FABRICATION AND CALIBRATION OF LOW COST CAPACITIVE SOIL HUMIDITY SENSOR

BY

CHERUIYOT SAMUEL KIPKOSGEI

SC/PGP/07/06

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE AWARD OF MASTER OF SCIENCE DEGREE IN THE SCHOOL OF SCIENCE, DEPARTMENT OF PHYSICS

UNIVERSITY OF ELDORET

NOVEMBER, 2013

DECLARATION

Declaration by the candidate

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

Name	Signature	Date
Cheruiyot Samuel Kipkosgei.	………………….	………….
(SC/PGP/06/07)		

Declaration by the supervisors

This thesis has been submitted for examination with our approval as university supervisors

Name	Signature	Date
Prof Wilson Ng'etich.	……… …	………….
Department of Soil Science		
University of Eldoret		

Name	Signature	Date
Dr. Joel Tonui	…………….	………………
Department of Physics		
University of Eldoret		

DEDICATION

I dedicate this work to National Council for Science and Technology (NCST) and my family.

ABSTRACT

Soil humidity is critical in crop production and its control is essential to water conservation. The knowledge of soil humidity to majority of farmers in Kenya is based on effects of weather on crops and soil texture. Projected population increase leads to requirement of food in large quantities which is a challenge to sustain on rain fed agriculture .The country will be compelled to practice irrigated agriculture to satisfy the demand of food by its population. Research has shown that high yield is realized when irrigation is done with an aid of soil moisture census such that, water applied to crops is done at the right time and amount applied is just enough for their hydric needs at various stages of crop growth and development. This derives the need to develop soil humidity sensor that can give continuous signal reflecting amount of water in the soil. The research focused on fabrication of a capacitive soil humidity sensor using cheap locally available materials and calibration of the sensor using oven dry method in which capacitance of the soil, was measured with corresponding gravimetric soil water content. Results shows that the relationship between capacitance (C) of the soil and gravimetric soil water content Θ_g is polynomial equation of third degree with strong correlation coefficient R^2 ranging from 0.95249 to 0.9877 for four soil texture classes calibrated. Therefore calibrated capacitance can be used for real-time estimation of gravimetric water content.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

LIST OF ACRONYMS AND SYMBOLS

ASALs	Arid semi-arid lands
2D	Two Dimensional
3D	Three Dimensional
C	Capacitance of the sensor
DMM	Digital multi meter
EC-	Electrical Conductivity
IAEA	International Atomic Research Institute
KARI	Kenya African Research Institute
M (Dry ssp) (g)	Mass 0f dry soil sample
M (S,C&P)(g)	Mass of the sensor, container and receiver plate.
M (Wetssp) (g)	Mass of wet soil sample
MDGS	Millennium Development Goals
Mwet. Set-up (g)	Mass of wet soil, sensor, plastic container and plate
MWI	Ministry of Water Irrigation
NIB	National Irrigation Board
RDA	Regional Development Authority
RH	Relative Humidity
SSI	Small Scale Irrigation Unit
SST	Sum of total squares
SSR	Sum of Square Residuals
SWC	Soil Water Content
TDR-	Time Domain Reflectometry
Θ_g	Gravimetric soil humidity contented in ($KgKg^{-1}$)
θv	Volumetric water content in (m^3/m^3)

ACKNOWLEDGMENTS

I wish to thank my supervisors Prof Wilson Kipkoech Ng'etich and Dr Joel Kipkorir Tonui for their focused attention accorded to me and their corrections which led to attainment of research set objectives.

I also thank my family especially moral and financial support provided to me by my Father Dr. Philip Kotut.

This project work was fully funded by National Council for Science and Technology (N.C.S.T) if it were not for their financial support my graduate work could still be under deferment. Almighty GOD bless you all for your contributions to my studie

CHAPTER ONE

INTRODUCTION

Water is an important constituent for plant growth and development and its provisions in adequate amount are paramount to crop production. Water content can be viewed in two ways, first as a ratio of amount of water present in solids to volume of dry solids Θ_v and secondly as ratio of mass of water present in solids to mass of dry solids Θ_g. Water constrain is one of the main environmental constrains shaping plant growth, development and physiology. Crop experiencing water stress, exhibit metabolic limitation because carbon dioxide diffusion co_2 is lowered by stomatol closure, resulting in lower rate of carbon (c) assimilation and causes more (c) to be allowed to non photosynthesis organs and as a result in adequate food is manufactured by plants (Stitt *et al.*, 2010). Excess water on the other hand causes leaching of soluble minerals such as manganese and nitrates. Leached minerals not only deprive plants required nutrients but also contaminate ground water. It has been observed that water containing nitrate-nitrogen exceeding 40 parts per million (ppm) cause ‘methemoglobinemia, when used by human beings and ruminant animals, according to research carried out by (Mahler *et al.*,2011) in Idaho, Moscow. Other minerals such as manganese have been associated with toxicity of nervous system. Humidity sensors are therefore necessary to aid in optimizing water utilization in irrigated farms.

A country is categorized as ‘water stressed’ if it is annual renewable freshwater supplies are between 1000 and 1700 cubic meters per capita per annum and ‘water scarce’ if it is renewable freshwater supplies are less than 1000 cubic meters per capita per annum(Ministry of Water and Irrigation, 2005). Kenya with 647 cubic meters of renewable freshwater supplies per capita per annum is categorized as ‘water scarce country’

(Ministry of Water and Irrigation, 2005). Kenya as a country is facing a number challenges related to water resource management as result of climate variability and increasing demand for water due to population pressure and rapid development which are factors difficult to control and requires mitigation measures to be effected. A large fraction land in Kenya of approximately 80% coverage is arid and semi-arid centers (ASALs) (Kandji, 2006). In these areas annual rainfall ranges from 200-500 mm periodical. Drought is one of the huddles that may prevent Kenya from achieving the Millennium Development Goals (MDGS) especially those related to food security, poverty eradication and environmental degradation.

The causes exposing Kenyans to drought is over dependence on rainfall in crop production. Majority of farmers in Kenya rely entirely on rain-fed agriculture and thus prevailing climatic condition is a major factor determining crop yield. The knowledge of soil humidity content to farmers is derived from soil texture and wilting of crops during dry weather. Water sensors which continuously monitor soil humidity content are available in research institutes and few large scale investors owing to high cost of purchase and installation making it difficult for the rural poor to practice modern irrigation in their small scale farms. There is need to develop low cost soil moisture sensor using locally available materials which is easy to install and develop programmable interface circuit. Research has shown that automated irrigation system increase the yield of crops. Kenya Agricultural Research Institute (KARI) through International Atomic Energy Agency (IAEA) developed automated small scale irrigation technologies to improve water and nutrient use efficiencies of tomato crop (International Atomic Energy Agency IAEA, 2011).

Yields of the crop were compared under rain fed conditions, traditional watering hand method and small scale drip irrigation with neutron probe to determine soil water content at any time during their growing season and the optimal timing of amount of water to be applied. Using these technologies tomato yields of 9.7 tones per hectare (t/ha) were obtained under rain fed conditions with 221mm of rainfall, 13t/ha with traditional hand watering of 927mm and 32t/ha under drip irrigation with neutron probe hence increasing the yield by 3.3 and 2.5 times compared to rain fed and hand watering respectively. This yield increase was obtained despite a 45% reduction in the amount of water applied to the crop (IAEA, 2011). Therefore modern irrigation guarantees high yield and economizes available water.

A sustainable irrigation policy must therefore be based on an integrated water resources management policy by developing systems which monitors humidity content of soil at various stages of growth and development of crops. The system should be aimed at measuring soil humidity content with accuracy to be used in making decisions on the amount of water to irrigate a crop at a given instant of its growth and development. Excessive use of water for irrigation leads to conflict between downstream and upstream users which sometimes take violent dimensions in some parts of our country, Kenya (Ngigi, 2009).

The traditional small scale irrigation practices that have been ongoing in some areas in Kenya for the past 400 years, large scale irrigation schemes have also been in existence from the time of the colonial era (Neubert *et al*., 2007). From 1966 large scale irrigation schemes have been managed by the National Irrigation Board (NIB) a government parastatal of the Ministry of Water and Irrigation (MWI). NIB is semi autonomous and operated relatively independent of the ministry but by the year 2000 nearly all these irrigation schemes were operating under capacity or not operating at all due to the managerial problems.

In 1977 the Small Scale Irrigation Unit (SSIU) was setup within the ministry of agriculture (MOA) to supplement the NIB. The main objective of SSIU was to support the development of small holder irrigation schemes. The SSIU has also worked absolutely with Regional Development Authorities (RDA) in promotion of irrigated agriculture. Presently there are approximately 2500 small holder irrigation schemes covering an area of about 47,000ha. This figure accounts for 46% of the total area under irrigation in Kenya. (Neubert *et al*., 2007)

Large scale irrigation schemes managed by NIB cover an area of 13,000 ha accounting to 12% of Kenya's irrigated land. These schemes produce about 90% of rice consumed in Kenya and employs 12% of Kenyan active farmers in irrigation (Ngigi, 2009).
Commercial flowers and vegetable farms cover 42,800 ha accounting to 42% of land under irrigation. These farms offer employment to some 70,000 persons. Secure access to water among other factors remains the greatest challenge to all forms of irrigation due to declining water levels in rivers and lakes supplying water to irrigated farms. Past experience have shown that, small scale irrigation schemes have posted major economic gains than large scale irrigation schemes in Kenya. It is therefore more viable to expand small scale irrigated farms with low cost technology such as capacitance soil humidity sensors to monitor amount of water available for crop use.

1.1 Statement of the problem

Food is basic human needs that sustains life and provide energy required to perform work. Production of food in Kenya has often experienced inadequate rainfall leading to crop failure. This calls for shift in farming practices to give room for irrigation to improve crop yield enough to attain food secure state. However water is scarce in most parts of the country and this demand optimal use of water in irrigated plantations. Optimization of water requires farmers to be equipped with knowledge of determining accurately soil moisture content using non- destructive sensors of short response time. Commercially available sensors are of high cost and small scale farmers who are often low income earners cannot afford and thus become limited in practicing modern irrigation methods in their farms. In this study a low cost soil moisture sensor that uses locally available materials is designed and built.

1.2 Objectives

The general objective of the study is to develop capacitance soil humidity sensor using locally available materials and characterize for different texture classes of soil. The following were the specific objectives for the study

1. To design capacitive soil humidity sensor
2. To fabricate capacitive soil humidity sensor
3. To calibrate fabricated capacitive soil humidity sensor.

1.3 Justification of the study

Irrigated agriculture is envisaged as future solution to meet the growing demand for food to supply for growing population to the world over. With reducing land space for agriculture and declining water levels in rivers and lakes, there is need to embrace modern affordable technologies in farming to improve food production. Performance of irrigated small holder schemes gives encouraging net earnings of USD 200 to 1200 per month for single crop enterprise in Kenya. It is for this reason that efficient use of water which is already scarce resource is to implement use of soil moisture sensors in monitoring soil moisture content to give sufficient information to farmer on when and how much water to be applied on crops. Efficient use of water in irrigation is possible only when the soil moisture content is monitored accurately. The capacitance sensor was therefore designed, built and calibrated using low cost locally available materials with an objective to lay solid foundation of an interface circuit by characterizing capacitance of the fabricated sensor with gravimetric water content. This study provides basis of affordable automatic irrigation system.

CHAPTER TWO

LITERATURE REVIEW

Indirect measurement of soil humidity was proposed nearly one hundred years ago by measurement of electrical resistance between two parallel electrodes embedded in soil (Rende and Biage, 2002). It was discovered that electrical resistance of the block decrease with increasing water potential. Over long years of studies, it was found that measurement of electrical resistance was negatively affected by chemical composition of the soil and prevailing temperature but efforts to minimize these effects became minimal (Alva and Fares, 2000). Soil water content is determined directly using thermo-gravimetric method but the method is labor intensive, time consuming, destructive and discrete for repetitive measurements (Rende and Biage, 2002) but the method is accurate and is used to calibrate indirect soil humidity sensors.

2.1 Soil Moisture Measuring Devices

2.1.1 Conventional oven method

In this method amount of water in the soil is found by measuring the mass of moist soil sample, drying in an oven the sample to remove the moisture and then mass of the oven dried sample is measured again. Letting mass of the moist soil be M_{ms} and dry soil be M_{ds}. Mass of water contained in the sample (M_w) will be given by;

$$M_w = M_{ms} - M_d \qquad 2\text{-}1$$

and the gravimetric water content of the soil is given by;

$$\theta = \frac{M_{ms} - M_{ds}}{M_{ds}} = \frac{M_w}{M_{ds}} \qquad 2\text{-}2$$

M_{ds} is oven dried weight of soil and Θ_g is gravimetric water content (Evans,Cassel and Sneed, 1996).

2.1.2 Neutron scattering

In this technique neutrons with high energy are emitted by a radioactive source, in to the soil and are slowed (thermalized) by elastic collisions with nuclei of atoms (Dorigo *et al.*, 2011). Hydrogen has a very low atomic weight; it can slow neutrons more effectively than other elements. The density therefore of the resultant cloud of slowed neutrons is taken to be proportional to the total number of hydrogen atoms per unit volume of the soil. The assumption made is that hydrogen atoms have a direct correlation with soil moisture, the volumetric moisture content can be determined from an established calibration curve.

In establishing a calibration curve, count ratio (i.e. direct count to standard count) is commonly used instead of direct count so that any change in counting time does not invalidate the calibration curve. Also count ratio automatically corrects for electronic drift and source delay. Provided the above information remains valid, the relationship between count ratio and volumetric water content can generally be assumed to be linear (Yuen *et al*, 2000)

This method is faced with the following limitations;

1 Bound Hydrogen Effect-soil such as clay contains hydrogen bound in minerals or organic matter. This hydrogen also decelerate moving neutron, just like hydrogen in free water.

2 Neutron Capture Effect- Neutrons being slowed (thermalized) are subject to capture by various elements in the measuring medium that have affinity for neutrons and their capture cross section are as shown in table 2.1 (Yuen *et al*, 2000) . The common elements

which can capture are iron, potassium and chloride. Elements such as boron with high absorption capacities are less common in soil.

Table2.1: Capture cross section for thermal neutrons of common soil element (Yuen *et al*, 2000)

Element	Capture cross sections (barns)
Oxygen	0.0016
Hydrogen	0.2
Silicon	0.16
Carbon	0.0045
Chloride	33
Boron	795
Iron	2.5
Calcium	0.43
Sodium	0.5
Potassium	2.2
Magnesium	0.4

2.1.3 Time domain reflect meter

Time-domain reflectometry (TDR) is measurement technique used to determine the characteristics of electrical lines by observing reflected waveforms. TDR begins with sending pulse of energy into a system and a subsequent observation of the energy reflected by the system. By analyzing the magnitude, duration and shape of the reflected waveform, the nature of the impedance variation in the transmission system can determined.

TDR measures soil water content (SWC) indirectly by measuring the travel time through the soil of a short pulse of electromagnetic energy. The travel time of an electromagnetic wave trough a given thickness of material is directly proportional to the square root of the dielectric constant of that material (Parchomchuk *et al.*, 1997). For soil, the apparent relative dielectric constant $\mathbf{k_a}$, varies greatly with volumetric SWC and ranges from”4” for dry soil to as 40 for wet soil. Studies by Topp found the following third degree polynomial.

$$\theta = (4.3\text{x}10^{-6})k_a^3 - (5.5.\, x\ 510^{-4})k_a^2 + (2.92\ x\ 10^{-2})k_a + (5.3x10^{-2}) \qquad 2\text{-}3$$

TDR probe comprise of two parallel metal rods with specified rod diameter to spacing ratio (Runkles *et al.*, 2006). These rods are referred as wave guides. The instrument determines travel time of an electromagnetic wave along the wave guide by transmitting a high frequency pulse and measuring voltage amplitude of the reflected pulse at known time increment following the transmission of the pulse. The process is repeated to generate a graph of reflected voltage versus time from which the travel time along the imbedded waveguides can be determined and calibrated with SWC.

Plate 2.1: Time domain reflectometry probes (Runkles *et al.*, 2006)

Neutron scattering is one of the most accurate indirect method of measuring water content but it is expensive and pose health risks if not handled with care, therefore capacitive sensor is the appropriate alternative owing to its low cost of materials used and flexibility of geometrical design.

2.2 Theory of Capacitive Sensors

The electrical capacitance of a capacitor is given by the relation.

$$C=\frac{\varepsilon d}{A} \qquad 2\text{-}4$$

Where C is capacitance, A is area of the plates and d is the distance between the plates"

Permittivity ε of the capacitor from equation 2-4 is directly related to capacitor c if area A and distance d is kept constant. Permittivity is the property of the material which varies with humidity. Dielectric constant of dry soil range between 4-7 and that pure water is 78 this wide variation of dielectric soil and dry soil forms reliable basis of taking sensor capacitance whose dielectric is a surrogate parameter of detecting water content in the soil (Rende and Biage, 2002). The sensor focuses change of capacitance as a result of variation of water content in the soil. Permittivity is a physical quantity that describes how an electric field affects and is affected by a dielectric medium and is determined by the ability of a material to polarize in response to the field. This permittivity relates to a material's ability to transmit electric field. Water molecules exhibit hydrogen bonds which allow it to be polarized therefore; the same charge is stored within smaller electric field leading to increased capacitance. In linear, homogeneous, isotropic materials with instantaneous response in electric field, its displacement field is given by;

$$\mathbf{D}=\varepsilon\mathbf{E} \qquad 2\text{-}5$$

Where ε is a dielectric, **D** is displacement field and **E** is electric field. εis not constant it varies with position of the medium, frequency of the applied field, humidity, temperature and other parameters. Permittivity can take on real or complex values. Vacuum permittivity (ε_0) is given by:

$$\varepsilon_o = 8.85 \times 10^{-12} \frac{F}{M} \qquad 2\text{-}6$$

Where C_0 is speed of light in free space and μ_0 is permeability constant. Linear permittivity of homogeneous material is expressed relative to vacuum permittivity (ε_0). Relative permittivity (ε_r) is related to ε_0 through the equation:

$$\varepsilon = \varepsilon_r \varepsilon_o = (1 + \chi_e)\varepsilon_o \qquad 2\text{-}7$$

Where χ is electric susceptibility of the material, and ε is the actual permittivity. When an external electric field is applied to real medium, current flows, the total current consists of two parts: conduction and displacement current. The displacement current reflects change in electrostatic energy stored within the material and can be separated in to a vacuum and one arising from the material by

$$D = \varepsilon E = \varepsilon_0 E + P = \varepsilon_0 E + \varepsilon_0 \chi E = \varepsilon_0 E(1 + \chi) \qquad 2\text{-}8$$

Where P is polarization, χ is electric susceptibility and ε_r is given

$$\varepsilon_r = \chi + 1 \qquad 2\text{-}9$$

The response of normal materials to external field is not instantaneous. It takes place after application of electric field. For this reason, permittivity is treated as complex function. Hence permittivity is defined by:

$$D_o e^{i\omega t} = \varepsilon(\omega) E_o e^{-i\omega t} \qquad 2\text{-}10$$

Where D_o is amplitude of displacement and E_o isamplitude of electric field and i is imaginary.Since the response of materials to alternating field is characterized by complex permittivity, it is separated to real and imaginary parts (Schwank *et al.,* 2006)

$$\varepsilon(\omega)=\varepsilon'(\omega) + i\varepsilon''(\omega)=\frac{D_o}{E_o}(\cos\sigma + i\sin\sigma) \qquad 2\text{-}11$$

Where $\varepsilon^{//}$ is imaginary part of the permittivity, $\varepsilon^{/}$ is real part of the permittivity and σ is surface charge density.

The complex permittivity is complicated function since it is superimposed description of dispersion phenomena occurring at multiple frequencies. At a given frequencies, imaginary part of ε(ω) leads to absorption loss if it is positive and gain if it is negative. In case of lossy medium, the total current density flowing is:

$$J_{tot}=J_c+J_d=\sigma E-i\omega\varepsilon' E=-i\omega\varepsilon(\omega)E \qquad 2\text{-}12$$

Where σ is surface charge density of the medium, $\varepsilon^{/}$ is real part of permittivity and ε (ω) is the complex permittivity.

The size of displacement current is dependent on the frequency (ω) of the applied field **E**. There is no displacement current in a constant field. Thus complex permittivity is given by:

$$\varepsilon(\omega)=\varepsilon' + i\frac{\sigma}{\omega} \qquad 2\text{-}13$$

1. Absorption of electromagnetic energy by dielectrics is covered by the following mechanism, which influence the shape of permittivity as a function of frequency Relaxation effect associated with permanent and induced molecular dipoles which at low frequencies changes slowly enough to allow dipoles to reach equilibrium before the field has measurably changed.

2. Resonant effects arise from the rotation or vibration of atoms, ions, or electrons. These processes are observed in the neighborhood of their characteristic absorption frequencies.

The above mechanism combines to cause non-linear effects within capacitance. In terms of quantum mechanism, permittivity is explained by atomic and molecular attractions. At low frequencies, molecules in polar dielectrics are polarized by an applied dielectric field, which induces periodic rotation. For water, periodic rotation breaks hydrogen bonds and energy is absorbed as heat. At moderate frequencies, the energy is too high to cause rotation and too low to affect electrons directly. Thus it is absorbed in the form of resonant molecular vibrations. In water, absorptive index starts to drop sharply and the minimum of imaginary permittivity is at the frequency of blue light (optical regime). At high frequencies, molecules cannot relax and the energy is purely absorbed by atoms, exciting electron energy levels, therefore are classified as ionizing radiations.

2.3 Capacitive humidity sensor

The capacitive humidity sensor consists of a hygroscopic dielectric material placed between a pair of electrodes, which forms a small capacitor. Most capacitive sensors use plastic or polymer as the dielectric material, with atypical dielectric constant ranging two to fifteen. When no moisture is present in the sensor, both this constant and the sensor geometry determine the value of capacitance (Roveti, 2001).

At normal room temperature, the dielectric constant of water vapor has a value of about eighty, much higher than the constant of the sensor dielectric material. Therefore, absorption of water vapor by the sensor results in an increase in sensor capacitance. At equilibrium conditions, the amount of moisture present in a hygroscopic material depends on both ambient temperature and the ambient water vapor pressure. This is true also for the hygroscopic dielectric material used on the sensor.

By definition relative humidity (RH) is a function of both ambient temperature and water vapor pressure. Therefore RH, the amount of moisture present in the sensor, and sensor capacitance are related and this relationship forms the base of a capacitive humidity instrument's operation.

Electronic configuration of the capacitive humidity sensor is shown in figure 2.1 below. A polymer layer is placed between a metal electrode and a coated glass substrate. The dielectric permittivity of the polymer depends on its water content. The electronics of the instrument measure the capacitance of the sensor and convert it into humidity readings.

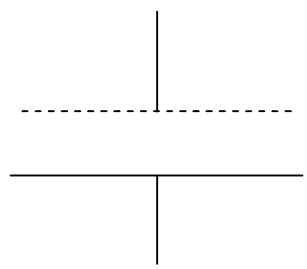

Figure 2. 1*:* Capacitive soil humidity sensor (Roveti, 2001)

The capacitance of the sensor c is as follows:

$$C_{RH} = \frac{\varepsilon'_{RH}\, \varepsilon_o . A}{d} \qquad 2\text{-}14$$

Where $C_{(RH)}$ is a sensor capacitance at a given relative humidity; ε'_{RH} relative dielectric permittivity;ε_o is permittivity of vacuum; A is the area of the electrode; and *d* is the distance between electrodes.

Each capacitive sensor is individually calibrated in a precision humidity chamber with a chilled mirror hygrometer as reference. Thin film capacitive sensors may include monolithic signal conditioning circuitry integrated onto the substrate. The most widely used signal conditioner incorporates a CMOS timer to pulse the sensor and to produce a near-linear voltage output. Dielectric constant of soil solids is between four and five and that of pure water is seventy eight. Due to wide gab in dielectric constants between pure water and solid soils real part of dielectric constants in soil is dominated by water, (Dorigo *et al.,* 2011). According to (Oleszczuk,2005) volumetric water content (Θ_v) and apparent dielectric constant of soil are related as shown in equation 2-14

$$\theta_v = \left(4.3x10^{-6}\right) k_a^3 - \left(5.5x10^{-4}\right) k_a^2 + \left(2.92x10^{-2}\right) k_a + 5.3x10^{-2} \qquad 2\text{-}15$$

Where,

$$\theta_v = \frac{\text{Volume of water}}{\text{Volume of solids}}$$

Equation (4.1) is polynomial of order (3). According to this equation, dielectric constant of soil medium k_a does not linearly vary with volumetric water content. Volumetric water content (Θ_V) can be expressed in terms gravimetric content (Θ_g) by the equation (Dorigo *et al.,* 2011)

$$\theta_v = \theta_g \frac{\rho_d}{\rho_w} \qquad 2\text{-}16$$

Replacing Θ_V in equation 4.1 gravimetric water content $\Theta_g$is given by equation

$$\theta_g = \frac{\rho_w}{\rho_d}\left(4.3x10^{-6}\right) k_a^3 - \left(5.5x10^{-4}\right) k_a^2 + \left(2.92x10^{-2}\right) k_a + 5.3x10^{-2} \qquad 2\text{-}17$$

Variation in Topp's equation dielectric relationship with volumetric water content is attributed to soil density and texture effects (Oleszczuk,2005). Soil is conducting media due to the presence of electrically charged particles on the surface of the solids and ions dissolve electrolytes in rain water. The bulk electrical conductivity relates to dielectric constant of solids by the equation

$$Ec_b = \frac{\sqrt{k_a}}{120\pi L_p} \ln\left(\frac{v_1}{v_2}\right) \qquad 2\text{-}18$$

Electrical conductivity is influenced by other factors such as pore water, mineralogy, soil structure, degree of saturation and surface conductance.

Therefore based on the results of results findings it is evident that dielectric constant of the soil depends on many factors but water content dominates and its therefore necessary to calibrate sensors for each specific soil (Morgan *et al.*, 1999)

CHAPTER THREE

MATERIALS AND METHODS

3.1 Introduction

Soil is a composition of many minerals which differ from their parent material in their structure, texture, colour and other physical characteristics. Soil forms a structure comprising of pore spaces, water, minerals and organic materials. These components largely influence soil physical properties including dielectric constant of the soil. The investigation begun with simulation of capacitance sensor using quick field software (http.//www.quickfield. com) followed by fabrication and humidity sensors. After fabrication the sensors were tested to establish their range in capacitance in air. The soil samples were collected within a depth of two to fifteen centimeters from different zones within Uasin Gishu and Elgeyo Marakwet counties and taken to laboratory of soil science in Chepkoilel University College in which texture and conductivity tests were done.

The calibration finalized the process and was carried out by inserting probes into the soil samples in 2Kg plastic containers and the sensor remained in the soil during the entire period. Reading of the sensor capacitance and mass of the setup was done every morning until there were very small changes in masses of the setup.

3.2 Simulation

The sensor similar model was simulated in students quick field Electromagnetic soft ware (http.//www.quickfield. com). Capacitance of a capacitor depends on the geometry of the electrodes making up the capacitor. There are formulae that define various geometric shapesderived from Gaus law (Golbani and Azimi, 2009). This formulae does not apply to complex shaped capacitors. Electromagnetic soft ware provides an appropriate interface tool for estimating capacitance of capacitors of complicated geometric orientation. It is equipped with features that allow drawing of models, characterization of surrounding conditions of the sensor such as permittivity of the soil and designating electric potential to surface of conductors. Electrostatic problems are described by the poisons equation for scalar electric potential U (E= -grad U) E is electric field intensity vector. The equation for planar case is given by

$$\frac{\partial}{\partial x}\left(\varepsilon_x \frac{\partial U}{\partial x}\right)+\frac{\partial}{\partial y}\left(\varepsilon_y \frac{\partial U}{\partial y}\right)=-\rho \qquad \text{3-1}$$

and for axisymmetric is given by;

$$\frac{1}{r}\frac{\partial}{\partial r}\left(\varepsilon_r \frac{\partial U}{\partial r}\right)+\frac{\partial}{\partial z}\left(\varepsilon_z \frac{\partial U}{\partial z}\right)=-\rho \qquad \text{3-2}$$

Where $\varepsilon_{x,}$ ε_y $\varepsilon_{z,}$ $\varepsilon_{r,}$ and ρ components of dielectric and volume electric charge density which are constants within each block of the model. Quick field calculates capacitance based on measured electric potential produced by known charge. To get capacitance of a capacitor constant potential is put at the surface of an electrode and an arbitrary non zero electric charge is distributed over conductor surface and other field sources is turned off in the model. The capacitance is obtained from the equation;

$$c=\frac{q}{u} \qquad \text{3-3}$$

Where q is electric charge and u is the potential of the conductor. To calculate mutual capacitance between two conductors between conductors a charge is put on one conductor and electric potential on another is measured. Constant potential boundary condition has to be applied to the surface of both conductors.

$$c_{12}=\frac{q_1}{u_2} \qquad \text{3-4}$$

The energy of electric field is given by

$$w=\frac{1}{2}\int(E.D)dv \quad 3\text{-}5$$

and total charge is

$$q=\int D.nds \quad 3\text{-}6$$

3.3 Fabrication

The sensor was fabricated using low cost available materials. The probes are made of stainless steel obtained from screw drivers of diameter of 0.6cm. The steel screw rods were sharpened at one end to enable the sensor to penetrate into soil matrix with ease and threads inscribed at the other end to facilitate tight fitting into the rigid housing support. The four steel rods were assembled to protrude in circular rigid housing with a spacing of 3cm along the diagonal and the probes are positioned in vertices of a close to a rhombus plane figure.

The diagonal were connected to be one electrode therefore the sensor is an equivalent of two capacitors in parallel. The circular housing support was derived from used tractor tire which was easy to groove to allow circuitry connection within the housing and provided strong mechanical support to the probe. Water proof lid was fitted at the housing end to cover circuit connection to prevent water from entering circuitry part.

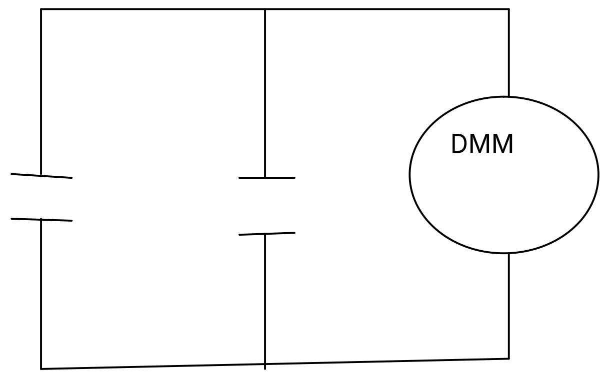

Figure 3.1: Equivalent circuit of the sensor (Source: Author, 2011)

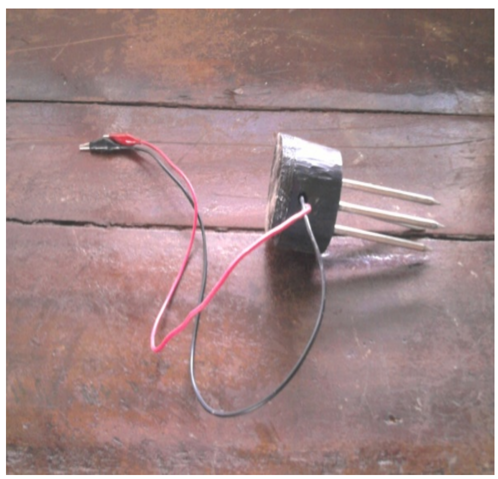

Plate 3 1 Fabricated sensor (Source: Author, 2011)

3.4 Soil sampling

The soil samples are collected at Kerio Valley (Cheptepo location), Uasin-Gishu (Chepkang'a) location and Keiyo highlands (Kaptarakwa location). These regions experience different climatic conditions and collection of samples focused on soils which are favorable to crop production. The soil within a depth of 2cm-15cm were sampled out, this region is where crops derive water from. Soils collected were air dried in an open atmosphere and later transported to laboratory

3.5 Particle size analysis

The texture test of soil samples were done in soil science laboratory using hydrometer method and the texture classes were assigned to the samples based on soil texture triangle.

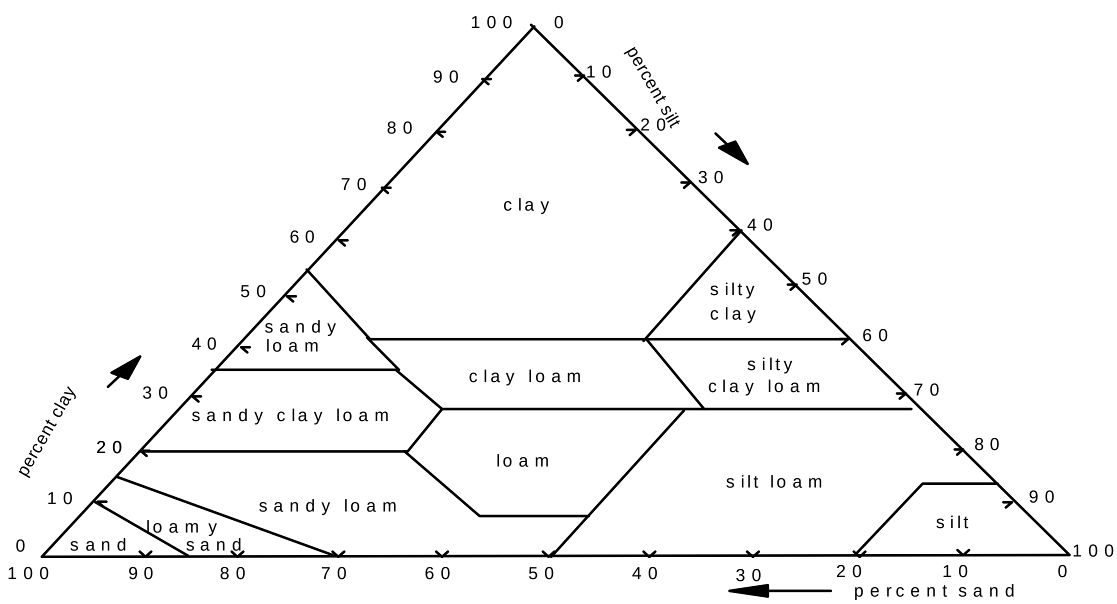

Figure 3. 2: Soil texture triangle (Bonan, 2002)

3.6 Hydraulic conductivity

Conductivity test of soil was conducted using falling head method and the sample soils were rated based on classes developed by (Thomas *et al.*, 1996).

Table 3. 1: Soil permeability classes (Thomas *et al.,* 1996).

Classification	Infiltration rate in Inches per hour
Very Slow	Less than 0.06
Slow	0.06 – 0.2
Moderately Slow	0.2 - 0.6
Moderate	0.6 – 2.0
Moderately Rapid	2.0 – 6.0
Rapid	6.0 – 20.0
Very Rapid	Greater than 20.0

3.7 Calibration

The calibration process begun by making holes of diameter (1-2) mm at the bottom of 2Kg containers to, drain out excess water during humidification. The mass of 2Kg plastic container, capacitance sensor and bottom plate for each set was measured ($m_{(s,c\&p)}$) and recorded. Soil samples were packed in 2Kg plastic containers to the brim and labeled A,B,C and D which were sandy clay loam (Chepkang'a), loamy sand (Kaptarakwa), clay loam (Chepkang'a) and sandy loam (Cheptebo) respectively. Tap water was applied on the packed soil samples by pouring gently and in beats to allow water permeate to all parts of the soil until saturation was attained as observed by water seeping out of the holes at the bottom of the containers. The portable fabricated sensor was hand driven gently at approximately the centre of the surface such that its probes were fully immersed in the soil and it remained undisturbed in the same position for the entire calibration period. The four soil samples were allowed to dry in green house conditions to accelerate drying because the weather was cloudy and rainy during investigation period and could not dry out with ease under atmospheric conditions. The mass of set (sensor, wet soil sample, container and bottom plate) $m_{(wet\text{-}set\ up)}$ was measured using digital electronic balance with resolution of 0.1g in the morning and recorded. In the moment of reading of the mass, capacitance (C) of the sensor was measured using digital meter of resolution 0.1µF and recorded. The readings of the mass and capacitance were taken continuously in the morning until there was very low lose of mass. After measurements of capacitance, the sensors were removed carefully and soils still sticking on sensor probes were scrapped using metal plate and emptied in their respective containers. Mass of eight empty $m_{(empty\ tray)}$ oval metallic trays were measured and recorded. Soil samples were emptied in oval metallic trays of which each soil sample occupied two trays in preparation for oven drying. The mass of wet soil in the trays were taken as $m_{(tray\ and\ wet\ sample)}$ and kept in the oven for 48 hours which was regulated at (105-110)^{o}c. After two days the mass of oven dried samples in trays were measured and recorded as $m_{(tray\ and\ dry\ sample)}$.

The soil water content was given by the equation;

$$\theta_g = \frac{(m_{wetsetup}) - m_{s,c,p}) - m_{dryssp})}{m_{dryssp}} \qquad 3\text{-}6$$

Plate 3. 2: Saturated soil Samples (Source: Author, 2011)

Plate 3. 3: Sample soils with installed sensors (Source: Author, 2011)

Plate 3. 4: Oven dried soil samples in metallic trays (Source: Author, 2011)

3.8 Data analysis

The data was analyzed using KaleidaGraph software which fitted appropriate curve on plotted data and evaluated its fitness using standard errors, Chi square and $\mathbf{R^2}$(coefficient of fitness).

Considering **i** as index of observation on the data pairs **(x,y)** such that fitted curve fits $\hat{y}_i$ to actual observation y_i then the residual associated with each pair of data value is given by

$$\widehat{u_i} = y_i - \widehat{y_i} \qquad 3\text{-}7$$

and the sum of square residuals can be written as

$$SSR=\sum \widehat{u_i} = \sum y_i - \widehat{y_i})^2 \qquad 3\text{-}8$$

Taking n as the number of data points and k to the number parameters to be estimated, the standard error is given by;

$$\hat{\sigma}=\sqrt{\frac{SSR}{n-k}} \qquad 3\text{-}9$$

Standard error is sensitive to the units of measurements of the dependent variable. A more standardized statistic which gives a measure fitness of estimated equation is R^2 (Cottrel, 2011).

$$R^2=1-\frac{SSR}{\sum (y_i^2-\bar{y})^2}=1-\frac{SSR}{SST} \qquad 3\text{-}10$$

Where SST is total sum of squares of the dependent variable amount about its mean value (Cottrel, 2011).

The value of R^2 range from zero to one $0 \leq R^2 \leq 1$. When $R^2=1$, is a perfect score and shows that all data points lie exactly along the fitted curve and $R^2=0$ shows all data points lie outside the fitted curve (Cottrel, 2006)

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Introduction

Materials and set methods were executed to attain set objectives. Simulation of capacitance sensor using quick field software projected linear relationship between charge of the capacitance and the dielectric constant of the soil in a label mover serial analysis. Fabrication of the sensor was done using four screw drivers which were sharpened at one end to have tips that can easily penetrate the soil and the other ends were circumscribed with threads to allow tight fitting into the hard rubber rigid support using nuts. After fabrication the sensors were tested to establish their range in capacitance in air and in water which showed ranges of 0.427, 2.099, 1.898 and 2.198 Microfarads which was observable sensitivity range. The texture results categorized soil in to four textural classes and conductivity tests showed that soils under investigation had a range of (0.9615-4.267) Inches/hour.

The calibration finalized the process and was carried out by inserting probes into the soil samples in 2Kg plastic containers and the sensor remained in the soil during the entire period. Reading of the sensor capacitance and mass of the setup was done every morning until there were very small changes in masses of the setup. The capacitances of the sensor were plotted against gravimetric water content and non linear graphs obtained were analyzed in Kaleidagraph.

4.2 Simulation

The simulation conducted in quickfield soft ware was four probes of diameter 1.2cm and L_z projection of 15cm located at coordinates (1,0),(0,1),(-1,0) and (0,-1). The surface of alternate probes were assigned equivalent potential such that those located at (1,0) and (0,-1) had a potential of 12V and the other two with ground potential. The four probes were surrounded by dielectric medium of dielectric constant of four. The model through a label mover projected linear variation of charge and dielectric constant of the dielectric and running contour across the sensor showed variation of electric field strength E.

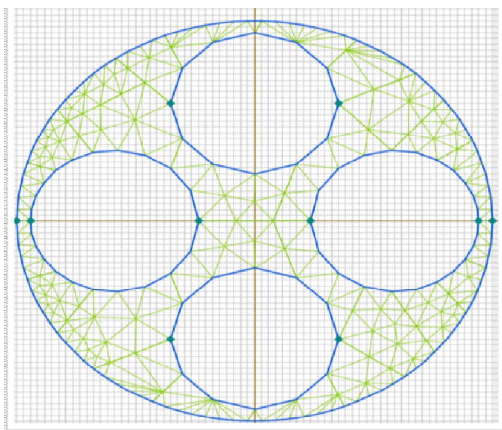

Figure 4. 12D mesh of the sensor in quikfield (http.//www.quickfield. com)

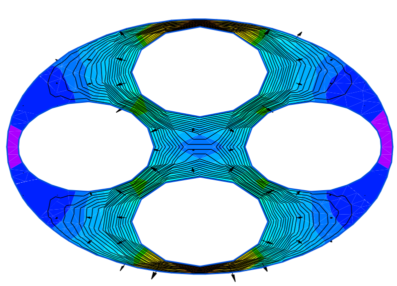

Figure 4. 2: Solved model showing potential lines and colour distribution of field strength,E (http.//www.quickfield. com)

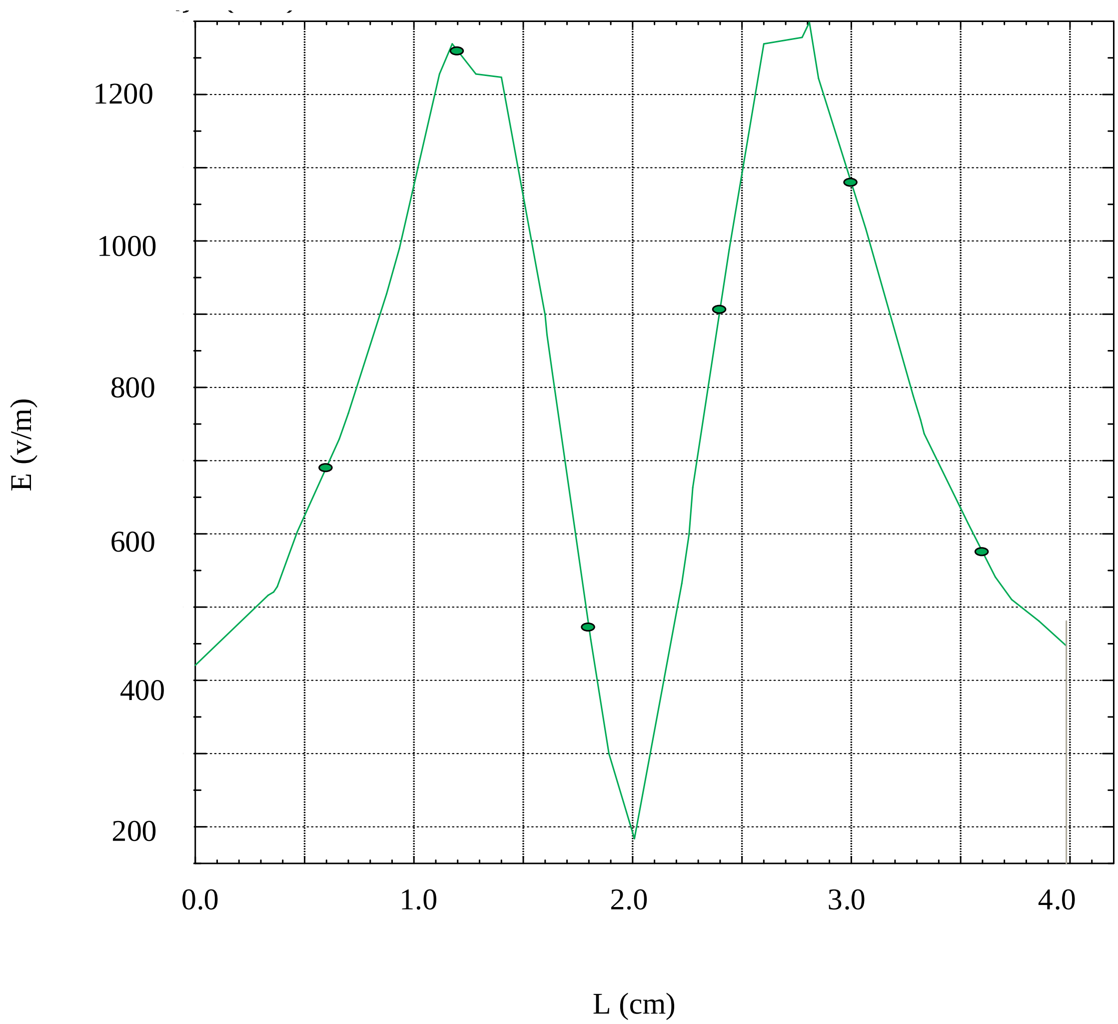

Figure 4. 3: Graph of field strength (E) against L (http.//www.quickfield. com)

4.3 Soil particle analysis

The granular compositions of soil were performed hydrometer method and samples showed that all soils contained sand, clay and silt in varying proportions. Samples collected from Kaptarakwa had high percentage of sand those from Chepkang'a and Cheptebo had high proportions of clay and silt respectively however soil samples of

Kaptarakwa and Cheptebo had lowest proportion of silt and clay respectively. The soil samples were classified into four textural classes as shown in the table of results below

Table 4. 1:Soil texture results (Source: Author, 2011)

Sample label	Lab code	Sand (%)	Clay (%)	Silt (%)	Texture class
Chepkanga(sandy)	1	54	27	19	Sandy Clay Loam
Kaptarakwa(Keyio highlands)	2	84	3	13	Loamy Sand
Chepkanga(clay)	3	38	45	17	Clay Loam
Cheptebo(Kerio)	4	64	13	23	Sandy Loam
Chepkanga(loam soil)	5	58	25	17	Sandy Clay Loam

4.4 Hydraulic conductivity

Permeability is a measure of the ability of air and water to move through it. Permeability is influenced by the size, shape and continuity of the pore spaces, which in turn are dependent on the soil bulk density, structure and texture. Through falling head method the following results were obtained and the assigned to permeability classes as shown in table 4.2. Clay loam (Chepkang'a) had high hydraulic conductivity of $3.01x10^{-5}$ ms^{-1} and loamy sand (Kaptarakwa) had least conductivity of 3.03×10^{-6} ms^{-1}

Table 4. 2: Soil hydraulic conductivity results (Source: Author, 2011)

Site	Texture	$K_s(ms^{-1})$	Permeability Class
Chepkang'a	Sandy clay loam	$1.02x10^{-5}$	Moderate
Cheptebo	Sandy loam	$2.75x10^{-5}$	Moderately Rapid
Kaptarakwa	Loamy sand	$3.03x10^{-6}$	Moderately Slow
Chepkang'a	Clay loam	$3.01x10^{-5}$	Moderately Rapid

Where K_s is hydraulic conductivity

Soil with slow, very slow, rapid and very rapid permeability are considered to be very poor for irrigation. The soil samples under study fall in good permeability class appropriate for irrigation as proposed by (Thomas *et al*., 1996).

4.5 Calibration and calibration equation

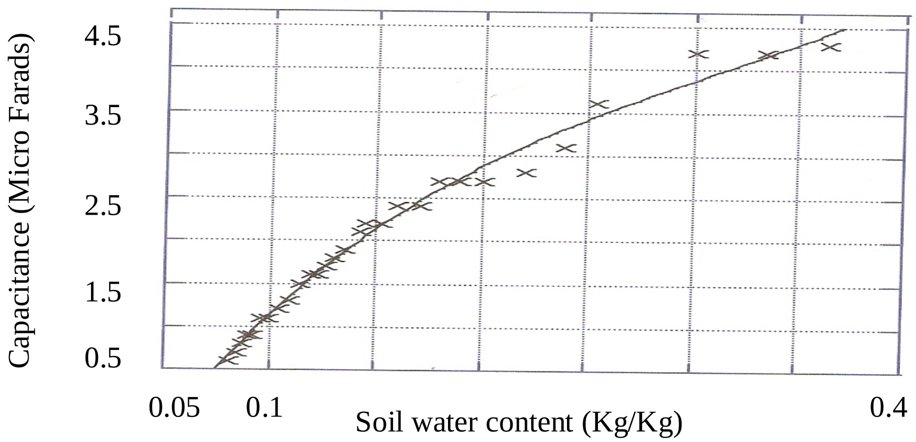

Figure 4. 4 Graph of sensor Capacitance against SWC of Sandy Loam collected from Cheptebo (Source: Author, 2012)

Sandy loam (Cheptebo) has a field capacity of 40.383% and lost 32.281148 % during investigation. Capacitance of the soil begun with 3.6µF and increased to 4.3µF as a result of compaction increased with initial loss of water and thereafter capacitance dropped with time. The capacitance of sandy loam has polynomial variation with gravimetric water content and its regression curve is supported by 98.767% of the points. Therefore the calibration curve of the soil is linear relation given by:

$$C=-2.006 + 40.666\theta_g - 103.750\theta_g^2 + 111.840\theta_g^3 \quad \text{4-1}$$

$\Theta_g$is gravimetric soil water content and C is sensor capacitance

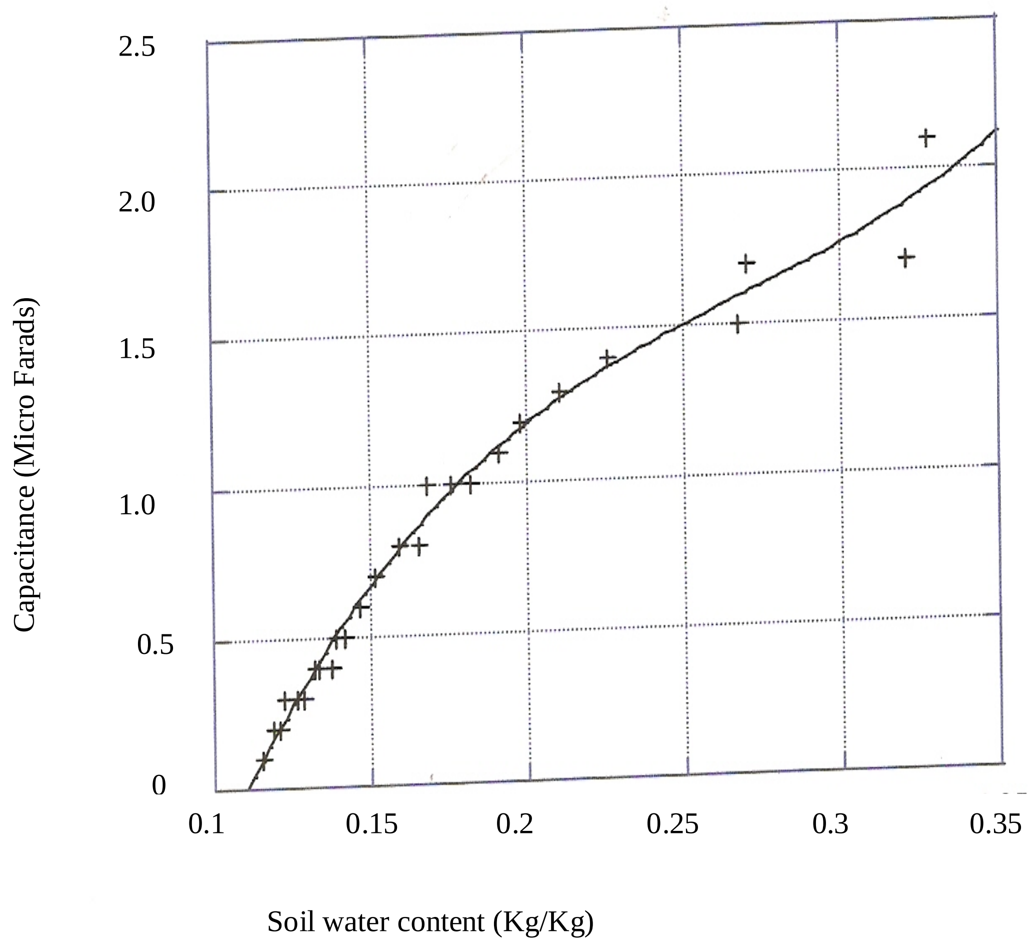

Figure 4.5: Graph of sensor Capacitance against SWof Sandy Clay Loam Collected from Chepkang'a (Source: Author, 2012)

Sandy clay loam soil has field capacity of 36.3089% and during investigation it lost 24.8006%, it started with capacitance of 4.1 μF and dropped with time until 0.1 μF as shown in appendix C. The capacitance of sandy clay loam and its gravimetric water content have polynomial variation of order three and regression curve fit has support of 98.44% of the points plotted. The calibration curve equation of the sandy clay loam (Chepkang'a) is given by;

$$C=-3.7604 + 50.088\theta_g - 168.27\theta_g^2 + 2.09.05\theta_g^3 \qquad 4\text{-}2$$

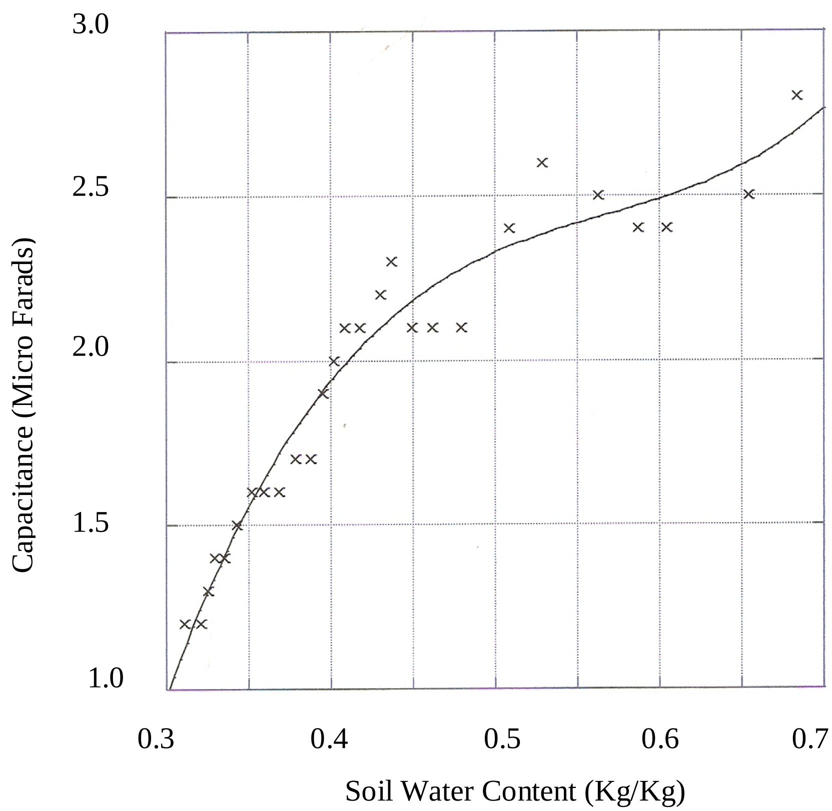

Figure 4. 6 Graph of sensor Capacitance against SWC of Loamy Sand collected from Kaptarakwa (Source: Author, 2012)

Loamy sand soil of Kaptarakwa is rich with humus it absorbed greater amount of water to 79.5857% which dropped with time to 31.11178% therefore losing 48.4679% of water during the entire period. Its capacitance begun with 4.8 μF and decreased to 1.2 μF. Capacitance of loamy sand soil is related by polynomial equation of order three with gravimetric water content and regression curve for the soil is in support of 95.249% of the points therefore appropriate calibration curve for the soil is;

$$C= -8.6348 + 55.732\theta_g - 95.758\theta_g^2 + 56.293\theta_g^3 \qquad 4\text{-}3$$

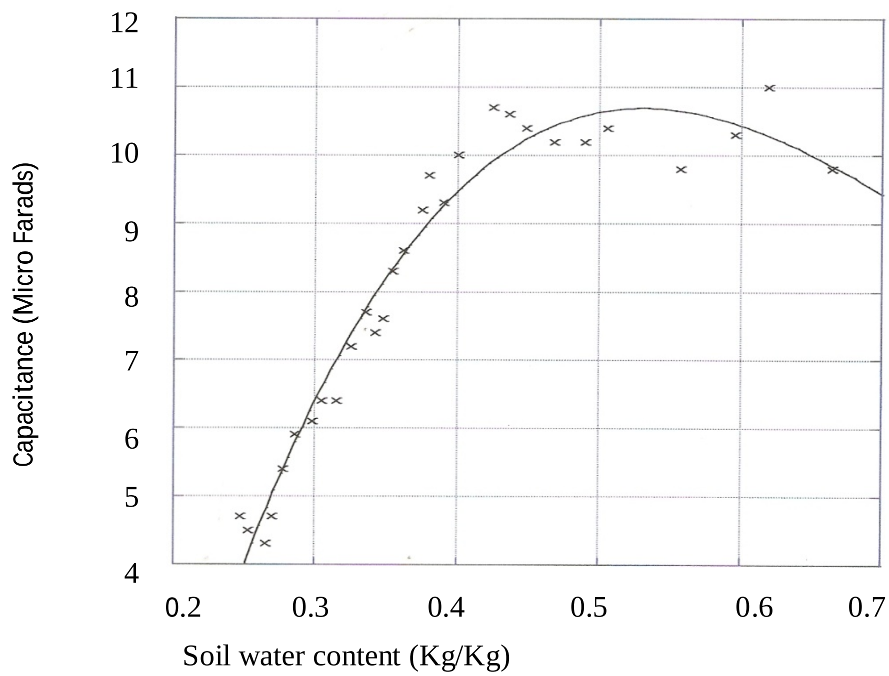

Figure 4. 7: Graph of sensor Capacitance against SWC of Clay Loam collected from Chepkan'ga (Source: Author, 2012)

Clay loam is dark sticky clay with high field capacity 66.40159%, it lost 41.6998% of the water during the entire investigation period. Its capacitance begun with 9.8 μF and increased to 11 μF as compaction increases and later dropped with time showing non consistent pattern because as soil dries up its soil structure change s at some point the soil developed deep wide cracks. The capacitance of clay loam soil is linked to gravimetric water content by polynomial equation of order three and regression curve developed is in support of 95.856% of the data points therefore its calibration curve is;

$$C = -19.518 + 139.050\theta_g - 202.230\theta_g^2 + 89.4820\theta_g^3 \quad 4\text{-}4$$

Generally there was high correlation between capacitance and gravimetric soil water content for all soil types. The study conducted by (Jukka and Hannu, 2005) for humus of slots pine and Norway Spuce in Southern Finland fitted the following models to predict volumetric soil water content

$$\theta_v = \sqrt[a]{k_a} - b \qquad 4\text{-}5$$

$$\theta_v = a + bk_a + ck_a^2 + dk_a^3 \qquad 4\text{-}6$$

$$\theta_v = a \ln k_a - b \qquad 4\text{-}7$$

and found polynomial model worked well for moderately dry conditions and logarithm model predicts water content well both at high and low water content. Taking into consideration that dielectric constant is directly proportional to capacitance of a capacitor irrespective of geometric orientations, the results agree on the nature of models which are polynomial. Expressing soil water content as a function of capacitance translates to the following third degree polynomial;

$$\theta_g = 0.074091 + 0.0040717C + 0.01631C^2 - 0.00067722C^3 \qquad 4\text{-}8$$

For sandy loam(Cheptebo) with R^2=0.98296,

$$\theta_g = 0.12517 - 0.029958C + 0.1088C^2 - 0.021888C^3 \qquad 4\text{-}9$$

For sandy clay loam (Chepkang'a) with R^2=0.96792

$$\theta_g = 0.36617 - 0.1014C + 0.033907C^2 + 0.0015451C^3 \qquad 4\text{-}10$$

For loamy sand (Kaptarakwa) with R^2=0.88667

$$\theta_g=0.36617 - 0.1014C + 0.033907C^2 + 0.0015451C^3 \qquad 4\text{-}11$$

For clay loam (Chepkang'a) with R^2=0.71624

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

The low cost soil humidity sensor was successfully designed, fabricated and used on experimental analysis of soil humidity of four textural classes of soil collected from three different locations. The calibrations equations obtained were third degree polynomial equations with R^2 ranging from 0.88 to 0.98. The response time of the sensor is short and can be automated making it suitable for irrigation scheduling at affordable cost to small scale farmers in Kenya.

5.2 Recommendations

The research focused only on fabrication and calibration of the sensor for soil water content at the laboratory level. However it is evident that other factors which are function of dielectric constant of the soil as depicted by (Runkles *et al.,* 2006) such as temperature, soil conductivity of which the research work was limited in accounting the scale of their effect on capacitance of the soil, therefore there is need to investicate challenges it can give in designing appropriate circuit interface. It is possible to develop variety of low cost capacitance sensors of different geometric shapes and an interface circuit which is flexible enough to be programmed for wide variety of capacitance range. Since field calibration was not conducted, it is recommendations of this research work for field calibration to be conducted so as to make comparison with laboratory calibration results before developing appropriate circuit interface.

REFERENCES

Alva.K.A, and Fares.A (2000). Soil Water Components Based on Capacitance Probes in a Sandy Soil. *Soil Science Society of America J,64 : 311-318.*

Bonan.G.(2002). Soil Texture Triangle. Retrieved August 23, 2011, from http://www.cgd.ucar.edu

Cottrel.A. (2011). Statistics. Retrieved August 14, 2012, from http://www.wfu.edu

Davood.N and Mahmoud.(2012*)*. Evaluation of dielectric constant by clay mineral and soil physiochemical properties.*African Journal of Agricultural Research J,7 :170-176.*

Dorigo.W.A, Wagner.W, Hohensinn.R, Hann.S, Paulic.C, Xarvel.A *et al.*,. (2011). The International Soil Moisture Network: data hosting facility for global in situ soil moisture measurement. Hydrology and Earth System Science.

Evans.R, Cassel, K, and Sneeds.R . (1996). Calibrating Soil-Water Measuring Device. North Carolina: North Corolina Cooperative Extension Services.

Golbani.H and Azimi.P. (2009). Precise Formulation of Electrical Capacitance for

Neubert.S, Hesse.V, Onyando.J, Onchoke.W,Peters.V, Seelaff.A *et al.,* (2007). Poverty Oriented Irrigation Policy in Kenya . German Development Institute.

International Atomic Energy Agency. (2011). Soils Newsletter. Viena.

Jukka.P and Hannu. (2005). Calibration of time domain reflectometry for forest soil

humus layers. Boreal Environment Research , 589-595.

Kandji.S.T.(2006).Retrieved August12, 2011, from http://www.worldagroforestry.org

Mahler.R and Colter.A, HIrnyck.R. (2007).Nitrate and Ground Water. Moscow.

Ministry of Water and Irrigation. (2005). Kenya National Water Development.

Nairobi: Government press

Morgan.K.T, Parsons.L.R, Wheaton.T.A, Pitts.D.J and Obreza.T.A. (1999). Field

Calibration of Water Content Pribe in Fine Sand Soils. *Soil Society of American J,63 : 987-989*

Ngigi.N.S. (2009). Climate Change Adaptation Strategies. New York: The MDG.

Centre for East and South Africa, The Earth Institute of Columbia University

Oleszczuk. R. (2005). Calibration of TDR for Moisture Content Monitoring in

Moorsh layer. Warsaw Agriculture University.

Parchomuk.P, Tan.C.S and Berard.R.G. (1997). Practical Use of Time Domain

Reflectometry for Monitoring Soil Water Content in Microirrigated

Orchads Research Report. Canada.

Quick field Electromagnetic Software.(2005).Retrieved 22 August 2007 from

http://www.quickfield.com

Rende.A and Biage.M.(2002). Characterization of capacitive sensors for measurement of moisture in irrigated soil. *Brazillian Society of Mechanical Sciences , 24:3*

Roveti. (2001). Sensors. Retrieved July 17, 2008, from http://www.utexus.edu

Runkles.B, White.N and Ashmawy.A. (2006). Calibration and Accuracy Assessment of the TDR one step Method for Quality Control of Compacted Soils. Florida: Forida Department of Transport.

Schwank.M, Green.R.T, Matzler.C, Benedicter.H, and Fuhler.H.(2006). Laboratory.

Characterization of a Commercial Capacitance Sensors for Estimating Permittivity and Inferring Soil Water Content. *Vadoze Zone J ,5:1048-1064*

Stitt, Gibbon.Y, Muller.B. (2010). Retrieved September 15, 2012, from American

Society of Plant Biologists: http:// www.plantphysiol.org

Thomas.F.S, Bruce.S and David.F. (1996). Soil Water and Plant Characteristics Important to Irrigation Retrieved October 19, 2011, 09:29 from: http:www.ag.ndsu.edu

Yuen.S.T.S, McMohan.T.A, and Styless.J.R.(2000). Monitoring In Situ Moisture Content of Municipality Solid Waste Landfills. *Journal of Environmental Engineering: 1088*

APPENDICES

Appendix A

SANDY LOAM (CHEPTEPO)

DATE	TIME	C(µF)	Mwet.set-up(g)	M(S,C&P)(g)	M(Wetssp)(g)	M(Dry ssp)(g)	M(water)(g)	Ɵg(g/g)
20/8/2011	8:30	3.6	3.741	0.4055	3.3355	2.376	0.9595	0.40383
21/8/2011	8:30	4.3	3.643	0.4055	3.2375	2.376	0.8615	0.362584
22/8/2011	8:30	4.2	3.573	0.4055	3.1675	2.376	0.7915	0.333123
23/8/2011	8:30	4.2	3.496	0.4055	3.0905	2.376	0.7145	0.300715
25/8/2011	8:30	3.6	3.385	0.4055	2.9795	2.376	0.6035	0.253998
26/8/2011	8:30	3.1	3.349	0.4055	2.9435	2.376	0.5675	0.238847
27/8/2011	8:30	2.8	3.304	0.4055	2.8985	2.376	0.5225	0.219907
28/8/2011	8:30	2.7	3.257	0.4055	2.8515	2.376	0.4755	0.200126
29/8/2011	8:30	2.7	3.232	0.4055	2.8265	2.376	0.4505	0.189604
30/8/2011	8:30	2.7	3.208	0.4055	2.8025	2.376	0.4265	0.179503
31/8/2011	8:30	2.4	3.186	0.4055	2.7805	2.376	0.4045	0.170244
1/9/2011	8:30	2.4	3.16	0.4055	2.7545	2.376	0.3785	0.159301
2/9/2011	8:30	2.2	3.144	0.4055	2.7385	2.376	0.3625	0.152567
3/9/2011	8:30	2.2	3.126	0.4055	2.7205	2.376	0.3445	0.144992
4/9/2011	8:30	2.1	3.119	0.4055	2.7135	2.376	0.3375	0.142045
5/9/2011	8:30	1.9	3.102	0.4055	2.6965	2.376	0.3205	0.134891
6/9/2011	8:30	1.8	3.091	0.4055	2.6855	2.376	0.3095	0.130261
7/9/2011	8:30	1.7	3.081	0.4055	2.6755	2.376	0.2995	0.126052
8/9/2011	8:30	1.6	3.074	0.4055	2.6685	2.376	0.2925	0.123106
9/9/2011	8:30	1.6	3.064	0.4055	2.6585	2.376	0.2825	0.118897
10/9/2011	8:30	1.5	3.052	0.4055	2.6465	2.376	0.2705	0.113847
11/9/2011	8:30	1.3	3.04	0.4055	2.6345	2.376	0.2585	0.108796
12/9/2011	8:30	1.2	3.028	0.4055	2.6225	2.376	0.2465	0.103746
13/9/2011	8:30	1.1	3.019	0.4055	2.6135	2.376	0.2375	0.099958
14/9/2011	8:30	1.1	3.009	0.4055	2.6035	2.376	0.2275	0.095749
15/9/2011	8:30	0.9	3.001	0.4055	2.5955	2.376	0.2195	0.092382
16/9/2011	8:30	0.9	2.994	0.4055	2.5885	2.376	0.2125	0.089436
17/9/2011	8:30	0.8	2.988	0.4055	2.5825	2.376	0.2065	0.086911
18/9/2011	8:30	0.7	2.981	0.4055	2.5755	2.376	0.1995	0.083965
19/9/2011	8:30	0.6	2.974	0.4055	2.5685	2.376	0.1925	0.081019

Appendix B

SANDY CLAY LOAM (CHEPKANG'A)

DATE	TIME	C(μF)	Mwet.set-up	M(S,C&P)(	M(Wetssp)	M(Dry ssp)	M(water)	Ɵg(g/g)
5/8/2011	8:30	4.1	4.051	0.462	3.589	2.633	0.956	0.363084
8/8/2011	8:30	2.1	3.959	0.462	3.497	2.633	0.864	0.328143
9/8/2011	8:30	1.7	3.939	0.462	3.477	2.633	0.844	0.320547
11/8/2011	8:30	1.7	3.807	0.462	3.345	2.633	0.712	0.270414
12/8/2011	8:30	1.5	3.799	0.462	3.337	2.633	0.704	0.267376
15/8/2011	8:30	1.4	3.689	0.462	3.227	2.633	0.594	0.225598
16/8/2011	8:30	1.3	3.649	0.462	3.187	2.633	0.554	0.210406
17/8/2011	8:30	1.2	3.616	0.462	3.154	2.633	0.521	0.197873
18/8/2011	8:30	1.1	3.598	0.462	3.136	2.633	0.503	0.191037
19/8/2011	8:30	1	3.574	0.462	3.112	2.633	0.479	0.181922
20/8/2011	8:30	1	3.558	0.462	3.096	2.633	0.463	0.175845
21/8/2011	8:30	1	3.538	0.462	3.076	2.633	0.443	0.168249
22/8/2011	8:30	0.8	3.53	0.462	3.068	2.633	0.435	0.165211
23/8/2011	8:30	0.8	3.514	0.462	3.052	2.633	0.419	0.159134
25/8/2011	8:30	0.7	3.493	0.462	3.031	2.633	0.398	0.151158
26/8/2011	8:30	0.6	3.48	0.462	3.018	2.633	0.385	0.146221
27/8/2011	8:30	0.5	3.468	0.462	3.006	2.633	0.373	0.141664
28/8/2011	8:30	0.5	3.46	0.462	2.998	2.633	0.365	0.138625
29/8/2011	8:30	0.4	3.457	0.462	2.995	2.633	0.362	0.137486
30/8/2011	8:30	0.4	3.446	0.462	2.984	2.633	0.351	0.133308
31/8/2011	8:30	0.4	3.443	0.462	2.981	2.633	0.348	0.132169
1/9/2011	8:30	0.3	3.434	0.462	2.972	2.633	0.339	0.12875
2/9/2011	8:30	0.3	3.427	0.462	2.965	2.633	0.332	0.126092
3/9/2011	8:30	0.3	3.417	0.462	2.955	2.633	0.322	0.122294
4/9/2011	8:30	0.2	3.413	0.462	2.951	2.633	0.318	0.120775
5/9/2011	8:30	0.2	3.408	0.462	2.946	2.633	0.313	0.118876
6/9/2011	8:30	0.1	3.398	0.462	2.936	2.633	0.303	0.115078

Appendix C

LOAMY SANDY (KAPTARAKWA)

DATE	TIME	C(µF)	Mwet.set-	M(S,C&P)(	M(Wetssp	M(Dry ssp	M(water)(	Өg(g/g)
20/8/2011	8:30	4.8	3.406	0.4015	3.0045	1.673	1.3315	0.795876
21/8/2011	8:30	3.7	3.295	0.4015	2.8935	1.673	1.2205	0.729528
22/8/2011	8:30	2.8	3.218	0.4015	2.8165	1.673	1.1435	0.683503
23/8/2011	8:30	2.5	3.169	0.4015	2.7675	1.673	1.0945	0.654214
25/8/2011	8:30	2.4	3.085	0.4015	2.6835	1.673	1.0105	0.604005
26/8/2011	8:30	2.4	3.056	0.4015	2.6545	1.673	0.9815	0.586671
27/8/2011	8:30	2.5	3.016	0.4015	2.6145	1.673	0.9415	0.562762
28/8/2011	8:30	2.6	2.958	0.4015	2.5565	1.673	0.8835	0.528093
29/8/2011	8:30	2.4	2.925	0.4015	2.5235	1.673	0.8505	0.508368
30/8/2011	8:30	1.5	2.902	0.4015	2.5005	1.673	0.8275	0.49462
31/8/2011	8:30	2.1	2.876	0.4015	2.4745	1.673	0.8015	0.479079
1/9/2011	8:30	2.1	2.847	0.4015	2.4455	1.673	0.7725	0.461745
2/9/2011	8:30	2.1	2.826	0.4015	2.4245	1.673	0.7515	0.449193
3/9/2011	8:30	2.3	2.805	0.4015	2.4035	1.673	0.7305	0.436641
4/9/2011	8:30	2.2	2.794	0.4015	2.3925	1.673	0.7195	0.430066
5/9/2011	8:30	2.1	2.773	0.4015	2.3715	1.673	0.6985	0.417513
6/9/2011	8:30	2.1	2.757	0.4015	2.3555	1.673	0.6825	0.40795
7/9/2011	8:30	2	2.746	0.4015	2.3445	1.673	0.6715	0.401375
8/9/2011	8:30	1.9	2.736	0.4015	2.3345	1.673	0.6615	0.395397
9/9/2011	8:30	1.7	2.723	0.4015	2.3215	1.673	0.6485	0.387627
10/9/2011	8:30	1.7	2.707	0.4015	2.3055	1.673	0.6325	0.378063
11/9/2011	8:30	1.6	2.691	0.4015	2.2895	1.673	0.6165	0.3685
12/9/2011	8:30	1.6	2.675	0.4015	2.2735	1.673	0.6005	0.358936
13/9/2011	8:30	1.6	2.663	0.4015	2.2615	1.673	0.5885	0.351763
14/9/2011	8:30	1.5	2.648	0.4015	2.2465	1.673	0.5735	0.342797
15/9/2011	8:30	1.4	2.635	0.4015	2.2335	1.673	0.5605	0.335027
16/9/2011	8:30	1.4	2.625	0.4015	2.2235	1.673	0.5505	0.32905
17/9/2011	8:30	1.3	2.618	0.4015	2.2165	1.673	0.5435	0.324866
18/9/2011	8:30	1.2	2.611	0.4015	2.2095	1.673	0.5365	0.320681
19/9/2011	8:30	1.2	2.595	0.4015	2.1935	1.673	0.5205	0.311118

Appendix D

CLAY LOAM (CHEPKANGA)

DATE	TIME	C(µF)	Mwet.set-up(	M(S,C&P)	M(Wetssp)	M(Dry ssp)	M(water)	Θg(g/g)
20/8/2011	8:30	9.8	3.751	0.403	3.348	2.012	1.336	0.664016
21/8/2011	8:30	11	3.661	0.403	3.258	2.012	1.246	0.619284
22/8/2011	8:30	10.3	3.614	0.403	3.211	2.012	1.199	0.595924
23/8/2011	8:30	9.8	3.536	0.403	3.133	2.012	1.121	0.557157
25/8/2011	8:30	10.4	3.432	0.403	3.029	2.012	1.017	0.505467
26/8/2011	8:30	10.2	3.4	0.403	2.997	2.012	0.985	0.489563
27/8/2011	8:30	10.2	3.356	0.403	2.953	2.012	0.941	0.467694
28/8/2011	8:30	10.4	3.316	0.403	2.913	2.012	0.901	0.447813
29/8/2011	8:30	10.6	3.292	0.403	2.889	2.012	0.877	0.435885
30/8/2011	8:30	10.7	3.269	0.403	2.866	2.012	0.854	0.424453
31/8/2011	8:30	4	3.248	0.403	2.845	2.012	0.833	0.414016
1/9/2011	8:30	10	3.22	0.403	2.817	2.012	0.805	0.400099
2/9/2011	8:30	9.3	3.2	0.403	2.797	2.012	0.785	0.390159
3/9/2011	8:30	9.7	3.178	0.403	2.775	2.012	0.763	0.379225
4/9/2011	8:30	9.2	3.169	0.403	2.766	2.012	0.754	0.374751
5/9/2011	8:30	8.6	3.142	0.403	2.739	2.012	0.727	0.361332
6/9/2011	8:30	8.3	3.127	0.403	2.724	2.012	0.712	0.353877
7/9/2011	8:30	7.6	3.114	0.403	2.711	2.012	0.699	0.347416
8/9/2011	8:30	7.4	3.103	0.403	2.7	2.012	0.688	0.341948
9/9/2011	8:30	7.7	3.09	0.403	2.687	2.012	0.675	0.335487
10/9/2011	8:30	7.2	3.068	0.403	2.665	2.012	0.653	0.324553
11/9/2011	8:30	6.4	3.048	0.403	2.645	2.012	0.633	0.314612
12/9/2011	8:30	6.4	3.027	0.403	2.624	2.012	0.612	0.304175
13/9/2011	8:30	6.1	3.014	0.403	2.611	2.012	0.599	0.297714
14/9/2011	8:30	5.9	2.99	0.403	2.587	2.012	0.575	0.285785
15/9/2011	8:30	5.4	2.972	0.403	2.569	2.012	0.557	0.276839
16/9/2011	8:30	4.7	2.957	0.403	2.554	2.012	0.542	0.269384
17/9/2011	8:30	4.3	2.948	0.403	2.545	2.012	0.533	0.264911
18/9/2011	8:30	4.5	2.924	0.403	2.521	2.012	0.509	0.252982
19/9/2011	8:30	4.7	2.912	0.403	2.509	2.012	0.497	0.247018

Appendix E

OVEN DRY DETAILS

Label	M(empty tray)	M(t& wet sample)	M(tray and dry sample)	M(dry sample)	M(total soil sample)
A1	0.267	1.404	1.183	0.916	
A2	0.253	1.273	1.01	0.757	1.673
C1	0.269	1.699	1.554	1.285	
C2	0.274	1.765	1.622	1.348	2.633
D1	0.278	1.561	1.366	1.088	
D2	0.271	1.471	1.195	0.924	2.012
E1	0.25	1.581	1.506	1.256	
E2	0.255	1.464	1.375	1.12	2.376

Appendix F

PERMEABILITY RESULTS

SOIL TYPE	t1	t2	t3	tav	d	Td	A	BTd	A
Sandy clay loam(chepkanga)	100.72	101.87	102.45	101.68	5	0.41	0.13204255	2.25	3.976594
Sandy clay loam(chepkang,a)	70.33	70.94	70.93	70.73333	5	0.41	0.13204255	2.25	3.976594
Sandy loam(Kerio valley)	74.33	74.85	74.21	74.46333	15	0.41	0.13204255	2.25	3.976594
Loamy sandy(kaptarakwa	244.73	239.85	242.46	242.3467	5	0.41	0.13204255	2.25	3.976594
Clay loam(Chepkanga)	22.52	22.62	22.29	22.47667	5	0.41	0.13204255	2.25	3.976594

	Lsc	H2	H1	LogH1	LogH2	K(cm/s)	K(inches/hour
Sandy clay loam(chepkanga)	24.9	57.4	62.4	1.7951846	1.7589119	0.0006784	0.9615011
Sandy clay loam(chepkang,a)	26.5	58.4	63.4	1.8020893	1.7664128	0.0010208	1.44680183
Sandy loam(Kerio valley)	27	58.4	73.4	1.8656961	1.7664128	0.0027493	3.89675639
Loamy sandy(kaptarakwa	26.5	57.4	62.4	1.7951846	1.7589119	0.0003029	0.42933346
Clay loam(Chepkanga)	22.7	53.2	58.2	1.764923	1.7259116	0.003009	4.26472485