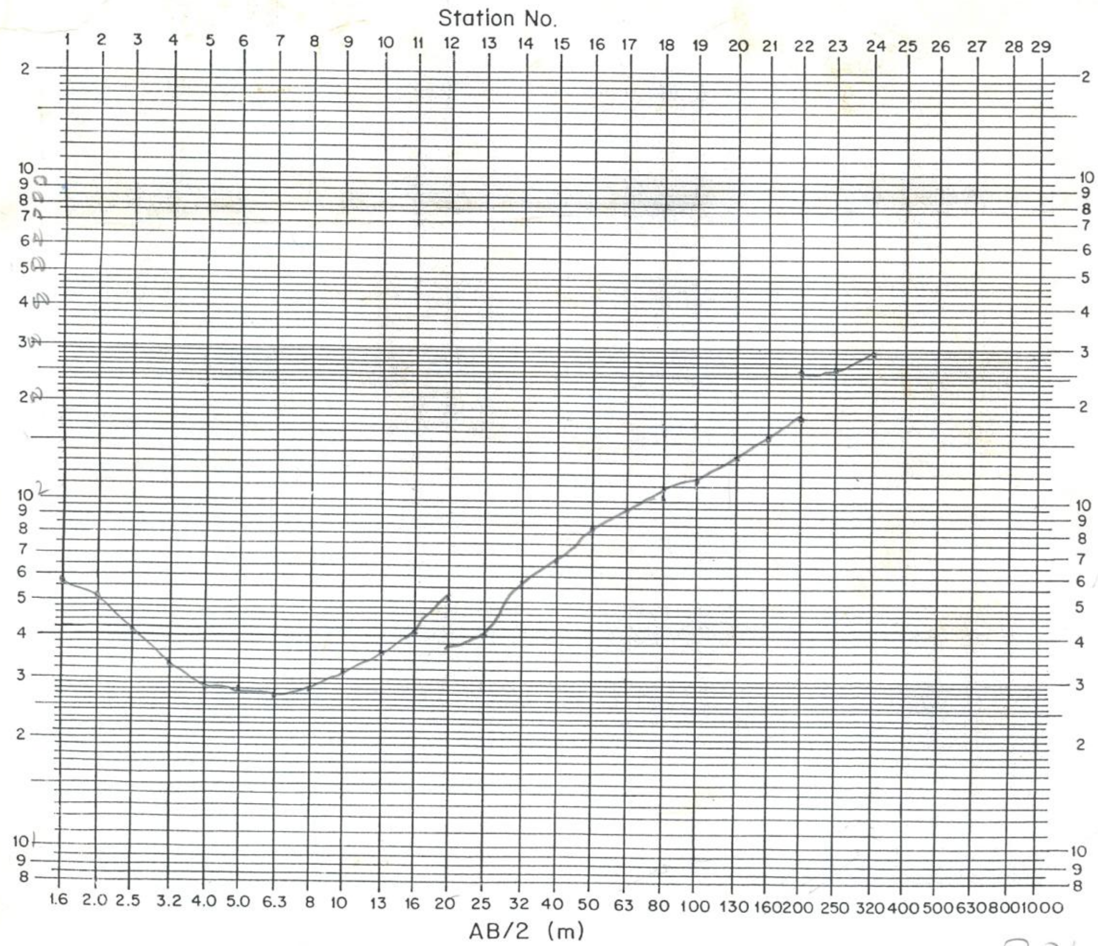


Location: KiLANGA Date: 16/01/2013

Mapsheet: ______ Coord. X: 0356339 Y: 9636594 Azimuth: NE SW

VES/Profile No: VES 1 Station interval: ______ m Operator: Beatrice Wambui

MN/2	AB/2	K	ΔV / I	ρ	MN/2	AB/2	K	ΔV / I	ρ	MN/2	AB/2	K	ΔV / I	ρ
0.5	1.6			57.2	5.0	25			45.3		320			294.7
	2.0			50.4		32			57.3					
	2.5			42.8		40			69.0					
	3.2			33.8		50			83.4					
	4.0			28.7		63			95.3					
	5.0			28.2	5.0	80			106.3					
	6.3			27.4	10	80			107.3					
	8.0			28.8		100			115.8					
	10			31.7		130			135.9					
	13			36.0		160			154.5					
	16			41.5	10	200			192.6					
0.5	20			50.3	25	200			246.1					
5.0	20			37.0		250			267.8					



30

Waypoint 017   03° 21' 00.5" S   037° 40' 46.6' E

ELEV 892M

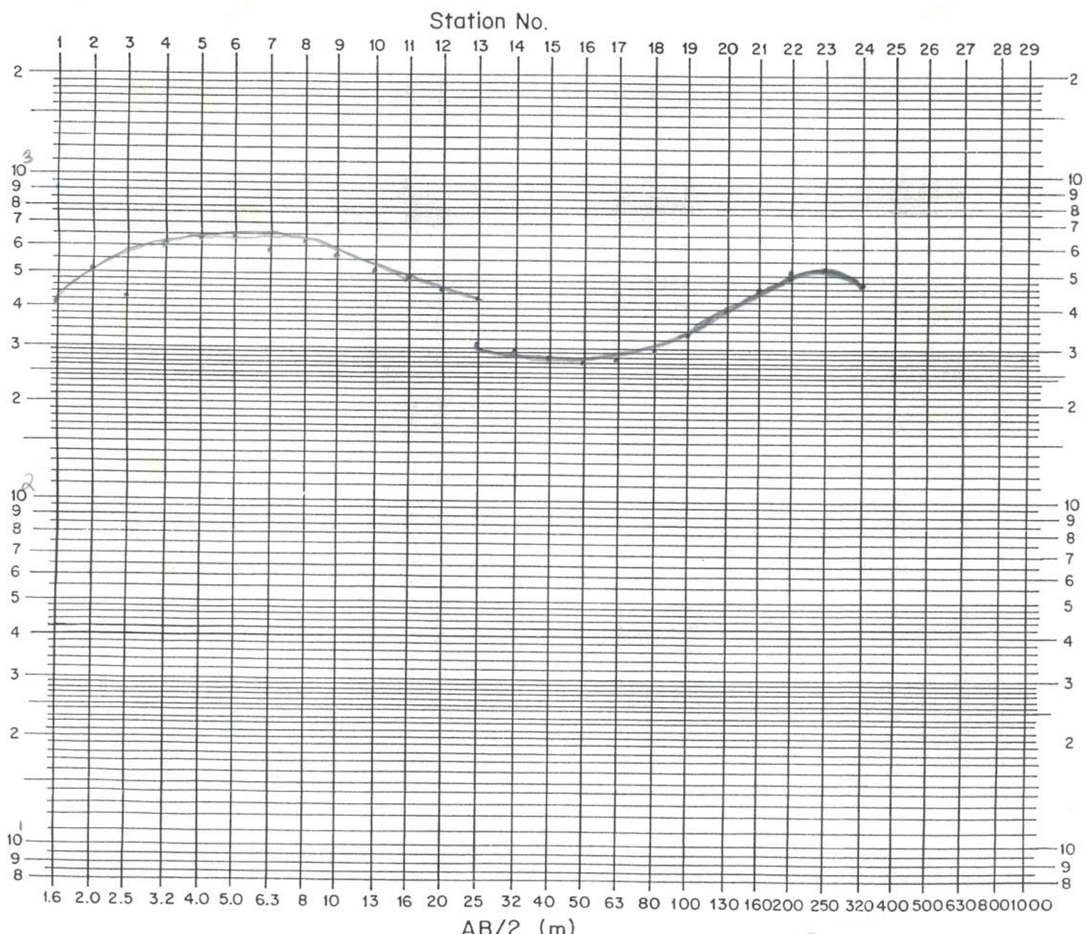
RESISTIVITY SURVEY

Location: Mamsera Kitondoni (TZ)   Date: 11/01/2013

Mapsheet: Coord. X: 0352968 Y: 9630103   Azimuth: E - W

VES/Profile No: VES 4   Station interval: ______ m   Operator: Beatrice Wambui

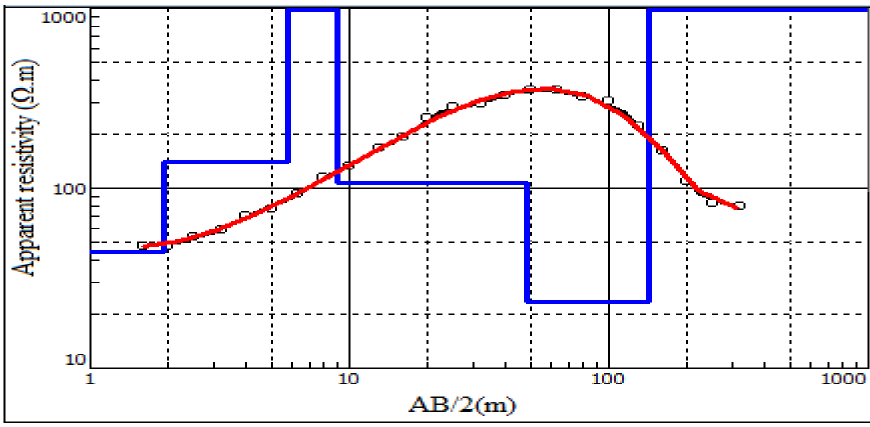
MN/2	AB/2	K	ΔV / I	ρ	MN/2	AB/2	K	ΔV / I	ρ	MN/2	AB/2	K	ΔV / I	ρ
0.5	1.6			410.7	5	25			313.4					
	2.0			501.4		32			295.7					
	2.5			426.9		40			277.0					
	3.2			609.6		50			274.6					
	4.0			625.4		63			277.1					
	5.0			642.7		80			297.4					
	6.3			596.2		100			331.7					
	8.0			635.2		130			399.3					
	10			559.4		160			455.6					
	13			503.7	5	200			503.2					
	16			496.6	10	200			495.2					
	20			453.3		250			538.0					
0.5	25			424.2		320			464.0					



Appendix 3: Modeled Electrical Resistivity Curves

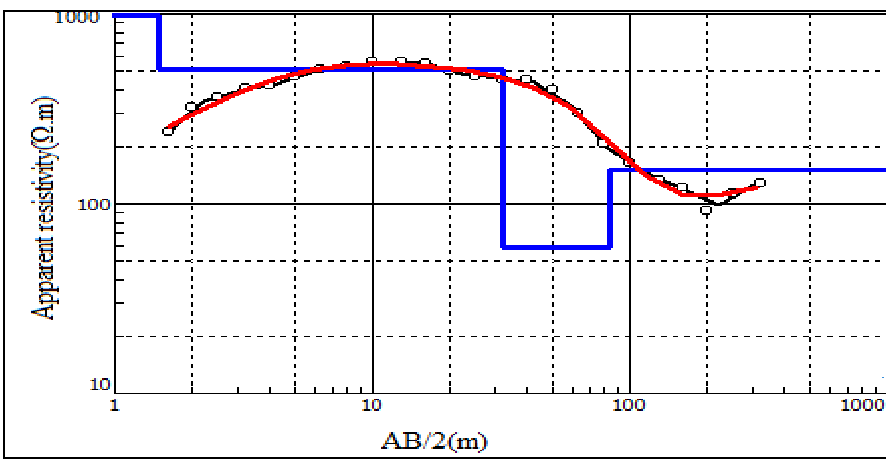
The black circles represent the measured data, red line represents the calculated data and the blue line represents the interpreted resistivity sections, N is the number of layers, ρ is the apparent resistivity, h is the thickness and d is the depth to interface of each layer.

VES.1



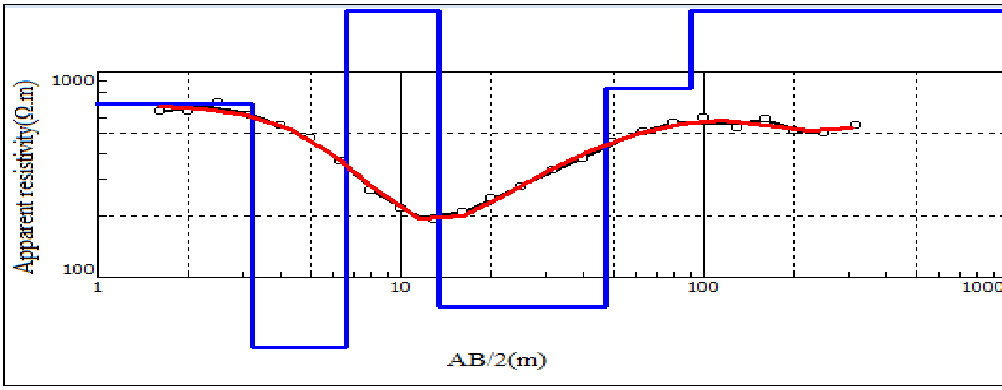
N	ρ	h	d
1	44.1	1.94	1.94
2	141	3.8	5.74
3	5785	3.32	9.06
4	107	39.4	48.5
5	23.2	93.8	142
6	2280		

VES.2



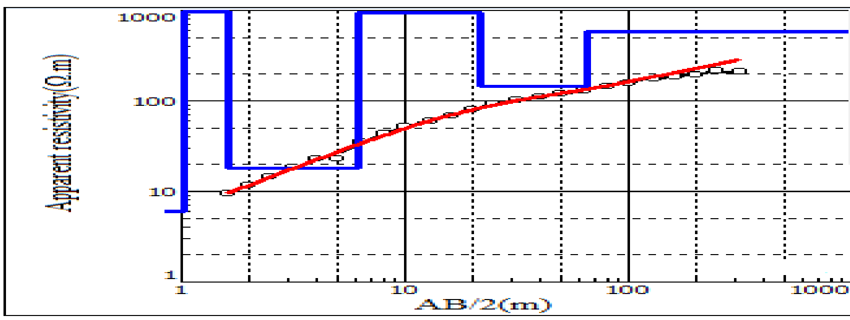
N	ρ	h	d
1	162	0.896	0.896
2	2380	0.588	1.48
3	509	30.7	32.2
4	59.1	50.9	83.1
5	149		

VES.3



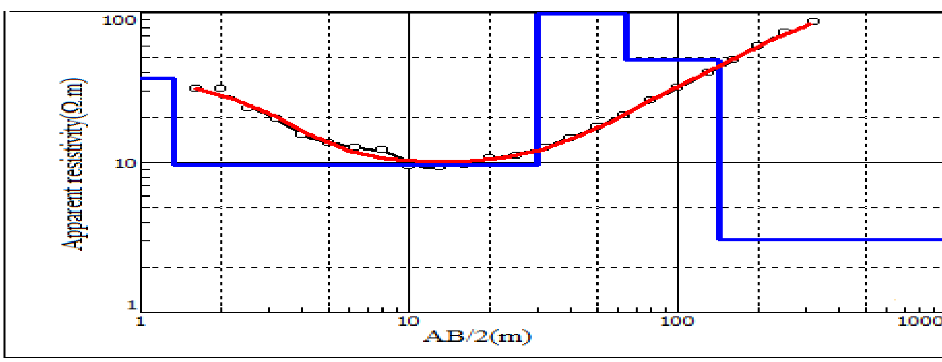
N	ρ	h	d
1	696	3.21	3.21
2	45.3	3.38	6.59
3	7942	6.76	13.4
4	71.8	34.5	47.8
5	830	43.1	90.9
6	4769		

VES.4



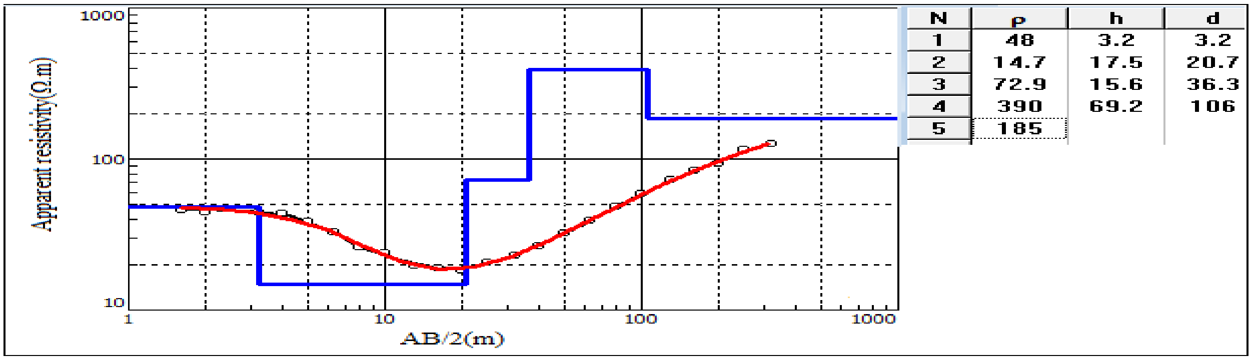
N	ρ	h	d
1	6.03	1.04	1.04
2	4507	0.572	1.61
3	18.2	4.64	6.25
4	941	15.6	21.9
5	144	42.9	64.8
6	585		

VES.5



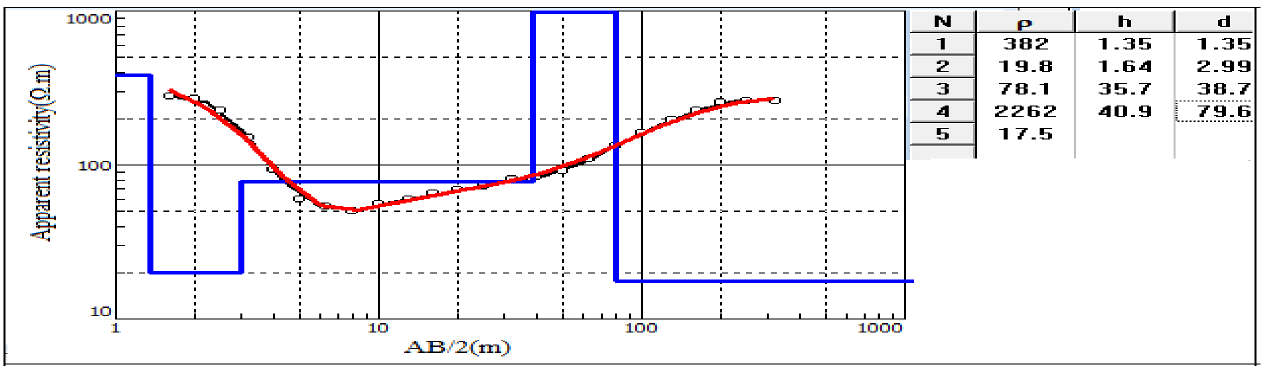
N	ρ	h	d
1	36.4	1.33	1.33
2	9.58	28.5	29.8
3	3261	34.2	64
4	48.7	77.7	142
5	3.07		

VES.6



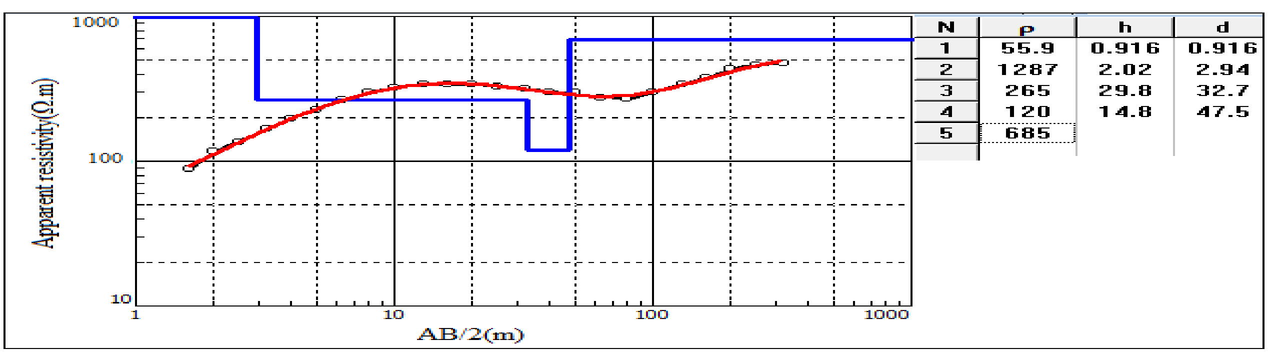
N	ρ	h	d
1	48	3.2	3.2
2	14.7	17.5	20.7
3	72.9	15.6	36.3
4	390	69.2	106
5	185		

VES.7



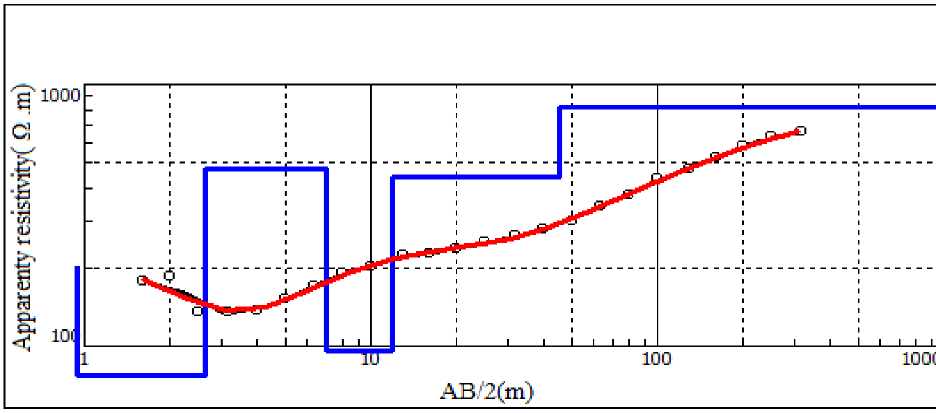
N	ρ	h	d
1	382	1.35	1.35
2	19.8	1.64	2.99
3	78.1	35.7	38.7
4	2262	40.9	79.6
5	17.5		

VES.8



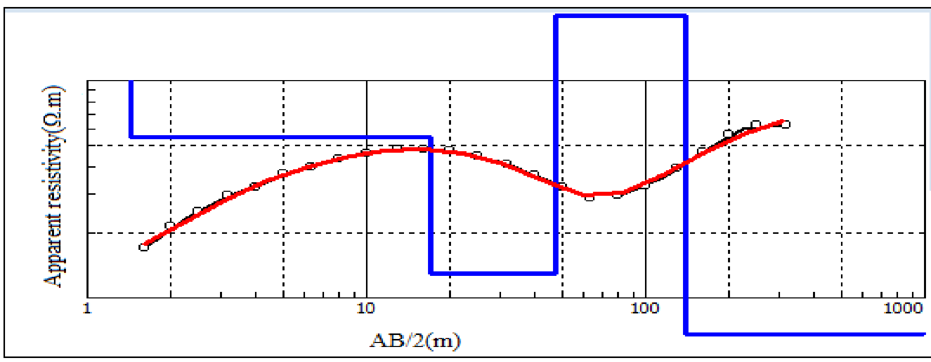
N	ρ	h	d
1	55.9	0.916	0.916
2	1287	2.02	2.94
3	265	29.8	32.7
4	120	14.8	47.5
5	685		

VES.9



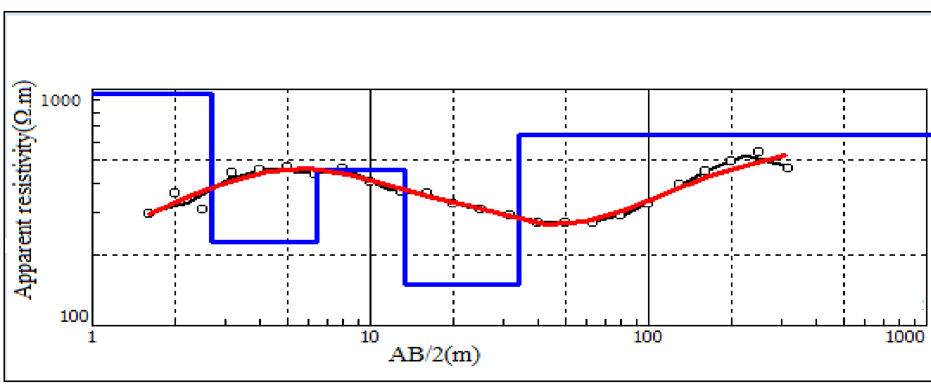
N	ρ	h	d
1	232	0.95	0.95
2	77.6	1.68	2.63
3	476	4.36	6.98
4	95.3	4.97	12
5	441	33.5	45.5
6	823		

VES.10



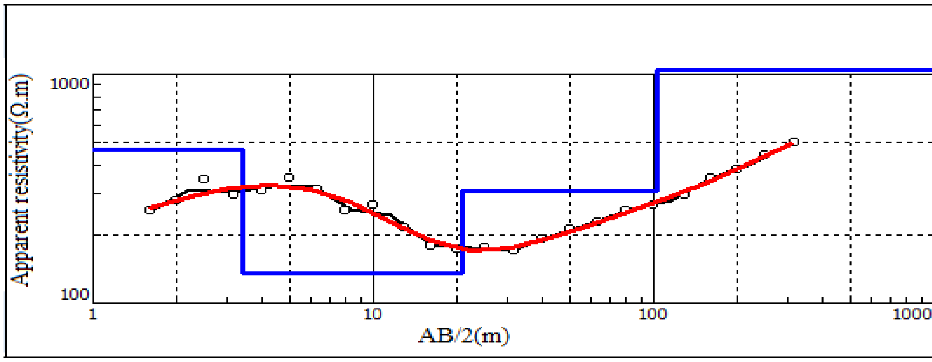
N	ρ	h	d
1	105	0.845	0.845
2	1622	0.594	1.44
3	545	15.6	17
4	130	30.8	47.8
5	3316	91.5	139
6	68.1		

VES.11



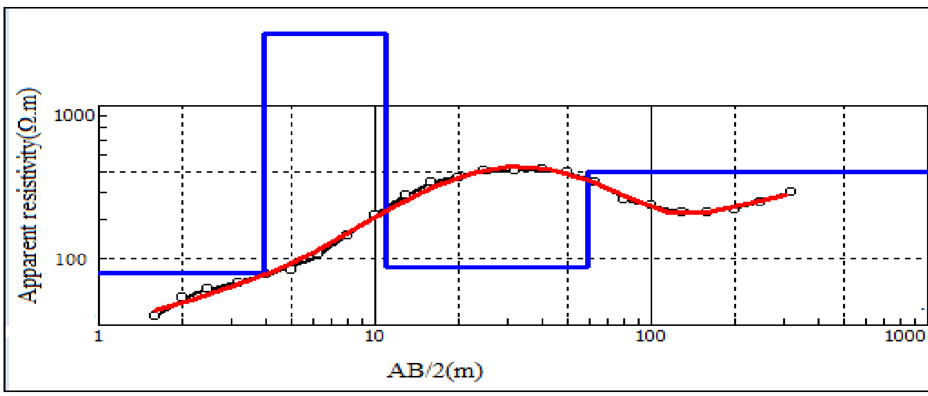
N	ρ	h	d
1	213	0.927	0.927
2	960	1.77	2.7
3	226	3.68	6.38
4	455	6.91	13.3
5	150	20.9	34.2
6	642		

VES.12



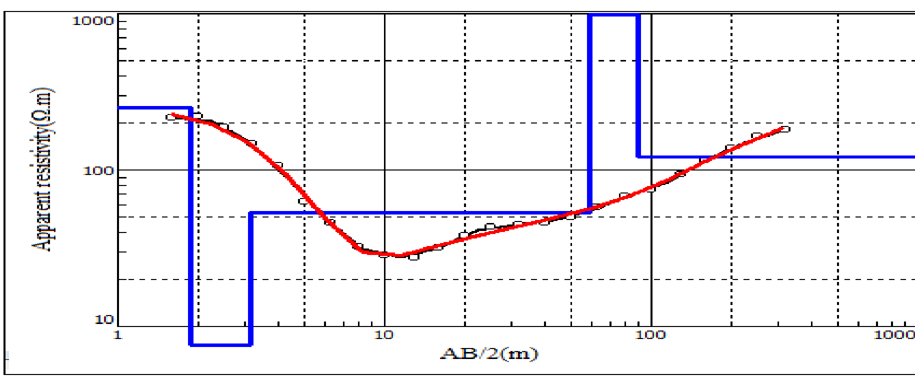
N	ρ	h	d
1	200	0.8	0.8
2	470	2.63	3.43
3	136	17.2	20.6
4	309	82.6	103
5	1043		

VES.13



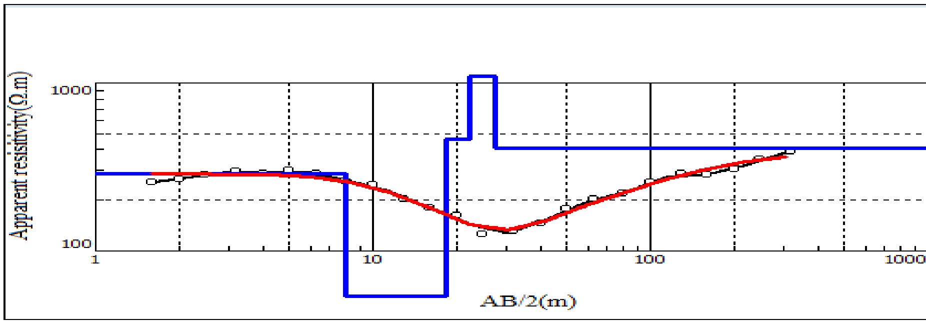
N	ρ	h	d
1	92.4	0.8	0.8
2	173	3.14	3.94
3	2122	6.96	10.9
4	184	47.9	58.8
5	497		

VES.14



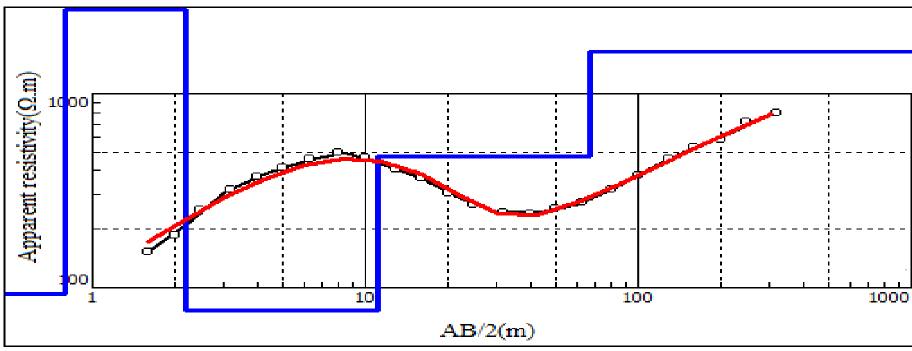
N	ρ	h	d
1	251	1.87	1.87
2	5.48	1.28	3.15
3	53.4	55.3	58.5
4	4406	30.5	88.9
5	122		

VES.15



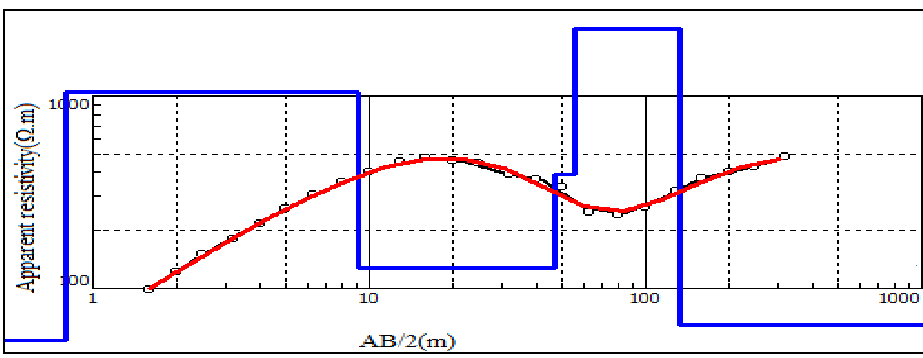
N	ρ	h	d
1	289	7.92	7.92
2	53.8	10.4	18.3
3	461	4.12	22.4
4	1097	5	27.4
5	411		

VES.16



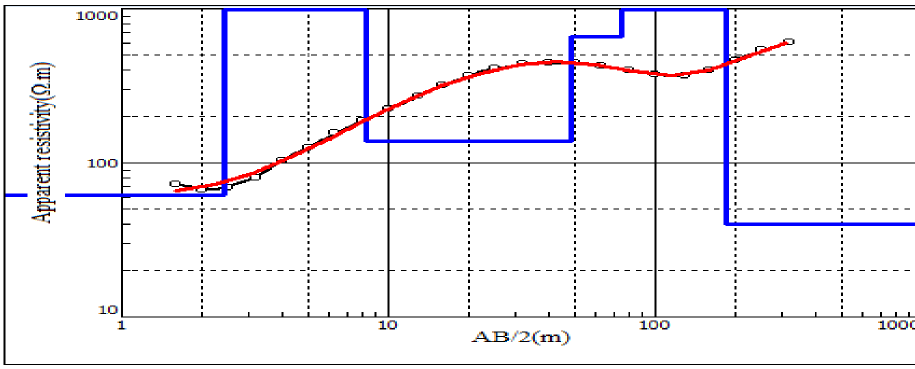
N	ρ	h	d
1	92.4	0.8	0.8
2	2957	1.39	2.19
3	76	9.01	11.2
4	473	55	66.2
5	1642		

VES.17



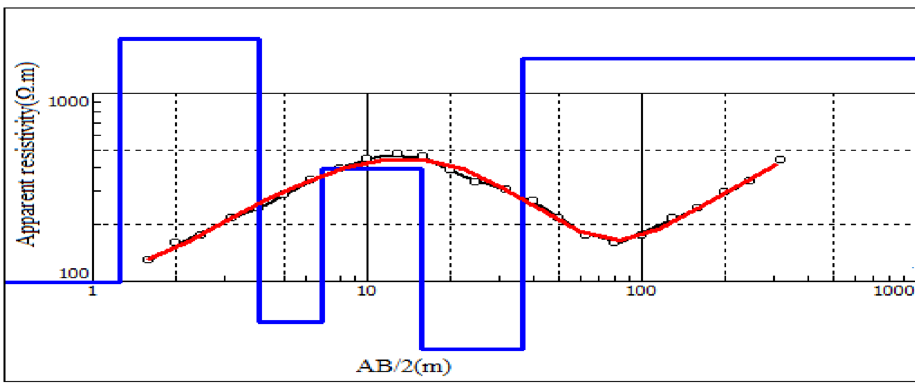
N	ρ	h	d
1	53.9	0.8	0.8
2	1039	8.29	9.09
3	127	37.5	46.6
4	389	8.41	55
5	2223	77.8	133
6	64.2		

VES.18



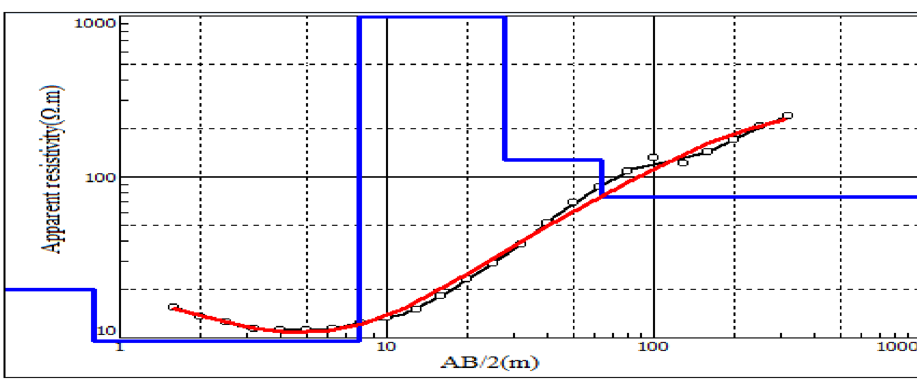
N	ρ	h	d
1	61.8	2.41	2.41
2	2713	5.83	8.24
3	139	40.6	48.8
4	656	25.8	74.6
5	4185	111	186
6	39.8		

VES.19



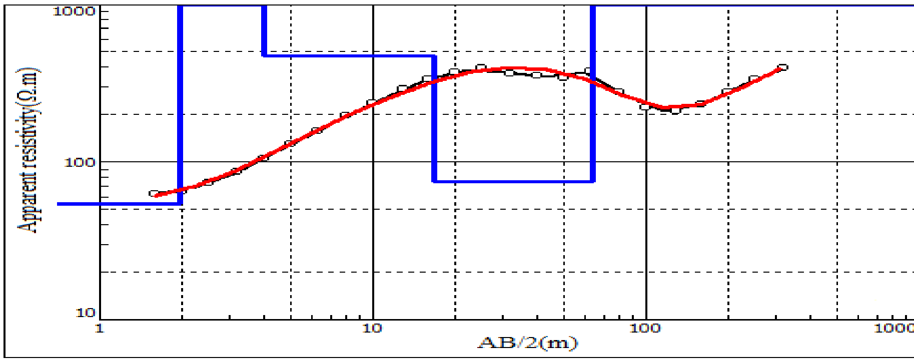
N	ρ	h	d
1	98.1	1.26	1.26
2	1937	2.79	4.05
3	60.7	2.76	6.81
4	394	8.92	15.7
5	43.5	20.9	36.6
6	1528		

VES.20



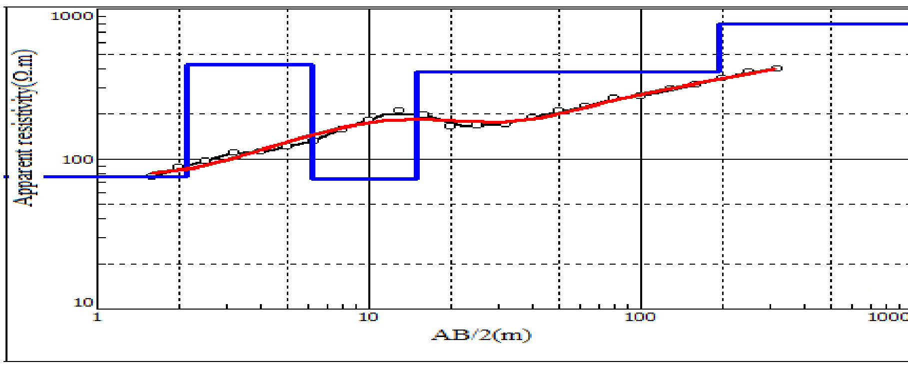
N	ρ	h	d
1	19.8	0.8	0.8
2	9.46	7.11	7.91
3	1404	4.83	12.7
4	5511	14.8	27.6
5	128	36.2	63.8
6	75		

VES.21



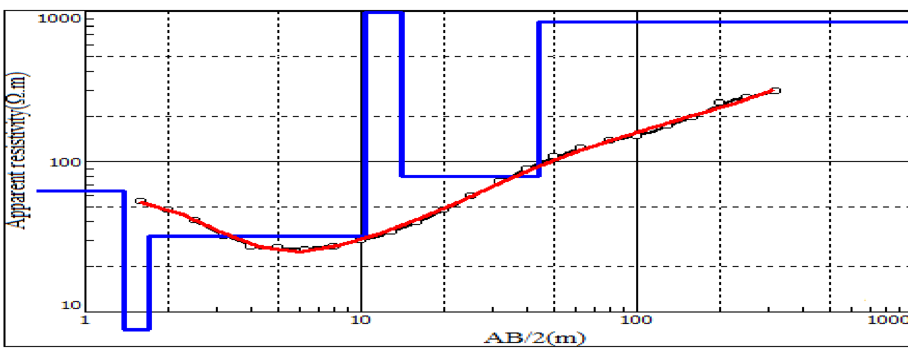
N	ρ	h	d
1	54.2	1.96	1.96
2	3734	2.05	4.01
3	470	12.6	16.6
4	75.3	46.6	63.2
5	2392		

VES.22



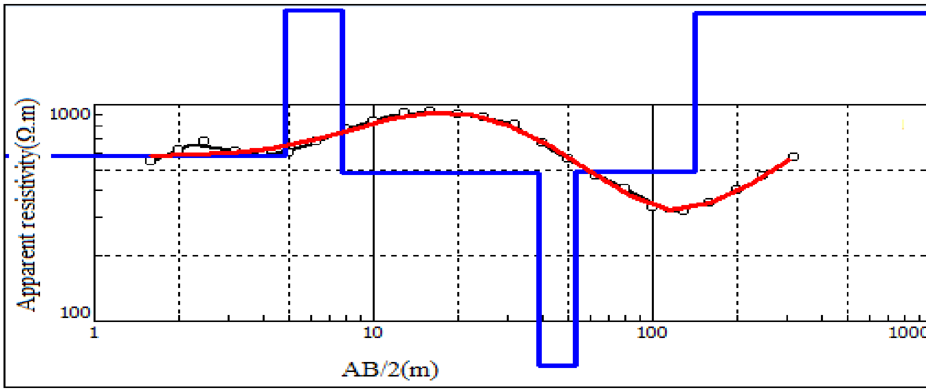
N	ρ	h	d
1	75.7	2.12	2.12
2	424	4.07	6.19
3	73.3	8.76	15
4	378	177	192
5	802		

VES.23



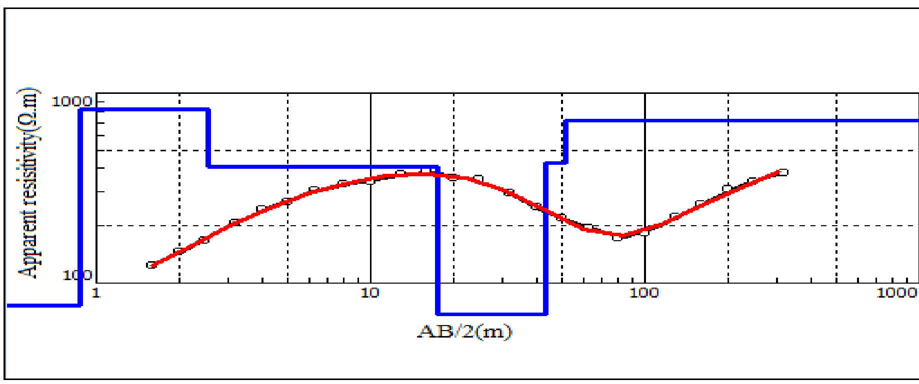
N	ρ	h	d
1	63.7	1.39	1.39
2	3.21	0.319	1.71
3	31.7	8.64	10.4
4	3342	3.62	14
5	80.1	29.9	43.9
6	854		

VES.24



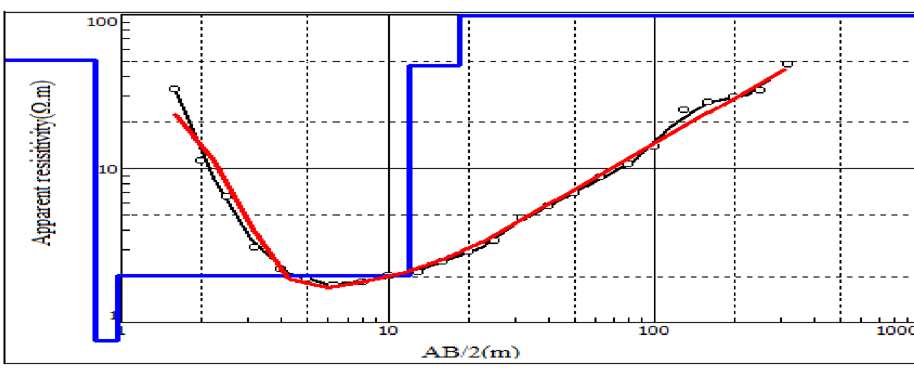
1	579	4.81	4.81
2	3523	2.9	7.72
3	482	31.7	39.4
4	62.2	13.8	53.1
5	493	87.9	141
6	2623		

VES.25



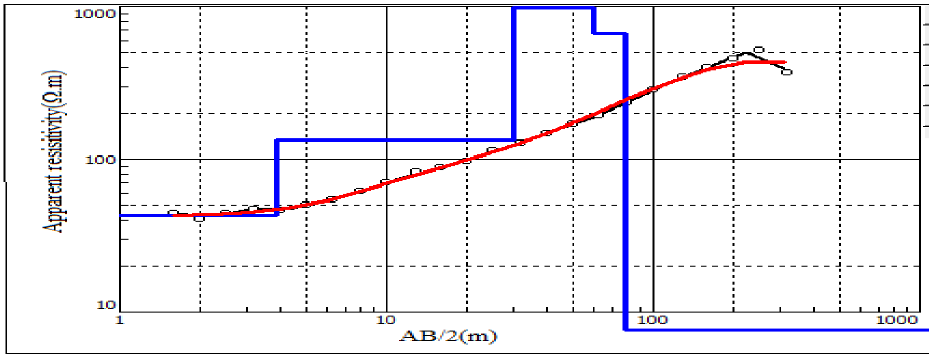
N	ρ	h	d
1	75.6	0.878	0.878
2	817	1.67	2.55
3	411	15	17.5
4	68.1	25.9	43.4
5	427	7.64	51.1
6	712		

VES.26



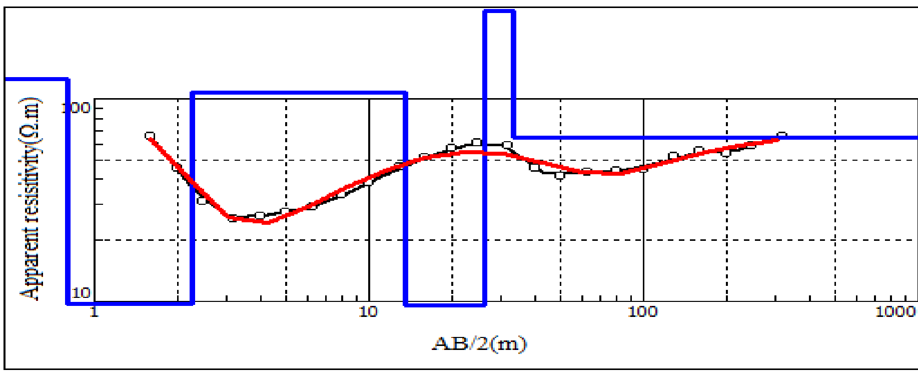
N	ρ	h	d
1	51.2	0.8	0.8
2	0.129	0.163	0.963
3	2.03	11	12
4	46.9	6.52	18.5
5	1854		

VES.27



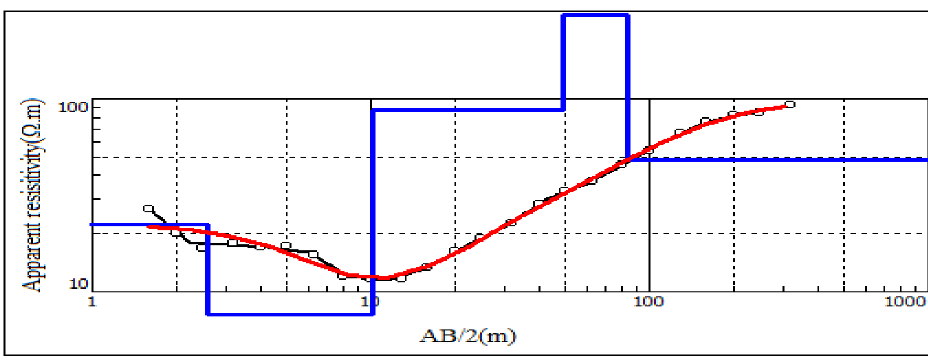
N	ρ	h	d
1	42.5	3.89	3.89
2	133	25.8	29.7
3	4072	30.5	60.2
4	665	18.5	78.7
5	4.03		

VES.28



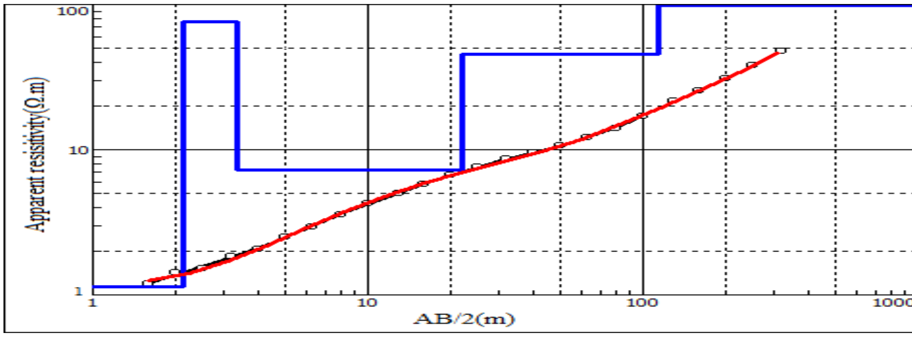
N	ρ	h	d
1	125	0.8	0.8
2	9.77	1.45	2.25
3	108	11.3	13.6
4	9.56	13	26.5
5	531	7.29	33.8
6	64.2		

VES.29



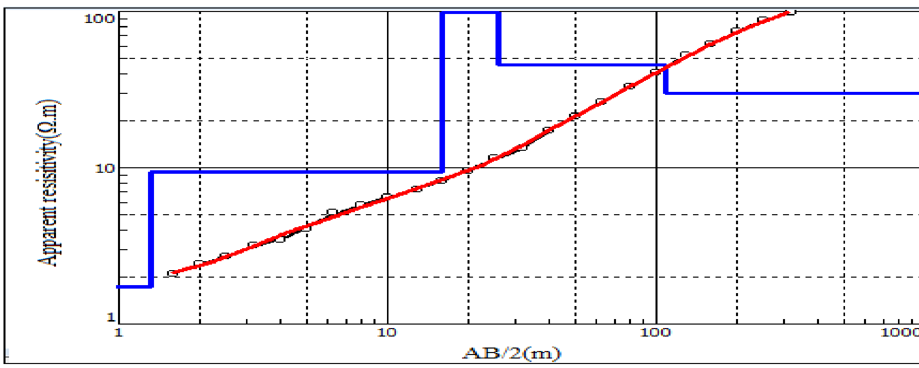
N	ρ	h	d
1	22.2	2.6	2.6
2	7.59	7.61	10.2
3	87.4	38.6	48.8
4	535	34.7	83.5
5	48.1		

VES.30



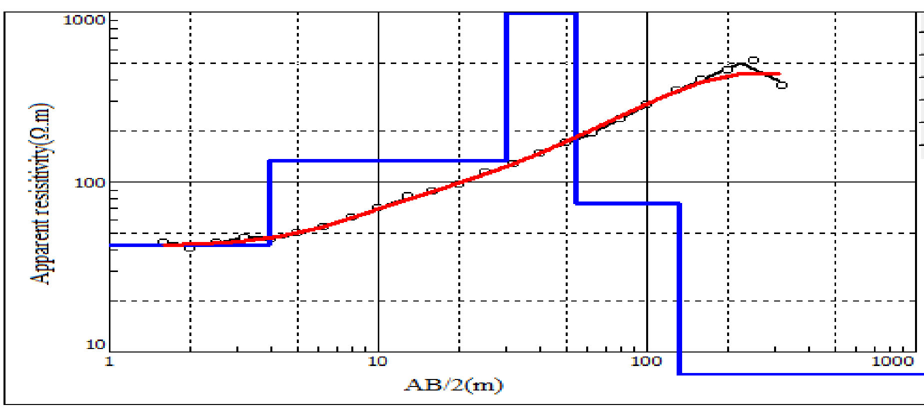
N	ρ	h	d
1	1.14	2.12	2.12
2	75.6	1.21	3.33
3	7.28	18.8	22.1
4	45.1	91	113
5	1365		

VES.31



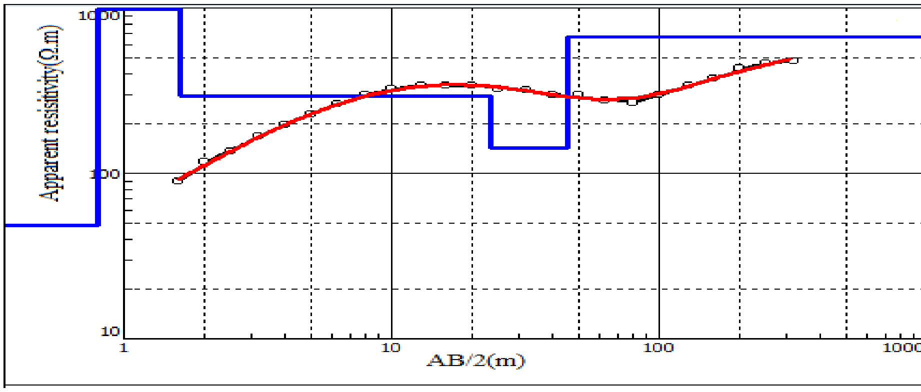
N	ρ	h	d
1	1.74	1.32	1.32
2	9.38	14.7	16
3	7884	9.97	26
4	45.5	82.7	109
5	29.7		

VES.32



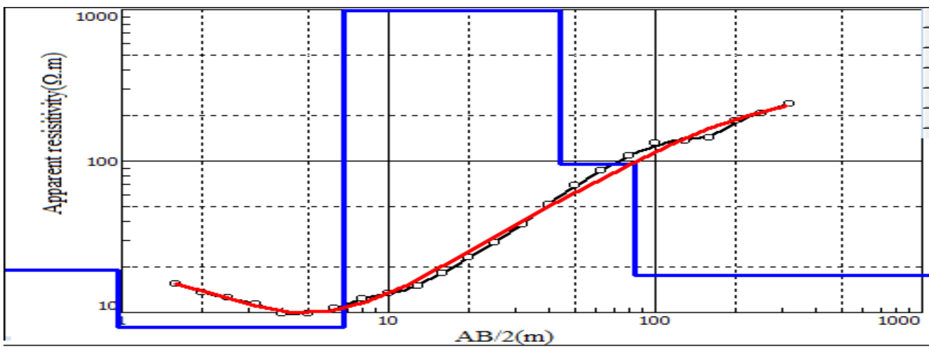
N	ρ	h	d
1	42.5	3.92	3.92
2	134	26.1	30
3	5328	24.5	54.5
4	75.4	76.8	131
5	7.42		

VES.33



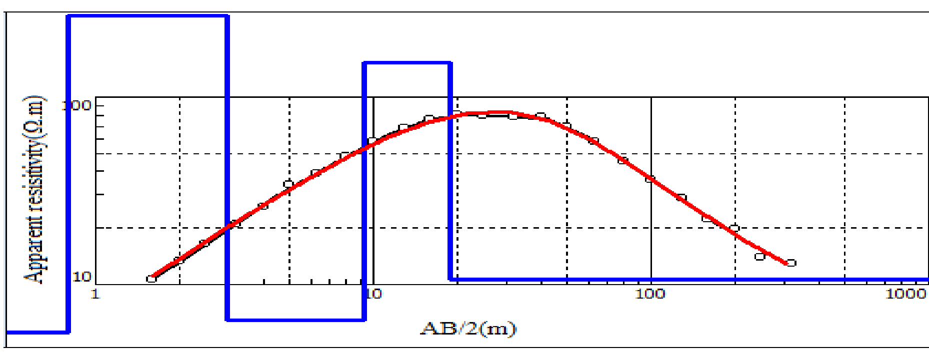
N	ρ	h	d
1	48.5	0.8	0.8
2	2647	0.824	1.62
3	293	22	23.6
4	143	21.8	45.4
5	668		

VES.34



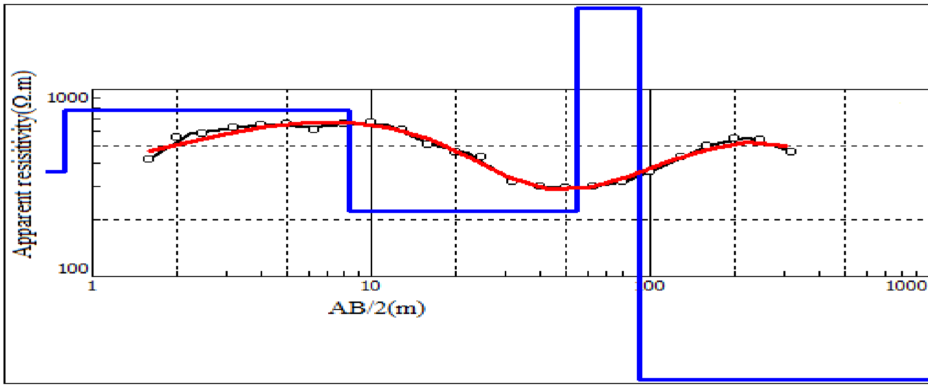
N	ρ	h	d
1	19.1	0.968	0.968
2	8.02	5.87	6.84
3	2837	37.1	43.9
4	95.2	39.8	83.7
5	17.6		

VES.35



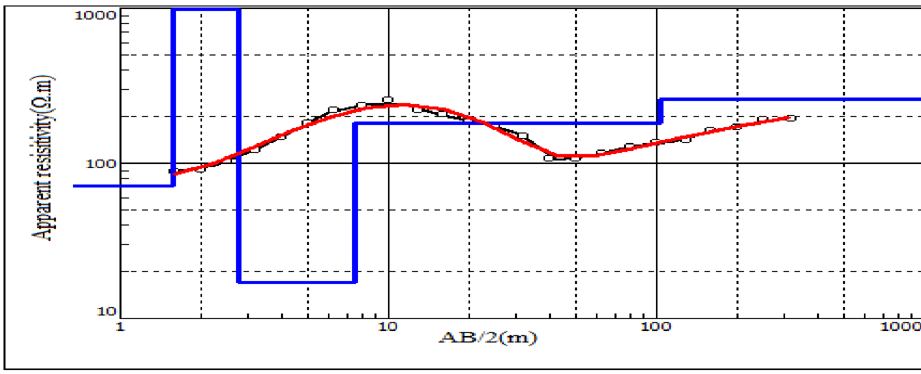
N	ρ	h	d
1	5.55	0.8	0.8
2	1026	2.19	2.99
3	6.49	6.25	9.24
4	153	9.75	19
5	10.6		

VES.36



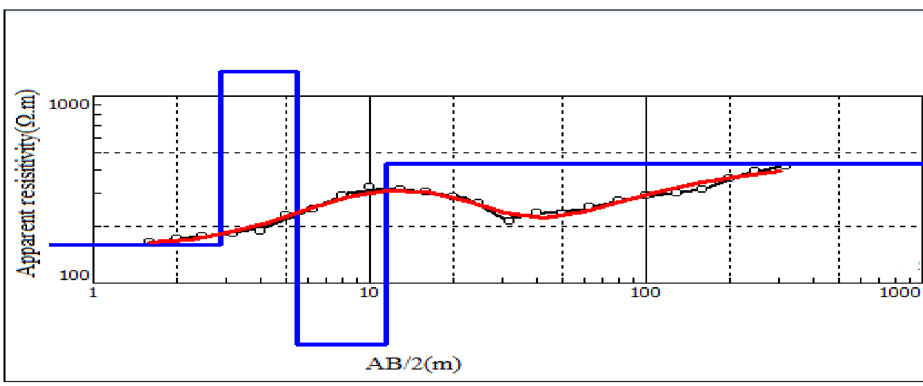
N	ρ	h	d
1	364	0.8	0.8
2	778	7.56	8.36
3	224	46.4	54.8
4	3788	36.3	91.1
5	10.4		

VES.37



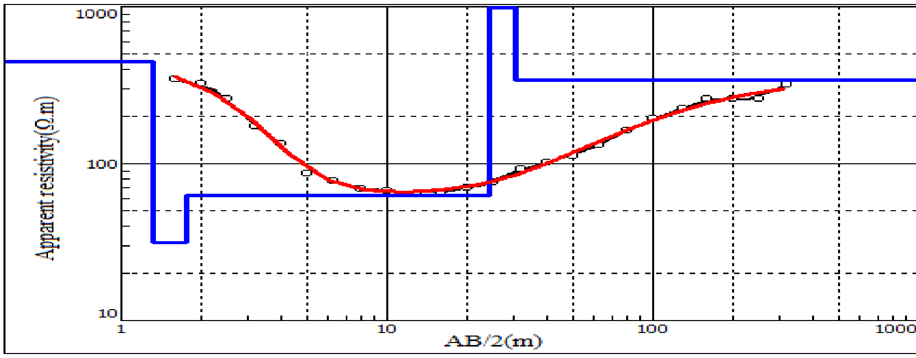
N	ρ	h	d
1	70.9	1.57	1.57
2	2369	1.19	2.76
3	17	4.75	7.51
4	181	95.8	103
5	260		

VES.38



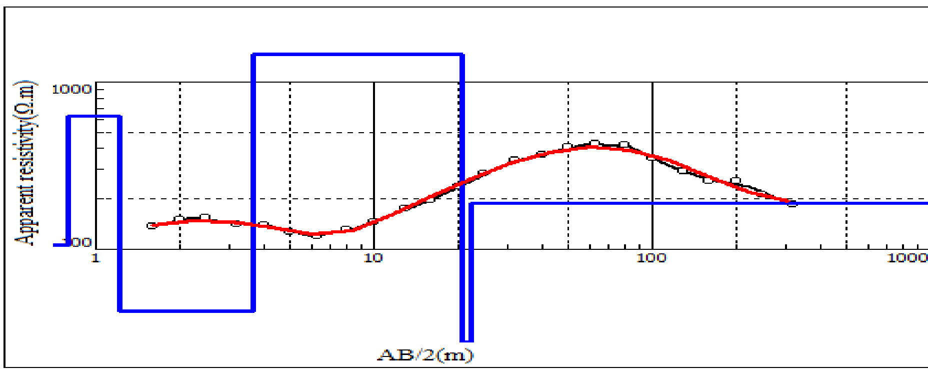
N	ρ	h	d
1	159	2.89	2.89
2	1362	2.57	5.46
3	46.8	5.95	11.4
4	432		

VES.39



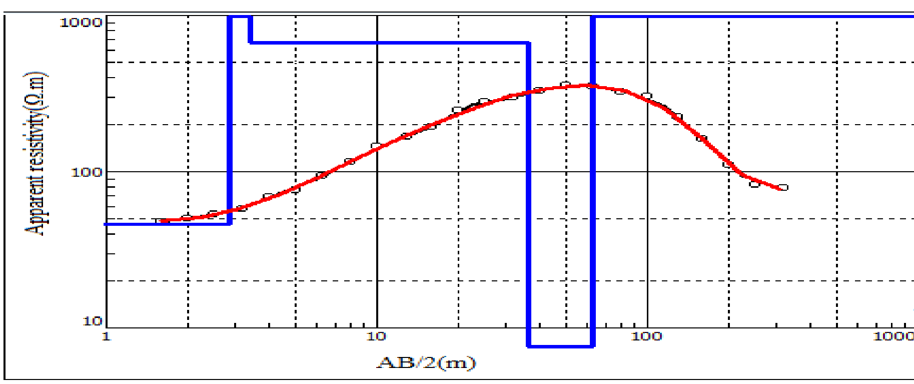
N	ρ	h	d
1	448	1.32	1.32
2	31.2	0.441	1.76
3	62.7	22.4	24.2
4	2731	6.04	30.2
5	339		

VES.40



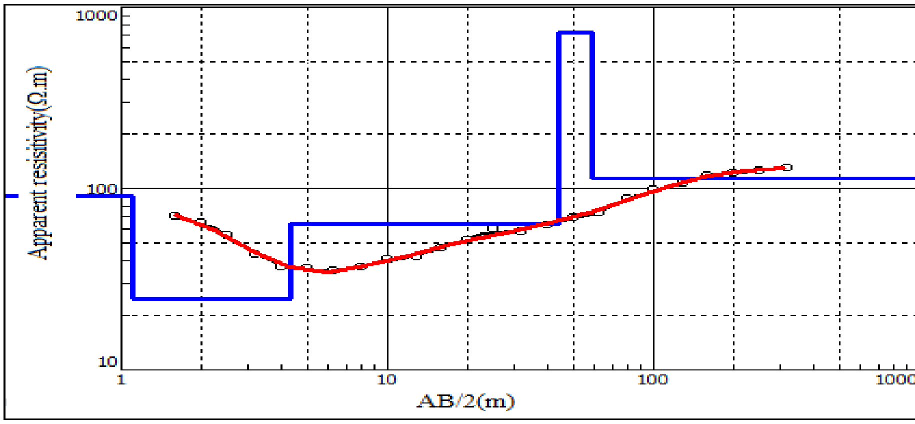
N	ρ	h	d
1	106	0.8	0.8
2	622	0.416	1.22
3	43.1	2.47	3.69
4	1466	17.1	20.8
5	6.13	1.69	22.5
6	189		

VES.41



N	ρ	h	d
1	46.3	2.86	2.86
2	3850	0.567	3.43
3	673	32.6	36
4	6.25	26.6	62.6
5	1561		

VES.42



N	ρ	h	d
1	90.3	1.1	1.1
2	24.8	3.2	4.3
3	64	39.6	43.9
4	727	14.7	58.6
5	113		

Appendix 4: Summary of Resistivity Survey Data

VES NO.	LAT	LON	Elevation (masl)	Resistivity (ohm)	Thickness (m)	Depth (m)	RMS (%)	Aquifer bottom Elevation (masl)	Transmissivity m^2 /day/	Porosity (%)
1	-3.43054	37.615347	736	107	39.4	48.5	2.61	648.1	0.01182	31
2	-3.40886	37.698673	740	59.1	50.9	83.1	5	606	0.01527	41
3	-3.3716	37.607772	919	71.8	34.5	47.8	3.13	836.7	0.01035	37
4	-3.38303	37.667333	792	144	42.9	64.8	4.96	684.3	0.01287	26
5	-3.39514	37.717259	755	42.6	77.8	142	4.28	535.2	0.02334	48
6	-3.39064	37.721315	755	72.9	15.7	36.3	1.91	703	0.00471	37
7	-3.38649	37.725173	758	77.1	35.7	38.7	4.37	685.1	0.01065	36
8	-3.34521	37.688958	885	120	14.8	47.5	2.67	883.4	0.00024	28
9	-3.34459	37.601385	1034	95.5	4.97	12	1.72	1017.03	0.001491	32
10	-3.34864	37.657022	921	139	30.8	47.8	2.27	842.4	0.00924	27
11	-3.35014	37.679611	892	150	20.9	34.2	4.34	836.9	0.00627	26
12	-3.34617	37.692306	878	136	17.2	20.6	4.04	843.2	0.00468	27
13	-3.35185	37.71413	827	184	47.9	58.8	3.81	820.9	0.000465	28
14	-3.3533	37.718925	797	53.4	55.4	58.6	3.76	683	0.01662	43
15	-3.35324	37.723245	793	53.8	10.4	18.3	4.91	764.3	0.00312	43
16	-3.35424	37.73349	809	76	9.01	11.2	5	788.79	0.002703	36
17	-3.33615	37.705502	860	127	37.5	46.5	2.94	776	0.01125	28
18	-3.31656	37.665561	965	139	40.6	48.8	3.73	875.6	0.01218	27
19	-3.31766	37.716334	848	43.5	20.9	36.6	3.77	708.7	0.01902	30
20	-3.31974	37.717222	844	128	36.2	63.8	3.6	744	0.01086	28
21	-3.30014	37.726333	893	75.3	46.6	63.2	4.83	783.2	0.01398	36
22	-3.29912	37.68559	937	73.3	8.76	15	4.51	913.24	0.002628	40
23	-3.29147	37.714528	912	65.2	25.7	42.1	3.17	844.2	0.002397	39

24	-3.28983	37.724222	900	62.2	13.8	53.1	4.13	833.1	0.00414	40
25	-3.29211	37.733169	889	68.1	25.9	43.5	2.09	829.6	0.00777	38
26	-3.27764	37.750573	899	46.9	6.52	18.5	13.9	873.98	0.001815	46
27	-3.27711	37.760644	901	133	25.8	29.7	4.92	845.5	0.00774	27
28	-3.33244	37.688129	976	108	11.3	13.6	3.81	951.1	0.00339	30
29	-3.33615	37.705503	984	87.4	38.6	48.8	4.53	896.6	0.01158	34
30	-3.49364	37.747569	707	45.1	91	113	2.46	503	0.0273	47
31	-3.49719	37.745926	710	45.2	82.7	109	2.24	518.3	0.02481	47
32	-3.293	37.683	946	75.4	56.8	84	4.94	805.2	0.01704	36
33	-3.292	37.691	940	143	21.8	45.5	2.37	872.7	0.00654	26
34	-3.306	37.669	992	95.2	39.8	83.8	4.54	868.4	0.01194	32
35	-3.30318	37.685968	934	57.9	46.1	82	2.63	805.9	0.01383	42
36	-3.3053	37.681551	950	182	34.3	47.1	3.09	868.6	0.01029	23
37	-3.29989	37.680146	962	106	33.2	61.2	5	867.6	0.00996	31
38	-3.29892	37.692418	916	67.2	6.81	13.4	4.51	895.79	0.002043	39
39	-3.30327	37.692854	913	54.4	18.9	26.3	3.61	867.8	0.00567	43
40	-3.295	37.672	993	68.5	23.2	67	3.82	902.8	0.00696	38
41	-3.299	37.665	1004	180	43	54.3	2.33	906.7	0.0129	24
42	-3.294	37.662	1008	42.7	41.6	46.3	1.99	920.1	0.01248	48