EVALUATION OF GROUNDWATER FLOW CHARACTERISTICS AND PROPERTIES OF A SHALLOW AQUIFER

A Case of Nyabondo Plateau, Kenya

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A thesis submitted to the Graduate School in partial fulfilment of the requirements of a Master of Science degree in Agricultural Engineering of Egerton University

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DECLARATION AND RECOMMENDATION

Declaration

This is to declare that this thesis is my original work and has not been submitted for award of any degree or diploma in any other University known to me.

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Recommendation

This thesis has been submitted to Egerton University Graduate School with our recommendation as supervisors.

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DEDICATION

This thesis is dedicated to my daughter Candy and son Henry. They have been a source of inspiration to me. The Lord Almighty has been truthful by giving the courage to persist and do what is right.

ABSTRACT

The Nyabondo plateau aquifer is an important source of water to the local population. Water is abstracted from the shallow wells which are hand dug using buckets and hand operated pumps. The wells have been dug to depths ranging from 3m to 11m, are mainly open and unlined. Increased demand for water has resulted in the construction of more wells coupled with increased abstraction rates which may not be sustainable. In order to determine the groundwater flow characteristics of the area, aquifer properties such as hydraulic head, specific yield and hydraulic conductivity were determined using field methods and laboratory experiments. Mean values of these properties were entered into the MODFLOW model. Model evaluation resulted in goodness of fit (R^2) of 0.51; Root Mean Squared Error (RMSE) of 5.87 and a Nash-Sutcliffe model efficiency of 0.397. These results showed that the model could satisfactorily estimate the groundwater flow properties of a shallow aquifer system. The study covered the period between January and May which was a wet season with a computed recharge flux of 0.00173m/day. The model outputs included two dimensional hydraulic head surface maps and cell by cell flows in the front and right faces. These would be important reference material to water planners and decision makers. A volumetric groundwater budget for the area showed that measures need to be taken to reduce the strain on groundwater.

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LIST OF ABBREVIATIONS AND ACRONYMS

AQUA3D	Three Dimensional Finite-Element Groundwater Flow and Transport Model
CCK	Communication Commission of Kenya
GFLOW	Groundwater Flow Model
GIS	Geographical Information System
GoK	Government of Kenya
GPS	Geographical Positioning System
HHS	Hydraulic Head Surface Map
ICRAF	International Centre for Research in Agro-forestry
LBDA	Lake Basin Development Authority
MicroFEM	Finite-Element For Multiple Aquifer Groundwater Flow Modeling
MODFLOW	Modular Three Dimensional Finite Difference Groundwater Flow Model
MoWI	Ministry of Water and Irrigation
MT3DMS	Multi-Species Three Dimensional Solute Transport Model
NGWA	National Groundwater Association
NWRMS	National Water Resources Management Strategy
RMSE	Root Mean Squared Error
SEAWAT	Computer Program for Simulation of Three-Dimensional Variable-Density Ground-Water Flow
SIDA	Swedish International development Agency
SSG	Scientific Software Group
USCS	Unified Soil Classification System
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
UTM	Universal Transverse Marcater

CHAPTER ONE

INTRODUCTION

1.0 Background Information

Nyabondo Plateau is located in Upper Nyakach division, Nyanza Province of Kenya. It is situated between the Sondu-Miriu River and Awach Kano River which flow into Lake Victoria. With a population density of 368 persons per square kilometer (CCK, 2006), the area is one of most densly populated rural areas in Kenya. The estimated annual population growth rate for the area is 3% resulting in doubling of the population every 22 to 25 years (Mbaria, 2006; Ong'or, 2005). The provision of water for domestic use in sufficient quantity and quality to meet the needs of the growing population has therefore remained a challenge. The main sources of water are springs, surface ponds, piped water supply and shallow wells. While the springs are far apart, the surface ponds are mainly used for drinking by livestock hence are heavily polluted. The Nyakach Water Project is a piped water supply system drawing water from Sondu-Miriu River. It was funded by the Government of Kenya with support from the Swedish International Agency (SIDA) but currently it is undergoing management and capacity problems (Ouko, 2005). To complement the above water sources, shallow wells have been dug in many homesteads to depths ranging from 2m to 11m. The water table is shallow and fluctuates during the year depending on rainfall amounts. As a result, some of the wells dry up during the dry season. According to the Lake Basin Development Authority's (LBDA) Water Resources Survey Report of 1987 for Nyakach Division, a total of 268 shallow wells were identified of which 95% were located within the Nyabondo plateau. The three sub-locations (based on 1987 administrative boundaries) which fall within the plateau, namely Kajimbo, Kadianga East and Koguta East had 22%, 50% and 51% of their populations relying on the shallow wells for their daily water needs (LBDA, 1987).

There is little technical data available on the area's groundwater potential making sustainable planning, design and construction of hand dug wells difficult. As indicated in the National Water Resources Management Strategy (NWRMS) 2007-2009 report, it may not be possible to make reliable decision without relevant and up to date data, therefore, the need to give more attention to monitoring ground water resources to address data inadequacy. (MoWI, 2007).

Models are developed to simulate groundwater flow but these would require adequate hydro geological data which may not be readily available for most parts in

Kenya (MoWI, 2007). Therefore, rather than start model development from scratch, it is advisable to adopt an existing model, verify its applicability and modify it in order to handle the unique properties of the new environment (James and Stephen, 1982). Despite the fact that the forecasts may be imprecise, this could offer the best decision making information availablein a particular situation. The model simulation results need to be presented in a simplified format for policy making, planning and design applications. In this study a finite difference groundwater flow model, MODFLOW 2000 which has so far been evaluated for deep aquifer conditions and boreholes in Kenya (Kiptanui, 2006) was tested for applicability to shallow aquifer conditions. Field tests combined with laboratory analysis were used to estimate the aquifer properties of the area. Due to the spatial variability of the hydro geological data collected, GIS was used to collate and analyse the data. Hydrogeological-GIS techniques were applied to link the input data, the model and the model outputs and to produce hydraulic head surface maps for groundwater evaluation.

1.1 Statement of the Problem

Many shallow wells have been dug to meet the domestic water demand for the growing population within the Nyabondo Plateau. This has often been done with little technical planning or design considerations hence there were risks of quality degradation and/or over abstraction and therefore may not be sustainable. The aquifer properties and capacity of wells are not clearly defined which can make well development activities to impact negatively on the environment.

1.2 Objectives

The broad objective of this study was to evaluate the groundwater flow characteristics and properties of a shallow aquifer in Nyabondo plateau, Kenya.

The specific objectives were:

1.) To determine the aquifer properties and their spatial variation within the Nyabondo plateau.

2.) To test MODFLOW model and use it to estimate groundwater flow characteristics in a shallow aquifer.

3.) To determine the existing groundwater potential that can be abstracted using the shallow wells in the study area.

1.3 Research Questions

1.) How do the aquifer properties vary spatially over the study area?

2.) How accurately does MODFLOW model estimate the prevailing groundwater flow conditions in a shallow aquifer with respect to the study area?

3.) What is the existing groundwater potential in the area that can safely be abstracted using shallow wells?

1.4 Justification

To meet a community's water demand, various water sources including both surface and ground water need to be identified and developed. The extent to which either of the water sources are developed depends on several factors such as reliability of supply, cost and availability of finances, operational and maintainance requirements. Some of the gains made in the provision of safe water have been threatened by over-extraction, competition and environmental pollution. In Nyabondo plateau, shallow wells have been dug to either supplement or supply the total family water demand. However, more effort is required to develop systems that result in better planning, design and management of the groundwater resource to ensure that current and future demands for water are met. These include identifying the groundwater potential of the area, recharge zones which may require protection, safe yields under varying climatic conditions and groundwater mapping combined with equipping the community with appropriate technical tools and knowledge required to manage the local water resources in a more sustainable manner.

The improved design of the wells based on the capacity of the aquifer is therefore expected to result in a more reliable groundwater system in the area. Improved management of the groundwater resources would also ensure more water is available to the consumers hence assist the people of Nyabondo Plateau to meet one of the Millenium Development Goals of halving the proportion of people without sustainable safe drinking water by the year 2015.

CHAPTER TWO

LITERATURE REVIEW

2.0 Groundwater

Groundwater is the water located beneath the ground surface in soil pore spaces and in the fractures of lithologic formations. It is estimated that of all the freshwater that exists, about 75% is stored in the polar ice and glaciers. Groundwater accounts for approximately 25% while rivers and lakes account for less than 1% of the world total fresh water reserves. This shows the importance of groundwater since the bulk that is stored in polar ice and glaciers is not readily available. Specifically, groundwater is able to provide farms and small rural communities with water supplies relatively cheaply and in close proximity to the users often without the need for complex treatment (MacDonald and Davies, 2000). However, the increasing abstraction to meet the rising demand is raising concerns on the sustainability of the resource and the livelihoods that may rely on it (Gale et al., 2002).

2.1 Groundwater Recharge and Discharge

Recharge of groundwater occurs where precipitation that falls on the land area is able to infiltrate into the ground or due to water in the surface water bodies moving into the ground. Water enters the soil through infiltration to become soil water and may or may not completely fill the pores between the soil particles resulting in the saturated zone or unsaturated zone respectively. Flow in the unsaturated zone is essentially vertical due to gravity but can also be upward due to the evapotranspiration process or lateral due to the matric potential. The recharge may be affected by topography and geology of the area, precipitation amounts, runoff and ponding of water, irrigation, rivers, soil depth and the unsaturated zone.

The depth to the water table affects the method used in abstracing groundwater for various applications. In areas where the water table is at great depth, well construction and pumping for domestic purposes can be prohibitively expensive. Water is accessed by drilling deep, small diameter boreholes which are held open by the metal casings. In this case, pumps are installed to lift water out of the boreholes. For shallow water tables, shallow wells are used. These wells are often dug by hand and are typically of large diameters. Water is withdrawn from the wells using buckets or hand operated pumps. Hand dug wells are a common feature in the rural areas of sub-Saharan Africa mainly because they are relatively inexpensive to construct and require little technical expertise and materials (Morris et al., 2003).

2.2 The Aquifer System

An aquifer is defined as a geological formation which not only store water but easily transmits and yields it in sufficient quantity to permit economic development. An aquifer system comprises of the geometry of the aquifer, the boundary conditions, aquifer type and the hydraulic parameters of the aquifer.

2.2.1 The Aquifer Geometry and Type

The aquifer geometry is determined by the extent and thickness of the aquifer. The geometric parameters are derived from the study of geology of the area, borehole drilling data, geophysical well logs and geophysical surface studies such as geo-electrical surveys.

Aquifers can be confined, semi-confined (leaky), or unconfined (phreatic). Confined aquifers are completely filled with water and bounded above and below by an impervious layer as shown in Figure 1(a) below. Unconfined aquifers on the other hand are bounded below by an impervious layer but not restricted by a confining layer at the top as shown in Figure 1(b). Its upper boundary is the water table that is free to rise and fall. Semi confined aquifers are those whose upper and lower boundaries are aquitards or one boundary may be an aquitard while the other is an aquiclude with the water being free to move up or down through the aquitards. A perched water table can also result when vertical flow is impeded by an impervious layer to be completely filled and become saturated.

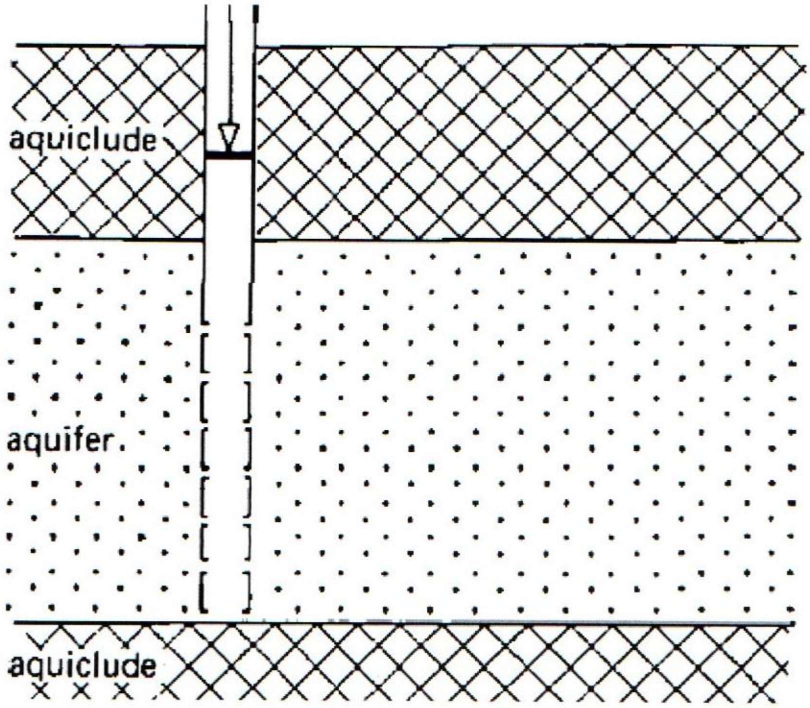


Figure 1(a): Confined aquifer

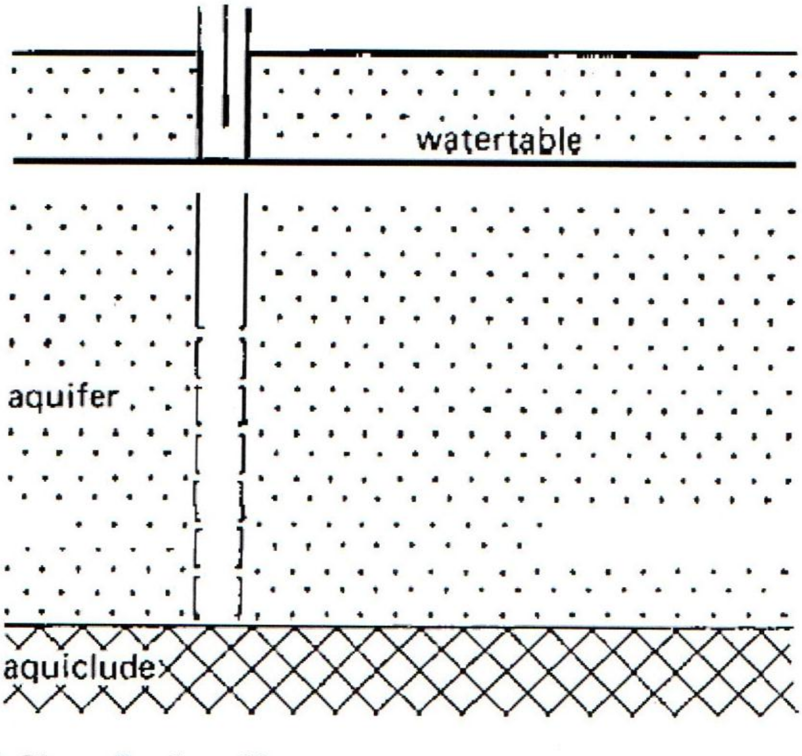


Figure 1(b): Unconfined aquifer

2.2.2 Boundary Conditions

Various types of boundary conditions exist. A no-flow boundary results when the boundary of an aquifer consists of an impervious barrier. However, if the boundary is pervious, flow may occur if there is a head difference between the groundwater on either side of the boundary, hence a head controlled boundary results. If the flow across the boundary is not determined by a head difference, then the boundary is said to be flow controlled.

2.2.3 Porosity

Porosity, η is defined as the ratio of the pore volume to the total volume of the formation. Unconsolidated granular sediments such as sand or gravel contain pore spaces between the grains and the water content can exceed 30% of the volume. However this volume is reduced when the proportion of finer materials such as silt and clay increase and as consolidation occurs.

In general, the porosity of a soil or rock sample depends on the shape and arrangement of particles, level of sorting, cementation or compaction, removal of material by solution, fracturing and jointing. It is expressed as;

$$\eta = \frac{V_t - V_s}{V_t} = \frac{V_v}{V_t} \tag{1}$$

V_t is the total volume of a soil or rock sample, V_s is the volume of solids in the sample and V_v is the volume of openings or voids which can be determined through laboratory analysis of the aquifer material.

2.2.4 The Coefficient of Permeability (Hydraulic Conductivity)

The coefficient of permeability, K of a material comprising a formation is a measure of the materials capacity to transmit water expressed as the rate of flow through a unit cross sectional area under 100 percent hydraulic gradient. The horizontal permeability of the vadose zone is normally greater than the vertical permeability especially in layered soils. Permeability can be determined using either field or laboratory methods. The laboratory methods are often used to determine the vertical hydraulic conductivity of soil samples and include the falling head method used for fine grained aquifers or cohesive soils and the constant head method for coarse grained aquifer. In both cases, disturbed or undisturbed soil samples may be used. Permeameters for in situ permeability determination are also available. For example, the Guelph permeameter which is a constant head permeameter designed for field application. It involves measuring the steady state rate of water recharge into unsaturated soil from a 5 cm cylindrical hole in which constant head is maintained. Its application is however limited to a depth range of 15cm to 75cm (Rickly Hydrological Company, 2010).

It has been noted that field measurement of hydraulic conductivity can be problematic since the value of hydraulic conductivity obtained may vary over several orders of magnitude depending on soil type. It can vary markedly in space even with apparently minor changes in soil characteristics. It is also direction dependent such that at a specific point, the vertical and horizontal hydraulic conductivities may not necessarily be the same.

2.2.5 Coefficient of Transmissivity

The coefficient of transmissivity, T is expressed as the rate of flow of water at the prevailing temperature through a vertical strip of the aquifer of unit width extending the full saturated height of the aquifer under hydraulic gradient of 100% (Ferris et al., 1962).

$$T = Kb \tag{2}$$

Where;

T is the transmissivity

K is the hydraulic conductivity

b is the saturated depth of the aquifer

2.2.6 The Storage Coefficient and Specific Yield

This is the volume of water an aquifer can release or take into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface. It plays a vital role for the transient behaviour of groundwater flow and the estimation of withdrawal rates from an aquifer. For a confined aquifer, the water released from or taken into storage in response to a change in head is attributed solely to the compressibility of the aquifer material and of water (Ferris et al., 1962).

For an unconfined aquifer, the water released from or taken into storage in response to change in head is attributed partly to gravity drainage or refilling of the zone through which the water table moves, and partly to the compressibility of water and aquifer material in the saturated zone. However, the water attributable to compressibility is usually negligible compared to the total water released and can be ignored. The storage coefficient is therefore equivalent to the specific yield of the aquifer.

2.3 Determination of the Aquifer Hydraulic Parameters

2.3.1 The Pumping Test

It can be used to determine the hydraulic conductivity and where the thickness of the aquifer is known, the transmissivity and the storage coefficient or specific yield for a confined or unconfined aquifer respectively. The test uses the principle that if water is pumped from a well, the discharge and resulting drawdown in the well and in piezometers located at known distances from the well measured against specific time can be substituted into well flow equations and the hydraulic characteristics of the aquifer calculated using either graphical or computer programs.

Pumping tests provide results that are more representative of aquifer characteristics than those that may be predicted by slug tests. However, it requires a greater degree of activity and expense and may therefore not be justified at all levels of groundwater investigation. This is because apart from the test well, observation wells also need to be drilled at known distances and sufficient personnel be availed, at least one person per well. It also requires longer duration of pumping which may range from one day to three days depending on the aquifer (USEPA, 1994).

In an attempt to reduce the cost of conventional pumping test, Gross (2008) explored the possibility of using manual pumping test to measure the specific capacity of rope pump wells in Nicaragua but found the method to overestimate the specific yield by 41% compared to the conventional method when the data was analyzed using the equilibrium approximation method. Using the time-drawdown analyses gave results that agreed to within 14% and 31% during the pumping and recovery phases respectively.

2.3.2 The Recovery Analysis

The recovery data collected after pumping has stopped can be analysed to check the results from the pumping test. This is based on the principle of superposition in that it is assumed that after the pump has been shut down, the well starts to receive an imaginary recharge equal to the discharge. This analysis is particularly important if the pumping test is done without the use of piezometers and observations are only recorded from the test well.

2.3.3 Slug Test

A small volume (slug) of water is suddenly removed from a well after which the fall and then rise in water level in the well is measured. Alternatively, a small slug of water can be poured into the well and the rise and subsequent fall of the water level are measured from which the aquifer transmissivity can be determined.

Slug test is considerably more cost effective and simpler because it can be performed by only one or two operators and requires relatively simple equipment. It may therefore be one of the best options for measuring in-situ hydraulic conductivity especially in formations of low hydraulic conductivity (Choi et al., 2008).

Due to the substantial well storage in large diameter dug wells, considerable pumping (slug out) time may be required to lower the water level to a desired position. However in comparative analyses, it has been found that this should not affect the calculated hydraulic conductivity provided that the recovery time is longer than the pumping time (Ratej and Brencic, 2005).

2.3.4 Single Well Tests

In some cases, the hydraulic parameters may have to be determined when there are no observation wells or piezometers and the water level changes are measured only in the pumped well. This may be due to technical or financial constraints in constructing the observation wells or in some cases, no appreciable water level changes are observed in the adjacent well or piezometers. The drawdown in a pumped well is influenced by well losses and well bore storage but in the hydraulics of well flow, the bore storage is assumed negligible. In reality, this storage may be large compared to the storage in an equal volume of aquifer material. This method therefore offers the advantage of accounting for the well bore storage in the analysis of drawdown data. It can be set up as either pumping, slug test or for recovery analysis.

In a comparative analysis of single well aquifer test methods in Borst, it was found that the time of pumping was a key factor. The value of hydraulic conductivity obtained by the various analyses methods closely compared in cases where the pumping times were shorter than the ‘critical time’ which was determined as 30 minutes for that area. However, for longer pumping times, the distinction between the pumping test and slug test results became greater. In such cases, the slug test method could underestimate hydraulic conductivity by as much as two orders of magnitude (Ratej, and Brencic, 2005). In this study, the slug test set up for a single well test was adopted.

2.4 Analysis of Aquifer Test Data

Several aquifer test data analysis methods have been developed. These include graphical as well as numerical methods. Computer programs for analysing the data are also available and most of these can enable the selection of the analysis method based on the data available. Generally, the numerical methods can be grouped as;

i) The curve fitting methods which try to find the best possible fit between emperical data and type curves e.g. the Cooper method.

ii) Straight line methods which derive the drawdown equation with certain operations and/or simplification to the form that yields a straight line graph. The computation of aquifer parameters is facilitated by the slope of the line and its intersection with the ordinate axis. Examples include the Theis, Thiem, Jacob and Bouwer and Rice methods.

2.4.1 Theis Equation

Theis in 1935 developed an equation that could predict transient evolution of head due to pumping one or a number of wells. The Theis formula was based on a heat-flow analogy and accounts for the effect of time and storage characteristics of the aquifer. The Theis equations used to determine the transmissivity and storage are;

$$T = \frac{QW(u)}{4\pi s} \qquad \text{and} \qquad S = \frac{4Ttu}{r^2} \tag{3}$$

Where;

T is transmissivity, S is storage coefficient, Q is pumping rate, s is drawdown, t is time, r is distance from the pumping well to the observation well and, $W(u)$ is well function of u

$$W(u) = -0.577516 - \log u + u - \frac{u^2}{2*2!} + \frac{u^3}{3*3!} - \frac{u^4}{4*4!} + - - - \tag{4}$$

$$u = \left(r^2 s\right)\left(4Tt\right) \tag{5}$$

Graphical or numerical methods are used to solve the Theis equations provided the Theis assumptions are observed. The assumptions are;

- the aquifer is confined and has apparent infinite extent
- the aquifer is homogeneous, isotropic and of uniform thickness
- the well is fully penetrating
- the well diameter is small so that well bore storage is negligible

2.4.2 The Thiem Equation

The quasi-steady state equation for small diameter wells given below was developed by Thiem in 1906.

$$Q = 2\pi T \frac{(h_1 - h_2)}{\ln\left({r_2}/{r_1} \right)} \tag{6}$$

Where;

Q is the constant pump discharge

T is the aquifer transmissivity

h_1 and h_2 are the drawdowns in observation wells at radial distances r_1 and r_2 respectively measured from the center of the test well

This equation was based on the assumption that;

- the aquifer is confined with infinite areal extent
- the aquifer is homogeneous, isotropic and of uniform thickness
- the well must be fully penetrating.

Based on the Thiem equation, Sen (1996) developed a graphical method for storage coefficient determination and found that the results were within acceptable limits of approximation. The use of this method was recommended where no time series showing complete change of drawdown with time during a complete aquifer test were available.

2.4.3 The Jacob Method

This is the most frequently used method for pumping tests. It is based on the Theis equation except that it is applicable to drawdown data. The hydraulic conductivity, K is given by the equation;

$$K = \frac{2.3Q}{4\pi D \Delta s} \tag{7}$$

Where;

Δs is the change in head per on log cycle of time, t on a semi-log plot

D is the diameter of the well.

An additional assumption that must be satisfied for single well tests is introduced as;

$$t > \frac{25r^2}{KD} \qquad r \text{ is the radius of the well.} \tag{8}$$

2.4.4 The Bouwer and Rice Method

The Bouwer and Rice slug test method was developed by Bouwer and Rice in 1976 for unconfined or leaky confined aquifers with incompressible and/or partial penetration. It was designed to more accurately estimate the hydraulic conductivity by better accounting for the well geometry using the equation;

$$K = \frac{r^2 \ln\left(R_{cont} / R \right)}{2L} \frac{1}{t} \ln \frac{h_o}{h_t} \tag{9}$$

Where;

r = well radius

R = radius measured from centre of well to undisturbed aquifer material

R_{cont} = contributing radial distance over which the difference in head, h_0, is dissipated in the aquifer

L = the length of the screen

h_0 = head in well at $t_0 = 0$

h_t= head in well at $t > t_0$

Since the contributing radius of aquifer is seldom known before the test, Bouwer and Rice developed some empirical curves to account for this radius by three coefficients (A, B, C) which are all functions of the screen length (L) to radius (R) ratio. Coefficients A and B are used for partially penetrating wells whereas coefficient C is used only for fully penetrating wells. The analysis is based on the assumption that;

- the aquifer is unconfined and of infinite extent
- the aquifer is homogeneous, isotropic and of uniform thickness
- the well is fully or partially penetrating

- the well bore storage is not negligible and therefore taken into account
- there is instantaneous change in head
- flow into the well is steady state.

This method was adopted during the study as it took into consideration most of the aquifer and well properties of the area.

2.5 Groundwater Flow

Groundwater flow systems consist of water that moves along three dimensional flow paths from points of recharge to points of discharge. Flow is estimated by the Darcy equation which was derived by Henri Darcy in 1856. Based on the continuity equation, discharge is given by the product of velocity and the cross sectional area. The Darcy equation is given by;

$$Q = -KA\frac{dh}{dx} \tag{10}$$

Where;

K is the hydraulic conductivity of the aquifer (LT^{-1})

dh = change in hydraulic head;

dx = horizontal distance

The negative sign signifies that flow is in the direction of falling groundwater head. The term dh/dx is also referred to as the hydraulic gradient, i and can be obtained by calculating the change in water levels measured in monitoring wells within an aquifer divided by the horizontal distance between the wells. For horizontal flow through a unit width of the aquifer,

$$Q_h = -T^*i \tag{11}$$

Where;

Q_h is the horizontal discharge

T is the transmissivity given by;

$$T_x = \sum K_x dz \qquad and \qquad K = \frac{k\rho g}{\mu} \tag{12}$$

ρ and μ are the density and viscosity of water respectively

g is the acceleration due to gravity.

For flow through a unit cross sectional area of the aquifer, the Darcy equation becomes;

$$q = -K\frac{dh}{dx} \tag{13}$$

2.6 Well Hydraulics

The derivation of groundwater flow equation is based on the Dupuit's assumptions which state that;

- The curvature of the free surface is very small so that streamlines can be assumed to be horizontal at all sections.
- The hydraulic grade line is equal to the free surface slope and does not vary with depth.

The three dimensional groundwater flow is defined by the following equations;

$$\frac{\partial}{\partial x}\left(-k_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(-k_y\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(-k_z\frac{dh}{dz}\right)=0 \tag{14}$$

$$\frac{\partial^2 h^2}{\partial x^2}+\frac{\partial^2 h^2}{\partial y^2}+\frac{\partial^2 h}{\partial z^2}=0 \tag{15}$$

2.6.1 Well Flow in Unconfined Aquifer

The discharge, Q of a well penetrating unconfined aquifer can be determined with Dupuits assumptions as:

$$Q = 2\pi K \, {}^{dh}\!/_{dr} \tag{16}$$

which after integration yields;

$$Q = \pi K\frac{h_o{}^2 - h_w{}^2}{\ln {}^{r_o}\!/_{r_w}} \tag{17}$$

The variables in the equation are as described in Figure 2 and can be determined using the pumping tests.

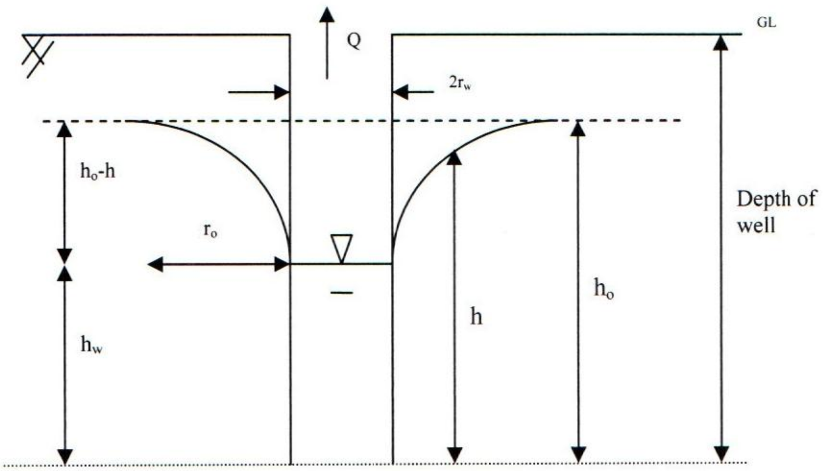


Figure 2: Well discharge in an unconfined aquifer

Shallow wells are often dug to depths of up to 10m and tap their water mainly from unconfined aquifers. When the water is drawn out, the water level inside the well is lowered. The difference between the water table elevation and water level in the well is referred to as depression head *(H),* hence the discharge Q is given by;

$$Q = K_o H \tag{18}$$

K_o is the proportionality constant which depends on the characteristics of the aquifer and well area. It is also referred to as the specific capacity of the well and can be determined by the recuperation test (Subramanya, 2008). This involves pumping the well at a constant rate of Q until a drawdown H_1 is obtained. The pump is stopped and the well allowed to recuperate. The water level in the well is measured at various time intervals, t starting from when pumping stopped as shown in Figure 3. The test setup is similar to the recovery test. The drawdown, h is measured positive downward from the water table and considering a small time interval Δt;

$$Q.\,\Delta t = K_o h.\Delta t = -A.\Delta h \tag{19}$$

$$dt = \frac{A}{K_o}\frac{dh}{h} \quad \text{and integrating;} \quad \int_0^{T_r} dt = -\frac{A}{K_o}\int_{H_1}^{H_2}\frac{dh}{h} \tag{20}$$

$$T_r = \frac{A}{K_o}\ln\frac{H_1}{H_2} \quad \text{or} \quad \frac{K_o}{A} = \frac{1}{T_r}\ln\frac{H_1}{H_2} \tag{21}$$

where $\frac{K_o}{A} = K_s$ = specific capacity per unit well area and can be used in designing dug wells within the aquifer with the discharge Q given as;

$$Q = K_s.AH \tag{22}$$

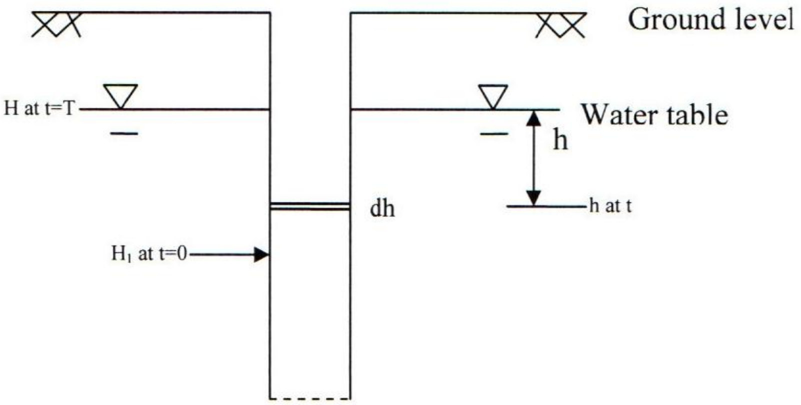


Figure 3: Recuperation test setup for an open well

2.7 Groundwater Flow Models

Apart from use as predictive tools, computer simulation models can also be employed as learning tools to identify additional data that are required to better define and understand groundwater systems. They have the capacity to test and quantify the consequences of various errors and uncertainties in the information necessary to determine cause-effect relationships and related model based forecasts (Alley et al., 1999). Some of the groundwater models include;

2.7.1 SEAWAT

This is a coupled version of MODFLOW and MT3DMS designed to simulate three dimensional variable density saturated groundwater flow. Equations have been added to allow fluid density to be calculated as a function of one or more species of MT3DMS species or as a function of fluid pressure. It can solve simultaneous solute and heat transport with the combined effects of concentration and temperature variable density flow (Langevin et al., 2008). Initial conditions, hydraulic properties and stresses must be specified for every model cell in the finite difference grid.

SEAWAT is a public domain computer program with the source code and software being distributed free by the United States Geological Survey (USGS). Its outputs include hydraulic head, concentration, drawdown, flow budget and transport budget data. The program is therefore suitable where both groundwater flow and solute (contaminant) simulation is required.

2.7.2 MicroFEM

MicroFEM is a finite element program for multiple aquifer steady state and transient groundwater flow modelling. It can simulate confined, semi-confined, unconfined, stratified and leaky multi-aquifer systems with up to a maximum of 20 aquifers. This program is however no longer on offer.

2.7.3 AQUA3D

This program was developed to solve three dimensional groundwater flow and transport problems using the Galerkin finite element method. It can solve transient groundwater flow with inhomogeneous and anisotropic flow conditions. Boundary conditions may be prescribed nodal head and prescribed flow as a function of time or head dependent flow (SSG, 2009). It can be useful in solving transient transport of contaminants and heat with convection, decay, adsorption and velocity dependent dispersion. It has the following main features;

- it enables areal variation of all geological parameters
- any layer can be wetted and dewatered
- real time varying data can be entered from actual observed records
- rivers or estuaries can be simulated in different ways
- contaminant flow model is fully integrated with the flow model
- the model can be changed any time once set up

2.7.4 GFLOW

This is a stepwise groundwater flow modelling system based on the analytic element method. It models steady state flow in a single heterogeneous aquifer using the Dupuit-Forchheimer assumption. This model is particularly suited for modelling regional horizontal flow but also supports conjunctive surface and groundwater using stream networks with calculated base flow (SSG, 2009).

GFLOW has the advantage that it can facilitate stepwise approach to modelling in that it allows one to quickly set up an initial model and build it up as the knowledge of groundwater regime grows. It also offers conjunctive surface water and groundwater solutions. However, as is with other analytic element models, it has the limitation that both transient flow and three dimensional flows are only partially implemented. Gradually varying aquifer properties cannot be represented and it does not support multi-aquifer flow.

2.7.5 MODFLOW

MODFLOW is a computer program that numerically solves the three dimensional groundwater flow equation for porous media using the finite difference method. It uses the partial difference equation of groundwater flow given by;

$$\frac{\partial}{\partial x}\left(Kxx\frac{\partial h}{\partial x}\right)+\left(\frac{\partial}{\partial y}Kyy\frac{\partial h}{\partial y}\right)+\left(\frac{\partial}{\partial z}Kzz\frac{\partial h}{\partial z}\right)+w=S_s\frac{\partial h}{\partial t} \qquad (23)$$

Where;

K_{xx}, K_{yy} and K_{zz} = values of hydraulic conductivity along the x, y and z coordinate axes which are assumed to be parallel to the major axes of hydraulic conductivity (L/T).

h = the potentiometric head (L).

w = the volumetric flux per unit volume representing sources and/or sinks of water with $w<0.0$ for flow out of the groundwater system and $w>0.0$ for flow into the system (T^{-1})

S_s = the specific storage of the porous media (L^{-1}), and t is the time (T).

The above equation is combined with boundary and initial conditions to describe the transient three dimensional flow in a heterogeneous and anisotropic medium provided that the principal axes of hydraulic conductivity are aligned with the coordinate directions (Harbaugh et al., 2000). The finite difference form of the MODFLOW equation is given as;

$$\begin{aligned}&CR_{i,j-\frac{1}{2},k}(h^m_{i,j-1,k}-h^m_{i,j,k})+CR_{i,j+\frac{1}{2},k}(h^m_{i,j+1,k}-h^m_{i,j,k})+CC_{i-\frac{1}{2},j,k}(h^m_{i-1,j,k}-h^m_{i,j,k})\\&+CC_{i+\frac{1}{2},j,k}(h^m_{i+1,j,,k}-h^m_{i,j,k})+CV_{i,j,k-\frac{1}{2}}(h^m_{i,j,k-1}-h^m_{i,j,k})+CV_{i,j,k+\frac{1}{2}}(h^m_{i,j,k+1}-h^m_{i,j,k})\\&+P_{i,j,k}h^m_{i,j,k}+Q_{i,j,k}=SS_{i,j,k}(DELR_j\times DELC_i\times THICK_{i,j,k})\frac{h^m_{i,j,k}-h^{m-1}_{i,j,k}}{t^m-t^{m-1}}\end{aligned} \qquad (24)$$

Where ;

$h^m_{i,j,k}$ = head at cell i, j, k at time step m (L)

CV, CR and CC = hydraulic conductances or branch conductances, between node i, j, k and a neighbouring node (L^2/T)

$P_{i,j,k}$ = the sum of coefficients of head from source and sink terms (L^2/T)

$Q_{i,j,k}$ = the sum of constants from source and sink terms with $Q_{i,j,k}$ <0.0 for flow out of the ground water system, and $Q_{i,j,k}$ > 0.0 for flow in (L^3/T)

$SS_{i,j,k}$ = the specific storage (L^{-1})

$DELR_j$ = the cell width of column j in all rows (L)

$DELC_i$ = the cell width of row i in all columns (L)

$THICK_{i,j,k}$ = the vertical thickness of cell i, j, k (L) and

t^m = the time at time step m (T).

For steady state stress periods, the storage term is set to zero otherwise the simulation process is transient. This must be clearly defined in the time parameters dialogue box of the model.

MODFLOW uses three processes, the Observation Process which generates model calculated values for comparison with measured or observed values; Parameter Estimation Process (PEST) to adjust values of user selected parameters in an iterative procedure using the Gauss Newton method; and Sensitivity Process to calculate the hydraulic heads throughout the model with respect to specified parameters using the sensitivity equation method (Hill, 2000).

Many computer codes have been developed to be used with MODFLOW. These codes are integrated with MODFLOW each dealing with a particular technique for solving the system of equations or features of the hydrologic system to be included. These codes include; Horizontal Flow Barrier, Interbed Storage, Reservoir, Time Variant Specified Head amongst others (Webtech, 2002).

MODFLOW is designed to have a modular structure which gives it the advantage of ease of understanding and ease of enhancement that has allowed continued addition of new capabilities. From the user's perspective, the program is divided into packages. Each hydrologic capability, such as leakage to rivers, recharge, and evapotranspiration that is included within the ground-water flow equation is a separate package. Further, because there are many methods for solving the simultaneous equations resulting from the finite-difference method, each solution method is a package. This has made it easier to assess the effect of a particular package by either activating or deactivating it during the model simulation process.

2.8 Application of MODFLOW

The MODFLOW model in its various versions and related codes have been applied extensively under different environments to model groundwater systems in various parts of the world. Ruud and Harter (2001) developed a conjunctive use model for the Tule River groundwater basin in the San Joaquin Valley of California. Their objective was to simulate groundwater changes when pumping was required to supplement inadequate surface water deliveries. The developed model consisted of MODFLOW and the Land-Atmosphere Interface and Unsaturated Zone (LAUZ) models. Doble (2008) used MODFLOW 2000 to model evapotranspiration and recharge for shallow groundwater problems in South Eastern Australia where irrigation development next to the semi arid River Murray had led to increased base flow of saline water and higher rates of evapotranspiration on the flood plains. In this study, MODFLOW 2000 was modified to allow the groundwater flux to be represented as a continuous recharge-discharge function.

The MODFLOW model was also used to compute the steady state head and flux distribution in a study by Horn and Harter (2009) which was aimed at estimating the capture zone of typical aquifers and to study the influence of gravel pack length on well inflows. In the Northern Utah Valley, MODFLOW was used to develop a groundwater model to simulate the regional flow system in the basin-fill deposits and surrounding bedrock (Gardner, 2009).

In Tanzania, MODFLOW was applied to simulate water table elevation for groundwater management in the Arusha aquifer where RMSE between observed and simulated water levels of 0.66 and 1.01 were obtained for two different scenarios. Kiptanui (2006) in his analysis of the groundwater potential in the Middle Njoro River watershed in Kenya concluded that MODFLOW simulation under relatively heterogeneous characteristics of the aquifer system in the area was satisfactory based on the results which gave R^2 of 0.56 and model efficiency of 0.38. He however recommended further simulation to test and verify the model performance.

This study was based on Kiptanui's recommendation and those from similar studies such as by Jimoh et al. (2009) on the shallow aquifer resources in the Federal Capital Territory of Nigeria which recommended caution in the use of the shallow wells due to limitations in the water quantities hence the need to identify ways through which these limitations could be minimized. Field and laboratory methods were combined with MODFLOW 2000 simulation to determine the hydraulic parameters and groundwater flow characteristics in a shallow aquifer in which water was mainly abstracted from hand dug wells.

2.9 Geographic Information Systems (GIS)

GIS integrates hardware, software and data and is used for capturing, managing, analysing and displaying all forms of geographically referenced information. GIS can be viewed in three ways; the database view, the map view and model view. In groundwater hydrology, GIS enables upload of basin data such as the areal extent of the basin, lithologic, hydrologic, chemical and groundwater system management historical data (Gupta et al., 1996). For example, in a comparative study of the methods of preparing hydraulic-head surfaces (HHS), automated hydrogeolocal-GIS techniques which take into account the hydro-geomorphic and topographic controls produced the most realistic surfaces compared to manual contouring and use of geo-statistical packages (Salama et al, 1996). Mapping of hydraulic-head surfaces is important since the maps are used to define the direction of groundwater movement, areas of recharge and discharge and to infer changes in hydraulic parameters. The hydrogeolocal-GIS technique allows the preparation of the HHS maps with a small number of data points.

The application of GIS to groundwater studies is expanding with the development of new software which have the advantage of enabling fast production of initial recharge and discharge maps that can further be enhanced using groundwater flow models (Lin et al., 2009).

2.9.1 GIS and MODFLOW

The use of GIS enables the graphical combination of output from MODFLOW with other spatial data such as lamnd use systems, thus facilitating the analysis and understanding of groundwater flow systems and the evaluation of the impact of human activities. MODTOOLS is a set of computer programs for translating data of MODFLOW into GIS output (Orzol, 1997). The outputs include;

- Contours of input/output arrays
- Velocity vectors indicating the direction and magnitude of groundwater velocity,

- Cell values in GIS files that contain the specific data arrays corresponding to model grid cells.

2.10 Scope, Limitations and Assumptions

This study involved the determination of aquifer properties such as hydraulic conductivity, transmissivity, static water levels, specific yields, porosity and bulk density and their spatial distribution over the study area. These properties formed the input into the MODFLOW model which was tested based on head observations, calibrated and used to simulate the groundwater flow characteristics such as hydraulic heads, flow magnitude and directions.

Digging up new wells would have required extra capital and time. Hence, existing shallow wells were adopted as the observation and discharge wells during the study. This also limited the aquifer tests to single well tests. The geographical boundary of the study area was selected so that limited variations in hydro-geological topographical characteristics over the area were achieved.

It was assumed that the hydraulic properties did not change during the duration of the study. In addition, the daily water requirement was assumed to be 0.06 m^3 per capita per day. The discharge wells were based on a 1987 inventory but the number of consumers was projected at double the number of consumers then. This was meant to cater for increase in population and the number of wells.

CHAPTER THREE

MATERIALS AND METHODS

3.0 Description of the Study Area

Nyabondo Plateau is located in Upper Nyakach division of Nyanza province, Kenya. It lies between longitudes 34.92°E and 35°E and latitudes 0.34°S and 0.41°S respectively. The plateau extends from the Kericho border in the East to the Upper Nyakach divisional headquarters (Ogoro) in the West covering an approximated area of $46km^2$. The map of the study area is as shown in Figure 4 below. It rises to an elevation of up to 1800m above sea level, slopes gently over the top of the plateau but steeply at its edges.

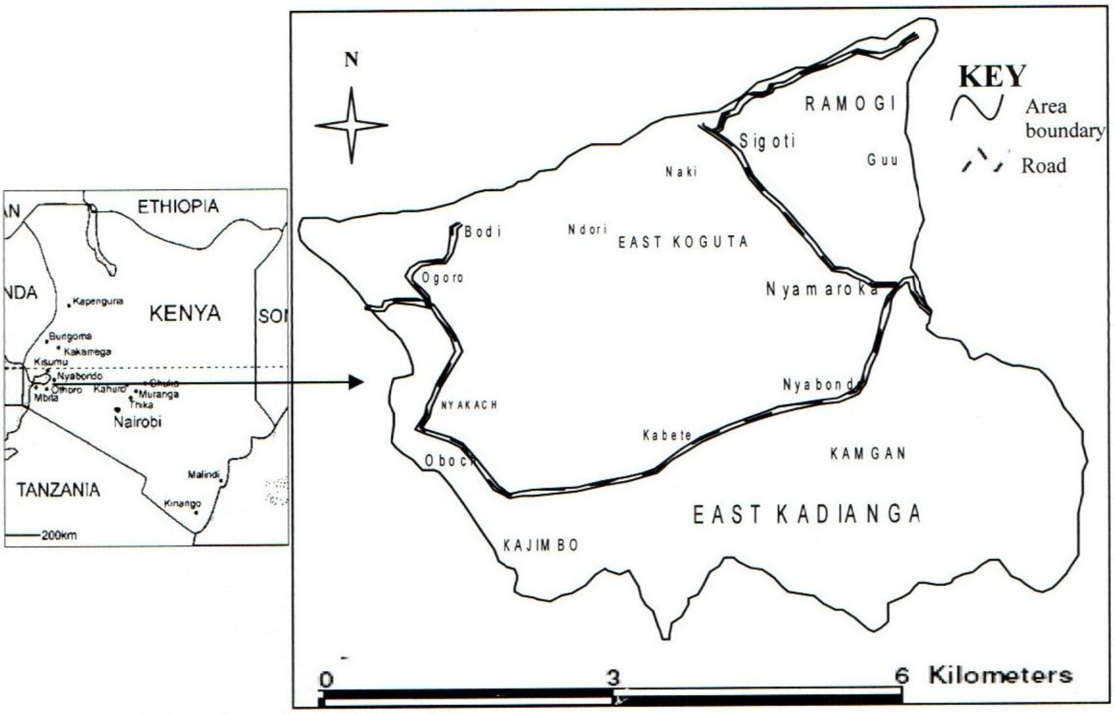


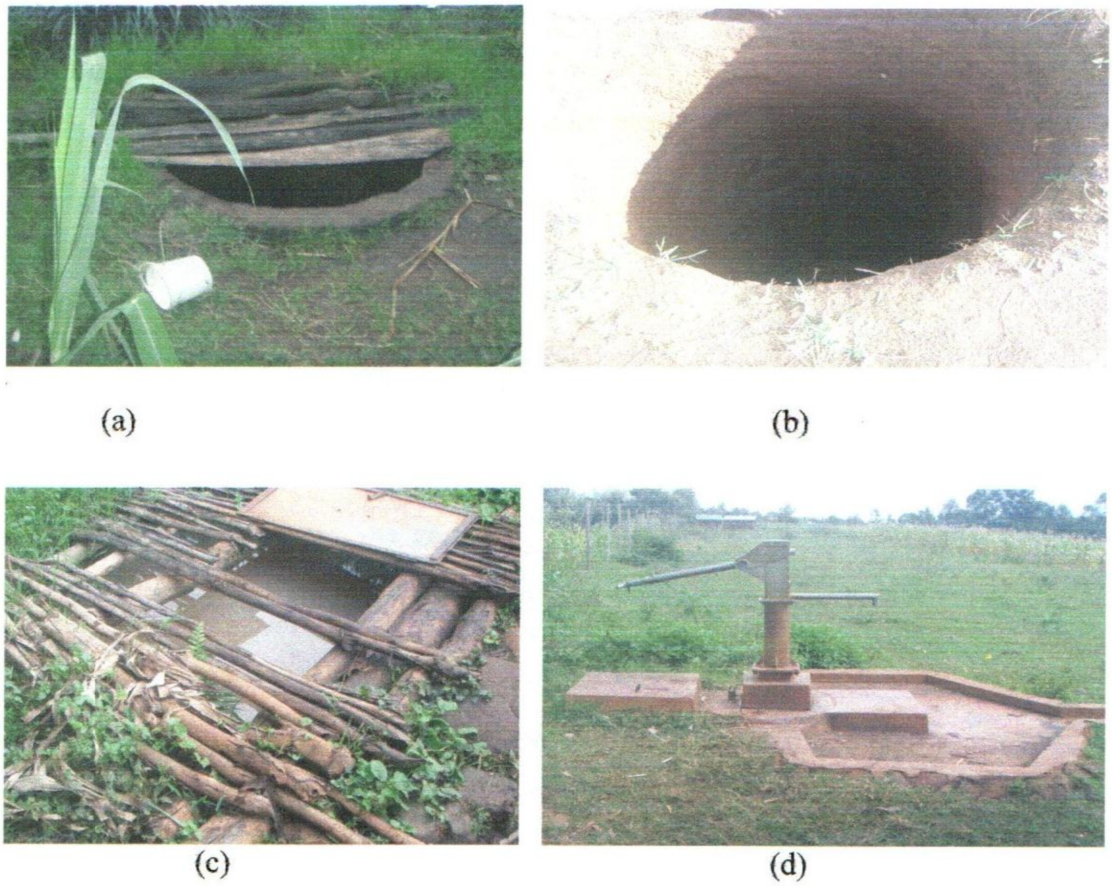
Figure 4: Map showing the study area

The area receives a bimodal type of rainfall. The long rains fall between March and May and the short rains fall between September and November. The mean annual rainfall is 1630mm while temperatures range between 20°C and 35°C. There are no major streams in the area hence limiting surface water sources to ponds and seasonal drains which have poor quality water (LBDA, 1987)

Geologic characteristics of the area include lateritic ironstone (murram) underlain by phonolitic and granitic rocks. The soils therefore vary between clay soils, sandy clay loam soils, granitic soils and laterised lava soils including murram (GoK, 2004; Wynn and Retallack, 2000; Saggerson, 1952). The land tenure system is individual land ownership with the main economic activities being small scale mixed farming, brickmaking and quarry.

3.1 Determination of Aquifer Properties Within the Study Area

The existing shallow wells were randomly sampled from the plateau. These wells are individually owned but access for water collection is often open to neighboring families. The wells were hand dug and most of them were not lined. The mode of water extraction was by use of buckets. Prior permission was sought from the owners before the selected wells could be used for the study. There also existed a number of lined wells fitted with hand pumps. These wells were also hand dug but culverts were used for lining with screens fitted at the bottom. These wells were constructed by the Lake Basin Development Authority (LBDA) as communal water points. Some of them however were not functional and required rehabilitation. Since the wells were closed, it was not possible to use them for water level measurement. However, they provided useful information on the aquifer based on records from LBDA. Plate 1 shows some of the wells that were found in the plateau.



(a) (b)

(c) (d)

Plate 1: Shallow wells found in the study area

A completed well was as shown Plate 1(a). The bucket used for withdrawing water is shown lying by the side and logs were used to cover the top of the well. The well shown in Plate 1(b) was still under construction while Plate 1(c) showed how close to the ground surface the water table could rise. The well in Plate 1(d) was an example of the wells constructed by the LBDA and fitted with a hand operated pump. An initial 25 shallow wells were randomly sampled for purposes of the study. Out of these, 22 wells were selected based on accessibility and permission as granted by the owner(s). Their geographical location (altitude, latitude and longitude) were determined using a GPS unit. The depth and dimensions of each well was also measured.

Field and laboratory methods were applied to determine the various aquifer properties. These tests were done to determine the variation of the properties both spatially and directionally. The field methods included groundwater elevation measurements and slug test while the laboratory tests included bulk density and porosity test, permeability test, mechanical sieve analysis, sedimentation test and specific yield test. For laboratory tests, soil samples were collected from point locations within the study area. The samples were also collected from various depths. The equipment used in sample collection included soil augers, measuring tape, core rings, hammer and soil bags. Plate 2 shows sampling of soil using an auger.

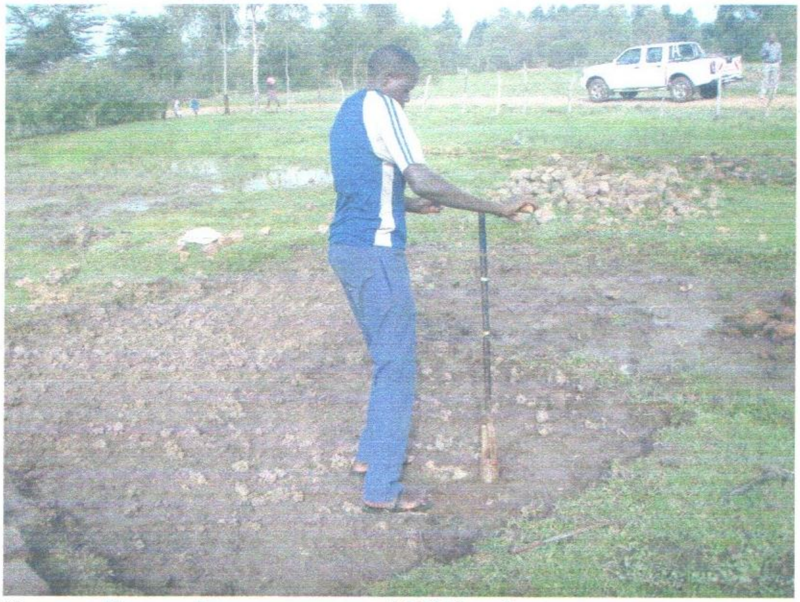


Plate 2: Soil sampling using an auger at K'Onyiero

3.1.1 Groundwater Elevation Measurement

The groundwater elevation also referred to as hydraulic head provides the total energy to move water through an aquifer. The depth to water level in the sampled wells was measured using a tape attached to a float such that the tape would sag once the float touched the water surface. The hydraulic head was then obtained by deducting the depth to water table from the ground surface elevation at the point. The same datum was taken as for the ground elevation, that is, height above the mean sea level. Two sets of measurement were made, first, at the onset of the long rains and the second, towards the end of the long rains during which period, the ground was nearly fully saturated.

The measured water elevation in each well was plotted against the ground surface elevations. From the scatter diagram, it was visually possible to determine the most appropriate model and a suitable regression equation was developed. In order to determine how close the equation approximated the actual values, the correlation coefficient r^2, was determined and also, the standard error of estimate s_e^2 and the residual sum of squares were calculated using the equations below;

$$s_e^2 = \frac{1}{n-2}\sum_{i=1}^{n}(y_i - \hat{y})^2 \qquad (25)$$

$$rss = (n-2)s_e^2 \qquad (26)$$

Where;

y_i = is the observed value

$\hat{y}$ = the estimated/model value

n = number of paired observations

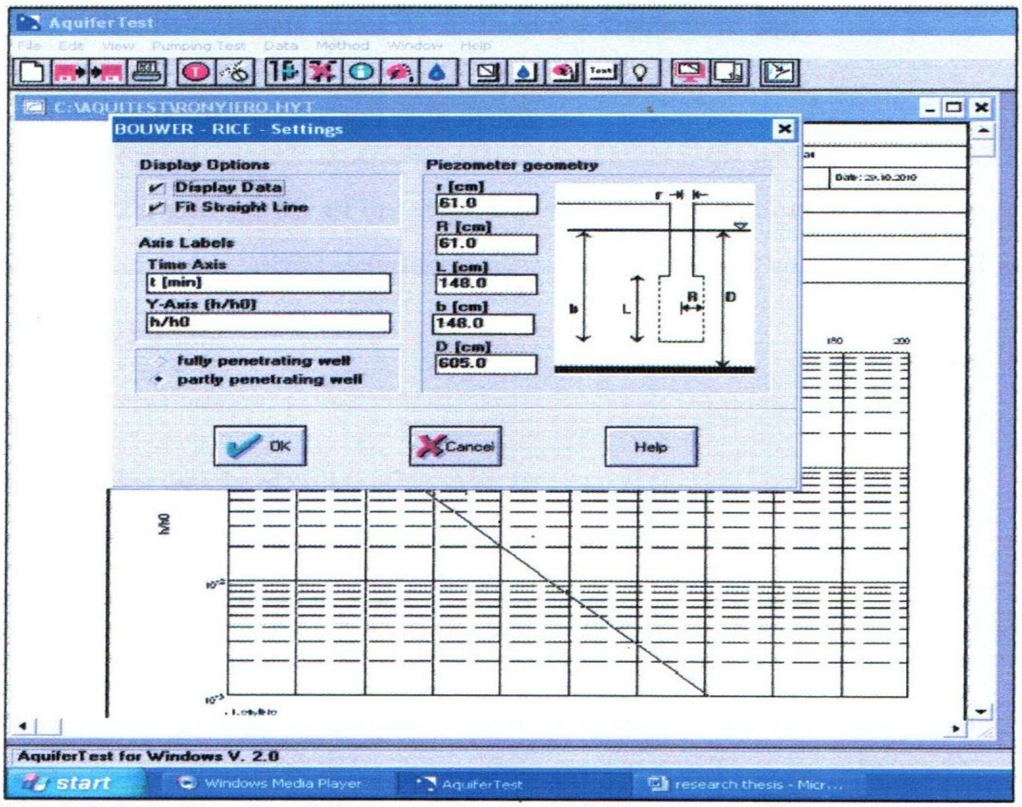
Water table elevation maps were developed using the Spatial Analyst program in ArcView GIS which enabled construction of equipotential lines. The inverse weighted distance method was used to interpolate the data based on the 12 nearest neighbours.

3.1.2 Slug Test

A field method was used to determine the horizontal hydraulic conductivity of the aquifer in situ. The Bouwer-Rice Slug Test analysis was applied to estimate hydraulic conductivity at six well locations distributed over the plateau. This analysis was designed to more accurately estimate the hydraulic conductivity of the aquifer material by better accounting for the well geometry. The single well slug test method was adopted where the initial head was measured and then water suddenly withdrawn from the wells resulting in a drawdown. The head in the well was recorded against time during the recovery process as shown in Plate 3(a). Plate 3(b) shows the equipment used for water withdrawal which included a petrol pump, high density suction pipe and a horse pipe.

Plate 3: a) water level measurement b) slug/pumping test kit

The data was plotted with time on a linear x-axis and h_t/h_o on a logarithmic y-axis. The test results were analyzed using the Aquifer Test program for Windows Version 2.01 developed by the Waterloo Hydrogeologic Inc. as shown in Figure 5.



Display Options
☑ Display Data
☑ Fit Straight Line

Axis Labels
Time Axis: t [min]
Y-Axis (h/h0): h/h0

○ fully penetrating well
● partly penetrating well

Piezometer geometry
r [cm]: 61.0
R [cm]: 61.0
L [cm]: 148.0
b [cm]: 148.0
D [cm]: 605.0

Figure 5: Interface for defining well properties in the Aquifertest Program

3.1.3 Bulk Density and Porosity Test

A soil core sampler was driven into the soil adjacent to the sampled wells. The soil around the ring was then removed and the ring retrieved out. Using a flat bladed knife, the excess soil protruding on either side of the ring was trimmed. The samples were placed in soil sample bags and labelled. The sample collection kit was as shown in Plate 4 below. In the laboratory, the samples were weighed, oven dried at 105°C for 24 hours and their volume calculated using the internal dimensions of the ring.

Plate 4: a) Driving the core sampler in soil b) Core sampler, knife and soil bags

The soil bulk density and porosity were calculated as;

$$\text{Soil bulk density (g/cm}^3\text{)} = \frac{\text{oven dry weight of soil}}{\text{Volume of soil}} \tag{27}$$

$$\text{Soil porosity} = 1 - \frac{\text{soil bulk density}}{\text{SG}} \tag{28}$$

The specific gravity, *SG* of the soil sample which was determined using the specific gravity test and involved determining the dry weight and volume of a soil sample.

$$SG = \frac{M_s}{V_s \gamma_w} \tag{29}$$

Where;

M_s = the dry weight of soil

V_s = the volume of soil and

γ_w = the specific gravity of water

3.1.4 Permeability Test

The permeability test was done in the laboratory to determine the vertical hydraulic conductivity for soil samples taken from within the aquifer. Both constant head and falling head permeability test methods were used since the aquifer material varied between coarse grained or non-cohesive and fine grained particles. The K-610 permeameter which is designed for performing either of the tests was used. The unit consisted of a standard compaction mould and collar, mounting base with porous stone and brass pipe fitting, and a head with air escape valve and fitting. For constant head method, a constant head tank and a pipette were connected as shown in Plate 5 below.

Plate 5: Constant head permeability test arrangement

Since the soil samples had been disturbed during collection, they were lightly tramped using a compaction hammer so that similar physical conditions in the field such as bulk density and porosity could be achieved. The coefficient of permeability, k (cm/s) was computed as;

$$k = \frac{qL}{Ah} \tag{30}$$

Where;

q = discharge in cm^3/s

L = length of specimen (cm)

A = cross-sectional area of the specimen (cm^2) and

$h = (h_1 - h_2)$ = constant head causing flow (cm)

h_1 is measured from the base of the specimen to the constant water level in the tank;

h_2 measured from top of specimen to the water level in the pipette.

For the falling head method, the constant head tank was replaced with a pipette connected to the air escape valve. The outlet at the base was allowed to discharge at a height. The hydraulic conductivity, *k* was calculated as;

$$k = \frac{2.3aL \log {h_1}/{h_2}}{At} \tag{31}$$

Where;

t = time interval for fall in head in standpipe

a = cross sectional area of standpipe

h_1, h_2 = initial and final reading of standpipe respectively

A, L = cross sectional area and length of specimen respectively

3.1.5 Geological Composition

The soil samples were analysed o determine their particle size distribution. This was done to assist in making comparisions between the tabulated values and results obtained from laboratory tests to determine the hydraulic properties such as permeability. The mechanical sieve analysis test was used to grade the soil samples collected from the study area. These were used to refine the geological description of the area. Corresponding to 10%, 30% and 60% finer, diameters denoted as D_{10}, D_{30}, D_{60} respectively were obtained from the gradation curves. These were used to compute the coefficient of concavity, C_c (measure of shape of the curve between D_{10} and D_{60}) and the coefficient of uniformity, C_u which represent how well the soil is graded i.e whether the soil is well-graded, gap-graded or poorly graded. This was done for each soil sample collected and calculated as;

$$C_U = \frac{D_{60}}{D_{10}} \tag{32}$$

$$C_C = \frac{D_{30}^2}{D_{10} D_{60}} \tag{33}$$

Together with the soil textural triangle, symbols *G*, *S* and *M* were used to define the soils as gravels, sands or silt respectively or a mixture of two or more of them. The symbols *W* and *P* were also used to denote if the soil sample was well graded or poorly graded respectively. The gradation criteria used was based on the Unified soil Classification System (USCS) which requires that for the well graded gravels (GW) the Cu must be greater than 4 while for the well graded sands, Cu greater than 6 is required. For both cases, the Cc must be between 1 and 3 (US Department of Army, 1992)

The sedimentation test was used to measure the percent sand, silt and clay in soil samples that had higher clay contents resulting in tightly bonded aggregates. To dissolve the aggregates and keep the individual particles separated, 8% Calgon solution was used. Soil sample weighing 100g was placed in a dispersion cup. Water and the Calgon solution were added. The mixture was thoroughly stirred using a mechanical stirrer shown in Plate 6 for 5 minutes. This was transferred into a 1000ml hydrometer jar which was left to settle for 24 hours.

Plate 6: Sedimentation test set up

After the 24 hours, the depth of settled soil was measured for each sample to give the total depth. The jar was capped and vigorously shaken again for 5 minutes and let to stand. Sand depth was measured after 40 seconds, silt depth determined by subtracting the sand depth from the depth measured after another 30 minutes. The remaining unsettled particles were taken as clay with the depth calculated by subtracting silt and sand depth from total depth. The percentage of each soil separate was computed as:

$$\% \text{ sand} = \frac{\text{sand depth}}{\text{total depth}} \text{ X } 100 \qquad (34)$$

$$\% \text{ silt} = \frac{\text{silt depth}}{\text{total depth}} \text{ X } 100 \qquad (35)$$

$$\% \text{ clay} = \frac{\text{clay depth}}{\text{total depth}} \text{ X } 100 \qquad (36)$$

The soil classification was done using the United States Department of Agriculture (USDA) Soil Textural Triangle shown in Figure 6.

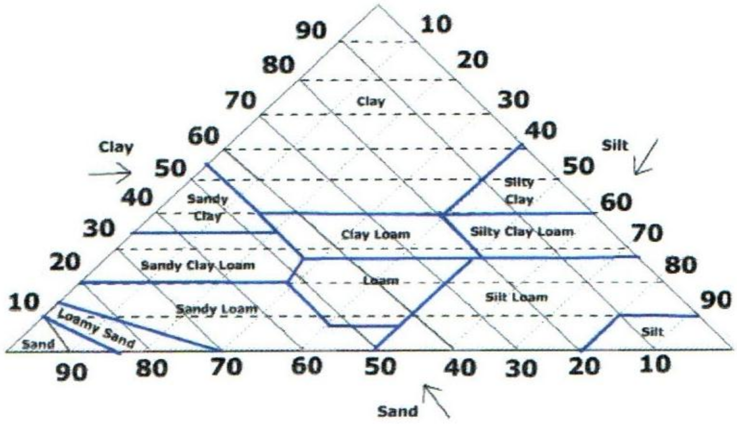


Figure 6: Soil textural triangle

3.1.6 Specific yield

The specific yield or the proportion of water that can be drained by gravity from a saturated soil sample was determined through laboratory analysis. The saturated soil was left to drain over a 24 hour period. The specific yield was computed from the equation;

$$S_y = \frac{v_w}{v_s} x100\% \qquad (37)$$

Where;

S_y = specific yield of soil

v_w = volume of water drained

v_s = the volume of soil sample

This was used to estimate well yield (y_w) from the equation used by Jimoh et al. (2009) as follows;

$$y_w = S_y V \tag{38}$$

$$V = \frac{\pi D^2 \Delta h}{4\Delta t} \tag{39}$$

Where;

V = the volumetric flow rate of water into the well

D = the diameter of the well

Δh = change in water level and

Δt = the difference in time when head reading were taken in the wells

The above parameters were derived from the slug test data. The safe yield for the wells was determined by multiplying the well yield by a safety factor of 0.75.

3.2 MODFLOW Simulation

Processing Modflow Pro version 7.0 which supports MODFLOW 2000 and related packages and contains a graphical user interface which includes advanced three dimensional visualization and animation was used in the groundwater flow simulation to estimate the flow characteristics in the aquifer. A model grid was generated consisting of cells. Based on the grid extent of 11000m by 8000m, the number of columns and rows were set at 55 and 40 respectively. This gave a cell dimension of 200m by 200m. A single layer was selected with the type of aquifer set to strictly unconfined, denoted by 1 in the aquifer type dialogue box. The delineated map of Nyabondo plateau was imported into the grid and the boundaries marked by creating an IBOUND array using 1 for active cells and 0 for inactive cells. There were no constant head boundaries due to the absence of a river or lake within the area.

The input parameters to the model were defined and these included time, initial hydraulic heads, horizontal hydraulic conductivity, effective porosity and specific yield. A single time period was used with a length of 115 days which was derived from the duration between the two hydraulic head measurements in January and May. The simulation time unit was set to days and the number of time steps as one. A transient simulation flow type was adopted since hydraulic heads at the beginning and end of simulation were not constant hence the storage term was not equal to zero.

The mean hydraulic conductivity, effective porosity and specific yield values determined from laboratory and field tests were used. The geometric averaging method was adopted to determine the mean values using the equation;

$$K = \sqrt[n]{(K_1 K_2 --- K_n)} \tag{40}$$

Where K was the measured parameter such as hydraulic conductivity.

The discharge wells and observation wells were imported to the model grid. The GPS Universal Transverse Marcater (UTM) coordinates were converted into X and Y coordinates. The hydraulic head measurements for January 2010 were used as the initial head observations while those for May were used as the head observations at the end of the simulation period hence all the sampled wells were treated as observation wells. Transmissivity was calculated by the model.

3.2.1 The Model Packages

The MODFLOW Recharge and Well packages were activated. To obtain the recharge flux for the area, rainfall data from three metereological stations; Kisumu, Kericho and Kisii which are located 38 km, 37.5 km and 38.4 km from the plateau respectively were analysed. The amount of monthly rain falling on the plateau was calculated using the distance weighted method as;

$$P = \frac{\sum P_i D_i}{\sum D_i} \tag{41}$$

Where;

P = rainfall amount for Nyabondo plateau

P_i = rainfall recorded in station i

D_i = average distance from station i to the plateau

The recharge into groundwater, G was calculated from the water balance equation given by;

$$Input = output + changes\ in\ groundwater\ storage$$

$$P = R + ET + G + S \tag{42}$$

Where;

P = precipitation

R = runoff

ET = evapotranspiration

S = change in groundwater storage

The runoff coefficient for the area was taken as 10%, the potential evaporation as 2000mm and the actual evapotranspiration calculated using factors of 0.6 and 0.5 for the wet and dry seasons respectively (LBDA, 1987).

For a Well flow package, the discharge or recharge rate for a pumping and recharging well was specified respectively. Discharging wells were given negative values while recharge wells were given positive values. A total of 257 wells were used based on the Water Resources Survey Report (LBDA, 1987). Because of the scale, some of the cells had more than one well. In such cases, the cell discharge rate was the sum of individual well discharges. It was noted that the number of wells have since increased as well as the number of users. To cater for these changes, the well discharges were doubled, assuming a uniform increase in the area's population which is estimated to double every 22 to 25 years (Mbaria, 2006; Ong'or, 2005). The well discharge was calculated based on the daily water requirement per person of 0.06 m^3 (60 liters) and the projected number of users.

3.2.2 Model Evaluation

The Root Mean Squared Error (RMSE) and the Nash-Sutcliffe model was used to evaluate how the model simulated the actual flow characteristics. The observed hydraulic heads were plotted against calculated heads, a regression line fitted and the goodness of fit (R^2) determined. The RMSE was also calculated as;

$$\text{RMSE} = \sqrt{\frac{\left(\sum_{i=1}^{n} h_{oi} - h_{si}\right)^2}{n}} \tag{43}$$

Where;

h_{oi} = the observed head

h_{si} = the simulated head and;

n = the total number of observations

The Nash–Sutcliffe model efficiency coefficient (E) was used to assess the ability of the MODFLOW model to predict hydraulic heads. It was defined by the equation:

$$E = 1 - \frac{\sum (h_o - h_s)^2}{\sum \left(h_0 - \bar{h}_o \right)^2} \qquad (44)$$

Where;

h_0 = observed head,

h_s = simulated head.

$\bar{h}_o$ = the mean of the observed heads

The Nash–Sutcliffe efficiencies range from $-\infty$ to 1 with an efficiency of one corresponding to a perfect match of modeled heads to the observed data. An efficiency of zero would indicate that the model predictions were as accurate as the mean of the observed data, whereas efficiency less than zero would occur when the observed mean was to be a better predictor than the model. The model was set to carry out self validation. Calibration was done by making adjustments to the model parameters so as to achieve meaningful results.

3.2.3 Estimation of Groundwater Flow Characteristics Using the MODFLOW Model

The outputs from running the MODFLOW model included contours of hydraulic heads, two dimensional visualization of hydraulic head (hydraulic head surface map) and cell by cell flow for both the front and right faces. A complete summary of the simulation results was given in the MODFLOW 'output' file which detailed the water entering and leaving the aquifer.

3.3 Estimation of the Groundwater Potential using the MODFLOW Model

The MODFLOW model was used to estimate the ground water potential from the water balance equation. During the simulation process, only the recharge and well packages were activated. Evapotranspiration and Drainage packages were included in the calculation of Recharge and therefore deactivated. The density of the water was assumed constant and reservoirs, rivers and lakes were absent in the area. Flow was considered IN or OUT if it was entering or leaving the aquifer respectively using the units of m^3/day for the given stress period. A summation of all the inflows minus the outflows was saved in the WATERBDG file based on the packages used during the simulation process.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.0 The Nyabondo Plateau Aquifer

The refined map of the study area which showed the position of the well points on the Nyabondo plateau map was as shown in Figure 7. The identity and location of the sampled wells were summarized in Table 1. The depths indicated in the table were those for the sampled wells measured from the ground surface level but not necessarily to the impervious layer.

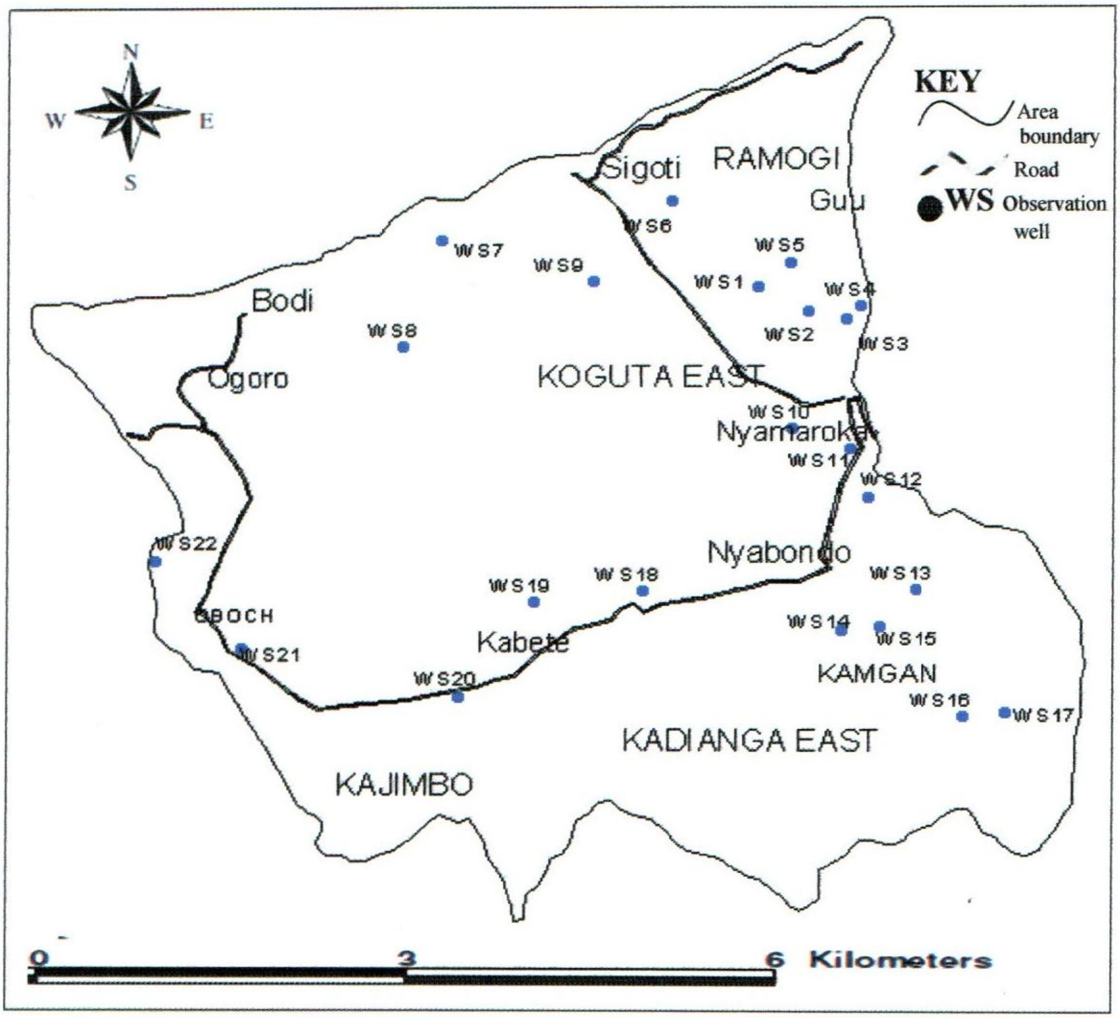


Figure 7: Map of Nyabondo Plateau showing the well sampling points

All the wells sampled were not lined except for well WS12 which was constructed by the Lake Basin Development Authority (LBDA) and was lined with culverts. It was initially fitted with a hand pump which later broke down hence the users have resorted to use of buckets to lift water out. The wells although randomly sampled, were representative of the area. The wells ranged from 3m to 11m in depth.

Table 1: Sampled Wells from Nyabondo Plateau

Site Name	Well ID	Village	Well Owner	Geographical Location			Depth (m)
				Alt (m)	Longitude.	Latitude.	
Koguta East	WS1	Kadero	Rusalia O.	1584.35	00°21.535’S	034°58.6’E	3.46
Koguta East	WS2	Kobala	H. Okolo	1585.26	00°21.650’S	034°58.823’E	6.15
Koguta East	WS3	Kamuga	N Agimba	1588.92	00°21.688’S	034°58.989’E	6.15
Koguta East	WS4	Kamuga	O. Yoga	1589.53	00°21.630’S	034°59.054’E	6.46
Koguta East	WS5	Kobala	J. Owino	1585.57	00°21.419’S	034°58.738’E	3.69
Ramogi	WS6	Kokumu	R. Omollo	1577.95	00°21.135’S	034°58.219’E	5.85
Koguta East	WS7	Ndori	Eunita	1573.07	00°21.315’S	034°57.213’E	4.31
Koguta East	WS8	Ndori	C. Okatch	1569.72	00°21.821’S	034°57.050’E	3.08
Koguta East	WS9	Naki	Otieno	1583.74	00°21.515’S	034°57.885’E	3,08
Koguta East	WS10	Kadero	Oyie Jowi	1576.73	00°22.210’S	034°58.753’E	4.0
Koguta East	WS11	Kadhiambo	Kolith	1580.69	00°22.306’S	034°59.001’E	8.0
South Nyakach	WS12	Kamgan	Communal	1605.38	00°22.524’S	034°59.084’E	9.23
South Nyakach	WS13	Kamgan	M. Junior	1641.65	00°22.885’S	034°59.284’E	9.85
South Nyakach	WS14	Nyabondo	Kodum	1652.02	00°23.14’S	034°59.136’E	7.38
South Nyakach	WS15	Nyabondo	J. Ayieko	1659.33	00°23.159’S	034°58.971’E	9.85
South Nyakach	WS16	Ochol	Kodiga	1660.25	00°23.566’S	034°59.513’E	9.54
South Nyakach	WS17	Kobongo	Obuya	1661.47	00°23.543’S	034°59.692’E	12.3
South Nyakach	WS18	Kodonga	G. Agutu	1629.16	00°22.961’S	034°59.297’E	8.62
South Nyakach	WS19	Kodul	J. Ajuelu	1600.50	00°23.022’S	034°57.626’E	8.62
South Nyakach	WS20	Kabete	S. Oyomo	1613.61	00°23.471’S	034°57.293’E	11.08
Kajimbo	WS21	Oboch	Owako	1591.06	00°23.240’S	034°56.342’E	3.08
Kajimbo	WS22	Odowa	G. Kere	1583.74	00°22.826’S	034°55.961’E	5.49

4.1 Aquifer Properties

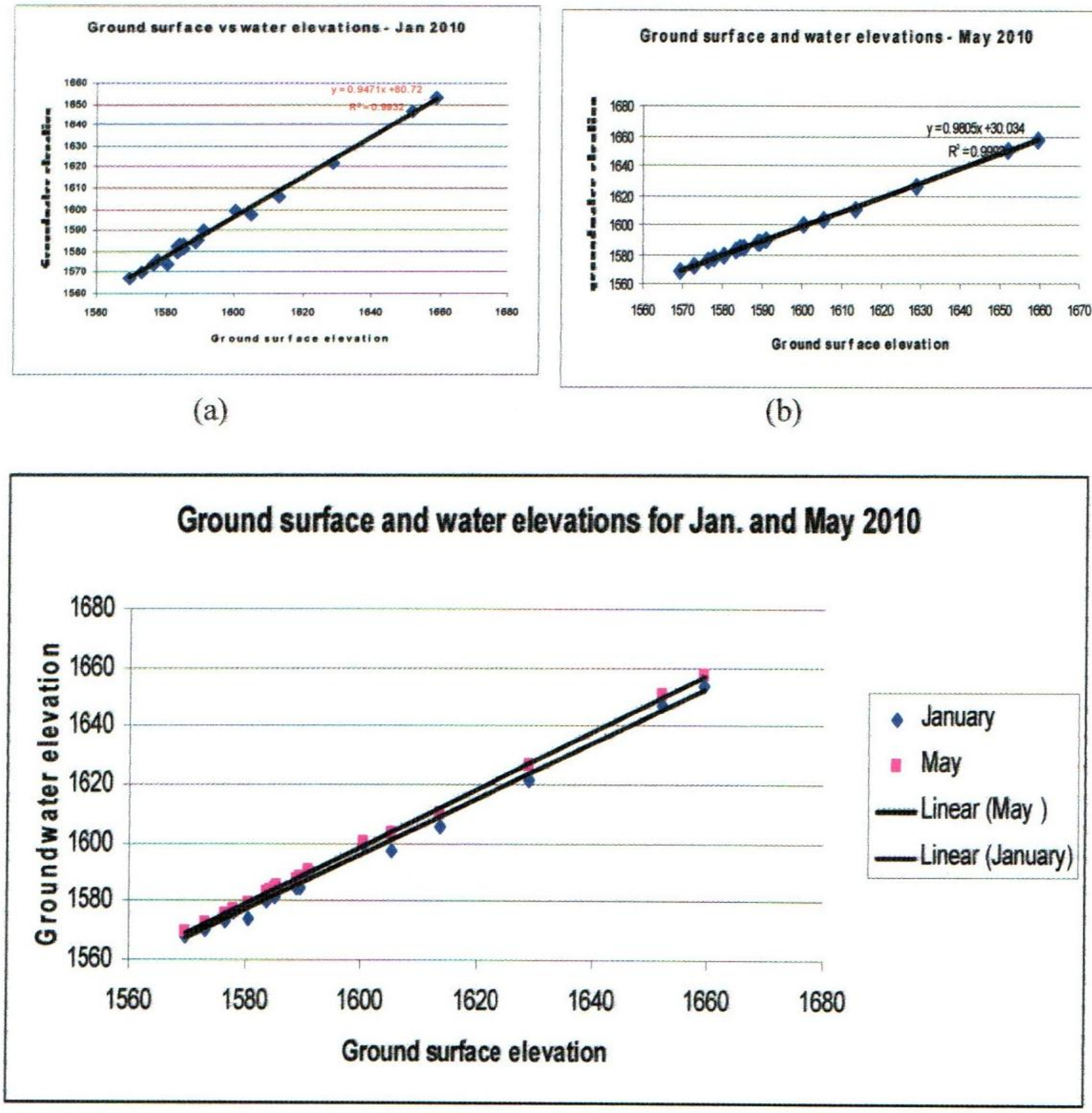
4.1.1 Measured Groundwater Elevations

The depth to water table measured at each of the sampled wells varied from point to point. A variation was also observed in groundwater elevations between the two observation periods of January and May with each of the wells registering rise in water level. The measured depths to water and the computed groundwater elevations are shown in Table 2 below. The wells were ranked in ascending order of ground surface altitude.

Table 2: Water Level Observations

WELL NAME	WELL ID	D TO WT (m)		GROUND SURFACE ALTITUDE (M)	GW ELEV. (m)		RISE (m)
		JAN	MAY		JAN	MAY	
1. C. Okatch	WS8	1.7272	0.2032	1569.72	1567.993	1569.517	1.524
2. Eunita	WS7	2.4384	0.4826	1573.073	1570.634	1572.59	1.9558
3. Oyie Jowi	WS10	3.048	0.7874	1576.73	1573.682	1575.943	2.2606
4. R. Anyango	WS6	1.5494	0.4064	1577.95	1576.4	1577.543	1.143
5. Olith	WS11	6.4008	0.8636	1580.693	1574.292	1579.829	5.5372
6. Otieno	WS9	1.3462	0.4572	1583.741	1582.395	1583.284	0.889
7. George Kere	WS22	3.6576	1.778	1583.741	1580.083	1581.963	1.8796
8. R. Onyiero	WS1	1.1684	0.254	1584.35	1583.182	1584.096	0.9144
9. H. Okollo	WS2	3.3528	0.8382	1585.265	1581.912	1584.427	2.5146
10. Julius Owino	WS5	1.778	0.4064	1585.57	1583.792	1585.163	1.3716
11. N. Agimba	WS3	4.318	0.9906	1588.922	1584.604	1587.932	3.3274
12. Oriedo Yoga	WS4	4.5212	1.0414	1589.532	1585.011	1588.491	3.4798
13. Owako	WS21	1.2954	0.6604	1591.056	1589.761	1590.396	0.635
14. J.Ajwelu	WS19	0.4318	0.2032	1600.505	1600.073	1600.302	0.2286
15. Kamgan	WS12	7.62	2.0574	1605.382	1597.762	1603.324	5.5626
16. S. Oyomo	WS20	7.7724	3.0226	1613.611	1605.839	1610.589	4.7498
17. George Agutu	WS18	7.3152	2.5654	1629.156	1621.841	1626.591	4.7498
18. Odum	WS14	5.334	1.0922	1652.016	1646.682	1650.924	4.2418
19. Jacob Ayieko	WS15	5.7912	1.9812	1659.331	1653.54	1657.35	3.81
20. Odiga	WS16	6.7056	3.516	1660.246	1653.54	1656.73	3.18

From the measurements of ground altitude and water elevations in the wells, scatter plots made for January and May both showed linear trends and therefore best straight lines were fitted and linear regression equations obtained. The fitted line, the regression equations, the correlation coefficients (R^2) and a graphical comparison of the January and May models were as shown in Figure 8 below.



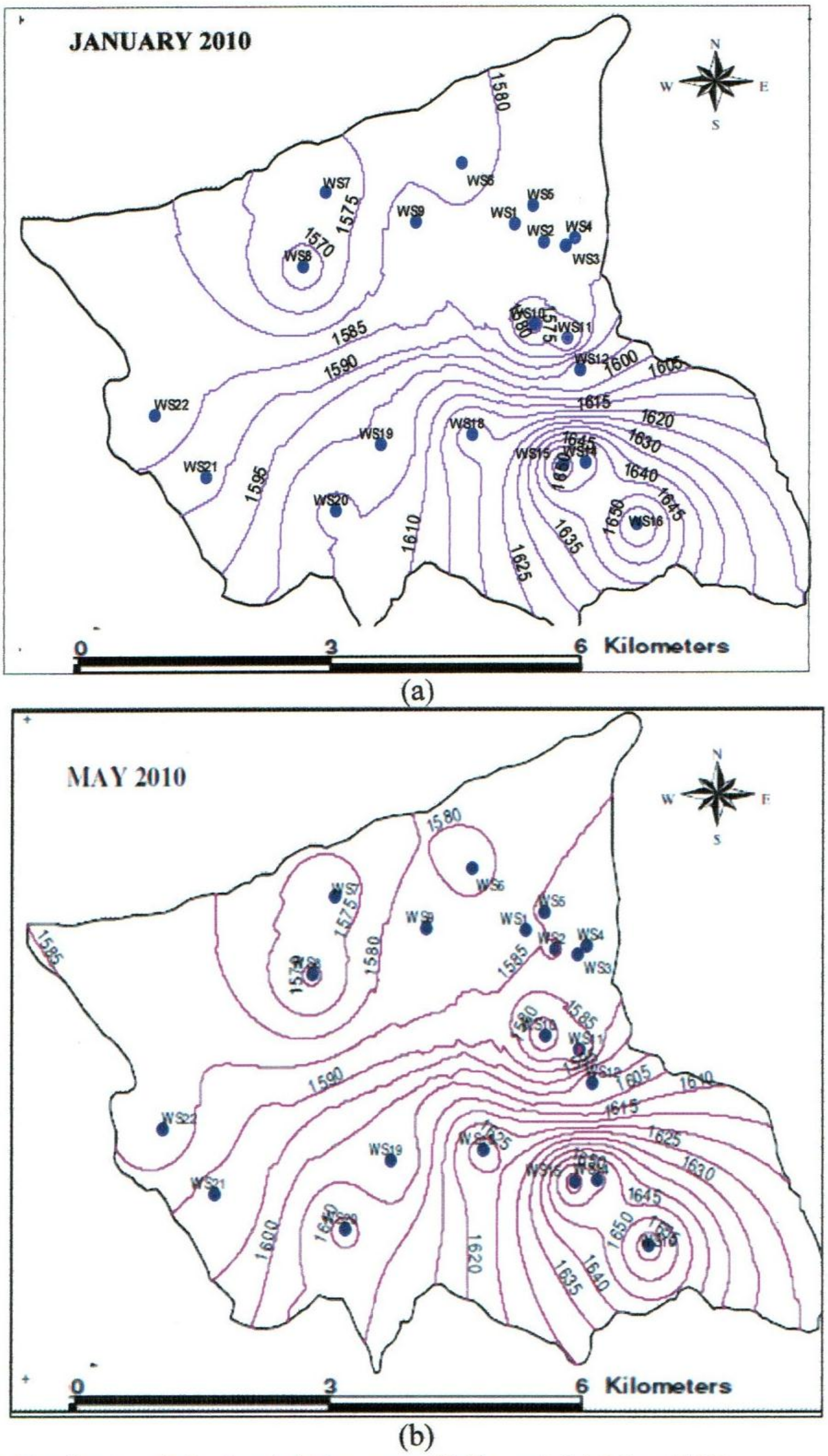
(a) (b)

(c)

Figure 8: Correlation between ground surface and water table elevations

Correlation coefficients of 99.32% and 99.93% were obtained for January and May respectively. Additionally, the standard error of estimate, s_e and the residual sum of squares (rss) were 3.93 and 70.72 for January; 0.45 and 8.1 for May A lower R^2 combined with higher s_e and rss in January could be attributed to higher water abstraction rates from the wells leading to localized depression zones resulting in higher drawdowns. The general trend for both measurement periods suggested that the water table within the plateau is topographically controlled and that recharge was basically from rainfall. Therefore, if the ground altitude at a point was known, then water table could be estimated.

Hydraulic head surface maps developed using ArcView GIS with contours of equal hydraulic head (equipotentials) spaced at intervals of 5m is as given in Figure 9(a) and (b) for January and May respectively. The orientation of the equipotentials was nearly the same for both January and May periods but slightly displaced to cater for the uneven rise in groundwater elevation.



(a)

(b)

Figure 9: Equipotentials for (a) January 2010 and (b) May 2010

4.1.2 Horizontal Hydraulic Conductivity

The horizontal hydraulic conductivity, K_h of the aquifer determined using the Bouwer and Rice slug test analysis method ranged from 0.56m/day to 29.38m/day. The results obtained from the test wells are summarized in Table 3. Results from one of the wells (Oyie Ojowi) could not be analyzed because the slug out rate could not give any appreciable drawdown. It is therefore not included in Table 3. This was attributed to inflow rates into the well being higher than the slug out rate.

Table 3: Summary of Horizontal hydraulic conductivity from slug test analysis

Test well	K_h (m/day)
R. Onyiero	4.26
Sammy	1.53
Otieno	5.904
J. Owino	0.557
G. Kere	29.376

A spatial variability in the K_h values was observed with the average value for the Nyabondo plateau aquifer. This variability was in terms of two orders of magnitude which was considerably low and therefore acceptable. It could be attributed to variations in the composition of the aquifer, amount of fine particles present and the estimated saturated depth of the aquifer. However, errors in test set up which included water abstraction prior to the test could also have resulted in variations. Kere's well which had not been used for 22 hours prior to the test offered the best test conditions as the initial water level was fairly static. The mean hydraulic conductivity for the area was calculated as 3.63 m/day which falls within the moderate category which is given by a range of beween 1 to 10m/day (http://www.connectedwater.gov.au). Therefore the area could be categorized as suitable for groundwater development. The time-drawdown curves, time-h/h_o graphs as plotted using the Aquifertest program and the time drawdown tables for each of the tested wells are as given in Appendix 1.

4.1.3 Bulk Density and Porosity

The specific gravity of the soils varied from point to point and with depth. It ranged between 2.41 and 2.89 g/cm^3, with lower values being observed at depths nearer to the ground surface as shown in Table 4. The computed values of bulk desity and porosity of the soil samples are summerised in Table 5 below.

Table 4: Specific gravity of soil samples

Sample	Depth (m)	Mass (g)				Vol.of soil (cm^3)	Specific Gravity (g/cm^3)	
		Can	Can+ soil	soil+ water+ beaker	soil		Calc.	Corrected
G. Kere	0.3	91	390	894	299	113	2.65	2.68
G. Kere	0.6	82	374	844	292	109	2.68	2.71
G. Kere	2.0	82	408	916	326	125	2.61	2.64
Owako SP2	0.3	85	297	836	212	89	2.38	2.41
RO SP1	0.3	85	398	855	313	114	2.75	2.78
RO SP2	0.3			869	276	103	2.68	2.72
N. Agimba	3	50	435	960	385	135	2.85	2.89
Sigoti	2	48	371	916	323	116	2.78	2.82
Kamgan	0.6	48	303	701	255	97	2.63	2.66

Table 5: Bulk Density and Porosity of Soil Samples

Sample	Wt of dry soil + can (g)	Wt of can (g)	Vol. of core ring (cm^3)	Bulk density (g/cm^3)	Porosity
G. Kere (murram)	380	82	247.09	1.21	0.5431
G. Kere (top soil)	385	91	247.09	1.19	0.5441
Gk 2	401	82	247.09	1.29	0.4976
Owako SP2	291	85	247.09	0.83	0.6452
R. Onyiero	398	85	247.09	1.27	0.5325
R. Onyiero clay	1511	456	964.21	1.09	0.5855
Ajwelu	1175	0	964.21	1.22	0.5401

The bulk density ranged between 0.83g/cm^3 and 1.29 g/cm^3 while the porosity varied between 49.76% and 64.52%. The Owako sample was obtained from a tilled land having high organic matter content which explains the high porosity value obtained. The average values of soil bulk density and porosity were calculated as 1.157 g/cm^3 and 55.55% respectively. However, these values were for the top soil layers from which core samples could be obtained. Since infiltration is affected by porosity, the high values obtained suggested high infiltration rates in the area and hence high recharge rates. Combined the gently sloping topography, this resulted in low runoff amounts. The runoff coefficient used by DHV Consulting of 10% (LBDA, 1987) which was adopted during recharge computation was therefore satisfactory.

4.1.4 Vertical Hydraulic Conductivity

The coefficient of permeability results obtained from the permeability test were averaged for well sites sampled as shown in Table 6. Compared with the tabulated values for different soil composition, the hydraulic conductivity values also fell within the moderate category. The results also showed variations in the vertical hydraulic conductivity (K_v) between the different soil layers due to changes in aquifer composition. The upper top soil layers exhibited the highest spatial variation with the values ranging between 0.06m/day to 5.41 m/day. This could be attributed both to soil type and land use. The lowest K_v value of 0.06m/day was obtained from a well site where soil erosion had occurred exposing a compacted sub soil layer. On the other hand, the highest K_v value was obtained from a soil sampled from a tilled land rich in organic matter content. The full results were as given in Appendix 2.

Table 6: Average vertical hydraulic conductivities

Well site	Kv (m/day
George Kere	1.172
H. Okolo	2.818
N. Agimba	1.869
Sigoti	1.26
R. Anyango	1.6
G. Agutu	2.84
R. Onyiero	5.4
Owako	1.361

From the above results, the average vertical hydraulic conductivity for the area was calculated as 2.004 m/day. This compared closely with the mean horizontal hydraulic conductivity of 3.63 m/day since both were within the same order of magnitude. These results however showed preferential flow in the horizontal direction attributable to an underlying impervious layer composed of the phonolitic rocks which could be used explain the occurrence of the aquifer.

4.1.5 Geological Composition

The plateau comprised of different soil layers which exhibited varying depths. These layers were distinct in terms of texture, colour and soil type as shown in Plate 7. The depth of the top soil layer also varied from point to point but was generally deeper in the southern part of the plateau.

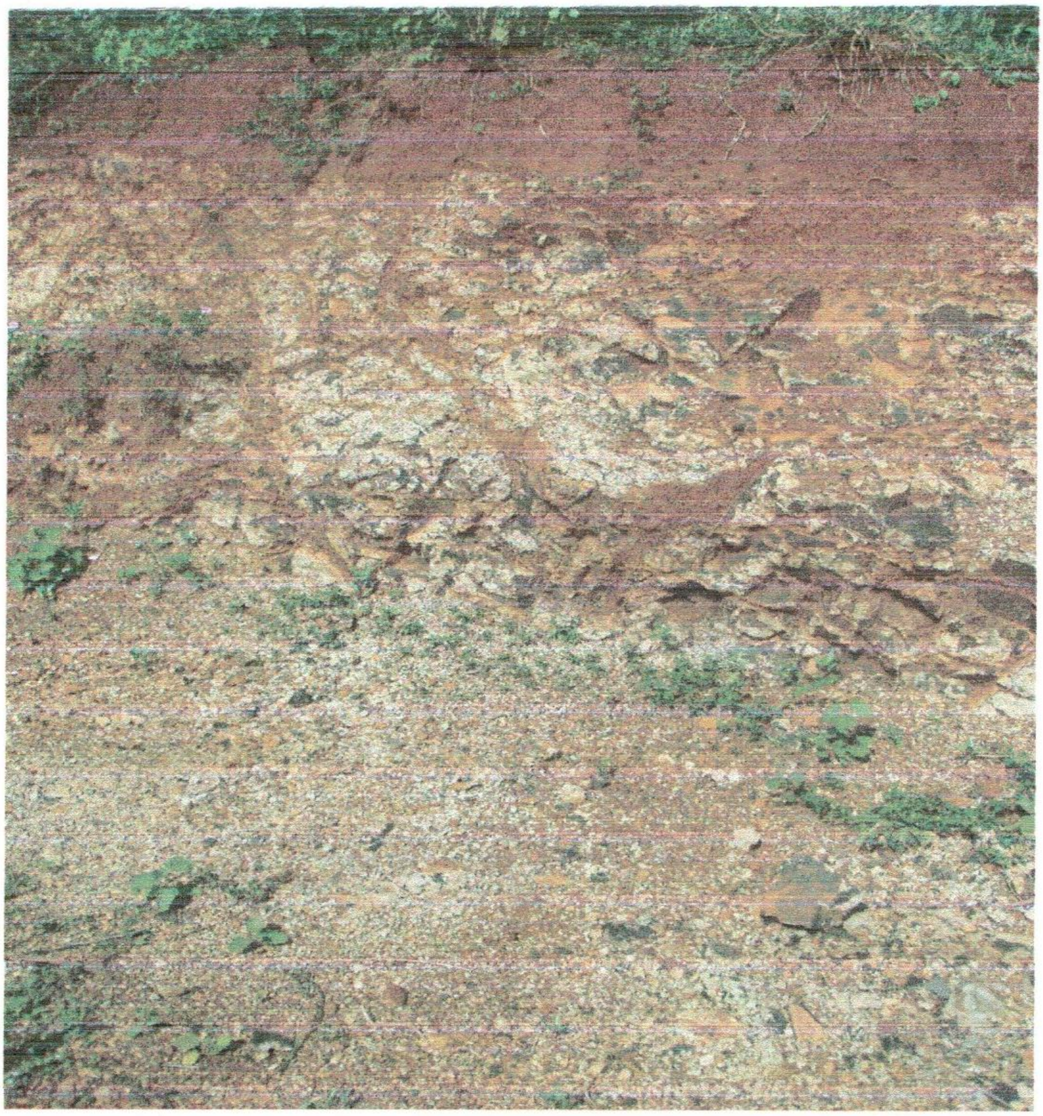
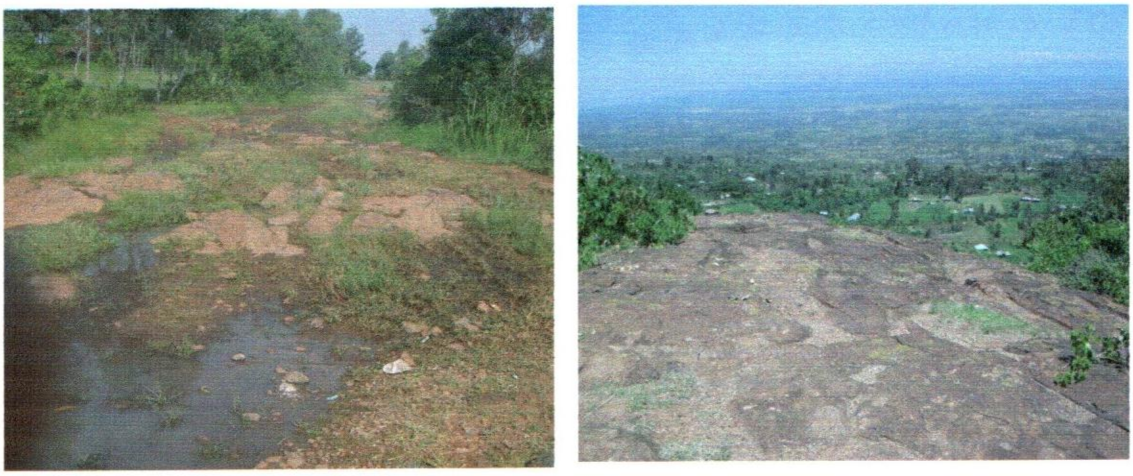


Plate 7: A typical soil profile at Nyamaroka

In some areas however, the basement rock had been exposed through erosion. This was especially true at the edges of the plateau. Plate 8 (a) and (b) show examples of exposed rock at Nyamaroka and Sigoti respectively.



(a) **Nyamaroka** b) **Sigoti**

Plate 8: Exposed rock layers

The water seeping onto the exposed rock layer at Nyamaroka indicated how close the water table was to the ground surface. This is the source of Nyamaroka stream, which drains out of the plateau but reduces to disjointed pools of water when the dry weather sets in.

The geological composition as analyzed using gradation curves showed that the soils varied from loamy sand especially in the top soil layers of up to 0.6m depth below the ground surface. However, below this layer, the soils tended to gravelly sands and partially weathered rock material. The C_u and C_c calculated also showed fairly uniform distribution of various particle sizes within the samples analyzed with the effective sizes ranging from 0.06mm to 0.5mm. The maximum sampling depth was limited to 3m below the ground surface because of the available auger or dug out well material, but even where samples were obtained from depths below 3m, the weathered rock material sizes could not meet the gradation requirements. Larger effective sizes outside the range given were therefore expected from samples extracted from more than 3m depths. . The gradation curves for each soil sample analyzed are attached in Appendix 3 while Table 7 gives a summary of the classification of the samples based on the USCS and USDA textural triangle.

Table 7: Summary of the Aquifer Material Composition based on the Grading Curves

Sample name.	Sample depth (m)	D10 (mm)	D30 (mm)	D60 (mm)	C_U	C_C	%Finer sieve #200	Retained in sieve #4	Retained in sieve #200	Soil Class	Symbol
G. AGUTU	2.0	0.35	2.2	5.2	14.9	2.7	1.3	54.2	98.7	Gravelly sand	SW
H. OKOLO	1.2	0.31	2.4	5	16.1	3.7	2.4	46.9	97.6	sandy gravel	GW
G. AGUTU	0 - 0.3	0.07	0.33	0.8	11.4	1.9	12.7	100.0	87.3	loamy sand	SM
G. KERE	3	0.5	1.1	6	12.0	0.4	2.5	56.1	97.5	Gravelly sand	SW
G. KERE	0.3 - 0.6	0.4	2.7	5.1	12.8	3.6	1.0	54.1	99.0	Gravelly sand	SW
OWAKO	0.6 - 0.9	0.14	0.34	0.9	6.4	0.9	1.1	100.0	98.9	Sands	SW
H. OKOLO	0.3 - 0.6	0.34	1.6	3.3	9.7	2.3	1.0	77.0	99.0	Sands	SW
OWAKO	0 - 0.6	-	0.15	0.5	-	-	19.1	100.0	80.9	silty sand	SM
G. KERE	0.3 - 0.6	0.07	2.1	3.5	50.0	18.0	11.5	76.7	88.5	silty sand gravel mixture	GM
H. OKOLO	0 - 0.3	0.06	0.13	0.33	-	-	15.1	100.0	84.9	loamy sand	SM
H. OKOLO	0.6 - 0.9	0.31	1.8	4	12.9	2.6	1.9	68.0	98.1	Gravelly sand	SW
KAMGAN	2.0	1.5	5.2		0.0	-	0.9	26.9	99.1	sandy gravel	GW
H. OKOLO	2.0	0.4	2	5	12.5	2.0	2.6	58.3	97.4	Gravelly sand	SW
R. ANYANGO	2.0	0.18	1.1	4	22.2	1.7	3.3	63.0	96.8	Gravelly sand	SW
SIGOTI	2.0	0.18	1	4	22.2	1.4	4.2	65.1	95.9	Gravelly sand	SW
N. AGIMBA	2.0	0.14	0.8	4.1	29.3	1.1	4.9	64.0	95.2	Gravelly sand	SW
N. AGIMBA	0.3 - 0.6	0.35	1.3	3	8.6	1.6	1.7	84.6	98.3	Sand	SW
G. KERE	0 - 0.3	0.09	0.31	2	22.2	0.5	6.7	72.6	93.3	Sand	SW
N. AGIMBA	3.0	1.8	5.1		-	-	0.7	27.7	99.3	sandy gravel	GW
R. ONYIERO	0.3 - 0.6	0.34	2	3.8	11.2	3.1	2.1	27.7	97.9	Sand	SW
G. KERE	2.0	0.5	2.1	4.7	9.4	1.9	1.6	60.7	98.4	sandy gravel	GW
N. AGIMBA	0 - 0.3	0.07	0.37	2	28.6	1.0	11.8	87.5	88.2	loamy sand	SM
R. ONYIERO	0 - 0.3	0.08	0.34	1.6	20.0	0.9	9.5	99.2	90.5	Sand	SW

For soil samples having high clay contents (sticky soils), the sedimentation test was used to analyze the composition and the test results were as given in Table 8. The classification was based on the USDA soil textural triangle

Table 8: Sedimentation Test Results

Sample	Total depth	Sand depth	Silt depth	Clay depth	% sand	% silt	% clay	Soil Class
Owako SP2	65	26	24	15	40	37	23	
Owako SP2	62	31	15	16	50	24	26	
Average	**64**	**29**	**20**	**16**	**45**	**31**	**24**	**clay loam**
R. Onyiero SP2	33	15	10	8	45	30	24	
R. Onyiero SP2	50	21	19	10	42	38	20	
Average	**42**	**18**	**15**	**9**	**44**	**34**	**22**	**clay loam**
Ogonji	58	16	15	27	28	26	47	
Ogonji	34	10	12	12	29	35	35	
Ogonji	30	12	10	8	40	33	27	
Average	**41**	**13**	**12**	**16**	**32**	**31**	**36**	**clay**

SP2 refers to sampling point 2

The soils varied from clay to clay loams making these areas not suitable for well development due to the low hydraulic conductivity. For example wells dug by the Lake Basin Development Authority between 1989 and 1990 in Nyabondo Mixed and Nyagweno Primary schools, both having deep clay soils were abandoned even after achieving depths of 10m and 5.3m respectively implying that proper siting of well is important for successful well development.

From the results of both the mechanical sieve analysis and sedimentation test, the area comprised of fine soil materials at the top horizon and partly weathered rock material in the sub-soil and below, the phonolitic rock which according to tests done by DHV Consulting comprised of layers of semi-pervious rock and impervious rock with very few fault lines. This meant that well development past these layers would not necessarily result in improved water yields and therefore may not be worth the cost involved. This could explain the absence of bore holes within the plateau.

4.1.6 Specific Yield

The specific yields for the soil samples tested ranged from 5.5% to 10.6% which fell within the ranges for clay and gravel of 2% and 19% respectively (Heath, 1987). The specific yield results were tabulated in Table 9 below. Using an average value of specific yield, the well yield and safe yields were calculated as shown in Table 10.

Table 9: Specific yield of soil samples

Well name	Depth of sample (m)	Vol. drained (cm^3)	Specific yield (%)
Kamgan	1	53	10.6
R. Onyango	2	35	7
G. Kere	3	42.5	8.5
R. Anyango	2	47	9.4
G. Kere	2	49.5	9.9
G. Kere	0.3 – 0.6	44.5	8.9
R. Onyiero	0.3 – 0.6	36	7.2
G. Kere	0.3 – 0.6	38	6.3
N. Agimba	0.3 – 0.6	33	5.5
H. Okolo	1.2	61	10.2
Sigoti	2	49	8.2
Average			8.34

Table 10: Volumetric Inflow, Well Yields and Safe Yields

Well name	Area (m^2)	h (m)	t (hr)	V (m^3/hr)	y_w (m^3/hr)	Safe yield (m^3/d)
R. Onyiero	1.168987	1.21	1.667	0.848684	0.0708	1.2740
Sammy	1.114837	0.08	1.167	0.076446	0.0064	0.1148
Otieno	0.785398	0.09	0.333	0.212058	0.0177	0.3183
J. Owino	1.317946	0.15	0.667	0.296538	0.0247	0.4452
G. Kere	2.059351	0.1	0.117	1.765158	0.1472	2.6499
Average						0.9604

Based on the average safe yield of $0.9604m^3/day$, a well could supply on average 16 persons at 60 litres per capita per day. However, since well yields depend on the amount of recharge at any specific time, this figure may vary between the wet and dry seasons. Sharing of wells was therefore possible especially between households of less than 10 persons hence the concept of community wells is feasible.

4.2 MODFLOW Simulation

The mean values of aquifer properties which were input into the MODFLOW model are summarized in Table 11 below;

Table 11: Mean Values of Aquifer Properties

Property	Symbol	Mean value
Bulk density	ρ_b	1.157g/cm3
Porosity	η	55.55%
Vertical hydraulic conductivity	K_v	2.004m/day
Horizontal hydraulic conductivity	K_h	3.63m/day
Specific yield	S	8.34%

4.2.1 Model Packages

The amount of rain falling in Nyabondo plateau for the period between January and June 2010 was estimated as 1148.52mm. The mean monthly and total rainfall for the area was estimated as shown in Table 12 below.

Table 12: Rainfall Data

	Rainfall amounts in mm			
Month	**Kisumu**	**Kericho**	**Kisii**	**Nyabondo**
January	96.8	163.3	108.6	122.6724
February	107.7	222.9	106.5	145.2234
March	175.5	293.5	217.7	228.5771
April	307.4	243.1	244.6	265.0579
May	195.3	167.3	348.3	237.6635
June	30.7	164.1	252.3	149.3299
Total				1148.52

By rearranging the water balance equation, the groundwater recharge, G was computed from the rainfall data as shown below.

$$G = P - ET - R - S \qquad (45)$$

For the period from January to June (wet season)

P = 1148.52mm

ET = 0.6 x 1000 = 600mm

R = 0.1 x 1148.52 = 114.85mm

S = $2.87 \times 10^3 \times 0.5 \times 0.08$ = 114.8mm

G = 318.87mm = 0.3189m

The recharge flux obtained by dividing the total recharge by 183 days, being the duration of the rainfall record, was 0.00174m/day. The well names, geographical location, projected number of users and the computed daily water volume discharged from each well is attached as Appendix 4. These discharge rates were entered into the model. There were no recharge wells identified in the area. Where more than one well occurred within a cell, the cell discharge was the total discharge from all these wells. The distribution of the observation wells and the discharge wells over the model grid were as shown in Figures 10 and 11 respectively.

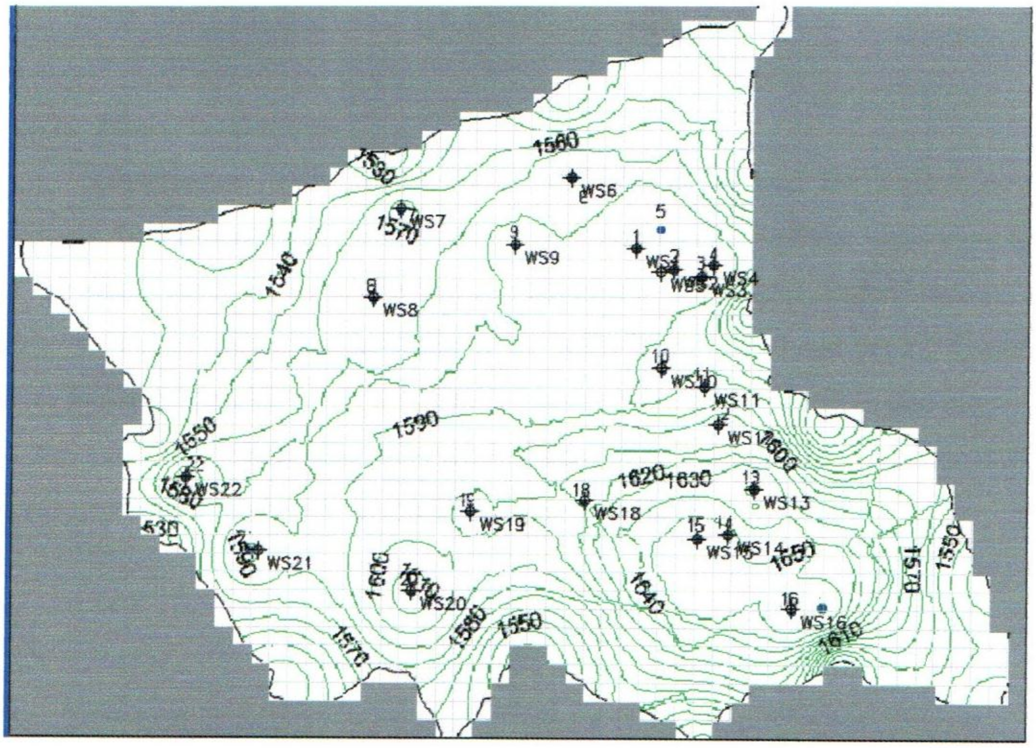


Figure 10: The model grid showing distribution of the observation wells

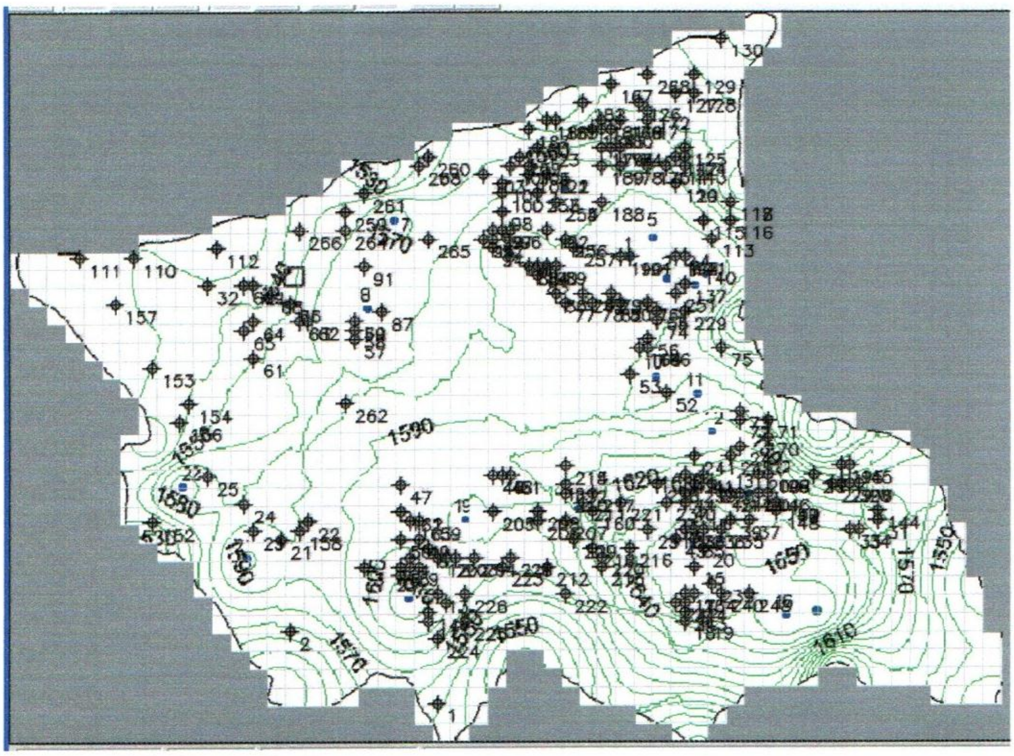
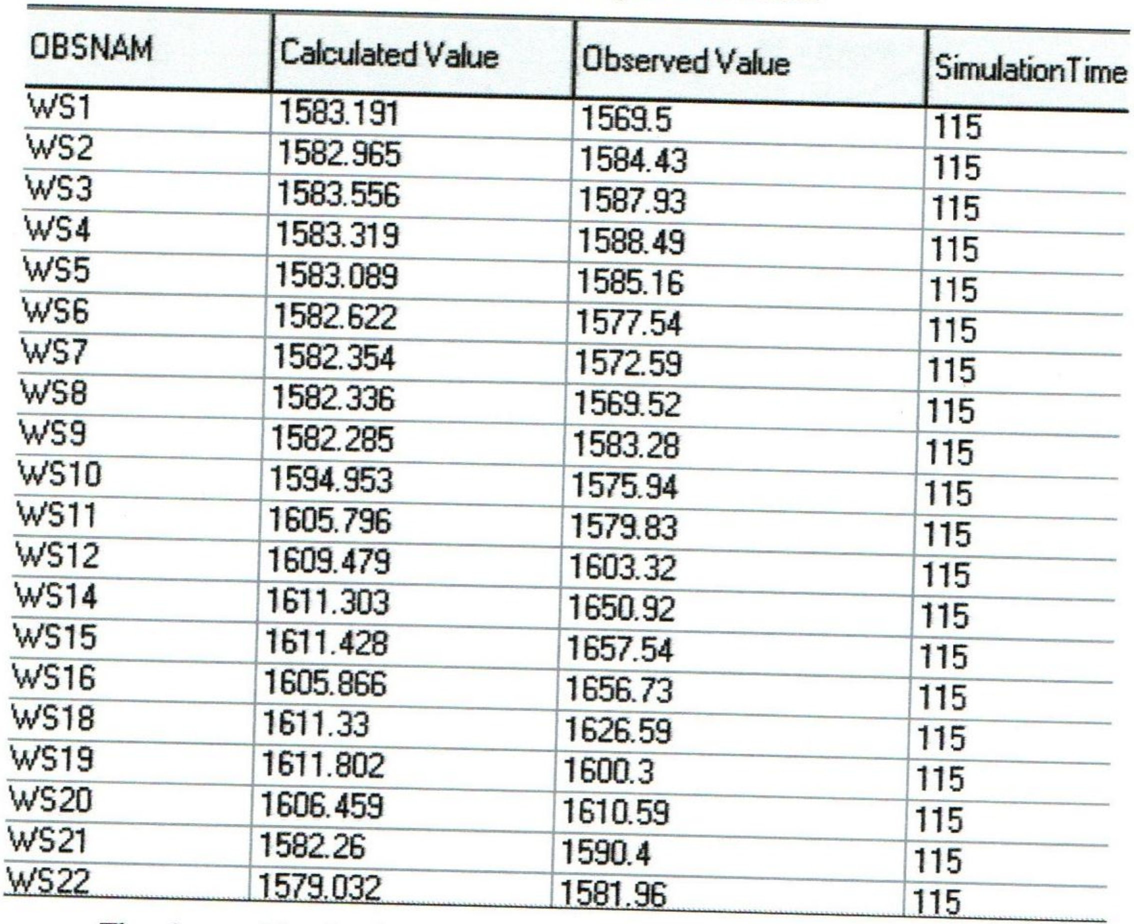


Figure 11: The distribution of the discharge wells

4.2.2 Model Evaluation

Observation wells WS14, WS15 and WS16 showed the highest deviation between the observed and calculated hydraulic heads. All the three wells were located in the south eastern part of the plateau. However, the closest approximations to the observed heads were given by wells WS2, WS5, WS9, WS20 and WS22. These wells were found in the Northern part of the plateau where the water table was much closer to the ground surface. The tabulated observed and calculated hydraulic heads as generated by the model are as given in Table 13 below.

Table 13: Observed and model calculated hydraulic heads



OBSNAM	Calculated Value	Observed Value	SimulationTime
WS1	1583.191	1569.5	115
WS2	1582.965	1584.43	115
WS3	1583.556	1587.93	115
WS4	1583.319	1588.49	115
WS5	1583.089	1585.16	115
WS6	1582.622	1577.54	115
WS7	1582.354	1572.59	115
WS8	1582.336	1569.52	115
WS9	1582.285	1583.28	115
WS10	1594.953	1575.94	115
WS11	1605.796	1579.83	115
WS12	1609.479	1603.32	115
WS14	1611.303	1650.92	115
WS15	1611.428	1657.54	115
WS16	1605.866	1656.73	115
WS18	1611.33	1626.59	115
WS19	1611.802	1600.3	115
WS20	1606.459	1610.59	115
WS21	1582.26	1590.4	115
WS22	1579.032	1581.96	115

The observed heads plotted against the model calculated values gave goodness of fit, R^2 of 0.51 as shown in Figure 12 below. Based on a goodness of fit scale of 0 to 1, the R^2 obtained was satisfactory as the value fell between 0.4 and 0.6. This meant that MOFLOW could be used to simulate the groundwater flow characteristics in the area but the data should be refined for improved results or the model packages enhanced to improve their performance. In a study using borehole data in the Middle Njoro River catchment by Kiptanui (2006) an R^2 of 0.56 obtained.

The RMSE and Nash- Sutcliffe model efficiency were calculated as 5.87 and 0.397 respectively. However, in the calculation of RMSE, the data was filtered to remove the calculated and observed values for wells WS14, WS15 and WS16 which had comparatively high deviations. Based on the Nash-Sutcliffe model efficiency range, the model performed well as the calculated values were more accurate than the mean of the observed data

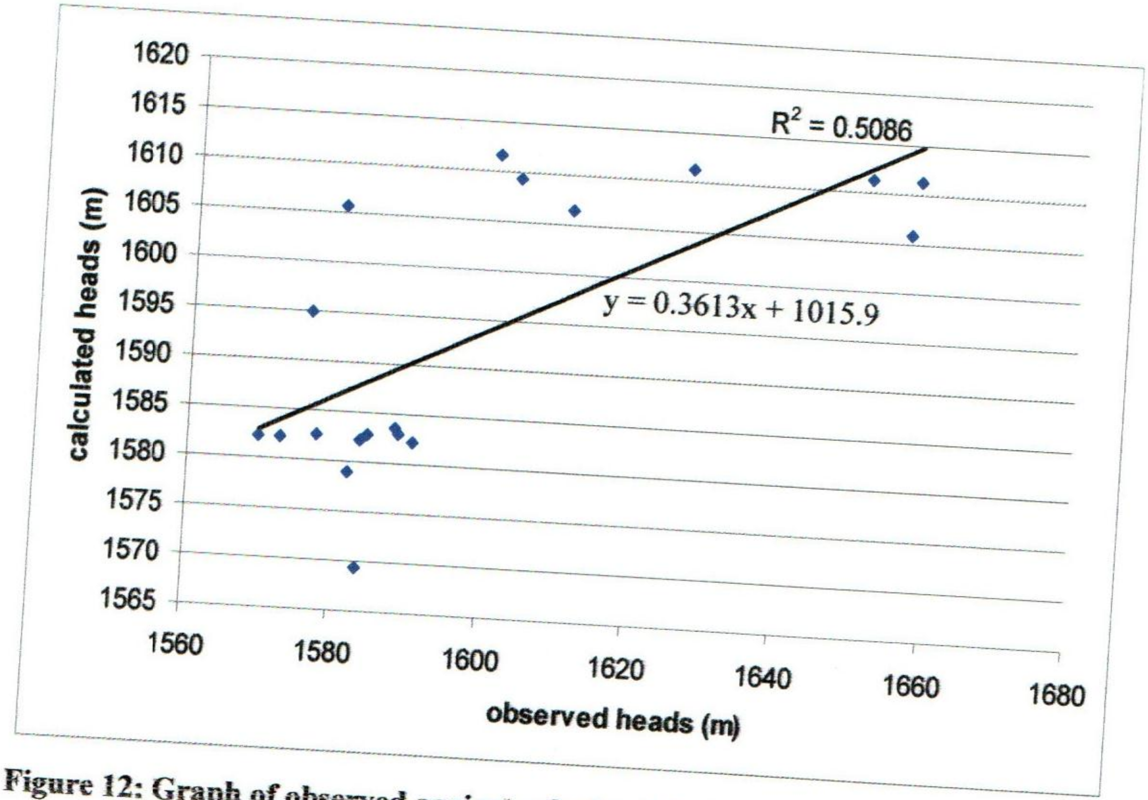


Figure 12: Graph of observed against calculated hydraulic heads

. The deviations between the observed and calculated heads could be attributed to the following reasons;

i. The observation wells were assumed to be neither recharging nor discharging wells. However this was not the case as the wells were in use during the study.

ii. The bottom of layer which is the elevation of the impervious layer was estimated. However no study has yet been carried out to determine its exact position.

iii. The MODFLOW assumes that all the wells are fully penetrating. However this was not true of the wells within the plateau.

In general therefore, the MODFLOW model could be adopted for groundwater simulation in a shallow aquifer and would be expected to perform better with more data refinement.

4.2.3 Groundwater Flow Characteristics

The MODFLOW run command resulted in tabular, graphical and two dimensional visualization outputs of hydraulic head, and cell by cell groundwater flow terms in the right and front faces over the stress period.

A two dimensional hydraulic head surface map for the area produced hydraulic heads that ranged from 1522.649m to a high of 1603.038m above mean sea level. None of the cells had its hydraulic head above the ground surface elevation. However some cells on the cliff towards the southern part of the plateau registered no flow. A physical check in these areas revealed protruding rocks at Oboch in Kajimbo location as shown in Plate 9. The rocks in these areas meant more impervious cover resulting into increased runoff and less infiltration of water into the ground. The no flow cells were found where the simulated hydraulic heads occurred below the model bottom layer. The HHS map produced was as shown in Figure 13 below.

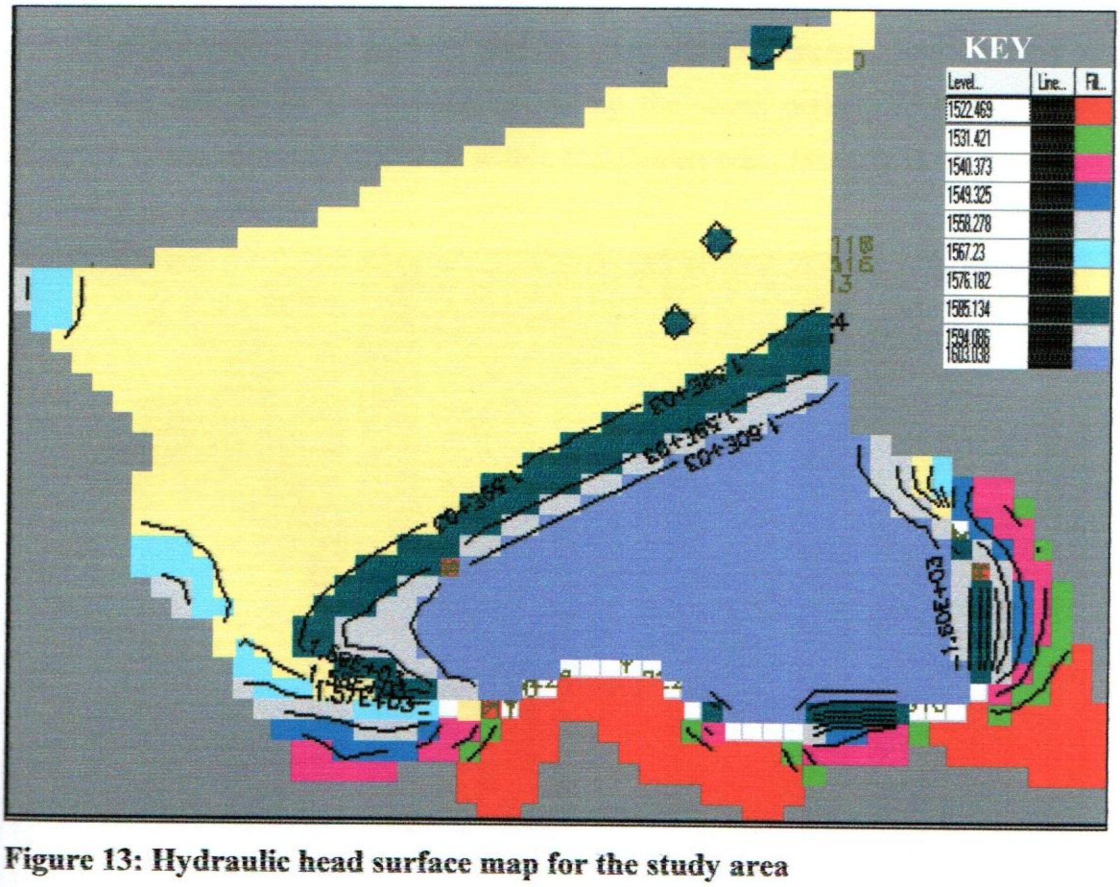


Figure 13: Hydraulic head surface map for the study area

Plate 9: Protruding rock resulting in no groundwater flow zone

The model produced two dimensional cell by cell flow maps for both the *x*-direction (right face) and the *y*-direction (front face). These are shown in Figures 14 and 15 respectively. The positive and negative values denoted flow entering or leaving the cell in the given direction during the stress period. From the values obtained, it was observed that flow within the plateau was generally in all directions but varied in magnitude.

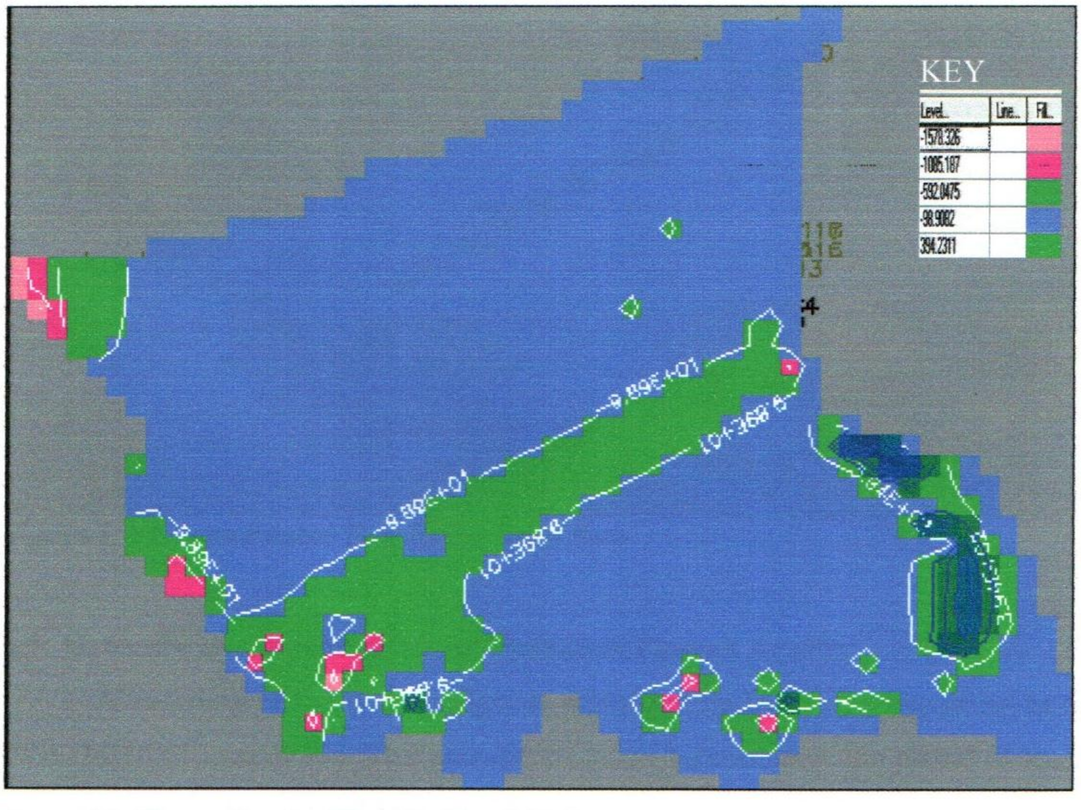


Figure 14: Groundwater Flow in the right face

The area at the middle of the plateau which exhibited the highest estimated flows of $992m^3$ in the x-direction fell within the alluvium section of the plateau. It was also a transition point between the southern and northern parts of the plateau hence had relatively higher gradient. This showed that the ground slope was directly related to the groundwater slope hence the surface gradient and the hydraulic gradient exhibited similar characteristics and was the most critical factor affecting groundwater flow over the plateau. For most of the plateau, flow was relatively uniform at about $98.9m^3$ during the stress period. In Figure 15, a larger area had negative flows. This meant that most of the flow out of the plateau was towards the northern boundary. This could be true because the northern part of the plateau is at a lower altitude than the southern part.

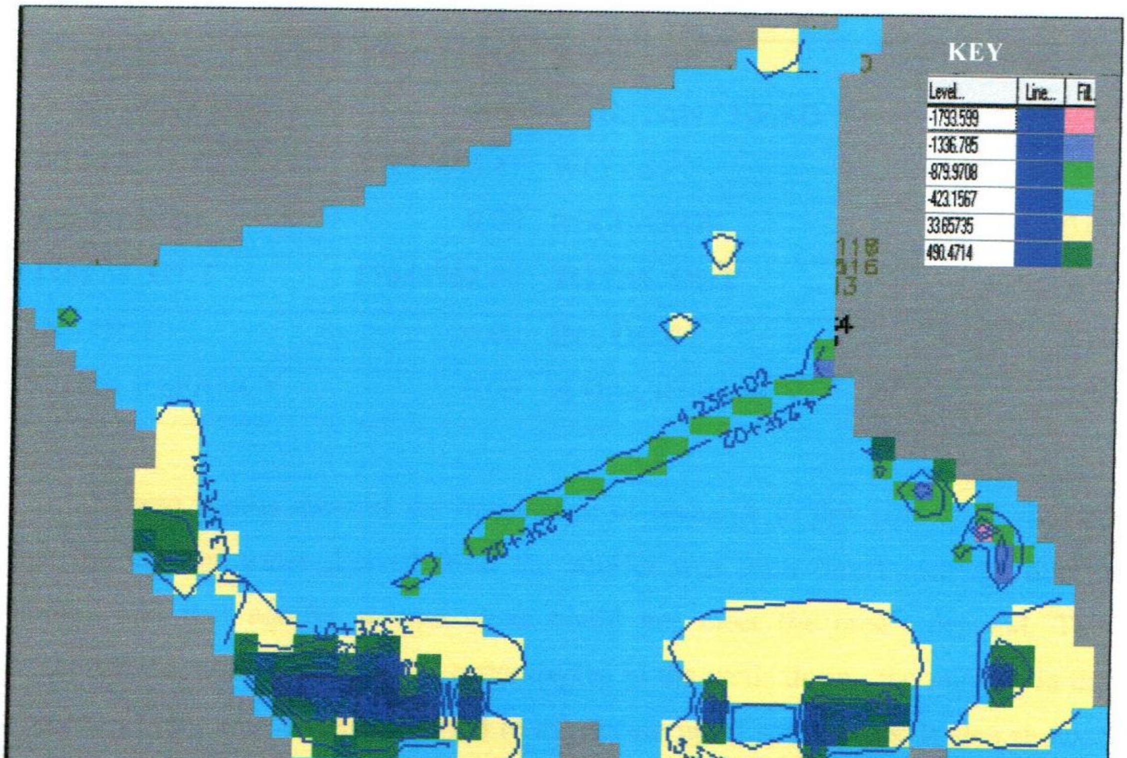


Figure 15: Groundwater flow in the front face

4.3 Groundwater Potential for the Nyabondo Plateau Aquifer

A summary of the water budget as calculated by the model was given in the 'WATERBDG' output file. This showed the water balance over the period of study. This summary was as reproduced in Table 14 below;

Table 14: Volumetric budget for entire model at end of time step 1 in stress period

CUMULATIVE VOLUMES m^3		**RATES FOR THIS TIME STEP** m^3/day	
IN		**IN**	
STORAGE	8069215.00	STORAGE	70167.086
CONSTANT HEAD	0.00	CONSTANT HEAD	0.00
WELLS	0.00	WELLS	0.00
RECHARGE	9575774.00	RECHARGE	83267.60
TOTAL IN	**17644988.00**	**TOTAL IN**	**153434.69**
OUT		**OUT**	
STORAGE	17345116.00	STORAGE	150827.09
CONSTANT HEAD	0.00	CONSTANT HEAD	0.00
WELLS	299846.41	WELLS	2607.36
RECHARGE	0.00	RECHARGE	0.00
TOTAL OUT	**17644962.00**	**TOTAL OUT**	**153434.45**
IN - OUT	**26.00**	**IN - OUT**	**0.23**
% DISCREPANCY	0.00	% DISCREPANCY	0.00

These results showed the importance of recharge to this aquifer. It showed that the bulk of water derived from the aquifer was from direct recharge due to rainfall and that aquifer storage alone could not meet the area's demand. This explained the sudden variation in water depths in the wells during the rains or in the absence of rain which sometimes led to the drying up of some wells. It also showed that the threshold for this aquifer had almost been reached and alternative sources of water needed to be explored given the low net volumetric rate of $0.2344m^3$/day.

For the groundwater storage component, the amount of water into the aquifer was lower than that leaving the aquifer. This meant that part of the recharge flowed out of the aquifer either through the seasonal springs located within the plateau or as sub surface flow towards the lower regions including the Sondu Miriu River.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.0 Conclusions

Aquifer properties such as the bulk density, porosity, vertical and horizontal hydraulic conductivity, geologic composition, specific yield and hydraulic heads were determined for the plateau. They were found to vary both spatially and directionally. The aquifer was therefore heterogenous and anisotropic. Mean values of 1.16g/cm^3, 55.6%, 2.004m/day, 3.63m/day and 8.34% were obtained for bulk density, porosity, vertical hydraulic conductivity, horizontal hydraulic conductivity and specific yield respectively. The vertical and horizontal hydraulic conductivities were within the same order of magnitude but the slight variation could be attributed to the presence of an impermeable layer resulting in preferential horizontal flow. The water table varied temporally but showed linear relationship with ground surface altitude hence it was concluded to be topographically controlled.

Recharge to groundwater was basically from rainfall. The computed recharge flux for the period between January and May was 0.00173m/day. The MODFLOW model evaluation resulted in R^2 of 0.51, RMSE of 5.87 and model efficiency of 0.397. These results showed that MODFLOW could be applied to simulate shallow groundwater conditions but would require more data refinement or enhancement of the model packages for improved performance. The accuracy of the results could be enhanced if more data were available. Groundwater flow was found to be generally in all directions but varied in magnitude. This included flow out the plateau through springs or sub surface flow.

The groundwater budget showed that most of the water flowing into the aquifer was being extracted using the shallow wells. The net volumetric rate of 0.2344m^3/day could imply that the threshold for the aquifer has been reached and that alternative water sources such as rainwater harvesting should be explored to reduce the strain on groundwater. Due to the importance of recharge from rainfall, any activity that could result into reduced infiltration capacity of the soils should be discouraged as this would have a direct impact on the groundwater system in the area.

5.1 Recommendations

Continuous monitoring of the groundwater system should be initiated in the area. These would provide more data which would further assist in the evaluation of the MODFLOW model. In addition data covering both wet and dry seasons collected over a long period would minimize errors hence improve on data reliability. A study to determine the actual depth of the impervious layer within the aquifer is necessary.

Any future development of the wells within the Nyabondo plateau should be guided by the existing groundwater data. Instead of individual wells, the community should explore the option of community wells and incorporate water harvesting technologies to reduce the strain on groundwater.

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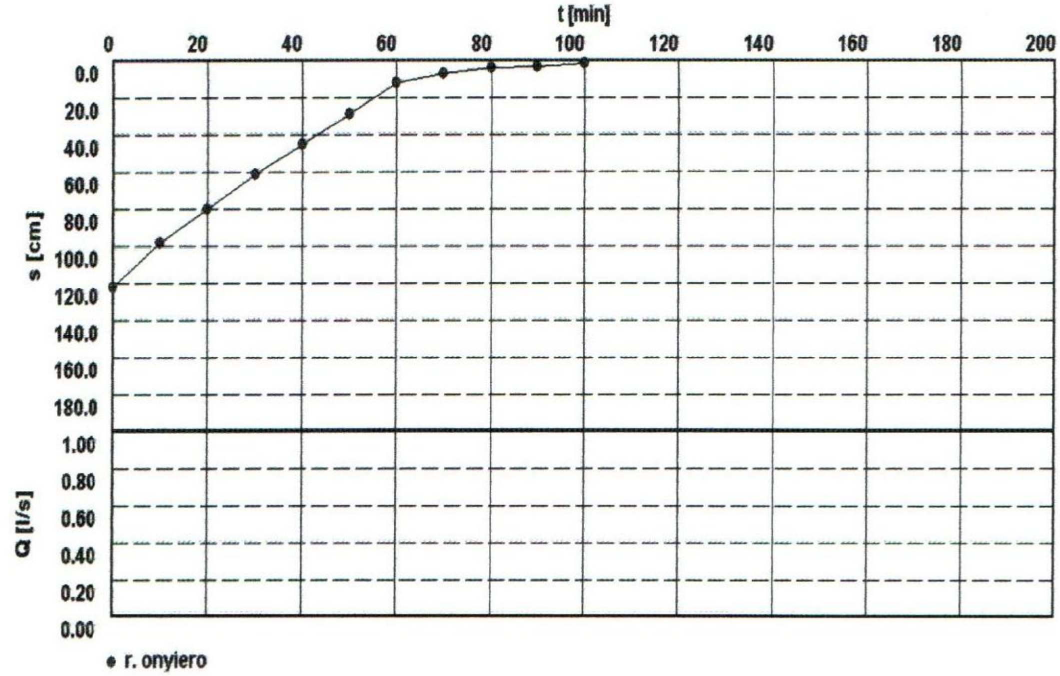
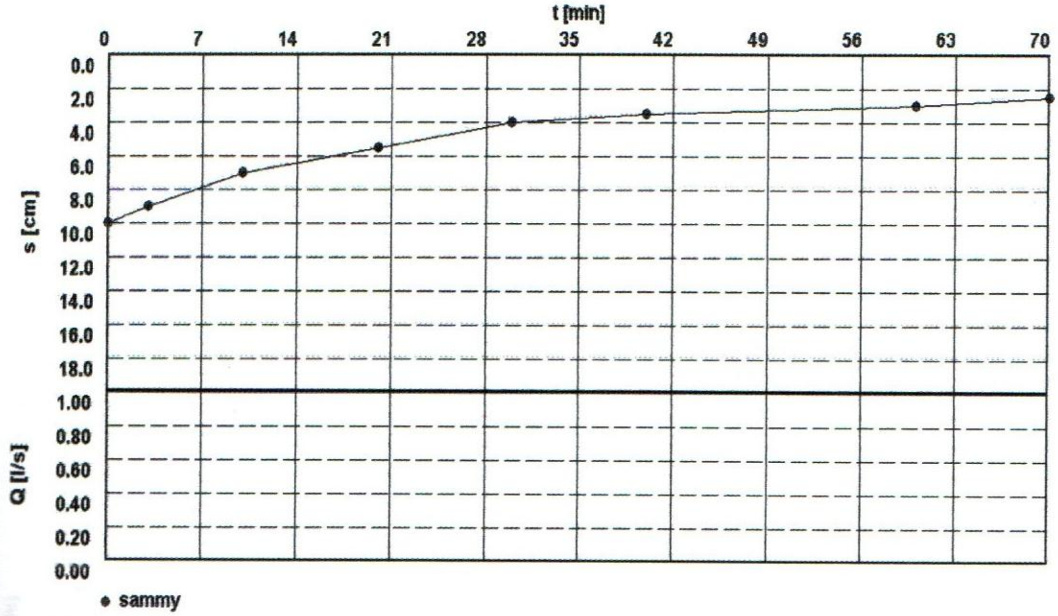
APPENDIX 1

SLUG TEST RESULTS

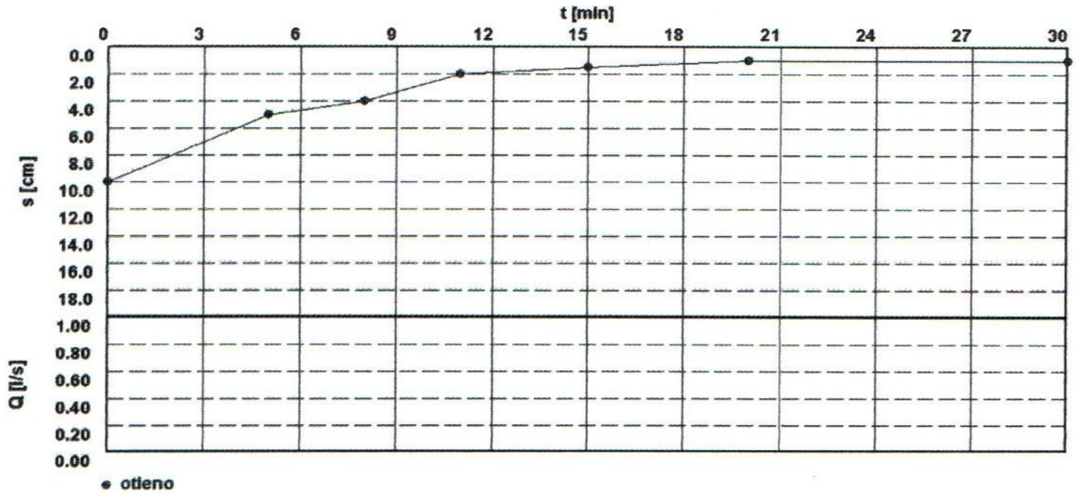
TIME-DRAWDOWN CURVES



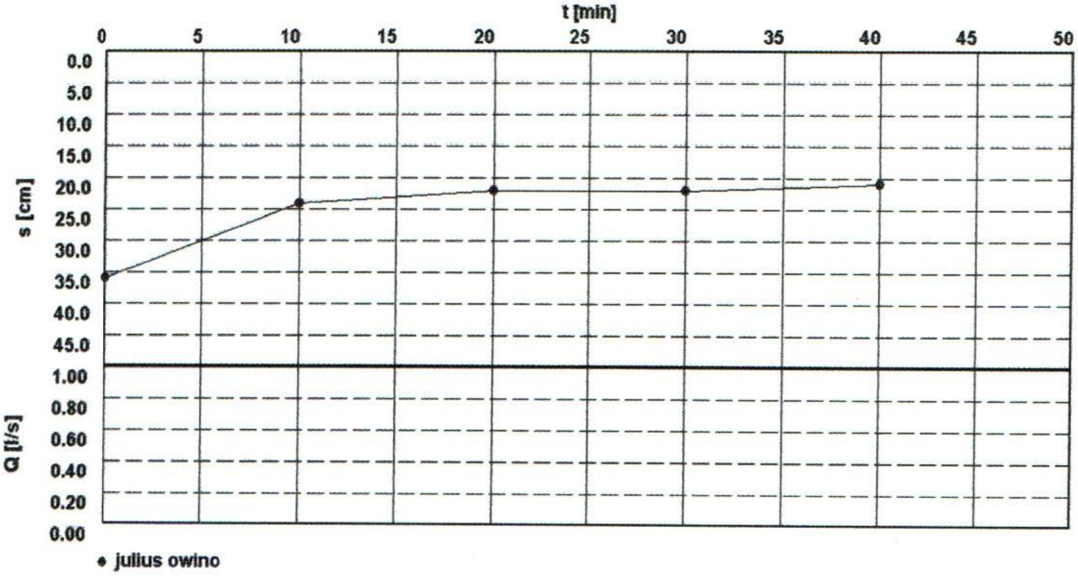
Time-Drawdown curve for Onyiero well



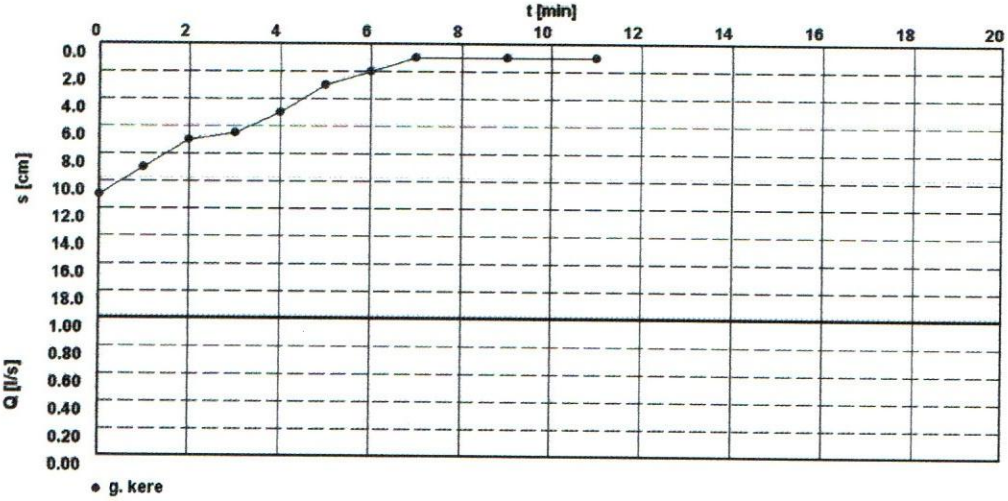
Time-Drawdown curve for Sammy well



Time-Drawdown curve for Otieno well



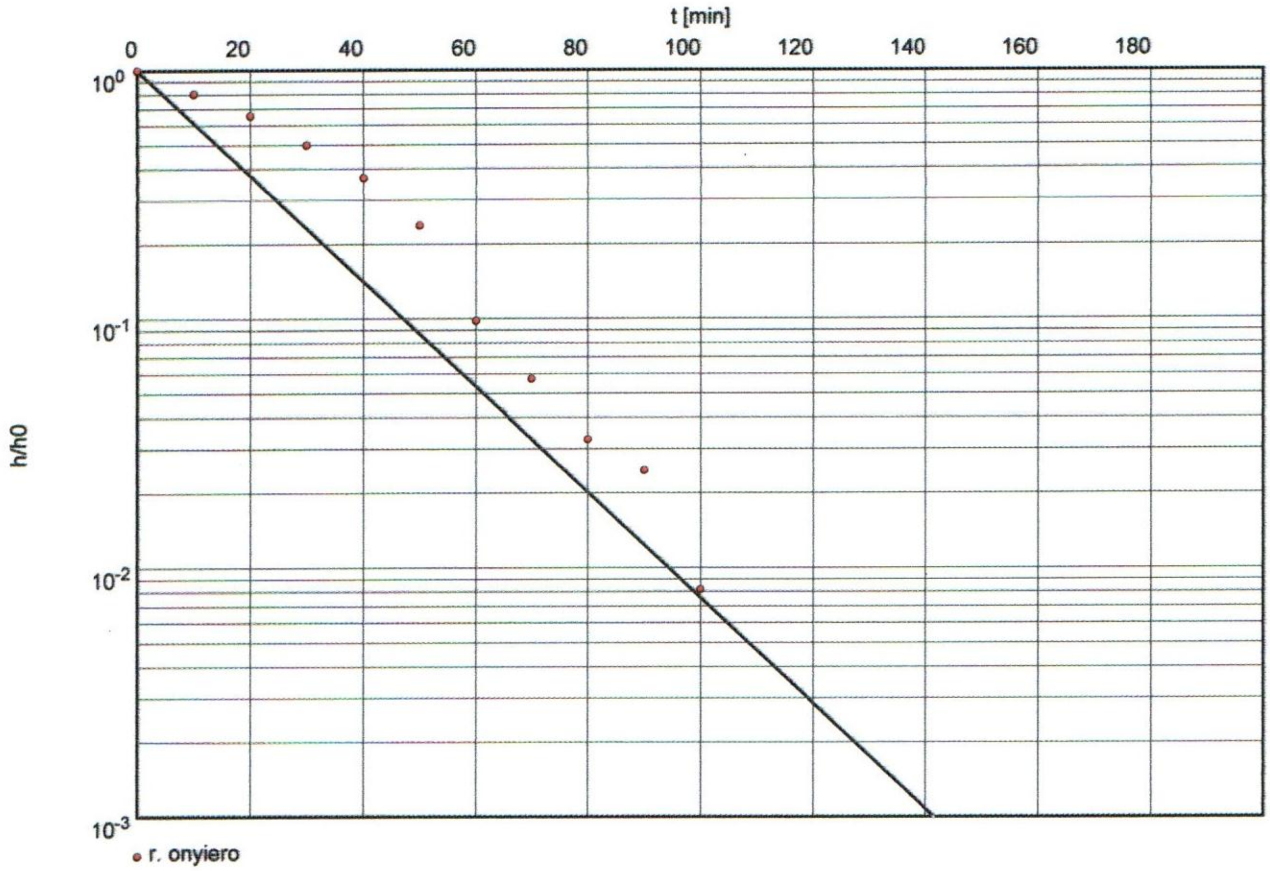
Time-Drawdown curve for Owino well



Time – drawdown curves for Kere well

Egerton University P.O. Box 536 Egerton	slug/bail test analysis BOUWER-RICE's method	Project: nyabondo plateau Evaluated by: Date: 29.10.2010

Slug Test No. 1	Test conducted on: 29/10/2010
r. onyiero	

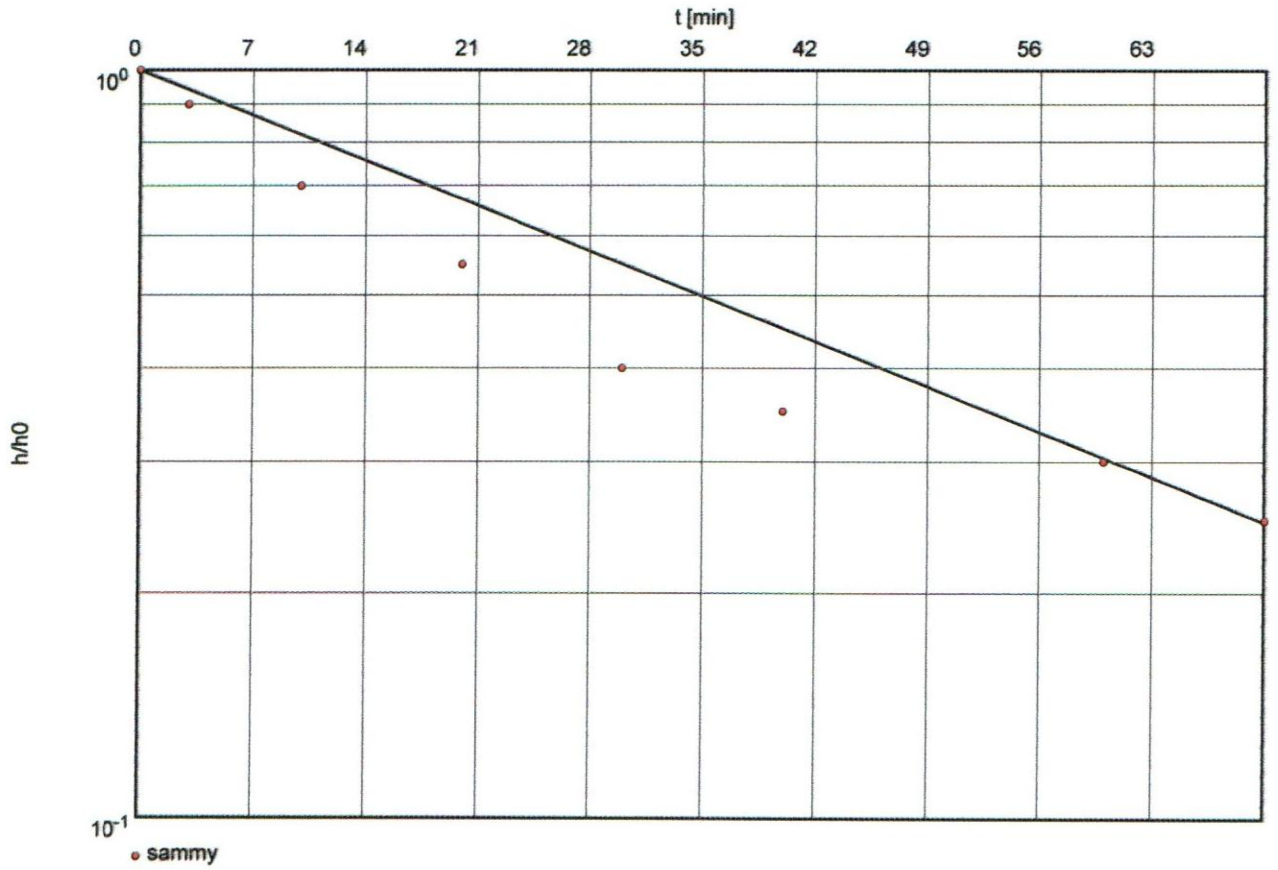


Hydraulic conductivity [cm/min]: 2.96×10^{-1}

Egerton University P.O. Box 536 Egerton	Slug/Bail test analysis BOUWER-RICE's method	Project: NYABONDO PLATEAU
		Evaluated by: S.N.
		Date: 04.11.2010

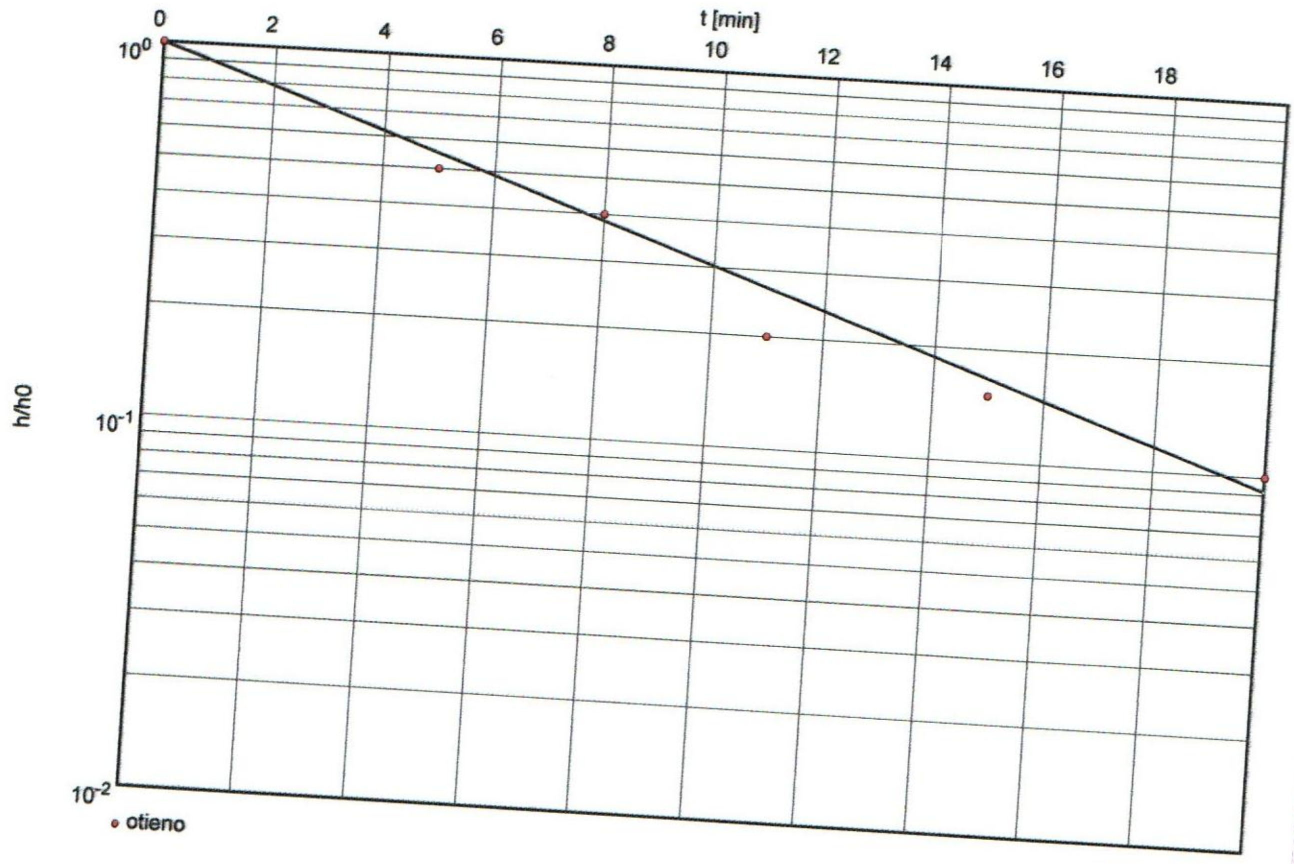
Slug Test No.

Test conducted on: 30/10/10



Hydraulic conductivity [cm/min]: 1.06×10^{-1}

Egerton University P.O. Box 536 Egerton	slug/bail test analysis BOUWER-RICE's method	Project: nyabondo plateau
Slug Test No. 2		Evaluated by: nyakach sDate: 01.11.2
otieno	Test conducted on: 30/10/2010	



Hydraulic conductivity [cm/min]: 4.10×10^{-1}

Egerton University
P.O. Box 536
Egerton

slug/bail test analysis
BOUWER-RICE's method

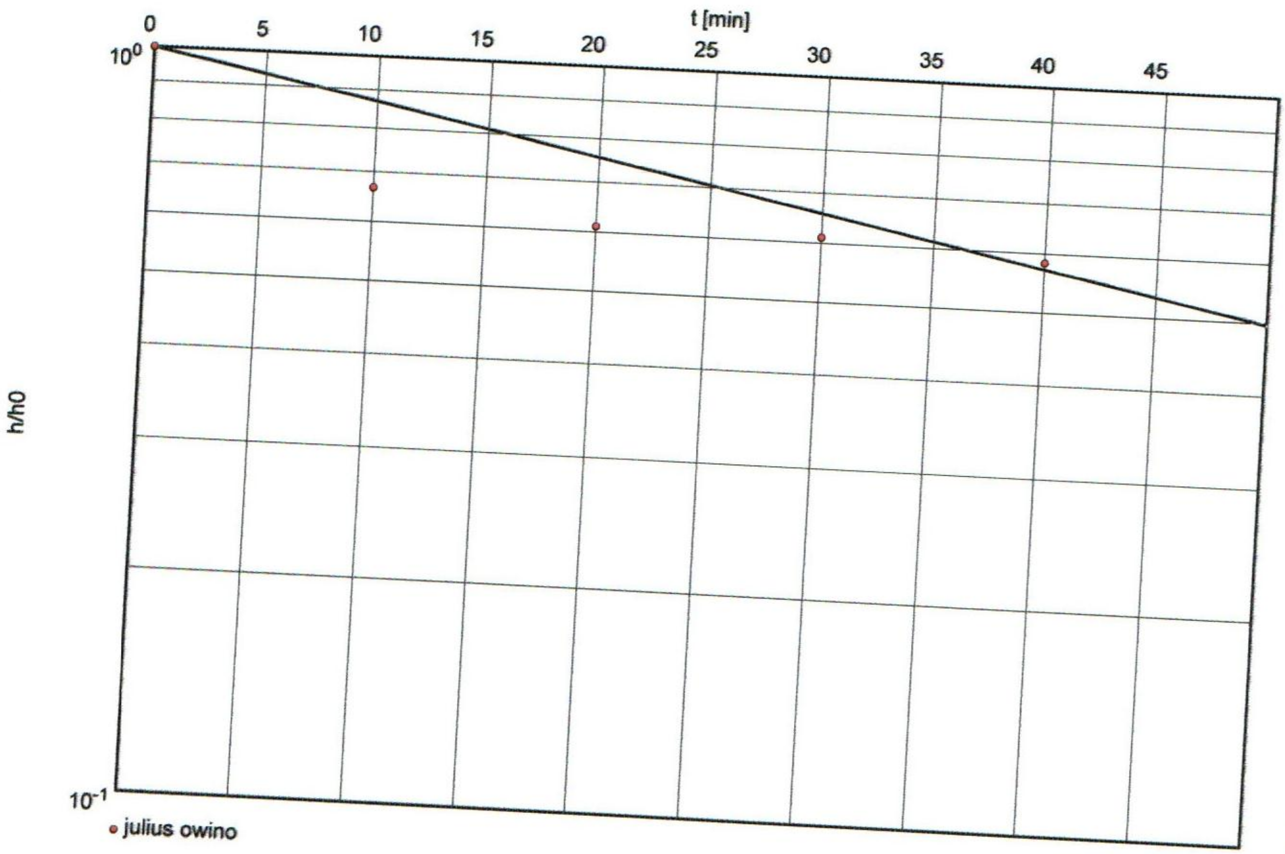
Project: nyabondo plateau

Evaluated by: nyakach,S

Date: 04.11.2010

Slug Test No.

Test conducted on:



Hydraulic conductivity [cm/min]: 3.87×10^{-2}

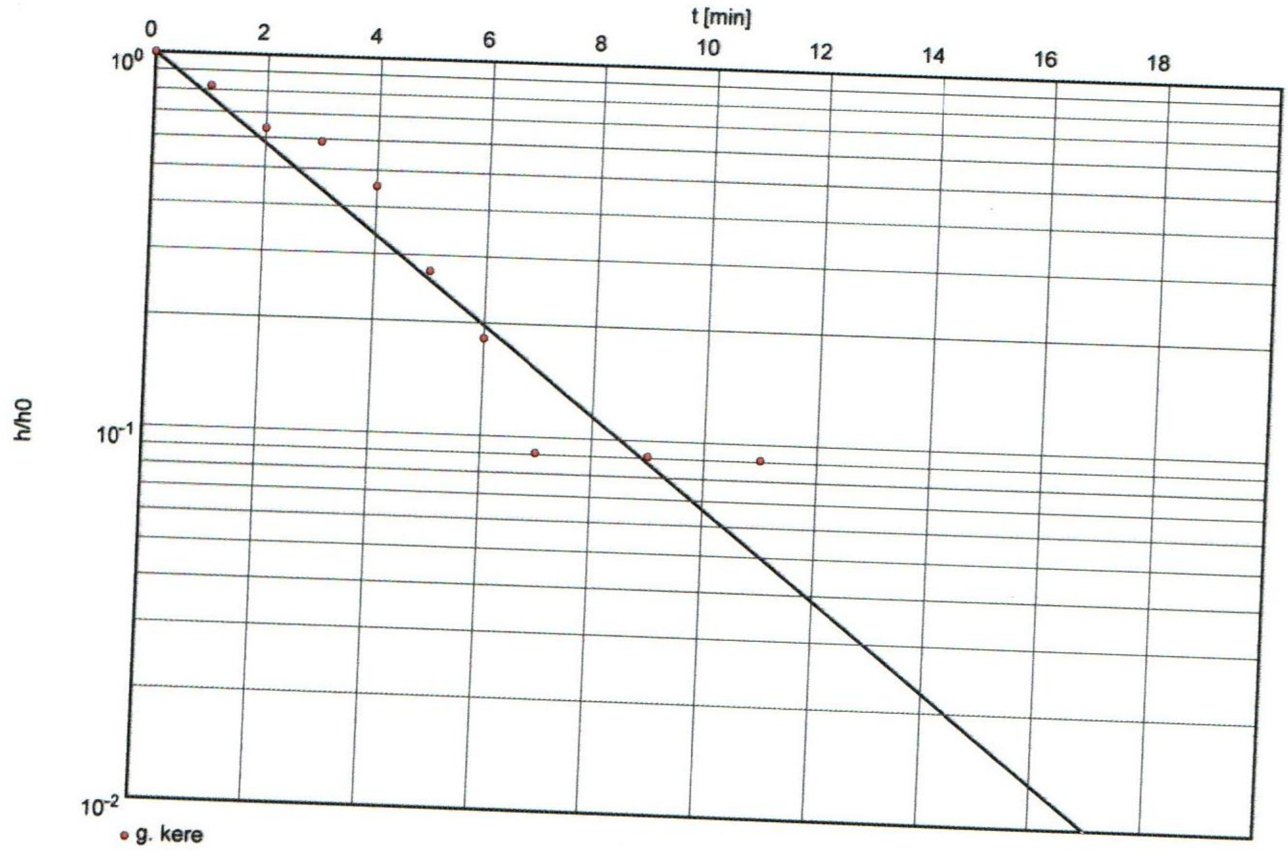
Egerton University
P.O. Box 536
Egerton

slug/bail test analysis
BOUWER-RICE's method

Project: nyabondo plateau
Evaluated by: nyakach,sDate: 04.11.2010

Slug Test No.

Test conducted on: 30/10/10



Hydraulic conductivity [cm/min]: 2.04×10^0

Egerton University
P.O. Box 536
Egerton

BOUWER-RICE's method

Project: nyabondo plateau

Evaluated by:

Date: 29.10.2010

Slug Test No. 1

Test conducted on: 29/10/2010

r. onyiero

r. onyiero

Static water level: 195.0 cm below datum

	Pumping test duration [min]	Water level [cm]	Drawdown [cm]
1	0.00	317.0	122.0
2	10.00	293.0	98.0
3	20.00	275.0	80.0
4	30.00	256.0	61.0
5	40.00	240.0	45.0
6	50.00	224.0	29.0
7	60.00	207.0	12.0
8	70.00	202.0	7.0
9	80.00	199.0	4.0
10	90.00	198.0	3.0
11	100.00	196.0	1.0

Egerton University P.O. Box 536 Egerton	slug/bail test analysis BOUWER-RICE's method	Project: NYABONDO PLATEAU	
		Evaluated by: S.N.	Date: 04.11.2010

Slug Test No.	Test conducted on: 30/10/10
	sammy

Static water level: 206.0 cm below datum

	Pumping test duration [min]	Water level [cm]	Drawdown [cm]	
1	0.00	216.0	10.0	
2	3.00	215.0	9.0	
3	10.00	213.0	7.0	
4	20.00	211.5	5.5	
5	30.00	210.0	4.0	
6	40.00	209.5	3.5	
7	60.00	209.0	3.0	
8	70.00	208.5	2.5	

Egerton University P.O. Box 536 Egerton	slug/bail test analysis BOUWER-RICE's method	Project: nyabondo plateau Evaluated by: nyakach sDate: 01.11.2010

Slug Test No. 2	Test conducted on: 30/10/2010
otieno	otieno

Static water level: 269.0 cm below datum

	Pumping test duration [min]	Water level [cm]	Drawdown [cm]	
1	0.00	279.0	10.0	
2	5.00	274.0	5.0	
3	8.00	273.0	4.0	
4	11.00	271.0	2.0	
5	15.00	270.5	1.5	
6	20.00	270.0	1.0	
7	30.00	270.0	1.0	

Egerton University P.O. Box 536 Egerton	slug/bail test analysis BOUWER-RICE's method	Project: nyabondo plateau Evaluated by: nyakach,S Date: 04.11.2010

Slug Test No.	Test conducted on:
	julius owino

Static water level: 292.0 cm below datum

	Pumping test duration [min]	Water level [cm]	Drawdown [cm]	
1	0.00	328.0	36.0	
2	10.00	316.0	24.0	
3	20.00	314.0	22.0	
4	30.00	314.0	22.0	
5	40.00	313.0	21.0	

Egerton University P.O. Box 536 Egerton	slug/bail test analysis BOUWER-RICE's method	Project: nyabondo plateau Evaluated by: nyakach,sDate: 04.11.2010

Slug Test No.	Test conducted on: 30/10/10
	g. kere

Static water level: 409.0 cm below datum

	Pumping test duration [min]	Water level [cm]	Drawdown [cm]
1	0.00	420.0	11.0
2	1.00	418.0	9.0
3	2.00	416.0	7.0
4	3.00	415.5	6.5
5	4.00	414.0	5.0
6	5.00	412.0	3.0
7	6.00	411.0	2.0
8	7.00	410.0	1.0
9	9.00	410.0	1.0
10	11.00	410.0	1.0

APPENDIX 2

PERMEABILITY TEST RESULTS

Sample	Depth	Test	Vol. (cc)	Time (sec)	H1 (cm)	H2 (cm)	K (cm/s)	k (m/d)	K (avg)	
									(cm/s)	(m/d)
G. KERE	0-30cm	1	59	6480	64	46	0.0001	0.0631	0.0001	0.06
G. KERE	30-60cm	1	102	150	64	35.5	0.0034	2.9769	0.0034	2.96
		2	200	246	64	35	0.0040	3.4979		
		3	84	150	64	35	0.0028	2.4093		
G. KERE	60-90cm	1	200	150	64	36	0.0069	5.9414	0.0094	8.14
		2	200	94	64	36	0.0110	9.4809		
		3	200	99	64	36	0.0104	9.0020		
G. KERE	2m	1	200	870	64	24	0.0008	0.7171	0.0008	0.72
		2	54	300	64	24.5	0.0007	0.5686		
		3	49	180	64	24.5	0.0010	0.8599		
G. KERE	3m	1	200	343	64	34	0.0028	2.4250	0.0025	2.12
		2	200	408	64	33	0.0023	1.9729		
		3	200	440	64	35	0.0023	1.9556		
H. OKOLO	00-30cm	1	200	347	64	32	0.0026	2.2473	0.0028	2.42
		2	210	347	64	32.5	0.0028	2.3971		
		3	200	288	64	31	0.0030	2.6256		
H. OKOLO	30-60cm	1	200	425	64	37	0.0025	2.1746	0.0027	2.35
		2	200	396	64	38	0.0028	2.4236		
		3	200	401	64	38.5	0.0028	2.4403		
H. OKOLO	60-90cm	1	200	127	64	38	0.0087	7.5571	0.0088	7.57
		2	200	121	64	38	0.0092	7.9319		
		3	200	133	64	38	0.0084	7.2162		
H. OKOLO	90-120cm	1	200	153	64	37	0.0070	6.0406	0.0069	5.98
		2	200	159	64	37.5	0.0069	5.9223		
		3	200	167	64	39	0.0069	5.9769		
H. OKOLO	2m	1	200	883	64	26	0.0009	0.7437	0.0008	0.69
		2	200	808	64	25	0.0009	0.7919		
		3	78	450	64	24	0.0006	0.5407		
N. AGIMBA	0-30cm	1	200	765	64	41	0.0016	1.4182	0.0016	1.40
		2	200	1021	64	43.5	0.0014	1.1922		
		3	77	300	64	44	0.0019	1.6012		
N. AGIMBA	30-60cm	1	200	629	64	45.5	0.0025	2.1444	0.0022	1.92
		2	200	665	64	46	0.0024	2.0847		
		3	96	450	64	46.5	0.0018	1.5210		

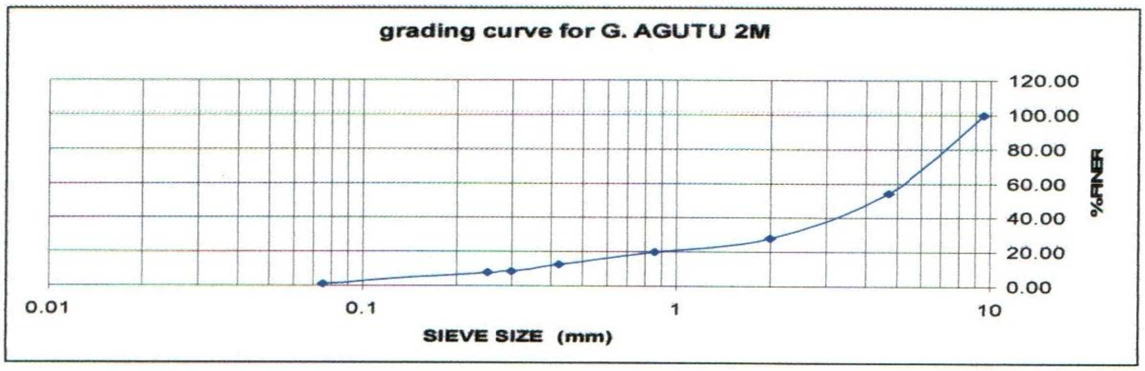
Sample	Depth	Test	Vol. (cc)	Time (sec)	H1 (cm)	H2 (cm)	K (cm/s)	k (m/d)	K (avg) cm/s	K (avg) m/d
N. AGIMBA	1.5m	1	200	299	64	37	0.0036	3.0910	0.0043	3.72
		2	200	287	64	41	0.0044	3.7803		
		3	200	253	64	41	0.0050	4.2883		
N. AGIMBA	3m	1	200	542	64	25.5	0.0014	1.1958	0.0014	1.22
		2	200	526	64	26	0.0014	1.2484		
		3	200	585	64	28.5	0.0014	1.2016		
SIGOTI	2m	1	200	505	64	28	0.0016	1.3726	0.0015	1.26
		2	200	521	64	28	0.0015	1.3304		
		3	200	619	64	27	0.0013	1.0895		
R. ANYANGO	2m	1	44	180	64	37	0.0013	1.1296	0.0019	1.60
		2	200	478	64	38	0.0023	2.0079		
		3	200	518	64	35	0.0019	1.6611		
		4	200	520	64	34	0.0019	1.5996		
G. AGUTU	3m	1	200	240	64	28	0.0033	2.8882	0.0033	2.84
		2	200	238	64	28	0.0034	2.9124		
		3	200	252	64	27.5	0.0031	2.7129		
R. ONYIERO	30-60cm	1	200	120	64	25	0.0062	5.3320	0.0063	5.41
		2	200	121	64	26	0.0063	5.4271		
		3	200	120	64	26	0.0063	5.4723		
R. ONYIERO	0-30cm	1	200	131	64	29	0.0063	5.4425	0.0062	5.39
		2	200	129	64	29	0.0064	5.5268		
		3	200	137	64	29	0.0060	5.2041		
0WAKO	0-60cm	1	83	210	64	24	0.0014	1.2328	0.0013	1.15
		2	56	150	64	24	0.0013	1.1645		
		3	84	240	64	23	0.0012	1.0651		
OWAKO	60-100cm	1	200	541	64	36	0.0019	1.6473	0.0019	1.61
		2	200	557	64	36	0.0019	1.6000		
		3	200	561	64	36	0.0018	1.5886		

APPENDIX 3

MECHANICAL SOIL ANALYSIS RESULTS

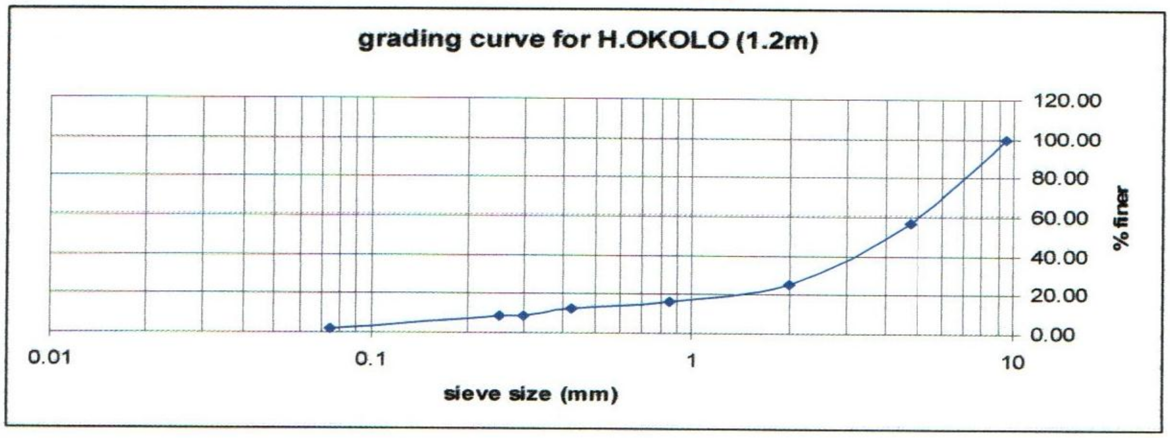
MECHANICAL SIEVE ANALYSIS FOR G. AGUTU 2M

sieve no.	sieve size	weight of sieve	retained soil+sieve	soil retained	% soil retained	cum. % retained	% finer
3/8	9.5	549	549	0	0.00	0.00	100.00
4	4.75	514	933	419	45.79	45.79	54.21
10	2	439	677	238	26.01	71.80	28.20
20	0.85	440	517	77	8.42	80.22	19.78
40	0.425	329	394	65	7.10	87.32	12.68
50	0.3	454	489	35	3.83	91.15	8.85
60	0.25	349	354	5	0.55	91.69	8.31
200	0.075	285	349	64	6.99	98.69	1.31
pan	0	344	356	12	1.31	100.00	0.00
				915			



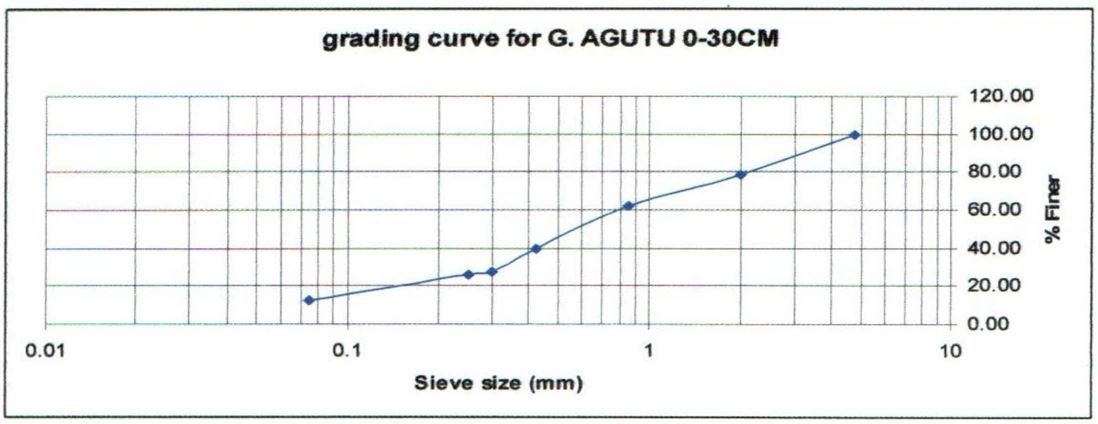
MECHANICAL SIEVE ANALYSIS FOR H. OKOLO 1.2M

sieve no.	sieve size	weight of sieve	retained soil+sieve	soil retained	% soil retained	cum. % retained	% finer
3/8	9.5	549	549	0	0.00	0.00	100.00
4	4.75	514	931	417	43.08	43.08	56.92
10	2	439	743	304	31.40	74.48	25.52
20	0.85	440	526	86	8.88	83.37	16.63
40	0.425	329	369	40	4.13	87.50	12.50
50	0.3	454	485	31	3.20	90.70	9.30
60	0.25	349	355	6	0.62	91.32	8.68
200	0.075	285	346	61	6.30	97.62	2.38
pan	0	344	367	23	2.38	100.00	0.00
				968			



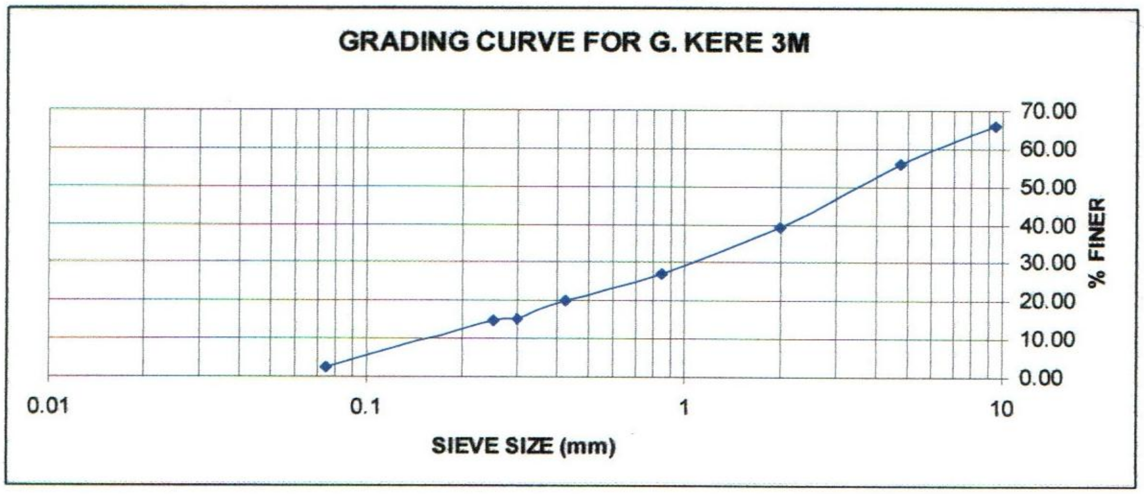
MECHANICAL SIEVE ANALYSIS FOR G. AGUTU 0-30CM

sieve no.	sieve size	weight of sieve	retained soil+sieve	soil retained	% soil retained	cum. % retained	% finer
3/8	9.5	549	549	0	0.00	0.00	100.00
4	4.75	514	514	0	0.00	0.00	100.00
10	2	439	656	217	21.49	21.49	78.51
20	0.85	440	602	162	16.04	37.52	62.48
40	0.425	329	561	232	22.97	60.50	39.50
50	0.3	454	573	119	11.78	72.28	27.72
60	0.25	349	362	13	1.29	73.56	26.44
200	0.075	285	424	139	13.76	87.33	12.67
pan	0	344	472	128	12.67	100.00	0.00
				1010			



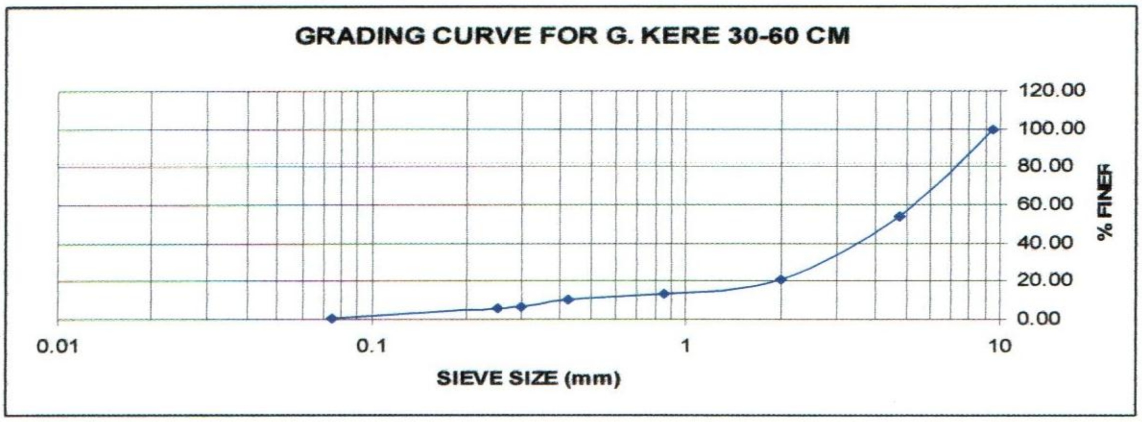
MECHANICAL SIEVE ANALYSIS FOR G. KERE 3M

sieve no.	sieve size	weight of sieve	retained soil+sieve	soil retained	% soil retained	cum. % retained	% finer
3/8	9.5	549	877	328	33.92	33.92	66.08
4	4.75	514	611	97	10.03	43.95	56.05
10	2	439	602	163	16.86	60.81	39.19
20	0.85	440	558	118	12.20	73.01	26.99
40	0.425	329	396	67	6.93	79.94	20.06
50	0.3	454	500	46	4.76	84.69	15.31
60	0.25	349	355	6	0.62	85.32	14.68
200	0.075	285	403	118	12.20	97.52	2.48
pan	0	344	368	24	2.48	100.00	0.00
				967			



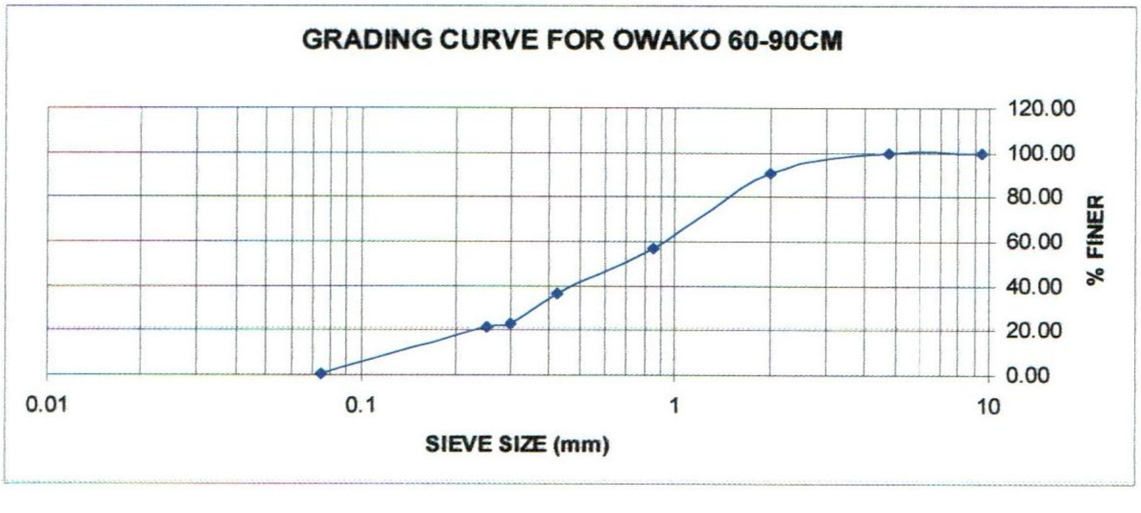
MECHANICAL SIEVE ANALYSIS FOR G. KERE 30-60CM

sieve no.	sieve size	weight of sieve	retained soil+sieve	soil retained	% soil retained	cum. % retained	% finer
3/8	9.5	549	549	0	0.00	0.00	100.00
4	4.75	514	958	444	45.87	45.87	54.13
10	2	439	761	322	33.26	79.13	20.87
20	0.85	440	508	68	7.02	86.16	13.84
40	0.425	329	364	35	3.62	89.77	10.23
50	0.3	454	487	33	3.41	93.18	6.82
60	0.25	349	355	6	0.62	93.80	6.20
200	0.075	285	335	50	5.17	98.97	1.03
pan	0	344	354	10	1.03	100.00	0.00
				968			


GRADING CURVE FOR G. KERE 30-60 CM

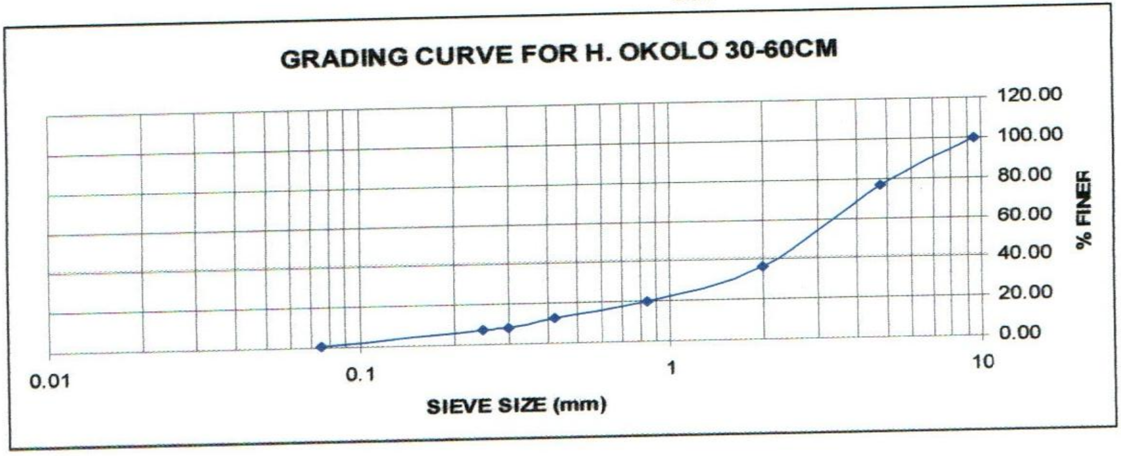
MECHANICAL SIEVE ANALYSIS FOR OWAKO 60-90CM

sieve no.	sieve size	weight of sieve	retained soil+sieve	soil retained	% soil retained	cum. % retained	% finer
3/8	9.5	549	549	0	0.00	0.00	100.00
4	4.75	514	514	0	0.00	0.00	100.00
10	2	439	530	91	8.93	8.93	91.07
20	0.85	440	784	344	33.76	42.69	57.31
40	0.425	329	542	213	20.90	63.59	36.41
50	0.3	454	587	133	13.05	76.64	23.36
60	0.25	349	364	15	1.47	78.12	21.88
200	0.075	285	497	212	20.80	98.92	1.08
pan	0	344	355	11	1.08	100.00	0.00
				1019			


GRADING CURVE FOR OWAKO 60-90CM

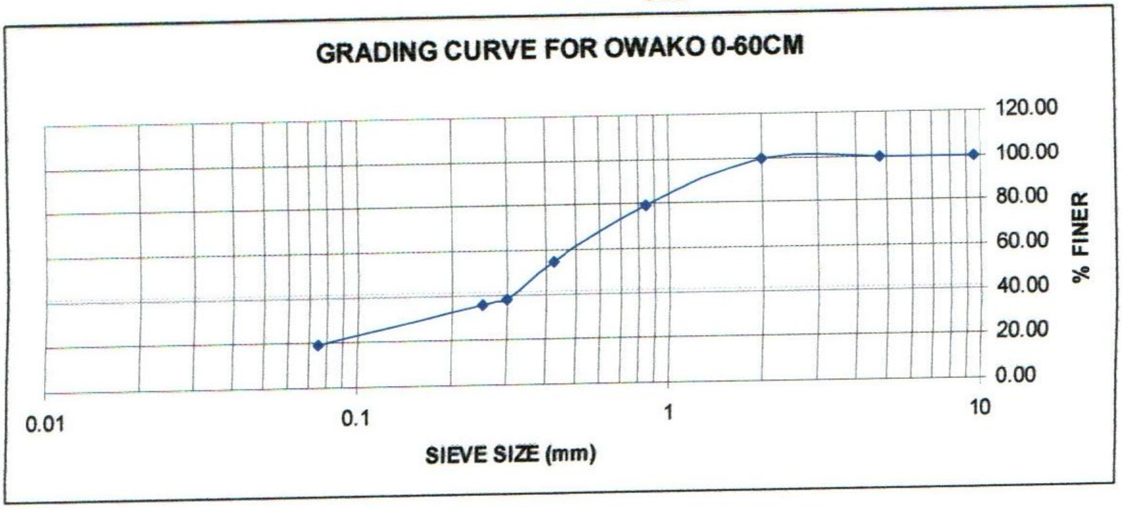
MECHANICAL SIEVE ANALYSIS FOR H. OKOLO 30-60CM

sieve no.	sieve size	weight of sieve	retained soil+sieve	soil retained	% soil retained	cum. % retained	% finer
3/8	9.5	549	549	0	0.00	0.00	100.00
4	4.75	514	736	222	22.96	22.96	77.04
10	2	439	832	393	40.64	63.60	36.40
20	0.85	440	598	158	16.34	79.94	20.06
40	0.425	329	403	74	7.65	87.59	12.41
50	0.3	454	496	42	4.34	91.93	8.07
60	0.25	349	355	6	0.62	92.55	7.45
200	0.075	285	347	62	6.41	98.97	1.03
pan	0	344	354	10	1.03	100.00	0.00
				967			


GRADING CURVE FOR H. OKOLO 30-60CM

MECHANICAL SIEVE ANALYSIS FOR OWAKO 0-60CM

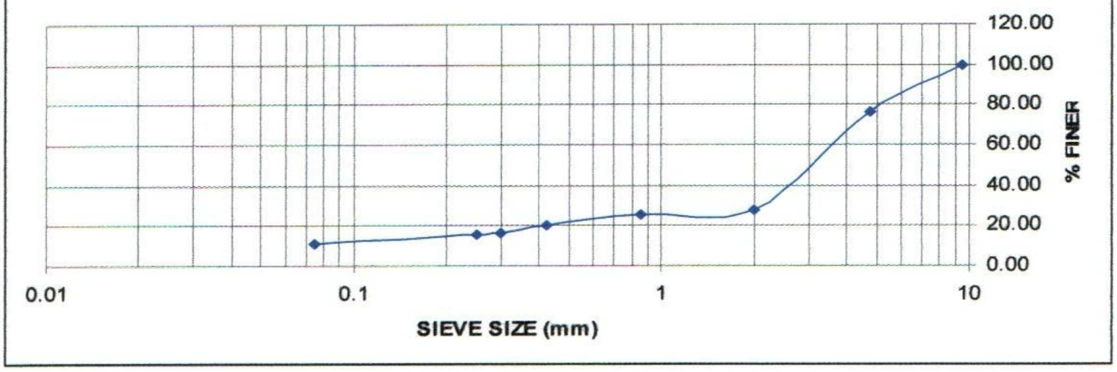
sieve no.	sieve size	weight of sieve	retained soil+sieve	soil retained	% soil retained	cum. % retained	% finer
3/8	9.5	549	549	0	0.00	0.00	100.00
4	4.75	514	514	0	0.00	0.00	100.00
10	2	439	439	0	0.00	0.00	100.00
20	0.85	440	642	202	20.24	20.24	79.76
40	0.425	329	577	248	24.85	45.09	54.91
50	0.3	454	617	163	16.33	61.42	38.58
60	0.25	349	371	22	2.20	63.63	36.37
200	0.075	285	457	172	17.23	80.86	19.14
pan	0	344	535	191	19.14	100.00	0.00
				998			


GRADING CURVE FOR OWAKO 0-60CM

MECHANICAL SIEVE ANALYSIS FOR G. KERE 30-60CM

sieve no.	sieve size	weight of sieve	retained soil+sieve	soil retained	% soil retained	cum. % retained	% finer
3/8	9.5	549	549	0	0.00	0.00	100.00
4	4.75	514	743	229	23.30	23.30	76.70
10	2	439	920	481	48.93	72.23	27.77
20	0.85	440	465	25	2.54	74.77	25.23
40	0.425	329	380	51	5.19	79.96	20.04
50	0.3	454	486	32	3.26	83.21	16.79
60	0.25	349	357	8	0.81	84.03	15.97
200	0.075	285	329	44	4.48	88.50	11.50
pan	0	344	457	113	11.50	100.00	0.00
				983			

GRADING CURVE FOR KERE 30-60CM



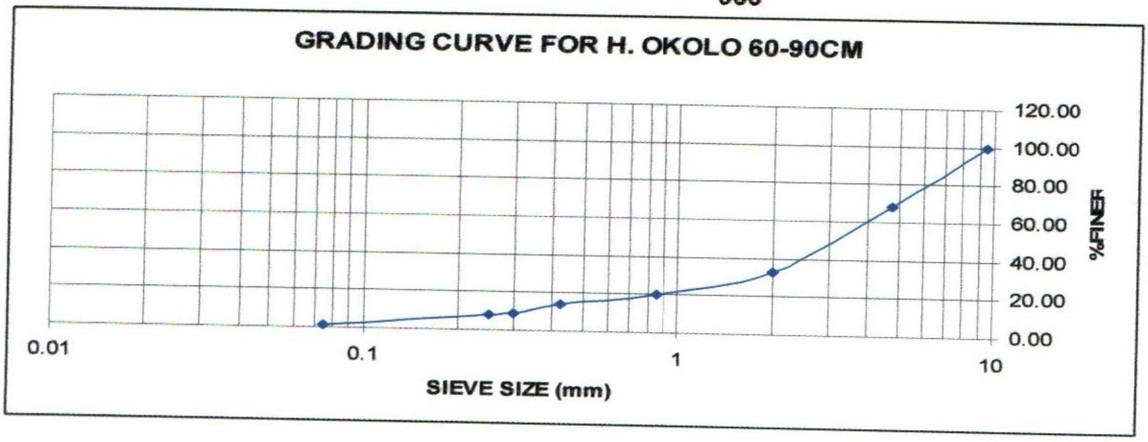
MECHANICAL SIEVE ANALYSIS FOR H. OKOLO 0-30CM

sieve no.	sieve size	weight of sieve	retained soil+sieve	soil retained	% soil retained	cum. % retained	% finer
3/8	9.5	549	549	0	0.00	0.00	100.00
4	4.75	514	514	0	0.00	0.00	100.00
10	2	439	439	0	0.00	0.00	100.00
20	0.85	440	487	47	9.48	9.48	90.52
40	0.425	329	433	104	20.97	30.44	69.56
50	0.3	454	536	82	16.53	46.98	53.02
60	0.25	349	364	15	3.02	50.00	50.00
200	0.075	285	458	173	34.88	84.88	15.12
pan	0	344	419	75	15.12	100.00	0.00
				496			

GRADING CURVE FOR H. OKOLO 0-30CM

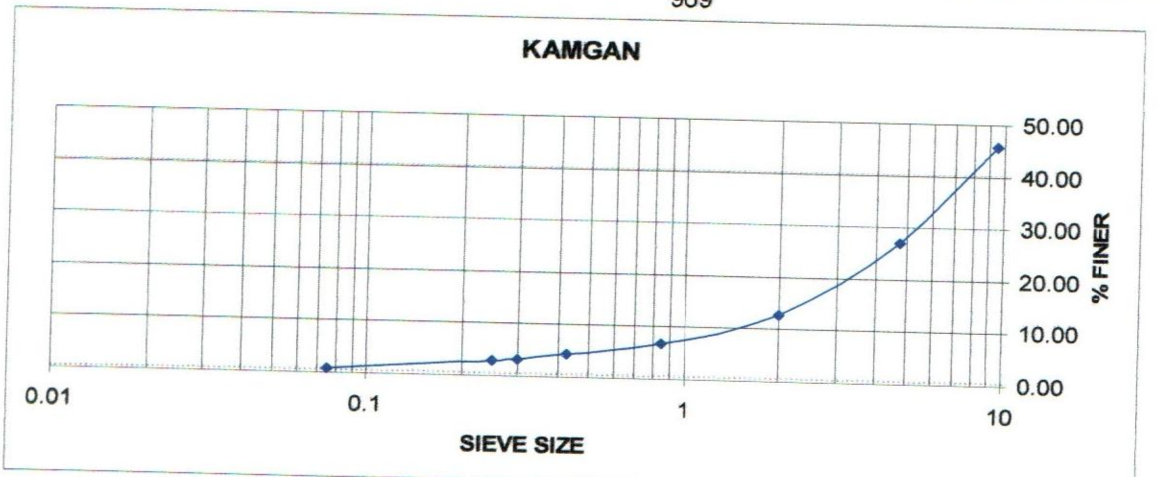
MECHANICAL SIEVE ANALYSIS FOR H. OKOLO 60-90CM

sieve no.	sieve size	weight of sieve	retained soil+sieve	soil retained	% soil retained	cum. % retained	% finer
3/8	9.5	549	549	0	0.00	0.00	100.00
4	4.75	514	823	309	31.99	31.99	68.01
10	2	439	776	337	34.89	66.87	33.13
20	0.85	440	565	125	12.94	79.81	20.19
40	0.425	329	389	60	6.21	86.02	13.98
50	0.3	454	499	45	4.66	90.68	9.32
60	0.25	349	358	9	0.93	91.61	8.39
200	0.075	285	348	63	6.52	98.14	1.86
pan	0	344	362	18	1.86	100.00	0.00
				966			



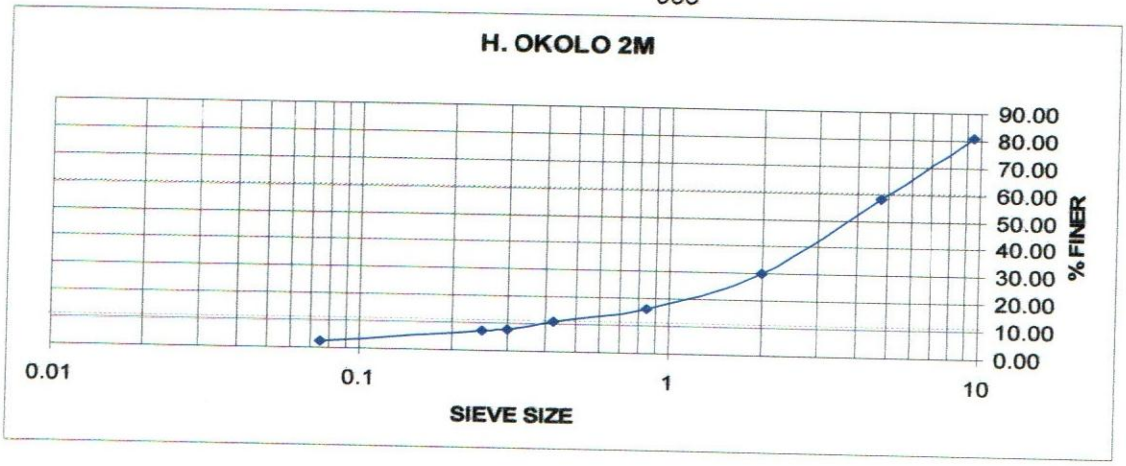
MECHANICAL SIEVE ANALYSIS FOR KAMGAN

sieve no.	sieve size	weight of sieve	retained soil+sieve	soil retained	% soil retained	cum. % retained	% finer
3/8	9.5	549	1075	526	54.28	54.28	45.72
4	4.75	514	696	182	18.78	73.07	26.93
10	2	439	576	137	14.14	87.20	12.80
20	0.85	440	498	58	5.99	93.19	6.81
40	0.425	329	352	23	2.37	95.56	4.44
50	0.3	454	466	12	1.24	96.80	3.20
60	0.25	349	352	3	0.31	97.11	2.89
200	0.075	285	304	19	1.96	99.07	0.93
pan	0	344	353	9	0.93	100.00	0.00
				969			



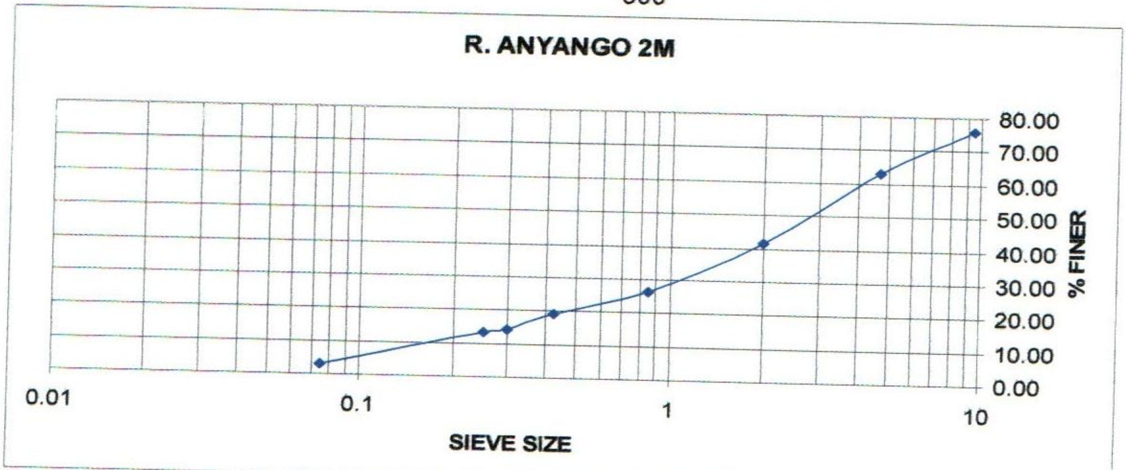
MECHANICAL SIEVE ANALYSIS FOR H.OKOLO 2M

sieve no.	sieve size	weight of sieve	retained soil+sieve	soil retained	% soil retained	cum. % retained	% finer
3/8	9.5	549	730	181	18.74	18.74	81.26
4	4.75	514	736	222	22.98	41.72	58.28
10	2	439	710	271	28.05	69.77	30.23
20	0.85	440	574	134	13.87	83.64	16.36
40	0.425	329	381	52	5.38	89.03	10.97
50	0.3	454	483	29	3.00	92.03	7.97
60	0.25	349	355	6	0.62	92.65	7.35
200	0.075	285	331	46	4.76	97.41	2.59
pan	0	344	369	25	2.59	100.00	0.00
				966			



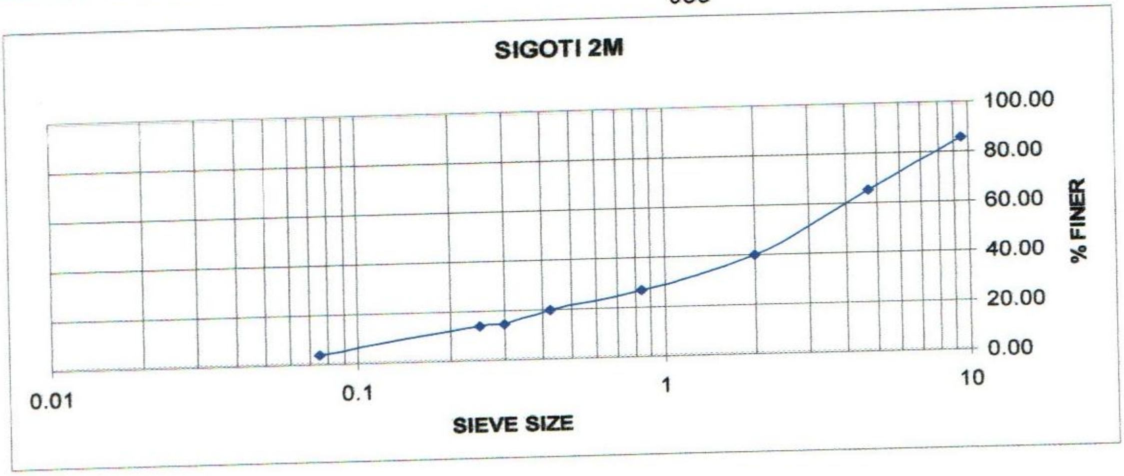
MECHANICAL SIEVE ANALYSIS FOR R. ANYANGO 2M

sieve no.	sieve size	weight of sieve	retained soil+sieve	soil retained	% soil retained	cum. % retained	% finer
3/8	9.5	549	740	191	23.88	23.88	76.13
4	4.75	514	619	105	13.13	37.00	63.00
10	2	439	611	172	21.50	58.50	41.50
20	0.85	440	560	120	15.00	73.50	26.50
40	0.425	329	389	60	7.50	81.00	19.00
50	0.3	454	492	38	4.75	85.75	14.25
60	0.25	349	357	8	1.00	86.75	13.25
200	0.075	285	365	80	10.00	96.75	3.25
pan	0	344	370	26	3.25	100.00	0.00
				800			



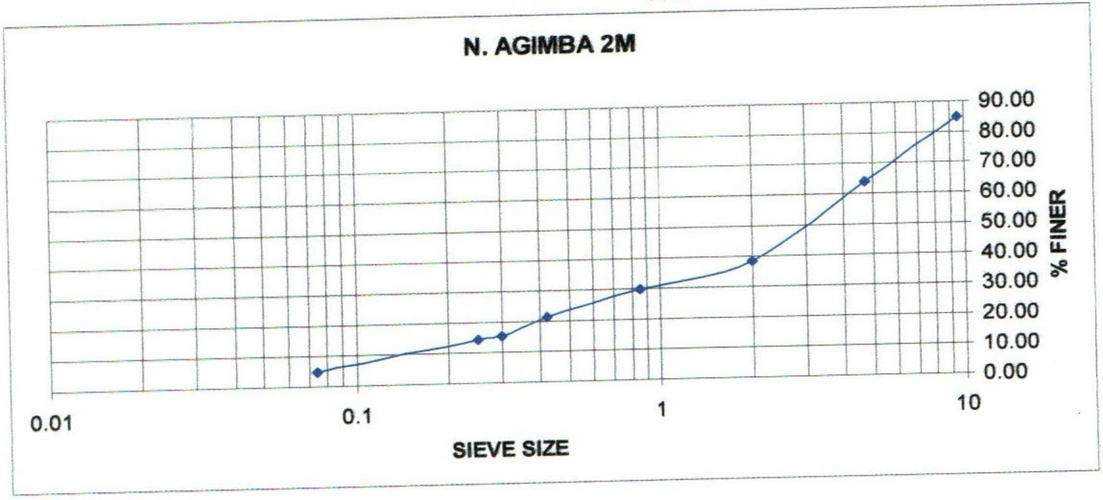
MECHANICAL SIEVE ANALYSIS FOR SIGOTI 2M

sieve no.	sieve size	weight of sieve	retained soil+sieve	soil retained	% soil retained	cum. % retained	% finer
3/8	9.5	549	683	134	13.89	13.89	86.11
4	4.75	514	717	203	21.04	34.92	65.08
10	2	439	683	244	25.28	60.21	39.79
20	0.85	440	563	123	12.75	72.95	27.05
40	0.425	329	395	66	6.84	79.79	20.21
50	0.3	454	505	51	5.28	85.08	14.92
60	0.25	349	355	6	0.62	85.70	14.30
200	0.075	285	383	98	10.16	95.85	4.15
pan	0	344	384	40	4.15	100.00	0.00
				965			



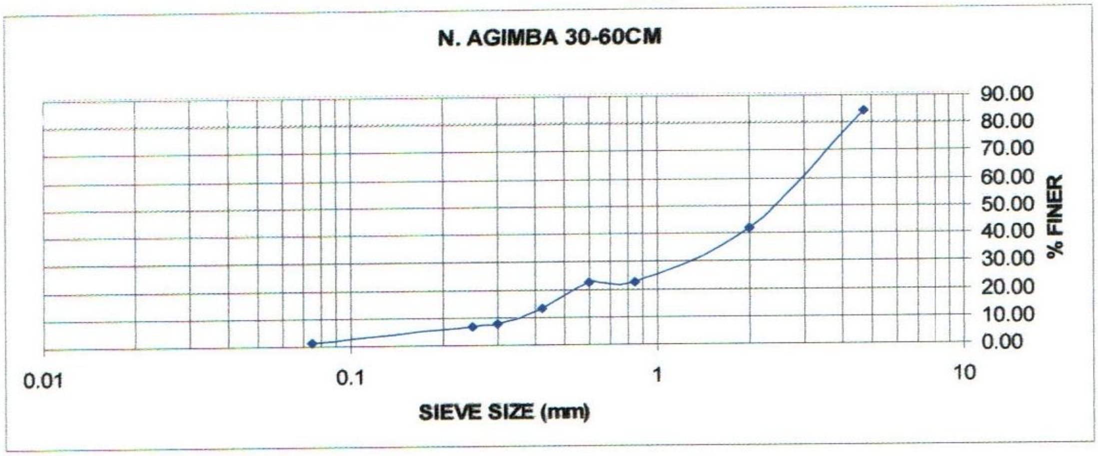
MECHANICAL SIEVE ANALYSIS FOR N. AGIMBA 2M

sieve no.	sieve size	weight of sieve	retained soil+sieve	soil retained	% soil retained	cum. % retained	% finer
3/8	9.5	549	687	138	15.20	15.20	84.80
4	4.75	514	703	189	20.81	36.01	63.99
10	2	439	672	233	25.66	61.67	38.33
20	0.85	440	514	74	8.15	69.82	30.18
40	0.425	329	407	78	8.59	78.41	21.59
50	0.3	454	510	56	6.17	84.58	15.42
60	0.25	349	358	9	0.99	85.57	14.43
200	0.075	285	372	87	9.58	95.15	4.85
pan	0	344	388	44	4.85	100.00	0.00
				908			



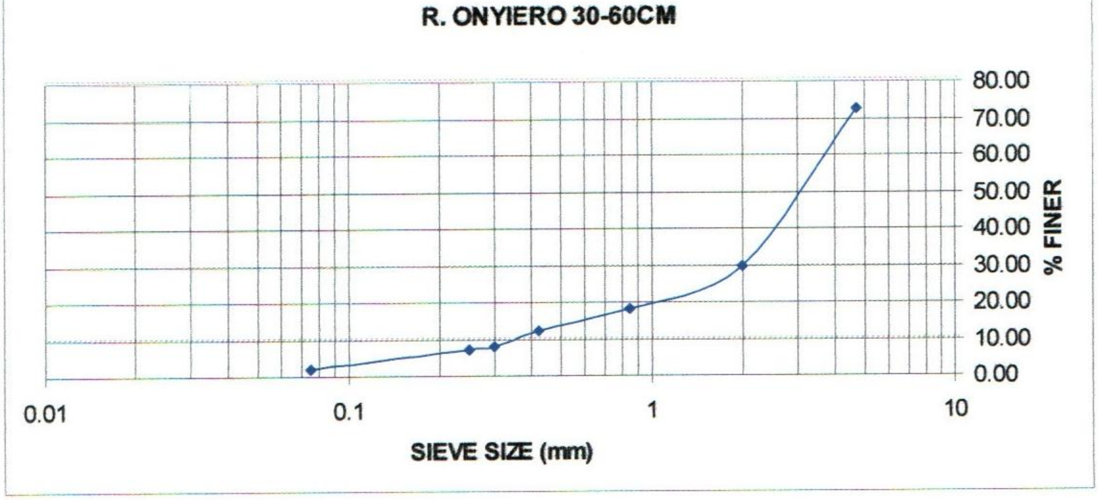
MECHANICAL SIEVE ANALYSIS FOR N. AGIMBA 30-60CM

sieve no.	sieve size	weight of sieve	retained soil+sieve	soil retained	% soil retained	cum. % retained	% finer
4	4.75	514	661	147	15.42	15.42	84.58
10	2	439	846	407	42.71	58.13	41.87
20	0.85	440	624	184	19.31	77.44	22.56
30	0.6	403	403	0	0.00	77.44	22.56
40	0.425	329	416	87	9.13	86.57	13.43
50	0.3	454	505	51	5.35	91.92	8.08
60	0.25	349	358	9	0.94	92.86	7.14
200	0.075	285	337	52	5.46	98.32	1.68
pan	0	344	360	16	1.68	100.00	0.00
				953			



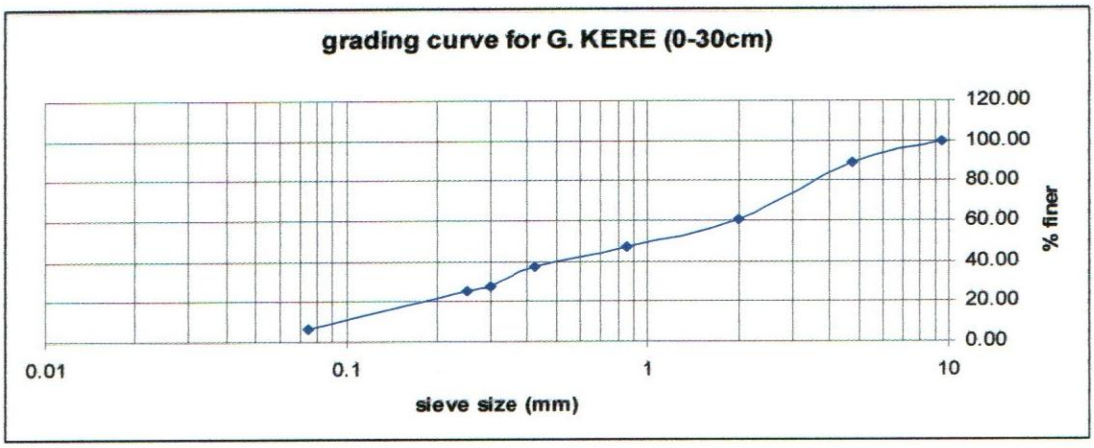
MECHANICAL SIEVE ANALYSIS FOR R. ONYIERO 30-60CM

sieve no.	sieve size	weight of sieve	retained soil+sieve	soil retained	% soil retained	cum. % retained	% finer
4	4.75	514	777	263	27.37	27.37	72.63
10	2	439	852	413	42.98	70.34	29.66
20	0.85	440	551	111	11.55	81.89	18.11
40	0.425	329	385	56	5.83	87.72	12.28
50	0.3	454	494	40	4.16	91.88	8.12
60	0.25	349	357	8	0.83	92.72	7.28
200	0.075	285	335	50	5.20	97.92	2.08
pan	0	344	364	20	2.08	100.00	0.00
				961			



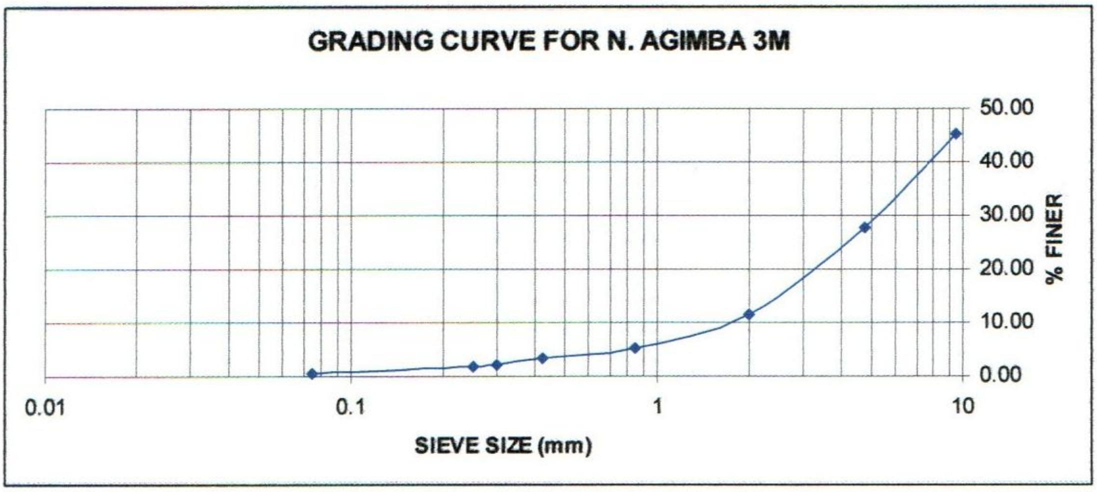
MECHANICAL SIEVE ANALYSIS FOR G. KERE 0-30CM

sieve no.	sieve size	weight of sieve	retained soil+sieve	soil retained	% soil retained	cum. % retained	% finer
3/8	9.5	549	549	0	0.00	0.00	100.00
4	4.75	514	623	109	10.88	10.88	89.12
10	2	439	721	282	28.14	39.02	60.98
20	0.85	440	574	134	13.37	52.40	47.60
40	0.425	329	429	100	9.98	62.38	37.62
50	0.3	454	551	97	9.68	72.06	27.94
60	0.25	349	371	22	2.20	74.25	25.75
200	0.075	285	476	191	19.06	93.31	6.69
pan	0	344	411	67	6.69	100.00	0.00
				1002			



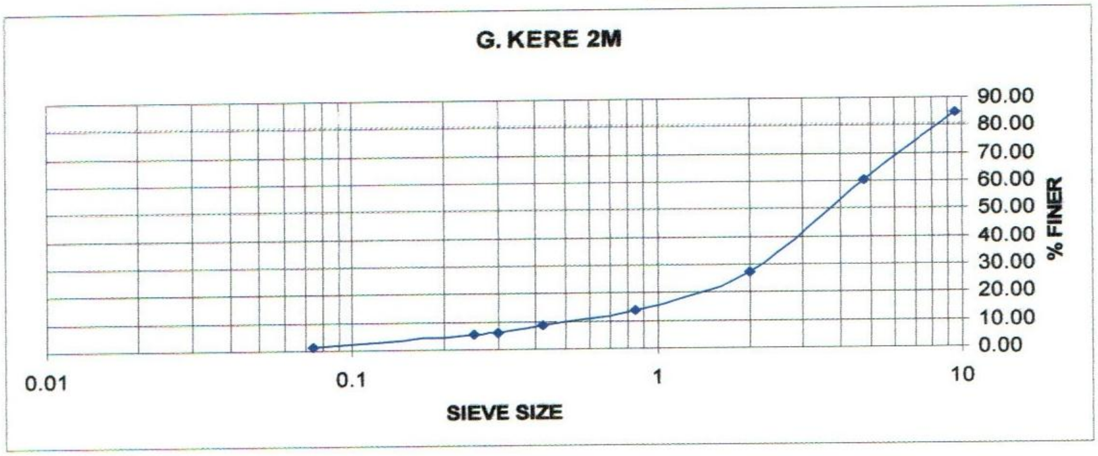
MECHANICAL SIEVE ANALYSIS FOR N. AGIMBA 3M

sieve no.	sieve size	weight of sieve	retained soil+sieve	soil retained	% soil retained	cum. % retained	% finer
3/8	9.5	549	1108	559	54.54	54.54	45.46
4	4.75	514	696	182	17.76	72.29	27.71
10	2	439	605	166	16.20	88.49	11.51
20	0.85	440	502	62	6.05	94.54	5.46
40	0.425	329	351	22	2.15	96.68	3.32
50	0.3	454	465	11	1.07	97.76	2.24
60	0.25	349	352	3	0.29	98.05	1.95
200	0.075	285	298	13	1.27	99.32	0.68
pan	0	344	351	7	0.68	100.00	0.00
				1025			



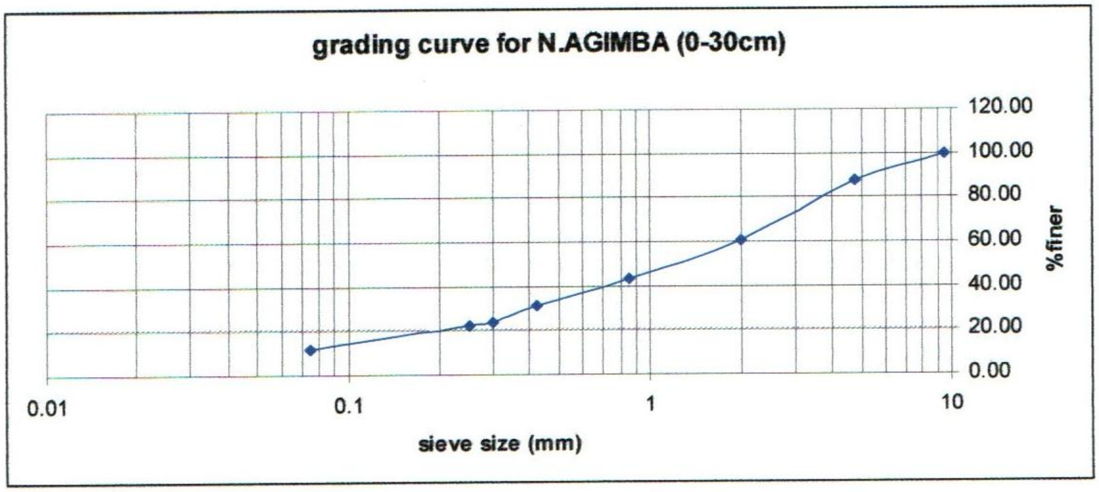
MECHANICAL SIEVE ANALYSIS FOR G. KERE 2M

sieve no.	sieve size	weight of sieve	retained soil+sieve	soil retained	% soil retained	cum. % retained	% finer
3/8	9.5	549	696	147	15.11	15.11	84.89
4	4.75	514	749	235	24.15	39.26	60.74
10	2	439	761	322	33.09	72.35	27.65
20	0.85	440	572	132	13.57	85.92	14.08
40	0.425	329	379	50	5.14	91.06	8.94
50	0.3	454	481	27	2.77	93.83	6.17
60	0.25	349	355	6	0.62	94.45	5.55
200	0.075	285	323	38	3.91	98.36	1.64
pan	0	344	360	16	1.64	100.00	0.00
				973			



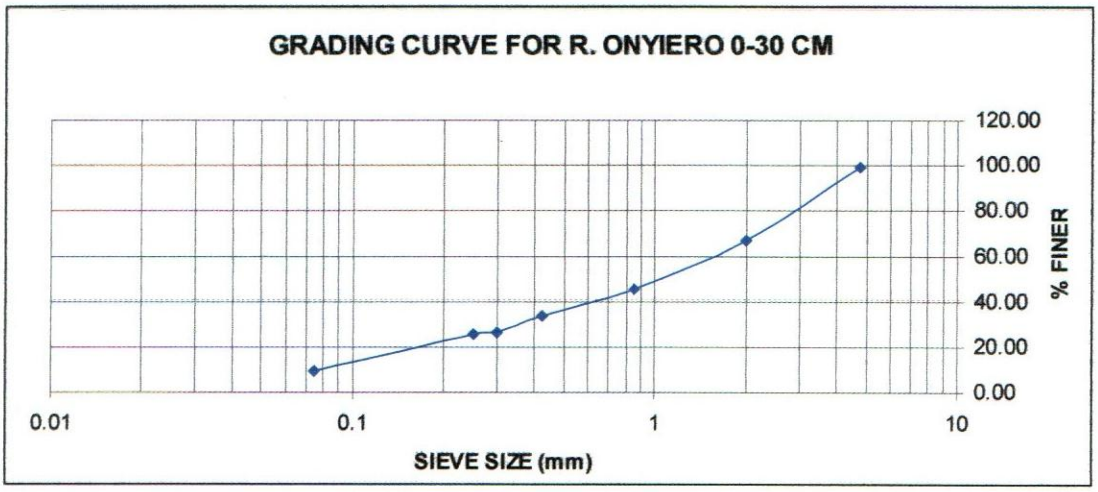
MECHANICAL SIEVE ANALYSIS FOR N. AGIMBA 0-30CM

sieve no.	sieve size	weight of sieve	retained soil+sieve	soil retained	% soil retained	cum. % retained	% finer
3/8	9.5	549	549	0	0.00	0.00	100.00
4	4.75	514	640	126	12.50	12.50	87.50
10	2	439	711	272	26.98	39.48	60.52
20	0.85	440	608	168	16.67	56.15	43.85
40	0.425	329	450	121	12.00	68.15	31.85
50	0.3	454	535	81	8.04	76.19	23.81
60	0.25	349	364	15	1.49	77.68	22.32
200	0.075	285	391	106	10.52	88.19	11.81
pan	0	344	463	119	11.81	100.00	0.00



MECHANICAL SIEVE ANALYSIS FOR R. ONYIERO 0-30CM

sieve no.	sieve size	weight of sieve	retained soil+sieve	soil retained	% soil retained	cum. % retained	% finer
4	4.75	514	522	8	0.80	0.80	99.20
10	2	439	759	320	31.94	32.73	67.27
20	0.85	440	659	219	21.86	54.59	45.41
40	0.425	329	442	113	11.28	65.87	34.13
50	0.3	454	528	74	7.39	73.25	26.75
60	0.25	349	360	11	1.10	74.35	25.65
200	0.075	285	447	162	16.17	90.52	9.48
pan	0	344	439	85	9.48	100.00	0.00
				1002			


GRADING CURVE FOR R. ONYIERO 0-30 CM

APPENDIX 4

WELL DATA FOR NYABONDO PLATEAU

Well Name	Well Id	UTM		Water drawn* (m3/d)	Projected no. of users**	Diam. (m)	Depth (m)
		Lat.	Long.				
Koliyo	W1	717900	9955300	2.4	40	1.2	3
Kogoti	W2	716300	9956500	2.4	40	1.3	9.3
Kajuma	W3	717100	9956800	1.44	24	1.0	6.8
Kambeda	W4	717600	9956900	12	200	1.0	8.7
Kosir	W5	717500	9956800	26.4	440	1.0	8.7
Karagot	W6	717600	9956800	6	100	1.0	11.9
Kojenge	W7	717500	9956700	24	400	1.0	8.9
Komollo	W8	717800	9957000	50.4	840	1.0	8.9
Kasigu	W9	717700	9956800	1.08	18	1.0	9.8
Kabok	W10	718000	9956400	7.2	120	1.3	12.2
Kasigu	W11	717800	9956200	0	0	1.0	
Kogutu	W12	717900	9956900	8.4	140	1.0	14.5
Kogutu	W13	717900	9956500	0.96	16	1.0	12.2
Konyullo	W14	717800	9956300	26.4	440	1.0	13.6
Koywaya	W15	720700	9956800	14.4	240	1.0	11
Kombee	W16	720700	9956500	3.6	60	1.0	10.3
Kokech	W17	720600	9956500	3.6	60	1.0	10.2
Kogutu	W18	720600	9956200	2.4	40	1.0	7.7
Kalwara	W19	720800	9956200	0.96	16	1.0	7.9
Komiru	W20	720800	9957000	1.08	18	1.0	9.7
Kodimbo	W21	716200	9957200	6	100	1.2	5.1
Kamimo	W22	716500	9957300	24	400	1.1	3.5
Ka-Auko	W23	715900	9957200	14.4	240	1.5	10.6
Kowako	W24	715800	9957500	9.6	160	1.2	3
Kawere	W25	715400	9957800	2.4	40	1.0	8
Kochola	W26	722000	9957800	6	100	1.2	7.3
Kawuoche	W27	722200	9957700	2.4	40	1.3	5.5
Koyier	W28	722500	9957700	0.72	12	1.0	8.9
Kokoth	W29	722300	9957700	12	200	1.0	8.3

Karawago	W30	722400	9957700	12	200	1.2	8.1
Kogutu	W31	722700	9957300	3.6	60	1.3	8.1
Ka-Omollo	W32	715400	9959900	7.2	120	1.1	3.7
Kojuang	W33	722400	9957200	54	900	1.0	6.6
Kamasere	W34	722500	9957200	7.2	120	1.0	7.1
Kookemba	W35	720700	9957100	12	200	1.0	13.2
Kawiti	W36	720700	9957200	8.4	140	1.0	9.8
Kasamwel	W37	721300	9957300	6	100	1.0	11.2
Koboge	W38	720600	9957200	30	500	1.0	8.5
Kokumu	W39	721100	9957300	4.8	80	1.0	9.4
Korwa	W40	720600	9957500	3.6	60	1.0	8.1
Koyamo	W41	720800	9957800	14.4	240	1.0	9.3
Kayieko	W42	720600	9957800	26.4	440	1.0	8.5
Kodiang	W43	720500	9957100	0.6	10	1.0	7.7
Koliech	W44	720600	9957600	8.4	140	1.0	8.7
Kakengo	W45	721000	9957600	27.6	460	1.0	7.2
Kowuor	W46	718500	9957800	18	300	1.0	6.8
Kosire	W47	718500	9957700	12	200	1.0	6.3
Konyango	W48	718600	9957800	1.92	32	1.1	8.2
Kwaria	W49	717700	9957100	19.2	320	1.0	7.7
Koyomo	W50	717500	9957100	7.2	120	1.0	9.3
Kowadi	W51	718700	9957800	8.4	140	1.0	4
Kobungu	W52	720400	9958700	4.8	80	1.0	6.6
Kadiema	W53	720000	9958900	2.4	40	1.0	4.6
Kaguya	W54	720300	9959600	9.6	160	2.4	4
Kaguya	W55	720300	9959600	0	0	2.0	
Koyiejowi	W56	720200	9959300	9.6	160	1.0	6.9
Koyoo	W57	717000	9959300	42	700	1.2	6.3
Kongoro	W58	717000	9959400	6	100	1.5	5.6
Kakola	W59	717000	9959500	6	100	1.0	3.2
Kodero	W60	717000	9959500	2.4	40	1.1	3.1
Kademba	W61	715900	9959100	19.2	320	2.1	3.7
Kokelo	W62	716500	9959500	5.4	90	1.6	4.1

Ka-Aringo	W63	716400	9959500	72	1200	1.0	4.4
Kokech	W64	715900	9959500	8.4	140	1.0	5.5
Komnyisi	W65	715800	9959400	15.6	260	1.2	5.6
Kagembo	W66	716300	9959700	60	1000	1.3	4.5
Kakwanya	W67	715800	9959900	14.4	240	3.0	5
Kagombe	W68	716100	9959800	6	100	1.6	3.6
Kouko	W69	715900	9959900	4.8	80	1.2	4
Kowili	W70	721500	9958200	12	200	1.9	6.2
Kariga	W71	721500	9958400	6	100	1.8	7.2
Kokongo	W72	721200	9958400	12	200	1.5	8.4
Kokongo	W73	721200	9958500	12	200	1.2	4.8
Kateyo	W74	720300	9959000	1.2	20	0.9	6
Kamgan	W75	721000	9959200	8.4	140	1.5	6
Kochieng	W76	720200	9959700	6	100	1.0	3.4
Kandonga	W77	719300	9959700	24	400	1.2	3.4
Kadiga	W78	719600	9959700	12	200	1.5	4.5
Komollo	W79	719800	9959800	1.8	30	1.5	3.4
Kagengo	W80	719900	9959700	3	50	1.2	5.5
Kombewa	W81	719800	9959700	4.8	80	2.0	3.6
Koyele	W82	719800	9959700	18	300	1.5	4
Kombewa	W83	719000	9960000	18	300	1.0	4.4
Koigo	W84	719000	9960100	7.2	120	1.5	5.2
Kawuor	W85	719200	9959800	3.6	60	1.0	4
Kayako	W86	719200	9959800	6	100	1.5	3.8
Koudia	W87	717300	9959600	12	200	1.2	4.9
Kobong	W88	718900	9960100	7.2	120	1.2	4.4
Kochung	W89	719200	9960100	12	200	1.5	3.5
Kochiewo	W90	719100	9960100	6	100	1.0	4.2
Kongoro	W91	717100	9960100	7.2	120	0.5	4
Kowako	W92	718500	9960400	1.2	20	2.0	4.8
Kopar	W93	719300	9960400	6	100	1.0	5.3
Kayona	W94	718500	9960300	6	100	1.5	4.6
Kodero	W95	718400	9960400	2.4	40	1.0	4.6

Kodongo	W96	718700	9960500	15.6	260	1.0	6.5
Kagai	W97	718600	9960500	30	500	1.0	5.2
Kambuyi	W98	718600	9960700	9.6	160	1.6	4.8
Kanyamita	W99	718500	9960500	12	200	1.2	5
Kodongo	W100	718600	9960900	1.8	30	1.0	4.6
Kabok	W101	718600	9961000	2.4	40	1.5	4.4
Kasoro	W102	719100	9960500	30	500	0.9	4.5
Naki	W103	718400	9961100	54	900	1.2	4.7
Kotula	W104	718900	9961200	3.6	60	1.5	6
Koselu	W105	718900	9961200	1.8	30	1.5	7.2
Kaguya	W106	718900	9961100	24	400	1.1	6.4
Kaluko	W107	718700	9961200	2.4	40	1.0	4.6
Kobango	W108	718700	9960200	3	50	1.0	4.2
Kamusa	W109	718800	9961300	24	400	1.5	6
Kogongo	W110	714600	9960300	2.4	40	1.1	4.3
Kanyango	W111	714000	9960300	1.2	20	1.3	4.7
Kabonyo	W112	715500	9960500	8.4	140	1.2	4.2
Kopere	W113	720900	9960400	2.4	40	1.2	5.9
Guu Church	W114	720400	9961200	24	400	1.0	4.9
Kondoro	W115	720800	9960600	4.8	80	1.0	5.8
Kotieno	W116	721100	9960600	3.6	60	1.2	6
Komoro	W117	721100	9960800	12	200	1.5	6.2
Kawuor	W118	721100	9960800	6	100	1.2	6.9
Kondego	W119	720500	9961000	1.2	20	1.5	5.2
Kajometho	W120	720500	9961000	3.6	60	1.2	5.2
Kotula	W121	719100	9961100	6	100	1.2	5.6
Koongoro	W122	719100	9961100	24	400	1.4	5
Kokony	W123	719000	9961400	6	100	1.9	4.3
Kalik	W124	720600	9961300	2.4	40	1.6	3.3
Kamadanga	W125	720600	9961400	2.4	40	1.3	4.3
Kopiyo	W126	720100	9961900	3.6	60	1.0	3.4
Kachingo	W127	720500	9962000	6	100	1.2	5.4
Kanyandiko	W128	720700	9962000	4.8	80	1.1	4.7

Kambuge	W129	720700	9962200	48	800	1.2	6.3
Kodonge	W130	721000	9962600	1.8	30	1.2	5.2
Kambwaro	W137	720600	9959900	12	200	1.2	5.8
Korondo	W140	720700	9960100	3.6	60	0.9	6.6
Kobala	W141	720600	9960200	12	200	1.1	6.8
Kawino	W142	720500	9961300	18	300	1.2	4.7
Kadiambo	W143	720600	9960200	24	400	1.0	7.2
Rio-Okora	W144	722700	9957400	6	100	1.1	8.2
Rio-Okech	W145	722400	9957900	1.2	20	1.0	7.6
Korinda	W146	721500	9957600	2.4	40	1.0	10.7
Kasiguda	W147	721200	9957600	4.8	80	1.0	12.3
Kowango	W148	721600	9957400	4.8	80	1.0	14.3
Kachayo	W149	721600	9957500	3.6	60	1.0	10.7
Kowuor	W150	721600	9957500	1.2	20	1.0	10.8
Kaminudi	W151	721600	9957500	2.4	40	1.0	10.4
Kayoge	W152	714800	9959300	3.6	60	1.6	3.2
Kokal	W153	714800	9959000	2.4	40	1.6	2
Kamalaki	W154	715200	9958600	3.6	60	1.5	1.9
Samson	W155	712600	9958900	36	600	1.3	4
Kodeng	W156	715100	9958400	12	200	1.5	6.1
Kogutu	W157	714400	9959700	24	400	1.0	2.9
Midega	W158	716400	9957200	2.4	40	1.2	7.2
Katingo	W159	717700	9957300	7.2	120	1.1	5.8
Kabudi	W160	719600	9957400	12	200	0.8	2.8
Kokiki	W161	717500	9957400	24	400	1.1	6.9
Okiki	W162	717500	9957400	24	400	1.2	5.3
Kojenge	W163	717600	9957300	2.4	40	1.2	8.5
Kobong	W164	720100	9959200	18	300	1.2	7.2
Kawadawe	W165	720100	9959200	3.6	60	1.0	9
Kaguya	W166	720200	9959200	2.4	40	1.2	11
Kobiero	W167	719800	9962100	4.8	80	1.3	3.7
Kotieno	W168	719900	9961700	6	100	1.5	4
Koguta	W169	719900	9961700	7.2	120	1.2	4.5

Kochola	W170	719900	9961700	2.4	40	1.6	4
Kowana	W171	720200	9961700	7.2	120	1.3	5.1
Kopiyo	W172	720200	9961800	3.6	60	2.0	3.7
Koyoo	W173	719700	9961600	6	100	1.5	4.7
Koyore	W174	719900	9961400	8.4	140	1.4	4.7
Kondenge	W175	720200	9961200	12	200	1.2	5.4
Kabilla	W176	719800	9961400	8.4	140	1.4	4.1
Komoto	W177	719800	9961400	7.2	120	2.0	4.5
Kajuma	W178	719900	9961200	6	100	0.9	4.2
Kandege	W179	719700	9961400	3.6	60	1.7	2.9
Kabuop	W180	719800	9961600	9.6	160	1.4	4.5
Kołweny	W181	719700	9961700	4.8	80	1.4	4.5
Komego	W182	719500	9961900	12	200	1.2	4.7
Kobiero	W183	719600	9961600	3.6	60	1.6	6.1
Kanyambuga	W184	719600	9961600	4.8	80	1.1	5.1
Kogutu	W185	719100	9961700	2.4	40	1.3	2.8
Kongoro	W186	719100	9961700	18	300	1.0	5.6
Komollo	W187	718900	9961600	4.8	80	1.2	2.5
Kandhere	W188	719700	9960800	9.6	160	1.2	4.5
Kolero	W189	719700	9961200	7.2	120	1.4	3.5
Kandonga	W190	719900	9960200	7.2	120	1.1	4.1
Koluk	W191	720000	9960200	6	100	0.8	5.4
Kachan	W192	720500	9960200	3.6	60	1.2	6.3
Kachan	W193	720500	9960200	8.4	140	0.8	7.3
Kamalaki	W195	722300	9957900	4.8	80	1.0	7.2
Nyakoko	W196	722400	9957700	6	100	1.0	10.4
Krawago	W197	722400	9957700	12	200	1.0	10
Kasunga	W198	721500	9957800	4.8	80	1.0	7.2
Koyier	W199	721500	9957800	8.4	140	1.0	7.9
Kagenga	W200	721400	9957800	6	100	1.0	6.9
Kananda	W201	721400	9957600	1.08	18	1.0	8.9
Kasigu	W202	718000	9956900	3.6	60	1.0	12.3
Kabienge	W203	718100	9956900	1.2	20	1.0	11

Kojwang	W204	718300	9956900	4.8	80	1.0	11.8
Kasembo	W205	718500	9957400	2.4	40	1.2	8
Kalingo	W206	719000	9957300	14.4	240	1.2	7
Kodera	W207	719300	9957300	3.6	60	1.5	4.2
Kabunde	W208	719000	9957400	2.4	40	1.0	7.2
Kabok	W209	719400	9957100	4.8	80	1.4	5.9
Kabuoro	W210	719300	9956600	7.2	120	1.6	10.4
Kajwang	W211	719500	9956500	2.4	40	1.0	8.9
Kakere	W212	719100	9956800	1.2	20	1.2	8.6
Kowiwa	W213	719700	9956800	2.4	40	1.0	9.1
Kayako	W214	719300	9957900	8.4	140	1.0	7.4
Kondoro	W215	719300	9957900	18	300	1.1	6.88
Kowino	W216	720000	9957000	0.6	10	1.2	9.6
Kondoro	W217	719600	9957600	30	500	1.0	8.1
Komollo	W218	719600	9957000	30	500	1.2	5.1
Kajwang	W219	719600	9957000	36	600	1.2	4.5
Kajwang	W220	719700	9956900	12	200	1.2	6
Kothim	W221	719900	9957500	3.6	60	1.1	11.4
Kajuja	W222	719300	9956500	2.4	40	1.4	9.1
Korwa	W223	718600	9956600	2.4	40	1.2	10.2
Kamoro	W224	717900	9956000	12	200	1.3	9.8
Kayo	W225	718200	9956200	1.2	20	1.1	12.5
Karagot	W226	718200	9956500	12	200	1.0	10.2
Kondena	W227	718700	9956900	12	200	1.0	8.9
Kajalango	W228	718700	9956900	0.72	12	1.0	9.2
Kodongo	W229	720500	9959600	1.8	30	2.0	4.2
Kokelo	W230	720300	9957700	24	400	1.3	8.2
Kuondo	W231	720200	9957200	12	200	1.5	8.2
Kaito	W232	720200	9957700	14.4	240	1.2	6.7
Kagombe	W233	720700	9957700	12	200	1.5	9.6
Kokelo	W234	720700	9956500	1.8	30	1.1	10.2
Kadula	W235	721000	9957200	4.8	80	1.2	7.6
Kolwengo	W236	720800	9957200	0.96	16	1.2	8.5

Kamwaya	W237	720400	9957500	9.6	160	1.1	8.5
Kanyadori	W238	720300	9957700	2.4	40	1.5	10.4
Kaseka	W239	720900	9956600	0.96	16	1.2	8.5
Komollo	W240	721000	9956500	6	100	1.1	8.5
Kanandi	W241	720700	9957000	1.32	22	1.0	10.4
Kombai	W242	720500	9956400	7.2	120	1.0	8.3
Kagak	W243	720600	9956300	2.16	36	1.0	7.2
Kothim	W244	720600	9956400	9.6	160	1.4	8.5
Komira	W245	721100	9958000	0.84	14	1.1	8.7
Kanyamwanda	W246	720900	9957700	13.2	220	1.3	8.5
Komill	W247	721100	9957600	12	200	1.2	10.2
Kowande	W248	721300	9956500	1.2	20	1.2	8.9
Kanundu	W249	721200	9958100	0.72	12	1.1	8.9
Kawere	W251	720500	9959600	2.4	40	1.3	4.8
Kodindo	W252	718800	9961300	12	200	1.3	4.4
Kokelo	W253	719000	9960900	36	600	1.0	6.2
Kobiero	W254	719200	9960800	0.84	14	0.8	3.5
Kakumu	W255	719200	9960800	24	400	1.0	4.3
Kanorman	W256	719300	9960400	6	100	4.0	4.8
Komino	W257	719400	9960300	0.84	14	1.0	4.4
Korinda	W258	717700	9961400	18	300	1.5	4.7
Koremo	W259	716900	9960700	60	1000	1.0	2.5
Komollo	W260	717800	9961300	60	1000	1.5	7
Kowere	W261	717100	9959900	24	400	1.0	3.9
Kochuka	W262	716900	9960600	12	200	0.9	3.3
Korwa	W263	717700	9961200	1.2	20	1.2	4.8
Komiya	W264	716900	9960500	4.8	80	1.0	3
Kagembo	W265	717800	9960400	3.6	60	1.5	4.9
Kabutho	W266	716400	9960500	2.4	40	1.5	4.5
Kadiga	W267	719500	9959800	72	1200	1.0	11.5
Kanyangwe	W268	720200	9962200	0		1.4	4

Source: Nyakach Division Water Resources Survey Report, 1987

*daily water requirement of 0.06m^3 per person

**number of users adjusted by doubling of 1987 users.