3D GEOELECTRICAL STRUCTURE OF THE KABATINI WELL FIELD IN NAKURU BASIN – KENYA RIFT

By

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156/P/8525/2006

A dissertation submitted in partial fulfillment of the requirement for Master of Science degree in Geology (Applied Geophysics).

University of Nairobi

June 2012
DECLARATION AND CERTIFICATION

This is my original work and has not been presented for a degree in any other university or any other award.

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To my dear husband Atanasio Njue, my dear parents Mr & Mrs John Mwangi, Mr & Mrs Josh N Nthuumbi and my siblings David, Moses, Jerems & Cecy.
ABSTRACT

Kabatini well field in Bahati area of Nakuru in the Kenya Rift, which has the highest yielding boreholes that supply 80% of the water needs in Nakuru, was selected for the geophysical study to obtain the electrical resistivity structure. Vertical electrical soundings (VES), electrical resistivity tomography (ERT) were conducted in the Kabatini area. These methods involve injecting of current into the ground and the flow of current is dependent on the pore fluid content of the rock and salinity of the fluid. The resistivity method measures the apparent resistivity of the subsurface, including effects of any or all of the following: soil type, bedrock fractures, contaminants and ground water. Variations in electrical resistivity/conductivity may indicate changes in composition, layer thickness or contaminant levels. The resistivity method is useful for simultaneously detecting lateral and vertical changes in subsurface electrical properties. The 1 D vertical electrical sounding (VES) was used to obtain a 3D geoelectric structure. To do this the data was collected in a uniform grid of 16 soundings and processed individually and plotted using a 3D plotting software to give the aquifer dimensions. Electrical resistivity tomography, a new technique in geophysics, widely used in environmental geophysics and engineering was applied in the Kabatini well field. This method had not been applied to this well field before hence was used to provide more information about the area. The results obtained from the electrical resistivity tomography (ERT) complimented the VES results hence resolved the near surface region. The near surface region of the aquifer showed that the main aquifer found at a depth of about 60 meters is semi confined. In addition, the 3D model showed the aquifer is structurally controlled and is recharged by a river flowing in a shallow channel and a deeper channel. This indicates the fault structures control ground water movement in Kabatini. The main objective of the methods was to map the subsurface resistivity distribution of the layers and in addition show the depth to the water table in both 2D and 3D models and this was successfully achieved. The results, therefore, indicate that the aquifer in Kabatini is on an open channel which has been inferred as River Ngorsur and the lateral extent is seen to be semi bound on the western side. The aquifer extends beyond 165 meters depth.

Key words: Electrical Resistivity, Electrical conductivity, Electrical resistivity tomography
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CHAPTER 1

1.0 INTRODUCTION

The current and enduring drought in many parts of the world, shared with ever increasing demands from water users, in both urban and rural areas, has impacted groundwater resources. The various water uses are mainly for the municipals, industries, agriculture and environmental as well as domestic needs. Nakuru area found in the Great Rift Valley of Kenya shares this sentiment. Nakuru town is the third largest town in Kenya and has a population of close to 900,000 people. The water needs in this area has increased over the years and this has resulted to the search for ground water to cover for these needs. The ground water recourses now have been overstretched and therefore the need to search for new resources as well as managing the already existing ones. The area selected for this study herein referred to as the study area is Kabatini found within the Nakuru basin (Figure 1.1).

Figure 1.1: Map showing the Nakuru Basin in and the location of Kabatini well field. The map also shows the physical changes in growth of Nakuru town over the years (modified from Odada et al, 2006)
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Figure 1.1: Map showing the Nakuru Basin in and the location of Kabatini well field. The map also shows the physical changes in growth of Nakuru town over the years (modified from Odada et al, 2006)
The Lake Nakuru catchment is a unique ecosystem containing a variety of habitats that include an alkaline lake which is home to millions of flamingoes "greatest ornithological spectacle on earth" (Raini and Kulecho, 2008), the largest Eurphorbia forest stand in East Africa, a wild life rich savannah and highland forest. The nature, geology, climate, soils and ecology all interact to make this vulnerable and fragile ecosystem (Raini and Kulecho, 2008).

1.1 Description of the study area

1.1.1 Location and accessibility

The study area is located within the Lake Nakuru basin in the Rift Valley Province of Kenya and is in the county of Nakuru. It is found on the north eastern part of the Nakuru Basin at a mean altitude of 1898 m above sea level. It is accessible by the Nairobi –Nakuru highway and the Nyahururu main road.

1.1.2 Physiography, Land use and Climate

The study area is in the gently sloping Bahati uplands of Nakuru basin. Figure 1.2 shows the physiographic map of the greater region of the Rift in which the study area lies. To the west lies the steep Menengai crater which stands at a height of about 2100m. Nakuru basin is a closed drainage system which has its boundaries as the Bahati high lands to the east, Mau escarpment to the west, Eburru crater to the south and the Menengai crater to the north. Lake Nakuru is the bottom most part of the basin and it lies to the southwestern part of the study area. The drainage is from the north east to the north west as shown in Figure 1.2. In addition, the area lies in a river course which flows underground and only flows on the surface in very wet seasons. This river, named River Ngosur, drains into the Lake Nakuru and it flows into the faulted structures upstream and disappears only to reappear at the hippo pools near the Lake Nakuru.
The land in this area was allocated to individuals through settlement schemes on existing huge pieces of land since the Kenya was granted independence as a country. The uses of the land in the area is agriculture, mostly subsistence farming, range land for dairy cattle, and settlements. Outside the study area, land use involves horticulture, game sanctuary around Lake Nakuru and natural vegetation where there is little human activity.

The climate of the Nakuru area has a mean annual precipitation of 600 to 800 mm in the rifts and about 1300 mm annual precipitation in the plateau. Modern climate in tropical East Africa is mainly controlled by the Intertropical Convergence Zone (ITCZ) and the African-Asian summer monsoon, both being very sensitive to the El Niño/ Southern Oscillation (ENSO) (Marwan et al.,
The average monthly temperature ranges from 15.9°C to 17.8°C. The rain seasons are from April to May and October to November. The annual potential evaporation is estimated at about 1700 mm. Figure 1.3 and 1.4 show the annual precipitation from 1964 to 2006 and average rainfall during per month for a year.

Figure 1.3: Time series of the recorded precipitation during 1964-2006. (Data adopted from the Kenya Meteorological Institute)

Figure 1.4: A graph of average, minimum and maximum rainfall recorded over the years
1.1.3 Drainage

The drainage of the area on a regional scale is from the highlands of Mau escarpment on the west to the Abardares on the eastern side. The Nakuru basin is bounded by the Eburru volcano to the south and the Menengai crater to the north. The drainage is from these slopes to the lowest point of the basin occupied by Lake Nakuru. Most of the run-off comes from the western side of the Rift Valley, as all but one affluent originates on the Mau Escarpment, but there are alkaline springs along the north, northeastern and eastern shores. The Bahati escarpment from which rivers flow towards the Lake Nakuru is where the Kabatini aquifer is found and due to the porous nature of the weathering volcanic sequence, river Ngosur disappears into the ground and reappears at the hippo pools on the shores of Lake Nakuru. The area at the highlands is the catchment zone for the basin and the drainage is centrally towards Lake Nakuru.

1.1.4 Regional Geology and Structures

Three major episodes of faulting are recognized in the Nakuru area (Baker and Wohlenberg, 1971). The first episode represents the development of major faults which occurred on both sides of the rift valley during the Late Miocene. These faults are referred to as the boundary faults (William 1941; Macharia and Dindi, 1985). The second episode is related to the rifting which occurred within the rift valley forming fault steps, horst and graben structures during the Late Pliocene (Sikes 1934; Pulfrey 1951; Pundit 1976). The third episode represents the development of major, almost parallel, faults during the Quarternary.

The study area geologically lies on a plain which is commonly described as the Bahati plane below the slopes of the Menengai Crater, east of Lake Nakuru and west of the Aberdare ranges. It is covered by sediments which are derived from the erosion of Tertiary-Quarternary volcanic rock suites derived from the eruption of the Menengai crater (Baker, 1986; Kagasi et al, 1988). The sediments are underlain by sequences of volcanic rocks which were erupted over different periods over time. The oldest volcanic rocks are the Tertiary Samburu basalts which form contact with the Precambrian igneous basement. The basalt lava flows were as a result of faulting tilting and warping during the formation of the rift valley. These are then overlain by phonolites which were later covered by Bahati tuffs. The Tertiary-Quarternary volcanism was accompanied
by different episodes of faulting and tilting and hence the volcanic sequences in the area are complicated (Tilloston, 1937; McCall, 1967; Lowry and Shive, 1990). There are major unconformities in the geologic sequences between the Pliocene and the Pleistocene. During the Pleistocene, pumice showers from Menengai Pumice Tuffs, welded tuff 'Ignimbrite' and sediments forming unconformable outliers on the Kinangop and Bahati tuffs were emplaced. Superficial deposits are seen on the surface and syenite boulders from the Menengai caldera are commonly found lying on the surface.

The aquifers around the Nakuru area are generally formed at the contact zones of the lava flows where a layer of an old surface with very weathered tuffs were covered by a fresh flow from new lava. The underlain tuffs and old surfaces form aquifers within the basin. Major faulting and weathering of the old surfaces form cavities and conduits below the surface which may not be observed at the surface, where subsurface water flow is made possible. The rivers lose much of their water through rapid transition from surface to subsurface water flows. The surface to subsurface transition occurs due to prevalence of highly porous unconsolidated volcanoclastic sediments and the numerous fissures along their courses. River Ngosur, Naishi and Njoro disappear into the fault lines and recharge the deeper aquifers. On the slopes of the Menengai crater, there is very low surface run-off due to the porous nature of the volcanoclastic formations which cover the older consolidated lava flows. The small streams which originate from the crater often disappear quickly into the subsurface drainage in the upper reaches of the crater slopes.

1.2 Problem Statement

The whole world is experiencing climate change and the biggest impact is caused by man on nature. The effect of climate change on ecosystems, in particular the consequences of temperature increase on plant and animal life is a topic of paramount importance (Zhou et al., 2003). Analysis of temperature records from meteorological stations shows unprecedented rate of temperature change during the past 25 years (Hansen et al., 1999). The northern latitudes experienced enhanced warming, especially during the winter and spring periods. Changes in global climate may alter hydrologic conditions and have a variety of effects on human settlements and ecological systems. The effects include changes in water supply and quality for domestic, irrigation, recreational, commercial, and industrial uses (Hurd et al., 1999). In the Lake
Nakuru basin, there has been a high level of ground water abstraction and this has led to uncertainty whether the resource is renewable or non renewable. There is need to understand whether the resource is being mined or over exploited and therefore manage the ground water resource sustainably. In addition, the existing electrical resistivity data for mapping and locating aquifers in the Nakuru basin is based on 2D VES sounding data. Therefore by constructing a 3D structure of the Bahati well field, the project will improve the understanding of the aquifer and serve as a base for future extensive study of the area.

1.3 Scope of the research

The research was conducted around the Kabatini well field, an area of about 40,000 m². This involved collection of vertical electrical soundings (VES) and electrical resistivity tomography (ERT). The soundings were inverted using 1D inversion program and the model generated was used to generate a 3D model showing the resistivity structure of the Kabatini well field.

1.4 Justification and Significance

The rise in ground water demand for use in agriculture has placed constraint in groundwater resources all over the world. Every day the demand for water is increasing hence a dire need for exploration of clean water provided by groundwater to meet this demand. Notwithstanding, exploration of groundwater resources is vital and monitoring of this resources is equally important to ensure we preserve the aquifers and ensure recharge to make the resource renewable. Geophysical methods are very reliable in determining the subsurface structure and therefore play a leading role in groundwater exploration and monitoring. This study is geared to meet the challenges associated with the utilization of groundwater and mitigating problems of overexploitation.

Bahati aquifer is a very important aquifer in the Nakuru area in that it sustains the livelihood of the town and its environs. It is the most productive aquifer in the area with the boreholes producing 80 m³ per day. With the global climate changing so rapidly, there is need to map for new ground water resources so as to cover the demand for water to ensure survival and, furthermore, sustaining already existing resources.
1.5 Research Objectives

Aim

The main aim of carrying out this project is to determine the lateral and vertical distribution of the aquifer in the basin and the groundwater flow within the aquifer by establishing the relationship of ground water to the structures and lithology.

Specific objectives

1). Construct a 3D structural model of the Bahati aquifer using geophysical techniques.

2). Determine the geophysical characterization of the subsurface.

3). Determine the lateral and vertical distribution of the aquifer.

1.6 Methodology

The methodology for this study involved desktop studies which involved gathering geographical information of the Nakuru area and literature review of the area. This gave insight about the general information of the area on the geological setting, hydrogeology, climate and the social economic activities of the study area. A field work was then conducted in the project area which involved use of Direct Current (DC) method and electrical resistivity tomography. SYSCAL R2 unit was used to collect the DC data while SYSCAL R1 PLUS unit was used to perform the electrical resistivity tomography. These instruments are manufactured by IRIS instruments, France. The 1D data obtained was then analyzed and interpreted using AGI Earth imager software from AGI advanced geosciences Inc, USA and the 3D data was plotted using Visual data software from Graphnow company. The results obtained are discussed in this dissertation.
2.0 GEOLOGY, HYDROGEOLOGY AND STRUCTURES OF NAKURU AREA

2.1 Geology and Structures

The Nakuru area lies within the inner graben of the central Kenya rift valley and has experienced continual outpourings of trachyte magma during the last 6.2 Ma (Figure 2.1). The volcanic rocks of intermediate composition are usually overlain and not exposed while basaltic rocks are rare. There volcanic rocks were extruded at various times and hence there is an old surface and this intercalation of sedimentary rocks with volcanic rocks is very common. Volcanic rocks older than 6.2 Ma must underlie the area, contributing to the total volcanic and sedimentary rift fill which is constrained by seismic data to be 4 km thick (Leat, 1991). Five major stratigraphic groups of trachytic volcanic rocks are identified. They consist of voluminous ignimbrites (at least seventeen) with individual volumes probably 20–30 km³, lava flows, with volumes of 0.01–2.0 km³, strombolian deposits, widespread (probably mostly sub-plinian) air-fall deposits and hydromagmatic tuff cone deposits. Because the lithology of these volcanic rocks, and apparently their typical volumes, have remained unchanged for 6 Ma, it is considered that the sub-volcanic plumbing systems in this part of the rift also remained similar. Volcanic plumbing system is a term which is commonly used to describe the magma storage at depth. The various eruptive styles of trachyte can be explained by eruption from relatively large magma chambers, capped by trachytic magmas and emplaced in the upper crust, like that thought to exist below the Recent volcano Menengai (Leat, 1991).

The larger Nakuru area is highly faulted and some faults are buried. As a result, areas of Nakuru town and its environs often undergo subsidence along the parallel fault zones during and after heavy rainfall. During the rainy season, when most of the subsidence occurs, the overlying unconsolidated volcanoclastic sediments become oversaturated with water. The water reduces the shear strength of the sediments and also introduces extra loading through saturation leading to subterranean erosion along faults. The unconsolidated sediments then collapse into the subsurface water channels which closely follow the fault zones, leading to formation of sinkholes. The frequent incidences of ground subsidence in the study area, have caused several fatalities, destroyed settlements and physical infrastructure, (Ng’ecu and Nyambok, 2000).
The area is predominantly underlain by phonolitic lava flows and partly by basalts and tuffs (Table 2.1).
Table 2.1: The geology and rock succession of Nakuru area (after Kuria and Woldai, 2008)

<table>
<thead>
<tr>
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<th>IGNEOUS INTRUSIVES</th>
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<td><strong>Recent</strong></td>
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<tr>
<td>Superficial deposits, soils and alluvium. Upper Menengai Volcanics</td>
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<td><strong>Pliocene</strong></td>
<td>Syenite boulders on Menengai slopes</td>
<td>Minor Faulting - Solai, Marigat, and West of Nakuru Major Faulting.</td>
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<td>Tuffs and sediments - Nakuru Basin, Tuffs and fluviatile sediments- Mugurin, Pumice showers from Menengai. Pumice Tuffs, welded tuff ‘Ignimbrite’ and sediments forming unconformable outliers on the Kinangop and Bahati tuffs.</td>
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<td>Unconformity</td>
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<td><strong>Tertiary</strong></td>
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<td>Pliocene: Kwaibus basalt, Kisanana sediments, Mau Tuffs, Bahati Tuffs, Kinangop Tuffs, Lower Menengai Volcanic Series. <strong>Miocene:</strong> Rumuruti phonolites. <strong>Samburu Series,</strong> Simbara Series.</td>
<td></td>
<td>Major Faulting</td>
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<td>Basement System</td>
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<td>Precambrian Orogenic movements</td>
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The following sections give a brief description of the rock types occurring in the Nakuru region which applies for the project area. Kuria and Woldai (2008) summarized the geology of the Nakuru area as follows:

2.1.1 Samburu Basalts

Samburu basalts are the oldest rocks in the area and are porphyritic in texture, interspersed with tuffs. The Samburu basalts are predominantly lavas. Agglomerates are absent, however, tuffs, light in colour, well stratified and pumiceous, and occasionally with diatomite, are found at the top of the series and intercalated in the lavas.

2.1.2 Bahati Tuffs

A continuous series of tuffs and ‘ignimbrite’ extends from Bahati, immediately east of Menengai to Ol Bolosat (outside this area) and sporadically outcrop in the north and north-east of Menengai Crater. To the north of Menengai Crater and in Bahati Forest, phonolites of the Rumuruti formation come out from under the tuff group, and northwards the tuff gradually thin out and disappear. The northernmost outliers are seen to the north of Subukia. To the north-east of Bahati the tuffs are fairly well developed in Lower Solai but thin out into a series of minor outliers overlying the Dispeil-Lake Hannington phonolites at Kisanana and Ngendalel, and to the north of these localites are absent. To the west of Solai there is a northerly trending belt extending from Menengai Crater through Olobanita swamp and Lomolo where the tuffs are completely absent.

2.1.3 Menengai tuffs

These rocks outcrop around Menengai Crater. The pumice tuffs of this series are the yellow creamish buff pumice tuffs predominantly composed of coarse vitric tuff, grading into lapili tuff. These tuffs consist of glass fragments and feldspar crystals. They weather readily to clayey material and also show a deep red clayey soil capping where they form the land surface. Many of these yellow pumice tuffs contain both angular boulders of trachyte and pumice and obsidian lumps.
2.1.4 Upper Menengai series

This series is composed of pumice mantle and trachyte lavas. The pumice mantle cover a big area to the west of the crater. Obsidian, trachyte and syenite fragments appear as inclusions in the pumice. The trachyte lavas completely cover the floor of the caldera. The products of these late eruptions include blocky flows apparently entirely composed of jumbled boulders, some massive flows, and also flows composed of twisted ropes of vitreous lavas. The lavas are characteristically black in colour and are for the most part vitreous, though they grade from nearly holocrystalline types to streaky obsidian.

2.1.5 Quaternary deposits

The Quaternary deposits in the area comprise superficial deposits, volcanic soils, screes and alluvium.

2.2 Hydrology and Hydrogeology

The Nakuru basin occupies a total catchment area of 1,800 km² and the Lake Nakuru as its lowest point. Lake Nakuru is one of the lakes within the Kenya rift. The Lake is fed by one permanent river (Ngosur) and four seasonal rivers (Njoro, Nderit, Makalia and Lamudhiak). Treated waste water from Nakuru town is also discharged into this Lake. The lake has very little recharge through fault systems compared to other lakes within the rift owing to its high elevation. Lake Nakuru is a very shallow alkaline lake located in Kenya's rift valley, with a surface area of 44 km² and an average depth of 2.5 meters. There is no outflow from the Lake and in the long run, all rainfall is lost by evapo-transpiration in the catchment area. Some of the rivers (Njoro, Ngosur, Naishi) become influent, disappearing along the fault lines to recharge deep aquifers (Odada et al, 2006).

The rift valley has a huge potential of groundwater owing to the recharge from the catchment areas in the flanks and the highlands. However, most of this water is lost through faults and fractures formed due to very active tectonics during the rift formation. The porous and permeable surface of volcanic ashes, pumiceous pyroclastics and faulted lava and tuff provide for percolation of runoff, leading to potentially high groundwater storage. Most of the drainage from
the escarpments tapers off and disappears into pyroclastics and ashes covering the plains. The lake is alkaline and saline (sodium-bicarbonate) as a result of evaporation and is recharged by rainfall, surface runoff and groundwater (Clarke et al., 1990). Most aquifers in the rift will be formed through old land surfaces in between lava flows. The faulting within the floor of the rift plays a significant role in ground water movement as the faults act as barriers or conduits leading to groundwater accumulation.

The ground water movement is directed towards Lake Nakuru which is the lowest part of the basin as discussed earlier. This is evident as the five seasonal rivers Makalia, Nderit, Naishi, Njoro and Larmuriac of the basin all drain finally into the lake. There are large flat plains around the lake and this is indicative of low drainage. There is a ground water divide, beyond Lake Elementaita and also at the Menengai crater (Figure 2.1). The south divide separate the two basins i.e. the Nakuru basin and the Lake Naivasha basin.
Figure 2.2: Ground water flow in the Nakuru basin showing also the water divide between Lake Nakuru basin and Lake Naivasha basin (modified from Yihdego, 2005)
CHAPTER 3

3.0 PRINCIPLES OF DIRECT CURRENT ELECTRICAL RESISTIVITY METHODS

The direct current method (DC) is an electrical method which involves sending a current into the ground and measuring the ground response (Reynolds, 2011). These methods involve vertical electrical sounding and electrical resistivity tomography.

3.1 Vertical Electrical Sounding (VES)

In vertical electrical sounding 4 electrodes are needed where two of these are used as current electrodes (A and B) while the other two are used as potential electrodes (M and N) as shown in figure 3.1. The current is injected through electrode A and received in electrode B.

![Diagram of Vertical Electrical Sounding](http://www.nga.com/Flyers_PDF/NGA_DC_Resist)

Figure 3.1: The diagram shows current injected into the ground through current electrodes A and B and the lines of equipotentials on a homogeneous half space. (Adapted from Northwest Geophysical Associates, Inc http://www.nga.com/Flyers_PDF/NGA_DC_Resist)

The set up in Figure 3.1 above illustrates the electric field around the electrodes A and B and the distribution of equi-potentials and current lines. The equi-potentials are represented as imagery.
shells which have the shape of bowls surrounding the current electrodes. The electrical potential is equal everywhere. The current lines represent a sampling of the infinitely many paths followed by the current, paths that are defined by the condition that they must be everywhere normal to the equipotential surfaces.

The potential electrodes M and N measure the potential difference. To ensure good ground contact the electrodes are driven to the ground well to ensure proper contacts. The current also should be sufficient to ensure deep penetration into the ground. The resistivity method has its origin in the 1920’s due to the work of the Schlumberger brothers. In this method, the centre point of the electrode array remains fixed, but the spacing between the electrodes is increased to obtain more information about the deeper sections of the subsurface. The measured apparent resistivity values are plotted on the log-log graph paper. To interpret the data from such a survey, it is assumed that the subsurface consists of horizontal layers. A one dimensional of the subsurface is used to interpret the measurements (Loke, 2000).

The one dimensional model has been used successfully in locating the depth to the water table. The major limitation of the resistivity sounding method is that it does not take into account the lateral changes in the layer resistivity. The lateral changes should be taken into consideration because in most cases the ground has complex geology and therefore the 1D model may have errors. In this case, to try to take into consideration the lateral changes, the apparent resistivity was measured in a grid. When the resistivity changes are smooth, 1D technique can be used to interpret the data (Muiuane and Pedersen, 1999).

Electrical resistivity is principally sensitive to saturated porosity and conductivity of fluids (or total dissolved solids in water), and less so to lithology in crustal materials (Touloukian and Ho, 1981).

A notable exception to this is the clay because electrical conduction along surfaces of minerals with thin films of water can lower the electrical resistivity (Ward, 1965). Clays have large effective surface areas and a few percent of clay content can significantly lower the electrical resistivity of a rock or sediment (Owen et al, 1991).


3.2 Electrical Resistivity Tomography

Electrical Resistivity Tomography is a method of survey which was inspired from medical tomography such as Computerized Axial Tomography (CAT) scans and Magnetic Resonance Imaging (MRI) in the medical fields. The tomography portion of ERT comes from taking many groups of current source / voltage measurements at as many locations as possible. Each group of measurements is a traditional test and the tomography involves the joint inversion of many independent tests, using an algorithm to discern subtle details from differences which would not be seen in any one test. Electrical resistivity tomography is widely used for mapping shallow subsurface geological structure (Storz et al., 2000), solute distribution (Binley et al., 1996), water content (Zhou et al., 2002), and other environmental, hydrological, and engineering features (Dah-lin, 2000).

The method is based on the introduction of electrical current into the soil through two surface electrodes and the simultaneous measurement of the induced potential gradient with other electrodes on the surface. Each measurement of the potential gives insight into the electrical properties of the subsurface materials.

The basic parameter of a DC electrical measurement is resistivity. Resistivity is a fundamental electrical property of rock materials closely related to their lithology, the determination of the subsurface distribution of resistivity from measurements yield useful information on the structure or composition of buried formations (Dobrin and Savit, 1988).

Resistance ($R$) is measured in ohms, a result of an electrical measurement, where according to Ohm’s Law:

\[ V = \frac{I}{R} \quad \text{or} \quad R = \frac{V}{I} \quad (3.1) \]

Where $V$ = voltage in volts and $I$ = current in amps.

Resistivity of a material is a fundamental physical property related to the ability of a material to conduct electricity. If $R$ is the resistance of a block of conductive material having a length $L$ and cross-sectional area $A$, then the resistivity is given as:
\[ \xi = \frac{RA}{L} \quad (3.2) \]

Resistivity measurements of the ground are normally made by injecting current through two current electrodes and measuring the resulting voltage difference at two potential electrodes. From the current (I) and voltage (V) values, an apparent resistivity (\(\xi_a\)) value is calculated.

\[ \xi_a = \frac{kv}{I} \quad (3.3) \]

where \(k\) is the geometric factor which depends on the arrangement of the four electrodes.

The subsurface is comprised of soils, unconsolidated sediments and rocks which are mainly derived from silicate minerals which form about 90% of the earth’s crust. The resistivity of the silicate minerals is in the order of 1000 Ohm-m and they can be referred to as insulators because they allow no current to pass through. Current is transmitted in these materials through ionic conduction in the pore fluid of the rock. The most conductive minerals are the metals such as copper, iron and iron ore and also semi conductor are massive sulphides and graphite (Figure 3.2).

Figure 3.2: Summary of resistivity of rocks. (Adapted from http://www.ualberta.ca/~unsworth/UA-classes/223/notes223/223B1-2009.pdf)
In most rocks near the earth's surface, the conduction is dominated by electrolytic conduction in aqueous solution of common salts distributed through the pores of the rock and/or at the rock-water interface. The rock matrix itself is normally an insulator. The electrical resistivity of rocks depends on:-

- Porosity and the pore structure of the rock
- Amount of water (saturation)
- Salinity of the water
- Temperature
- Water-rock interaction and alteration (Hersir and Árnason, 2009)

Groundwater, through the various dissolved salts it contains, is ionically conductive and enables electric currents to flow into the ground. Consequently, measuring the ground resistivity gives the possibility to identify the presence of water, taking into consideration the following properties:

- A **hard rock** without pores or fracture and a dry sand without water or clay are very resistive: several tens thousands ohm.m

- A **porous or fractured rock** bearing free water has a resistivity which depends on the resistivity of the water and on the porosity of the rock, several tens to several thousands ohm.m

- An **impermeable clay layer**, which has bound water, has a low resistivity: several units to several tens ohm.m

- **Mineral ore bodies** (iron, sulphides) have very low resistivities due to their electronic conduction: usually lower or much lower than 1 ohm.m

As ground water becomes more important source of uncontaminated water, DC method is efficient for locating good aquifers. Direct Current (DC) electrical survey determines the subsurface resistivity distribution of the ground, which can then be related to physical conditions of interest such as lithology, porosity, the degree of water saturation, and the presence of voids in the rock.
CHAPTER 4

4.0 DATA ACQUISITION, PRESENTATION AND INTERPRETATION

4.1 Instrumentation

The geophysical equipments used in the field to acquire data were SYSCAL R2 unit and SYSCAL R1 PLUS unit. These instruments are manufactured by IRIS instruments, France.

SYSCAL R2

This equipment is designed for direct current (DC) electrical surveys applied to groundwater exploration, environmental studies, civil engineering structural geology investigation and mineral exploration. This equipment is manufactured by IRIS instruments, a company in Orleans, France which specializes in manufacture of geophysical equipments for various applications. The SYSCAL R2 uses an external DC source for energizing the ground (800 V maximum output voltage): 250 W DC/DC converter supplied by a 12V battery and 1200 W AC/DC converter supplied by a standard motor generator. In addition, it is automatic i.e. it is controlled by a microprocessor for automatic Self-Potential compensation, automatic gain ranging for both current and voltage measurements and automatic digital stacking to enhance the signal-to-noise ratio and to optimize the acquisition time. The SYSCAL R2 equipment is easy to use; whereby it computes and displays the apparent resistivity automatically for the most common electrode arrays (Schlumberger and Wenner sounding and profiling -gradient -dipole-dipole etc). It also measures Induced Polarization and displays the apparent chargeability (Induced Polarization parameter).

SYSCAL R2 has a high accuracy in that it features:

• A noise monitoring system for pre-injection control, consisting of a DC digital voltmeter function.
• A line check/ground resistance measurement which permits to check that the electrodes are properly connected to the resistivity-meter.
• A low-pass analog filter, which reduces the effect of higher frequency natural and cultural noises (50-60 Hz).
• A resolution after stacking of 1μV allowing to measure some low-amplitude signals; the standard deviation is displayed to give an indication of the noise level during the measurement.
Syscal R1 Plus 72

This is electrical resistivity imaging/sounding equipment which has been manufactured also by IRIS Company. The Syscal R1 Plus Switch plus is a new all in one multimode resistivity imaging system. It features an internal switching board for 72 electrodes and an internal 200 W power source. The output current is automatically adjusted (automatic ranging) to optimize the input voltage values and ensure the best measurement quality. The system is designed to automatically perform pre-defined sets of resistivity measurements with roll-along capability. Four strings of cable with 18 electrode take-out each are connected on the back of the resistivity meter. Made of heavy duty seismic cable, these strings are available with standard 5 or 10 m electrode spacing. Customized cables may also be assembled for special arrays or non-standard applications. Figure 4.1 shows two photos, from the left is the author and the geophysics team from Iris instruments taking an electrical resistivity profile while on the right is one of the current electrodes connected with a copper connector.

Figure 4.1: Photo showing the Syscal R1 Plus tomography equipment during field set up

The SYSCAL R1 PLUS Switch-72 measures both resistivity and chargeability (IP). The equipment in this case was used for mapping shallow ground water aquifers at a depth of 60 meters. This equipment can be used for other uses such as environmental and civil engineering
applications such as pollution monitoring and mapping, salinity control, depth-to-rock
determination and weathered bedrock mapping.

4.2 Pre-field work

Before the field work preparation were made before hand to acquire the various items required
for the field. This involved acquiring the geophysical equipments and the maps for the study
area. A field work programme was made which would act as a guideline during the fieldwork.

4.3 Field work

The field work was carried out in the month of May 2008 and during this period the weather was
cool with occasional rainy afternoons. The first few days’ reconnaissance study was done on the
Nakuru area. This involved making courtesy calls to the local authorities, the residents of the
case study area basin in general surveying the geology of the basin.

A total of 16 stations were selected to carry out soundings so as to capture the dimensions of the
aquifer at the well field. To carry out a sounding, the traverse line had to be selected and
inspected before laying the system to ensure that there would be easy access and also verify that
long cable lines would be passed through. The traverse lines were all in East –West direction and
this was ideal because in general the faults trends are in the North south direction. Figure 4.2 is a
photo showing the author and Prof Barongo collecting data along profile 0-0.
A total of 16 stations were selected on a square grid of 50m by 50m between each station, so as to capture the dimensions of the aquifer at the well field. The grid set up is displayed in Figure 4.3 below.
The measuring tapes would be laid out to measure the distances accurately and peg these markings on the ground up to a distance of \( \frac{AB}{2} = 300 \) meters. The long cables are made of copper wire insulated by rubber coatings and caution had to be taken especially where a major road was traversed to ensure that heavy vehicles or passengers did not damage the cables. The system would be laid out according to the array chosen and in this case it was the Schlumberger configuration. The metal electrodes used to inject current were hammered into the ground and in very dry ground they were driven in to depths of more than 50 cm and watered to improve contact. With the system laid out well, the current was injected into the ground and the apparent resistivity measured and recorded in a note book at different distances.

4.4 Post field work

4.4.1 Data presentation

After the field work there are several processes that have to be done on the data to prepare the data for inversion. Before commencement of data analysis the first step was to put the raw data in a database where copies are maintained to ensure data safety. This process enables easy manipulation of data. The data is tabulated into 3 columns of \( \frac{AB}{2} \), \( \frac{MN}{2} \) and the apparent resistivity for each of the 16 stations to their corresponding GPS positions. As a first step in the analysis was to plot apparent resistivities values at all \( \frac{AB}{2} \) depths for all the stations so as to have a general overview of the apparent resistivity distribution in the area. The data from Syscal R2 are plotted in the computer into apparent resistivity plots with depth. The software used in plotting is the gnu plot software. The data is edited to check the outliers and bad data points are identified by observing the trend.

Figure 4.4, 4.5, 4.6 and 4.7 shows a plot apparent resistivity with depth for the sixteen stations in Kabatini.
Figure 4.4: Plot of 4 apparent resistivity with electrode separation for profile 0

Figure 4.5: Plot of 4 apparent resistivity with electrode separation for profile IS
Figure 4.6: Apparent resistivity plots of four stations with electrode separation distance for profile 2S

Figure 4.7: Plot of 4 apparent resistivity with electrode separation for profile 3S
4.4.2 Data Interpretation

The resistivity data was generally interpreted using the modeling process. To do this a software called Earth imager was used to model the 1D sounding data. The modeling processes are forward modeling and inverse modeling. This is where an imaginary model of the earth and its resistivity structure is generated and the theoretical electrical resistivity response over that model is then calculated. The theoretical response is then compared with the observed field response and differences between observed and calculated are noted. This is known as the forward modeling. The hypothetical earth model is then adjusted to create a response which more nearly fits the observed data. This iterative process is referred to as inverse modeling. This process was done for all the soundings and results obtained. After this process the first thing to do is to note the shape of the curve generated. Usually there are four basic shapes referred to as K, A, Q, and H type. These types can also be combined to describe curves that may have several more layers.

Zohdy (1989) produced a technique of resistivity sounding curves. Least squares optimization is used in which a starting model is adjusted successfully until the difference between the observed and the model pseudo sections is reduced to a minimum (Barker, 1992). An assumption is made that the number of data points in a sounding curve are equivalent to the number of layers in the subsurface. The mean depth of each layer is taken as the electrode spacing at which the apparent resistivity was measured multiplied by some constant. The value of this constant is one which reduces the difference between the observed and model resistivity curves to a minimum and is determined by trial and error. The starting model is used to generate a theoretical synthetic sounding curve which is compared with the field data. An iterative process is then carried out to adjust the resistivities of the model while keeping the boundaries fixed. After each iteration the theoretical curve is recalculated and compared with the field data. This process is repeated until the root means square (RMS) difference between the two curves reaches minimum.
**K type curves**

This type of curves is generated when the first layer from the surface is lower than the second layer and the third layer has also a lower resistivity than the second layer i.e. $\ell < \ell > \ell$. Figure 4.8 shows the display of K-type curve.

![K-type curve diagram](image)

Figure 4.8: Shows K-type curves for a three layered earth (Keary et al., 2002)

**H type curves**

This type of curves is generated when the first layer from the surface is lower than the second layer and the third layer has also a lower resistivity than the second layer i.e. $\ell < \ell > \ell$. Figure 4.9 shows the display of K-type curve.

![H-type curve diagram](image)

Figure 4.9: Shows H-type curves for a three layered earth (Keary et al., 2002)
A type curves

The A type curves for three layer earth where the first layer is less than the second layer and the third layer is greater than the second layer i.e. \( \ell_1 < \ell < \ell_2 \). It can be described as an uphill climb. Figure 4.10 shows the A type curves.

![A type curves](image)

Figure 4.10: Shows A-type curves for a three layered earth (Keary et al., 2002)

Q type curves

For Q type curves the resistivity for the first layer is higher than the second layer and the third layer resistivity is lower than the second layer i.e. \( \ell_1 > \ell > \ell_2 \). It can be described as a down hill descent. Figure 4.11 shows the Q type curves.

![Q type curves](image)

Figure 4.11: Shows Q-type curves for a three layered earth (Keary et al., 2002)
Combined Curves

This where there are more than 3 layers present. Below is an example of H and K curve combination (Figure 4.12). Examples of possible combinations of H and K curve where there are more than 3 layers.

![Combined Curves](image)

Figure 4.12: Shows HK-type and KH type combined curves where 4 layers are present (Keary et al., 2002)
CHAPTER 5

5.0 RESULTS AND DISCUSSIONS

5.1 1D Sounding Results

These are the results for the modelling process and are presented as Logarithmic plots of the apparent resistivity values versus depth. The 16 soundings are individually inverted and a layered resistivity model obtained which show the resistivity variation with increasing depth. The measured data is plotted with the measured data and the fit of the two data set is represented by the RMS (root means square) error and it shows how best the model fit the measured data. When the RMS error is as low as possible this show how close the model is to the actual measurements.

The resistivity models are obtained as layered models and this means that the resistivity variation is assumed to be changing only with depth. A total of 16 models were derived from each sounding and the plots are displayed as resistivity plots. These resistivity plots show measured data displayed as dots and a line fitting the data displayed in red. After the inversion process a model is generated (displayed as a block blue line) and is interpreted in terms of the number of layer and the resistivity values for each layer from the surface to the effective depth. The layer resistivity model with is plotted in a legend format in the right hand side.

Each of the 16 resistivity plots for each sounding station are discussed below and are grouped for discussion in profiles. There are four profiles and they are displayed to show the position of each sounding.
Profile 0

This profile has four stations namely 1W-0, 0-0, 1E-0 and 2E-0 (Figure 5.1).

<table>
<thead>
<tr>
<th>(50m)</th>
<th>0-0</th>
<th>1E-0</th>
<th>2E-0</th>
<th>profile 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>1W-1S</td>
<td>0-1S</td>
<td>1E-1S</td>
<td>2E-1S</td>
<td>profile 1S</td>
</tr>
<tr>
<td>1W-2S</td>
<td>0-2S</td>
<td>1E-2S</td>
<td>2E-2S</td>
<td>profile 2S</td>
</tr>
<tr>
<td>1W-3S</td>
<td>0-3S</td>
<td>1E-3S</td>
<td>2E-3S</td>
<td>profile 3S</td>
</tr>
</tbody>
</table>

Figure 5.1: Profile 0 showing 1W-0, 0-0, 1E-0 and 2E-0 stations

Station 1W-0

In this station (Figure 5.2) there are 3 major layers which can be identified in this station.

Figure 5.2: Resistivity plot for station 1W-0 showing the final geoelectric model after the inversion process. The resistivity curve has a HK shape.
Layer 1

The upper layer is 28 meters thick with layer having resistivity variation from 45 ohm-m to a high of 287 ohm-m. The top of this layer is very resistive and a low resistivity zone is seen at about 10 meters depth. This layer is a thin conductive lens located which maybe attributed to soil moisture.

Layer 2

The second layer from the surface is about 73 meters thick with a low resistivity of 11 ohm-m. This layer is encountered at 27 meters depth. This is the major aquifer and it is confined with a resistive layer at the top and bottom. The bottom of this aquifer is 100 meters depth.

Layer 3

This is the bottom layer and is very resistive at 300 ohm-m. The layer has infinite depth and is confining the aquifer at depth.

Station 0, 0

In this station (Figure 5.3) there are 5 major layers which can be identified in this station.

Figure 5.3: Resistivity plot for station 0-0 showing the final geoelectric model after the inversion process. The resistivity curve has a HK shape.
Layer 1

The layer is from the surface to about 17 meters depth. The layer displays resistivity variation with the first layer showing 117.7 ohm-m and lowers to 54.8 ohm-m. A thin film of about 7 meters is seen from the surface and this is interpreted as a minor aquifer with a resistivity of 49.5 ohm-m.

Layer 2

The second layer from the surface is about 12 meters thick with a very high resistivity of 72 ohm-m. This geoelectric layer is seen as a semi porous having with a film of water. The layer is encountered at 17 to 30 meters depth.

Layer 3

This layer is 24 meters thick and has high resistivity than the second layer. This layer is 160 ohm-m and is not water bearing. The layer is encountered at 30 to 53 meters depth.

Layer 4

This layer is 41 meters thick and has a resistivity of about 122 ohm-m and is overlain by layer 3 which is of a higher resistivity. Layer 4 forms the cap of the major aquifer in Kabatini confining it from the surface. This layer is compact i.e. not water bearing and is encountered at 53 meters depth to 95 meters depth.

Layer 5

Layer 5 forms the major aquifer in Kabatini and the water saturated zone is encountered at 95 meters depth and the resistivity of this zone is 40.8 ohm-m.
Station 1E, 0

In this station (Figure 5.4) there are 5 major layers which can be identified in this station. Layer 1, 2, 3 and 4 are layers that have good aquifer properties but are not very water saturated.

![Figure 5.4: Resistivity plot for station 1E-0 showing the final geoelectric model after the inversion process. The resistivity curve has a KH shape](image)

Layer 1 and Layer 2

Layer 1 is 23 meters thick where the surface is high resistivity at the surface and low resistivity below. The second layer from the surface is about 15 meters thick with a resistivity of 58 ohm-m. This geoelectric layer is seen as water bearing. These two layer host an aquifer and it is which is seen at 10 to 38 meters depth.

Layer 3

This layer is 23 meters thick and overlaying is a lower resistivity layer 2. This layer is 68.2 ohm-m and is seen as having good aquifer properties. The layer is encountered at 38 to 61 meters depth.
Layer 4

This layer is 34 meters thick and has a resistivity of about 95 ohm-m and is overlain by layer 3 which is of a lower resistivity. Layer 4 forms the upper part of the major aquifer in Kabatini and the resistivity lowers with depth. This layer is indicates that it semi porous meaning it has some potential for holding fluid but it is not water saturated and it is encountered at 61 meters depth.

Layer 5

This layer is very resistive with a resistivity of 169 ohm-m and it occurs at 95 meters from the surface. The layer persists with depth.

Station 2E, 0

In this station (Figure 5.5) there are 4 major layers which can be identified in this station.

![Resistivity plot for station 2E-0 showing the final geoelectric model after the inversion process. The resistivity curve has a HK shape](image)

Figure 5.5: Resistivity plot for station 2E-0 showing the final geoelectric model after the inversion process. The resistivity curve has a HK shape.
Layer 1

The upper is 15 meters thick and has on average low resistivity of 26 ohm-m. This zone is water saturated.

Layer 2

This layer is encountered at about 20 meters depth from the surface and it has a high resistivity of about 121 ohm-m. This geoelectric layer is seen as a compact rock and not water bearing. The layer is 30 meters thick.

Layer 3

This layer forms the major aquifer is water saturated zone is encountered at 51 meters and the resistivity of this zone is 23 ohm-m.

Layer 4

This layer about 66 ohm-m and it persists with depth. This zone is porous but it not fully water saturated.

Profile 1S

Figure 5.6 displays the profile 1S which is highlighted in red comprising of stations 1W-1S, 0-1S, 1E-2S and 2E-1S. This is the second profile to the South.

Figure 5.6: Profile 1S showing 1W-1S, 0-1S, 1E-1S and 2E-1S stations
Station 1W, 1S

In this station (Figure 5.7) there are 3 major geoelectric layers which can be identified in this station.

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Iteration = 3</th>
<th>RMS = 4.18%</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>32.30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>53.54</td>
<td></td>
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</tr>
<tr>
<td>92.48</td>
<td></td>
<td></td>
</tr>
<tr>
<td>165.00</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 5.7: Resistivity plot for station 1W, 1S showing the final geoelectric model after the inversion process. The resistivity curve has a KH shape

Layer 1

This surface layer is 20 meters thick and has an average resistivity of 68 ohm-m. This zone hosts the first aquifer. This zone is seen from the surface to about 20 meters depth.

Layer 2

This layer has a high resistivity of 133.4 ohm-m and it is 10 meters thick and is found between 20-32 meters. This geoelectric layer is seen as a compact rock and not water bearing.
Layer 3

This layer is 22 meters thick and is a lower resistivity than the second layer. This layer is 96.6 ohm-m and is seen as having good aquifer properties. The layer is encountered at 33 to 53 meters depth.

Layer 4

This layer forms the major aquifer in Kabatini and the water saturated zone is encountered at 53.4 and this zone persists with depth.

Station 0, 1S

In this station (Figure 5.8) there are 4 major layers which can be identified in this station.

Figure 5.8: Resistivity plot for station 0, 1S showing the final geoelectric model after the inversion process. The resistivity curve has a HK shape.

Layer 1

The first layer is about 10 meters thick and which is high resistivity with an average resistivity of 156 ohm-m.
Layer 2

This surface layer is below the high resistivity layer and has a low resistivity of 22 ohm-m and it is interpreted as the first aquifer. This zone is about 71 meters thick.

Layer 4

This layer has a high resistivity of 231.7 ohm-m and it is 10 meters thick and is found between 20-32 meters. This geoelectric layer is seen as a compact rock and not water bearing.

Layer 5

This layer forms the major aquifer in Kabatini and the water saturated zone is encountered at 100 meters and this zone persists with depth.

Station 1E, 1S

In this station (Figure 5.9) there are 3 major layers which can be identified in this station.

Figure 5.9: Resistivity plot for station 1E, 1S showing the final geoelectric model after the inversion process. The resistivity curve has a KH shape.
Layer 1

The first 30 meters from the surface indicate in general high resistivity but the surface of this layer is weathering and hence lower part of this layer is resistive showing 138 ohm-m.

Layer 2

This layer is 22 meters thick and is a lower resistivity than the second layer. This layer is 104.9 ohm-m and is seen not to have water. The layer is encountered at 32 to 55 meters depth.

Layer 3

This layer forms the major aquifer in Kabatini and the water saturated zone is encountered at 54 meters and the resistivity of this zone is 41 ohm-m. This layer persists with depth.

Station 2E, 1S

The geo electric layer for this station (Figure 5.10) show very interesting result of about 3 distinct layers in terms of resistivity variations.

Figure 5.10: Resistivity plot for station 2E, 1S showing the final geoelectric model after the inversion process. The resistivity curve has a HK shape.
Layer 1

The upper surface shows a high resistive layer of about 30 meters and which overlays a conductive layer. This layer acts as the cap of the main aquifer below this layer.

Layer 2

The second layer host the main aquifer and is encountered at 30 meters is water saturated to about 76 meters. The resistivity value for this layer is 25.5 ohm-m.

Layer 3

This layer is has a resistivity of 66.4 ohm-m and is found at 76 meters depth and this layer persist with beyond 165 meters. This layer also bears water and is makes the periphery of the aquifer.

Profile 2S

The profile 2S is shown highlighted in Figure 5.11.

![Diagram of Profile 2S](image)

Figure 5.11: 1W-0, 0-0, 1E,0 and 2E-0 stations highlighted in block red line along Profile 2S.
Station 1W, 2S

In this station (Figure 5.12) there are 3 major layers which can be identified in this station.

![Resistivity plot for station 2E, 1S showing the final geoelectric model after the inversion process. The resistivity curve has a KH shape.](image)

**Layer 1**

This layer is generally high resistivity layer which is 20 meters thick and the average resistivity of 300 ohm-m.

**Layer 2**

This layer forms part of the major aquifer and is about 18 meters thick with resistivity between 84 ohm-m to 115 ohm-m. This is of moderate resistivity and its about 30 meters in depth. It is the transition zone between the high resistivity and the low resistivity zones. This layer has some water holding capabilities.
Layer 3

This layer forms the major aquifer in and is encountered at 66 meters. This layer is water saturated and has a resistivity of 29.6 ohm-m.

Station 0, 2S

In this station (Figure 5.13) there are major 4 layers which can be identified in this station.

Figure 5.13: Resistivity plot for station 0, 2S showing the final geoelectric model after the inversion process. The resistivity curve has a KH shape.

Layer 1

The upper is 22 meters thick and a resistivity variation from 74.5 ohm-m to a high of 169.8 ohm-m. This is due to dry sediments at the surface and within the layer, 7 meters depth, is a thin film of water about 10 meters thick underlying the resistive sediments and below.
Layer 2

The second layer from the surface is about 23 meters thick with a very high resistivity of 455 ohm-m. This geoelectric layer is seen as a compact rock and not water bearing. The layer is encountered at 22 to 45 meters depth. The layer reduces in resistivity between the boundary of the third layer.

Layer 3

This layer is 15 meters thick and has a resistivity of about 87.9 ohm-m and is overlain by layer 3 which is of a higher resistivity. Layer 4 forms the upper part of the major aquifer in Kabatini and the resistivity lowers with depth. This layer is mostly porous which means has water holding capacity and is encountered at 45 meters depth.

Layer 4

This layer forms the major aquifer in Kabatini and the water saturated zone is encountered at 60 meters and the resistivity of this zone is 10 ohm-m. The low resistivity persists with depth.
Station 1E, 2S

In this station (Figure 5.14) there are major 4 layers which can be identified in this station.

![Resistivity plot for station 1E, 2S showing the final geoelectric model after the inversion process. The resistivity curve has a KH shape.](image)

**Layer 1**

The upper is 24 meters thick and an average resistivity of about 20 ohm-m. This is due to wet sediments at the surface and within the layer, 8 meters depth, is a thin film of water about 5 meters thick underlying the resistive sediments and below.

**Layer 2**

The second layer from the surface is about 20 meters thick with high resistivity of 166 ohm-m. This geoelectric layer is seen as a compact rock and not water bearing. The layer is encountered at 33 to 53 meters depth. The layer reduces in resistivity between the boundary of the third layer to 107 ohm-m.
Layer 3

This layer is 36 meters thick and has a resistivity of about 53.7 ohm-m and is overlain by layer 3 which is of a higher resistivity. This layer forms the upper part of the major aquifer in Kabatini and the resistivity lowers with depth. This layer is mostly porous which means has water holding capacity and is encountered at 45 meters depth.

Layer 4

This layer forms the major aquifer in Kabatini and the water saturated zone is encountered at 88 meters and the resistivity of this zone is 10 ohm-m. The low resistivity persists with depth.

Station 2E, 2S

In this station (Figure 5.15) there are 5 major layers which can be identified in this station.

![Resistivity plot](image)

**Figure 5.15:** Resistivity plot for station 2E, 2S showing the final geoelectric model after the inversion process. The resistivity curve has a KH shape.
Layer 1

The upper is 20 meters thick and a resistivity variation from 44.7 ohm-m to a high of 123.4 ohm-m. The resistivity variation is due to top soils and sediments due to which are moist and they overlie a resistive rock.

Layer 2

The second layer from the surface is about 24 meters thick with a very high resistivity of 226 ohm-m. This geoelectric layer is seen as a compact rock and not water bearing. The layer is encountered at 20 to 43 meters depth.

Layer 3

This layer is 59 meters thick and is a lower resistivity than the second layer. This layer has an average resistivity of 23 ohm-m and is seen to host the first aquifer. The layer is encountered at 43 to 102 meters depth.

Layer 4

This layer is 39 meters thick and has a high resistivity of 152 ohm-m. This layer act as a barrier between the first aquifer and the second major aquifer which is found right below this layer. The layer is encountered at 102 to 140 meters depth.

Layer 5

Layer 5 forms the major aquifer in Kabatini and the water saturated zone is encountered at 140 meters and the resistivity of this zone is 10 ohm-m.

Profile 3S

The 4 stations in profile 3S is highlighted in Figure 5.16 below.
Figure 5.16: Stations 1W-3S, 0-3S, 1E-3S, and 2E-3S along profile 3S

Station 1W, 3S

In this station (Figure 5.17) there are 3 major layers which can be identified in this station.

Figure 5.17: Resistivity plot for station 1W,3S showing the final geoelectric model after the inversion process. The resistivity curve has a KH shape.
Layer 1

The upper is 22 meters thick and a resistivity variation from 93 ohm-m to a high of 244 ohm-m. These are the sediments and silts at the ground surface.

Layer 2

This layer is 45 meters thick and is a lower resistivity than the first layer. This layer has average resistivity of is 83 ohm-m and is seen as having good aquifer properties though is not saturated. The layer is encountered at 22 to 67 meters depth.

Layer 3

This layer forms the major aquifer in Kabatini and the water saturated zone is encountered at 67 meters and the resistivity of this zone is at 68 ohm-m to 28 ohm-m and this layer persist beyond 165 meters.

Station 0, 3S

In this sounding (Figure 5.18) the layers are very distinct with 3 layers the major aquifer appearing at 70 meters depth. The resistivity curve has a KH shape.

Figure 5.18: The measured and modeled data for Station 0, 3S with layered resistivity model.
Layer 1

The upper is 23 meters thick and a resistivity variation from 57 ohm-m to a high of 202 ohm-m. The layer is very resistive and compact.

Layer 2

The second layer from the surface is about 49 meters thick with a very high resistivity of 148.5 ohm-m. This geoelectric layer is also seen as a compact rock and not water bearing. The layer is encountered at 23 to 71 meters depth.

Layer 3

This layer forms the major aquifer in Kabatini and the water saturated zone is encountered at 71 meters depth and the resistivity of this zone is 48.8 ohm-m.

Station 1E, 3S

In station 1E-3S (Figure 5.19) there are 5 major layers which can be identified in this station.

Figure 5.19: The measured and modeled data for Station 1E, 3S with layered resistivity model. The resistivity curve has a KH shape.
Layer 1

The upper is 22 meters thick and a resistivity variation from 38 ohm-m to a high of 104 ohm-m. The low resistivity zone is seen in top of the layer as a very thin film which is less than 5 meters in thickness. This thin layer is followed by a high resistivity layer of 104 ohm-m which reduces to 92 ohm-m still within this layer.

Layer 2

The second layer from the surface is about 16 meters thick with a very high resistivity of 98 ohm-m. This geoelectric layer is seen as a compact rock and not water bearing. The layer is encountered at 22 to 38 meters depth.

Layer 3

This layer is 36 meters thick and is a lower resistivity than the second layer. This layer is 74.5 ohm-m and is seen as having good aquifer properties. The layer is encountered at 38 to 74 meters depth.

Layer 4

This layer is 50 meters thick and has a resistivity of about 50 ohm-m and is overlain by layer 3 which is of a higher resistivity. Layer 4 forms the upper part of the major aquifer in Kabatini and the resistivity lowers with depth. This layer is mostly porous which means has water holding capacity and is encountered at 74 meters depth.

Layer 5

Layer 5 forms the major aquifer in Kabatini and the water saturated zone is encountered at 124 meters and the resistivity of this zone is 28 ohm-m.
Station 2E, 3S

The data in this station (Figure 5.20) show a KH type VES curve with five major layers.

![Measured and Modeled Data](image)

Figure 5.20: The measured and modeled data for Station 2E, 3S with layered resistivity model. The resistivity curve has a KH shape.

**Layer 1**

This layer is 28 meters thick and has 8 geoelectric layers identified. From the surface of this layer the resistivity is 73 ohm-m and it increases to 154 ohm-m which lowers to 79 ohm-m at the boundary with the second layer. The resistivity variation in this layer from 79 ohm-m to 154 ohm-m is attributed to the silt and clay minerals at the surface which are water bearing. This layer hosts the first but minor aquifer.

**Layer 2**

The second layer from the surface is about 16 meters thick with a very high resistivity of 123 ohm-m. This geoelectric layer is seen as a weathered surface of a more resistive rock below this layer. This layer is encountered between 28 to 45 meters depth.
Layer 3
This layer is 37 meter thick and is a high resistive layer with a resistivity of 197 ohm-m. This layer is high resistive and is interpreted as compact and is not water bearing. This layer is encountered between 45 to 82 meters depth.

Layer 4
This layer is 33 meters thick 90.5 ohm-m and is overlain by layer 3 which is of very high resistivity. This layer is semi porous which means has some amount of water. This layer is encountered between 82 to 116 meters depth.

Layer 5
Layer 5 forms the major aquifer in Kabatini and the top of this aquifer begins at 116 meters depth and is highly water saturated.

5.2 Two Dimensional (2D) Sounding Results

5.2.1 Electrical resistivity tomography 2D profile
The electrical resistivity tomography was done using Syscal R2 plus and was done on a north west - south east direction as shown in Figure 5.21.
After the layout has been done and data collected an electrical resistivity profile is generated automatically and 3 plots are displayed on a window of the instrument.

The first plot displays the measured apparent resistivity pseudosection which is a plot of apparent resistivity versus depth.

The second plot represents the pseudosection of apparent resistivities calculated from the current model. Pseudosection shows the variation of the measured parameter with position and with effective depth of penetration, rather than with true depth.

The third plot is a display of the resistivity model along the profile (Figure 5.20).

To obtain the results which are automatically plotted by the instrument, an inversion routine is applied by a program based on the damped least squares method. Figure 5.22 shows the results of the tomography section show the resistivity image to a depth of 65 meters. The tomography show the top of the main aquifer at 60 meters and it is not confined at the centre. The upper surface shows a resistive structure which overlies the major aquifer and a resistivity break is noticed at the centre of the profile about 160 meters on the profile length. There is a minor aquifer seen between 6 meters depth to about 20 meters depth and they are seen as isolated pockets and it shows that if there is a lot of recharge these surface aquifers are interconnected. The main aquifer is seen as structurally bound on the east-west direction. There is an indication of a channel which is oriented on a north south orientation and it forms the major Kabatini aquifer.
Figure 5.22: Electrical resistivities tomography profile showing 3 plots. From the top are measured apparent resistivity section, calculated apparent resistivity pseudosection and true resistivity with depth respectively.
5.2.2 Two Dimensional (2D) plots of Kabatini using 1D sounding data

The 1D plots using Earth ware interpretation software were plotted using a 4D programme. The programme enables display of data as 2D slices and 3D cubes showing the resistivity distribution. The data is arranged in X, Y and Z format, where the true resistivity value is named Resistivity (see appendix). The data is arranged to have the X and Y position on the ground while the Z is the depth at which the resistivity change occurs. The resistivity is value is displayed in colours where blue indicates low resistivity and lighter colours show the high resistivity where the colour intensity indicates change to red show the very high resistivity values.

Figure 5.23 shows the 2D cross-section displayed in slices cut in east-west direction. The resistivity variation shows a high resistivity at the surface and decreases with depth to indicate the aquifer which is seen to trend along the north south direction. The high resistivity zone is displayed in lighter colours i.e green and red while blue colour represents low resistivities in this case the aquifer. The cross section show that the aquifer is structurally controlled and has a north south orientation. The upper surface shows high resistivity which is broken by a linear trend below indicating water channel which is water saturated. The results of the planar sections show corelation with the tomography results and the advantage with the 2D sections is that the show deeper than the electrical resistivity tomography section.

The 2D and the 3D plots are displayed with cordinates which just show the relative positions to enable plotting. The point 170.0 shows the surface while point 0.0 shows the total depth to 170 meters.
Figure 5.23: Planar sections in east-west direction showing the flow movement in the north-south direction. The point 170, 0 denotes the surface while 0, 0 denotes the total depth of 170 meters. The X and Y shows the relative coordinate at depth.
Figure 5.24 below shows the cross section in north south direction which confirms the linear trend of the aquifer in the north south direction where the an open channel in the middle is water saturated. There is no structural boundary in the north and south confirming that the flow is on an open channel. The water saturated open aquifer has a northern and southern continuity but is seen to be semi bound on the west with a high resistivity wall.

Figure 5.24: A different side view of the aquifer which shows the lateral and aerial extent of the aquifer. This view enable a side view to delineate the high resistivity of the upper surface.
Figure 5.25 shows the iso resistivity planes from the surface and clearly show the aquifer extends beyond 165 meters depth. The high resistivity at the surface at some point show that the river channel is open towards the centre and some places confined. The open channel shows a structural trend as can be traced by the iso resistivity planes.

Figure 5.25: Planar sections of from the top surface to a bottom depth of 165 meters
5.3 3D Resistivity structure for Kabatini aquifer

The models data of the 1D sounding was arranged in a 3D format and plotted to give the 3D distribution of the resistivity with depth of each sounding and the program extrapolated to the nearest neighbouring sounding to form a volume. The Kabatini data hence is visually displayed in a volume to clearly map the geophysical structure of the area. This was achieved by the mode of collecting the data in a grid to ensure that the resistivity values with depth for each sounding is plotted relative to the neighbouring sounding. Figure 5.26 shows the dissected section of the volume to show the high resistivity zone and delineate the extent of the aquifer. The major aquifer is bound by a resistive surface confining it but below this the aquifer is an open channel and from the volume displayed the channel is running from north south direction (Figure 5.26).
Figure 5.26: A dissected block volume of the Kabatini aquifer displaying the sounding measurement in the red dots

The data was plotted as a complete volume showing the position and the amount of water within the aquifer. Figure 5.27 below show the complete volume of the aquifer showing the water saturation and open channel at the center of the volume which indicates the open channel and at depth the water saturates the geological formation.
Figure 5.27: A full block 3D volume displaying the Kabatini aquifer
5.2 Discussion of results

The 3D geophysical structure of Kabatini shows a water saturated aquifer with interconnections between the surface aquifer and the major aquifer found at 7 meters and 60 meters depth. The aquifer is recharged from the north and south because it shows an open channel from north and also in the south direction. The 1D models shows geoelectric layers with distinct resistivity properties. These are not correspondent to geologic layers due to the properties of the layer which determines the resistivity of the layer. The layers were identified by looking at the models and 2 aquifers were identified. The major aquifer at about 60 meters and the minor aquifer is occurs between 6 meter and 20 meters from the surface. When resistivity methods are used, limitations can be expected if ground in homogeneities and anisotropy are present (Senos Matias, 2002). The major limitations of the electrical resistivity method are resolution, suppression and equivalence. They are all associated with the concept of relative thickness which is defined as the ratio of the thickness of a layer to the depth to the top of the layer. Usually the resistivity method is unable to resolve thin layers i.e. relative thickness. It follows that the method can resolve considerable detail near the surface, but can see only bulk zones at depth. Usually, soundings can resolve no more than six to eight layers.

The borehole information (Table 5.1) of the Kabatini well field show that they are high yielding boreholes hence validating the 1D, 2D and 3D models that have been discussed herein.

Table 5.1: Kabatini bore hole information (Extracted from Ministry of Water, Kenya)

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The borehole information supports the conclusion that Kabatini is a highly saturated aquifer.
6.1 Conclusion

The VES and electrical resistivity tomography were used successfully to map out the 3D geophysical structure of Kabatini. The VES 1D models, the 2D sections and iso resistivity maps as well as the 3D electrical resistivity volume maps out the Kabatini aquifer spatially. There are mostly 3 to 5 layers seen and discussed in the Kabatini aquifer. The major aquifer extent has been seen as open on a north south direction but semi bound to the west. The aquifer extends more than 165 meters depth.

From the discussions above it can be concluded that:-

1. The aquifer is located on an open channel running north south which can be inferred to as a river channel owing to the River Ngosur disappearing upstream. The 3D resistivity volume confirms this.
2. The channel is structurally controlled and the movement of water is seen to be flowing southwards.
3. The aquifer shows a great potential for exploitation as it shows it is a highly saturated aquifer.

6.2 Recommendations

From this study it has shown that the vertical electrical sounding (VES) and electrical resistivity tomography methods are efficient for mapping out the subsurface and more so map out the aquifer geometry. This determines the extent and the volume of the aquifer. The results obtained in this dissertation can be used as a baseline for management of the aquifer in Kabatini to ensure protection from contamination and other environmental hazards. The changes in resistivity can be monitored over time and check if there is any pollution of the resource. The following recommendations are suggested from this study and they are:-

1. The aquifer is open hence it is important to keep monitoring it on a defined time period so that there may be no effluents that will leach into the aquifer. This can be done by
electrical resistivity tomography and results obtained over time are compared and interpreted for action and management.

2. Nakuru area has a rising population and hence further studies are recommended to ensure minimum strain in groundwater extraction in this aquifer.

3. From the results it is seen Kabatini is recharged by a river and basically the aquifer is located along a river channel hence it is important to manage the River Ngorsur upstream to ensure the catchment area is preserved to ensure the survival of the aquifer. In addition, it is important to obtain more data upstream to map out the outline of the river to the source.
REFERENCES


# APPENDIX

Appendix 1: Data used to plot the 2D planar sections and 3D volume.

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